Carboniferous-Triassic Paleomagnetism of South Korea

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Middle Carboniferous to Early Triassic paleomagnetic directions from Northeast Okchon Fold Belt of South Korea have been obtained and used to calculate the paleopoles of South Korea. Many samples collected are strongly overprinted by the Brunhes normal magnetic field, but thermal demagnetization has been successful in isolating ancient, dual-polarity characteristic directions of magnetization, with results passing reversal and fold tests. An Early Triassic direction ($D = 76.8^\circ/I = 37.2^\circ$, $\alpha_{95} = 8.9^\circ$, $k = 29.3$, $N_{\text{chr}} = 18$), a Late Permian direction ($D = 258.0^\circ/I = 12.2^\circ$, $\alpha_{95} = 16.4^\circ$, $k = 14.4$, $N_{\text{chr}} = 7$), and a Middle Carboniferous direction ($D = 100.5^\circ/I = -22.5^\circ$, $\alpha_{95} = 13.0^\circ$, $k = 17$, $N_{\text{chr}} = 18$) have been obtained from the Northeast Okchon Fold Belt of South Korea.

Southern Korea and South China Block (SCB) yield Jurassic and younger paleopoles that are to first approximation similar, but on the other hand Carboniferous-Triassic Apparent Polar Wander Path is different from that of SCB. Inclinations and declinations calculated from these two paths for the Korean reference site are significantly different in the Carboniferous-Triassic. It is, therefore, insisted that the southern part of Korean Peninsula and SCB were different tectonic masses before the Jurassic.

1. Introduction

Korean Peninsula is located in the northeastern margin of Asia, and is traditionally thought to be part of North China Block (e.g., LEE, 1987, pp. 231–234); but from the two paleomagnetic studies recently undertaken by SHIBUYA *et al.* (1988) and KIM and VAN DER VOO (1990), it became apparent that the traditional belief had to be reexamined. Triassic paleopoles from South Korea, North China Block (NCB), South China Block (SCB) and Eurasia are all different (KIM and VAN DER VOO, 1990). Without pre-Triassic paleomagnetic data, KIM and VAN DER VOO (1990) explained these differences by relative local rotations of the blocks about vertical axes. But their Triassic data can suggest also another possibility that Korean Peninsula was a different tectonic mass from both Chinese blocks and not a part of Eurasia before the Jurassic. SHIBUYA *et al.* (1988) studied Cambrian to Jurassic sedimentary rocks from Northeast Ogcheon Zone (also called Northeast Okchon Fold Belt) of South Korea, and obtained characteristic directions from a few sites of the Carboniferous-Triassic. They suggested that the Okchon Zone belonged to the SCB in the Carboniferous-Triassic based on the virtual pole positions of both tectonic provinces.

It is a matter of interest whether southern Korea has been a part of NCB, or SCB, or different tectonic mass from both of the two in the pre-Jurassic.

Paleomagnetism affords a possible record of the past motion of Korean Peninsula and hence its tectonic development. In order to test the paleo-geographic setting of Korea in

comparision with the SCB, Triassic-Carboniferous sediments were sampled for a paleomagnetic study.

2. Geology and Sampling

The Okchon Fold Belt (OFB) is divided into two parts, southwesterly metamorphosed zone and northeasterly non-metamorphosed or sedimentary zone (Fig. 1). The northeastern non-metamorphosed zone consists mostly of Cambro-Ordovician Choson Supergroup and Middle Carboniferous-Triassic Pyongan Supergroup lying disconformably above the former. The latter, which has been studied paleomagnetically by us, is overlain disconformably by Late Triassic-Early Jurassic Daedong Supergroup. Silurian strata appear only locally. Devonian and Lower Carboniferous strata are absent. Deposition of the Choson and Pyongan Supergroups in South Korea was almost entirely restricted to Northeast OFB. The Pyongan Supergroup is

Table 1. Summary of geology, and rock types collected in each sampling area.

