Remagnetization of the Pyeongan Supergroup in the Yeongwol Area, Korea

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Paleomagnetic and rock magnetic investigations have been carried out for the late Carboniferous-Permian Pyeongan Supergroup, exposed in the Yeongwol area in eastern South Korea. A total of 228 independently oriented core samples was drilled from thirteen sites for the study. The mean direction after bedding correction (D/I = 202.7°/-24.6°, k = 2.4, a95 = 36.9°) is more dispersed than the in-situ mean direction (D/I = 175.3°/-58.9°, k = 69.0, a95 = 5.3°), indicating that the fold test is negative at 95% confidence level. In addition, the stepwise unfolding of the characteristic remanent magnetization (ChRM) reveals a maximum value of k at 0% unfolding. Furthermore, authigenic magnetite and hematite grains are identified by the electron microscope observations. These results collectively imply that the ChRM directions were acquired after tilting of the strata by a chemical remanent magnetization when the secondary authigenic magnetic minerals formed. The ChRM directions of the Supergroup, however, pass the reversal test at 95% confidence level suggesting that the remagnetization occurred during the period including both normal and reversed polarity intervals. Because the paleomagnetic pole position (39.4°E, 85.6°N, a95 = 8.9°) of the Pyeongan Supergroup calculated from the mean site directions of the ChRMs is close to that of the Tertiary period of the Korean Peninsula, it is interpreted that the remagnetization in this area occurred during the Tertiary. However, it is also plausible that the study area might be rotated about 30° anticlockwise after the remagnetization at the end of the Daebo Orogeny, in the beginning of the Cretaceous period.

1. Introduction

Many paleomagnetic studies of Eastern Eurasia, a tectonically complicated area due to its many constituting cratonic blocks, have identified the relative movements of the blocks during the Mesozoic time (Enkin et al., 1992). Although the Korean Peninsula is geographically located in northeastern part of Eurasia, its affinities with the blocks to the west are subjected to arguments. Traditionally the Korean Peninsula has been considered as part of the North China Block (NCB) in a single Sino-Korean unit. However, many recent studies have suggested many other possible interpretations: that the Korean Peninsula belongs to the South China Block (SCB) (Lee et al., 1987), that the northern part of the peninsula is part of the SCB while the southern part belongs to the NCB (Cruzel and Cadet, 1992), that the northeastern part of the Okcheon Belt, whose basement is the Ryongnam Massif, belongs to the NCB (Doh and Piper, 1994), and that the Korean Peninsula is an individual terrane (Enkin et al., 1992).

Until now the paleomagnetic studies for the Korean Peninsula have been focused on the rocks of the Upper Mesozoic to Cenozoic time. In order to identify the tectonic relations of the Korean Peninsula within the Eastern Eurasia, the paleomagnetic data of the Lower Mesozoic and earlier times, when significant tectonic activities frequently occurred, are necessary. Although several paleomagnetic studies of the Upper Carboniferous-Lower Triassic Pyeongan Supergroup in South Korea have been carried out previously by many researchers (Shibuya et al., 1985, 1988; Kim and Jeong, 1986; Otofuji et al., 1986, 1989; Kim, 1989; Doh and Piper, 1994; Lee et al., 1996), it is believed that most of them failed to isolate original paleomagnetic components, and/or the number of specimens is insufficient to represent the long geologic time interval. Hence much more paleomagnetic data are required to identify the reliable tectonic location of the Korean Peninsula for the Paleozoic and Mesozoic era. This study, originally intended to...
isolate the ChRM directions, to determine the paleomagnetic pole positions, and to provide the data for the tectonic history of the study area within the Eastern Asia, presents the paleomagnetic results of the Upper Carboniferous-Lower Permian Pyeongan Supergroup in the Yeongwol area within the northeastern part of the Okcheon Belt.

