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The Okcheon Supergroup in the Lake Chungju area, Korea: Neoproterozoic volcanic and glaciogenic sedimentary successions in a rift basin

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ABSTRACT: The Okcheon Belt in southern Korea is an NE-SW trending fold-and-thrust belt consisting of two sedimentary basins of different origins: namely, the Chungcheong Basin and the Taebaeksan Basin. The Chungcheong Basin was a Neoproterozoic rift basin belonging to the South China Craton, while the Taebaeksan Basin was a Paleozoic shallow marine to non-marine sedimentary basin fringing the Sino-Korean Craton. These two basins merged to form the Okcheon Belt in the early Triassic by the collision of Sino-Korean and South China cratons and their boundary is currently demarcated by the South Korean Tectonic Line. The Okcheon Supergroup is herein refined to include the Neoproterozoic volcanic and glaciogenic sedimentary successions deposited in the Chungcheong Basin and is divided into the two groups: the Chungju Group consists of the Gyemyeongsan Formation, Hyangsanni Dolomite, and Daehyangsan Quartzite and the Suanbo Group is proposed to include the Munjuri, Hwanggangni, Myeongori, and Gounni formations in ascending order. The Myeongori Formation is emended to comprise the Geumgang Limestone and the Seochangni members. This lithostratigraphic scheme is correlatable with that of the Nanhua Basin in South China, suggesting that the Chungcheong Basin was an eastward extension of the Nanhua Basin during the Neoproterozoic. The geological structure of the Okcheon Supergroup in the Lake Chungju area is characterized by a number of isoclinal to tight, frequently overturned, anticlines and synclines. No major thrust faults were recognized within the study area, except the constraining bend of the South Korean Tectonic Line. Three deformational phases are empirically differentiated: D1 deformation most strongly affected the rocks of the Okcheon Supergroup; D2 deformation was produced by the collision between the Sino-Korean and South China cratons; and D3 deformation is represented by normal to strike-slip faults. D1, D2 and D3 deformational phases are referred to the Okcheon (mid-Paleozoic), Songnim (Triassic) and/or Daebo (Jurassic) orogenies, and post-Jurassic events, respectively. The Chungcheong Basin was initiated as a part of an intracratonic rift basin (Nanhua Basin) within the South China Craton in association with early Neoproterozoic break-up event of the supercontinent Rodinia. The bimodal volcanic succession of the Gyemyeongsan Formation corresponds to the initial rift episode of the Chungcheong Basin, and was succeeded by shallow marine Hyangsanni Dolomite and Daehyangsan Quartzite. The second phase of rifting at ~750 Ma accumulated a thick bimodal volcanic succession of the Munjuri Formation which is overlain by the diamictites of the Hwanggangni Formation representing the Cryogenian global glacial event, snowball Earth. The immediately-succeeding cap carbonate, Geumgang Limestone Member of the Myeongori Formation, recorded the deglaciation event. The Seochangni Member of the Myeongori Formation is characterized by dark gray slate/phyllite facies indicating a poorly-oxygenated basin during the Ediacaran. No stratigraphic unit overlying the Gounni Formation, the youngest Neoproterozoic formation of the Okcheon Supergroup, occurs in the Lake Chungju area, and thus little is known on the Paleozoic tectonic evolution of the Chungcheong Basin. It is inferred that the medium-pressure type regional metamorphism and the predominance of ductile deformation of the Okcheon Supergroup can be attributed to the mid-Paleozoic Okcheon Orogeny which would have been in line with the Wuyun Orogeny of South China. The South China and Sino-Korean cratons should have been drifted away from the Gondwana sometime during the mid-Paleozoic and collided to form the East Asian continent at ~250 Ma.

Key words: Okcheon Supergroup, Okcheon Belt, lithostratigraphy, Neoproterozoic, South China Craton

1. INTRODUCTION

The Okcheon (or Ogcheon) Belt in Korea is an NE-SW trending fold-and-thrust belt of ca. 50 km in width and over 350 km in length, bounded to the northwest by the Gyeonggi Massif and to the southeast by the Yeongnam Massif (Fig. 1). It is a composite tectonic unit formed by collision of the Sino-Korean (or North China) and South China cratons in the early Triassic (Cluzel et al., 1991b; Yin and Nie, 1993; Chough et al., 2000; Ree et al., 2001). Two sedimentary basins of different origins were involved in the formation of the Okcheon Belt: i.e., in pre-Mesozoic times the Chungcheong Basin (new name) to the southwest was part of the South China Craton, while the Taebaeksan Basin to the northeast belonged to the Sino-Korean Craton (Chough et al., 2000). The Chungcheong Basin is proposed herein to replace the formerly Okcheon Basin in Chough et al. (2000), as the term Okcheon Belt has long been employed in Korea. The Chungcheong Basin is characterized by poorly fossiliferous, medium-pressure type metasedimentary and metavolcanic rocks exposed mainly in Chungcheong Province, which are referred to the Neoproterozoic

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in age (see below). On the other hand, the Taebaeksan Basin comprises fossiliferous, non- to weakly-metamorphosed sedimentary rocks of Paleozoic age (Choi and Chough, 2005).

Metasedimentary and metavolcanic rocks of the Chungcheong Basin have been collectively called the Okcheon Supergroup. The Okcheon Supergroup was variably divided into more than twenty formations (Lee and Park, 1965; Kim, 1968, 1970; Son, 1970; Reedman et al., 1973; Kim and Kim, 1974; Lee, 1995; Lee et al., 1998; Lim et al., 2005, 2006, 2007), and the geologic ages and stratigraphic relationships of these formations remain controversial over the years (Table 1; also see the section of Historical Background for further details). Disagreement on the geologic ages and stratigraphy of the Okcheon Supergroup can be attributed to the paucity of reliable age indicators and few constraints on the tectonostratigraphic setting.

We attempt to unravel the stratigraphy and tectonic setting of the Okcheon Supergroup exposed in the Lake Chungju area (Figs. 1 and 2), covering the northeastern Chungcheong Basin and the westernmost Taebaeksan Basin. The two basins are separated by the transform suture between the Sino-Korean and the South China cratons: the South Korean Tectonic Line (Chough et al., 2000). The stratigraphy of the Okcheon Supergroup is constructed on the basis of the field observations and compilation of previous suggestions: 1) the Chungcheong Basin belonged to the South China Craton in pre-Mesozoic times (Chang, 1996; Chough et al., 2000; Oh et al., 2004; Choi, 2009, 2011); 2) the diamictites of the Hwanggangni Formation are glaciogenic sediments (Reedman et al., 1973; Kim and Kim, 1974; Lee et al., 1998); and 3) the diamictite-carbonate couplet of the Chungcheong Basin can be correlated with the Neoproterozoic glaciogenic diamictite-carbonate couplets of South China (cf. Wang and Li, 2003; Dobrzinski and Bahlburg, 2007; Wang et al., in press). The reported radiometric ages from the metavolcanic rocks of the Okcheon Supergroup (Lee, K.-S. et al., 1998; Cho et al., 2004; Kim et al., 2006) are also incorporated in establishing the stratigraphy of the Okcheon Supergroup.

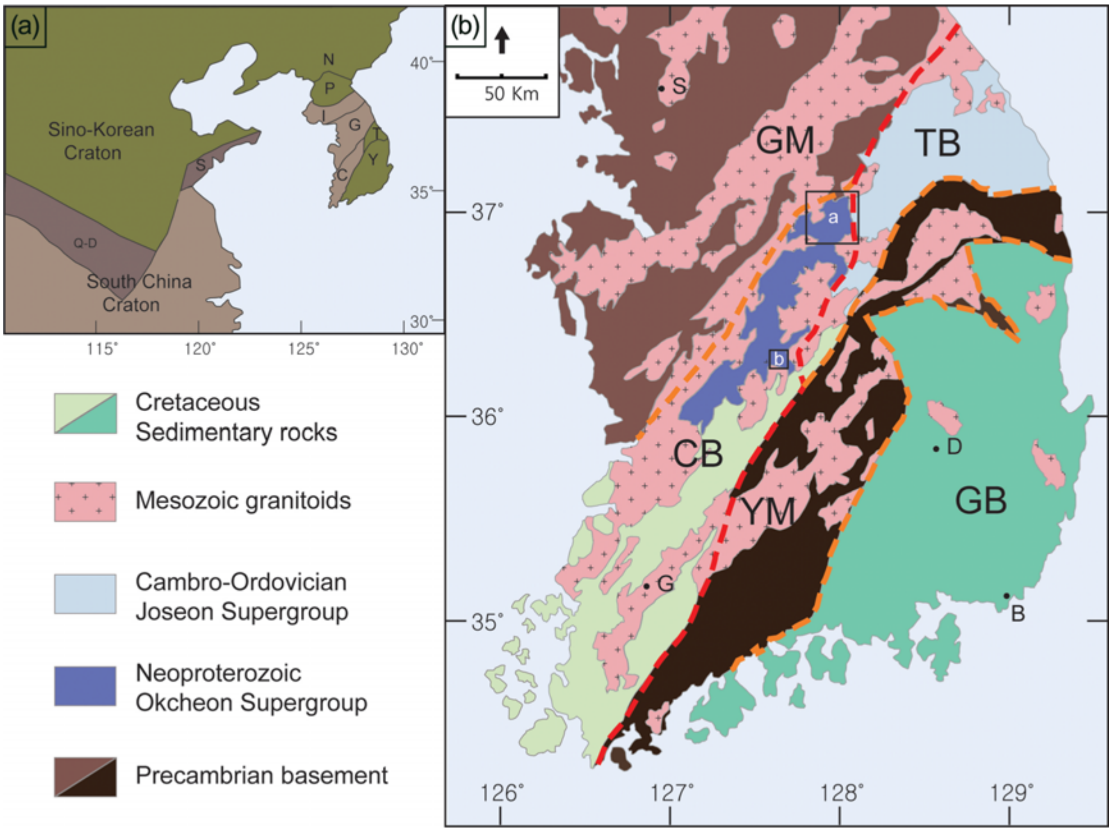

Fig. 1. (a) Tectonic map of East Asia displaying the configuration of the Sino-Korean (marked in green) and South China (marked in brown) cratons. C, Chungcheong Basin; G, Gyeonggi Massif; I, Imjingang Belt; N, Nangnim Massif; P, Pyeongnam Basin; Q-D, Qinling-Dabie Belt; S, Sulu Belt; T, Taebaeksan Basin; Y, Yeongnam Massif. (b) Simplified geologic map of southern Korea showing the tectonic provinces: GM, Gyeonggi Massif; TB, Taebaeksan Basin; CB, Chungcheong Basin; YM, Yeongnam Massif; GB, Gyeongsang Basin. The thick dotted lines in the geologic map indicate the boundary between the tectonic provinces. The red dotted line denotes the South Korean Tectonic Line (SKTL). The white open boxes a and b in the middle of the map represent approximate locations of Figures 2 and 6. (Dots with a letter on the geologic map: B, Busan; D, Daegu; G, Gwangju; S, Seoul). The Okcheon Belt is a composite tectonic unit comprising the Taebaeksan and Chungcheong basins.