Age	Formation	Sampling area	Rock type	Names of site	No. of samples
Early to Middle Triassic	<i>Nogam F.</i>				
	3000 m (max. thickness)	Tanyang	greenish & red s.s	Tty1,Tty2	47
	Greenish sandstone and shales interbedded with reddish sandstone beds	Chongson	greenish s.s & shale	Tcs1,Tcs2	36
	No fossil found	Taebaek	greenish & red s.s	Ttb1,Ttb2	32
Late Permian	<i>Gobangsan F.</i>				
	500 m (max. thickness)	Tanyang	grey & greenish s.s	Pty1,Pty2	20
	Sandstones and shales	Sabuk	grey & greenish s.s	Psb	10
	Plant fossils (Kawasaki, 1939, Kobayashi, 1953)	Taebaek	grey & greenish s.s	Ptb	7
Early Permian	<i>Sadong F.</i>				
	300 m (max. thickness) Grey s.s, shales, limestones & anthrasites. Fusulinid fossils (Cheong, 1971)	Tanyang	grey s.s & shale	Pty3,Pty4	12
Middle Carboniferous	<i>Hongjom F.</i>				
	500 m (max. thickness)	Tanyang	red s.s	Cty	5
	Red or greenish s.s & shales interbedded with limestone lenses	Taebaek	red or greenish sh. and s.s	Ctb	8
	Fusulinid fossils (Cheong, 1971, 1974; Lee, 1984) and plant fossils	Chongson	limestone	Ccs	11
		Yongwol	red & greenish s.s	Cyw1,Cyw2, & Cyw3	29

Fig. 1. Regional geologic map of Northeast Okchon Fold Belt (from REEDMAN and UM, 1975), with sampling sites (solid circles) indicated.

divided into four formations, viz., the Hongjom, Sadong, Gobangsan, and Nogam Formations in ascending order (Fig. 1; Table 1). The sediments of the lower part of the Pyongan sequence (the Hongjom and lower Sadong Formations) were deposited in shallow water marine basins, but a change to non-marine conditions was followed by the accumulation of coal-bearing beds and the non-marine, shallow water environment persisted during the deposition of the remaining strata of the sequence. The sedimentary basins remained stable until the Middle Triassic when Songnim Disturbance took place, resulting in east-west to northwest fold axis in the basins. The western margin of this trend swings to NE-SW direction due to the Late Jurassic-Early Cretaceous Daebo Orogeny.

The Pyongan Supergroup is best exposed in Tanyang (ty), Yongwol (yw), Chongson (cs), Sabuk (sb), and Taebak (tb) areas, where we have collected Permo-Carboniferous and Triassic samples for our paleomagnetic study (Fig. 1). The sequence displays just a little variation from one area to another. Table 1 summarizes the geology, rock types, site name, and number of samples collected.

The Hongjom Formations of the above areas were well dated by fusulinid fossils as Bashkirian-Moscovian (CHEONG, 1974; LEE, 1984), and 53 samples from 6 sites were collected (Fig. 1: Cty, Cyw-three sites, Ccs, Ctb). The Sadong and Gobangsan Formations were dated mainly by plant fossils (KAWASAKI, 1939), and each formation was correlated to Early and Late Permian, respectively. Twelve samples from two sites (Pty3, Pty4) from the Sadong, and 37 samples from 4 sites (Pty1 and Pty2, Psb, Ptb) from the Gobangsan were collected in Tanyang, Sabuk, and Taebak areas (Fig. 1). The Nogam Formation, lying above the Gobangsan Formation and below the Late Triassic-Early Jurassic Daedong Supergroup, has been considered to be Early Triassic with no fossils found. 115 samples from 6 sites were collected from the Nogam Formation distributed in Tanyang and Taebak areas (Fig. 1; Tty-two sites, Tcs-two sites, Ttb-two sites).

At individual sites six to thirty samples were collected over an area of several hundreds of square meters. Oriented block samples were collected using a magnetic compass and tripod. A present magnetic declination of 6°W was used for all magnetically determined azimuths and strikes. In the laboratory 2.5 cm diameter specimens were drilled and cut into 2.2 cm height.

3. Paleomagnetic Results

Most of measurements of Natural Remanent Magnetizations (NRM) were carried out on a Molspin magnetometer, with thermal demagnetizations performed using equipment made at the paleomagnetic laboratory of Chonbuk National University. Samples collected from Tty1 and Ptb sites were measured with a ScT cryogenic magnetometer at the paleomagnetic laboratory of the University of Michigan. Alternating field demagnetization did not succeed in isolating characteristic components of magnetization, so stepwise thermal demagnetizations have been used on all of the samples collected. Demagnetization results have been plotted in orthogonal vector diagrams (ZIJDERVELD, 1967) and in equal-area projection, followed by Principal Component Analysis (KIRSCHVINK, 1980). Demagnetization data of many samples (65% of the samples collected), when plotted, showed only Brunhes normal field (BNF) or random directional change up to 680°C and were discarded. The remaining 35% revealed two component magnetizations—low temperature BNF and high temperature characteristic components. The two components usually overlapped and a great-circle could be determined. In in-situ coordinates the low temperature components clustered generally about the BNF

Table 2. Triassic, Permian, and Carboniferous Paleomagnetic Results from Northeastern Okchon Folded Belt of South Korea.

