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The Early Tertiary chemical remagnetization in the Bakjisan Syncline, Korea: Its geotectonic implications

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Abstract

The Bakjisan Syncline is located in the northwestern part of the Taebaeksan Basin, Korea. New paleomagnetic data for the Upper Carboniferous–Lower Triassic Pyeongan Supergroup from the Pyeongchang area on the west limb of the Bakjisan Syncline have been obtained, and synthesized and compared with previous data from the Jeongseon area on the east limb of the syncline. A total of 350 specimens were collected from 21 sites to clarify the relationship between the spatial distribution of remagnetized areas and the thrust system in the Taebaeksan Basin. The characteristic remanent magnetization (ChRM) isolated from all samples was a remagnetized component acquired after tilting of the strata and carried by various magnetic minerals (magnetite, hematite and pyrrhotite). From rock magnetic studies, electron microscope observations and XRD analyses, the pervasive remagnetization is interpreted to be associated mainly with a fluid-mediated chemical remanent magnetization (CRM). This is consistent with the results of previous work in adjacent areas. The paleomagnetic pole position (88.3°E, 83.9°N, $A_{95} = 4.9°$) from the Pyeongan Supergroup in the Bakjisan Syncline indicates that the timing of the remagnetization event is Early Tertiary times (i.e. Paleocene to Eocene) by comparison with reliable paleopoles from the Korean Peninsula. Early Tertiary CRMs are also reported from previous studies of an adjacent region within the northwestern part of the Taebaeksan Basin. In contrast, a primary remanent magnetization was reported in the southeastern part of the Taebaeksan Basin. This implies that the major thrust system (the Gakdong thrust) which separates the two regions has caused them to experience substantially different geologic histories since deposition of the strata. Since many thrusts with NS trend are observed in the northwestern part of the Taebaeksan Basin compared with the southeastern region, it appears that the remagnetizing fluids pervasively penetrated the northwestern part of the basin by utilizing the already well-developed thrust system.

Keywords: Chemical remanent magnetization; Fluid; Paleomagnetism; Thrust; Remagnetization; Korea

1. Introduction

The Okcheon (or Ogcheon) Belt is a fold-and-thrust belt running diagonally (SW–NE) across the Korean Peninsula, and divides the peninsula into the Gyeonggi massif in the north from the Yeongnam massif in the south (Fig. 1a). The Okcheon Belt is divided into two parts: a metamorphosed southwestern subzone (the Okcheon metamorphic belt) and an unmetamor-

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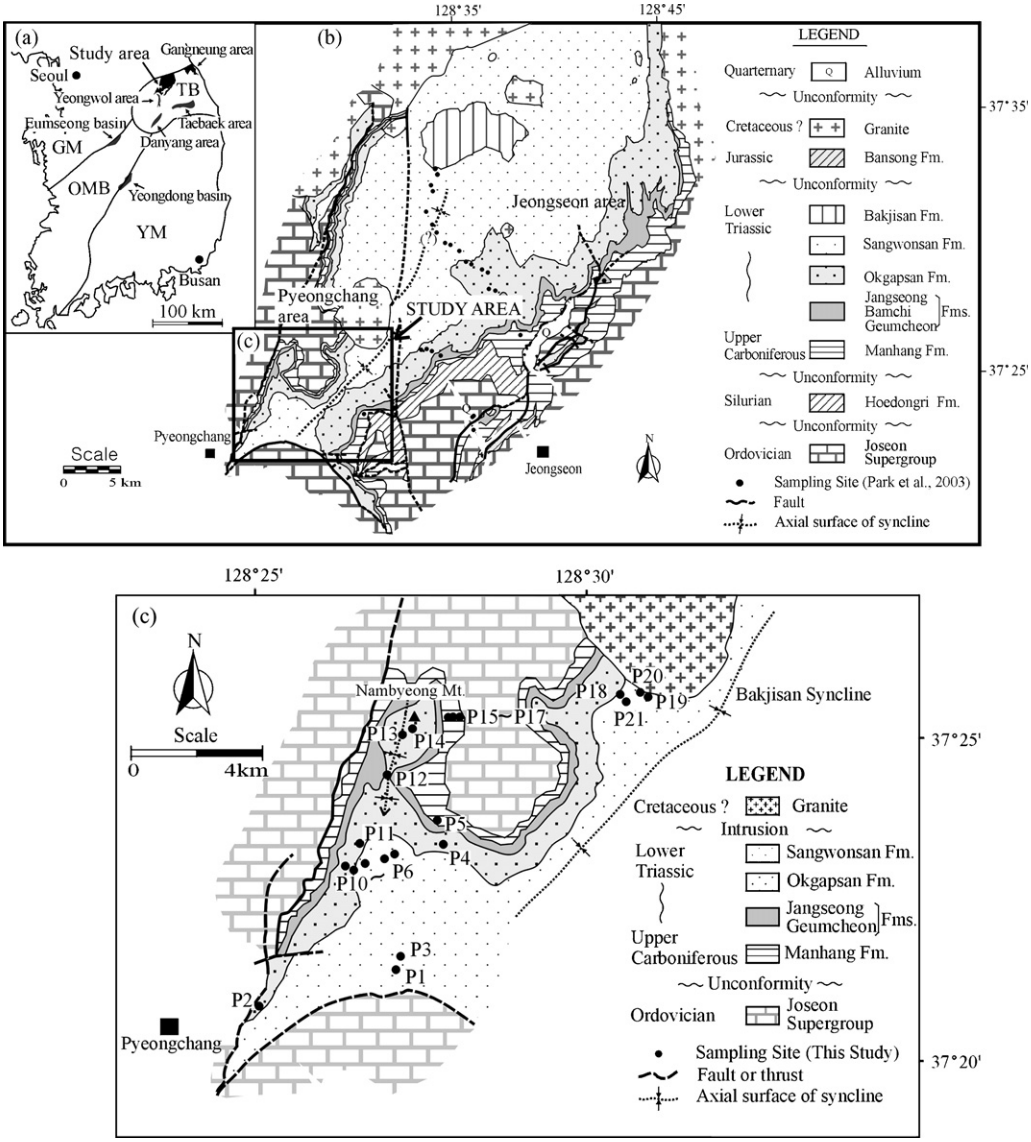

