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A synthesis of Cretaceous palaeomagnetic data from South Korea: tectonic implications in East Asia

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SUMMARY

Tectonic provinces in South Korea include the Precambrian Gyeonggi Massif, Palaeozoic Okcheon Belt, Precambrian Yeongnam Massif and Cretaceous Gyeongsang Basin, from northwest to southeast. The Cretaceous strata mainly occur in the Gyeongsang Basin as well as in several small basins along the boundaries of the Okcheon Belt and on the Gyeonggi Massif. This paper reviews and analyses previously published palaeomagnetic data from the Cretaceous successions in South Korea. A total of 23 Cretaceous palaeomagnetic poles, from 18 studies, satisfy more than four standard reliability criteria. The palaeomagnetic pole positions, from the Gyeongsang Basin and from small basins in the Gyeonggi Massif and the Okcheon Belt, are consistent with one another, indicating that the Korean Peninsula has been a single terrane since the Cretaceous. However, based on the comparison of the palaeomagnetic pole positions and the palaeolatitudes of blocks in the Gyeongsang Basin, it was observed that the Gyeongsang Basin had experienced tectonic adjustments during the Cretaceous Period. Within the Gyeongsang Basin, the geographically northern area (Yeongyang block) was rotated counterclockwise by $16.3^\circ \pm 4.6^\circ$ with respect to the southern area (Milyang and Uiseong blocks), based on the comparison of palaeomagnetic pole positions between the two areas. This palaeomagnetic result and some geological features in the Gyeongsang Basin collectively indicate that the Yeongyang block underwent counterclockwise rotations, accompanied by northwestward protrusion, into the Yeongnam Massif during the Late Cretaceous. These relative tectonic movements within the Gyeongsang Basin were probably due to the northwestward subduction of the proto-Pacific oceanic plate during the Late Cretaceous. The gradual eastward displacement of the Korea's Cretaceous palaeopoles, from the Eurasian pole, increases with stratigraphic age, indicating that the Korean Peninsula underwent progressive clockwise rotations, with respect to Eurasia, during the Cretaceous Period. The clockwise rotation of Southwest Japan, with respect to Eurasia, is ascribed to the Miocene opening of the East Sea, and has no connection with the Cretaceous clockwise rotations of the Korean Peninsula, indicating that the Korean Peninsula and Southwest Japan may have been independent terranes during the Cretaceous Period.

Key words: Cretaceous, East Asia, Korean Peninsula, palaeomagnetism, tectonics.

1 INTRODUCTION

Many palaeomagnetic studies of the Cretaceous strata in South Korea have been carried out since the first palaeomagnetic investigation, by Kienzle & Scharon (1966), on the Cretaceous volcanic rocks in the southeastern Korean Peninsula. There are two tectonic interpretations of the Korean Peninsula during the Cretaceous, based on the palaeomagnetism. On the one hand, it has been reported that the Korean Peninsula occupied its present position during the Late Jurassic–Early Cretaceous, and that it has not been subjected to any rotational movements since the Cretaceous (e.g. Otofuji *et al.* 1986; Kim *et al.* 1993b; Lee & Min 1995). On the other hand, some recent studies show a distinctive eastward declinational shifting of Cretaceous palaeomagnetic directions, from the southeastern part of South Korea (Gyeongsang Basin), with respect to those from Eurasia (e.g. Zhao *et al.* 1999; Doh *et al.* 2002). This result may indicate that the Korean Peninsula experienced clockwise rotations, with respect to the stable Eurasian Plate, during or after the Cretaceous Period. In addition, it is not clear whether the entire Korean Peninsula rotated, or just the Gyeongsang Basin, from which most of the palaeomagnetic data were acquired, experienced the rotation. Although there are many Cretaceous palaeomagnetic studies from

South Korea, such previous fragmentary interpretations, based on limited and independent palaeomagnetic data from unspecific areas, resulted in the tectonic uncertainties of the Korean Peninsula as above, which have been a major obstacle to reconstruct the Cretaceous tectonic framework in East Asia.

Another issue is when the Korean Peninsula underwent the clockwise rotation with respect to the Eurasian Plate: Cretaceous (Zhao *et al.* 1999; Doh *et al.* 2002) or Early Tertiary (Uchimura *et al.* 1996; Uno 2002). Many authors claimed that Southwest Japan had been flanked on the eastern side of the Korean Peninsula during the Cretaceous Period, and experienced rapid clockwise rotations, associated with the opening of the East Sea, in the Middle Miocene (e.g. Otofuji & Matsuda 1983, 1984, 1987; Otofuji *et al.* 1991, 1999; Ishikawa 1997; Kodama & Takeda 2002; Uno 2002). Recently, Uno (2002) interpreted that the tectonic history of Southwest Japan includes Early Tertiary clockwise rotation of about 23° and Middle Miocene clockwise rotation of about 42°, with respect to the North China Block, on the assumption that the clockwise rotation of the Korean Peninsula occurred during the Early Tertiary. However, it is still uncertain whether the Korean Peninsula and Southwest Japan behaved as a tectonically single terrane during the Cretaceous, because the timing of the clockwise rotation of the Korean Peninsula has not been precisely constrained. Therefore, the timing of the clockwise rotation of the Korean Peninsula on the basis of the palaeomagnetic constraints might provide an important clue on the relative tectonic movement between the Korean Peninsula and Southwest Japan since the Cretaceous.

It is recognized that some palaeomagnetic data lack structural correction, insufficient number of samples, inadequate demagnetization or poorly constrained age of magnetization. In addition, the possibility for relative movements or rotations of the microblocks within the Korean Peninsula was not thoroughly considered in previous studies. Thus, it is important to select and analyse reliable palaeomagnetic data from previously reported literatures to solve

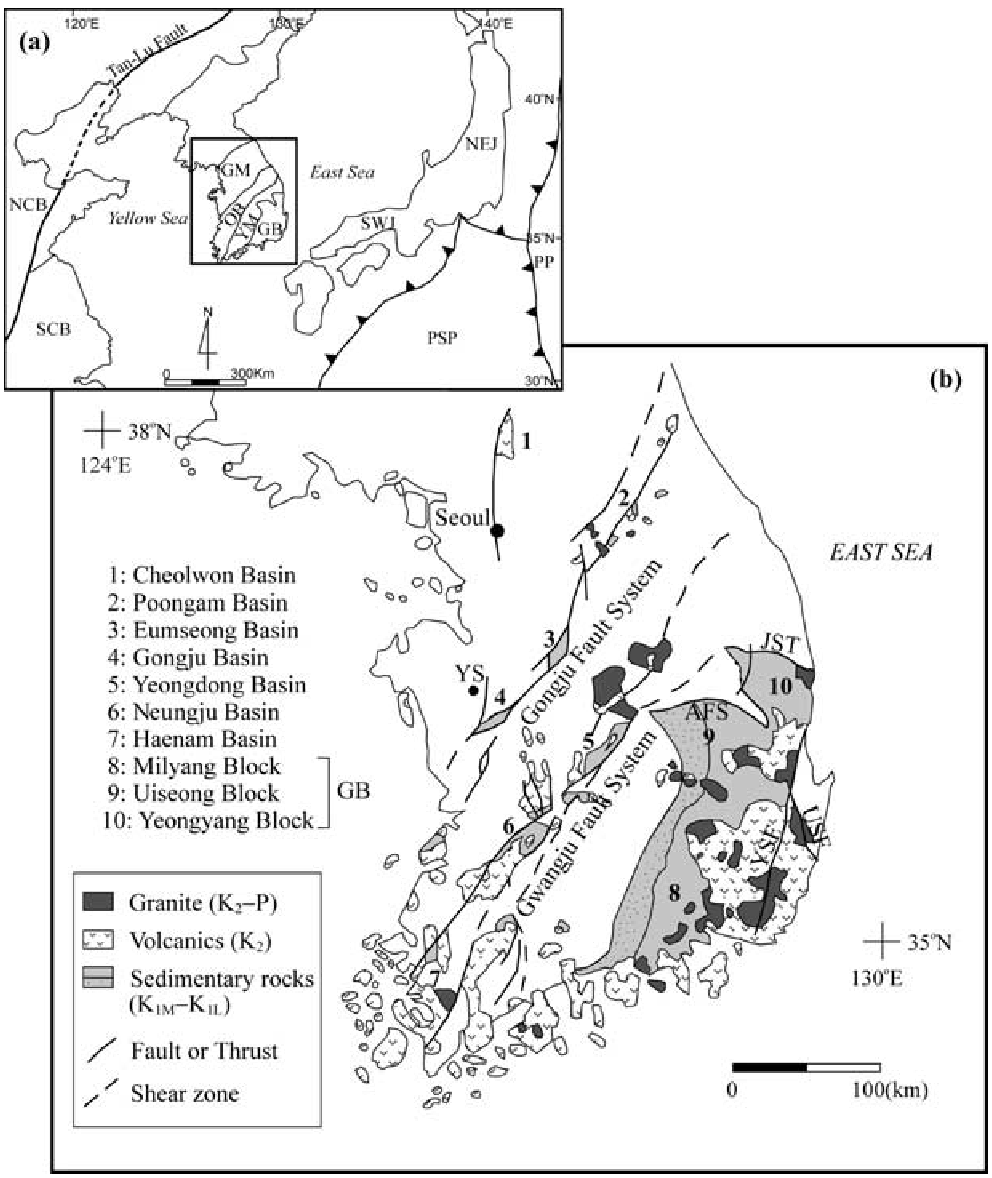

Figure 1. (a) Simplified tectonic map of Far East Asia. GM, Gyeonggi Massif; OB, Okcheon Belt; YM, Yeongnam Massif; GB, Gyeongsang Basin; NCB, North China Block; SCB, South China Block; SWJ, Southwest Japan; NEJ, Northeast Japan; PSP, Philippine Sea Plate; PP, Pacific Plate. (b) Distribution of the Cretaceous strata in South Korea. AFS, Andong fault system; JST, Jaesan thrust; USF, Ulsan fault; YSF, Yangsan fault; YS, Yesan area. K_{1M}, K_{1L}, K_2 and P refer to the middle Early Cretaceous, the late Early Cretaceous, the Late Cretaceous and the Palaeocene, respectively.

these tectonic problems of the Korean Peninsula for the Cretaceous Period.

We review previously published Cretaceous palaeomagnetic data from South Korea to yield representative palaeomagnetic poles for the middle Early Cretaceous, the late Early Cretaceous and the Late Cretaceous. The geodynamic evolution of the Korean Peninsula, in the tectonic framework of East Asia during the Cretaceous, will be discussed based on the comparisons of carefully selected reliable Cretaceous palaeomagnetic poles of South Korea and those of adjacent blocks.

2 GEOLOGICAL SETTING

Tectonic provinces in South Korea include the Precambrian Gyeonggi Massif, Palaeozoic Okcheon Belt, Precambrian Yeongnam Massif and Cretaceous Gyeongsang Basin, from northwest to southeast (Fig. 1a). These provinces have been regarded as a tectonically single terrane of an eastern continental margin of Asia, after the collisional event between the North and South China blocks during the late Palaeozoic to early Mesozoic (Chough *et al.* 2000). During the middle Jurassic, the orthogonal subduction of the Izanagi Plate beneath the Eurasian Plate led to the formation of NE–SW-trending magmatic belts along the Pacific continental margin (Maruyama *et al.* 1997), and initiated a NE–SW-trending dextral ductile shear event in the mid-southern Korean Peninsula (Yanai *et al.* 1985; Cluzel *et al.* 1991; Otoh *et al.* 1999; Chough *et al.* 2000) (Fig. 1b). During the Early Cretaceous, the Gyeongsang Basin was formed on the Yeongnam Massif by sinistral transtension during the oblique (northward) subduction of the Izanagi Plate beneath the Eurasian Plate (Otoh & Yanai 1996) (Fig. 2). The Gyeongsang Basin, the largest sedimentary basin in Korea, was a part of an Andean-type continental margin in northeastern Asia, where extensive crustal upheaval and non-marine sedimentation took place (Miyashiro 1974). Simultaneously, a number of pull-apart, or transtensional, basins along the boundaries of the Okcheon Belt were formed by NE-trending sinistral strike–slip faulting (Lee & Paik 1990) (Fig. 1b). Magmatism and volcanism were active from the Late Cretaceous to the Early Tertiary due to the northwestward (orthogonal) subduction of the proto-Pacific plate accompanied by ridge subduction (Uyeda & Miyashiro 1974; Maruyama & Seno 1986; Maruyama *et al.* 1997; Okada 2000).

Cretaceous non-marine sedimentary and volcanic successions, the Gyeongsang Supergroup, are mainly exposed in the Gyeongsang Basin of southeastern Korea. The detailed distribution of the Cretaceous strata is shown in Fig. 1(b). The Cretaceous Gyeongsang Supergroup is composed of three major lithostratigraphic units: the lower Sindong, middle Hayang and upper Yucheon groups (Chang 1975, 1977) (Fig. 2). The Sindong and Hayang groups mainly consist of thick siliciclastic successions of alluvial, fluvial and lacustrine sediments, while the Yucheon Group is characterized by the dominance of volcanic rocks (Chang 1975). The Sindong Group is well distributed along the western margin of the Gyeongsang Basin (Fig. 1b). Palaeontological studies (e.g. Um *et al.* 1978; Yang 1983; Choi 1985, 1989a,b; Yi *et al.* 1994; Matsukawa *et al.* 1998; Kozai *et al.* 2001) suggest that the ages of the Sindong and Hayang groups are the middle Early Cretaceous (Hauterivian to Early Aptian) and the late Early Cretaceous (Aptian to Albian), respectively (Fig. 2). The overlying Yucheon Group is regarded as the Late Cretaceous (Cenomanian to Maastrichtian) in age, based on the isotope age data of both the Yucheon volcanic rocks (Shin & Jin 1995a) and the plutonic rocks intruding all of the Cretaceous strata (Shin & Jin 1995b).