Site	Strike/Dip (mean)	N_{chr}	N	$D/I_{in situ}$	k	α_{95}	Characteristic direction $D/I_{tilt corr}$	k	α_{95}	Range	Remarks
Early Triassic Nogam Formation											
Tty1	172/30	5	32	249.9/0.8	7.7	29.5	255.3/-21.8	11.7	23.1	650-680	Two normal directions
Tty2	202/40	3	15	259.1/20.5	6.2	54.2	261.9/-14.9	40.3	19.7	650-680	All reversed directions
Tcs1	262/25	0	5	—	—	—	—	—	—	—	Unstable or BNF/younger age remanences only
Tcs2	189/34	0	10	—	—	—	—	—	—	—	One reversed direction
Ttb1	322/42	6	27	322.1/-63.9	74.4	7.8	268.3/-41.9	74.4	7.8	500-680	All reversed directions
Ttb2	335/32	4	5	302.4/-54.2	67.6	11.3	280.2/-31.4	67.6	11.3	500-680	Reversed directions are converted to normal
MEAN	chr chr+gc	4 4+14		93.8/29.4 31.8/56.0	2.8 4.3	67.2 56.7	89.2/31.4 76.8/37.2	29.4 29.3	17.2 8.9		
Late Permian Gobongsan Formation											
Pty1	195/40	0	12	—	—	—	—	—	—	—	Unstable or BNF/younger age remanences only
Pty2	230/45	0	8	—	—	—	—	—	—	—	All reversed directions
Ptb	220/45	4	7	239.9/27.7	11.1	28.8	253.3/6.3	29.2	23.2	640-680	All reversed directions
Psb	100/60	3	10	290.7/22.1	26.3	24.5	264.3/19.7	32.2	22.0	350-580	All reversed directions
MEAN		7		262.6/27.5	6.9	24.7	258.0/12.2	14.4	16.4		
Early Permian Sadong Formation											
Pty3	179/43	6		—	—	—	—	—	—	—	Unstable or BNF/younger age remanences only
Pty4	220/47	6		—	—	—	—	—	—	—	
Middle Carboniferous Hongjom Formation											
Cty	225/47	0	5	—	—	—	—	—	—	—	BNF/younger age remanence
Cyw1	350/85	3	5	139.8/49.2	10.9	39.4	118.7/-18.1	10.6	39.9	600-680	One reversed direction
Cyw2	169/40	4	7	291.5/64.3	21.8	20.1	272.2/27.7	21.9	20.1	550-680	All reversed directions
Cyw3	234/32	3	17	260.5/40.1	3.4	81.2	271.7/16.5	3.7	76.0	640-680	One normal direction
Ccs	220/51	5	11	263.1/42.2	12.9	22.2	277.6/0.2	15.1	20.3	200-370	All reversed directions
Ctb	220/45	3	8	277.4/34.5	101.2	12.3	287.6/-12.4	87.4	13.3	650-680	All reversed directions
MEAN	chr chr+gc	5 5+9		78.9/-56.6 93.6/-57.8	5.4 5.1	36.3 44.7	101.5/-10.0 100.5/-22.5	17.7 17.0	18.7 13.0		Reversed directions are converted to normal

Strike/Dip indicates mean bedding orientation; N_{chr} indicates number of samples which revealed characteristic directions; N indicates number of demagnetized samples; D/I , declination/inclination; k , precision parameter (FISHER, 1953); α_{95} , radius of 95% of confidence; Range, blocking temperature in °C. Reversed directions are converted to normal directions and then averaged to calculate site and overall means. chr+gc, characteristic direction combined with great circles.

Fig. 2. Orthogonal vector demagnetization diagrams (Zijderveld, 1967) of representative samples from the Early Triassic Nogam Formations, showing characteristic directions in in-situ coordinates. Open (solid) circles represent projections onto the vertical (horizontal) plane; temperatures (in degrees Celsius) are indicated. Intensities of magnetization along the axes are given in mA/m.

