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# Paleomagnetic results of the Late Permian Gobangsan Formation, Korean Peninsula: Remagnetization in the southeastern periphery of the Bagjisan Syncline

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Sedimentary rocks in the Late Permian Gobangsan Formation were collected at 7 sites for paleomagnetic study in the southeastern periphery of the Bagjisan Syncline, Korean Peninsula. The Gobangsan Formation revealed a stable secondary magnetization component with unblocking temperatures of 500–580°C and 650°C from two sites, while the other sites possessed only a present day viscous remanence. The secondary component resides in magnetite and hematite. The site-mean directions of the two sites before tilt correction ($D = 355.9°$, $I = 50.2°$ with $\alpha_{95} = 4.3°$ and $D = 355.7°$, $I = 53.3°$ with $\alpha_{95} = 6.1°$) suggest that the remagnetization occurred after Early Cretaceous. The most plausible mechanism of the remagnetization is considered to be a chemical authigenesis because the other possible mechanisms of the remagnetization such as thermoviscous process and Recent weathering can be ruled out by rock magnetic experiments. The timing of the remagnetization is constrained during Tertiary time, because the observed directions are distinguishable from the Cretaceous directions and because Recent remagnetization is unlikely. This is ascertained by good agreement between the observed and the Tertiary directions.

## 1. Introduction

The Korean Peninsula is situated to the east of the major tectonic blocks for East Asia (North and South China Blocks) (Fig. 1a). It is composed of three tectonic divisions with basement of Archean to middle Proterozoic age, namely the Nangrim, Gyeonggi and Ryeongnam Blocks from north to south (Reedman and Um, 1975; Cluzel *et al.*, 1990) (Fig. 1b). The former two blocks are bounded by the Imjingang Belt, and the latter two by the Ogcheon Belt. Paleomagnetic studies of the Korean Peninsula have been carried out to confirm affinity of these blocks with the China Blocks.

Paleomagnetic studies of the Late Carboniferous-Early Triassic Pyeongan Supergroup in the Korean Peninsula have been hampered by severe remagnetization from Mesozoic to Recent ages (Fig. 1c). Otofuji *et al.* (1989) observed a single remagnetized component from the Pyeongan Supergroup in the Baegunsan Synclinal area. A complete remagnetization was also found from the supergroup in Yeongweol area (Doh *et al.*, 1997). Kim *et al.* (1992) reported that 65% of the samples collected from the Pyeongan Supergroup showed remanence directions dominated by the present direction of the Earth's magnetic field or unstable erratic directions. Lee *et al.* (1996) could not obtain primary paleomagnetic directions from six out of all fourteen sampling sites in the Baegunsan Syncline and Yeongweol area. Uno (1999) pointed out a possibility that the Pyeongan Supergroup in the peripheral part of the Bagjisan Syncline suffered almost complete remagnetization because primary magnetization of the supergroup was observed only in the central part of the syncline ($D = 347.1°$, $I = 23.8°$ with $\alpha_{95} = 5.5°$). Accumulating paleomagnetic results of the Bagjisan Syncline enhances understanding the remagnetization of the Pyeongan Supergroup because most of the previous paleomagnetic results are concentrated in the Baegunsan Syncline and Yeongweol area.

This paper focuses on paleomagnetism of the Late Permian Gobangsan Formation to investigate the remagnetization nature in the peripheral part of the Bagjisan Syncline. The Gobangsan Formation is the upper part of the Pyeongan Supergroup and comprises peripheries of the Bagjisan Syncline. This paper presents paleomagnetic and rock magnetic data of the remagnetized rocks and gives an interpretation of the remagnetization in the southeastern periphery of the Bagjisan Syncline.

## 2. Geological setting and sampling

The northeastern part of the Ogcheon Belt (Fig. 1b) is covered by Paleozoic and Mesozoic sedimentary rocks from Early Cambrian to Early Jurassic ages (Reedman and Um, 1975; Lee, 1987). The Late Carboniferous-Early Triassic Pyeongan Supergroup unconformably overlies the Early Cambrian-Middle Silurian Joseon Supergroup, and is unconformably overlain by the Late Triassic-Early Jurassic Daedong Supergroup.

The Pyeongan Supergroup is distributed in the Bagjisan Syncline, the Baegunsan Syncline and Yeongweol area (Fig. 1c). The Pyeongan Supergroup is divided into four formations; namely, the Hongjeom, Sadong, Gobangsan and Nogam Formations in ascending order (Fig. 1d) (Reedman and Um, 1975; Lee, 1987). The ages of the Gobangsan formation is paleontologically determined to be of Late Permian (Kawasaki, 1939).