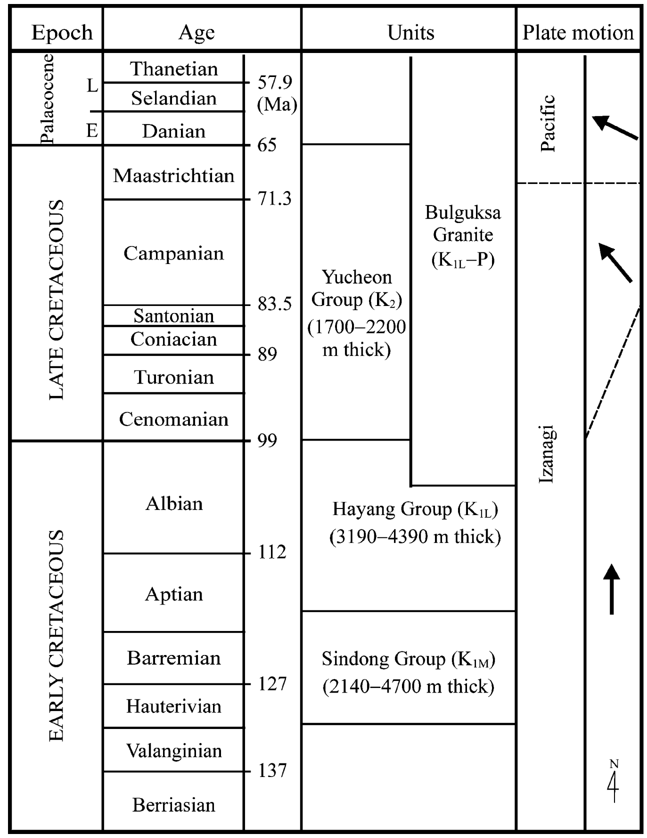

Figure 2. Stratigraphy of the Gyeongsang Supergroup in South Korea (after Chang 1975) and variations of the Pacific Plate motions from Maruyama & Seno (1986).

Due to the uneven distribution of three lithostratigraphic units (i.e. Sindong, Hayang and Yucheon groups), the Gyeongsang Basin has been subdivided into three smaller crustal segments: the Milyang, Uiseong and Yeongyang blocks (Fig. 1b). The Milyang and Uiseong blocks contain three distinct lithostratigraphic units, which show the traditional tripartite lithostratigraphic scheme in the Gyeongsang Basin. However, the northern Yeongyang block is mainly composed of the middle Hayang and upper Yucheon groups without the lower Sindong Group. The uneven distribution of three lithostratigraphic units in the basin may be related with the differential movement of each block during the basin formation and/or deformation (Ryu *et al.* 2003).

3 DATA SELECTION

A total of 44 Cretaceous palaeomagnetic poles, from 34 published studies, have been collected and reviewed in this study (see Appendix A). Van der Voo (1990) proposed seven reliability criteria for palaeomagnetic data as follows:

(1) well-determined rock age and a presumption that the magnetization is the same age;

(2) sufficient number of samples ($N \geq 24$), k (or K) ≥ 10 and α_{95} (A_{95}) ≤ 16.0;

(3) adequate demagnetization that demonstrably includes vector subtraction;

(4) field tests that constrain the age of magnetization;

(5) structural control and tectonic coherence with craton or block involved;

(6) the presence of reversals;
(7) no resemblance to palaeopoles of younger age (by more than a Period).

As with the scheme of Van der Voo (1990), one point was scored for each of the criteria that were judged to have been satisfied. Then a quality factor (Q), in the range 0–7, was derived from the overall point score, and was assigned to each palaeomagnetic data set (see Appendix A). Note that there is no Cretaceous palaeomagnetic data from the Korean Peninsula, which satisfy all of Van der Voo's criteria (i.e. $Q = 7$). Therefore, we retained generally accepted minimum reliability criteria which are designed to ensure that the palaeomagnetic data reflects the Earth's average magnetic field direction, over tens of thousands of years, at a specified geologic time. From this point of view, we considered the priority of the above criteria for the tectonic interpretation because some of criteria may not be available under certain circumstances. Field tests (i.e. the fourth criterion), such as the fold, conglomerate and contact tests, may not always be possible because of the limitations of outcrop and field settings (Van der Voo 1990). For instance, the primary magnetization obtained from a certain strata with the very shallow dip angle (e.g. Gyeongsang Basin) may not statistically pass the fold test. In addition, a large fraction of Cretaceous palaeomagnetic data, especially for the Cretaceous Long Normal Superchron (120.5–83.5 Ma, Gradstein *et al.* 1994), reveals the absence of the reversals (i.e. the sixth criterion). On the other hand, three criteria, such as (1) well-determined rock age, (2) sufficient statistical base and (3) adequate demagnetization that demonstrably include vector subtraction, are the most significant acceptance criteria for the reliable palaeomagnetic data. Still the latter four criteria (4), (5), (6) and (7) certainly enhance the reliability of palaeomagnetic data. Therefore, we consider the palaeomagnetic data that satisfy at least four criteria, surely including (1), (2) and (3), to be reliable. We reject palaeomagnetic data with a negative fold test or negative reversal test to ensure the absence of remagnetization. As a result, 23 Cretaceous palaeomagnetic data sets were accepted in this study (Tables 1 and 2).

Table 1. Summary of Cretaceous palaeomagnetic data from the Gyeongsang Basin.

Basin	Age	n/N	Palaeolatitude (°N)	Palaeomagnetic Pole Lat.(°N)	Palaeomagnetic Pole Long.(°E)	A_{95} (dp/dm)	Quality factor (Q)	Reference (*rock type*)
				Gyeongsang Basin			1,2,3,4,5,6,7*	
Milyang	K_2	75/12	37.6	76.0	205.0	(6.0/8.3)	o.o.o.x.x.o.x 4	Kim & Kim (1991)
	K_2	29/6	40.4	72.5	197.4	4.4	o.o.o.o.x.o.x 5	Kang *et al.* (2000)
	K_2	95/14	34.7	67.0	210.6	6.7	o.o.o.o.x.o.x 5	Kang & Kim (2000b)
	Mean	18 sites	35.9	73.1	204.6	7.0		(*volcanic rocks*)
	Mean	14 sites	37.5	71.5	205.2	3.7		(*sedimentary rocks*)
	Mean	**32 sites**	36.7	**72.4**	**204.9**	**4.1**		(*vol. + sed.*)
	K_{1L}	182/38	38.8	67.1	209.8	2.0	o.o.o.x.x.x.o 4	Kim & Jeong (1986)
	K_{1L}	402/35	38.9	67.0	202.0	(7.0/9.5)	o.o.o.o.o.x.o 6	Otofuji *et al.* (1986)
	K_{1L}	43/7	32.4	66.4	219.3	9.2	o.o.o.o.x.o.o 6	Lee *et al.* (1987)
	K_{1L}	155/20	37.4	66.4	204.1	4.2	o.o.o.o.x.x.o 5	Doh *et al.* (1994)
	K_{1L}	70/16	38.7	68.6	210.2	14.7	o.o.o.o.x.o.o 6	Zhao *et al.* (1999)
	Mean	6 sites	35.8	59.6	205.4	11.1		(*volcanic rocks*)
	Mean	5 studies	37.3	67.8	206.4	4.4		(*sedimentary rocks*)
	Mean	**5 studies**	37.2	**67.2**	**209.1**	**2.6**		(*vol. + sed.*)
	K_{1M}	77/20	46.5	57.5	186.3	4.5	o.o.o.x.x.x.o 4	Kim & Jeong (1986)
	K_{1M}	163/18	46.5	58.0	187.0		o.o.o.x.x.x.o 4	Otofuji *et al.* (1986)
	K_{1M}	108/8	42.8	60.8	194.2	6.5	o.o.o.o.x.o.o 6	Lee *et al.* (1987)
	K_{1M}	47/3	34.5	60.7	208.5	8.4	o.o.o.x.x.o.o 5	Kim *et al.* (1993a)
	K_{1M}	104/16	39.3	59.9	198.8	4.3	o.o.o.o.x.x.o 5	Doh *et al.* (1994)
	Mean	**5 studies**	41.9	**59.6**	**194.7**	**4.6**		(*sedimentary rocks*)
Uiseong	K_2**	84/19	41.5	81.3	79.0	(13.0/17.0)	o.o.o.o.x.o.o 6	Doh & Kim (1994) (*volcanic rocks*)
	K_{1L}	79/14	37.8	72.0	206.4	(4.9/6.7)	o.o.o.o.x.x.x 4	Doh & Kim (1994)
	K_{1L}	174/20	38.4	64.9	202.2	7.6	o.o.o.o.x.x.x 4	Suk & Doh (1996)
	Mean	5 sites	42.3	76.3	187.0	23.5		(*volcanic rocks*)
	Mean	29 sites	37.0	64.4	206.0	4.3		(*sedimentary rocks*)
	Mean	**34 sites**	37.8	**66.1**	**204.4**	**4.7**		(*vol. + sed.*)
Yeongyang	K_{1L}***	400/29	35.8	85.5	217.4	5.2	o.o.o.o.x.x.x 4	Doh *et al.* (1999a)
	K_{1L}***	179/28	36.7	68.4	210.7	6.0	o.o.o.o.x.o.x 5	Kang & Kim (2000a)
	Mean	12 sites	38.8	84.3	174.4	10.3		(*volcanic rocks*)
	Mean	45 sites	36.2	78.9	213.9	4.1		(*sedimentary rocks*)
	Mean	**57 sites**	36.9	**80.3**	**209.5**	**3.8**		(*vol. + sed.*)

n/N: number of samples/sites; Lat.: north latitude; Long.: east longitude; A_{95}: the radius of the 95 per cent confidence circle about the calculated mean pole; dp/dm: the semi axis of the confidence ellipse along/perpendicular to the great-circle path from site to pole; K_{1M}: middle Early Cretaceous; K_{1L}: late Early Cretaceous; K_2: Late Cretaceous. Quality factor (Q) using the reliability criteria by Van der Voo (1990) for each study is presented.
*Reliability criteria: 1, well-determined rock age and a presumption that magnetization is the same age; 2, sufficient number of samples; 3, adequate demagnetization that demonstrably includes vector subtraction; 4, field tests that constrain the age of magnetization; 5, structural control and tectonic coherence with craton or block involved; 6, the presence of reversals; 7, no resemblance to palaeopoles of younger age (by more than a period).
**Pole suspected of incomplete tilt correction.
***Poles suspected of suffering local vertical-axis rotation.

Table 2. Summary of Cretaceous palaeomagnetic data from the Okcheon Belt and the Gyeonggi Massif.

Basin	Age	n/N	Palaeolatitude (°N)	Palaeomagnetic Pole Lat.(°N)	Palaeomagnetic Pole Long.(°E)	A_{95} (dp/dm)	Quality factor (Q)	Reference (*rock type*)
				Okcheon Belt			1,2,3,4,5,6,7*	
Gongju	K_2	102/9	25.6	67.2	235.3	8.9	o.o.o.o.x.o.x 5	Doh *et al.* (2002) (*volcanic rocks*)
Neungju	K_2	38/11	32.0	78.8	228.3	4.8	o.o.o.o.o.o.x 6	Kim & Noh (1993) (*vol. + sed.*)
				Gyeonggi Massif				
Cheolwon	K_2	75/16	34.6	61.7	212.9	(6.1/8.7)	o.o.o.x.o.x.o 5	Kim & Song (1995)
	K_2	28/5	35.9	71.6	216.8	(7.1/10.0)	o.o.o.x.o.x.o 5	Lee *et al.* (2001)
	Mean	**21 sites**	**35.2**	**63.7**	**213.2**	**5.4**		(*volcanic rocks*)
Yesan	K_2***	41/9	26.2	60.8	25.8	7.6	o.o.o.x.x.o.x 4	Kim *et al.* (1997) (*volcanic rocks*)

See footnote of Table 1.

4 ANALYSES OF PALAEOMAGNETIC DATA

Selected palaeomagnetic data have been classified and analysed according to the location and age of their rock units. Then representative palaeomagnetic poles for each basin (or block) were basically recalculated on the study level from the original data using Fisher's statistics (Fisher 1953), if there were sufficient amount of palaeomagnetic data (i.e. more than four studies). If there were only two or three data sets, we recalculated mean poles on the site level from the original data. Cretaceous strata in the Korean Peninsula are composed of the Sindong, Hayang and Yucheon groups for the middle Early Cretaceous (referred to as K_{1M}), the late Early Cretaceous (referred to as K_{1L}) and the Late Cretaceous (referred to as K_2), respectively. The average palaeomagnetic poles of these three epochs (K_{1M}, K_{1L} and K_2) were then used to interpret the tectonic evolution of the Korean Peninsula.

The acquisition processes of the primary remanent magnetizations in our data set include a detrital remanent magnetization (DRM) and a thermoremanent magnetization (TRM), since we retain data from both sedimentary and volcanic rocks. The question of the relative reliabilities of the DRMs and the TRMs in our data set can be raised (e.g. inclination shallowing versus geomagnetic secular variation). One way to test whether the palaeomagnetic directions and palaeolatitudes derived from the sedimentary remanences (DRMs) are biased by the inclination shallowing is to compare them with those from synchronous volcanic remanences (TRMs), which are relatively immune from shallowing effects. When the palaeomagnetically determined palaeolatitudes between sedimentary and volcanic rocks of identical age from the Gyeongsang Basin are compared, no significant inclination shallowing of sedimentary remanences is recognized (Table 1). In addition, there were no previous palaeomagnetic reports, suspicious of including inclination shallowing by the original authors, from the Cretaceous sedimentary rocks in the Korean Peninsula. Therefore, our data set is considered as free of any large inclination shallowing effects. On the other hand, adequacy of averaging out geomagnetic secular variation for volcanic rocks, which have too short integration time for recording the representative geomagnetic field direction, should be taken into account. The number of sampling sites for volcanic data, used in this study, is sufficient to average out the secular variation (e.g. more than five lava flows) (Tables 1 and 2). When the α_{95} (or A_{95}) circle of the mean direction (or palaeomagnetic pole) from the volcanic rocks is extremely small, it can be suspected that the secular variation has not been averaged out sufficiently. However, there are no such extremely small α_{95} (or A_{95}) values in our data from the volcanic rocks ($A_{95} > 4.8°$). In the Gyeongsang Basin, moreover, palaeomagnetic pole positions obtained from the volcanic rocks are close to those from the sedimentary rocks, which have long integration time of recording the magnetization enough to average out geomagnetic secular variation. It is worth noting that the K_2 palaeopoles obtained from the volcanic rocks in the Uiseong block (Table 1) and the Gongju, Neungju and Yesan basins (Table 2) reveal the positive reversal test results by the original authors, indicating that they are time-averaged poles, equivalent to the geocentric axial dipole field direction when the volcanic rocks were formed. Thus, the effects of inclination shallowing or geomagnetic secular variation are thought to be insignificant in our data sets.