Table 3. Paleopoles for South Korea.

Age	Formation	Paleopole (Lat., Lon.)	dp	dm	Paleo- latitude	Reference
E.-M. Triassic	Nogam F.	22.6 N, 209.1 E	6.1	10.4	20.8 N	This study
Late Triassic	Songnim Granites	37.1 N, 215.5 E	12.1	20.4	21.6 N	Kim & Van der Voo (1990)
Late Permian	Gobangsan F.	5.7 N, 231.0 E	8.5	16.7	6.2 S	This study
M. Carboniferous	Hongjom F.	15.3 S, 222.0 E	7.3	13.8	11.7 S	This study
M. Carboniferous	Hongjom F.	1.6 N, 216.9 E			2.6 N	Shibuya <i>et al.</i> (1988)

The paleopoles are calculated from mean direction of Table 2. dp and dm , semi-axes of the elliptical error around the pole at 95% probability, dp in the colatitude direction and dm perpendicular to it. E., Early; M., Middle; F., formation.

Fig. 3. Equal-area plot with directions of high temperature component (upper two) and low temperature component (lower two) for the samples from the Early Triassic Nogam Formations before and after correction for the tilt of the strata. Open (solid) circles represent projections onto the upper (lower) hemisphere. Geocentric axial dipole field direction at the sampling site is represented by "star" (★).

Fig. 4. Representative equal-area plots and orthogonal vector diagrams showing thermal demagnetizations (after tilt correction) of samples from Early Triassic Nogam Formations. The best fit great-circles to the demagnetization trajectories are drawn in the equal-area projections, with the arrows indicating the direction of movement with progressive cleaning. For explanation see Figs. 2 and 3.

direction, whereas the high temperature component directions were highly scattered. In tilt-corrected coordinates the situation was reversed.

Mean direction of each site was calculated by assigning a unit weight for the specimens. The results are described below from the Triassic to Carboniferous and summarized in Tables 2 and 3.

3.1 Nogam Formation—Early Triassic

Early Triassic samples have been studied from the Nogam Formation distributed in Tanyang, Chongson, and Taebaek areas (Fig. 1). Ninety four Early Triassic samples were collected from these areas. Many samples (66 samples out of 94) showed only one component magnetization of BNF or unstable magnetizations, and were discarded. Twenty eight samples showed two component magnetizations—low and high temperature components. Demagnetization diagrams before tilt correction of the beds are shown in Fig. 2. Generally, between NRM and, at least, 600°C, linear demagnetization trajectories indicated the unblocking of a component of magnetization directed northward and moderately down (BNF direction). Above about 600°C, demagnetization trajectories that converged to the origin indicated unblocking of the characteristic magnetization. The high maximum unblocking temperature of both the BNF and characteristic components suggest that hematite is the predominant magnetic carrier of both components in the reddish or bluish samples, but a few greenish samples reveal the same magnetic directions carried by both magnetite and hematite (Ttb1–19 in Fig. 2). Eighteen samples of them revealed characteristic directions resolved from the low temperature component with relative easy, and 14 samples (including 4 samples out of the former)

Fig. 5. Equal-area plots with characteristic directions for the site-means (circles) of the Early Triassic Nogam Formations. For explanation see Fig. 3. Small triangles represent poles to great circles obtained from curved demagnetization trajectories for 14 samples from the Tty and Ttb sites. These poles, showing a great-circle distribution, have been combined with the stable-endpoint directions for the site-means to yield a common mean direction (large triangle) following BAILEY and HALLS (1984). The best fit great-circle to the small triangles is also drawn for reference.

displayed different great-circle paths plotted on an equal area net without showing stable-endpoint. The low temperature component directions in in-situ coordinates (mean $D/I = 3.8^\circ/55.4^\circ$) fail a fold test, with precision parameter k decreasing from 31.9 to 7.5 upon unfolding (Fig. 3). High temperature components of the two sites in Tanyang and two sites in Taebaek areas, on the other hand, yielded coherent results with nearly complete dual-polarity ENE-WSW directions. The normal and reversed directions were observed from different (the reversed directions from upper) horizons of the Tty1 and Ttb1 sites, which cover several strata. The clustering of directions increases significantly after tilt-correction from the radius of 95% confidence cone $\alpha_{95} = 67.2^\circ$ to 17.2°). In many cases stepwise demagnetization data of the red bed samples did not show well-defined stable endpoints on orthogonal vector diagrams and displayed different great-circles when plotted on an equal-area net (Tty1-2, Tty2-3 in Fig. 2;