2. Geologic Setting

The Upper Carboniferous-Lower Permian Pyeongan Supergroup near the Yeongwol area overlaid disconformably the Cambro-Ordovician Choson Supergroup (Table 1). The Pyeongan Supergroup, an

![Geologic map of the Yeongwol area](image)

Fig. 1. Geologic map of the Yeongwol area, showing (a) the locations of sampling sites (after Geological Investigation Corps of Taebaeksan Region, 1962), and (b) structural trends around the study area (after Son et al., 1969).
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Table 1. Stratigraphic classification of the Yeongwol area.

| Age       | Yeongwol area                          |
|-----------|----------------------------------------|
|           | Geological Investigation Corps of Taebaeksan Region (1962) | Lee (1987) |
| Permian   | Pyeongan Supergroup                      |
|           | Sadong Fm.                               |
|           | Mitan Fm.                                |
| Carboniferous | Hongjeom Fm.                           |
|           | Yobong Fm.                               |
| Ordovician| Choseon Supergroup                       |
|           | Younghung Fm.                            |
|           | Younghung Fm.                            |

An elongated body of about 20 km long north to south with very narrow width of about 5 km, is located at longitude 128°27'~128°30' E, and latitude 37°11'~37°22' N (Fig. 1). The Permo-Carboniferous strata in the study area were originally divided into the Hongjeom Formation for red rocks and the Sadong Formation for coal-bearing rocks. Recently, new subdivision was proposed: the Yobong Formation for the Hongjeom Formation, and the Pangyo, Bamchi, and Mitan Formations for the Sadong Formation. However, the original division of the Hongjeom and the Sadong Formations is used in this study for the Permo-Carboniferous strata, because it is hard to draw the exact boundaries between formations of the newly proposed subdivisions.

The Hongjeom Formation consists of alternating beds of sandstone, shale, and conglomerate of bright red and gray in color with an average thickness of about 200 m. Some fusulinids found in the middle of the formation indicate that the age of the formation is to be Bashkirian - Early Moscovian (Lee, 1984). The Sadong Formation is lying conformably on the Hongjeom Formation with a thickness about 500 m. The Sadong Formation consists mainly of gray to dark gray sandstone, shale, and limestone with 4 coal beds at the uppermost portion of the formation, which is dated to be Permian by plant fossils (Kawasaki, 1938). The Moscovian fusulinids are found at the base of this formation (Cheong et al., 1983).

3. Field and Laboratory Methods

In the field, 2.5 cm diameter cores were drilled with a gasoline-powered portable drill and oriented in situ with a magnetic compass. A total of 228 samples from 13 sites was collected: 10 sites from the Hongjeom Formation and 3 sites from the Sadong Formation. The locations of sampling sites are shown in Fig. 1.

Samples were trimmed into 2.2 cm long cylinders in the laboratory. After natural remanent magnetization (NRM) and magnetic susceptibility of samples were measured, the samples were demagnetized by stepwise alternating field (AF) and thermal demagnetizations. The ASC Scientific thermal demagnetizer (model TD-48) and the Molspin AC demagnetizer were used for the thermal and AF demagnetizations, respectively. Remanent magnetizations were measured using a Cryogenic magnetometer and a Molspin spinner magnetometer. All the samples were stored in mu-metal boxes to be protected from the external magnetic field such as the earth’s magnetic field. To avoid acquisition of systematic parasitic remagnetization during thermal demagnetization, the samples were turned over at each step.

Thermal demagnetization was performed at 100°C, 200°C, 300°C, 350°C, 400°C, 450°C, 500°C, and at intervals of 20°C from 520°C to 700°C. To detect any chemical alteration of magnetic carriers on heating, magnetic susceptibility was measured at each stage of thermal treatment using a Bartington MS2 magnetic susceptibility meter. AF demagnetization was performed at the field strength of 5~30 mT with 5 mT intervals, and 40~90 mT with 10 mT intervals.

For representative samples of each site, isothermal remanent magnetization (IRM) acquisition experiments and the Lowrie-Fuller test were carried out, and magnetic hysteresis properties were
measured with a vibrating sample magnetometer (Molspin Ltd., model VSM Nuvo). Electron microscope observations were carried out to confirm the characteristic size, shape, paragenesis, and composition of magnetic carriers.

The paleomagnetic data from all samples were projected on the orthogonal vector diagrams (Zijderveld, 1967) and the ChRM direction of each sample was determined using the principal component analysis (PCA) with anchored line fit method (Kirschvink, 1980) from at least three or more points. When the demagnetization procedures did not isolate stable end-point components and the direction of the remanent magnetization changed along a great circle on the equal-area stereonet, the ChRM component was determined using the great circle method with sector constraints (McFadden and McElhinny, 1988).