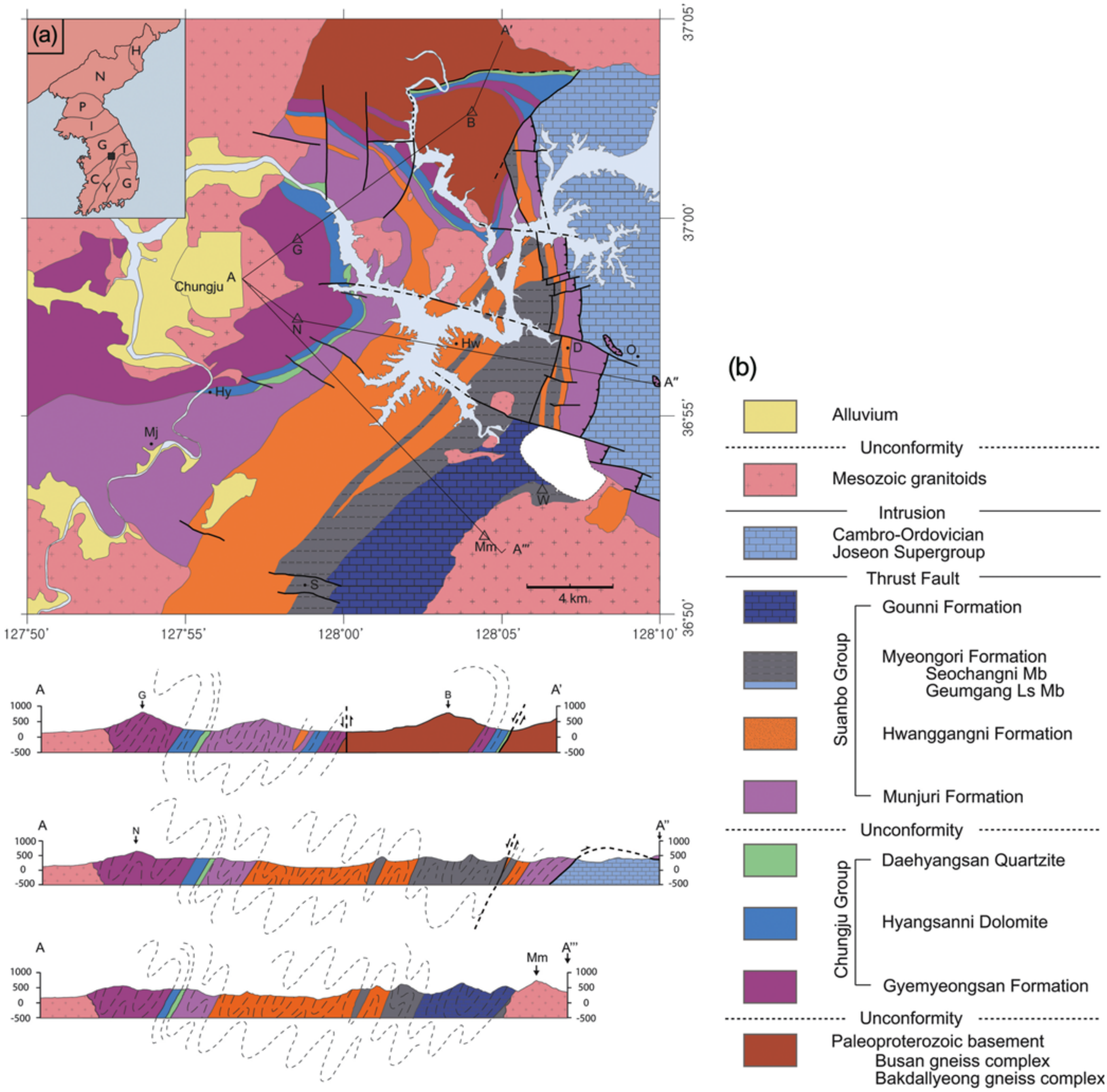

Fig. 2. (a) Geologic map and cross sections of the Lake Chungju area. Abbreviations in the geologic map and cross sections: B, Mt. Busan; D, Deokgokri, G, Mt. Gyemyeongsan, Hw, Hwanggangni; Hy, Hyangsanni; Mj, Munjuri; Mm, Mt. Malmoesan; N, Mt. Namsan; O, Otiri; S, Suanbo; W, Wolaksan. The black square in the index map indicate the location of the study area. Abbreviations in the index map are the same as those in Figure 1. (b) Legends for Figures 2a and 5.

2. HISTORICAL BACKGROUND

Nakamura (1923, 1924) was the first to apply the term Okcheon formation (or system) to the metasedimentary rocks exposed in Chungju and Hamchang areas and assigned it to the Precambrian age. Subsequently, the Okcheon formation and equivalent strata in the so-called metamorphosed Okcheon zone were studied by Japanese geologists during the Japanese ruling period, but their stratigraphic relationships and geologic ages remained unclear (Kobayashi, 1953).

The intensive study on the Okcheon Supergroup by Korean geologists was triggered by geologic mapping of the Chungju and Hwanggangni quadrangles in mid-1960s (Kim and Lee, 1965; Lee and Park, 1965). These early workers established a lithostratigraphy of the Okcheon Supergroup including in ascending order the Gounni, Seochangni, Buknori,

Table 1. History of the stratigraphic nomenclature of the Okcheon Supergroup in Chungcheong Basin, Korea

Geologic age	Lee & Park (1965)	Kim (1968)	Son (1970)		Reedman et al. (1973)	
Mesozoic						
Permian Carboniferous Devonian Silurian	Munjuri Fm Hwanggangni Fm Myeongori Fm Buknori Fm ~~~~~~~~ Seochangni Fm (Daehyangsan Qtz Hyangsanni Dol Gyemyeongsan Fm)		Okcheon Group ------------- Chungju Group	Hwanggangni Fm Ungokni Fm Seochangni Fm Munjuri Fm Miwon Fm Daehyangsan Qtz ~~~~~~~~ Daehyangsan Fm Gyemyeongsan Fm		
Ordovician Cambrian	Gounni Fm	Joseon Supergroup		Joseon Supergroup	Chungju Group	Gyemyeongsan Fm Daehyangsan Fm
Proterozoic		Gunjasan Fm ~~~~~~~~~ Hwanggangni Fm ~~~~~~~~~ Changni Fm (Seochangni Fm + Majeonni Fm) Munjuri Fm			Okcheon Group	Munjuri Fm Hwanggangni Fm Myeongori Fm Buknori Fm Seochangni Fm Gounni Fm

Geologic age	Chough & Bahk (1992)	Lee (1995)		Lee et al. (1998)	Lim et al. (2005, 2006, 2007)
Mesozoic					
Permian Carboniferous Devonian Silurian	Munjuri Fm Hwanggangni Fm Hansu Ls Myeongori Fm Buknori Fm ~~~~~~~~~~~~~~			Munjuri Fm Hwanggangni Fm Myeongori Fm Buknori Fm Seochangni Fm	E Fm Bibong Fm ~~~~~~~~~~~~~~~ C Fm B Fm A Fm
Ordovician Cambrian	Seochangni Fm ~~~~~~~~~~~~~~ Gyemyeongsan Fm Hyangsanni Dol Daehyangsan Fm	Deokpyeong Group	Myeongori Fm Naesari Fm Hwanggangni Fm Guryongsan Fm Hwajeonni Fm	Gounni Fm Joseon Supergroup	F Fm ------------(?)------------ Hwanggangni Fm
		Miwon Group	Ungyori Fm Jeungpyeong Fm		
Proterozoic					MV Fm (?)

Myeongori, Hwanggangni, and Munjuri formations, while the Gyemyeongsan Formation, Hyangsanni Dolomite, and Daehyangsan Quartzite were considered equivalent to the Seochangni Formation (Table 1). The putatively lowermost formation of the supergroup, Gounni Formation, was correlated with the Ordovician formations of the Joseon Supergroup, and accordingly the remaining formations of the supergroup were placed to the post-Ordovician. On the other hand, Kim (1968) suggested a completely different stratigraphy: the Okcheon system was divided into from old to young the Munjuri, Changni (Seochangni Formation + Majeonni Formation), Hwanggangni, and Gunjasan (= Buknori) formations, and was assigned to the Precambrian. In contrast, Son (1970) divided the Okcheon system into the Chungju and Okcheon groups and placed the Okcheon system superjacent to the Cambro-Ordovician Joseon system with modified stratigraphy: the Chungju Group comprises the Gyemyeongsan and Daehyangsan formations, while the Okcheon Group includes the Daehyangsan Quartzite, Miwon, Munjuri, Seochangni, Ungokni, and Hwanggangni formations in ascending order (Table 1). Meanwhile, Reedman et al. (1973) followed the stratigraphy proposed by Lee and Park (1965) with slight modification, but assigned the Okcheon Group to the Proterozoic and the Chungju Group to the lower Paleozoic: the Okcheon Group comprises in ascending order the Gounni, Seochangni, Buknori, Myeongori, Hwanggangni, and Munjuri formations, while the Chungju Group includes the Daehyangsan and Gyemyeongsan formations. The age assignment of the Chungju Group to the lower Paleozoic was based on the occurrence of an archaeocyathid from the Hyangsanni Dolomite (Lee et al., 1972).

In short, three contrasting views on the stratigraphy and geologic age of the Okcheon Supergroup were proposed in 1970s: 1) all of the formations were considered the Proterozoic (Kim, 1968, 1970; Kim and Kim, 1974); 2) they were assigned to the post-Ordovician (Lee and Park, 1965; Son, 1970); and 3) the lower part of the supergroup was placed to the Proterozoic, while the upper part to the Cambro-Ordovician (Reedman et al., 1973). Since then, no significant contributions have been made for the stratigraphy of the Okcheon Supergroup, but most of studies favored the Paleozoic for the geologic age of the Okcheon Supergroup (see Table 1; Cluzel et al., 1990, 1991a).

3. GEOLOGIC SETTING OF THE CHUNGCHEONG BASIN

3.1. Tectonic Framework of East Asia

It has been well appreciated that East Asia was formed by collision of two continental fragments derived from the Paleozoic Gondwana during the early Mesozoic times (McElhinny et al., 1981; Lin et al., 1985; Mattauer et al., 1985; Yin and Nie, 1996). These continental fragments are the Sino-Korean and South China cratons (Fig. 3). The term 'craton' is used here to include a shield area which is composed of Precambrian rocks and a platform area where Precambrian rocks are overlain by younger sedimentary strata (cf. Neuendorf et al., 2005). The Sino-Korean and South China cratons are separated by a collisional suture, the Qinling-Dabie-Sulu-Imjingang Belt, which extends over 2000 km in a roughly E-W direction (Chough et al., 2000).

The Sino-Korean Craton comprises most of North China, southern part of NE China, and northern and southeastern parts of the Korean Peninsula, and is bounded to the north by the Central Asian Orogenic Belt and to the south by the Qinling-Dabie-Sulu-Imjingang Belt (Lu et al., 2008). It should be emphasized that the southeastern part of the Korean Peninsula (Yeongnam Massif and Taebaeksan Basin) belongs to the Sino-Korean Craton (Chough et al., 2000; Choi et al., 2001; Ree et al., 2001; Choi and Kim, 2006). The Sino-Korean Craton has been divided into the Eastern and Western blocks which are separated by the Paleoproterozoic Trans-North China Orogen (Lu et al., 2008; Fig. 3). Most of the Korean Peninsula belongs to the Eastern Block, including the Nangnim Massif and the Pyeongnam Basin in northern Korea and the Yeongnam Massif and the Taebaek-

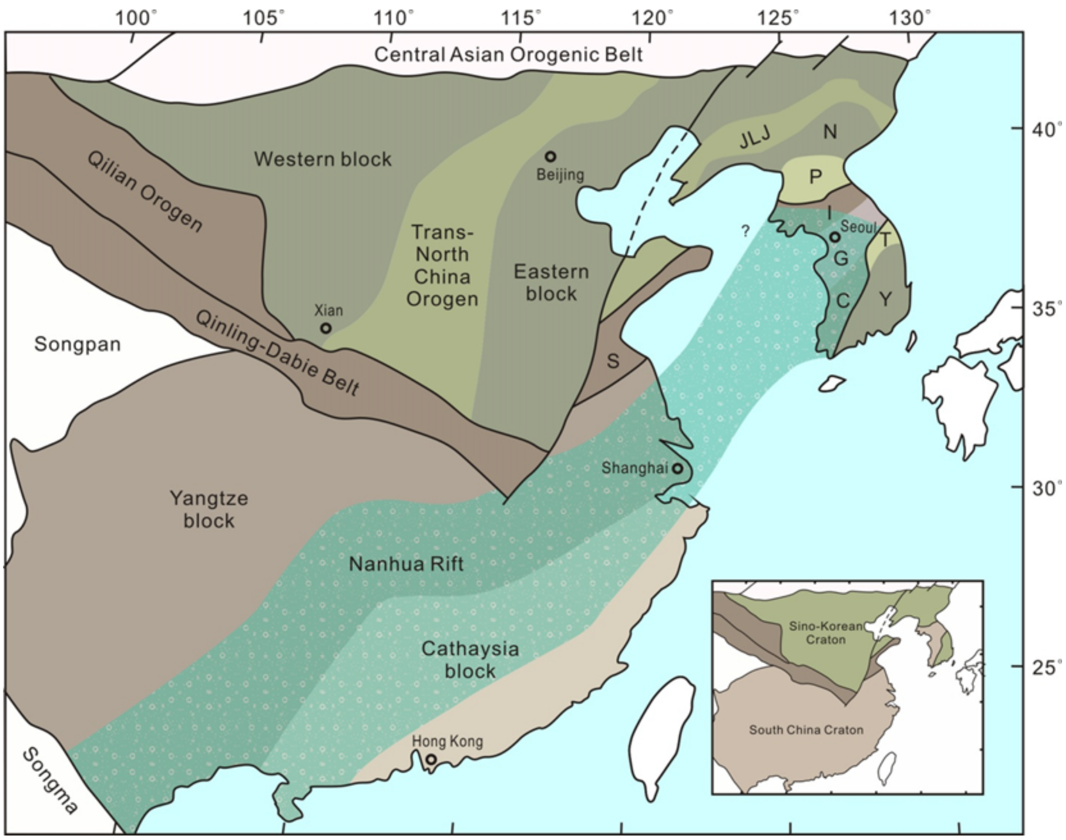

Fig. 3. Tectonic subdivision of East Asia. East Asia is composed of two cratons: Sino-Korean Craton to the north (green) and the South China Craton to the south (brown) (modified after Lu et al., 2008). Distribution of the Cryogenian diamictites in the South China Craton is marked in light blue with pattern (modified after Wang and Li, 2003). Abbreviations: C, Chungcheong Basin; G, Gyeonggi Massif; I, Imjingang Belt; JLJ, Jiao-Liao-Ji Belt; N, Nangnim Massif; P, Pyeongnam Basin; S, Sulu Belt; T, Taebaeksan Basin; Y, Yeongnam Massif.

san Basin in southern Korea (Choi, 2009, 2011; Fig. 3).