Fig. 6. Orthogonal vector demagnetization diagrams (ZIJDERVELD, 1967) in in-situ coordinates of representative samples from the Early Permian Sadong (Pty3-1) and Late Permian Gobangsang (Ptb, Psb) Formations. All of the samples from the Sadong Formation showed only present-day geomagnetic field direction as the Pty3-1 of this figure. For explanation see Fig. 2.

Fig. 4). Because it is uncertain that the characteristic component has been isolated, we have analysed the corresponding great-circles (Fig. 5). Poles to great circles (triangles) and stable-endpoint directions (circles), when combined, point to a common mean characteristic direction for the Triassic samples with $D/I = 76.8^\circ/37.2^\circ$, $\alpha_{95} = 8.9^\circ$ after tilt-correction (Table 2, Fig. 5) using the method of BAILEY and HALLS (1984). The common mean direction combined has a smaller α_{95} ($=8.9^\circ$) angle than that of characteristic direction ($\alpha_{95} = 17.2^\circ$). Two other sites in Chongson area (Tcs1, 2 in Fig. 1) yield no characteristic directions except for the BNF (Tcs2-4 in Fig. 2) as well as random or unstable magnetizations.

3.2 *Sadong and Gobangsan Formations—Early and Late Permian*

Early and Late Permian samples collected in Tanyang area (Pty1, 2, 3, 4 in Fig. 1) showed only BNF directions (Fig. 6; Pty3-1) as well as random or unstable components of magnetization. Seven Late Permian samples from Gobangsan Formation in Sabuk (Psb) and Taebaek

Fig. 7. Equal-area plots with directions of high temperature component (upper two) and low temperature component (lower two) for the samples of Late Permian Gobangsan Formation from Sabuk + Taebaek area before and after correction for the tilt of the strata. For explanation see Fig. 3.

(Ptb) areas, however, revealed both low and high temperature components. The low temperature component directions in in-situ coordinates (mean declination/inclination (D/I) = $357.9^\circ/49.7^\circ$, $k = 16.0$, $\alpha_{95} = 15.6^\circ$) were grouped about the BNF direction, but on the other hand those in tilt-corrected coordinates were highly scattered ($k = 6.8$, $\alpha_{95} = 24.8^\circ$), which gives a negative fold test (Fig. 7). The high temperature component directions, which are thought to be the characteristic directions and are quite different from the BNF, revealed WNW and shallow magnetizations, with mean tilt-corrected declination/inclination (D/I) = $258.0^\circ/12.2^\circ$. Table 2 and Fig. 7 give seven characteristic directions and site-means observed in Psb and Ptb sites of the Gobangsan Formation. The structural corrections for this formation allow a fold test, with k increasing from 6.9 to 14.4 upon unfolding. In the red bed samples collected from Ptb site, very high unblocking temperatures of 650 – 680°C suggest that hematite is the carrier of the characteristic remanence (Fig. 6; Ptb2-2, Ptb2-4), whereas the bluish sandstones and shales

Fig. 8. Orthogonal vector demagnetization diagrams (ZIJDERVELD, 1967) of representative samples from the Middle Carboniferous Hongjom Formations, showing characteristic directions in in-situ coordinates. For explanation see Fig. 2. Cyw, reddish sandstones or shales from Yongwol area; Ccs, limestones from Chongson area; Ctb, reddish s.s. from Taebaek area.

collected from Psb site have unblocking temperatures from 400°C to 580°C (Fig. 6; Psb1-1), which suggests that magnetite is the carrier. Moreover, the two different magnetic carriers reveal similar reversed remanences (Table 2). When reversed directions are converted to normals, the Gobangsan Formation gives mean declination of 78.0° and mean inclination of -12.2°. When the Late Permian directions are compared with those of the Early Triassic, they are similar in declinations but have shallower and negative inclinations.