4. Paleomagnetic Results

The NRM directions (directions before any demagnetization treatments) of the studied sedimentary rocks cluster more closely about the mean axial dipole field direction (D/I = 0°/56.5°) than about the present-day field direction at the sampling site (353.5°/50°, Fig. 2). It is therefore suggested that the NRM's are merely dominated by the secondary NRM components acquired for a fairly long time. The NRM intensities vary from 0.07 to 70.03 mA/m.

The demagnetization of pilot samples shows that the thermal demagnetization method isolates the characteristic component more effectively, while the AF demagnetization, even at the field strength of 90 mT, cannot remove the remanent magnetization successfully. The thermal demagnetization method was therefore applied to the remaining samples for this study to isolate ChRMs. During progressive thermal treatments, sample Y9-6, a typical dark gray limestone, shows that its magnetic intensity decreases continuously toward the origin up to 580°C, the Curie temperature of magnetite, above which the direction of remanent magnetization starts to randomize with a very weak intensity (Fig. 3(a)). The red beds reveal two distinctive types of thermal demagnetization behaviors. One shows simple decaying of remanence.

![Fig. 2. Total NRM directions in geographic coordinates. Lower hemisphere plots are shown as solid squares and upper hemisphere plots as open squares. Equal area projection.](image-url)
Fig. 3. Typical thermal demagnetization results of samples from the Sadong and Hongjeom Formations: normalized intensity curve and Zijderveld diagram in geographic coordinates. Demagnetization steps are shown below sample number. Crosses and open squares in Zijderveld diagrams indicate projections onto the horizontal and vertical planes, respectively.
| Formation | Site | Site | n/N | Dg  | Ig  | Ds  | Is  | k   | α_{95} | VGP | dp | dm |
|-----------|------|------|-----|-----|-----|-----|-----|-----|--------|-----|----|----|
|           |      |      |     |     |     |     |     |     |        |     |    |    |
|           |      |      |     |     |     |     |     |     |        |     |    |    |
| Sadong    | 3    | 128.47 | 37.27 | 5/13 | 169.6 | -62.0 | 145.7 | 7.0 | 20.6 | 17.3 | 146.6 | -54.5 | 8.7 | 17.4 |
|           | 9    | 128.48 | 37.30 | 18/19 | 3.8 | 49.7 | 341.5 | 34.6 | 28.9 | 6.5 | 282.4 | 82.5 | 5.8 | 8.7 |
|           | 16   | 128.47 | 37.30 | 11/12 | 196.7 | -54.2 | 79.7 | -60.8 | 99.3 | 4.8 | 44.2 | -76.3 | 4.7 | 6.7 |
| Mean      | 3/3  | 184.3  | -55.8 | 319.3 | 33.5 | 3.3 | 83.3 |
| Hongjeom  | 11*  | 128.48 | 37.30 | 26/26 | 3.8 | 13.6 | 355.2 | -1.0 | 146.1 | 2.4 | 301.1 | 59.4 | 1.3 | 2.5 |
|           | 15   | 128.49 | 37.30 | 8/16 | 166.3 | -70.5 | 263.6 | -26.7 | 123.1 | 5.9 | 284.6 | -70.3 | 8.8 | 10.2 |
|           | 14   | 127.49 | 37.30 | 13/14 | 353.9 | 55.1 | 310.9 | -3.3 | 44.4 | 6.4 | 21.5 | 84.8 | 6.5 | 9.1 |
|           | 2    | 128.47 | 37.22 | 8/10 | 183.2 | -45.1 | 216.4 | -25.8 | 47.5 | 8.8 | 113.2 | -79.1 | 7.1 | 11.1 |
|           | 4    | 128.48 | 37.27 | 20/21 | 183.0 | -64.2 | 236.7 | -1.6 | 122.8 | 3.1 | 322.0 | -81.0 | 4.0 | 5.0 |
|           | 6    | 128.48 | 37.28 | 16/16 | 174.1 | -53.8 | 234.9 | -5.6 | 40.4 | 6.2 | 188.7 | -84.4 | 6.1 | 8.7 |
|           | 8    | 128.50 | 37.30 | 12/14 | 163.5 | -57.2 | 111.1 | -23.3 | 75.2 | 5.2 | 225.8 | -76.9 | 5.5 | 7.6 |
|           | 10   | 128.48 | 37.30 | 18/27 | 162.2 | -62.4 | 244.1 | -8.7 | 70.0 | 5.7 | 249.5 | -75.1 | 7.3 | 9.4 |
|           | 13   | 128.48 | 37.30 | 12/18 | 151.8 | -70.1 | 232.2 | -10.0 | 79.6 | 5.1 | 268.6 | -64.4 | 7.6 | 8.8 |
|           | 12   | 128.48 | 37.30 | 22/22 | 176.5 | -57.3 | 228.4 | -2.9 | 135.5 | 2.7 | 232.0 | -87.2 | 2.9 | 3.9 |
| Mean      | 9/10 | 171.9  | -59.9 | 219.9 | -15.9 | 2.9 | 36.6 |
| Normal mean | 2/3 | 359.2  | 52.5 | 200.8 | 17.7 |
| Reversed mean | 10/10 | 174.3 | -60.2 | 65.4 | 6.0 |
| Mean      | 12/13 | 175.3  | -58.9 | 69.0 | 5.3 | 219.4 | -85.6 | 24.7 |