Folding event of the Pyeongan Supergroup occurred in the

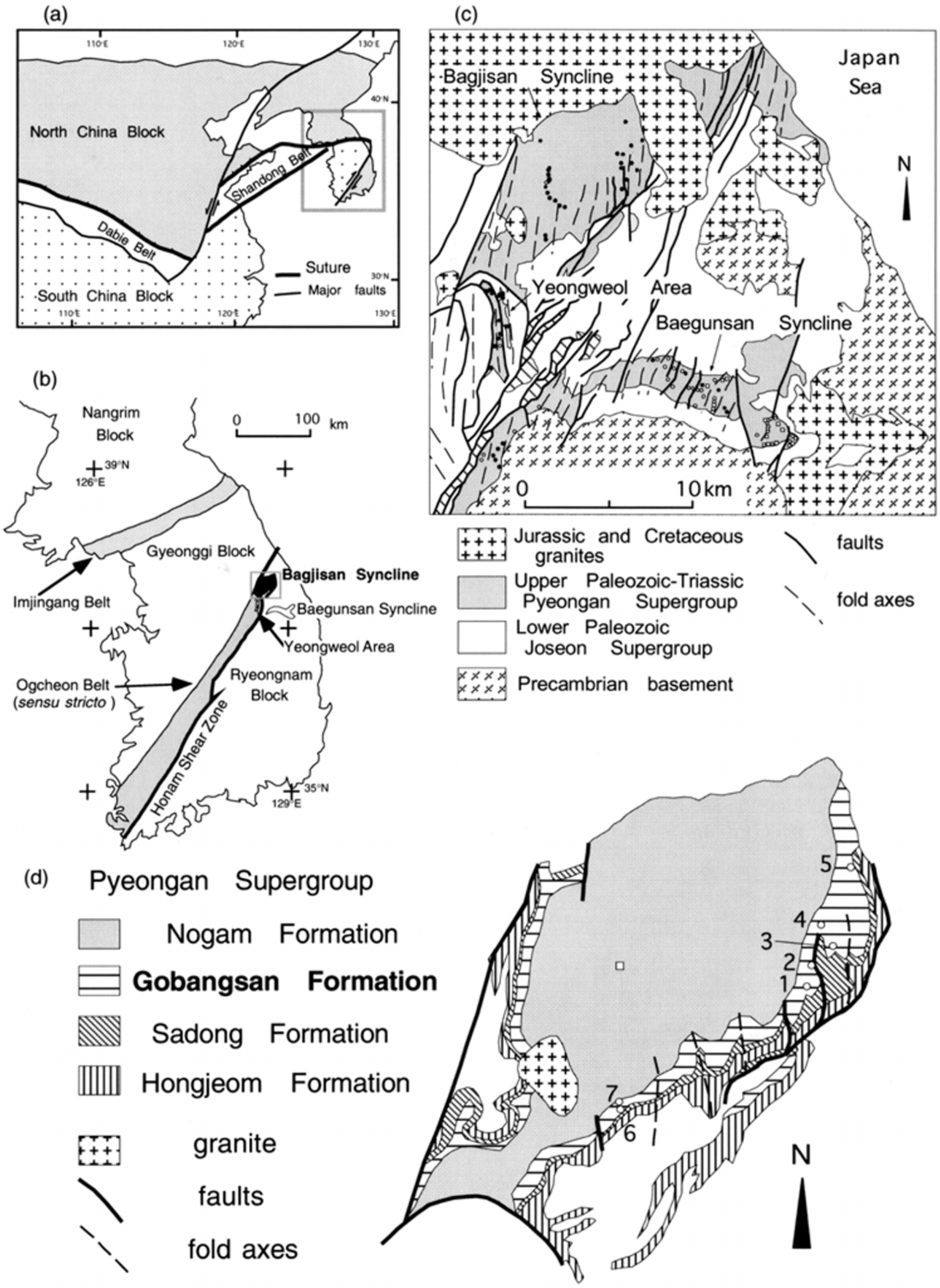


Fig. 1. (a) Tectonic map of the Korean Peninsula with adjacent area. (b) Tectonic division in the Korean Peninsula. (c) Structural map of the Bagjisan Syncline, the Baegunsan Syncline and Yeongweol area with paleomagnetic sampling sites (after Cluzel, 1991). Open circles = sites of primary magnetization; open squares = sites of secondary magnetization with northeasterly directions of normal polarity; solid circles = sites of secondary magnetization with northerly directions of normal polarity; solid squares = sites of secondary magnetization with southerly directions of reversed polarity. The sites are classified according to the conclusions by the original authors (Otofuji *et al.*, 1989; Kim *et al.*, 1992; Doh and Piper, 1994; Lee *et al.*, 1996; Doh *et al.*, 1997; Uno, 1999). (d) Geological map of the Bagjisan Syncline. Open circles denote the paleomagnetic sampling sites of the Gobangsan Formation. Open square denotes the sampling site of primary hematite magnetization (site SK8; Uno, 1999).

Middle Triassic (Cluzel *et al.*, 1991), which is ascertained by unconformity between the Pyeongan Supergroup and the Daedong Supergroup. In the Bagjisan Syncline, its western and southern margins are sharply cut by transcurrent faults activated in Middle-Late Triassic (Cluzel, 1991). The southeastern peripheries of the syncline are deformed by en-echelon faults and folds associated with the transcurrent faulting (Fig. 1d). The motion along these faults have caused the intermediate- to low-pressure metamorphism (Cluzel, 1991).