3.3 Hongjom Formation—Middle Carboniferous

Hongjom Formation was sampled from 6 sites in Tanyang (Cty), Yongwol (Cyw1, Cyw2, Cyw3), Chongson (Ccs), and Taebaek (Ctb) areas. Five sites showed two component magnetizations, except the Cty site (Table 2, Fig. 8). Some samples from Cyw and Ctb sites showed, generally between NRM and at least 630°C, linear demagnetization trajectories, which indicated the unblocking of a component of magnetization directed northward and

Fig. 9. Equal-area plots with directions of high temperature component (upper two) and low temperature component (lower two) for the samples of the Middle Carboniferous Hongjom Formations before and after correction for the tilt of the strata. For explanation see Fig. 3.

Fig. 10. Representative equal-area plots and orthogonal vector diagrams showing thermal demagnetizations (after tilt correction) of samples from the Middle Carboniferous Formations. The best fit great-circles to the demagnetization trajectories are drawn in the equal-area projections, with the arrows indicating the direction of movement with progressive cleaning. For explanation see Figs. 2 and 3.

moderately down. Generally between 630 and 680°C, demagnetization trajectories that converged to the origin indicated unblocking of the characteristic magnetization. The above indicates that both component magnetizations are carried by hematite (Fig. 8; excepting Cyw1-2 and Ccs4-2). But some reveal characteristic magnetizations carried by both magnetite and hematite as deduced from the unblocking temperatures (Fig. 8; Cyw1-2). The low temperature component directions were concentrated in in-situ coordinates around the mean ($D/I = 351.5^\circ/57.9^\circ$, $k = 50.9$, $\alpha_{95} = 5.0^\circ$), and were highly scattered in tilt-corrected ($k = 3.4$, $\alpha_{95} = 22.4^\circ$), which clearly indicates BNF overprinting (Fig. 9). Limestone samples from Chongson show also magnetizations of two components (Fig. 8; Ccs4-2). The low temperature component was unblocked completely after heating to 200°C, and the higher temperature component was isolated as it decayed with subsequent heating to 370°C. The higher temperature component direction in in-situ coordinates is west-southwest and moderately downward (Ccs4-2 in Fig. 8) which is different from the BNF direction and, in view of the results from Cyw and Ctb sites, this component can be considered as characteristic magnetization. Similar tilt corrections for the samples of the Ccs site slightly improve the clustering of the sample directions (Table 2), but this is not statistically significant. Figure 9 shows 18 characteristic directions (from five sites) having dual-polarity. Table 2 summarizes the site-means and overall mean direction with tilt-corrected $D/I = 101.5^\circ/-10.0^\circ$. It is thought that in many cases BNF direction is not completely eliminated from characteristic component even at high temperatures of 630–650°C as seen in Fig. 8 (Cyw2-2, Ctb1-5) and Fig. 10. Because it is uncertain that the characteristic component has been isolated above 630–650°C, and because data points move toward characteristic direction on a great-circle during stepwise demagnetizations (Fig. 10), we have

Fig. 11. Equal-area plots with characteristic directions for the site-means (circles) of the Middle Carboniferous Hongjom Formations. For explanation see Fig. 3. Small triangles represent poles to great circles obtained from curved demagnetization trajectories for 9 samples from the Cyw and Ctb sites. These poles have been combined with the stable-endpoint directions to yield a common mean direction (large triangle) following BAILEY and HALLS (1984). The best fit great-circle to the small triangles is also drawn for reference.

analysed the corresponding great-circles on an equal-area net (Fig. 11) just as we have done with Triassic data of Nogam Formations. Poles to great-circles and stable-endpoint directions, when combined, point to a common mean characteristic direction for the Hongjom Formations with $D/I = 100.5^\circ/-22.5^\circ$ ($\alpha_{95} = 13.0^\circ$) after tilt correction using the method of BAILEY and HALLS (1984). The combined direction has smaller radius of 95% confidence circle than that of characteristic directions ($D/I = 101.5^\circ/-10.0^\circ$, $\alpha_{95} = 18.7^\circ$).