n/N: number of samples used in average/measured; Dg and Ig: declination and inclination in geographic coordinates; Ds and Is: declination and inclination in stratigraphic coordinates; k: Fisherian precision parameter; α_{95}: radius of cone of 95% confidence interval; VGP: virtual geomagnetic pole; dp: the semi axis of the confidence ellipse along the great-circle path from site to pole; dm: the semi axis of the confidence ellipse perpendicular to that great-circle path; K: the best estimate of the precision parameter k for the observed distribution of site-mean VGPs; A_{95}: the radius of the 95% confidence circle about the calculated mean pole.

*Site mean omitted in calculation of the mean (see text for explanation).
toward the origin in the 200 to 660°C range above which the direction starts to randomize due to a weak intensity (Fig. 3(b)). The other shows the overlap of blocking temperature spectra and changes of remanence direction along a great circle during the treatment (Fig. 3(c)). For such specimens, the directions of the ChRM components are resolved by the great circles method with sector constraints of McFadden and McElhinny (1988).

The results of the stepwise demagnetization show that the rocks from the study area are magnetized both normally and reversely (Table 2). The mean direction of the ChRM calculated from all site-mean directions except site 11, which has an anomalously shallow inclination, is \( D/I = 175.3°/-58.9° \) (\( k = 69.0 \), \( α_{95} = 5.3° \)) before tilt correction and \( D/I = 202.7°/-24.6° \) (\( k = 2.4 \), \( α_{95} = 36.9° \)) after tilt correction. The
site-mean directions are more dispersed after tilt correction than before tilt correction (Fig. 4). Furthermore, the stepwise unfolding of the ChRM reveals that a maximum value of Fisher's precision parameter \((k)\) is observed at 0% unfolding (Fig. 5). These results indicate that the ChRM was acquired after tilting of the strata. Among thirteen site-mean directions, three are normally magnetized and ten are reversely magnetized (Table 2). The normal component (\(D/I = 359.2°/52.5°, \alpha_{95} = 17.7°\)) and reversed component (\(D/I = 174.3°/-60.2°, \alpha_{95} = 6.0°\)) before tilt correction, excluding results of site 11, are not significantly different from antipodal at the 95% confidence level. It is therefore indicated that the remagnetized component had been acquired during the period including both normal and reversed polarity intervals.