Fifty seven hand samples of sandstones and shales in the Gobangsan Formation were collected at 7 sites in the southeastern periphery of the Bagjisan Syncline for paleomagnetic measurements (Fig. 1d). Eight to nine hand samples are distributed over distance ranging up to 15 m in each site. They are oriented using a magnetic compass. The present geomagnetic field declination was calculated using the International Geomagnetic Reference Field (IAGA Division V, Working Group 8, 1995).

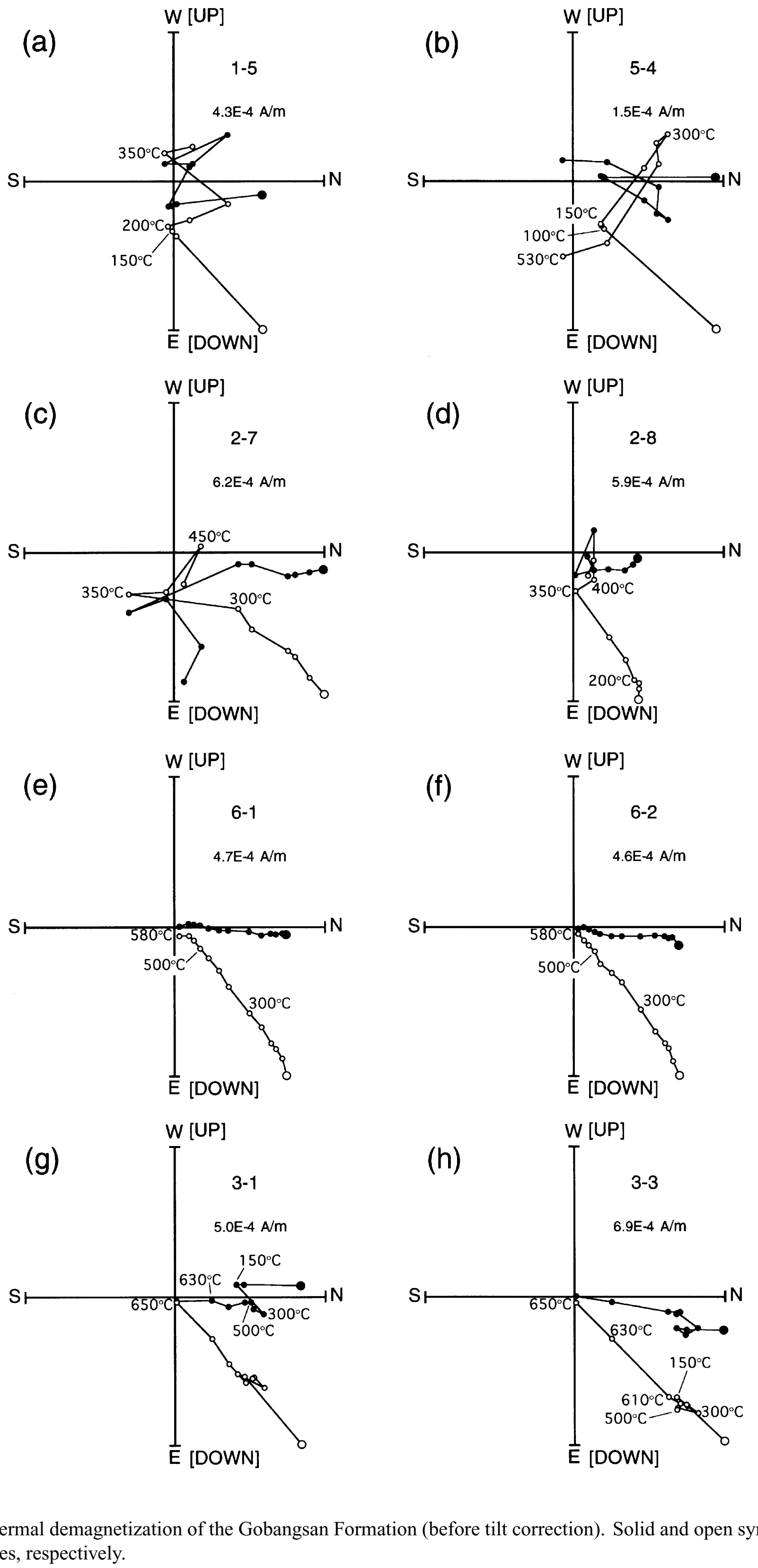


Fig. 2. Orthogonal plots of thermal demagnetization of the Gobangsan Formation (before tilt correction). Solid and open symbols represent projection on horizontal and vertical planes, respectively.

## 3. Paleomagnetic and rock magnetic methods

In the laboratory, individual samples of 25 mm in diameter and 22 mm length were prepared from each hand sample. The samples of the Gobangsan Formation consist of milky white sandstone (sites 1 and 5), dark gray sandstone (sites 2 and 3), black shale (site 4), and grayish sandstone (sites 6 and 7).

Natural remanent magnetizations (NRMs) were measured with a 2-G cryogenic magnetometer. All samples were subjected to progressive thermal demagnetization treatment with a Natsuhara TDS-1 thermal demagnetizer in step of 50°C up to 500°C. Demagnetization steps of 20°C or 30°C were used in the temperature range of 500–650°C.