Fig. 1. (a) Tectonic map of the Korean Peninsula showing the distribution of the Pyeongan Supergroup in the northeastern part (the Taebaeksan Basin) of the Okcheon Belt. GM: Gyeonggi Massif; YM: Yeongnam Massif; OMB: Okcheon Metamorphic Belt; TB: Taebaeksan Basin. Remagnetized Cretaceous basins are also shown. (b) and (c) are geologic maps of the Bakjisan Syncline and Pyeongchang area, respectively (Korea Inst. Geol. and Min. Res., 1978).

phosed northeastern subzone (the Taebaeksan Basin). The occurrence of widespread Late Cretaceous–Early Tertiary secondary magnetizations in the Taebaeksan Basin has been well documented (Doh et al., 1997; Park et al., 2003). The remagnetizations in the unmetamorphosed Taebaeksan Basin cannot be related to metamorphic processes, and therefore must be associated with low temperature processes such as acquisition of thermoviscous remanent magnetization (TVRM) or chemical remanent magnetization (CRM). Although remagnetizations conceal partly or completely the primary magnetizations in pre-Cretaceous strata, the timing and process of the remagnetization can provide important insight into mineralization and geochemical process in the Taebaeksan Basin, and also into tectonic evolution of the Korean Peninsula and Eastern Asia. From this point of view, identifying the spatial distribution of the remagnetized areas and discriminating the remagnetization process between TVRM and CRM are essential.

Recently two paleomagnetic studies of the Jeongseon area on the east limb of the Bakjisan Syncline (Fig. 1b) yielded contrasting results. Uno (1999, 2000) considered that the central part of the Jeongseon area has retained primary magnetization, whilst the peripheral part of the syncline suffered remagnetization. However, Park et al. (2003) argued that all rocks in the Jeongseon area have been chemically remagnetized, and assumed that the CRMs in the Jeongseon area were imparted by the hydrothermal fluids triggered by the Late Cretaceous–Early Tertiary igneous activity in the Korean Peninsula. This study is a continuation of the research of Park et al. (2003) on the Jeongseon area in the Bakjisan Syncline which has aimed to verify whether the Pyeongchang area on the west limb of the Bakjisan Syncline was also remagnetized, and to show the relationship between the spatial distribution of remagnetized areas and the major structures, and especially the thrust system in the Taebaeksan Basin.

2. Geological setting

The Upper Carboniferous–Lower Triassic Pyeongan Supergroup is well exposed in the Taebaeksan Basin of the Okcheon Belt (Fig. 1a). The Bakjisan Syncline is located in the northwestern part of the Taebaeksan Basin and separates the Pyeongchang area to the west from the Jeongseon area to the east (Fig. 1b). The Pyeongan Supergroup in the Pyeongchang area is divided into five formations, ranging from the Upper Carboniferous Manhang Formation to the Lower Triassic Sangwonsan Formation (Fig. 1c), and its estimated thickness is about 2 km (Lee, 1988). It consists mainly of greenish gray siltstone, red beds, dark gray to black sandstone and shale, and calcareous siltstone with interbedded thin shale layers, coal beds and lenticular gray limestone beds. It generally overlies Middle Ordovician limestones disconformably (Lee, 1988). The stratigraphic scheme of the study area is identical to that in the Jeongseon area and the details are described in Park et al. (2003).

The dip directions of most formations in the Pyeongchang area are toward the south or southeast, and are controlled by a NE–SW trending open fold (the Bakjisan Syncline). The northern part of the study area is folded with N–S trending fold axis with a low angle of plunge (about 5°) to the south (Fig. 1c). Many faults and thrusts in the western and southern margins of the study area were formed during Middle–Late Triassic times and modified by later Jurassic deformation during the Daebo Orogeny (Lee, 1988; Cluzel, 1991). During Late Cretaceous–Early Tertiary times, N–S or NE–SW trending thrusts were reactivated as left-lateral strike-slip faults (Kim et al., 2001), and many hydrothermal veins and skarn deposits were formed in the Taebaeksan Basin (Park et al., 1988).

3. Methods

Samples were cored with a gasoline-powered portable rock drill and oriented with a Brunton compass at 21 sites comprising 4 sites in the Manhang Formation (P5, P15, P16 and P17), 8 sites in the Okgapsan Formation (P2, P4, P9, P10, P11, P12, P13 and P14), and 9 sites in the Sangwonsan Formation (P1, P3, P6, P7, P8, P18, P19, P20 and P21) (Fig. 1c). To determine the connection of the quartz veins, which are frequently observed in the study area, with remagnetization, several samples were collected within and around the quartz veins at three sites (P15, P16 and P20). Standard paleomagnetic specimens (2.2 cm length) were trimmed from each core to yield a total collection of 350 specimens. Natural remanent magnetizations (NRM) of the specimens were measured using a 2G three-axis cryogenic magnetometer and a Molspin spinner magnetometer and specimens were demagnetized by stepwise thermal or alternating field (AF) demagnetization. The paleomagnetic data from all specimens were projected on to orthogonal vector diagrams (Zijderveld, 1967) and the characteristic remanent magnetization (ChRM) directions of each component were determined using principal-component analysis (PCA) from three or more points (Kirschvink, 1980).

Detailed rock magnetic experiments, including thermal demagnetization of three-axes composite isothermal remanent magnetization (IRM), hysteresis parameter measurements (i.e. the Day plot, Day et al., 1977) and modified Lowrie–Fuller tests (Lowrie and Fuller, 1971; Johnson et al., 1975), were previously conducted on various rock type in the Jeongseon area (Park et al., 2003) and we have carried out further IRM acquisition experiments and the coercivity of remanence (H_{cr}) measurements to aid identification of magnetic mineralogies. The IRM acquisition experiments were performed by successively exposing selected specimens to increasing field of up to 1 T using an ASC Scientific impulse magnetizer and H_{cr} was determined from stepwise backfield measurements. To determine the degree of clay alteration, optical microscope observations and X-ray diffraction (XRD) analyses on clay fractions of selected samples were carried out. In addition, scanning electron microscope (SEM) observations were performed to confirm the characteristic size, shape and composition of magnetic carriers.