The South China Craton comprises most of South China and middle part of the Korean Peninsula and is bounded to the north by the Qinling-Dabie-Sulu-Imjingang Belt but its southern boundary is indeterminate, except in the Korean Peninsula where the South Korean Tectonic Line (Chough et al., 2000) marks the southeastern margin of the South China Craton. The Imjingang Belt, Gyeonggi Massif, and Chungcheong Basin of the Korean Peninsula occupied the marginal part of the South China Craton during the Neoproterozoic and Paleozoic times (Choi, 2009, 2011; Fig. 3).

The Sino-Korean and South China cratons collided to form much of the current East Asian continent in the early Triassic. This tectonic event has long been known as the Indosinian Orogeny in China and the Songnim Orogeny in Korea (cf. Yin and Nie, 1996; Chough et al., 2000).

3.2. Neoproterozoic–Paleozoic Tectonic Evolution of the South China Craton

The South China Craton has been formed by amalgamation of the Yangtze and Cathaysia blocks in the early Neoproterozoic (Chen et al., 1991; Charvet et al., 1996; Zhao and Carwood, 1999; Wang et al., 2006; Li et al., 2007; Li, W.-X. et al., 2008; Li et al., 2009). The tectonic event has been known as the Sibao (or Jinning) Orogeny and occurred in 900–880 Ma. The paleogeographic position of the South China Craton during the Neoproterozoic has been controversial over the years: the South China Craton was treated as a terrane within the middle of Rodinia (Li et al., 2003, 2008), whereas recent studies (Yu et al., 2008; Hofmann et al., 2011; Zhao et al., 2011) favored that the South China Craton was located at the margin of Rodinia.

Multiple Neoproterozoic bimodal volcanic episodes in South China Craton were related to the break-up of the supercontinent Rodinia (Wang and Li, 2003; Li et al., 2003; Zhou et al., 2007; Li, W.-X. et al., 2010): first rift stage at 850–820 Ma and second phase of rifting at 780–750 Ma, respectively. These rifting events resulted in the formation of the Nanhua Basin (or Rift), in which thick successions (ca. 750 m to over 5000 m in thickness) of Neoproterozoic volcanic and sedimentary rocks were accumulated (Wang and Li, 2003; Wang et al., in press). Wang et al. (in press) recognized three tectonostratigraphic sequences within the Nanhua Basin: Sequence-I is of 850–820 Ma volcanic-sedimentary successions (Sibao, Lengjiaxi, and Shuangqiaoshan groups); Sequence-II is represented by 820–720 Ma volcanic-sedimentary successions (Banxi, Danzhou, and Xiajiang groups); and Sequence-III comprises 720–635 Ma glacial/interglacial deposits (see below). Zhou et al. (2009) related the Neoproterozoic sequence (872–835 Ma; Fanjingshan Group, equivalent to the Sibao Group in Guangxi) in Guizhou region to the arc magmatism and associated foreland deposition, whereas Li, X.-H. et al. (2008) and Li, W.-X. et al. (2010) suggested that the volcanic-sedimentary succession was accumulated in an intraplate rift basin formed by the break-up of Rodinia.

The Cryogenian sequence in South China Craton comprises two glaciogenic diamictite successions interrupted by an interglacial manganese-bearing shale/siltstone interval (Zhang et al., 2008, 2011). The upper diamictite succession (Nantuo Formation) shows a broader distribution than the lower one (Changan Formation) (Wang and Li, 2003). Zhang et al. (2011) constrained the age of the two Cryogenian glaciations: 725–663 Ma for the Changan (or Jiangkou) glaciation and 656–635 Ma for the Nantuo glaciation. The lack of significant volcanic activity during the Cryogenian has been interpreted to represent a transition from the continental rift phase to the sag phase (Wang and Li, 2003).

The Ediacaran succession in South China Craton is divided into the Doushantuo Formation and the Dengying/Liuchapo Formation. The Doushantuo Formation is composed predominantly of black shale and carbonate, and ranges in thickness from 40 m to 180 m (Zhu et al., 2007). The lowermost part of the Doushantuo Formation is characterized by the occurrence of a thin (several-m-thick) cap carbonate bed. The Doushantuo Formation also contains two phosphorite-bearing units [dated as ~599 Ma (Barfod et al., 2002) and ~576 Ma (Chen et al., 2004)] which yielded putative animal embryo fossils (Xiao et al., 1998; but see Huldtgren et al., 2011), multicellular algae, and acanthomorphic acritarchs (Zhang et al., 1998; Xiao, 2004). The boundary between the Doushantuo Formation and the Dengying Formation was dated as 551.1 ± 0.7 Ma (Condon et al., 2005) and 555.2 ± 6.1 Ma (Zhang et al., 2005). The overlying Dengying Formation comprises a thick succession of limestone and dolostone, with occasional black shale and bedded chert layers. Ediacaran body fossils and trace fossils were reported from the Dengying Formation (Sun, 1986; Xiao et al., 2005). The age of the upper boundary of the Dengying Formation was set at ~542 Ma (Jiang et al., 2011).

There is no major sedimentary break within the Paleozoic successions of the Yangtze Block, except the area that experienced mid-Paleozoic orogeny. The Devonian rocks therein are disconformably underlain by the Silurian rocks.

The mid-Paleozoic orogeny in South China Craton, Wuyun (or Wuyi-Yunkai) Orogeny (Li et al., 2010), is one of the major orogenic events in the formation of East Asian continent. The Wuyun orogeny lasted in age from mid-Ordovician (~460 Ma) to early Devonian (~400 Ma) (Faure et al., 2009; Li et al., 2010). Eastern Wuyun orogen experienced amphibolite facies metamorphism during the interval of 460–440 Ma, while retrograde metamorphic (or cooling) ages were estimated to be no younger than ~420 Ma (Li et al., 2010) or ~405 and ~397 Ma (Faure et al., 2009). This orogenic event was attributed to the intracontinental subduction (Faure et al., 2009) in which the Cathaysia Block was subducted beneath the Yangtze Block. In early Silurian (ca. 445–430 Ma), the exhumation of deeper part of the orogen was accommodated by deposition of a Silurian trubidite succession in the foreland basin. In contrast, Su et al. (2009) and Li et al. (2010) interpreted that the foreland basin was formed by NW-directed thrusting of the Cathaysia Block onto the Yangtze Block.

The formation of the East Asian continent had been completed by amalgamation of the Sino-Korean and South China cratons along the Qinling-Dabie-Sulu-Imjingang Belt in the early Mesozoic times (McElhinny et al., 1981; Lin et al., 1985; Mattauer et al., 1985; Yin and Nie, 1993, 1996; Ree et al., 1996; Chough et al., 2000).

3.3. Neoproterozoic Sedimentation in the Chungcheong Basin

The Chungcheong Basin is considered a northeastward extension of the Nanhua Basin of South China (Chang, 1996; Oh et al., 2004; Choi, 2009, 2011; Fig. 3). Accordingly, the tectonic evolution and sedimentation of the Chungcheong Basin is assumed to be closely related to that of the Nanhua Basin (Table 2).

The Gyemyeongsan Formation is characterized by bimodal volcanic rocks with dominantly felsic (trachyte) and some mafic (subalkaline and alkali basalt) composition and lesser amounts of quartzite and marble (Kim et al., 1998; Koh et al., 2005; Park et al., 2005). The detrital zircon age of ~870 Ma from the formation (Kim et al., 2006; Kang et al., 2012) can be related to the first rift stage (or Sequence-I) of the Nanhua Basin (Wang and Li, 2003; Wang et al., in press; Table 2). The Munjuri Formation includes greenish gray to dark gray phyllites, schists, and volcanic rocks of metatrachytes and amphibolites. The petrological studies and U-Pb zircon ages of the volcanic rocks revealed that the Munjuri Formation was formed in an intracratonic rift basin with bimodal volcanism at ca. 750 Ma (Lee, K.-S. et al., 1998; Cho et al., 2004; Kim et al., 2006), which can be equivalent to the second rift stage (or Sequence-II) of the Nanhua Basin (Wang and Li, 2003; Wang et al., in press; Table 2). The Hyangsanni Dolomite and Daehyangsan Quartzite are assumed to have been deposited in a normal marine setting between these two rifting stages.

Diamictites of the Hwanggangni Formation are assumed to be Cryogenian glaciogenic sediments and their ages may be broadly bracketed between 720 Ma and 635 Ma. The Cryogenian glaciogenic sediments are widespread in South China Craton and their distribution can be extended into the Korean Peninsula (Fig. 3). While two glaciogenic diamictite successions are documented in the Nanhua Basin of South China (Wang and Li, 2003; Zhang et al., 2008; Jiang et al., 2011), the Hwanggangni Formation is the only diam-

Table 2. Suggested correlation of the Neoproterozoic successions of the Chungcheong Basin, Korea with those of the Nanhua Basin, South China

Age	Chungcheong Basin (Korea)	Nanhua Basin (South China): Yangtze Gorge (Guizhou/Hubei/Hunan/Guangxi)	Nanhua Basin (South China): Jiangnan Ridge (Anhui/Zhejiang)	Tectonic events in South China
Paleozoic	Okcheon orogeny (?)			Wuyun orogeny/(460–400 Ma[k])
Ediacaran	Gounni Fm Myeongori Fm	Dengying/Liuchapo Fm (542–551 Ma[c]) Doushantuo Fm (551–635 Ma[d])	Piyuancun Fm Lantian Fm	deglaciation ----- 635 Ma -----
Cryogenian		Nantuo Fm (656–635 Ma[e])	Leigongwu Fm/ Nantuo Fm	
	Hwangangni Fm	Xiangmeng/Datangpo Fm (663–654 Ma[f])	Xiangmeng Fm/ Dongshanfeng Fm	Cryogenian glaciation
		Changan/Fulu/Guiping/Tiesiao Fm (725–663 Ma[g])	Xiuning Fm/ Zhitang Fm	----- 720 Ma -----
	Munjuri Fm (~750 Ma[a]) Daehyangsan Qtz Hyangsanni Dol	Liantuo Fm/Banxi Gp (748 Ma[h])	Jingtan Fm/ Shangshu Fm	2nd rift stage (820–720 Ma[l])
	Gyemyeongsan Fm (~870 Ma[b])	Sibao/Lengjiaxi/Shuangqiaoshan Gp (825–842 Ma[i]; 878–879 Ma[j])		----- 820 Ma ----- 1st rift stage (850–820 Ma[l])
Tonian				

Geochronologic data are from the following sources: [a]Lee, K.S. et al. (1998), Cho (2004), Kim et al. (2006); [b]Kim et al. (2006); [c]Condon et al. (2005), Jiang et al. (2011); [d]Condon et al. (2005); Zhang et al. (2005); Jiang et al. (2011); [e]Zhang et al. (2011); [f]Dobrzinski & Bahlburg (2007); Jiang et al. (2011); [g]Zhang (2008), Jiang et al. (2011); [h]Dobrzinski & Bahlburg (2007); [i]Wang et al. (in press); [j]Wang et al. (2008); [k]Faure et al. (2009), Li et al. (2010); [l]Wang et al. (in press).

Table 3. Summary of revised lithostratigraphy of the Okcheon Supergroup in the Lake Chungju area employed in this report

Age	Rock Unit			Major lithology	Remarks
Ediacaran	Suanbo Group	Gounni Formation		limestone, dolostone, marble	unfossiliferous; strongly metamorphosed
		Myeongori Formation	Seochangni Member	dark gray to black slate/phyllite	volcanics within Seochangni Member
			Geumgang Limestone Member	massive to bedded limestone & dolostone	cap carbonate
Cryogenian		Hwanggangni Formation		diamictite	glaciogenic sediments
		Munjuri Formation		volcanics, slate, phyllite & schist	zircon age: ca. 750 Ma (Lee, K.S et al., 1998; Cho & Kim, 2004; Kim et al., 2006)
	Chungju Group	Daehyangsan Quartzite		milky white quartzite	
		Hyangsanni Dolomite		dolostone, limestone	
		Gyemyeongsan Formation		schist, phyllite, volcanics, quartzite	zircon age: ca. 870 Ma (Kim et al., 2006)
Paleo-Proterozoic	Busan/Bakdallyeong Gneiss Complex			migmatitic banded gneiss, granitic gneiss, augen gneiss, schist, quartzite	1932 ± 65 Ma (Sagong & Kwon, 1998); 1937 ± 6 Ma (Horie et al., 2009)

ictite sequence recognized in the Chungcheong Basin. The Geumgang Limestone in the Chungcheong Basin is correlated with the cap carbonates documented elsewhere in the Nanhua Basin. The Geumgang Limestone is succeeded by the dark gray slate/phyllite facies of the Seochangni Formation (sensu Lee and Park, 1965). In this study, the Geumgang Limestone and the Seochangni Formation put together to form the lower and upper members of the Myeongori Formation, respectively (see below). The overlying Gounni Formation is characterized by the predominance of carbonates. The Myeongori and Gounni formations are correlatable with the Ediacaran Doushantuo and Dengying/Liuchapo formations of the South China Craton, respectively (Table 2) and are interpreted to have been deposited in an epeiric sea during the Ediacaran. No Paleozoic strata are known to occur within the Chungcheong Basin in the Lake Chungju area.