Table 1. Paleomagnetic results of the Gobangsan Formation.

| Site | N | In situ | | | | Tilt corrected | | | | Locality | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | D(°) | I(°) | k | $\alpha_{95}$(°) | D(°) | I(°) | k | $\alpha_{95}$(°) | Lat.(°N) | Long.(°E) |
| 1 | 3 | 351.8 | 47.0 | 21.2 | 27.4 | 340.1 | 10.8 | 21.1 | 27.5 | 37.481 | 128.597 |
| 2 | 8 | 343.1 | 41.0 | 17.3 | 13.7 | 343.1 | −10.9 | 18.9 | 13.1 | 37.481 | 128.587 |
| 3 | 9 | 355.9 | 50.2 | 148.3 | 4.2 | 315.1 | 18.8 | 147.6 | 4.3 | 37.490 | 128.579 |
| 4 | 5 | 346.0 | 48.0 | 10.9 | 24.3 | 319.0 | 15.9 | 10.8 | 24.4 | 37.493 | 128.570 |
| 5 | 7 | 2.2 | 37.5 | 6.2 | 26.3 | 331.0 | 18.5 | 6.2 | 26.3 | 37.500 | 128.566 |
| 6 | 3 | 355.7 | 53.3 | 398.2 | 6.2 | 338.2 | 6.9 | 407.5 | 6.1 | 37.510 | 128.562 |
| 7 | 2 | 331.7 | 52.8 | — | — | 318.6 | −3.8 | — | — | 37.519 | 128.565 |
| Mean | 7 | 349.8 | 47.5 | 80.8 | 6.8 | 327.5 | 6.8 | 31.6 | 10.9 | 37.500 | 128.500 |

*N* = the number of the samples in calculation for the means;
*D* and *I* = declination and inclination, respectively; k = the precision parameter;
$\alpha_{95}$ = radius of the cone of the 95% confidence;
Lat. = north latitude; Long. = east longitude.

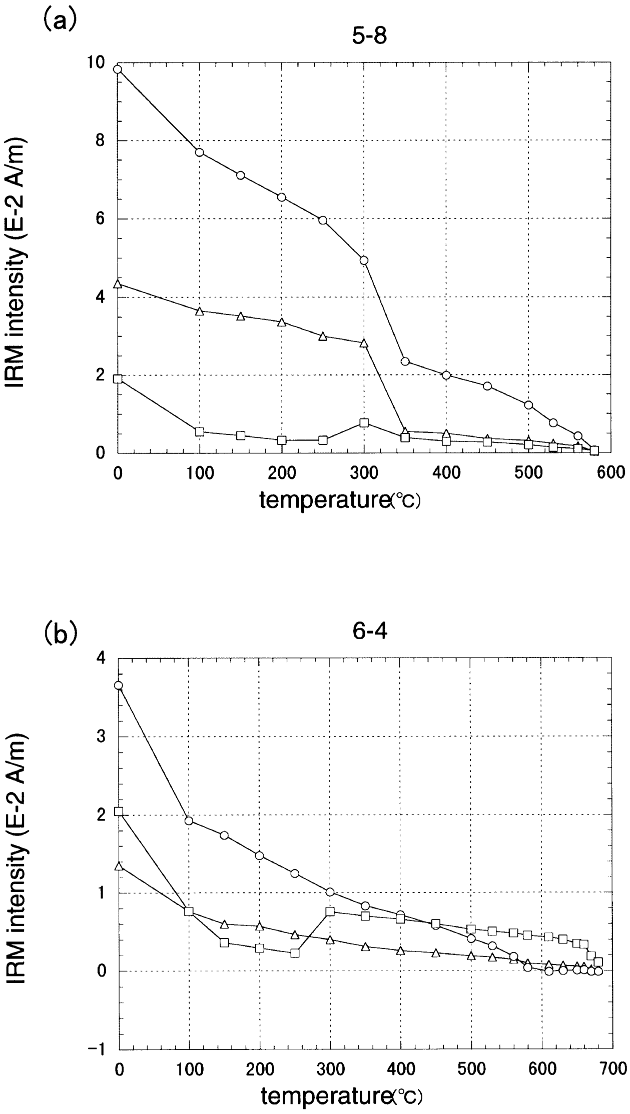


Fig. 3. Thermal demagnetization of the composite IRM: circles indicate soft component, 0.12 T field; triangles indicate medium component, 0.4 T field; squares indicate hard component, 2.7 T field.

Results for each sample were plotted on orthogonal vector diagram (Zijderveld, 1967) to evaluate demagnetization behaviors. Principal component analysis (Kirschvink, 1980) was used to estimate directions of the magnetic components (Table 1).

Progressive acquisition of saturation isothermal remanent magnetization (IRM) up to the maximum field of 2.7 T and thermal demagnetization of a three component IRM (Lowrie, 1990) were performed with a 2-G pulse magnetizer to identify ferromagnetic mineral components.