4. Discussion of Results

Samples from the Early Triassic, Permian, and Middle Carboniferous formations were severely overprinted by BNF. As many as 65% of paleomagnetic data showed only one component directions of BNF as well as random or unstable magnetizations. The maximum unblocking temperature for the BNF component in the hematite-bearing beds studied by us is in the range 600°C to 650°C. According to the relaxation time-blocking temperature (t - T) relations of PULLAIAH *et al.* (1975), this would indicate that the beds acquired a thermoviscous remanence near Curie temperature in the Brunhes. The lack of any evidence of high temperature regional or contact metamorphism of the formations, however, indicates that the remagnetization process of hematite-bearing beds most likely involved the chemical precipitation or alteration of hematite, following the results of KENT and MILLER (1987) and WITTE and KENT (1991), rather than a thermoviscous resetting of existing hematite. A possible interpretation for the maximum high unblocking temperature of the BNF and characteristic components, as suggested by IRVING and OPDYKE (1965) and WITTE and KENT (1991), is that the BNF component magnetization is associated with finer grained hematite, whereas the characteristic component magnetization may be preferentially carried by somewhat coarser hematite grains.

Despite severe overprinting by the recent geomagnetic field direction or remanence of younger ages, 18 samples from four sites of Nogam Formation of the Early Triassic distributed in Tanyang and Taebaek areas yield characteristic directions. They pass a fold test, and the remanences of both areas are of dual polarity, therefore passing a reversal test (Table 2). The fold test is statistically significant, and moreover the folding is of Middle Triassic Songnim Disturbance. Thus the positive fold test together with reversal test indicates that the magnetizations are primary. Although the site means from Tty1 and Tty2 have too large α_{95} and the data only seems to be not useful, the overall mean combined with great circles from Nogam Formation has smaller α_{95} ($=8.9^\circ$) and are reliable. The same argument as above can be applied to the Carboniferous and Permian data. Triassic paleomagnetic data were reported by KIM and VAN DER VOO (1990). Some of their data were obtained from Late Triassic granites distributed in northwestern Ryongnam Massif (RNM), and are roughly concordant with those of the Early Triassic Nogam Formation of this study. This fact also suggests that the magnetizations acquired by the Nogam samples are primary.

Many of the Gobangsan Formation of Late Permian age are also severely overprinted by the recent geomagnetic field direction, however, we succeed in extracting stable-endpoint directions from seven samples from two sites (Psb, Ptb in Fig. 1). The fold test is also statistically significant. Note that the polarity of the seven samples is reversed. This fact increases the possibility that the age of remanence measured from Gobangsan Formations might lie within the Late Paleozoic Kiaman Reversed Interval (MCELHINNY, 1973; KHRAMOV and RODIONOV, 1980; THOMPSON and MITCHELL, 1972). A previous paleomagnetic study, of the same Late Permian rocks we studied in Taebaek area yielded southwesterly and upward

directions (SHIBUYA *et al.*, 1988). The results of SHIBUYA *et al.* (1988) show similar WSW declination but higher inclination rather than shallower negative inclination of our study. Judging from their results which demonstrate very good clustering before tectonic correction, it seems that their samples were collected at a limited small area having similar bedding orientation. Therefore, their data could not give reliable positive fold test.

The characteristic directions from five sites of the Middle Carboniferous Hongjom Formations have dual-polarity directions, which are antipodal and pass a fold test (Table 2). Because the folding of this area are believed to be of Middle-Late Triassic age, this test suggests that the remanence pre-dates the Middle-Late Triassic. Moreover, the gradual change in directions (intermediate inclination in the Triassic, shallow in the Permian, shallow and negative inclination in the Carboniferous, with gradually increasing declinations observed) suggests well that the Middle Carboniferous magnetizations are primary. SHIBUYA *et al.* (1988) also studied the Hongjom Formations distributed in Jangseong (the same as Taebaek area of our study) and Mungyeong areas. Their Carboniferous data, which was collected from two sites with different bedding orientations, reveal good clustering after tilt correction, and are similar to those of our coeval paleomagnetic data. Their Carboniferous paleopole is included for reference in Table 3 and Fig. 12.

KIM and VAN DER VOO (1990) suggested on the basis of the Jurassic data that the southwesterly metamorphosed zone and the northeastern part of the northeasterly non-metamorphosed zone of the OFB were rotated counterclockwise by about 60° relative to the adjacent Kyonggi and Ryongnam Massifs. They deduced that the southern limit of the Okchon

Fig. 12. Carboniferous to Jurassic Apparent Polar Wander Paths for the Okchon Fold Belt of Korea (solid circles) and South China Block (solid squares). Korean poles plotted are from this study, KIM and VAN DER VOO (1990), and SHIBUYA *et al.* (1988). Carboniferous pole obtained by SHIBUYA *et al.* (1988) is indicated as Cm (Shi). All poles for the South China Block are from LIN *et al.* (1985) except for the Late Permian (ZHAO and COE, 1987). J, Jurassic; Tr, triassic; P, Permian; C, Carboniferous; u, Late; m, Middle; l, Early.

rotated terrane was clearly outlined for the metamorphosed zone, but that it was ambiguous for the non-mamorphosed zone. We sampled Carboniferous through Triassic samples in the southern part of the non-metamorphosed zone, which probably are in non-rotated area: the paleomagnetic directions from the Early Triassic sites roughly agree with those of the Late Triassic granites from the non-rotated Ryongnam Massif, as already discussed by KIM and VAN DER VOO (1990).