4.1 Palaeomagnetic data from the Gyeongsang Basin

18 out of 32 palaeomagnetic data from the Gyeongsang Basin satisfy our minimum reliability criteria. The average palaeomagnetic data for each group in the Gyeongsang Basin are summarized in Table 1.

4.1.1 Milyang block

The Milyang block, a southern part of the Gyeongsang Basin, is the most important region for palaeomagnetic investigation of the Cretaceous strata in Korea, because three distinctive stratigraphic units (the Sindong, Hayang and Yucheon groups) are well exposed. A total of 13 out of 21 palaeomagnetic data satisfy our minimum reliability criteria (Table 1).

The group-mean directions are tightly clustered with high k and low α_{95} values, and show directional differences according to the age of the rock units (Fig. 3a). The declination of the group-mean direction shifts westward, from the older Sindong Group, through the Hayang Group and to the younger Yucheon Group. The declinational difference between the Sindong and Yucheon groups is $15.6° \pm 7.1°$. Inclination of the Sindong Group is slightly steeper by $4.6° \pm 4.0°$ than that of the Yucheon Group (Fig. 3b). These directional discrepancies between the three groups seem to be small. However, they are meaningful, because the mean directions between the Yucheon and Sindong groups are statistically different from each other at the 5 per cent significance level, as well as those between the Hayang and Sindong groups (Fig. 3b). These results raise the possibility

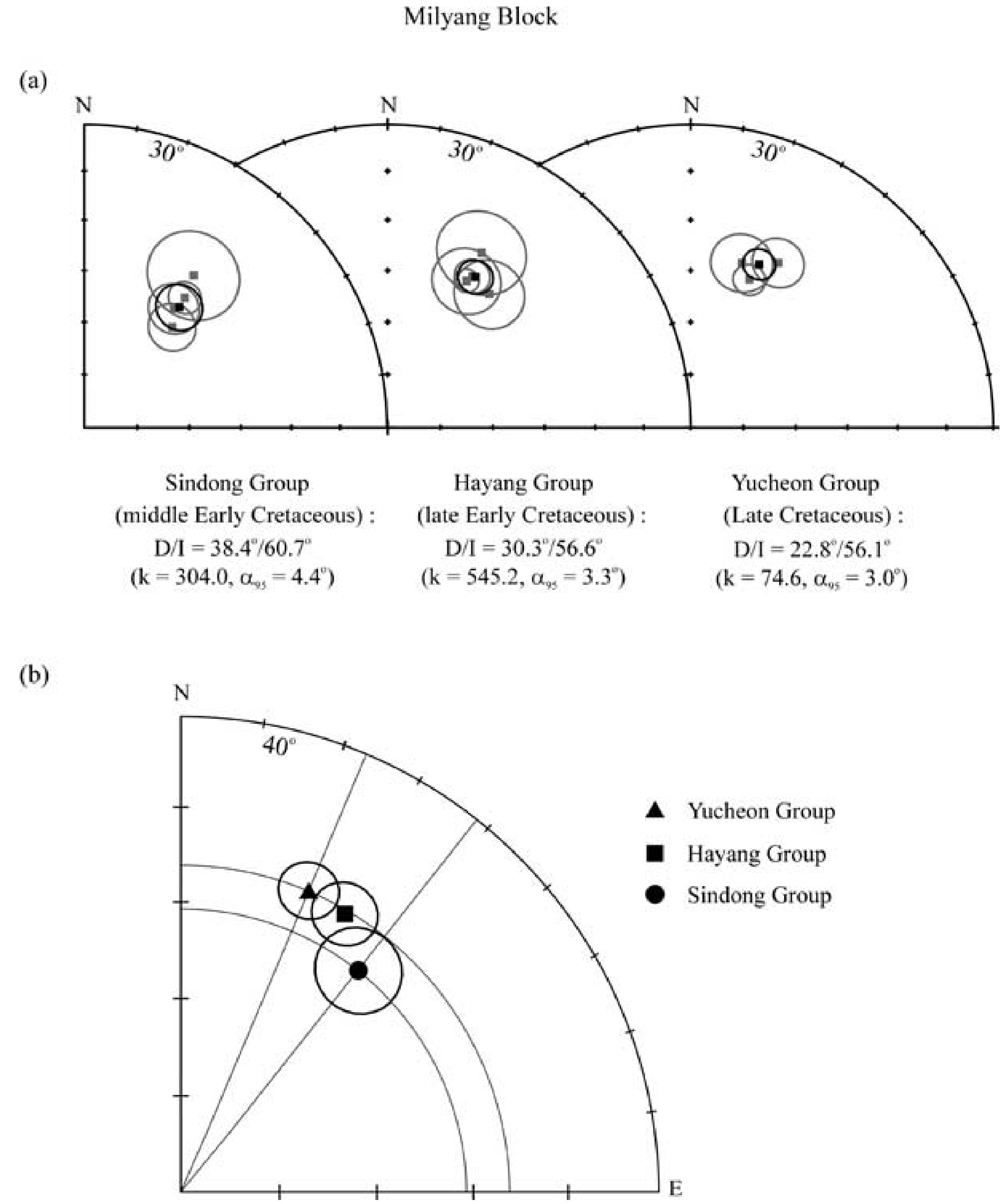

Figure 3. (a) Mean palaeomagnetic directions (black) for the Sindong, Hayang and Yucheon groups calculated from reliable published data (grey) from the Milyang block within the Gyeongsang Basin. (b) Comparison of the mean palaeomagnetic directions of the Sindong, Hayang and Yucheon groups. Solid symbols are lower hemisphere projections.

for the tectonic movement of clockwise rotation and southward migration of the Milyang block during the middle Early Cretaceous to Late Cretaceous.

4.1.2 Uiseong and Yeongyang blocks

Reliable palaeomagnetic data from the Uiseong and Yeongyang blocks are relatively rare compared to those from the Milyang block (Table 1): two results for the Hayang Group and one for the Yucheon Group from the Uiseong block; two for the Hayang Group from the Yeongyang block.

The westward declinational shifting, according to the age of rock units, is also observed in the Uiseong block: 29.9° for K_{1L} (Hayang Group) to 351.2° for K_2 (Yucheon Group) (Fig. 4a). However, the amount of declinational difference (38.7°) between K_{1L} and K_2 in the Uiseong block is much larger than that (7.5°) observed in the Milyang block. There are two possibilities for this large amount of declinational difference in the Uiseong block. One is a possibility that the declination for K_2 was superimposed by an effect of local counterclockwise rotation of the Yucheon Group (K_2), with respect to the Hayang Group (K_{1L}), within the Uiseong block. The other possibility is an imperfect tilt correction for the Yucheon Group, which consists entirely of volcanic rocks, in the Uiseong block. Any geological evidence for the former explanation cannot be found. At present, the latter seems to be more likely based on the fairly low value of precision parameter ($k = 10$) of the Yucheon Group in the Uiseong block.

Two palaeomagnetic results for the Hayang Group in the Yeongyang block, located in the northern part of the Gyeongsang Basin, reveal a well-grouped mean direction with a westward-deflected declination for K_{1L} in comparison of those from the Milyang and Uiseong blocks (Figs 4b and 5). This declinational

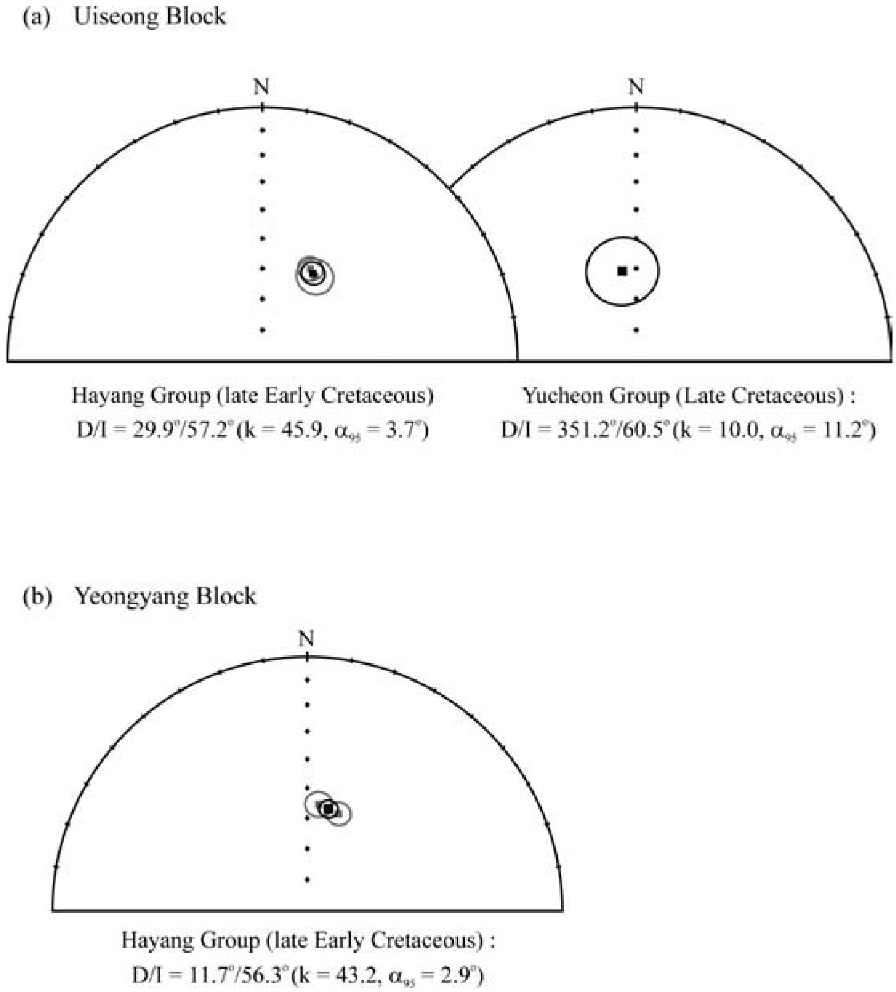

Figure 4. (a) Mean palaeomagnetic directions (black) calculated from reliable published data (grey) from the Uiseong block within the Gyeongsang Basin. (b) A mean palaeomagnetic direction (black) calculated from reliable published data (grey) from the Yeongyang block within the Gyeongsang Basin. Solid symbols are lower hemisphere projections.

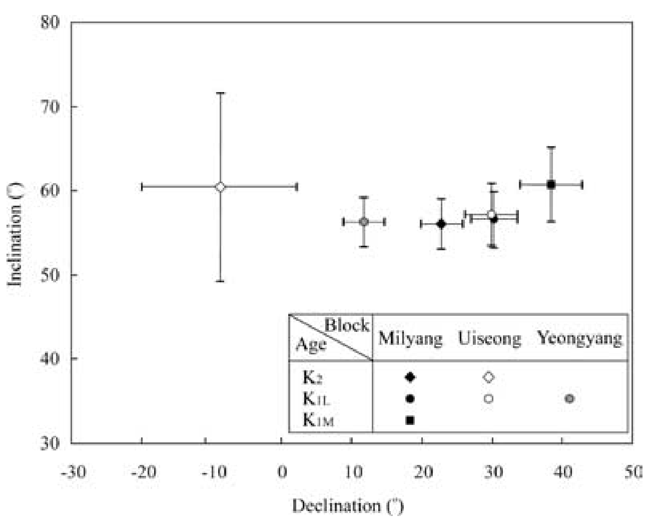

Figure 5. A diagram showing palaeomagnetic directions (declination and inclination) with their 95 per cent confidence limits from the Milyang, Uiseong and Yeongyang blocks within the Gyeongsang Basin. K_2, the Late Cretaceous; K_{1L}, the late Early Cretaceous; K_{1M}, the middle Early Cretaceous.

deflection indicates a possibility that the Yeongyang block experienced counterclockwise rotations, with respect to the Milyang and Uiseong blocks, after the sedimentation of the Hayang Group. This possibility will be further discussed in Section 5.1.

To summarize the palaeomagnetic data within the Gyeongsang Basin, it is observed that the declination of the younger rock unit is displaced westward relative to that of the older rock unit within each block (Fig. 5). Also, the declination from the geographically northern area (Yeongyang block) is deflected westward compared with that from the southern area (Uiseong and Milyang blocks) of the basin.

4.2 Palaeomagnetic data from small basins outside the Gyeongsang Basin

Secondary remanent magnetizations have been reported from several basins along the boundary of the Okcheon Belt (Fig. 1b) (e.g. Yeongdong Basin, Doh *et al.* 1996; Eumseong Basin, Doh *et al.* 1999b; Poongam Basin, Park & Doh 2004). The Cretaceous sedimentary rocks in the three basins were totally remagnetized during (Yeongdong Basin) or after (Eumseong and Poongam basins) the tilting of the strata. These remagnetization components have been considered to be a chemical remanent magnetization (CRM), carried by secondary authigenic magnetite and haematite, based on the results of the electron microscope observations and rock magnetic experiments (Doh *et al.* 1996, 1999b; Park & Doh 2004). It is also reported that the Late Palaeozoic sedimentary rocks, distributed in the northeastern part of the Okcheon Belt, were remagnetized by a fluid-mediated process during the Late Cretaceous–Early Tertiary (Doh *et al.* 1997; Park *et al.* 2003). Park *et al.* (2003) suggested that the remagnetizing fluids might be originated from the subduction of the proto-Pacific plate under the Eurasian Plate during the Cretaceous Period, and migrated pervasively along the well-developed thrust fault system within the Okcheon Belt. On the other hand, it seems that the Cretaceous strata within the Gyeongsang Basin and the Gyeonggi Massif did not suffer any severe chemical remagnetization.