The coercivity of remanence ($H'_{cr}$) of samples with hematite magnetization was measured according to Tauxe *et al.* (1990), in which it is reported that pigmental hematite can be distinguished from specular hematite in terms of $H'_{cr}$ values. An $H'_{cr}$ is the 'back field' required to destroy an IRM imparted to samples at the maximum field available (2.7 T). This experiment was carried out to a Gobangsan Formation sample of secondary hematite magnetization and a Nogam Formation sample of primary hematite magnetization (Uno, 1999) with a view to comparing the $H'_{cr}$ values of the secondary and primary hematite.

An anhysteretic remanent magnetization (ARM) in a peak alternating field (AF) of 100 mT and a biasing field of 50 $\mu$T was given to a magnetite-bearing sample. The ARM was progressively AF demagnetized. The sample was given an IRM at applied field of 300 mT and was then progressively AF demagnetized. The Lowrie-Fuller test was performed using these results of AF demagnetization (Lowrie and Fuller, 1971).

## 4. Paleomagnetism

Thirty seven samples out of the fifty seven provided interpretable demagnetization trajectories. Progressive thermal demagnetization of the samples separates the seven sampling sites into three categories.

Category A (sites 1, 2, 4, 5 and 7): A single magnetization component with unblocking temperatures of 150–350°C is revealed (Figs. 2a–d). Demagnetization trajectories in this category show that the trajectories do not decay to the origin in the initial stage of demagnetization and that an erratic behavior is observed in direction of remanent magnetization at temperatures higher than 150–350°C. This suggests two options of interpretation: (1) the linear segment in the initial stage is a remanence carried by magnetic minerals of lower unblocking temperatures such as goethite and pyrrhotite, or (2) the lower temperature component resides in magnetite and/or hematite as a viscous remanent magnetization (VRM). A comparison of thermal demagnetization of NRM with thermal demagnetization of the composite IRM ascertains that the option 2 is preferable. An example of the thermal demagnetization of NRM for site 5 is shown in Fig. 2b, in which an apparent unblocking temperature is observed around 150°C, and existence of goethite in the sample is expected. However, the composite IRM demagnetization for site 5 (Fig. 3a) shows contributions of magnetite in the soft component at 580°C and pyrrhotite in the soft and intermediate components at 350°C. Existence of goethite is not observed from Fig 3a, confirming the option 2.

Category B (site 6): A stable directional behavior that decays to the origin is observed during thermal demagnetization (Figs. 2e and f). Unblocking temperatures of 500–580°C suggest that magnetite carry the remanent magnetization. Thermal demagnetization of the composite IRM shows that magnetite coexists with hematite (Fig. 3b). Goethite appears absent because the composite IRM demagnetization (Fig. 3b) shows that a decrease in intensity at temperatures until 150°C is most prominent in the soft component which cannot be diagnostic of goethite.

Category C (site 3): High and low unblocking temperature components are revealed. The low temperature component is removed at 150°C. The high temperature component decays toward the origin (Figs. 2g and h). The unblocking temperature of the high temperature component is 650°C, indicating that this component is carried by hematite.

## 5. Discussion

The stable remanence that decays to the origin resides essentially in magnetite and hematite. The site-mean directions of magnetite remanence (site 6; $D = 355.7°$, $I = 53.3°$ with $\alpha_{95} = 6.1°$) and hematite remanence (site 3; $D = 355.9°$, $I = 50.2°$ with $\alpha_{95} = 4.3°$) are drawn with those of the other five sites (Fig. 4a). The seven directions show northerly declinations with intermediate inclinations before tilt correction ($D = 349.8°$, $I = 47.5°$ with $\alpha_{95} = 6.8°$). These directions after tilt correction are northwesterly directions with shallow inclinations ($D = 327.5°$, $I = 6.8°$ with $\alpha_{95} = 10.9°$). Tilt correction reduces the precision parameter from 80.8 to 31.6. The fold test is negative at the 95% confidence level (McFadden, 1990). This ascertains that the directions of the sites 3 and 6 is of post-folding origin as well as the other directions. Although the all seven directions are indistinguishable within the 95% confidence limit, it should be noted that the confidence limits of the sites 3 and 6 are fairly small (Fig. 4a). The confidence limits of the sites 3 and 6 are 4.3° and 6.1° respectively, whereas those of the other sites range from 13.1° to 27.5°. This implies that the two directions of the sites 3 and 6 may not be attributed to a VRM but a ‘stable’ secondary magnetization. Since the post-folding nature of the remanent magnetization of the sites 3 and 6 is also confirmed by significant divergence between the two directions after tilt correction (angular distance from $3.3° \pm 7.5°$ to $23.0° \pm 7.5°$ by applying tilt correction), the stable secondary magnetization of the two sites logically postdates the folding age of Middle Triassic (Cluzel *et al.*, 1991).