In summary, the Neoproterozoic sedimentary successions of the Chungcheong Basin in the Lake Chungju area, i.e., Okcheon Supergroup, can be divided into in ascending order the Gyemyeongsan, Hyangsanni Dolomite, Daehyangsan Quartzite, Munjuri, Hwanggangni, Myeongori (including Geumgang Limestone and Seochangni members), and Gounni formations (Table 3). This lithostratigraphic scheme can be correlated well with those of the Nanhua Basin in South China (Table 2). It should be emphasized that the current stratigraphy of the Okcheon Supergroup is profoundly different from those of previous studies (Table 1).

4. STRATIGRAPHY OF THE OKCHEON SUPERGROUP

4.1. General Statement

Lithologies in the Lake Chungju area can be subdivided into four major groups: they are the Paleoproterozoic metamorphic rocks, Neoproterozoic Okcheon Supergroup, lower Paleozoic Joseon Supergroup, and Mesozoic granitoids (Fig. 2).

The Paleoproterozoic metamorphic rocks, Busan and Bakdallyeong gneiss complexes, provided the basement for the Neoproterozoic metasedimentary and metavolcanic rocks of the Okcheon Supergroup. The gneiss complexes comprise migmatitic banded gneiss, granitic gneiss, augen gneiss, schist and quartzite, and experienced the amphibolite-facies peak metamorphism followed by the epidote-amphibolite and greenschist facies retrogression (Na, 1987). The U-Pb ages of the gneiss complexes were dated as 1932 ± 65 Ma (Sagong and Kwon, 1998) and 1937 ± 6 Ma (Horie et al., 2009).

The Neoproterozoic Okcheon Supergroup is herein revised to include the Chungju Group and the Suanbo Group (new name) (Table 3). The Chungju Group was originally proposed to comprise the Gyemyeongsan and Hyangsanni formations (Son, 1970), but later the Daehyangsan Quartzite was added to the group (Reedman et al., 1973). The Suanbo Group is proposed to replace the formerly Okcheon Group of Son (1970) and Reedman et al. (1973; see Table 1), as the name Okcheon has long been applied to the whole Neoproterozoic succession of the Chungcheong Basin. The Suanbo Group consists of the Munjuri, Hwanggangni, Myeongori (including the Geumgang Limestone and Seochangni members), and Gounni formations in ascending order (Table 3).

The Cambrian-Ordovician Joseon Supergroup is confined to the east of the South Korean Tectonic Line (Figs. 1 and 2). We do not attempt to differentiate the Joseon Supergroup into the lower stratigraphic unit, as it displays the lithologic succession somewhat different from those of the known groups of the Joseon Supergroup (cf. Choi and Chough, 2005). According to the proposal of Choi (1998), the Joseon Supergroup at the Lake Chungju area should belong to the Yeongwol Group, but Choi (1998) mentioned the difficulty in differentiating the supergroup in the western part of the Taebaeksan Basin.

Mesozoic granitoids are widely exposed around the Lake Chungju area. These granitoid rocks are mostly Triassic-Jurassic granites (Kim et al., 2011) which occupy the northeastern (Jecheon granite), northwestern (Chungju granite), and southwestern corners of the study area (Fig. 2; Kim and Shin, 1990). Cretaceous granites (Wolaksan granite) are restricted to the southeastern corner of the study area. In addition, small patches of granite and granite porphyry occur as dykes and stocks.

4.2. Chungju Group

The Chungju Group was originally defined to include the Gyemyeongsan and Daehyangsan formations (Son, 1970; Reedman et al., 1973), and was referred to be Paleozoic in age. In this study, the Chungju Group is revised to comprise in ascending order the Gyemyeongsan, Hyangsanni Dolomite, and Daehyangsan Quartzite formations, and is assigned to the early Neoproterozoic.

The Chungju Group is mainly exposed in the mid-western part of the study area, but also occurs in the northern part (in the vicinity of Mt. Busan) where the group rests unconformably on the Paleoproterozoic Busan/Bakdallyeong metamorphic complexes. The Chungju Group is in turn overlain disconformably by the Suanbo Group. The thickness of the Chungju Group is hardly estimated due to strong deformation, but assumed to be at least 300 m in the northern part of the study area.

4.2.1. Gyemyeongsan Formation

Definition: The Gyemyeongsan Formation is the lowermost unit of the Chungju Group. The formation is unconformably underlain by the Paleoproterozoic Busan/Bakdallyeong metamorphic complexes and conformably grades upward into the Hyangsanni Dolomite. The Gyemyeongsan Formation was originally established by Kim and Lee (1965) to denote an assemblage of schists and gneisses exposed in the Chungju area. It is composed predominantly of pelitic and psammitic phyllites/schists with lesser amounts of calc-silicates and quartzites. The pelitic and psammitic phyllites/schists are known to have been derived from felsic and mafic volcanic rocks (Na et al., 1982; Cluzel, 1992; Kang and Ryoo, 1997; Park et al., 2003; Koh et al., 2005; Park et al., 2005; Kim et al., 2006).

Distribution: The Gyemyeongsan Formation is widely exposed in the central western part of the study area (Fig. 2). At Mt. Busan area, the formation occurs in direct contact with the Paleoproterozoic Busan/Bakdallyeong metamorphic complexes. Exposures of the Gyemyeongsan Formation in Mt. Busan area (Fig. 2) was previously designated as the Seochangni Formation in the Jecheon quadrangle (Kim, K.W. et al., 1967).

Geologic age: Early Neoproterozoic; Kim et al. (2006) provided ca. 870 Ma zircon age from a felsic volcanic sample of the Gyemyeongsan Formation and Kang et al. (2012) also reported ~870 Ma zircon age from a coarse-grained metaplutonic acidic rock.

Remarks: Geochemical studies of the Gyemyeongsan Formation (Koh et al., 2005; Park et al., 2005) suggested that bimodal volcanic rocks were related to the intracratonic rifting of the paleocontinents. Ca. 870 Ma zircon age from the Gyemyeongsan Formation (Kim et al., 2006; Kang et al., 2012) is herein interpreted to represent the initial rift stage of the Chungcheong Basin, which can be equated with the first rift stage (or Sequence I) of the Nanhua Basin, South China (Wang and Li, 2003; Wang et al., 2006; Wang et al., in press; Table 2).

4.2.2. Hyangsanni Dolomite

Definition: The Hyangsanni Dolomite is characterized by milky white to light gray massive (occasionally bedded) dolostone/limestone with intercalation of thin (less than 1-m-thick) quartzite and mafic metavolcanic layers. The Hyangsanni Dolomite was originally established by Kim and Lee (1965) as the Hyangsanni Dolomitic Limestone.

Distribution: The Hyangsanni Dolomite is well exposed along the local road 531 in the west coast of Lake Chungju, where the Hyangsanni Dolomite runs in an N-S direction and then to the south in an NE-SW direction to Hyangsanni (Fig. 2). At Hyangsanni, the formation thins out to the west and cannot be traced further west. The Hyangsanni Dolomite is also well exposed in association with the Gyemyeongsan Formation at Mt. Busan area, but was previously referred to the Cambrian-Ordovician Joseon Supergroup in Jecheon quadrangle (Kim, K.W. et al., 1967).

Geologic age: No reliable information is available for the geologic age of the Hyangsanni Dolomite, but it is supposed that the formation be assignable to the Neoproterozoic based on its stratigraphic position between the Gyemyeongsan Formation (ca. 870 Ma; Kim et al., 2006) and the Munjuri Formation (ca. 750 Ma; Lee, K.-S. et al., 1998; Cho et al., 2004; Kim et al., 2006). The Cambrian age of the formation suggested previously based on the occurrence of an archaeocyathid (Lee et al., 1972) is doubted, as the archaeocyathid-affinity of the specimen has been disregarded (P. Kruse, 2011, personal communication).

Remarks: Park et al. (1995) subdivided the Hyangsanni Dolomite in the west coast of the Lake Chungju into the three parts: the lower and upper dolostone members were separated by pink bedded limestone member; and the thickness of the formation was estimated to be 300–400 m. Ryu and Kim (2009) also provided a detailed lithologic description of the Hyangsanni Dolomite in the Chungju area. Lee, H.-Y. et al. (1989) reported the occurrence of a putative

Cambrian fossil (?*Microdictyon* sp.) from the Hyangsanni Dolomite, but its occurrence should be reconfirmed.

4.2.3. Daehyangsan Quartzite

Definition: The Daehyangsan Quartzite is characterized by white to light gray massive (occasionally bedded) quartzite with thin dolostone layers and lenses. The formation is disconformably overlain by the Munjuri Formation. Disconformable relationship between the Daehyangsan Quartzite and the Munjuri Formation is postulated by the lateral discontinuity of the Daehyangsan Quartzite. The Daehyangsan Quartzite was named by Kim and Lee (1965).

Distribution: The Daehyangsan Quartzite is mainly exposed in association with the Hyangsanni Dolomite along the Lake Chungju in the vicinity of Mt. Namsan (Fig. 2). Additional occurrences are documented in the northern and southwestern parts of Mt. Busan, which were originally described as a member of the Seochangni Formation in Jecheon quadrangle (Kim, K.W. et al., 1967).

Geologic age: Like the Hyangsanni Dolomite, no reliable age information is available for the Daehyangsan Quartzite, and it is also supposed that the formation can be assigned to the Neoproterozoic based on its stratigraphic position between the Gyemyeongsan and the Munjuri formations.

Remarks: Ihm et al. (1991) attempted to reveal the deformation history of the Daehyangsan Quartzite based on the strain analysis of quartz grains. It should be mentioned that Park et al. (2011) reported a SHRIMP U-Pb age of the detrital zircons from the Daehyangsan Quartzite (423 ± 5.6 Ma) and suggested the age of the formation younger than early Silurian.

4.3. Suanbo Group (New Name)

The Suanbo Group is proposed to replace the formerly Okcheon Group of Son (1970) and Reedman et al. (1973) with modification (cf. Table 1). Son (1970) placed the Okcheon Group to the Paleozoic, while Reedman et al. (1973) assigned it to the Proterozoic. In this study, the Suanbo Group is defined to comprise the Munjuri, Hwanggangni, Myeongori (including the Geumgang Limestone and Seochangni members), and Gounni formations in ascending order and is assigned to the late Neoproterozoic (Table 3).

4.3.1. Munjuri Formation

Definition: The Munjuri Formation is the lowest unit of the Suanbo Group. The Munjuri Formation was originally proposed by Kim and Lee (1965) to denote greenish gray schists of sedimentary origin exposed widely in the Munjuri area. It is most likely that the Munjuri Formation is a heterogeneous unit comprising bimodal volcanic rocks (basanites, trachybasalts, trachytes, and rhyolites) and metasedimentary rocks (phyllites, schists, and slates) (Cluzel, 1992; Lee, K.-S. et al., 1998; Cho et al., 2004; Kim et al., 2006).

Distribution: The Munjuri Formation is extensively exposed in the southwestern part of the study area and extends into the north of the Chungju Dam (Fig. 2). A comparatively narrow-band of the formation, though intermittently dislocated by E-W trending strike-slip faults, runs in a roughly N-S direction along the west of the South Korean Tectonic Line, where the Munjuri Formation thrusts over the Cambro-Ordovician Joseon Supergroup. In addition, a couple of small patches belonging to the Munjuri Formation occur at Otiri and Mt. Yamisan as klippes in the east of the South Korean Tectonic Line (Fig. 2).

Geologic age: Neoproterozoic (Cryogenian); U-Pb zircon ages from the volcanics of the Munjuri Formation are 747 ± 7 Ma (Cho et al., 2004), 755.8 ± 1.3 Ma (Lee, K.-S. et al., 1998), and 762 ± 7 Ma (Kim et al., 2006).

Remarks: Rocks of the Munjuri Formation exposed along the South Korean Tectonic Line were originally referred to the Seochangni Formation by Lee and Park (1965), but were treated to belong to the Munjuri Formation (Reedman et al., 1973) or metavolcanic rocks of post-Ordovician age (Kim and Kim, 1974).

4.3.2. Hwanggangni Formation

Definition: The Hwanggangni Formation is characterized by light gray to dark gray diamictites with argillaceous and calcareous matrices. Clasts in the Hwanggangni Formation comprise quartzite, granite, shale, sandstone, limestone, and dolostone in lithology. Clasts range in size from granule to boulder (up to 2.3 m in length) and are variable in shape including chips, discs, balls, ribbons, and other irregular forms (Chough and Bahk, 1992).

The Hwanggangni and Buknori formations were originally considered to be distinct from each other by Lee and Park (1965), but they are herein treated as a single formation based on the recognition of thin limestone/dolostone beds between the Hwanggangni and the Myeongori formations (sensu Lee and Park, 1965) and between the Myeongori and Buknori formations (sensu Lee and Park, 1965).