Only two reliable palaeomagnetic results for the Late Cretaceous (K_2) strata were obtained from the Gongju Basin (Doh *et al.* 2002) and the Neungju Basin (Kim & Noh 1993) in the southwestern part of the Okcheon Belt (Fig. 1). In the Gyeonggi Massif, two Late Cretaceous (K_2) palaeomagnetic data from the northern area (Cheolwon Basin, Kim & Song 1995; Lee *et al.* 2001) and one from the southern area (Yesan area, Kim *et al.* 1997) were selected. The palaeomagnetic results from the four Cretaceous basins in the Okcheon Belt and the Gyeonggi Massif are summarized in Table 2. Most palaeomagnetic poles from small basins within the Okcheon Belt and the Gyeonggi Massif, except the southern Gyeonggi Massif (Yesan area), correspond to those from the Milyang block (Fig. 6). The palaeomagnetic pole position of the Yesan area is displaced westward by $55.8^\circ \pm 8.6^\circ$ with respect to the mean pole of the other areas, indicating that the southern Gyeonggi Massif (Yesan area) might have experienced a counterclockwise rotation with respect to the other areas. It can be interpreted that the northern Gyeonggi Massif, the southwestern Okcheon Belt and the Milyang block were tectonically coherent during the Cretaceous Period.

4.3 Representative Cretaceous palaeomagnetic poles of the Korean Peninsula

The mean palaeomagnetic poles for three epochs were averaged, using 19 out of 23 palaeopoles from both areas within and outside

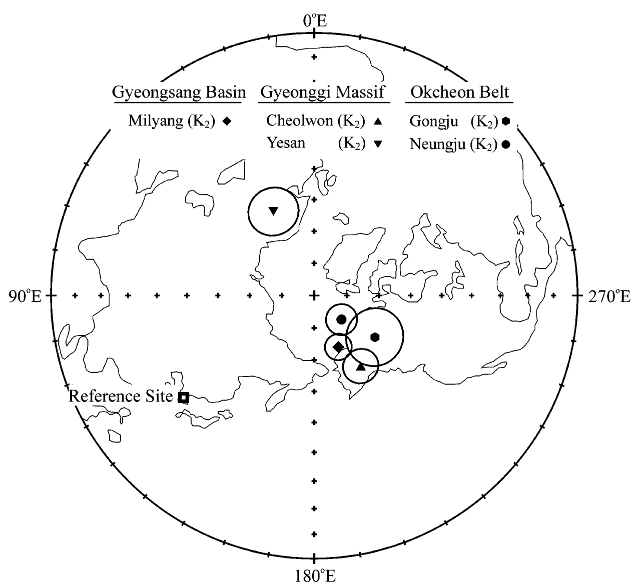

Figure 6. Late Cretaceous (K_2) palaeomagnetic poles from the Gyeongsang Basin (Milyang), Gyeonggi Massif (Cheolwon and Yesan) and Okcheon Belt (Gongju and Neungju).

the Gyeongsang Basin, in order to verify the tectonic relationship of the Korean Peninsula with respect to adjacent blocks during the Cretaceous Period (Table 3). Four palaeopoles, from the Uiseong, Yeongyang and Yesan areas, which were suspected of suffering local vertical-axis rotation or incomplete tilt correction, have been excluded from the average (Tables 1 and 2).

5 DISCUSSION

5.1 Relative movements of microblocks within the Gyeongsang Basin

5.1.1 Palaeomagnetic evidences for the counterclockwise rotations of the Yeongyang block with respect to the Milyang and Uiseong blocks

Comparison of the palaeomagnetic poles for the Hayang Group (K_{1L}) from three blocks within the Gyeongsang Basin is shown in Fig. 7. Three palaeopoles are plotted along a small circle centred at the reference point (centre of the Gyeongsang Basin). The confidence circles of the Uiseong and Milyang blocks include each other's palaeopoles, indicating that these two palaeopoles of the Uiseong and Milyang blocks are not statistically different from each other at the 5 per cent significance level. The mean palaeomagnetic pole of the Milyang and Uiseong blocks is at 67.3°N, 207.6°E with $A_{95} = 2.6^\circ$. Comparison of this palaeopole with that of the Yeongyang block suggests that the Yeongyang block rotated counterclockwise by $16.3^\circ \pm 4.6^\circ$, with respect to the southern area (Uiseong and Milyang blocks) within the Gyeongsang Basin, after the formation of the Hayang Group (K_{1L}) (Fig. 7). However, it is not known if the counterclockwise rotations of the Yeongyang block were accompanied by some lateral or latitudinal movements relative to the other blocks. The palaeomagnetically determined palaeolatitude of the Yeongyang block is 36.9°N ($+3.1^\circ/-2.9^\circ$), which is not statistically distinguishable from those of the Uiseong (37.8°N, $+4.1^\circ/-3.8^\circ$) and Milyang (37.2°N, $+3.6^\circ/-3.3^\circ$) blocks during the late Early Cretaceous, although the present latitude of the Yeongyang block ($36.6^\circ\text{N} \pm 0.2^\circ$) is higher than those of the Uiseong ($36.3^\circ\text{N} \pm 0.2^\circ$) and Milyang ($35.5^\circ\text{N} \pm 0.5^\circ$) blocks (Fig. 8). This result seems to reject the possibility of latitudinal translation of the Yeongyang block after the late Early Cretaceous. However, the possibility of small amount (e.g. $\sim 1^\circ$) of latitudinal movement is still retained. We will discuss more geological evidence for the latitudinal migration, as well as the counterclockwise rotation, of the Yeongyang block with respect to the Uiseong and Milyang blocks in the following section.

5.1.2 Syntheses of geological features within the Gyeongsang Basin and motion of the proto-Pacific plate: a possibility of protrusion of the Yeongyang block

The late Early Cretaceous palaeomagnetic pole (80.3°N, 209.5°E) of the Yeongyang block is displaced westward by $16.3^\circ \pm 4.6^\circ$ with respect to the coeval mean pole (67.3°N, 207.6°E) of the Uiseong and Milyang blocks. This palaeomagnetic result suggests that the Yeongyang block has experienced a counterclockwise rotation with respect to the Uiseong and Milyang blocks since the late Early Cretaceous. As mentioned in the previous section, the palaeolatitudes of the Yeongyang, Uiseong and Milyang blocks do not statistically support a possibility that the Yeongyang block translated northward, from the Milyang and Uiseong blocks, after the late Early Cretaceous. However, some geological evidence for the latitudinal movement of the Yeongyang block can be recognized. The Sindong

Table 3. Cretaceous palaeomagnetic poles for the Korean Peninsular and adjacent blocks.

Locality	Age	$N(n)$	Palaeomagnetic Pole		A_{95}	$R \pm \Delta R$	Reference
			Lat.(°N)	Long.(°E)	(°)	(°)	
Korean Peninsula	K_2	7	71.1	215.2	5.4	+6.1 ± 5.8	This study
	K_{1L}	7	67.6	207.7	2.5	+10.9 ± 3.4	This study
	K_{1M}	5	59.6	194.7	4.6	+21.9 ± 5.5	This study
Southwest Japan	K_2	5	26.8	201.4	7.4	+62.2 ± 7.5	[1, 2, 3, 4, 5]
	K_{1L}– earliest K_2	(18)	39.4	186.1	8.2	+51.5 ± 10.5	[6]
	K_{1L}– early K_2	(21)	41.5	189.4	8.5	+47.7 ± 10.4	[4]
North and South China blocks	84–65 Ma	8	72.6	208.0	6.5	+4.1 ± 6.9	[7]
	118–84 Ma	9	76.4	200.4	4.9	+0.2 ± 5.6	[7]
	145–118 Ma	11	76.8	210.2	3.1	+1.2 ± 3.9	[7]
Eurasia	130–65 Ma		76.2	202.8	2.2	—	[8]

$N(n)$, number of studies (sites); Lat., north latitude; Long., east longitude; A_{95}, the radius of the 95 per cent confidence circle about the calculated mean pole; R, rotation clockwise (+) or counterclockwise (−) with respect to Eurasia in pole space; ΔR, uncertainty (95 per cent limits) of R, estimated by the method of Demarest (1983); K_{1M}, middle Early Cretaceous; K_{1L}, late Early Cretaceous; K_2, Late Cretaceous.
Reference: [1] Uno (2000); [2] Fukuma & Torii (1990); [3] Kodama (1990); [4] Otofuji & Matsuda (1987); [5] Ito & Tokieda (1986); [6] Kodama & Takeda (2002); [7] Yang *et al.* (2001); [8] Besse & Courtillot (1991).

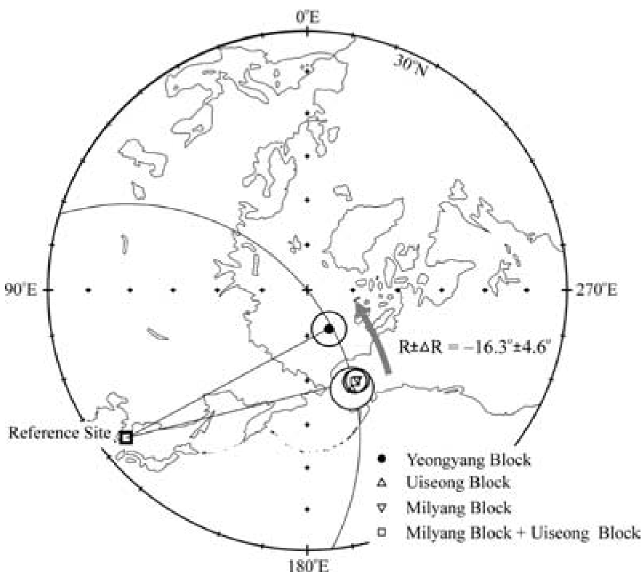

Figure 7. Comparison of the palaeomagnetic poles for the late Early Cretaceous (K_{1L}) from three blocks within the Gyeongsang Basin. R, rotation clockwise (+) or counterclockwise (−) in pole space; ΔR, uncertainty (95 per cent limits) of R, estimated by the method of Demarest (1983).

Group (K_{1M}), the lowermost unit of the Gyeongsang Supergroup, is distributed in the western part of the Milyang and Uiseong blocks, but does not occur within the Yeongyang block (Fig. 1b). Ryu *et al.* (2003) assumed that the absence of the Sindong Group within the Yeongyang block could be due to the lateral movement, such as northwestward protrusion, of the Yeongyang block with respect to the Uiseong and Milyang blocks. In conjunction with the palaeomagnetic result of the Gyeongsang Basin, it is evidenced that the Yeongyang block suffered the counterclockwise rotation and, simultaneously, the northwestward protrusion with respect to the main proto-Gyeongsang basin (the Uiseong and Milyang blocks) during the Late Cretaceous. This assumption is also confirmed by the previously estimated palaeostress regime in the Gyeongsang Basin during the Cretaceous in association with the motion of the proto-Pacific plate (Maruyama & Seno 1986; Choi *et al.* 2002; Ryu *et al.* 2003) (Fig. 2). The Late Cretaceous (K_2) N–S and NW–SE compression regimes, which can be stress sources of the northwestward protrusion of the Yeongyang block, within the Gyeongsang Basin, are well identified along the Andong fault system that is the northern boundary faults of the Uiseong block (Fig. 9a). The Andong fault system displays an E–W trending and northward convex pattern. Choi *et al.* (2002) interpreted the evolution of the Andong fault system based on structural analyses (i.e. geometry and slip vector of fault drag). The Andong fault system was a transfer fault during the opening of the proto-Gyeongsang basin during the Early Cretaceous, and then changed to a top-up-to-the-south reverse fault, due to the N–S compression, during the early Late Cretaceous (Fig. 9b). Continued N–S compression resulted in three different types of motion in the Andong fault: sinistral motion in the western segment, reverse motion in the central segment and dextral motion in the eastern segment (Fig. 9a). Later, NW-compression formed many NW-trending tear faults, which dissect the Andong fault during the late Late Cretaceous (Fig. 9b). A syncline with WSW-trending fold axis observed in adjacent area to the south of the Andong fault may also reflect the NW-trending compression in this area (Fig. 9a). The deformation history of the Jaesan thrust (Fig. 9a), which is the northern boundary of the Yeongyang block, may be similar to that of the Andong fault system, because the palaeostress regime, which originated from the subduction of the proto-Pacific plate under the Eurasian Plate, was likely to affect the whole Gyeongsang Basin (Ryu *et al.* 2003). The predominant NW-trending compression regime, recorded in the Andong fault system, and many tear faults on the northern boundary of the Gyeongsang Basin may be good evidence of the protrusion of the Yeongyang block. Thus, it is interpreted that the northwestward protrusion, and counterclockwise rotation, of the Yeongyang block might have occurred simultaneously, with respect to the Milyang and Uiseong blocks, by NW-compression during the late Late Cretaceous.