5. Rock Magnetic Results

The IRM acquisition experiments reveal different acquisition behaviors for the gray limestone and red bed (Fig. 6). Samples from the gray limestone (e.g. samples Y9-3 and Y9-6) show a steeply inclining IRM intensity to a field of 100 mT and about 80% of saturation is achieved at 300 mT or less. This behavior indicates that ferrimagnetic material like magnetite makes an important contribution to the IRM acquisition and the influence of canted antiferromagnetic material such as hematite is minor (Lowrie and Fuller, 1971; Johnson et al., 1975; Dunlop, 1983; Piper, 1987). Gray sandstone (e.g. sample Y3-5) acquires about 80% saturation at 400 mT and a gradual increase in IRM intensity at the field above 500 mT, indicating ferrimagnetic material and canted antiferromagnetic material contribute equally to the IRM acquisition. All samples from red bed show continuous increase in IRM intensity with increasing field up to 1 T, suggesting that canted antiferromagnetic material is the dominant magnetic phase contributing to the IRM acquisition. The results of the IRM acquisition experiments are in accordance with those of remanent coercivity (Hcr) measurements (Table 3) and thermal demagnetization behaviors (Fig. 3).

Hysteresis loops for selected samples were measured. Hysteresis parameters, such as saturation remanence (Mrs), saturation magnetization (Ms), Hcr and coercive force (Hc), obtained from the
hysteresis loops are listed in Table 3. The ratios of hysteresis parameters, $H_{cr}/H_c$ and $M_{rs}/M_s$, were used to diagnose the domain state of magnetic minerals (Day et al., 1977). From the plotting of the $M_{rs}/M_s$ versus $H_{cr}/H_c$ as shown in Fig. 7, it is found that the magnetite-dominant samples are either in pseudo-single domain (PSD) region (samples Y9-3 and Y9-6) or in multi domain (MD) state (sample Y3-5). Although the plot of $M_{rs}/M_s$ against $H_{cr}/H_c$ is used to determine the domain state of magnetite-bearing samples, results from red beds are also shown in Fig. 7. The values of $M_{rs}/M_s$ and $H_{cr}/H_c$ generally lie

Table 3. Hysteresis properties of selected samples.

| No.  | $H_{cr}$ (mT) | $H_c$ (mT) | $H_{cr}/H_c$ | $M_{rs}$ ($\mu$Am²) | $M_s$ ($\mu$Am²) | $M_{rs}/M_s$ | Formation   | Rock type     |
|------|---------------|------------|--------------|----------------------|------------------|--------------|-------------|--------------|
| Type 1|               |            |              |                      |                  |              |             |              |
| Y2-4 | 539           | 139        | 3.88         | 3.69                 | 26.69            | 0.14         | Hongjeom    | Red Shale    |
| Y4-2 | 516           | 130        | 3.97         | 2.06                 | 16.26            | 0.13         | Hongjeom    | Red Siltstone|
| Y6-2 | 394           | 198        | 1.99         | 2.16                 | 6.73             | 0.32         | Hongjeom    | Red Sandstone|
| Y8-2 | 464           | 157        | 2.96         | 1.38                 | 7.45             | 0.19         | Hongjeom    | Red Sandstone|
| Y10-10 | 492        | 125        | 3.93         | 6.87                 | 60.28            | 0.11         | Hongjeom    | Red Shale    |
| Y11-1| 602           | 7          | 86.00        | 0.43                 | 44.68            | 0.01         | Hongjeom    | Red Shale    |
| Y12-7| 588           | 173        | 3.40         | 4.41                 | 24.15            | 0.18         | Hongjeom    | Red Shale    |
| Y13-2| 477           | 120        | 3.98         | 2.91                 | 29.49            | 0.10         | Hongjeom    | Red Shale    |
| Y14-2| 490           | 61         | 8.03         | 0.05                 | 1.73             | 0.03         | Hongjeom    | Red Sandstone|
| Y15-2| 564           | 141.5      | 3.98         | 3.34                 | 23.37            | 0.14         | Hongjeom    | Red Siltstone|
| Y16-3| 560           | 175        | 3.20         | 10.52                | 60.76            | 0.17         | Sadong      | Red Sandstone|
| Type 2|               |            |              |                      |                  |              |             |              |
| Y3-5 | 121           | 1.5        | 80.67        | 0.02                 | 19.10            | 0.001        | Sadong      | Gray Sandstone|
| Y9-3 | 70            | 38.5       | 1.81         | 0.05                 | 0.93             | 0.05         | Sadong      | Gray Limestone|
| Y9-6 | 65            | 21.5       | 3.02         | 0.24                 | 2.65             | 0.09         | Sadong      | Gray Limestone|

$H_{cr}$: Coercivity of Remanence; $H_c$: Coercive Force; $M_{rs}$: Saturation Remanence; $M_s$: Saturation Magnetization.