Distribution: The Hwanggangni Formation is broadly exposed in the mid-southern part of the study area, running roughly in an NE-SW direction. To the north, the Hwanggangni Formation deflects to the northwest to form narrow bands, interrupted by vertical faults. Additional exposures are recognized in the east close to the South Korean Tectonic Line, which were originally mapped as the Buknori Formation by Lee and Park (1965) or the Gunjasan Formation by Kim and Kim (1974).

Geologic age: Neoproterozoic (late Cryogenian); this age assignment is based on the correlation with the diamictite sequences of South China (Zhang et al., 2008, 2011; Jiang et al., 2011) formed by the Neoproterozoic global glacial event, i.e., snowball Earth (Kirschvink, 1992; Hoffman et al., 1998; Evans, 2000).

Remarks: Reedman et al. (1973) were the first to suggest that the Hwanggangni Formation comprises tillites of glacial origin and has been correlated with the Proterozoic tillites of South China and northern Korea (see Kim and Kim, 1974; Reedman and Fletcher, 1976). Lee et al. (1998) also studied the diamictites of the Hwanggangni Formation in detail but concluded that they could be correlated with the Permo-Carboniferous glacial deposits of Gondwana. Chough and Bahk (1992) presented a detailed lithologic description of the Hwanggangni Formation in the Chungcheong Basin and interpreted that the diamictites of the Hwanggangni Formation were formed by submarine debris flows originated from slope failure of semi-consolidated sediments.

The occurrences of acid-resistant conodont fossils were reported from limestone clasts of the Hwanggangni Formation (Lee et al., 1989; Lee, H.-Y. et al., 1989), which subsequently provided a basis for age constraint of the Hwanggangni Formation to be post-Ordovician. Suzuki et al. (2006) reported a discovery of a ~370 Ma granitic gneiss clast from the Hwanggangni Formation and bracketed the age of the formation between 370 Ma and 280 Ma. However in this study, these age constraints are reserved until further confirmation is obtained.

Kim O.J. and Kim K.H. (1974) treated that the Buknori Formation (sensu Lee and Park, 1965) exposed in the Hwanggangni area belongs to the Hwanggangni Formation, but the exposures of the Buknori Formation in the Deokgokri area were considered distinct from the Hwanggangni Formation and were referred to the Gunjasan Formation. Based on the structural analysis of the Okcheon Supergroup in the Hwanggangni area, Choi and Kim (1981) and Lee and Kim (1988) independently reached to a conclusion that the Hwanggangni and Buknori formations belong to a single stratigraphic unit and that the Hwanggangni Formation is overlain by the Myeongori Formation.

4.3.3. Myeongori Formation (emended)

Definition: The Myeongori Formation is dominated by dark gray to black slate/phyllite with a thin milky white limestone/dolostone interval at the base of the formation and is herein formally subdivided into the lower Geumgang Limestone Member and the upper Seochangni Member. Very thin (a few-cm-thick) volcanic layers are rarely intercalated. The Myeongori and Seochangni formations were established by Lee and Park (1965), but are herein considered to represent a single lithostratigraphic unit based on the stratigraphic relationship between the Hwanggangni and Myeongori formations mentioned above. Hence, the concept of the Myeongori Formation is emended.

The Geumgang Limestone Member is characterized by milky white to light gray, massive and thinly-bedded limestone/dolostone. The thickness of the member ranges from less than 1 m to 30 m. The Geumgang Limestone was originally established in Okcheon (Kim et al., 1978) and was traced into the Lake Chungju area (Lee, 1995). The name Seochangni is survived to denote the upper member of the Myeongori Formation consisting largely of dark gray to black slate/phyllite.

Type locality: The boundary stratotype for the base of the Myeongori Formation is designated at a section (36°58'03"N; 128°04'29"E) along the lakeshore at Myeongori, Dongnyang-myeon, Chungju (Fig. 4), but the top of the formation is indeterminate due to poor exposure in the putative boundary intervals between the Myeongori and Gounni formations.

The Geumgang Limestone was originally established in the Okcheon quadrangle (Kim et al., 1978). Hence, the stratotype of the Geumgang Limestone Member is selected at a section (36°16'47"N; 127°40'07"E) along a road cut near the Geumgang Rest Area (Figs. 5 and 6). The boundary stratotype for the base of the Seochangni Member is designated at a section (36°58'03"N; 128°04'29"E) along the lakeshore at Myeongori, Dongnyang-myeon, Chungju (Fig. 4), while that for the top of the member is indeterminate due to the same reason given above.

Lithologic description of the type localities: The lakeshore section at Myeongori (Fig. 4) exposes the uppermost part of the Hwanggangni Formation, Geumgang Limestone Member, and the lowermost part of the Seochangni Member. This lakeshore section is about 130 m long but it is segmented by minor reverse faults. The lower and upper boundaries of the Geumgang Limestone Member are well exposed in the easternmost segment. The uppermost part of the Hwanggangni Formation consists of diamictite with brownish psammitic matrix and polymictic clasts of quartzite, granite, and limestone. The psammitic matrix is strongly foliated and the foliation is generally parallel to the bedding. Clasts in the uppermost 1 m interval of the formation consist mostly of small pebbles of metamorphic rocks including quartzite, whereas the clasts below the uppermost interval are larger (up to 25 cm in diameter) and variable in composition. The overlying Geumgang Limestone Member is about 3.8 m in thickness and the contact between the Hwanggangni Formation and the Geumgang Limestone Member is sharp and the lithologic change from diamictite to dolostone is abrupt. The lower part of the dolostone is characterized by faint lamination and irregularly aligned chert nodules. The middle part is thin-bedded while each thin bed displays homogeneous internal texture. The uppermost part of the Geumgang Limestone Member is represented by an alternation of thin dolostone and light-colored phyllite layers, which grades into foliated phyllite of the overlying Seochangni Member. The lower part of the Seochangni Member includes a few dolostone beds and thin calcareous intercalations.

The section at the Geumgang Rest Area (Fig. 6) well exposes the uppermost part of the Hwanggangni Formation, Geumgang Limestone Member, and the lowermost part of the Seochangni Member. The diamictite of the Hwang-

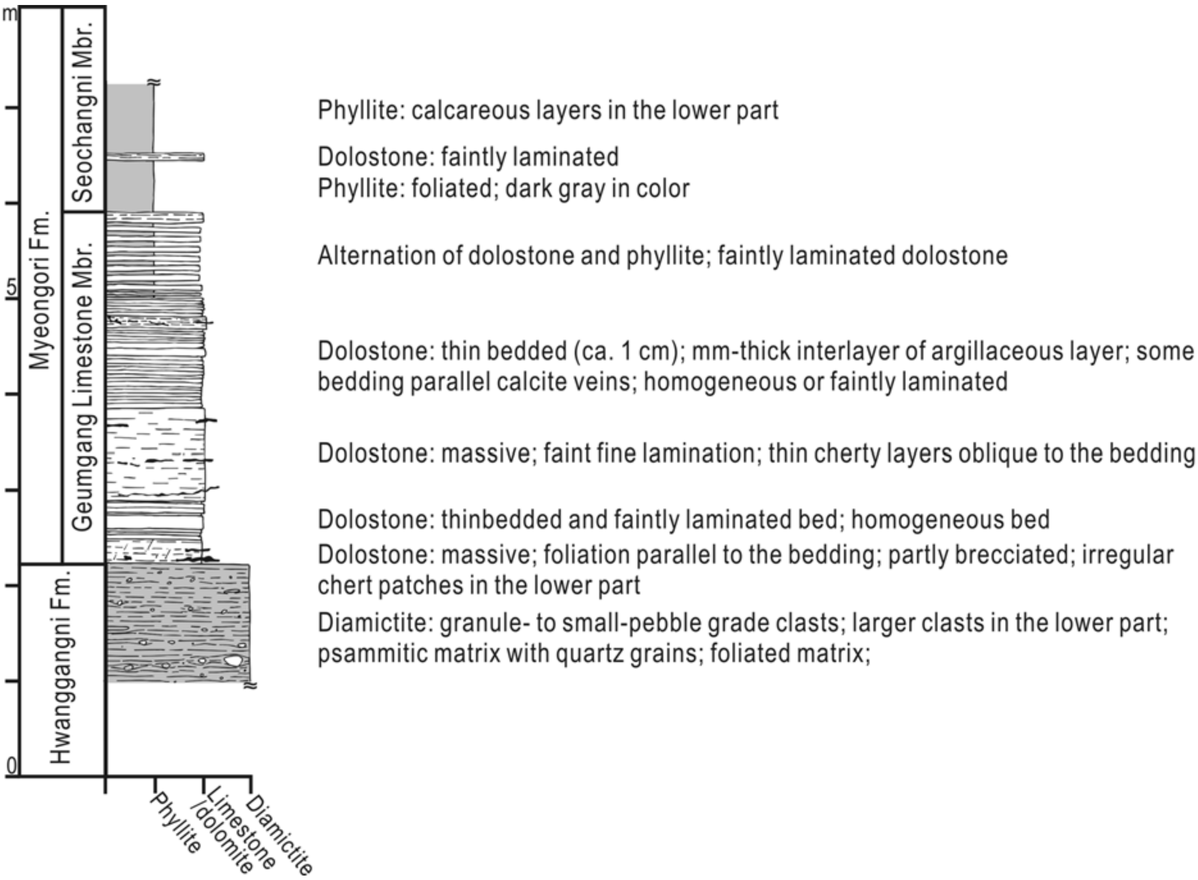

Fig. 4. Lithologic column of the boundary stratotypes of the Myeongori Formation and Seochangni Member at Myeongori.

gangni Formation in the section is composed of dark gray psammitic matrix and polymictic clasts. Although there are changes in clast size and composition in the diamictite, no clear unit boundaries are observed. The uppermost part of the diamictite is characterized by finer, small pebble-sized clasts excluding limestone clasts. The Geumgang Limestone Member is about 10 m in thickness and is composed of massive recrystallized limestone. The lowermost 1-m-thick interval is characterized by an alternation of limestone and dark gray phyllite which is similar to the matrix of the Hwanggangni diamictite. The alternating interval displays a transitional lithologic change from the Hwanggangni Formation to the Geumgang Limestone Member. The overlying 9-m-thick limestone bed is generally massive except for thin-bedded interval in the middle part. A few gray limestone clasts or nodules occasionally occur in the middle part of the member. An intermediate dyke cuts the uppermost part of the limestone and the very contact between the overlying phyllite is covered by an artificial drainage canal. The Seochangni Member is a thick monotonous succession of dark colored phyllite with punctuated intercalation of volcanic ash (?) layers in the lower part.

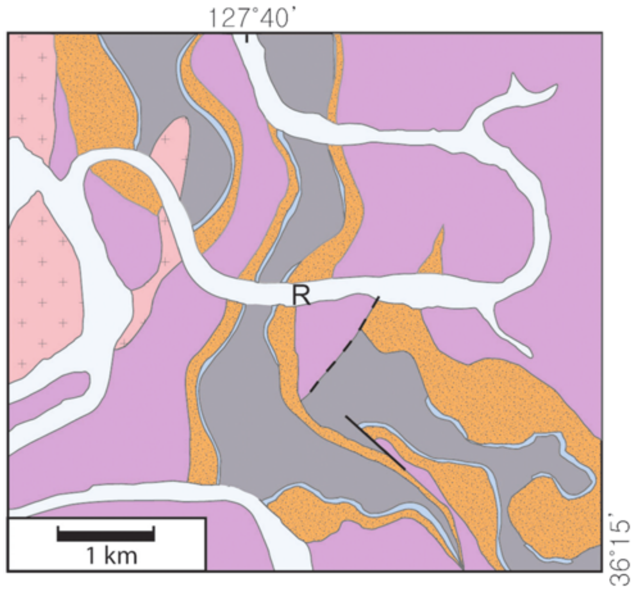

Fig. 5. Geologic map of eastern Okcheon area (from Kim et al., 1978), where the stratotype of the Geumgang Limestone Member is located. Legends in Figure 2b apply to this figure. R: Geumgang Rest Area.