5.1.3 A model of the tectonic evolutions of the Gyeongsang Basin during the Cretaceous

Syntheses of palaeomagnetic results of the three blocks, structural data of the Andong fault system, some geological features (i.e. distribution of the Sindong Group) and directional change of the proto-Pacific plate motion, may shed light on the geodynamic

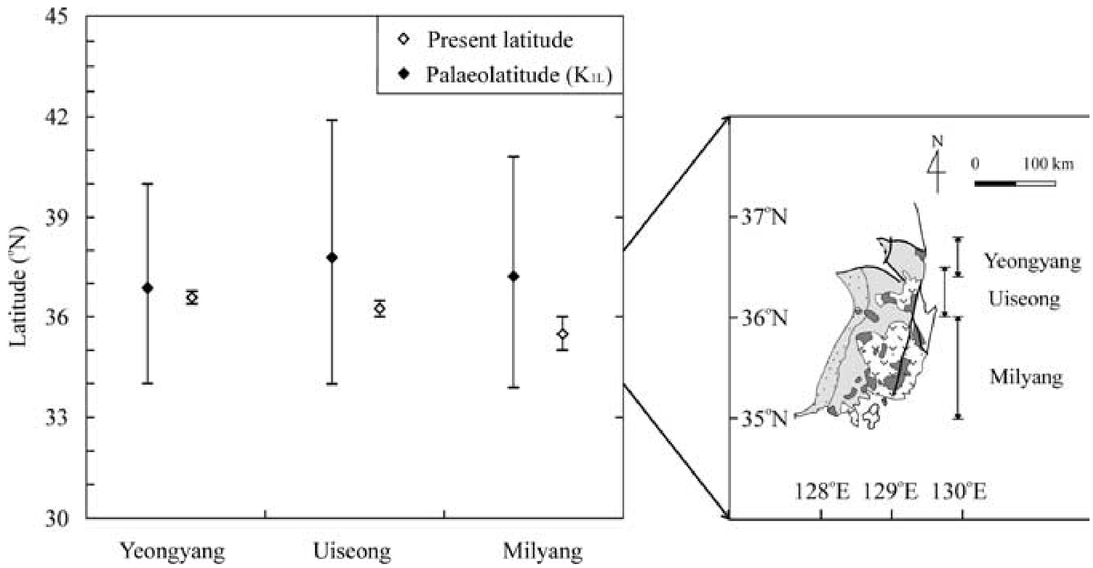

Figure 8. Palaeolatitudes and present latitudes of the Yeongyang, Uiseong and Milyang blocks with their 95 per cent confidence limits. K_{1L}: the late Early Cretaceous.

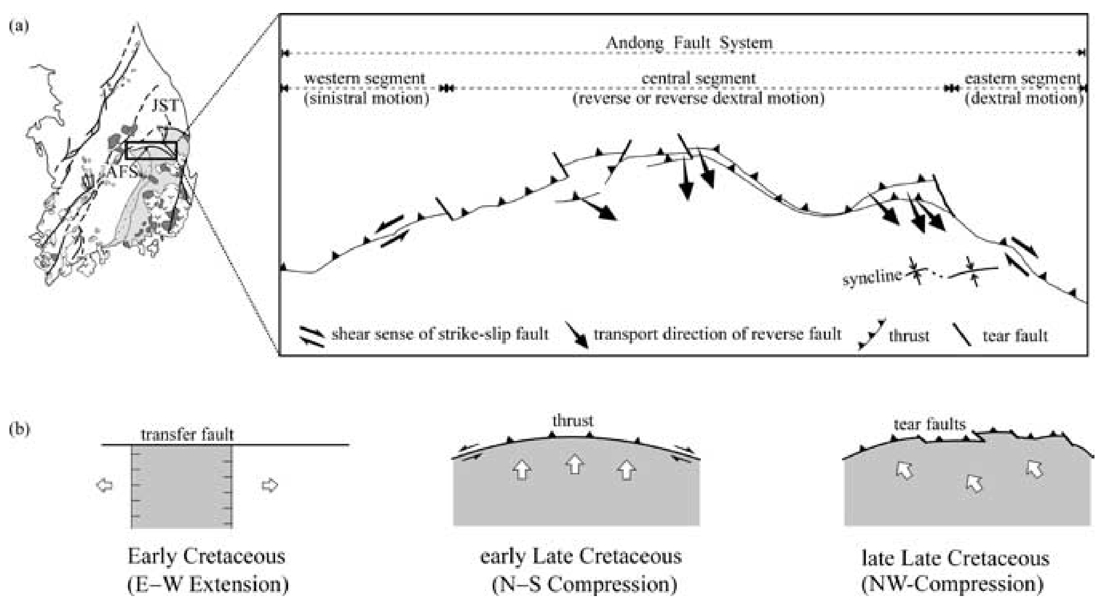

Figure 9. (a) Geometry and slip vectors of the Andong fault system (northern boundary of the Uiseong block) (modified from Fig. 9 in Choi *et al.* 2002). AFS: Andong fault system; JST: Jaesan thrust. (b) Schematic diagram of the evolution of the Andong fault system: a transfer fault during the opening of the proto-Gyeongsang basin (Early Cretaceous); the thrust formed by N–S compression (early Late Cretaceous); and tear faults in a NW–SE stress regime (late Late Cretaceous).

history of the Gyeongsang Basin during the Cretaceous Period. A simplified model for the stepwise tectonic evolution of the Gyeongsang Basin based on the above syntheses is shown in Fig. 10. In the Early Cretaceous (K_{1M} and K_{1L}), the Izanagi Plate (the proto-Pacific plate) moved northward, so that oblique convergence and sinistral strike–slip faulting contemporaneously occurred along the margin of East Asia (Fig. 10a). The sinistral strike–slip resulted in an E–W crustal extension in the southeastern Korean Peninsula, forming a large-scale pull-apart basin (Gyeongsang Basin). The E–W extension was gradually replaced by the N–S compression, during the early Late Cretaceous, until the Izanagi Plate completely changed the movement direction to the northwest (Fig. 10b). During the late Late Cretaceous, the Gyeongsang Basin experienced crustal deformation, accompanied by northwestward protrusion and counterclockwise rotation of the Yeongyang block, due to the NW-compression (Figs 10c and d). Consequently, the Yeongyang block might have moved in a northwest direction along a NW-trending tear fault (proto-Ulsan fault?), which demarcates the western boundary of the block, and may simultaneously have been rotated counterclockwise, by about 16°, with respect to the Milyang and Uiseong blocks. Certainly, a further precise definition of the western boundary of the Yeongyang block, as a NW-trending tear fault, is required from more structural syntheses and geological evidence to confirm this explanation.

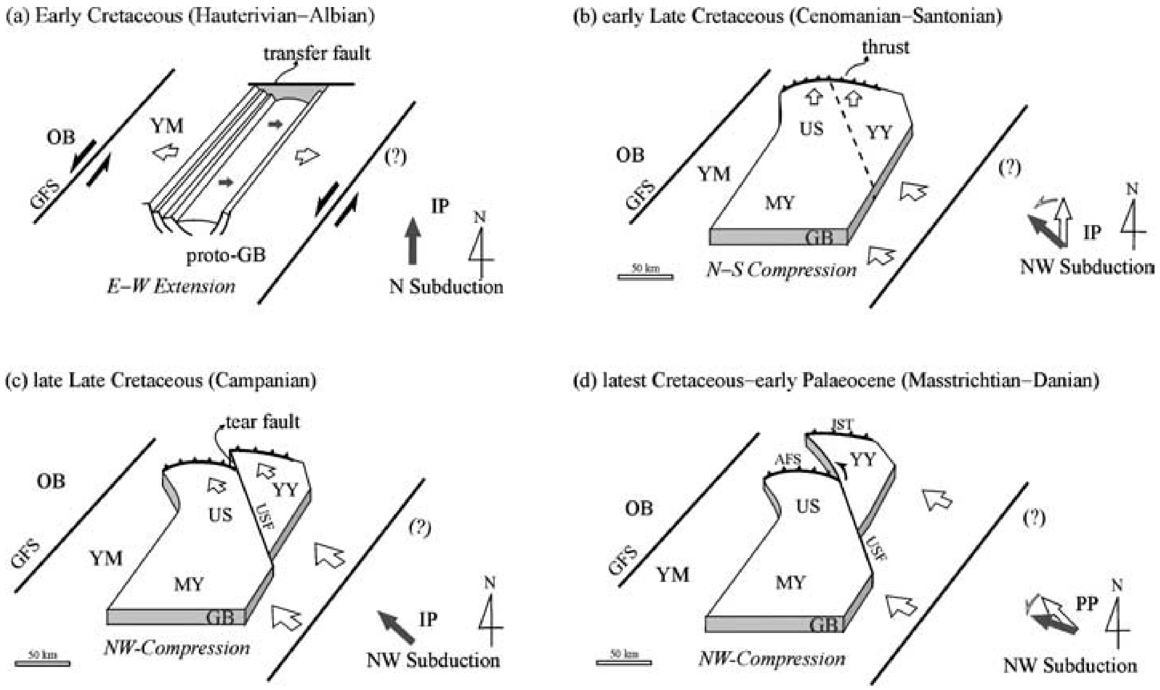

Figure 10. Simplified tectonic model for the Gyeongsang Basin (GB) during the middle Early Cretaceous (Hauterivian) to early Palaeocene (Danian), showing the northwestward migration of the Yeongyang block (YY) with respect to the Milyang block (MY). OB, Okcheon Belt; GFS, Gwangju fault system; YM, Yeongnam Massif; US, Uiseong block; AFS, Andong fault system; JST, Jaesan thrust; USF, proto-Ulsan fault; IP, Izanagi Plate; PP, Pacific Plate.

5.2 Tectonic relationships between the Korean Peninsula and adjacent blocks in East Asia during the Cretaceous

5.2.1 Clockwise rotations of the Korean Peninsula with respect to Eurasia

Several palaeomagnetic studies have suggested that the Korean Peninsula underwent clockwise rotations with respect to Eurasia or the North China Block (Lee *et al.* 1987; Ma *et al.* 1993; Doh & Piper 1994; Uchimura *et al.* 1996; Zhao *et al.* 1999; Uno 2000, 2002; Doh *et al.* 2002). Recently, there has been controversy on the timing of the rotation of the Korean Peninsula: Cretaceous (Zhao *et al.* 1999; Doh *et al.* 2002) or Early Tertiary (Uchimura *et al.* 1996; Uno 2002). To verify the timing of rotation, the improved palaeomagnetic poles, which represent three epochs (K_{1M}, K_{1L} and K_2) of the Cretaceous Period, of the Korean Peninsula were compared with the Cretaceous poles of Eurasia and the North and South China blocks (Figs 11 and 12, Table 3). Because the Eurasian palaeopole positions were at a standstill during the Cretaceous Period (Besse & Courtillot 1991), the mean pole of 130–65 Ma for Eurasia was calculated for a comparison (Fig. 11). The Cretaceous palaeopoles of the North and South China blocks were compiled by Yang *et al.* (2001), and the average palaeopoles for 84–65, 118–84 and 145–118 Ma were calculated from eight, nine and eleven studies, respectively (Table 3). The three poles from the North and South China blocks are located close to the Eurasian pole, indicating that these China blocks did not experience significant rotation or displacement with respect to Eurasia since the Cretaceous (Fig. 11). On the other hand, the Cretaceous poles of South Korea and Eurasia are plotted along a small circle centred at the reference point (37°N, 128°E, centre of South Korea), and the older Korean Cretaceous poles are gradually displaced clockwise with respect to the Eurasian pole (Fig. 12). This does not correspond to the expected result from the argument for the Early Tertiary rotations by Uno (2002). For the Early Tertiary rotations of the Korean Peninsula, it has been expected that the three Korean poles for each epoch should be clustered, and simultaneously, displaced from the Eurasian pole. Thus, this result suggests that the clockwise rotation of the Korean Peninsula was initiated since the middle Early Cretaceous, not after the Cretaceous Period. The clockwise rotations calculated for the Korean poles are of 21.9° ± 5.5°, 10.9° ± 3.4° and 6.1° ± 5.8°, with respect to the Cretaceous Eurasian pole, for the middle Early, late Early and Late Cretaceous, respectively (Fig. 12,

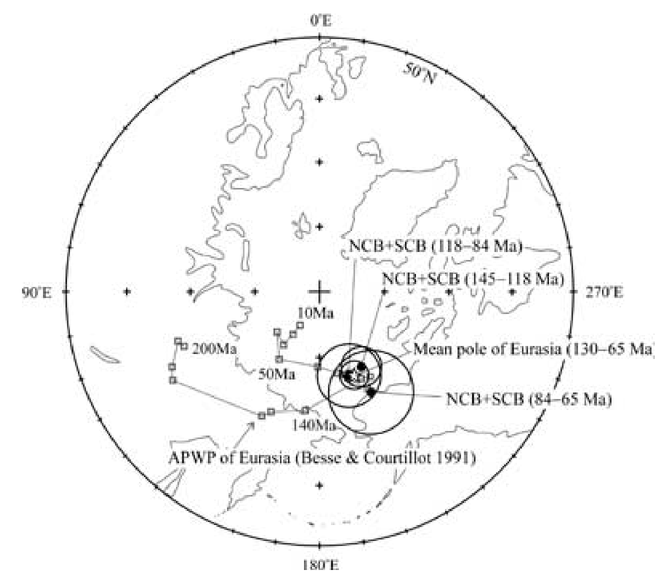

Figure 11. Averaged Cretaceous palaeomagnetic poles of Eurasia (135–65 Ma: Besse & Courtillot 1991) and the North and South China blocks (145–118 Ma, 118–84 Ma and 84–65 Ma: Yang *et al.* 2001). The apparent polar wander path (APWP) of Eurasia since 200 Ma (Besse & Courtillot 1991) is also shown.

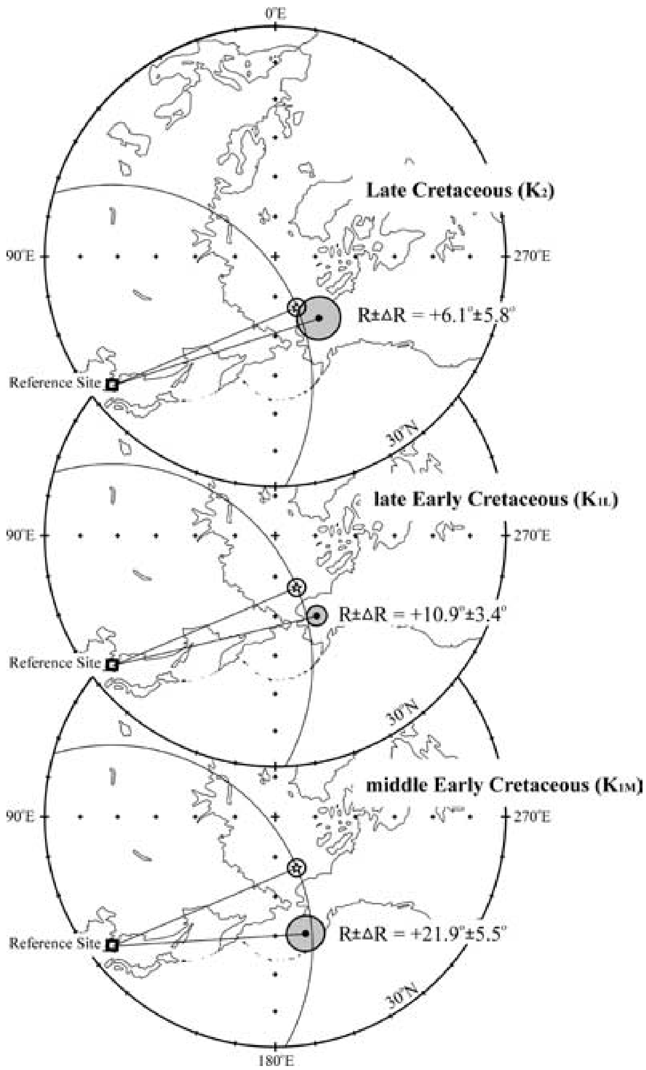

Figure 12. Representative Cretaceous palaeomagnetic poles of the Korean Peninsula compared with the mean pole of 130–65 Ma for Eurasia (star; Besse & Courtillot 1991). *R*, rotation clockwise (+) or counterclockwise (−) with respect to Eurasia in pole space; ΔR, uncertainty (95 per cent limits) of *R*, estimated by the method of Demarest (1983).