Reliable Jurassic and younger paleomagnetic results have been reported from Korea (KIM and VAN DER VOO, 1990; KIM, 1987; LEE *et al.*, 1987; OTOFUJI *et al.*, 1982; KANG and LI, 1977). The Jurassic and Cretaceous paleopoles for Korea are relatively similar to those for China, suggesting that Korean Peninsula and China Blocks have behaved as same tectonic entirety since Jurassic. Triassic-Carboniferous results from this study, on the other hand, reveal that pre-Jurassic paleopoles for South Korea (Northeast Okchon Fold Belt) are quite different from those of China. Because the tectonic relation between North China and South China Blocks have already been reported by several other researchers (LIN *et al.*, 1985; OPDYKE *et al.*, 1986; ZHAO and COE, 1987), we will discuss only the plate tectonic relation between Korea and SCB in the Triassic-Carboniferous. Middle Carboniferous-Early Triassic paleopoles and associated parameters have been calculated from the mean directions of each age. In Fig. 12 the Triassic, Permian, and Carboniferous paleopoles for the Northeast OFB of Korea can be compared with those of SCB. Chinese paleomagnetic poles plotted in Fig. 12 are from LIN *et al.* (1985) except for the Upper Permian (ZHAO and COE, 1987).

It is interesting to note that these two APWPs have similar shape. A comparison between South Korea and the SCB shows that while the Late Jurassic and younger poles are only slightly different as KIM and VAN DER VOO (1990) already discussed, the Triassic-Carboniferous paleopoles are quite different. These differences in paleopoles during the Triassic, Permian,

Fig. 13. Diagrams showing paleolatitude and declination change for Southern Korea and South China Block. Paleolatitudes are extrapolated for the Korean reference site (37°N/129°E). Pre-Cretaceous poles for Korea and China used in the calculation of paleolatitudes are the same as in Fig. 12. Cretaceous and Cenozoic poles for Korea are from KIM (1987), KIM and KIM (1991). Those for China are from LIN *et al.* (1985). The error bars of paleolatitude and declination are represented by dp and dm , respectively, the semi-axes of the elliptical error around the pole at 95% probability.

and Carboniferous resulted from declinations and inclinations; declinations and inclinations calculated for the same Korean reference site (37°N/129°E) using these two APW paths are significantly different (Fig. 13). Figure 13 shows paleolatitudes and declinations calculated for the reference site. The error bars of paleolatitude and declination represent the dp (error in paleolatitude) and dm (error in declination), the semi-axes of the elliptical error around the pole at 95% probability. The paleolatitude differences are 20 degrees in the Upper Permian and Middle Carboniferous, in the Triassic about 10 degrees, little differences in the post-Triassic; the error bars do not overlap in the Triassic-Carboniferous, whereas they overlap in the post-Triassic. We therefore conclude that the Northeast OFB of Korea and SCB were in different paleo-position before the Jurassic. The above argument suggests that the SCB and the Northeast OFB including the southern Ryongnam Massif (RNM) were different plate before the Jurassic, and they were joined together in the Jurassic. However, it is not certain, at this time, whether a suture zone exists in Korea or not.

5. Conclusions

The Early Triassic, Late Permian, and Middle Carboniferous rocks from Northeast Okchon Fold Belt of South Korea carry primary magnetizations which indicate paleoposition of southern hemisphere for the NE Okchon Belt in the Middle Carboniferous and Late Permian, and paleoposition of northern hemisphere significantly lower than the present latitude in the Early Triassic. The pre-Jurassic apparent polar wander path for South Korea and the South China Block are different from each other. These differences can be explained by both relative north-south movement and rotations. It is suggested that southern Korea might be sutured to South China Block in the Jurassic. It is, however, not certain where the suture zone is.

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