Distribution: The Myeongori Formation is mainly distributed in the southeastern part of the study area, trending roughly in an NE-SW direction. The Geumgang Limestone Member in the Okcheon area (Figs. 5 and 6) is in general

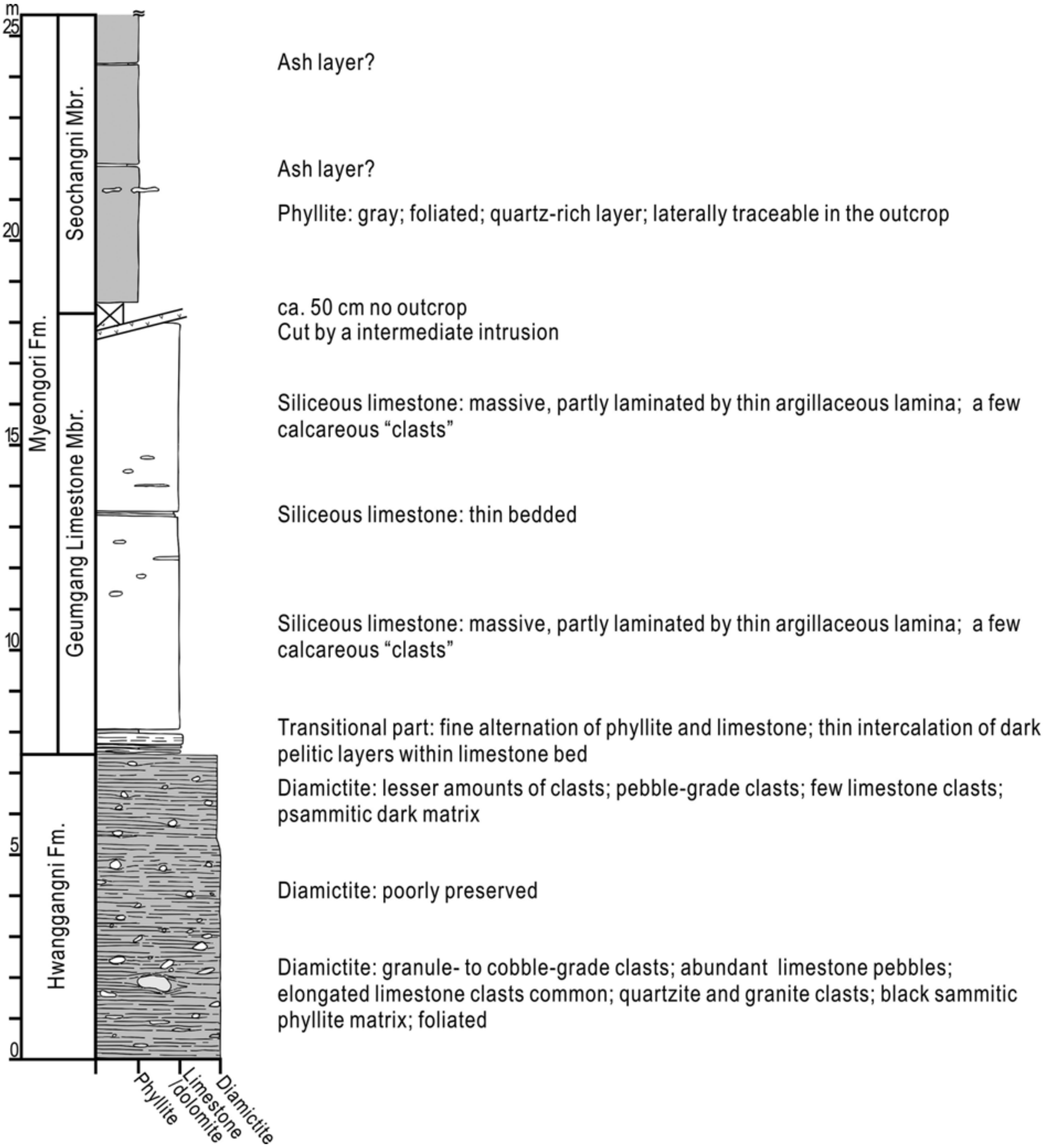

Fig. 6. Lithologic column of the stratotype of the Geumgang Limestone Member at eastern Okcheon area.

thicker and better exposed than that in the Lake Chungju area.

Geologic age: Neoproterozoic (early Ediacaran), based on the interpretation in that the Geumgang Limestone Member represents the cap carbonate which overlies the Cryogenian glacial deposits documented elsewhere (Shields, 2005; Corsetti and Lorentz, 2006).

Remarks: Kim and Kim (1974) considered that the Myeongori and Seochangni formations (sensu Lee and Park, 1965) exposed in Hwanggangni-Seochangni area are indistinguishable and accordingly were assigned to the Seochangni Formation, but to the east the exposures of the Seochangni Formation (sensu Lee and Park, 1965) in Deokgokri were referred to metavolcanic rocks of unknown age. Lee and Kim (1988), based on a structural analysis, also demonstrated that the Myeongori and Seochangni formations (sensu Lee and Park, 1965) in the Hwanggangni area represent a single stratigraphic unit.

In Lake Chungju area, the Geumgang Limestone Member was called as the Naesari Limestone (Lee, 1995) or Hansu Limestone (Chough and Bahk, 1992).

4.3.4. Gounni Formation

Definition: The Gounni Formation is a thick succession of light gray to dark gray, massive to thinly-bedded limestone/dolostone. The thinly-bedded limestone is composed of alternating calcareous and argillaceous layers and is strongly deformed. The Gounni Formation is assumed to overlie conformably the Seochangni Member of the Myeongori Formation, but the upper boundary of the formation is indeterminable due to deformation and granite intrusion. The Gounni Formation was established by Lee and Park (1965).

Distribution: The Gounni Formation is restricted to the southeastern part of the study area, where the formation was intruded by the Cretaceous Wolaksan Granite.

Geologic age: No reliable information on the geologic age of the Gounni Formation is currently available, but the formation is herein referred to the uppermost Proterozoic (late Ediacaran) with reservation based on the comparison with the Proterozoic sequences of South China. The Gounni Formation can be correlated to the carbonate-dominated Dengying or Liuchapo Formation of South China (cf. Jiang et al., 2011; Table 2).

Remarks: The Gounni Formation was also called as the Majeonni Formation (Kim and Kim, 1974) or Hwacheonni Formation in Mungyeong (Kim et al., 1967).

5. GEOLOGIC STRUCTURE

The geologic age, stratigraphy, and depositional setting of the Okcheon Supergroup have been controversial during the last four decades and at present no unequivocal agreements on these accounts have been made yet. As stated in the section 'Historical Background', a range of views on the stratigraphy and geologic age of the Okcheon Supergroup have been exercised (Table 1): all or most of the Okcheon Supergroup was assigned to Proterozoic (Kim, 1968, 1970; Kim and Kim, 1974) or to post-Ordovician (Lee and Park, 1965; Son, 1970; Kihm et al., 1996; Lee et al., 1998); Reedman et al. (1973) placed the Chungju Group to the Proterozoic and the Suanbo Group to the Cambro-Ordovician; and still others (Cluzel et al., 1990; Cluzel, 1992; Lee, 1995) believed that the Okcheon Supergroup is the lateral equivalent of the Cambro-Ordovician Joseon Supergroup. Different views on the stratigraphy and ages of the Okcheon Supergroup inevitably resulted in different interpretations on the geologic structure of the Lake Chungju area.

There have been two contrasting interpretations on the relationship between the Okcheon Supergroup of the Chungcheong Basin and the Joseon Supergroup of the Taebaeksan Basin: one is the thrust contact between the two groups in which the Okcheon Supergroup thrusts over the Joseon Supergroup (Kim and Kim, 1974, 1976; Cluzel et al., 1990, 1991a; Ree et al., 2001; Chough et al., 2006) and the other is the conformable or unconformable contact in which the Okcheon Supergroup is underlain by the Joseon Supergroup (Son, 1970; Kihm et al., 1996). This study supports the former interpretation on the ground that the Neoproterozoic Okcheon Supergroup overlies the Cambro-Ordovician Joseon Supergroup at the boundary (South Korean Tectonic Line; Chough et al., 2000). Chough et al. (2006) described in detail the deformational pattern along the boundary in the Bonghwajae section.

Within the Chungcheong Basin, Reedman et al. (1973) and Kim and Kim (1974) noted that the geologic structure of the Okcheon Supergroup is characterized by isoclinal to tight, frequently overturned, folds with some normal faults [see also Lee and Kim (1988)], whereas Cluzel et al. (1990, 1991a) postulated a series of thrust faults within the Okcheon zone.

In this study, no thrust faults are recognized in the Lake Chungju area, except the South Korean Tectonic Line [or Central Okcheon Thrust of Ree et al. (2001)] (Fig. 2). To highlight major structural features of the Okcheon Supergroup in the Lake Chungju area, an isochrone map (Fig. 7) has been constructed. The isochrone is defined as a line connecting all points that represent the same time value (cf. Neuendorf et al., 2005). The isochrone map has been employed in geography to show a river or drainage basin on which a series of time lines give the time of transit of water to flow down to the outlet of the system. Here, the isochrones are drawn on the basis of the age data presented in the heading 'Geologic age' of each formation. It should be, however, admitted that the age assignment is at best approximate and relative to each other: for instance, the Busan gneiss complex has been assumed to range in age from 2000 Ma to 1900 Ma, based on the reported radiometric ages (Sagong and Kwon, 1998; Horie et al., 2009); the base of the Gyemyeongsan Formation was assigned to ~850 Ma in age (Kim et al., 2006); the age of the Munjuri Formation has been bracketed within the range from 760 Ma to 720 Ma (Lee, K.-S. et al., 1998; Cho et al., 2004; Kim et al., 2006); the Hwanggangni Formation has been referred to the Cryogenian (720–635 Ma); the Geumgang Limestone Member represents the onset of the Ediacaran (ca. 635 Ma); and the geologic ages of other formations have been interpolated or extrapolated from these dates.

The isochrone map (Fig. 7) clearly demonstrates major structural features of the Okcheon Supergroup in the west of the South Korean Tectonic Line in which three anticlinal (or domal) and one synclinal (with two branches) structures are apparent. The northernmost anticline within the exposure of the Bakdallyeong metamorphic complex has not been studied in detail and hence will not be considered here. The other fold structures are called from north to south as the Busan Anticline, Gyemyeongsan Anticline, and Gongiri Synclinorium, respectively (Figs. 7 and 8).

5.1. Busan Anticline

The Busan Anticline is a composite structure of two anti-

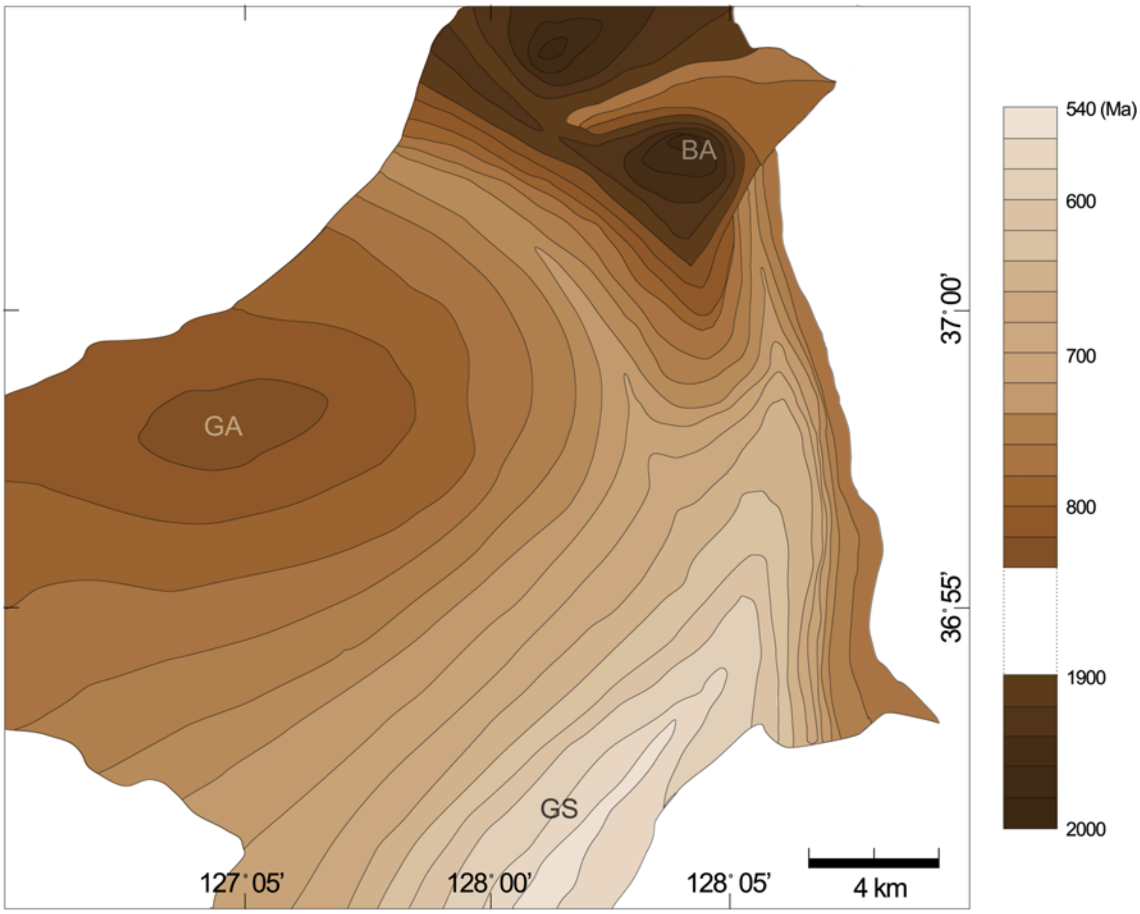

Fig. 7. Isochrone map of the Okcheon Supergroup in the Lake Chungju area. The isochrones represent a line connecting points with the same geologic age of the outcrops (see text for more information). Abbreviations: BA, Busan Anticline; GA, Gyemyeongsan Anticline; GS, Gongiri Synclinorium.

clines representing different phases of deformation (see below): one is an overturned fold with a roughly NW-SE trending strongly curviplanar axial surface which dips to the southwest and the other is an open fold with an NE-SW trending planar axial surface (Fig. 8). The core of the anticline is occupied by the Paleoproterozoic Busan gneiss complex, which is bounded to the north and southwest by the Neoproterozoic Chungju Group (Fig. 2). To the east the Busan gneiss complex is in fault contact with the Suanbo Group, while to the west it merges with the Bakdallyeong gneiss complex. The northern limb of the anticline is upside-down: i.e., the formations of the Chungju Group in the northern part of the Busan Anticline dip southwards with a roughly E-W strike (Fig. 8), as if the Busan gneiss complex sits on the less-metamorphosed Chungju Group, which led Kim, K.W. et al. (1967) to consider the Busan gneiss complex to be a high-grade equivalent of the Okcheon Supergroup (Seochangni Formation in their report). Different views on the Busan gneiss complex include that the gneiss complex is the basement rocks of the Gyeonggi Massif (Na, 1987; Cluzel et al., 1991a; Sagong and Kwon, 1998; Horie et al., 2009), a tectonically emplaced block from the Yeongnam Massif (Kang, 1994), and a basement unique to the Okcheon Belt (Ihm and Chang, 1993).