4. Paleomagnetic results

NRMs in the specimens vary from 0.02 to 354.12 mA/m in intensity, and show predominantly northerly positive directions. Among the total of 21 sites, 17 and

4 sites were subjected to progressive thermal and AF demagnetizations, respectively. Eight sites out of the 21 sites failed to yield ChRM components due to very weak intensities of magnetization.

Specimens in the study area show two different demagnetization behaviors depending on lithology rather than formation. Group 1 sites (P1, P3, P5, P9, P10, P11, P15 and P21) in gray sandstone and greenish

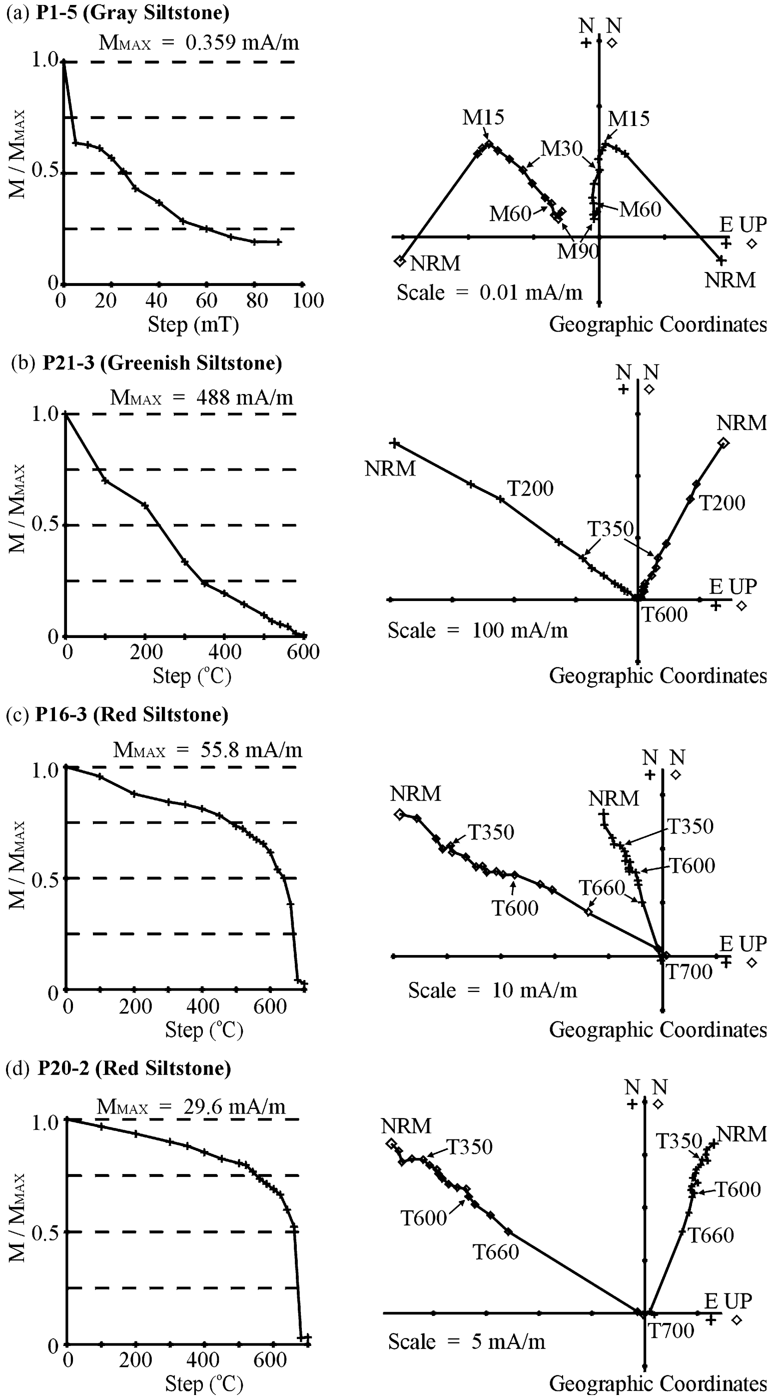

Fig. 2. Typical AF and thermal demagnetization results of samples from the study area: normalized intensity curve and Zijderveld diagram in geographic coordinates. Demagnetizing steps are also shown in the Zijderveld diagram (e.g. M15: AF demagnetization at field of 15 mT; T200: thermal demagnetization at 200 °C).

Table 1
Paleomagnetic results from the Pyeongan Supergroup in the Bakjisan Syncline

Site	n_u/n_m	Bedding		D_g (°)	I_g (°)	D_s (°)	I_s (°)	k	α_{95} (°)	VGP		dp (°)	dm (°)
		Strike (°)	Dip (°)							Longitude (°E)	Latitude (°N)		
Pyeongchang area (this study)													
Sangwonsan formation (128.29°E/37.25°N)													
P1	3/13	123	19	358.1	48.5	338.6	62.2	509.8	5.5	320.3	81.9	4.7	7.2
P3	14/20	113[a]	26[a]	10.3	55.7	339.2	79.9	67.2	4.9	223.1	81.7	5.0	7.0
P19	11/14	224	25	358.1	49.2	345.4	29.2	33.2	8.0	321.2	82.5	7.0	10.6
P20[b]	16/19	112	12	21.6	59.8	21.4	71.8	59.4	4.8	200.9	73.0	5.5	7.2
P21[c]	11/16	110	32	312.7	4.8	307.1	16.0	23.2	9.7	11.2	34.3	4.9	9.7
Okgapsan formation (128.26°E/37.23°N)													
P2	9/11	54[a]	81[a]	0.5	57.6	121.4	34.3	47.8	7.5	152.6	89.0	8.1	11.0
P9	7/15	33	18	345.3	48.8	5.6	60.1	36.0	10.2	10.7	75.6	8.9	13.4
P10	14/17	61[a]	36[a]	350.5	59.3	93.4	78.4	25.7	8.0	61.5	82.1	9.0	12.0
P11	16/16	67	26	4.9	72.7	119.9	76.7	112.1	3.5	135.7	69.1	5.4	6.0
Manhang formation (128.28°E/37.25°N)													
P5	6/17	320	10	351.7	67.1	7.5	60.6	26.0	13.4	105.4	76.2	18.4	22.2
P15[b]	16/19	235	7	335.6	55.7	334.1	49.2	32.3	6.6	42.5	70.5	6.8	9.4
P16[b]	8/14	193	16	349.4	63.6	327.3	54.3	48.6	8.0	86.2	78.9	10.0	12.7
P17	7/16	193	20	339.8	48.6	325.8	35.5	62.8	7.7	19.3	71.5	6.7	10.1
Mean	$N_u/N_m = 12/13$			354.7	57.8			59.7	5.7	65.5	85.7	$K = 36.3$	
						357.4	68.0	7.2	17.4			$A_{95} = 7.3$	
Jeongseon area (Park et al., 2003)													
Mean	$N_u = 17$			354.9	61.5			58.0	4.7	97.3	82.4	$K = 28.2$	
						345.3	38.4	4.8	18.2			$A_{95} = 6.8$	
Bakjisan Syncline (Pyeongchang + Jeongseon)													
Mean	$N_u/N_m = 29/30$			354.8	60.0			59.0	3.5	88.3	83.9	$K = 31.4$	
						348.5	51.4	4.9	13.5			$A_{95} = 4.9$	