To assign the remagnetization age, the directions of the sites 3 and 6 are compared with the paleomagnetic directions of Early Cretaceous and Tertiary times in Korea (Fig. 4b). The directions of the sites 3 and 6 are far apart from that of the Early Cretaceous ($D = 29.5°$, $I = 57.0°$ with $\alpha_{95} = 5.0°$; Lee *et al.*, 1987): the directions of the sites 3 and 6 show angular distances of $20.8° \pm 6.6°$ and $19.5° \pm 7.9°$ with respect to that of the Early Cretaceous, respectively. Furthermore, an another Early Cretaceous direction ($D = 50.2°$, $I = 62.0°$ with $\alpha_{95} = 5.4°$; Zhao *et al.*, 1999) is statistically indistinguishable from the remagnetized direction of Cretaceous age ($D = 58.8°$, $I = 55.5°$ with $\alpha_{95} = 5.1°$; Doh and Piper, 1994), whereas this Early Cretaceous direction is far apart from the observed remagnetized directions. To the contrary, the directions of the present study are in good agreement with that of the Tertiary derived from the Yeonil Group ($D = 1.7°$, $I = 50.4°$ with $\alpha_{95} = 3.6°$; Lee *et al.*, 1999) and the present Earth's field direction. The remagnetization age is, therefore, after the Early Cretaceous time. This post-Early Cretaceous timing of the remagnetization is also suggested by the facts that the direction of the Cretaceous remagnetization (Doh and Piper, 1994) is significantly distinguishable from the directions of the present study, and that the Tertiary remagnetized direction ($D = 175.3°$, $I = -58.9°$ with $\alpha_{95} = 5.3°$; Doh *et al.*, 1997) is statistically antiparallel to those of the present study. The remagnetized directions are uniformly of normal polarity. Since geomagnetic reversals are not observed from the remagnetized directions, the remagnetization may have occurred within a normal polarity chron. The normal polarity remanence in the sites 3 and 6 can be interpreted as a record of normal geomagnetic field in the Tertiary. A Tertiary paleomagnetic study revealed many sampling sites with a single normal polarity (Zheng *et al.*, 1991), suggesting that predominance of normal polarity seems likely in the two sites of the present study.

The process of the remagnetization has been approached from rock magnetic properties of hematite and magnetite, as will be shown below.

Approach from hematite: Many researches of the Pyeongan Supergroup have led to the conclusion that the secondary magnetization of hematite is carried by authigenic pigmental hematite (Otofuji *et al.*, 1989; Lee *et al.*, 1996; Doh *et al.*, 1997). According to Tauxe *et al.* (1990), pigmental hematite can be distinguished from specular hematite in terms of $H'_{cr}$ values: pigmental hematite is generally characterized by the value higher than 500 mT. An $H'_{cr}$ of the remagnetized sample from the site 3 was measured. A pigment-type test result has been obtained from the remagnetized sample (Fig. 5a). A back field ($H'_{cr}$) above 600 mT is required to destroy the IRM acquired at the maximum field of 2.7 T. This persistent behavior to the back field is interpreted as contribution of pigmental hematite, suggesting that the secondary magnetization of the site 3 is carried by pigmental hematite.

On the other hand, the same experiment was newly performed on a sample of primary magnetization from the