Fig. 7. Hysteresis properties and domain state for red shale (solid circles), gray limestone (solid squares) and gray sandstone (solid triangle) from study area (after Day et al., 1977).
in the PSD field and the results are comparable with those of hematite-dominant pinkish and reddish Italian pelagic limestones (Channel and McCabe, 1994). The results of the Lowrie-Fuller test are shown in Fig. 8. In case of gray limestone (sample Y9-3), IRM decreases rapidly than ARM with increasing AF field, yielding a test result of SD or PSD magnetite (Lowrie and Fuller, 1971). Gray sandstone (sample Y3-6) shows the inverse result, implying MD magnetite grains are the dominant magnetic carriers (Dunlop, 1973). Since both ARM and IRM imparted in hematite are rarely removed by AF demagnetization, the Lowrie-Fuller test for red shale, whose main magnetic carrier is hematite of high coercivity, is inadequate. In summary of the rock-magnetic experiments, the gray limestone contains mainly SD–PSD ferrimagnetic minerals and gray sandstone contains MD and/or superparamagnetic ferrimagnetic minerals with the influence from canted antiferromagnetic minerals, while the remanence in red bed is mainly carried by canted antiferromagnetic minerals.

Fig. 8. The Lowrie-Fuller test results for selected samples.

Fig. 9. Electron-Probe Microanalyzer photomicrographs of limestone samples. (a) Secondary electron image (SEI) of magnetite aggregates (small white grains) filling a void within calcite matrix (dark gray). (b) SEI of magnetite (gray grain) replacing pyrite (lighter grain at center).
6. Electron Microscope Observations

Electron microscope observations were carried out on representative samples of gray limestone, red sandstone, and red shale from the study area. Magnetite grains of 0.1–10 µm in size are most frequently

Fig. 10. Electron-Probe Microanalyzer photomicrographs of red beds. Scale bar is 10 µm. (a) Back-scattered electron image (BEI) of ilmenite lamellae within a hematite grain. (b) Secondary electron image (SEI) of the hematite grain shown in (a). (c) BEI of authigenic hematite as aggregates of individual grains. (d) BEI of pigmentary hematite. (e) SEI of hematite (light gray) containing a quartz inclusion (dark gray). (f) BEI of hematite scattered along the grain boundaries.
observed along the boundaries of carbonate grains and microcracks (Fig. 9). Octahedral/cubo-octahedral crystals of magnetite of less than 1 µm in diameter are scattered along the microcracks and/or filling a void in the form of aggregates (Fig. 9(a)). As shown in Fig. 9(b), individual crystals now having relic cores of pyrite with rims of magnetite clearly display partial replacement of pyrite by magnetite as a result of authigenesis (Suk et al., 1990a, b). Magnetite grains observed in gray limestone indicate that the magnetite grains are not detrital but secondary authigenic in origin.

The most frequently observed iron-oxide minerals in red bed are hematite grains accompanied by quartz, feldspar, and clay minerals. The hematite grains can be grouped into two types (Fig. 10). First, a few euhedral to subhedral hematite grains with ilmenite lamella (10–30 µm) are observed (Figs. 10(a) and 10(b)). Second, elongate hematite grains of 1–10 µm in length distributed along grain boundaries of quartz, feldspar, and clay minerals are frequently observed (Figs. 10(c)–10(f)). Figure 10(c) shows elongate pigmentary hematite grains, either in the form of aggregates of about 20 µm diameter or scattered in voids adjacent to quartz grains. Most pigmentary hematite grains are distributed along microcracks or around grains of other minerals such as quartz (Fig. 10(d)). A hematite grain with a quartz inclusion shown in Fig. 10(e) is the clear evidence of its authigenic origin. Significant amount of altered clay minerals found around pigmentary hematite (Fig. 10(f)) indicates that hematite grains were formed in the process of alteration of Fe-bearing minerals to clays. The results of the electron microscope observations indicate that magnetic carriers, both magnetite and hematite, are secondary products formed by the fluid mediated alteration.