n_u/n_m, number of samples used in average/measured; D_g and I_g, declination and inclination in geographic coordinates; D_s and I_s, declination and inclination in stratigraphic coordinates; k, Fisherian precision parameter; α_{95}, radius of cone of 95% confidence; 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; N_u/N_m, number of sites used in average/measured; 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.

[a] Average bedding plane.

[b] Sampling sites around quartz veins.

[c] Site-mean omitted in calculation of formation mean direction (see text for explanation).

siltstone show low coercivity/temperature components removed below 15 mT or 200 °C to recover a characteristic component with NNE and moderate down direction isolated mainly in the 30–80 mT or 300–580 °C range (Fig. 2a and b). Group 2 sites (P16, P17 and P20) in red beds also show two components of magnetization (Fig. 2c and d). The low temperature component is removed below 350 °C, followed by a high temperature component of NNW–NNE declination and moderately steep down inclination unblocked in the temperature range 600–680 °C. The low coercivity/temperature component is interpreted as a recent viscous remanent magnetization (VRM). Directions of characteristic components within sites are relatively well grouped (i.e. $\alpha_{95} \leq 13.4°$) (Table 1).

Specimens from site P21 show stable ChRM directions carried by magnetite and isolated during the thermal demagnetizations (Fig. 2b) which are well clustered ($\alpha_{95} = 9.7°$). However, the ChRM directions of the site P21 show anomalously shallow inclination compared with those of the other sites (Fig. 3 and Table 1). Therefore we have excluded site P21 site-mean from the group mean calculation. The mean direction of the ChRM calculated from 12 site-mean directions excluding P21 is $D/I = 354.7°/57.8°$ ($k = 59.7$, $\alpha_{95} = 5.7°$) in geographic coordinates and $D/I = 357.6°/68.0°$ ($k = 7.2$, $\alpha_{95} = 17.4°$) in stratigraphic coordinates (Table 1). The site-mean directions in stratigraphic coordinates are more dispersed than those in geographic coordinates, and yield a negative regional tilt test at the 95% confidence level (Table 1). The mean paleomagnetic directions of the Pyeongchang area in geographic coordinates (west limb of the Bakjisan Syncline) agree fairly well with those of the Jeongseon area (east limb of the syncline) as reported by Park et al. (2003) and we have calculated a combined result incorporating data from both limbs (Fig. 3 and Table 1). The combined paleomagnetic direction of the Bakjisan Syncline is $D/I = 354.8°/60.0°$ ($k = 59.0$, $\alpha_{95} = 3.5°$) in geographic coordinates and $D/I = 348.5°/51.4°$ ($k = 4.9$, $\alpha_{95} = 13.5°$) in stratigraphic coordinates. The parameter estimating the quality of the tilt test (Watson and Enkin, 1993) for the combined data yields a maximum k value at 0.7% untilting at the 95% confidence level from −2.9 to 4.6% untilting, when the number of parametric resampling is 1000 and the circular standard deviation of bedding planes is 52.8 (Fig. 4a). The direction-correction (DC) tilt test (Enkin, 2003) also yields a negative result (DC slope = 0.015 ± 0.064) (Fig. 4b), which accords well with the result of the parameter estimating tilt test. Collectively these results strongly indicate that rocks in the Bakjisan Syncline acquired their ChRMs after tilting of the strata.

5. Rock magnetism, XRD analyses, and SEM observations

Previous detailed rock magnetic data from the Pyeongan Supergroup in the Jeongseon area reveal that the major magnetic carriers of ChRM in the red beds, greenish gray siltstones and black shales are, respectively, hematite, magnetite and a coexistence of goethite and pyrrhotite/magnetite (Park et al., 2003). In the Pyeongchang area, however, black shales show unstable demagnetization behaviors and do not retain a ChRM component. IRM acquisition curves (Fig. 5) and H_{cr} values (Table 2) of selected samples from the

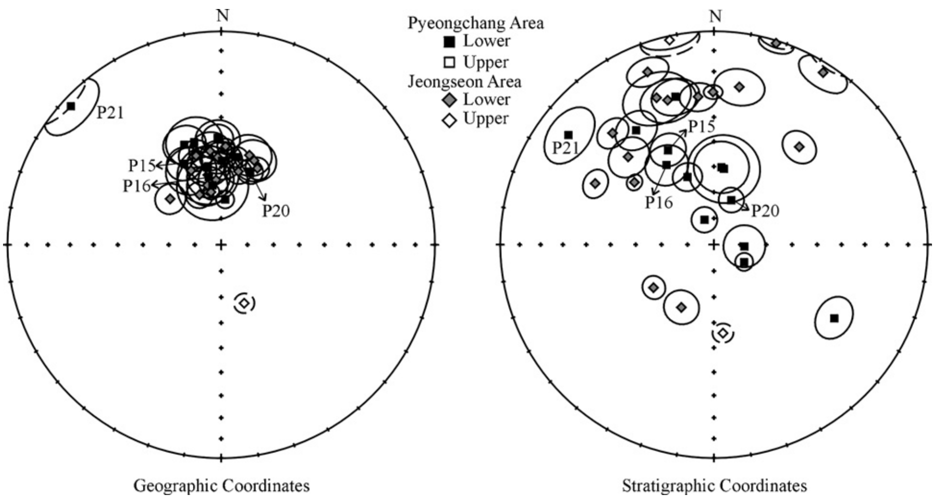

Fig. 3. Equal area projections of site-mean directions from the Pyeongchang (this study) and Jeongseon (Park et al., 2003) areas with 95% confidence circles before and after adjustment for tilt.