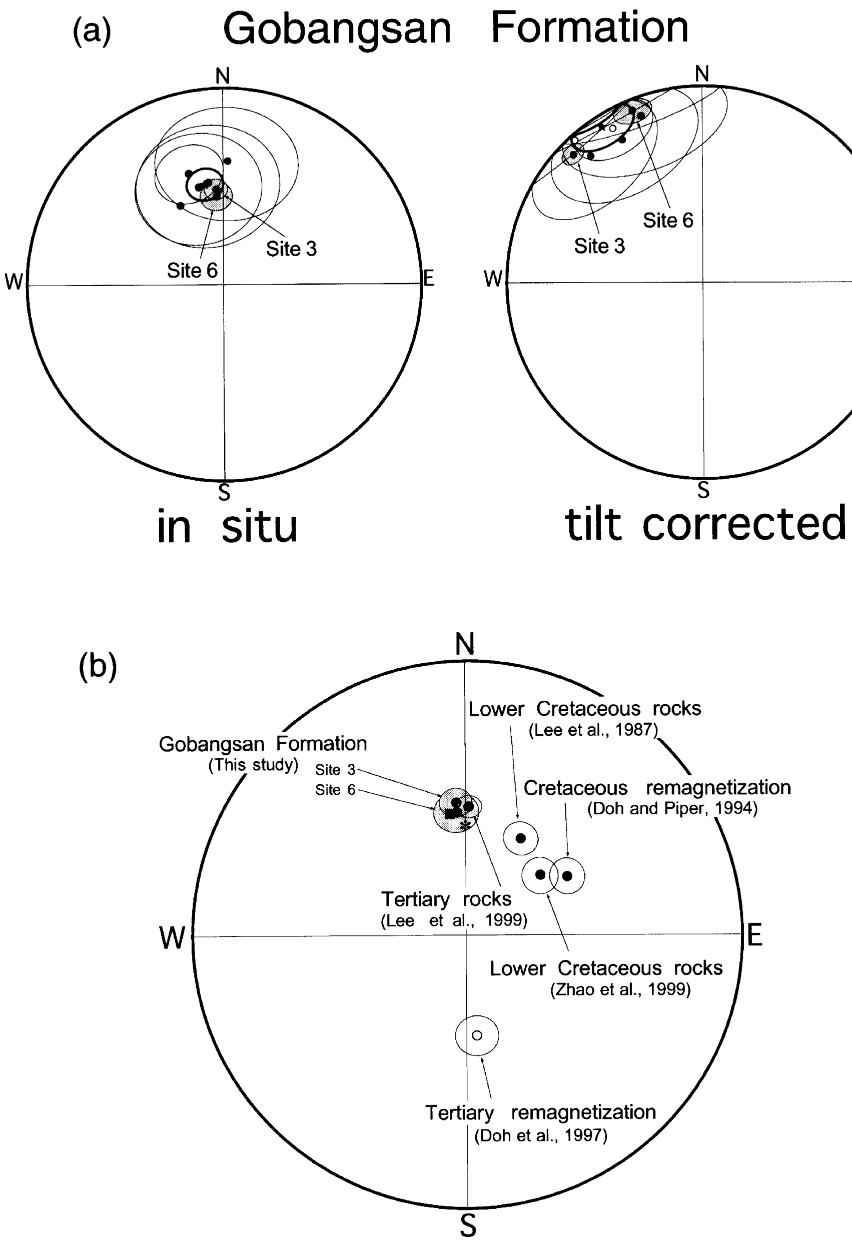


Fig. 4. (a) Equal area projections of the directions of the remanent magnetization components (with associated 95% confidence limits) from seven sites of the Gobangsan Formation. Star and thick circle represent the mean direction and associated 95% confidence limit, respectively. Site 7 has no confidence limit because of limited number of samples calculated (two samples). (b) Equal area projections of the primary and secondary directions between Cretaceous and Tertiary times (with associated 95% confidence limits) (Lee *et al.*, 1987; Doh and Piper, 1994; Doh *et al.*, 1997; Lee *et al.*, 1999; Zhao *et al.*, 1999). Solid square and asterisk represent the present Earth's field direction ($D = 352.3°$, $I = 53.3°$) and present axial dipole field direction ($D = 0.0°$, $I = 56.9°$), respectively.

Nogam Formation in the central part of the Bagjisan Syncline (Uno, 1999). This sample (from site SK8; Fig. 1d) yielded a hematite magnetization component with unblocking temperature of 680°C, and primary nature of this component is evidenced by the positive fold test (McFadden, 1990). In contrast to the remagnetized sample, a specular-type test result has been revealed from the sample of primary magnetization (Fig. 5b). The IRM acquired at 2.7 T shows abrupt decrease to the back field and destroyed by 150 mT. There is no evidence for presence of pigmental hematite, confirming that occurring of authigenic pigmental hematite is responsible for the secondary magnetization. The observed unblocking temperature of 650°C is lower by 30°C than the unblocking temperature of 680°C for hematite of primary magnetization (Uno, 1999). The lower unblocking temperature of hematite may give some implication for authigenic hematite: several authors have reported that authigenic pigmental hematite preferentially demagnetized at earlier stages of thermal demagnetization than detrital specular hematite of primary nature (Kim *et al.*, 1992; Lee *et al.*, 1996).

Approach from magnetite: Doh *et al.* (1997) have demonstrated that authigenic magnetite in the Pyeongan Supergroup also carries the stable secondary magnetization, which resides in both single-domain (SD)/pseudo-single domain

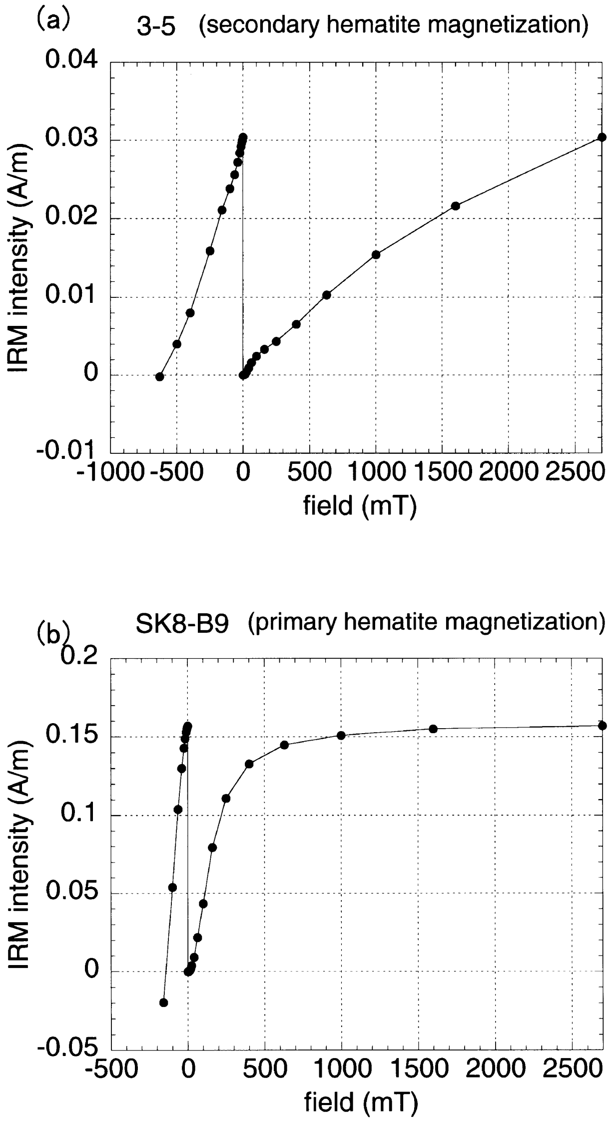


Fig. 5. IRM acquisition and back field plots for the samples from the sites 3 and SK8 in Uno (1999).