Table 3). The 95 per cent uncertainty of rotation ($\Delta R = 5.8^\circ$) between the Eurasian and Late Cretaceous Korean poles is smaller than the calculated amount of rotation ($R = 6.1^\circ$) by only 0.3 degree, indicating that the post-Cretaceous clockwise rotations of the Korean Peninsula are little or none with respect to Eurasia. This timing for the completion of the rotations can be supported by the proximity of Tertiary palaeopoles of the Korean Peninsula (Miocene, Lee *et al.* 1999), Eurasia (10 Ma and 20 Ma, Besse & Courtillot 1991) and North China Block (Miocene, Zhao *et al.* 1994) (Fig. 13). In addition, an angular unconformity between the Hayang (K_{1L})/Sindong (K_{1M}) and the Yucheon (K_2) groups can be observed in the central and southern parts of the Gyeongsang Basin (Chang *et al.* 1984; Lee 1988; Ryu *et al.* 2003). This angular unconformity is generally identified by that the basal formation of the Yucheon Group overlies the east- or southeast-tilted Hayang and Sindong groups with an angular discordance of about 30° (Chang *et al.* 1984). The tilting of the Hayang and Sindong groups might be resulted from progressive deformation of rocks while the Korean Peninsula rotated clockwise about a vertical axis with respect to Eurasia.

5.2.2 Tectonic relationship between the Korean Peninsula and Southwest Japan

To determine the tectonic relationship between the Korean Peninsula and Southwest Japan, the Cretaceous palaeomagnetic poles of Southwest Japan were collected from previously reported literatures (Table 3), and compared with those of the Korean Peninsula (Fig. 13). A representative Late Cretaceous (K_2) palaeopole of Southwest Japan was calculated from five available palaeomagnetic data (Ito & Tokieda 1986; Otofuji & Matsuda 1987; Fukuma & Torii 1990; Kodama 1990; Uno 2002). On the other hand, there are a few reliable Early Cretaceous palaeopoles from Southwest Japan. Otofuji & Matsuda (1987) reported a palaeopole for Albian to Coniacian (85–112 Ma; K_{1L}– early K_2) welded tuffs from the central area of Southwest Japan. A new palaeopole for Albian to Cenomanian (K_{1L}–earliest K_2) sedimentary rocks in the western part of Southwest Japan was presented by Kodama & Takeda (2002). The two palaeopole positions of Otofuji & Matsuda (1987) and Kodama & Takeda (2002) are not statistically distinguishable at the 5 per cent significance level (Fig. 13). Therefore, we consider the palaeopole by Kodama & Takeda (2002) as the representative late Early Cretaceous pole of Southwest Japan, because the age of the palaeopole by Otofuji & Matsuda (1987) extends to the half of the Late Cretaceous.

The Korean Peninsula and Southwest Japan have been regarded as a tectonically single terrane during the Cretaceous (e.g. Otofuji *et al.* 1999; Uno 2002). Thus, it was expected that the amount of Cretaceous clockwise rotations of Southwest Japan, with respect to Eurasia, would be similar to that of the Korean Peninsula. The Cretaceous palaeomagnetic poles from Southwest Japan are indeed displaced clockwise with respect to the Eurasian pole ($62.2^\circ \pm 7.5^\circ$ for K_2 and $51.5^\circ \pm 10.5^\circ$ for K_{1L}–earliest K_2) (Table 3, Fig. 13). Based on the assumption of the tectonic coherence between the Korean Peninsula and Southwest Japan during the Cretaceous, the far more clockwise rotations of Southwest Japan, compared to that of the Korean Peninsula, can be ascribed to the Cretaceous clockwise rotations overprinted by the effect of the Miocene opening of the East Sea (Otofuji & Matsuda 1987; Otofuji *et al.* 1999). Uno (2002) argued that Southwest Japan underwent the clockwise rotation by 23° during the Early Tertiary as well as the clockwise rotation by 42° during the Middle Miocene, resulting in a total rotation of Southwest Japan by 65°, with respect to the North China Block. In the study by Uno (2002), the magnitude of the Early Tertiary clockwise rotation of Southwest Japan was inferred from a comparison between the Cretaceous palaeomagnetic poles of the Korean Peninsula and North China Block. Uno's argument (2002) seems to be problematic, because the timing of the clockwise rotations of the Korean Peninsula have been determined as occurred during the Cretaceous, not the Early Tertiary, in the present study (Fig. 12). The Cretaceous palaeomagnetic poles of Southwest Japan, in Fig. 13, show that the degrees of rotation for the younger (K_2) and older ages (K_{1L}–earliest K_2) are almost the same, indicating no rotation of Southwest Japan, with respect to Eurasia, during the late Early Cretaceous to Late Cretaceous. Accordingly, the complete extent of the clockwise rotation of Southwest Japan, with respect to Eurasia, should be ascribed to a post-Cretaceous event, such as the Miocene opening of the East Sea. The temporal differences in the clockwise rotations between the Korean Peninsula and Southwest Japan suggest that these two blocks did not behave as a tectonically single terrane during the Cretaceous Period. This aspect can be also found in comparisons of the palaeolatitudes of the Korean Peninsula and Southwest Japan. The palaeolatitudes calculated from the

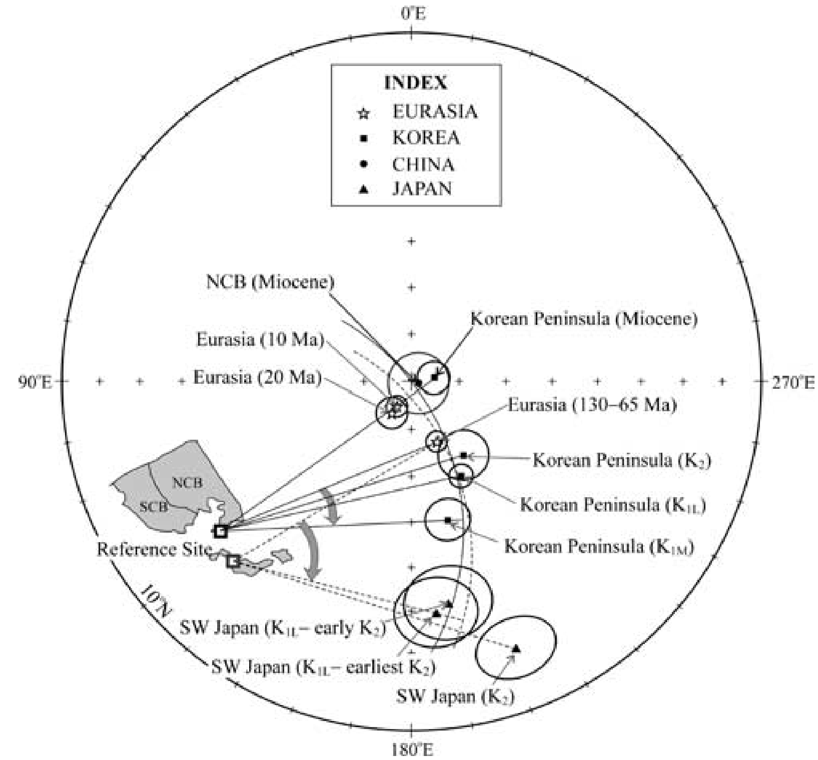

Figure 13. Cretaceous palaeomagnetic poles of the Korean Peninsula compared with those of Eurasia (135–65 Ma: Besse & Courtillot 1991) and Southwest Japan (K_{1L}–earliest K_2 (Albian–Cenomanian): Kodama & Takeda 2002; K_{1L}–early K_2 (Albian–Coniacian): Otofuji & Matsuda 1987; K_2: Uno 2002), showing clockwise rotations of the Korean Peninsula and Southwest Japan with respect to Eurasia. Tertiary palaeomagnetic poles of the Korean Peninsula (Miocene: Lee *et al.* 1999), North China Block (Miocene: Zhao *et al.* 1994) and Eurasia (10 Ma and 20 Ma: Besse & Courtillot 1991) are also plotted for comparison.

data of the Milyang block were 42°N for K_{1M} and 37°N for K_{1L} and K_2 (Table 1). This result indicates that the Korean Peninsula (including the Milyang block) was situated at about 42°N during the middle Early Cretaceous (K_{1M}), and drifted southward to its present latitude (37°N) during the late Early Cretaceous (K_{1L}). For Southwest Japan, a significant amount of latitudinal displacement was observed between the palaeopoles for K_{1L}–earliest K_2 and K_2 (Fig. 13). This palaeolatitudinal change of Southwest Japan, during Cretaceous times, has also been described in the result of Kodama & Takeda (2002). Kodama & Takeda (2002) suggested that Southwest Japan was situated at about 45°N until the late Early Cretaceous (K_{1L}), and underwent southward migration to its present position during the Late Cretaceous (K_2). Thus, it is interpreted that the Korean Peninsula and Southwest Japan may have been independent terranes since the Cretaceous Period, based on the temporal discrepancies of the clockwise rotations and southward migrations of the two blocks with respect to Eurasia.

6 CONCLUSIONS

From previously published 18 studies, 23 Cretaceous palaeomagnetic poles representing the Cretaceous strata in the Gyeongsang Basin as well as in several small basins along the boundaries of the Okcheon Belt and on the Gyeonggi Massif were carefully analysed and selected to shed light on the geodynamic evolution of the Korean Peninsula, in the tectonic framework of East Asia during the Cretaceous. A synthesis of Cretaceous palaeomagnetic data from South Korea gives rise to several tectonic implications as follows:

(1) It has been recognized that relative movements of microblocks occurred within the Gyeongsang Basin, located in the southeastern part of the Korean Peninsula, during the Late Cretaceous. The northern part (Yeongyang block) of the Gyeongsang Basin experienced counterclockwise rotation by 16.3° ± 4.6° with respect to the southern part (Uiseong and Milyang blocks). In conjunction with several geological observations, such as spatial distribution of the Sindong Group and structural deformation of the Andong fault system, we interpret that the Yeongyang block rotated counterclockwise and, simultaneously, protruded northwesterly into the Yeongnam Massif. These relative movements of the microblocks are interpreted as the tectonic adjustment of the Gyeongsang Basin responding to the directional change of the proto-Pacific plate motion. This tectonic model of the Gyeongsang Basin, inferred from the palaeomagnetic and some geological evidences, needs to be verified by further detailed structural synthesis and more geological observations.

(2) The Korean palaeomagnetic pole positions for the middle Early Cretaceous, the late Early Cretaceous and the Late Cretaceous are displaced eastward by 21.9° ± 5.5°, 10.9° ± 3.4° and 6.1° ± 5.8° from the Cretaceous Eurasian pole, respectively. This result suggests that the Korean Peninsula rotated clockwise about 22° with respect to Eurasia during the Cretaceous Period. On the other hand, the clockwise rotation (*ca.* 62°) of Southwest Japan, with respect to Eurasia, should be ascribed to the post-Cretaceous events (e.g. the Miocene opening of the East Sea). In addition, the southward latitudinal movements of these two blocks occurred at different times: the late Early Cretaceous for the Korean Peninsula and the Late Cretaceous for Southwest Japan. It is, therefore, interpreted that the Korean Peninsula and Southwest Japan were independent terranes during the Cretaceous Period. At the present, it remains unclear whether the total amount of clockwise rotation of

Southwest Japan, with respect to Eurasia, has been resulted from the only Miocene opening of the East Sea, or includes any other tectonic movements after the Cretaceous.

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REFERENCES

Besse, J. & Courtillot, V., 1991. Revised and synthetic polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma, *J. geophys. Res.,* **96,** 4029–4050.

Chang, K.H., 1975. Cretaceous stratigraphy of southeast Korea, *J. Geol. Soc. Korea,* **11,** 1–23.

Chang, K.H., 1977. Late Mesozoic stratigraphy, sedimentation and tectonics of southeastern Korea, *J. Geol. Soc. Korea,* **13,** 76–79.

Chang, K.H., Lee, Y.D., Lee, Y.G., Seo, S.J., Oh, K.Y. & Lee, C.H., 1984. Unconformity at the base of the Late Cretaceous Yucheon Group, *J. Geol. Soc. Korea,* **20,** 41–50.

Choi, D.K., 1985. Spores and pollen from the Gyeongsang Supergroup, southeastern Korea and their chronologic and paleoecologic implications, *J. Paleont. Soc. Korea,* **1,** 33–50.

Choi, D.K., 1989a. Palynology of the Geoncheonri Formation (Lower Cretaceous), Geoncheon–Ahwa area, Korea, *J. Paleont. Soc. Korea,* **5,** 1–27.

Choi, S.J., 1989b. Fossil charophytes from the Nagdong Formation in Seonsangun, Gyeongsangbukdo, Korea, *J. Paleont. Soc. Korea,* **5,** 28–38.