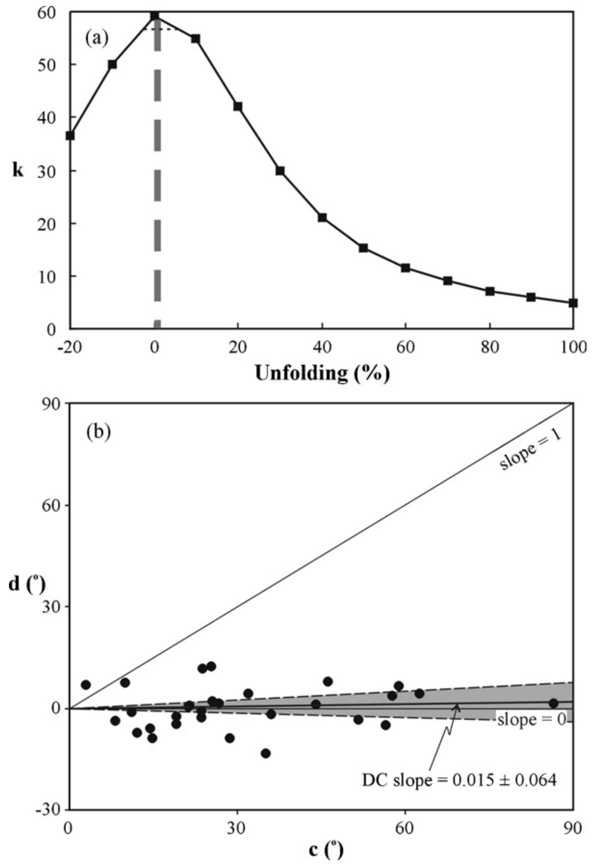

Fig. 4. (a) Stepwise untilting tests plotting Fisher's precision parameter (k) vs. percent untilting for the Bakjisan Syncline (the combined data from Pyeongchang area with those from Jeongseon area). The result of parameter estimating tilt test (Watson and Enkin, 1993) is also shown: the vertical thick dashed line denotes the best grouping untilting position and the horizontal thin dashed line shows the error bar for the tilt test. (b) The direction-correction (DC) tilt test (Enkin, 2003) for the combined data of the Bakjisan Syncline. c: Angle between the mean in geographic coordinates and the back correction of the mean in stratigraphic coordinates; d: angular separation between the mean in geographic coordinates and the site direction projection onto the circle connecting the mean and the back correction.

Pyeongchang area can be grouped into three types: a canted-antiferromagnetic dominant mineral (type 1), a ferrimagnetic dominant mineral (type 2) and a mixture of ferrimagnetic and canted-antiferromagnetic minerals (type 3). Rock magnetic results combined with thermal demagnetization behaviors (unblocking temperature) have been used to resolve the magnetic mineralogies of the samples. Samples from red beds have H_{cr} above 415.3 mT and unblocking temperatures up to 680 °C, indicating that the canted-antiferromagnets in red beds are hematite (type 1). Samples from the greenish siltstone and gray sandstone have H_{cr} values in the range 36.0–209.7 mT and maximum unblocking temperatures

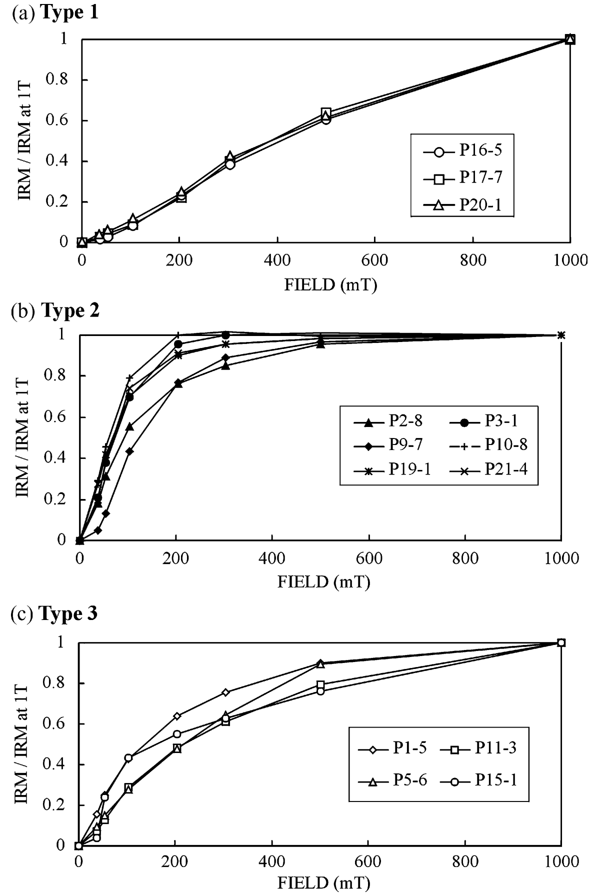

Fig. 5. IRM acquisition curves for samples showing (a) type 1, (b) type 2 and (c) type 3 behaviors.

of 580 °C, indicating that magnetite is the major magnetic carrier (type 2 and type 3). Type 2 samples show little influence of canted-antiferromagnetism, while type 3 samples show increasing H_{cr} values as the influence of

Table 2
Coercivity of remanence (H_{cr}) of selected samples

Type	No.	H_{cr} (mT)	Formation	Rock type
Type 1	P16-5	516.83	Manhang	Red siltstone
	P17-7	415.27	Manhang	Red siltstone
	P20-3	426.45	Sangwonsan	Red siltstone
Type 2	P2-8	75.89	Okgapsan	Gray sandstone
	P3-1	48.36	Sangwonsan	Greenish siltstone
	P9-7	103.89	Okgapsan	Greenish siltstone
	P10-8	40.00	Okgapsan	Greenish siltstone
	P19-1	47.57	Sangwonsan	Greenish siltstone
	P21-4	35.97	Sangwonsan	Greenish siltstone
Type 3	P1-5	127.77	Sangwonsan	Gray siltstone
	P5-6	209.66	Manhang	Gray sandstone
	P11-3	195.77	Sangwonsan	Greenish siltstone
	P15-1	139.87	Manhang	Greenish siltstone