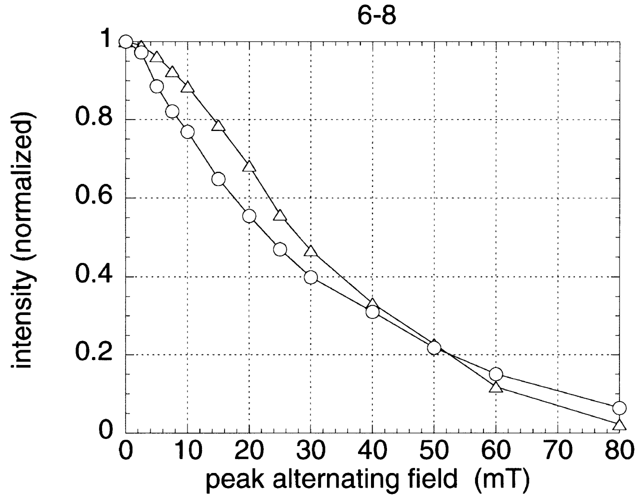


Fig. 6. The Lowrie-Fuller test result for the sample from the site 6. Circles and triangles show IRM and ARM, respectively.

(PSD) and multidomain (MD) magnetite ascertained by the Lowrie-Fuller test (Lowrie and Fuller, 1971). This test was performed on the sample from the site 6 in order to distinguish the domain state of magnetite. An SD/PSD-type test result has been observed (Fig. 6). ARM is more resistant to AF demagnetization than IRM at low to intermediate fields. The median destructive fields of ARM and IRM are about 28 mT and 23 mT, respectively. The remanence predominantly resides in SD or PSD magnetite.

The SD or PSD nature of magnetite gives a constraint for the process of the remagnetization. The relaxation time-blocking temperature relations of Pullaiah (1975) predict a remagnetizetion temperature above 550°C for SD magnetite if a thermoviscous remagnetization occurred for a few million years: I note the tendency for duration of normal polarity chrons since the Late Cretaceous as long as or less than a few million years (Cande and Kent, 1995). Assuming a mixture of SD and PSD grains, the relaxation time-blocking temperature relations of Middleton and Schmidt (1982) predict a remagnetization temperature of about 530°C. In either case, a thermoviscous remagnetization process requires a remagnetization temperature above 500°C. No thermal events of such temperature condition have been reported in the study area since the Late Cretaceous. Because the remagnetization timing postdates the Early Cretaceous time and because granite that intruded to the Bagjisan Syncline is of Jurassic age (Fig. 1d) (Reedman and Um, 1975), it is concluded that the Gobangsan Formation in the southeastern periphery had no opportunity to be heated by granitic emplacement. Therefore, a thermoviscous remagnetization can be ruled out.

An other possible process of remagnetization is a severe weathering in Recent time (Otofuji *et al.*, 1989). However, it is also considered to be unlikely because the secondary magnetization has been observed from both hematite and magnetite: Doh *et al.* (1999) claimed that a weathering process does not form hematite and magnetite at the same time. The stability of the observed paleomagnetic directions for the sites 3 and 6 (Fig. 4a) further ascertains that the secondary magnetization is not attributed to a Recent weathering, as suggested by Doh *et al.* (1999).

The experimental results that hematite is of authigenic origin and that magnetite is not ascribable to a thermoviscous remagnetization suggest that the most plausible mechanism of the remagnetization is a chemical authigenesis of secondary magnetic minerals. It is hard to assign the chemical remagnetization to a specific geological event after the Early Cretaceous, but there is no case for rejecting the hypothesis that the remagnetization is due to the chemical process, unlike the other possible processes of the remagnetization. Although the remagnetization can paleomagnetically have any age between the Late Cretaceous and Recent, I believe that the remagnetization occurred in the Tertiary because the remagnetized directions are identical to that of the Tertiary time and because a possibility of Recent remagnetization is denied by the stability of the remagnetized directions. An unresolved fluid migration might have permeated in the Tertiary along the fractured structures in the southeastern periphery in the Bagjisan Syncline: the Bagjisan Syncline has many faults and folds in its southeastern periphery and seems to have an opportunity to suffer a possible fluid migration. The Middle-Late Triassic faulting and folding in the southeastern periphery of the Bagjisan Syncline was not the direct cause of the remagnetization at that time, but this tectonic disturbance might be a cause that facilitated the remagnetization in the Tertiary time because of higher permeability in the rock bodies.

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