Contrasting views on the geologic structure involving the Busan gneiss complex and associated rocks had been exercised. Reedman et al. (1973) postulated an anticline with a slightly conical form, whereas Cluzel et al. (1991a) and Ihm and Chang (1993) interpreted that the Busan gneiss complex occupies the core of anticline, but in the north the Busan gneiss complex thrusts over the Okcheon Supergroup.

In this study the Busan Anticline is envisaged as an overturned anticline in which the northern limb of the anticline is upside-down, while the southwestern limb is right-side-up retaining a stratigraphically normal succession of the Okcheon Supergroup (A–A' in Fig. 2): i.e., the relationship between the Busan gneiss complex and the Chungju Group is not a thrust fault but an unconformity. This interpretation is consistent with the result of structural analysis of quartz grains by Ree et al. (1995), which showed the contact between the Bakdallyeong gneiss complex and the Daehyangsan Quartzite as a normal shear zone.

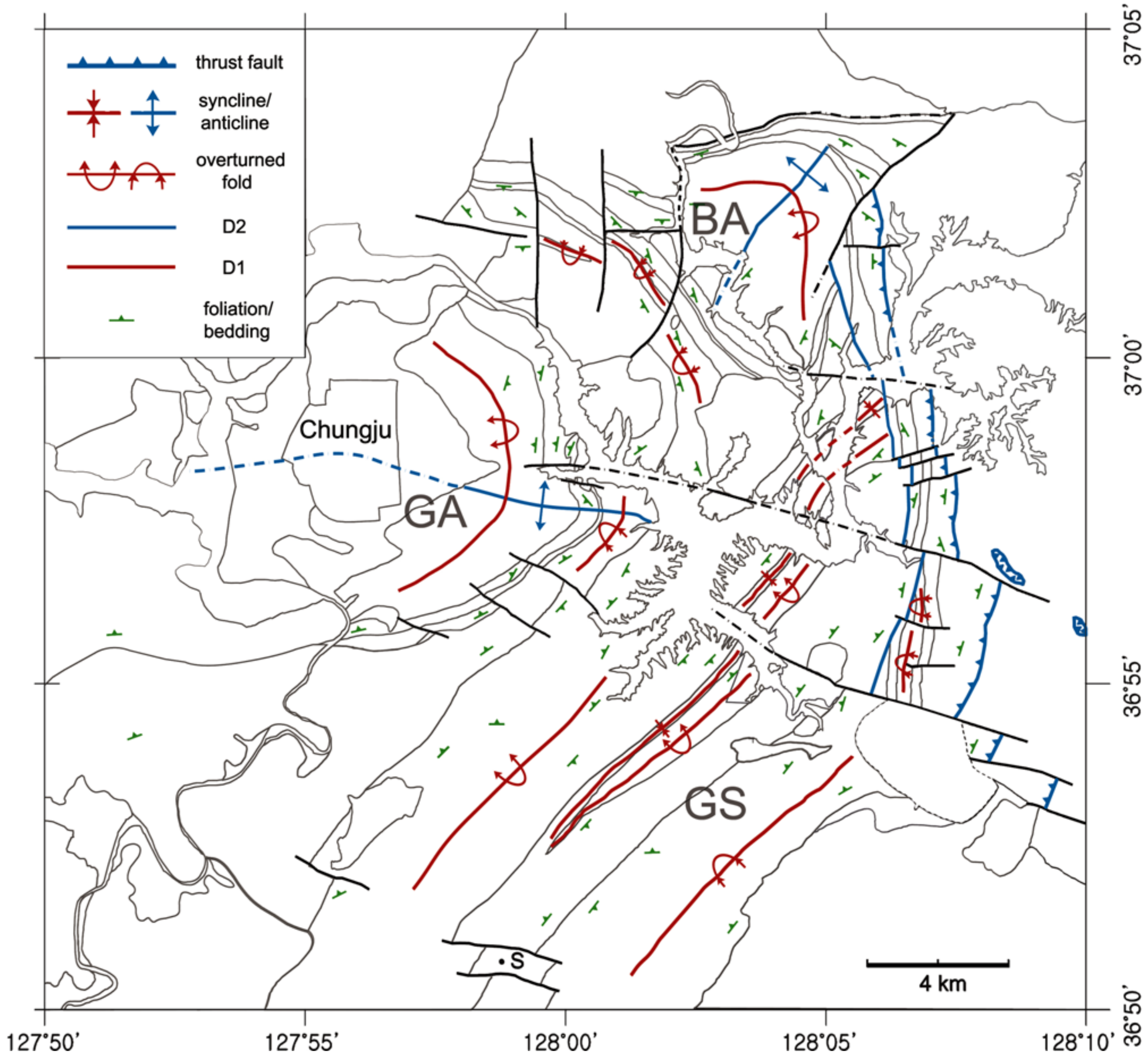

Fig. 8. Structural map of the Lake Chungju area, showing traces of axial surfaces of major folds and foliation/bedding. Abbreviations: BA, Busan Anticline; GA, Gyemyeongsan Anticline; GA, Gongiri Synclinorium.

5.2. Gyemyeongsan Anticline

The Gyemyeongsan Anticline is also a composite structure of two anticlines representing different phases of deformation (see below): one is an overturned fold with an N-S trending curviplanar axial surface which dips to the west and the other is an open fold with a roughly E-W trending planar axial surface (Fig. 8). The Gyemyeongsan Anticline comprises the Gyemyeongsan Formation in the core, which was intruded by the Jurassic Chungju Granite (Fig. 2). Presumably the Precambrian basement rocks, if any, would have sit on the very core of the Gyemyeongsan Anticline and must have been obliterated by the granite intrusion. In the eastern limb of the anticline, the Gyemyeongsan Formation is succeeded by the Hyangsanni Dolomite, Daehyangsan Quartzite and the Munjuri Formation in ascending order. The west-dipping strata of the Chungju Group in the area apparently led the previous workers (Kim and Lee, 1965; Lee and Park, 1965; Reedman et al., 1973; Ihm and Chang, 1993; Lee et al., 1998; Ryu and Kim, 2009) to consider that the formations be getting stratigraphically younger to the west.

In this study the Gyemyeongsan Anticline is recognized as an overturned anticline in which the eastern limb is upside-down and hence the formations are getting older to the west (see cross sections in Fig. 2). This stratigraphic order is consistent with the reported radiometric ages from the Gyemyeongsan (~870 Ma) and Munjuri formations (~750

Ma) (Lee, K.-S. et al., 1998; Cho et al., 2004; Kim et al., 2006). However, a recent detrital zircon age (~423 Ma) from the Daehyangsan Quartzite (Park et al., 2011) is in conflict with the stratigraphy presented here.

5.3. Gongiri Synclinorium

The Gongiri Synclinorium consists of a number of isoclinal to tight, mostly overturned, folds with an NE-SW trending planar axial surface and comprises the Gounni Formation in the core (Figs. 2 and 8). In the northern part of the study area, two smaller-scale synclines are also observed between the Gyemyeongsan and Busan anticlines and between the Busan Anticline and the South Korean Tectonic Line (Figs. 7 and 8). The two synclines plunge southwards and eventually merge to form the Gongiri Synclinorium which broadly plunges further southwestwards.

The western limb of the synclinorium is characterized by a series of second-order and third-order anticlines and synclines, most of which are overturned. Only some prominent second-order folds are illustrated in Figure 8, but smaller-scale anticlines and synclines were well documented by previous workers (Lee and Park, 1965; Lee and Kim, 1988). It is noted that Lee and Kim (1988) correctly recognized a set of second-order anticline and syncline in the Hwanggangni area (Hwanggangni Anticline and Myeongori Syncline in their article) based on the detailed analysis of structural elements and petrofabric study of detrital quartz grains. The nature of the eastern limb of this synclinorium is however indeterminable due to granite intrusion, but the attitude of the Suanbo Group in the easternmost part of the Chungcheong Basin bounded by the South Korean Tectonic Line and a normal fault (Figs. 2 and 8) indicates that the eastern limb may also comprise a series of smaller-scale anticlines and synclines.

5.4. Phases of Deformation

The Lake Chungju area is structurally very complex due to polyphase deformation of the Okcheon Supergroup (Reedman et al., 1973; Cluzel et al., 1990; Ihm and Chang, 1993). Although the detailed analysis of deformation history is beyond the scope of this study, three major phases of deformation are easily appreciated from a scrutiny of the geologic map (Figs. 2 and 8).

The first phase of deformation (D1) is recognized by a number of isoclinal to tight, overturned, second-order and third-order anticlines and synclines, which have most strongly affected the rocks of the Okcheon Supergroup in Lake Chungju area. The traces of axial surfaces of these folds are dominated by two orientations: one is an NE-SW trending one with an NW dipping in the southern part and the other is an NW-SE trending one with an SW dipping in the northern part (Fig. 8). The attitude of these D1 folds displays a strong ductility, suggesting that the deformation took place in a medium-pressure and medium-temperature metamorphic environment (cf. Cho and Kim, 2005). It is considered that the D1 deformation can be related to the mid-Paleozoic Okcheon Orogeny which was first proposed by Kim (1987) and subsequently suggested by Cluzel et al. (1991a). On the other hand, Cho and Kim (2005) suggested the onset of the Okcheon Orogeny to be an earliest Permian.

The second phase of deformation (D2) is probably the most influential in the tectonic evolution of the Okcheon Belt, as this deformation produced the prominent thrust fault, i.e., a constraining bend of the South Korean Tectonic Line, which was formed by collision between the Sino-Korean and the South China cratons (Chough et al., 2000; Ree et al., 2001). In later stage of this phase, the D1 folds and the thrust fault experienced refolding, which resulted in a broadly arcuate distribution of the Okcheon Supergroup in the Lake Chungju area (Figs. 2 and 8). Hence, the second phase of deformation may be divided into the early and late stages: early stage produced the thrust fault (constraining bend of the South Korean Tectonic Line) and associated structures, while the late stage refolded the earlier structures. The axial surfaces of these late D2 folds run in roughly E-W (Gyemyeongsan Anticline) and NE-SW (Busan Anticline) directions. The early stage of D2 deformation is referred to the Triassic Songnim Orogeny, but it is unclear whether the late stage of D2 deformation belongs to a part of the Songnim Orogeny or it was a product of the Jurassic Daebo Orogeny in Korea.

The third phase of deformation (D3) dissected all of earlier structures and is represented by a series of E-W to WNW-ESE trending normal to strike-slip faults. The precise timing of this phase of deformation is difficult to assess, but should post-date the Jurassic as the Jurassic granites were displaced by these faults.

The present account on the geologic structure of the Lake Chungju area is highly preliminary, and in-depth and rigorous structural analyses (e.g., Lee and Kim, 1988) are expected to elucidate the deformation history of the Chungcheong Basin as a whole.

6. GEOLOGIC EVOLUTION OF THE CHUNGCHEONG BASIN

The tectonic setting of the Okcheon Supergroup had been ambiguous in Korea, until Cluzel et al. (1990) proposed a geodynamic model in which the Okcheon Belt was viewed as an intracontinental rift basin in the early Paleozoic and within the basin the Joseon Supergroup and the Okcheon Supergroup were considered to represent a pre-rift shallow marine platform facies and a syn-rift deeper-water facies, respectively. However, the Okcheon Supergroup and the Joseon Supergroup are herein considered to have been deposited in tectonically independent Chungcheong and

Taebaeksan basins, respectively (Fig. 1; Chough et al., 2000; Choi and Kim, 2006; Choi, 2009, 2011): i.e., the Chungcheong Basin was connected to the Nanhua Basin of South China Craton during the Neoproterozoic, whereas the Taebaeksan Basin was a marginal facies of the Sino-Korean Craton in the Paleozoic. Therefore, the Chungcheong and Taebaeksan basins are genetically and temporally widely separated, until they merged to form the Okcheon Belt during the collisional processes of the South China and Sino-Korean cratons in the earliest Triassic (Cluzel et al., 1991b; Yin and Nie, 1993; Chough et al., 2000; Ree et al., 2001).