Choi, P.Y., Lee, S.R., Choi, H.I., Hwang, J.H., Kwon, S.K., Ko, I. & An, G., 2002. Movement history of the Andong Fault System: Geometric and tectonic approaches, *Geosci. J.,* **6,** 91–102.

Chough, S.K., Kwon, S.T., Ree, J.H. & Choi, D.K., 2000. Tectonic and sedimentary evolution of the Korean peninsula: a review and new view, *Earth Sci. Rev.,* **52,** 175–235.

Cluzel, D.J., Lee, B.-J. & Cadet, J.-P., 1991. Indosinian dextral ductile fault system and synkinematic plutonism in the southwest of the Okcheon belt (South Korea), *Tectonophysics,* **194,** 131–151.

Demarest, H.H., 1983. Error analysis of the determination of tectonic rotation from paleomagnetic data, *J. geophys. Res.,* **88,** 4321–4328.

Doh, S.J. & Kim, K.H., 1994. Paleomagnetism of Cretaceous rocks from the Uiseong area, *Econ. Environ. Geol.,* **27,** 263–279.

Doh, S.J. & Piper, J.D.A., 1994. Palaeomagnetism of the (Upper Palaeozoic–Lower Mesozoic) Pyeongan Supergroup, Korea: a Phanerozoic link with the North China Block, *Geophys. J. Int.,* **117,** 850–863.

Doh, S.J., Hwang, C.S. & Kim, K.H., 1994. A paleomagnetic study of sedimentary rocks from Gyeongsang Supergroup in Milyang Sub-basin, *J. Geol. Soc. Korea,* **30,** 211–228.

Doh, S.J., Cho, Y.Y. & Suk, D., 1996. Remagnetization of the Cretaceous sedimentary rocks in the Yeongdong Basin, *Econ. Environ. Geol.,* **29,** 193–206.

Doh, S.J., Suk, D. & Park, Y.H., 1997. Remagnetization of the Pyeongan Supergroup in the Yeongwol area, Korea, *J. Geomag. Geoelectr.,* **49,** 1217–1232.

Doh, S.J., Suk, D. & Kim, B.C., 1999a. Paleomagnetism of the Cretaceous Sedimentary rocks in the Yeongyang Sub-Basin, *Econ. Environ. Geol.,* **32,** 189–201.

Doh, S.J., Suk, D. & Kim, B.Y., 1999b. Paleomagnetic and rock-magnetic studies of Cretaceous rocks in the Eumseong Basin, Korea, *Earth Planets Space,* **51,** 337–349.

Doh, S.J., Kim, W., Suk, D., Park, Y.H. & Cheong, D., 2002. Palaeomagnetic and rock-magnetic studies of Cretaceous rocks in the Gongju Basin, Korea: implication of clockwise rotation, *Geophys. J. Int.,* **150,** 737–752.

Fisher, R.A., 1953. Dispersion on a sphere, *Proc. R. Soc. London,* **A217,** 295–305.

Fukuma, K. & Torii, M., 1990. Paleomagnetic pole from Late Cretaceous Koto Rhyolites, Southwest Japan, *Rock Mag. Paleogeophys.,* **17,** 65–72.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., van Veen, P., Thierry, J. & Huang, Z., 1994. A Mesozoic time scale, *J. geophys. Res.,* **69,** 2509–2519.

Ishikawa, N., 1997. Differential rotations of north Kyushu Islands related to middle Miocene clockwise rotation of SW Japan, *J. geophys. Res.,* **102,** 17 729–17 745.

Ito, H. & Tokieda, K., 1980. An interpretation of paleomagnetic result from Cretaceous granites in South Korea, *J. Geomag. Geoelectr.,* **32,** 275–284.

Ito, H. & Tokieda, K., 1986. Tilting movement of the Japanese islands inferred from Cretaceous and early Tertiary paleomagnetic data, *J. Geomag. Geoelectr.,* **38,** 361–386.

Jeon, Y.S., Min, K.D., Lee, Y.S., Lee, Y.H. & Lee, D.Y., 1998. Paleomagnetic study of remagnetization by a dike in the Gyeongsang supergroup, *Econ. Environ. Geol.,* **31,** 311–324.

Kang, H.C. & Kim, I.S., 2000a. Palaeomagnetic study on the Early Cretaceous Hayang group in Yongyang area, northeastern Kyongsang basin, *J. Geol. Soc. Korea,* **36,** 47–71.

Kang, H.C. & Kim, I.S., 2000b. Palaeomagnetism of the Cretaceous Yuchon Group in Kosong area, southern Kyongsang basin, *J. Korean Earth Sci. Soc.,* **21,** 663–674.

Kang, H.C., Kim, I.S. & Yun, S.H., 2000. Palaeomagnetic study on the Cretaceous rocks in the Konchonri area of the northern Milyang Subbasin, Korea, *J. Korean Geophys. Soc.,* **3,** 1–12.

Kienzle, J. & Scharon, L., 1966. Paleomagnetic comparison of Cretaceous rocks from South Korea and Late Paleozoic and Mesozoic rocks of Japan, *J. Geomag. Geoelectr.,* **18,** 413–416.

Kim, I.S., 1988. Palaeomagnetism of Cretaceous Tadaepo formation, Pusan area: its stratigraphic and tectonic significances, *J. Geol. Soc. Korea,* **24,** 211–233.

Kim, K.H. & Jeong, B.I., 1986. A study on the paleomagnetism of southern Korea since Permian, *J. Korean Inst. Mining Geol.,* **19,** 67–83.

Kim, K.H. & Kim, D.S., 1991. Magnetostratigraphy of the Chaeyaksan, Konchonri, and Jusasan formations distributed in Taeku-Kyongju area, *J. Geol. Soc. Korea,* **27,** 40–51.

Kim, K.H. & Noh, B.S., 1993. Palaeomagnetic Study of the Cretaceous Rocks in the Okcheon Belt: Palaeomagnetism of the Sedimentary Rocks in the Neungju Basin, *J. Korean Earth Sci. Soc.,* **14,** 44–57.

Kim, K.H. & Song, M.Y., 1995. Structure and physical properties of the mid-west crust of Korea; paleomagnetism of the Cretaceous volcanic rocks in Jeonggog–Yeoncheon area, *J. Korean Earth Sci. Soc.,* **16,** 65–73.

Kim, I.S., Kang, H.C. & Lee, H.K., 1993a. Paleomagnetism of Early Cretaceous sedimentary rocks in Chingyo–Sachon Area, southwestern Kyongsang Basin, Korea, *J. Korea Inst. Mining Geol.,* **26,** 519–539.

Kim, I.S., Lee, H.K., Yun, H.S. & Kang, H.C., 1993b. Paleomagnetism of Cretaceous rocks in the Uiseong area, Kyongsang basin, Korea, *J. Korea Inst. Mining Geol.,* **26,** 403–420.

Kim, K.H., Song, M.Y., Jeong, J.G., Kim, Y.S. & Lee, D.W., 1997. Structure and physical properties of the Mid-west crust of Korea (III): paleomagnetism of the Cretaceous volcanic rocks in the Southern Chugaryeong rift zone, *J. Korean Earth Sci. Soc.,* **18,** 332–338.

Kim, T.S., Min, K.D., Lee, Y.S., Lee, Y.H. & Lee, D.Y., 1998. Paleomagnetic study on the remanent magnetization of the Silla Conglomerate formation in Jinju and Goryeong areas, *Econ. Environ. Geol.,* **31,** 325–338.

Kodama, K., 1990. Magnetostratigraphy of the Izumi Group along the Median Tectonic Line in Shikoku and Awaji Islands, Southwest Japan, *J. Geol. Soc. Japan,* **96,** 265–278.

Kodama, K. & Takeda, T., 2002. Paleomagnetism of mid-Cretaceous red beds in west-central Kyushu Island, southwest Japan: paleoposition of Cretaceous sedimentary basins along the eastern margin of Asia, *Earth planet. Sci. Lett.,* **193,** 273–285.

Kozai, T., Ishida, K., Chang, K.H. & Park, S.O., 2001. Correlation of Early Cretaceous non-marine bivalve fauna of SW Japan and Korea, in *Abstracts of 3rd Symp. IGCP 434: Carbon Cycle and Bio-Diversity Change During the Cretaceous*, pp. 11–12, Lhasa, China.

Lee, D.S., ed., 1988. *Geology of Korea*, 2nd edn, pp. 175–190, Kyohak-Sa Publishing Co., Seoul.

Lee, D.W. & Paik, K.H., 1990. Evolution of strike–slip fault-controlled Yongdong Basin, Korea: a genetic study in the northern part of the basin, *J. Geol. Soc. Korea,* **27,** 246–251.

Lee, Y.S. & Min, K.D., 1995. Paleomagnetic study for tectonism on the Okcheon zone since Mesozoic, *Econ. Environ. Geol.,* **28,** 493–501.

Lee, G.D., Besse, J., Courtillot, V. & Montigny, R., 1987. Eastern Asia in the Cretaceous: new paleomagnetic data from South Korea and a new look at Chinese and Japanese data, *J. geophys. Res.,* **92,** 3580–3596.

Lee, M.W., Won, C.K. & Kim, K.H., 1992. The Cretaceous volcanic activities and petrology in Kyonggi massif: on the Kapcheon, Eumsung and Kongju basin, *J. Geol. Soc. Korea,* **28,** 314–333.

Lee, Y.S., Nishimura, S. & Min, K.D., 1997. Paleomagnetotectonics of east Asia in the Proto-Tethys ocean, *Tectonophysics,* **270,** 157–166.

Lee, Y.S., Ishikawa, N. & Kim, W.K., 1999. Paleomagnetism of Tertiary rocks on the Korean Peninsula: tectonic implications for the opening of the East Sea (Sea of Japan), *Tectonophysics,* **304,** 131–149.

Lee, Y.S., Min, K.D. & Hwang, J.H., 2001. The Geodynamic evolution of the Chugaryeong Fault Valley in a view point of Paleomagnetism, *Econ. Environ. Geol.,* **34,** 555–571.

Lim, M.T., Lee, Y.S., Kang, H.C., Kim, J.Y. & Park, I.H., 2001. Paleomagnetic study on Cretaceous rocks in Haenam area, *Econ. Environ. Geol.,* **34,** 119–131.

Ma, X., Yang, Z. & Xing, L., 1993, The Lower Cretaceous reference pole for North China, and its tectonic implications, *Geophys. J. Int.,* **115,** 323–331.

Maruyama, S. & Seno, T., 1986. Orogeny and relative plate motions: example of the Japanese Islands, *Tectonophysics,* **127,** 305–329.

Maruyama, S., Isozaki, Y., Kimura, G. & Terabatashi, M., 1997. paleogeographic maps of the Japanese Islands: plate tectonic synthesis from 750 Ma to the present, *Island Arc,* **6,** 121–142.

Matsukawa, M., Ito, M., Hayashi, K., Takahashi, O., Yang, S.Y. & Lim, S.K., 1998. Evaluation of nonmarine bivalves as chronological indices, based on examples from the Lower Cretaceous of East Asia, in *Lower and Middle Cretaceous Terrestrial Ecosystems,* Vol. 14, pp. 125–133, eds Lucas, S.G., Kirkland, J.I. & Estep, J.W., New Mexico Museum of Natural History and Sci. Bull, Albuquerque, USA.

Miyashiro, A., 1974. Volcanic rock series in island arcs and active continental margins, *Am. J. Sci.,* **74,** 321–355.

Okada, H., 2000. Nature and development of Cretaceous sedimentary basins in East Asia: a review, *Geosci. J.,* **4,** 271–282.

Otofuji, Y. & Matsuda, T., 1983. Paleomagnetic evidence for the clockwise rotation of Southwest Japan, *Earth planet. Sci. Lett.,* **62,** 349–359.

Otofuji, Y. & Matsuda, T., 1984. Timing of rotational motion of Southwest Japan inferred from paleomagnetism, *Earth planet. Sci. Lett.,* **70,** 373–382.

Otofuji, Y. & Matsuda, T., 1987. Amount of clockwise rotation of Southwest Japan: fan shape opening of the southwestern part of the Japan Sea, *Earth planet. Sci. Lett.,* **85,** 289–301.

Otofuji, Y., Oh, J.Y., Hirajima, T., Min, K.D. & Sasajima, S., 1983. Paleomagnetic and K–Ar age determination of Cretaceous rocks from Korean Peninsula–Gyeongsang Supergroup in South Korea, in *Tectonic and Geologic Evolution of Southeast Asian Seas and Island II,* Vol. 27, pp. 388–396, ed. Hayes, D.E., Am Geophys. Union, Geophys. Monogr.

Otofuji, Y., Kim, K.H., Inokuchi, H., Morinaga, H., Murata, F., Katao, H. & Yaskawa, K., 1986. A paleomagnetic reconnaissance of Permian to Cretaceous sedimentary rocks in Southern part of Korean Peninsula, *J. Geomag. Geoelectr.,* **38,** 387–402.

Otofuji, Y., Itaya, T. & Matsuda, T., 1991. Rapid rotation of southwest Japan: palaeomagnetism and K–Ar ages of Miocene volcanic rocks of southwest Japan, *Geophys. J. Int.,* **105,** 397–405.

Otofuji, Y., Enami, R., Yokoyama, M., Kamiya, K., Kuma, S., Saito, H. & Matsuda, T., 1999. Miocene clockwise rotation of southwest Japan and formation of curvature of the Median Tectonic Line: Paleomagnetic implications, *J. geophys. Res.,* **104,** 12 895–12 907.

Otoh, S. & Yanai, S., 1996. Mesozoic inversive wrench tectonics in Far East Asia, in *The Tectonic Evolution of Asia*, pp. 401–419, eds Yin, A. & Harrison, M., Cambridge Univ. Press, Cambridge.

Otoh, S., Tsukada, K., Sano, K., Nomura, R., Jwa, Y.J. & Yanai, S., 1999. Triassic to Jurassic dextral ductile shearing along the eastern margin of Asia: a synthesis, in *Gondwana dispersion and Asian accretion*, pp. 89–113, ed. Metcalfe, I., IGCP 321 Final Result vol.