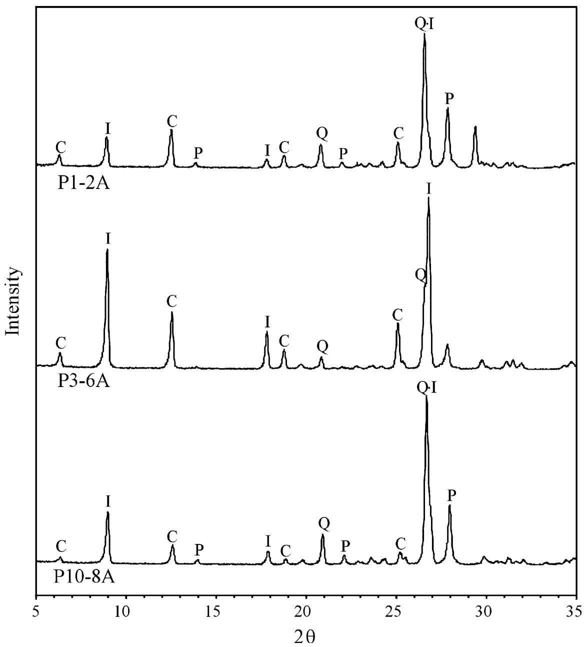

Fig. 6. Representative XRD patterns of air-dried powder specimens of <2 μm fractions of siltstone from the study area. C: Chlorite; I: illite; P: plagioclase; Q: quartz.

hematite or goethite increases (Table 2). Therefore, we consider that the remagnetized component is recorded mainly by both hematite and magnetite in the Bakjisan Syncline (Jeongseon and Pyeongchang areas), although goethite and pyrrhotite are also magnetic carriers of the remagnetized component in some samples of black shales from the Jeongseon area.

XRD analyses were performed on air-dried powder specimens of <2 μm fractions of selected samples of siltstone and sandstone to determine the clay mineralogy (Fig. 6). The XRD patterns show that illite and chlorite are the dominant clays, while kaolinite and smectite are minor or absent, indicating that significant alteration in the form of illitization and chloritization has occurred in rocks of the study area. Optical microscopy of greenish siltstones at site P15 shows that illites are mainly distributed along the boundaries of quartz grains (Fig. 7a). Evidence for significant alteration of the host rock (e.g. alteration of rock fragment and feldspar) directly due to vein-forming fluids around quartz veins is rarely observed by microscopic observation (Fig. 7b). Fig. 7c is an example of newly formed carbonates accompanied by illites growing within a quartz vein and indicat-

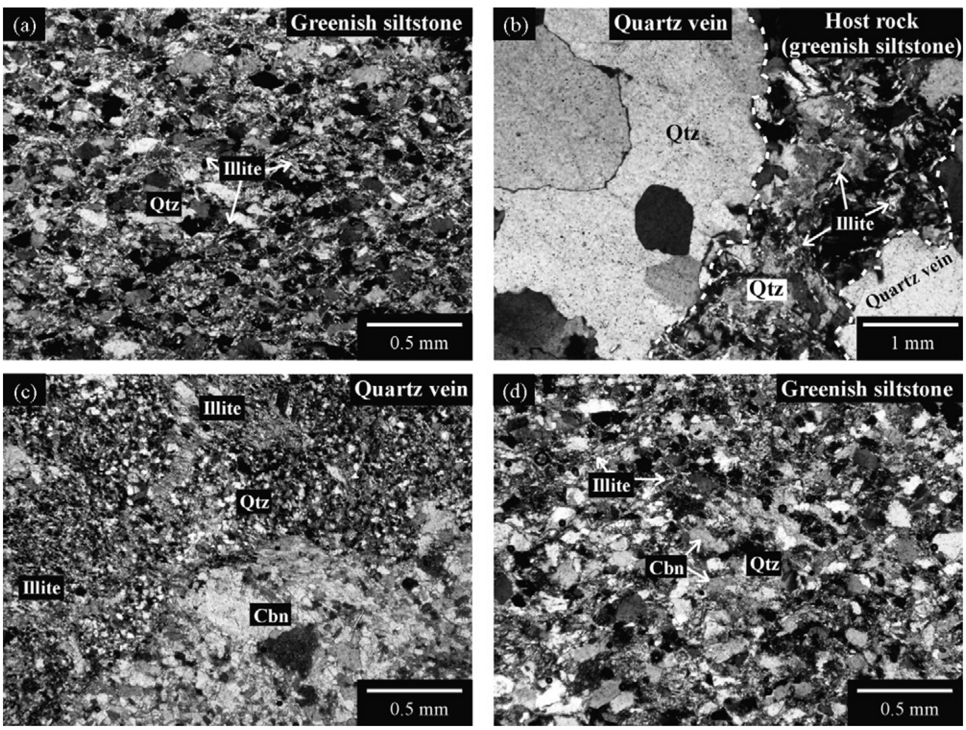

Fig. 7. Transmitted light optical microscope images with crossed nicols of selected samples from site 15. (a) A thin section of the host rock (greenish siltstone) located far from the quartz veins, showing illites distributed along the boundaries of quartz (Qtz) grains. (b) A thin section showing the contact boundary between quartz vein and host rock (greenish siltstone). Dashed lines shown in (b) indicate the boundary between the veins and the host rocks. (c) A thin section of the quartz vein, showing that carbonates (Cbn) and illites postdate the quartz grains. (d) A thin section of the host rock (greenish siltstone), showing that carbonates and illites are enclosing quartz grains or distributed along the grain boundaries.

ing that precipitation of carbonates and illites occurred after formation of the quartz vein. We assume that precipitation of illites occurred at relatively higher temperature and followed by precipitation of carbonates at lower temperature but they were resulted from a single fluid-related event. Carbonates and illites enclosing quartz grains are also frequently observed in host rocks located far from the quartz veins (Fig. 7d) and optical microscopy suggests that pervasive infiltration of carbon-rich hydrothermal fluids has occurred after precipitation of quartz veins in the studied rocks.