Based on the stratigraphy, geologic ages, and geologic structures of the Okcheon Supergroup presented above, the geologic evolution of the Chungcheong Basin is described below. The geologic evolution of the Chungcheong Basin appears to be closely related to that of the Nanhua Basin of South China Craton (see Section 3.2 for detailed information), which is graphically summarized in Figure 9.

In the early Neoproterozoic, the Chungcheong Basin was nucleated during the process of break-up of the Rodinia as a part of the Nanhua Basin which was an intracontinental rift basin within the South China Craton (Fig. 3). Multiple bimodal volcanic episodes recognized within the Chungcheong Basin are referred to the first and second rift stages (Fig. 9). The first rift event at ~870 Ma (Kim et al., 2006) accumulated a succession of bimodal volcanic rocks (Kim et al., 1998; Koh et al., 2005; Park et al., 2005) on the Paleoproterozoic gneiss complexes, which formed the Gyemyeongsan Formation. Although no sedimentological studies have been done for the Gyemyeongsan Formation, it is postulated that the volcanic activity may have been associated with intermittent shallow marine sedimentation evidenced by the occurrences of thin quartzite and dolostone layers within the Gyemyeongsan Formation. The Gyemyeongsan

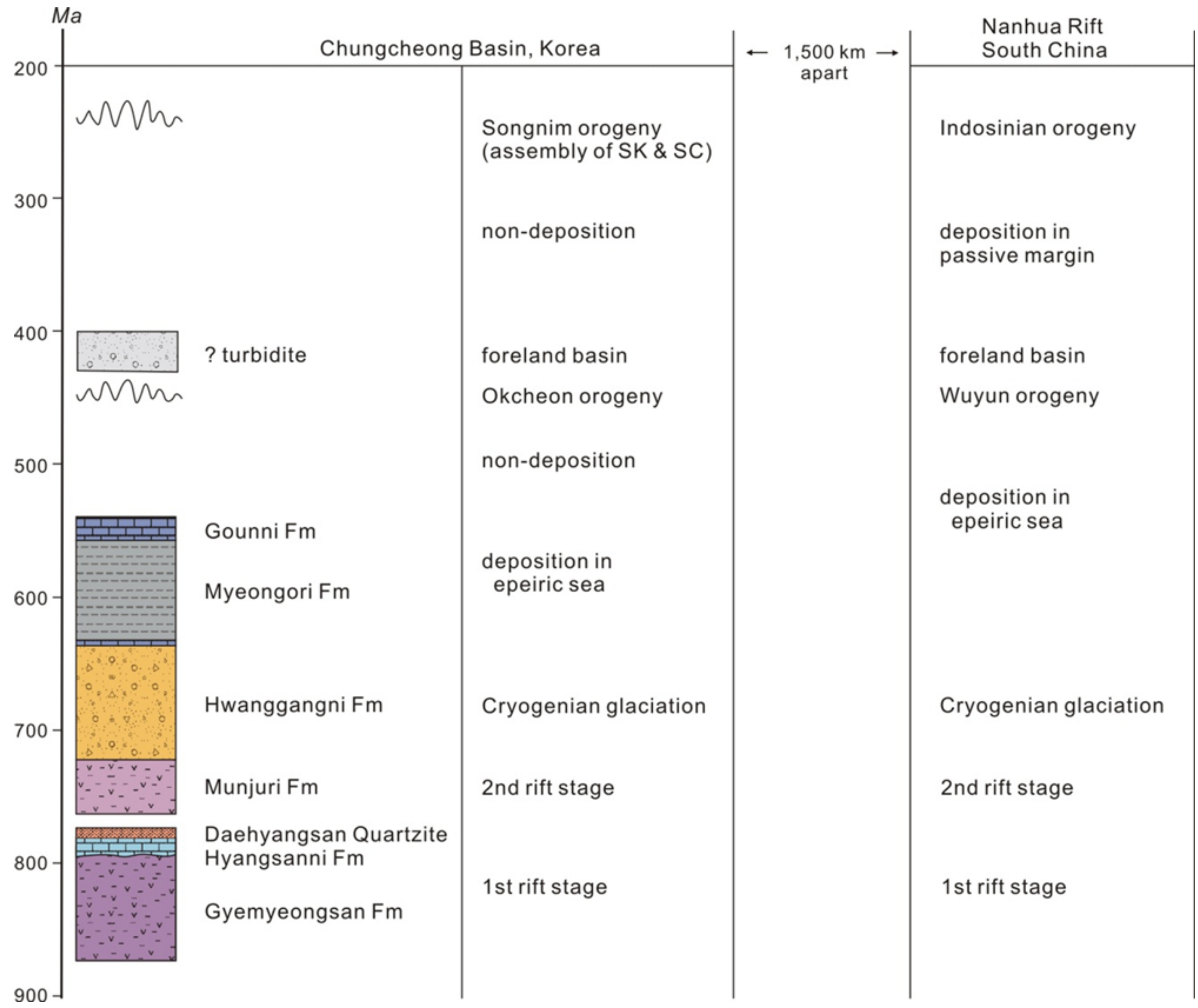

Fig. 9. Schematic diagram summarizing the Neoproterozoic and Paleozoic tectonic evolution of the Chungcheong Basin, in comparison with that of the Nanhua Basin, South China.

Formation is succeeded by the Hyangsanni Dolomite and Daehyangsan Quartzite, which are indicative of shallow marine sedimentation during the waning period of volcanism. Currently no reliable age constraints are available for the Hyangsanni Dolomite and Daehyangsan Quartzite.

The second rift event resumed at ca. 760 Ma (Kim et al., 2006) and associated volcanic activity resulted in deposition of a thick succession of volcanic-sedimentary rocks of the Munjuri Formation. The radiometric ages of the Munjuri Formation (Lee K.-S. et al., 1998; Cho et al., 2004) suggested that the second stage volcanism may have lasted for tens of millions years. The Munjuri Formation is conformably overlain by the Hwanggangni Formation which represents the Cryogenian glaciogenic sedimentation in the Chungcheong Basin. While the Hwanggangni Formation is a sole glaciogenic unit in the Chungcheong Basin, two Cryogenian glaciogenic sequences (Changan and Nantuo formations) have been documented in the Nanhua Basin of South China (Wang and Li, 2003; Zhang et al., 2008, 2011; Jiang et al., 2011). Although no reliable age information is currently available for the Hwanggangni Formation, the Hwanggangni Formation can be correlated with the diamictites of the global snowball Earth event (Hoffman et al., 1998; Evans, 2000), including the Nanhua Basin of South China. The geologic age of the Cryogenian glaciogenic sequences in Nanhua Basin has been well constrained between 720 Ma and 635 Ma (Zhang et al., 2008, 2011; Jiang et al., 2011; Wang et al., in press).

Immediately above the Hwanggangni Formation, a thin carbonate bed, Geumgang Limestone Member of the Myeongori Formation, was deposited in the Chungcheong Basin. The Geumgang Limestone Member is interpreted as cap carbonate representing deglaciation event, which marks the onset of the Ediacaran Period at ~635 Ma. (Knoll et al., 2006). The succeeding Seochangni Member of the Myeongori Formation is characterized by the predominance of black slate/phyllite facies which may indicate a deposition in a poorly-oxygenated environment. This carbonate-black shale couplet of the Myeongori Formation can be correlated with that of the Doushantuo Formation, Nanhua Basin, South China (Zhu et al., 2007; Jiang et al., 2011). The overlying Gounni Formation is dominated by carbonates with intercalations of thin argillaceous layers and is strongly deformed and metamorphosed. The depositional environment of the Gounni Formation is difficult to assess due to the obliteration of primary sedimentary structures, although deposition on a slope to basinal environment was suggested (Lee et al., 1998). The Gounni Formation is correlated with the Dengying Formation of the Nanhua Basin, based on the dominant occurrence of carbonates (Table 2). In the Lake Chungju area, no stratigraphic unit overlying the Gounni Formation has been known and hence the demise of the Chungcheong Basin is indeterminate.

The early Paleozoic paleogeographical positions of the South China and Sino-Korean cratons remain controversial. Li and Powell (2001) treated the South China and Sino-Korean cratons as isolated terranes separated from the Gondwana by trenches, whereas Veevers (2004) and Metcalfe (2006) argued that the South China and Sino-Korean cratons occupied the marginal part of the Gondwana close to Australia. The latter view is well accommodated with a recent paleobiogeographical analysis of McKenzie et al. (2011). A revised paleogeographic model (Fig. 10) displays that in the early Paleozoic the Sino-Korean and South China cratons were located close to Australia and India along the margin of the Gondwana.

The Paleozoic tectonic evolution of the Chungcheong Basin has hitherto been equivocal, as no Paleozoic sedimentary successions are known to occur within the Chungcheong Basin in the Lake Chungju area. [It should be however mentioned that Lim et al. (2005, 2006, 2007) reported the Permian plant fossils from the southwestern part of the Chungcheong Basin.] The medium-pressure, medium-temperature regional peak metamorphism (Cho and Kim, 2005) and the predominance of ductile deformation of the Okcheon Supergroup indicate that rocks of the Okcheon Supergroup must have experienced deep burial as deep as 30 km. This regional metamorphism was previously referred to the mid-Paleozoic (Silurian-Devonian) Okcheon Orogeny by Kim (1987) and Cluzel et al. (1991a), but Cho and Kim (2005) attributed the timing of the orogeny to early Permian based on radiometric ages. This study

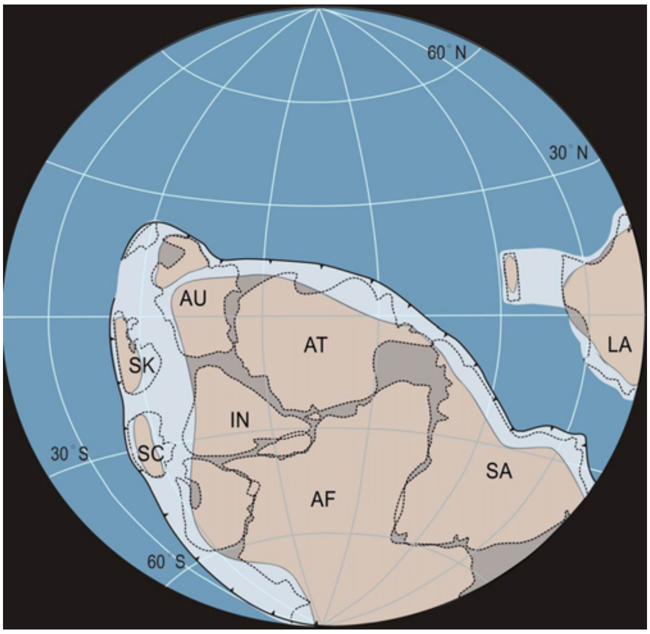

Fig. 10. Early Paleozoic paleogeographic map (from Choi, 2011). Light to dark brown, light blue, and dark blue regions in the map indicate the land, shallow marine and deep marine environments, respectively. Abbreviations: AF, Africa; AT, Antarctica; AU, Australia; IN, India; LA, Laurentia; SA, South America; SC, South China Craton; SK, Sino-Korean Craton.

favors the former suggestion based on an assumption that the Chungcheong Basin may have experienced a comparable tectonism with the Nanhua Basin, South China: i.e., the Okcheon Orogeny occurred contemporaneously with the Wuyun Orogeny (460–400 Ma) of South China Craton (Faure et al., 2009; Li et al., 2010). In relation to this, recognition of an upper Paleozoic turbidite succession (Taean Formation) far west on the Gyeonggi Massif (Choi et al., 2009; Cho et al., 2010) is noteworthy. In South China, mid-Paleozoic turbidite sequences were related to the foreland sedimentation associated with the mid-Paleozoic Wuyun orogeny (Faure et al., 2009; Li et al., 2010), which may also be applicable to the Chungcheong Basin and the Gyeonggi Massif: that is, the Taean Formation may herald the foreland sedimentation associated with the Okcheon Orogeny in Korea.

One of notable geological features in the Sino-Korean Craton is a widespread regional disconformity between the Cambro-Ordovician and the Permo-Carboniferous sequences, representing ca. 140 my time gap (Chough et al., 2000). Choi (2009) presented a scientific scenario for the tectonic history of the Sino-Korean Craton during the period of nondeposition: i.e., the Sino-Korean Craton should have drifted away from Gondwana during the mid-Paleozoic. The South China Craton may also have drifted away from the Gondwana and should have been an isolated terrane during the mid-Paleozoic. These two terranes were collided around 250 Ma to form much of East Asian continent (Yin and Nie, 1996).

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