Park, Y.H. & Doh, S.J., 2004. Paleomagnetic and rock-magnetic studies of Cretaceous sedimentary rocks in the Poongam Basin, *Econ. Environ. Geol.,* **37,** 195–206.

Park, Y.H., Doh, S.J. & Suk, D., 2003. Chemical remagnetization of the Upper Carboniferous-Lower Triassic Pyeongan Supergroup in the Jeongseon area, Korea: fluid migration through the Ogcheon Fold Belt, *Geophys. J. Int.,* **154,** 89–103.

Ryu, I.C., Choi, S.G., Wee, S.M. & Lee, S.Y., 2003. Tectonics, sedimentation, and magmatism of the Cretaceous Gyeongsang (Kyongsang) Basin, Korea: integrated approach to defining basin history and event mineralization, in *Proceedings of Int. Symp. Genetic Model of Epithermal Gold Deposit*, pp. 27–31, Gwangju, Korea.

Shin, S.C. & Jin, M.S., 1995a. *Isotope Age Map of Volcanic Rocks of Korea*, Korea Inst. Geol. Mining and Materials, Korea.

Shin, S.C. & Jin, M.S., 1995b. *Isotope Age Map of Plutonic Rocks of Korea*, Korea Inst. Geol. Mining and Materials, Korea.

Song, M.Y. & Kim, K.H., 1995. Structure and physical properties of the mid-west crust of the Korean Peninsula: Paleomagnetism of the Late Cretaceous Chonsuman formation in Chonsuman Bay area, *J. Korean Earth Sci. Soc.,* **17,** 75–80.

Suk, D. & Doh, S.J., 1996. Paleomagnetism of the Cretaceous rocks in Uiseong area revisited, *J. Geol. Soc. Korea,* **32,** 47–64.

Uchimura, H., Kono, M., Tsunakawa, H., Kimura, G., Wei, Q., Hao, T. & Liu, H., 1996. Palaeomagnetism of late Mesozoic rocks from northeastern China: the role of the Tan-Lu fault in the North China Block, *Tectonophysics,* **262,** 301–319.

Um, S.H., Paik, K.H., Lee, H.Y. & Bong, P.Y., 1978. *A study on depositional environment of the Gyeongsang Strata*, pp. 9–34, Research Report 4, Korea Res. Inst. of Geosci. and Mineral Res., Seoul, Korea.

Uno, K., 2000. Clockwise rotation of the Korean Peninsula with respect to the North China Block inferred from an improved Early Triassic palaeomagnetic pole for the Yeongnam Block, *Geophys. J. Int.,* **143,** 969–976.

Uno, K., 2002. Late Cretaceous palaeomagnetic results from Southwest Japan: new insights for early Cenozoic clockwise rotation, *Geophys. J. Int.,* **149,** 617–624.

Uyeda, S. & Miyashiro, A., 1974. Plate tectonics and the Japanese Islands: a synthesis, *Bull. geol. Soc. Am.,* **85,** 1159–1170.

Van der Voo, R., 1990. The reliability of paleomagnetic data, *Tectonophysics,* **184,** 1–9.

Won, C.K., Lee, M.W., Kim, K.H., Hong, Y.K., Woo, J.G. & Lee, J.M., 1990. The study on Cretaceous volcanism in the Sunchang trough: compare study between Kyeongsang basin Sunchang trough and inner-zone of SW Japan, *J. Geol. Soc. Korea,* **26,** 165–184.

Yanai, S., Park, B.S. & Otoh, S., 1985. The Honam shear zone (South Korea): deformation and tectonic implication in the Far East, *Scient. Pap. College Arts Sci. Univ. Tokyo,* **35,** 181–210.

Yang, S.-Y., 1983. On the subgenus Wakinoa (Cretaceous non-marine bivalvia) from Gyeongsang group, Korea, *Trans. Proc. Palaeontol. Soc. Japan,* **131,** 177–190.

Yang, Z., Yin, J., Sun, Z., Otofuji, Y. & Sato, K., 2001. Discrepant Cretaceous paleomagnetic poles between Eastern China and Indochina: a consequence of the extrusion of Indochina, *Tectonophysics,* **334,** 101–113.

Yi, M.S., Cho, B.H. & Chi, J.M., 1994. Palynomophs from the Jinju Formation in the Euiseong area, Korea, *J. Paleont. Soc. Korea,* **10,** 41–56.

Zhao, X., Coe, R.S., Zhou, Y., Hu, S., Wu, H., Kuang, G., Dong, Z. & Wang, J., 1994. Tertiary paleomagnetism of North and South China and a reappraisal of late Mesozoic paleomagnetic data from Eurasia: implications for the Cenozoic tectonic history of Asia, *Tectonophysics,* **235,** 181–203.

Zhao, X. *et al.*, 1999. Clockwise rotation recorded in Early Cretaceous rocks of South Korea: implications for tectonic affinity between the Korean Peninsula and North China, *Geophys. J. Int.,* **139,** 447–463.

APPENDIX A: CRETACEOUS PALAEOMAGNETIC DATA OF SOUTH KOREA

Table A1. Cretaceous palaeomagnetic data obtained from the Gyeongsang Basin, Okcheon Belt and Gyeonggi Massif.

Location (Basin/Block)	n/N	Palaeomagnetic Pole Lat. (°N)	Palaeomagnetic Pole Long. (°E)	A_{95} (dp/dm)	Rock Type	Age	Quality factor (Q)	Remarks	Reference
			<Within the Gyeongsang Basin>				1·2·3·4·5·6·7*		
MY	35/5	73.9	219.4	(9.2/13.2)	volcanics	K	x.o.x.x.x.x.x 1	No structural correction	Kienzle & Scharon (1966)
MY+OB	45/6	86.5	180.0	(8.9/12.1)	granite	K	x.o.x.x.x.x.x 1	No structural correction	Ito & Tokieda (1980)
US	22/1	73.2	203.6	(20.9/28.5)	andesite	K_2	o.x.x.x.x.x.x 1	Low demag. level	Otofuji *et al.* (1983)
US	106/5	68.9	191.2	(10.1/12.9)	An, Ba, Ss, Sh	K	x.o.x.x.x.x.x 1	Low demag. level	Otofuji *et al.* (1983)
MY†	182/38	67.1	209.8	2.0	sedimentary rx	K_{1L}	o.o.o.x.x.x.o 4		Kim & Jeong (1986)
MY†	77/20	57.5	186.3	4.5	sedimentary rx	K_{1M}	o.o.o.x.x.x.o 4		Kim & Jeong (1986)
MY†	402/35	67.0	202.0	(7.0/9.5)	shale	K_{1L}	o.o.o.o.o.x.o 6		Otofuji *et al.* (1986)
MY†	163/18	58.0	187.0	–	shale	K_{1M}	o.o.o.x.x.x.o 4		Otofuji *et al.* (1986)
MY†	43/7	66.4	219.3	9.2	sed.vol. rx	K_{1L}	o.o.o.o.x.o.o 6		Lee *et al.* (1987)
MY†	108/8	60.8	194.2	6.5	sedimentary rx	K_{1M}	o.o.o.o.x.o.o 6		Lee *et al.* (1987)
US	55/5	77.9	207.1	11.6	sedimentary rx	K_{1L}	x.o.o.o.x.o.x 4	Poor age constrain	Lee *et al.* (1987)
MY	28/	58.6	234.0	(3.9/6.5)	Sh, Ss, Cg, An	K_{1M}	x.o.o.x.x.o.x 3	Poor age constrain, No field test	Kim (1988)
MY†	75/12	76.0	205.0	(6.0/8.3)	tuff, andesite	K_2	o.o.o.x.x.o.x 4		Kim & Kim (1991)
MY	25/2	62.2	208.2	5.3	Sh, Ss	K_{1L}	o.x.o.x.x.o.o 4	Small number of sample	Kim *et al.* (1993a)
MY†	47/3	60.7	208.5	8.4	Ss, Sh	K_{1M}	o.o.o.x.x.o.o 5		Kim *et al.* (1993a)
US	12/2	73.1	227.4	–	tuff, andesite	K_2	o.x.x.x.x.o.x 2	Blanket demagnetization	Kim *et al.* (1993b)
US	42/5	61.7	211.6	–	Sh, Ss	K_{1L}	o.o.x.x.x.x.x 2	Blanket demagnetization	Kim *et al.* (1993b)
US	23/3	64.5	213.8	–	sandstone	K_{1M}	o.x.x.x.x.o.x 2	Blanket demagnetization	Kim *et al.* (1993b)
MY†	155/20	66.4	204.1	4.2	Ss, Sh, Silt, Cg	K_{1L}	o.o.o.o.x.x.o 5		Doh *et al.* (1994)
MY†	104/16	59.9	198.8	4.3	Ss, Sh, Silt, Cg	K_{1M}	o.o.o.o.x.x.o 5		Doh *et al.* (1994)
US†	84/19	81.3	79.0	(13.0/17.0)	volcanics	K_2	o.o.o.o.x.o.o 6	Incomplete tilt correction?	Doh & Kim (1994)
US†	79/14	72.0	206.4	(4.9/6.7)	Sh, Ss	K_{1L}	o.o.o.o.x.x.x 4		Doh & Kim (1994)
MY+OB	/12	65.1	204.9	7.1	red beds	K	x.o.o.o.x.x.x 3	Poor age constrain	Lee & Min (1995)
US†	174/20	64.9	202.2	7.6	Ss, Sh, Silt	K_{1L}	o.o.o.o.x.x.x 4		Suk & Doh (1996)
MY+OB	/8	66.9	204.8	(3.9/5.4)	red beds	K_{1M}	o.o.x.o.x.x.x 3	Too wide area	Lee *et al.* (1997)
MY	5/1	72.6	204.6	(11.6/16.0)	Cg, Ss	K_{1M}	o.x.o.x.x.x.x 3	Small number of sample	Kim *et al.* (1998)
MY	No regional remagnetization by dike in the Goryeong area within the Milyang block. (not averaged palaeomagnetic data)								Jeon *et al.* (1998)
YY†	400/29	85.5	217.4	5.2	red beds, Ba	K_{1L}	o.o.o.o.x.x.x 4	Vertical-axis rotation?	Doh *et al.* (1999a)
MY†	70/16	68.6	210.2	–	red beds, Vol	K_{1L}	o.o.o.o.x.o.o 6		Zhao *et al.* (1999)
YY†	179/28	68.4	210.7	6.0	tuff, Ba, Ss, Sh	K_{1L}	o.o.o.o.x.o.x 5	Vertical-axis rotation?	Kang & Kim (2000a)
MY†	95/14	67.0	210.6	6.7	tuff	K_2	o.o.o.o.x.o.x 5		Kang & Kim (2000b)
MY†	29/6	72.5	197.4	4.4	tuff, Ss	K_2	o.o.o.o.x.o.x 5		Kang *et al.* (2000)
			<outside the Gyeongsang Basin: the Okcheon Belt>						
Sunchang	13/2	–	–	–	ryolite	K_2	–	Not averaged	Won *et al.* (1990)
GC+ES+GJ	40/7	–	–	–	volcanic rocks	K_{1L}–K_2	–	Not averaged	Lee *et al.* (1992)
Neungju†	38/11	78.8	228.3	4.8	Sh, Ss, tuff	K_2	o.o.o.o.o.o.x 6		Kim & Noh (1993)
Yeongdong	247/25	79.3	194.2	3.9	Cg, Ss, Sh	K	–	Remagnetized component	Doh *et al.* (1996)
Eumseong	714/36	53.7	79.8	3.4	red/green beds	K	–	Remagnetized component	Doh *et al.* (1999b)
Haenam	15/2	72.5	199.9	(14.2/19.5)	rhyolite, tuff	K_2	o.x.o.x.x.x.x 2	Small number of sample	Lim *et al.* (2001)
Gongju†	102/9	67.2	235.3	8.9	andesite	K_2	o.o.o.o.x.o.x 5		Doh *et al.* (2002)
Poongam	103/11	81.6	214.3	7.4	red beds	K	–	Remagnetized component	Park & Doh (2004)
			<outside the Gyeongsang Basin: the Gyeonggi Massif>						
Cheolwon†	75/16	61.7	212.9	(6.1/8.7)	andesite, tuff	K_2	o.o.o.x.o.x.o 5		Kim & Song (1995)
Cheonsuman	22/5	–	–	–	volcanic rocks	K_2	–	Not averaged	Song & Kim (1995)
Yesan†	41/9	60.8	25.8	7.6	volcanic rocks	K_2	o.o.o.x.o.x.x 4	Vertical-axis rotation?	Kim *et al.* (1997)
Cheolwon†	28/5	71.6	216.8	(7.1/10.0)	acidic volcanics	K_2	o.o.o.x.o.x.o 5		Lee *et al.* (2001)

n/N, number of samples/sites; Lat., north latitude; Long., east longitude; A_{95}, the radius of the 95 per cent confidence circle about the calculated mean pole; dp/dm, the semi axis of the confidence ellipse along/perpendicular to the great-circles path from site to pole; K, Cretaceous; K_{1M}, middle Early Cretaceous; K_{1L}, late Early Cretaceous; K_2, Late Cretaceous; MY, Milyang block; OB, Okcheon Belt; US, Uiseong block; YY, Yeongyang block; GC, Gapcheon Basin; ES, Eumseong Basin; GJ, Gongju Basin; YS, Yesan area; An, andesite; Ba, basalt; Ss, sandstone; Sh, shale; sed. rx, sedimentary rocks; vol. rx, volcanic rocks; Cg, conglomerate; Silt, siltstone; demag., demagnetization.

*Reliability criteria (after Van der Voo 1990): 1, well-determined rock age and a presumption that magnetization is the same age; 2, sufficient number of samples; 3, adequate demagnetization that demonstrably includes vector subtraction; 4, field tests that constrain the age of magnetization; 5, structural control and tectonic coherence with craton or block involved; 6, the presence of reversals; 7, no resemblance to palaeopoles of younger age (by more than a period).

†Palaeomagnetic results showing a Quality index of $Q \geq 4$ (including the criteria 1, 2 and 3) after Van der Voo (1990).