Electron microscopic observations were carried out on representative samples of red and greenish siltstones. To identify the magnetic carriers and their relationship to adjacent grains or matrix, compositional analyses using an energy dispersive X-ray spectrometry (EDS) system were performed. Iron oxides, which are assumed to be hematites based on the rock magnetic results and thermal demagnetization behaviors, are frequently observed in association with quartz, K-feldspar and clay minerals in samples of red siltstone. Grain sizes vary from submicron sizes up to 25 μm. Some pure iron oxides fill pore spaces or are interlocked with adjacent quartz and chlorite grains (Fig. 8a), whereas others occur as void-filling single grains (Fig. 8b). Importantly, some grains of iron oxide were observed to contain quartz inclusions as shown in Fig. 8b, implying that the iron oxide is a younger phase than the inclusions (Suk et al., 1990). In samples of greenish siltstone, pure iron oxide grains of 1–10 μm in size fill micro-cracks (Fig. 8c). Iron oxide grains enclosing K-feldspar grains are also observed (Fig. 8d). Such results of electron microscopic observations suggest that these ferromagnetic grains in the studied rocks are secondary in origin. Significant amount of altered clay minerals are found around the presumably authigenic iron oxides and indicate that pure iron oxides are formed by precipitation from Fe-bearing fluids. The Fe is enriched in these fluids by processes of alteration of Fe-bearing minerals to clays (Walker et al., 1981). Although authigenic pure iron oxides are predominant ferromagnetic grains in the studied rocks, detrital Fe–Ti oxide grains of relatively large size (up to 30 μm) are rarely observed in a sample of greenish siltstone (large grains in the upper and lower corners of right side of Fig. 8c).

The results of the XRD analysis and optical/electron microscopic observations in this study are similar to those from the Jeongseon area (Park et al., 2003), and support the interpretation that the remagnetization resulted from acquisition of a CRM when new magnetic minerals (magnetite and hematite) formed long after sedimentation and during diagenesis at low temperatures.

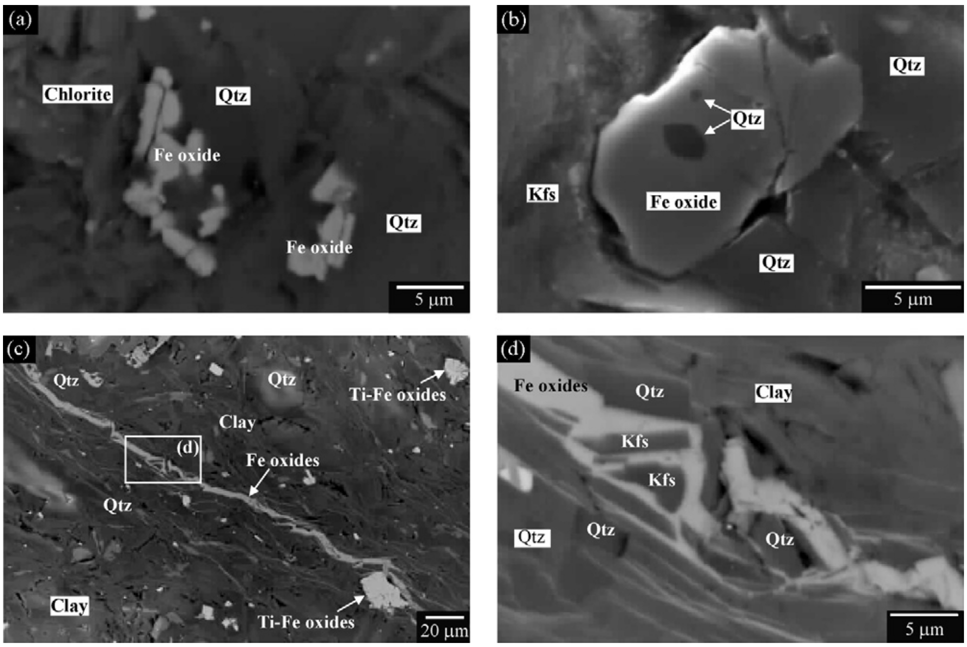

Fig. 8. Scanning electron microscopy photographs of samples from red siltstone (a and b) and greenish siltstone (c and d). Qtz: quartz; Kfs: K-feldspar. (a) Back-scattered electron image (BEI) of authigenic iron oxide (hematite) grains filling pore spaces between adjacent quartz and chlorite grains. (b) Secondary electron image (SEI) of an iron oxide containing quartz inclusions. (c) BEI of authigenic iron oxides formed along micro-crack. Also, detrital Ti-bearing iron oxides are shown on the upper and lower right corners. (d) Enlarged BEI of the square in (c) shows K-feldspar inclusions.

6. Discussion and conclusions

6.1. Process of the chemical remagnetization in the Bakjisan Syncline

Pervasive remagnetization processes at low temperature and unrelated to metamorphism are generally assigned to a TVRM (Kent, 1985; Jackson, 1990) or a CRM origin (McCabe et al., 1983). It is also reported that stress can reset magnetizations carried by magnetite and hematite in rocks during deformation (Borradaile, 1992, 1994a,b, 1996). However, a stress-induced remagnetization seems unlikely because major deformation (e.g. folding and thrusting) of the studied rocks occurred during Middle–Late Triassic and Jurassic times (Lee, 1988). Park et al. (2003) suggested that the Late Cretaceous–Early Tertiary remagnetization in the eastern limb of the Bakjisan Syncline (Jeongseon area) was a CRM rather than a TVRM, based mainly on three observations: (1) the consistency of both magnetite and hematite component directions, (2) the observation of authigenic magnetic minerals and (3) the low estimated paleotemperature (340 °C) in the Bakjisan Syncline (Park et al., 1988; Park and Park, 1990; Park and Hwang, 1992). CRMs are thought to be acquired in association with various fluids by processes that have been proposed to include: (i) the lateral migration of orogenic/basinal fluids (Oliver, 1986), (ii) the introduction of meteoric or magmatic fluids (Hagstrum and Johnson, 1986) and (iii) the in situ precipitation of pore waters released by tectonic pressure (Elmore et al., 1993). CRMs can be also acquired by burial diagenesis leading to clay alteration (Katz et al., 2000) and maturation of organic matter (Banerjee et al., 1997).