7. Discussion

Although it was not successful to obtain the paleomagnetic directional changes from the upper Carboniferous to the Permian in this study, it was discovered that the Pyeongan Supergroup in the Yeongwol area has been remagnetized. On the contrary to our results, Lee et al. (1996) reported the mean direction (D/I = 255°/-2.4°, α95 = 20.8°) obtained from the samples of red shale in the Yeongwol area and in the Baekunsan Syncline as the primary remanent magnetization. However, it is doubtful that the results by Lee et al. (1996) represent the Permo-Carboniferous Pyeongan Supergroup because only eight samples from two sites (sites 605 and 608) were collected from the Yeongwol area. Site 608, very close to sites 4 and 6 of this study, yielded D/I = 186.2°/–68.9° (α95 = 6.4°) before tilt correction and D/I = 249.2°/–4.4° (α95 = 6.9°) after tilt correction, being similar to that of this study, while site 605, close to site 10 of this study, yielded D/I = 215.6°/88.2° (α95 = 11.7°) before tilt correction and D/I = 265.5°/11.9° (α95 = 11.8°) after tilt correction which are different from the mean direction of this study (Table 2, Fig. 4). On the basis that the mean direction of the ChRM of the Permo-Carboniferous Pyeongan Supergroup from this study is interpreted as remagnetized component, it is more likely that the mean direction of site 608 of Lee et al. (1996), which is similar to that of this study, must have been acquired after tilting of the strata.

The mean ChRM direction before tilt correction is very close to the present axial dipole field, and the normal component and the reversed component are not significantly different from antipodal at the 95% confidence level. These results indicate that the remagnetization occurred during the period including both normal and reversed polarity intervals, which is long enough to average out geomagnetic secular variations. The periods in which geomagnetic field was characterized by frequent reversals with roughly equal duration for the normal and reversed states after the formation of the Pyeongan Supergroup are the late Jurassic-early Cretaceous and the late Cretaceous-Quaternary (Harland et al., 1990). Therefore, the remagnetized ChRM could be acquired during one of these periods. Compared to the paleomagnetic poles from Permian to Quaternary in Korea (Kim and Jeong, 1986; Lee et al., 1987; Kim and Kang, 1989; Doh et al., 1994), the paleomagnetic pole position (39.4°E, 85.6°N, α95 = 8.9°) calculated from the remagnetized component is close to the Tertiary pole position (Fig. 11). Thus, it can be interpreted that the remagnetization occurred during Tertiary.

Although this comparison indicates that the remagnetization in the study area could have occurred during the Tertiary, any remarkable geologic events, such as orogeny and igneous activity that might cause
the remagnetization, in this period are not recognized. An alternative interpretation of the timing of remagnetization can be late Jurassic-early Cretaceous (Pre-Barremian) in age associated with the Daebo Orogeny. If the Cretaceous paleomagnetic direction ($D/I = 28.5°/58.4°, \alpha_{95} = 11.7°$) at the Yeongwol area recalculated using the paleomagnetic pole of the Kyeongsang Basin ($205.1°E, 67.4°N$, Lee et al., 1987) is compared with the mean direction ($D/I = 355.3°/58.9°, \alpha_{95} = 5.3°$) before tilt-correction of this study, the difference of about 30° in declination between the two paleomagnetic directions is close to the degree of rotation of the structural trend of the Yeongwol area from the main Okcheon Belt (see also Fig. 1). The structural trends in the Yeongwol area are NS direction, while those in the southeastern region out of the Yeongwol area are NE-SW and ENE-WSW (Fig. 1(b), Son et al., 1969). The geologic structures in the study area were initiated during the Songnim Orogeny (Triassic) and were subsequently further intensely folded and overthrusted during the Daebo Orogeny (Lee, 1987). Moreover, the fact that stepwise unfolding test of the Pyeongan Supergroup has maximum $k$ value at 0% unfolding (Fig. 5) also constrains the timing of the remagnetization to the end of or after the Daebo Orogeny. Based on these facts, it can be postulated that the study area might be rotated about 30° counterclockwise after the remagnetization occurred at the end of the Daebo Orogeny (late Jurassic-early Cretaceous). This interpretation is supported by the reconstruction of the North Sino-Korean and South Sino-Korean Blocks in a way that the two blocks collided during Middle-Late Triassic time and the consequently broken pieces of the North Sino-Korean Block, the eastern and western part of the North Sino-Korean Block, suffered clockwise and counterclockwise rotations, respectively, until Jurassic time (Lee et al., 1997). The paleomagnetic pole calculated...
from the remagnetized component adjusted for about 30° of clockwise rotation is located at 210.8°E, 67.8°N (A95 = 8.9°) and this pole is comparable to the Cretaceous pole position (Fig. 11). Nevertheless, any concrete evidence of the rotation is not found yet, mainly because there are few structural studies on the Yeongwol area until now. The confirmation of the interpretation that the remagnetization followed by the counterclockwise rotation occurred at the end of or after the Daebo Orogeny will be made when the geologic evidence is found.

There are two fundamentally different explanations for remagnetization processes. One invokes the realignment of magnetization within pre-existing grains to the ambient field when the pre-existing magnetic grains are exposed to the elevated temperature above 250–300°C and below the Curie temperature of the magnetic grains for prolonged period of time, known as thermoviscous remanent magnetization (TVRM) (Jackson, 1990). The second mechanism involves a chemical remanent magnetization (CRM) acquired when new magnetic minerals formed long after the formation of the rocks in the direction of the ambient field at low temperature, by the chemical alterations accompanied by the tectonically driven fluid migration from active plate margins (McCabe et al., 1983; Oliver, 1986). TVRM is most likely to have occurred in rocks when the rocks were buried to depths on the order of kilometers for millions of years (Kent, 1985) and when they were under the influence of the regional metamorphism or igneous activities. The conodont color index indicates that the paleotemperature in this study area is about 300°C (Seo, 1990), which is only high enough to cause the acquisition of TVRM for magnetite of MD grains (Jackson, 1990). The major magnetic carriers of gray limestone in this area determined from the electron microscope observations and rock-magnetic experiments are in SD ~ PSD state. Moreover any intrusives are not found in and around the study area. Thus remagnetization by TVRM can be denied. On the other hand, the electron microscope observations of magnetic carriers in the samples of the Pyeongan Supergroup, such as octahedral/cubo-octahedral magnetite crystals in and along the voids and microcracks, pyrite partially replaced by magnetite, and pigmentary hematite grains accompanied by quartz, feldspars and clay minerals, strongly suggest that the magnetic minerals in the rocks are secondary authigenic in origin. Thus the major process that causes the remagnetization in the rocks of the study area is the acquisition of CRM due to the formation of the authigenic magnetic minerals under the influence of fluids, which might be triggered by the orogeny or igneous activity.

8. Conclusions

(1) The characteristic remanent magnetization (ChRM) in the Upper Carboniferous-Lower Permian Pyeongan Supergroup in the Yeongwol area is carried by both single domain ~ pseudo-single domain magnetite grains and hematite grains.

(2) Since the site-mean directions are more dispersed after tilt correction (k2/k1 = 0.03), it is concluded that the ChRM was remagnetized after tilting of the strata.

(3) The mean direction and the paleomagnetic pole position of the remagnetized component are D/I = 175.3°/-58.9° (k = 69.0, a95 = 5.3°) and at 39.4°E, 85.6°N (A95 = 8.9°), respectively, and the pole position is comparable to the Tertiary paleomagnetic pole position. Hence, it can be safely concluded that the remagnetization occurred during the Tertiary. However, the paleomagnetic pole position, recalculated from the remagnetized component adjusted for 30° of clockwise rotation, is at 210.8°E, 67.8°N (A95 = 8.9°) which is close to that of the Cretaceous of Korean Peninsula. It can be hypothesized that the remagnetization followed by the counterclockwise rotation occurred at the end of or after the Daebo Orogeny, in the beginning of the Cretaceous period, although this hypothesis should be tested when the geologic evidence is available.

(4) The remagnetized component in this area is acquired by the chemical remanent magnetization due to the formation of authigenic magnetic minerals under the influence of fluid migration.

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