The formation of CRMs by burial diagenesis in this case is unlikely because the Pyeongan Supergroup in the Bakjisan Syncline was not buried to depths (i.e. more than 2 km) deep enough to cause burial diagenesis and remagnetization during the Late Cretaceous to Tertiary (Lee, 1988). In addition, reported K–Ar age dates from hydrothermal vein deposits (94–52 Ma, Park et al., 1988, 1992; Park and Park, 1990; Park and Hwang, 1992) and from rhyolite and quartz porphyry volcanics (67–56 Ma, Shin and Jin, 1995) within the Taebaeksan Basin imply that the fluid-mediated processes and igneous activity occurred during the Late Cretaceous to Early Tertiary. Thus, acquisition of CRMs in the Pyeongan Supergroup of the study area could have been associated mainly with fluid-mediating processes and igneous activity rather than with burial diagenesis; such an interpretation is supported by the electron microscope observations of this study (Fig. 8).

Hur and Park (2000) report hydrogen and oxygen isotope compositions of hydrothermal fluids from the Shinjeongseon and Sinch mines near the study area and suggest that the mineralizing fluids were of mixed magmatic (dominant)–meteoric origin. Hence, we tentatively interpret the CRMs observed in this study as related to mixed magmatic–meteoric fluids which formed many of the hydrothermal vein deposits in the study area.

A large number of quartz veins with various widths (several millimetres to tens of centimetres) are observed at outcrop and we have sampled cores at varying distances from these veins to determine whether paleomagnetic directions change with distance from the veins at three localities (sites P15, P16 and P20). Such a test could provide evidence for the influence of vein-forming fluids on remagnetization (i.e. a contact vein test, after Elmore et al., 1993). Because specimens cored from the quartz veins show very weak NRM intensities and unstable demagnetization behavior, we used specimens cored from the host rock at various distances (0–10 m) from the quartz veins for within-site comparison of paleomagnetic directions at these sites. Within each site, the paleomagnetic directions cluster well in geographic coordinates ($\alpha_{95} = 4.8$–$8.0°$) (Table 1), but do not show significant variation with the distance from the veins. In addition, site-mean directions of sites P15, P16 and P20 in geographic coordinates, which are sited where large numbers of quartz veins are observed, do not deviate significantly from those of other sites with little or no veining (Fig. 3). Since the contact vein tests apparently indicate no direct connection between CRMs and the spatial distribution of quartz veins, there seem to be two possibilities: (1) vein-forming fluids penetrated pervasively into the host country rocks causing remagnetization in the study area, and/or (2) remagnetization of rocks both near and far from the quartz veins occurred in association with new mineralizing fluid influx after formation of the veins.

Most sets of the quartz veins in more porous coarse sandstones show random orientations, while those in siltstones and shales crystallized along the more permeable bedding planes, implying that influx of vein-forming fluids into the host rocks was controlled by porosity and permeability of the rocks. The fluid-pressures in the veins, in which quartz formed by precipitation from fluids, should have been equivalent to, or higher than, the load-pressures on the rocks (Pollard and Segall, 1987). Hence previous workers (Ryu et al., 1999) have considered that the remaining pore-filling fluids under high fluid-pressures might form many of the fissures and veins within the Pyeongan Supergroup in the Taebaeksan Basin. The above arguments collectively imply that vein-forming fluids could pervasively circulate through the host rock resulting in the formation of veins and causing remagnetization. In contrast, however, no evidence for significant alteration of the host rocks around the veins in the outcrops has been observed in the field or by the microscopic observations. Instead, the occurrence of carbonates, both in quartz veins and host country rocks, suggests the pervasive and widespread influx of another mineralizing fluid into the study area after formation of the quartz veins (Fig. 7). From the present evidence, we can only conclude that the remagnetization is mainly due to fluid-mediated processes and are unable to clarify the nature of the remagnetizing fluids. Further investigations incorporating isotopic and fluid inclusion studies on the host country rocks and hydrothermal vein deposits should help to amplify this conclusion.

6.2. *Timing of the remagnetization in the Bakjisan Syncline and its tectonic implications*

The paleomagnetic pole position calculated from the remagnetized component in the Bakjisan Syncline is at 83.9°N, 88.3°E (A_{95} = 4.9°) (Table 1). This paleomagnetic pole position is far from Cretaceous paleopoles recently established from reliable paleomagnetic data sets in Korea (Park et al., 2005) and indicates that remagnetization occurred after the Late Cretaceous (Fig. 9a). The paleopole of the remagnetized component is also statistically distinguishable from the Korean Miocene pole at the 5% significance level. The lack of any significant Quaternary orogeny or igneous activity in the Korean Peninsula suggests that post-Miocene remagnetization is unlikely. From the observation of many hydrothermal vein deposits and igneous activity dated as Late Cretaceous to Early Tertiary (94–52 Ma), the timing of the remagnetization can be constrained to Early Tertiary (i.e. Paleocene to Eocene) times.

The paleomagnetic poles of middle Early Cretaceous to Miocene age from Korea plot along a small circle centered at the study area and indicate that the Korean Peninsula was located at similar latitude to the present position, although subject to clockwise rotation about a vertical axis during the Cretaceous (Fig. 9a). The Cretaceous clockwise rotation of the Korean Peninsula with respect to the adjacent blocks has been reported by several recent paleomagnetic studies (e.g. Zhao et al., 1999; Uno, 2000; Doh et al., 2002; Park et al., 2005). Park et al. (2005) suggested that the clockwise rotation of the Korean Peninsula ceased after the Cretaceous Period. Hence remagnetization in the study area appears to have occurred after the clockwise rotation of the Korean Peninsula.

Fluid-mediated CRMs are also observed in several areas within the Okcheon Belt including the Jeongseon area (Park et al., 2003), the Yeongwol area (Doh et al., 1997), the Eumseong Basin (Doh et al., 1999) and the Yeongdong Basin (Doh et al., 1996) (Fig. 1a). Park et al. (2003) suggested that remagnetizing fluid migration propagated northward or northeastward within and along the boundaries of the Okcheon Belt until early Tertiary times, based on the discrepancy between paleomagnetic pole positions calculated from the remagnetized component in the Yeongdong Basin and those in the Jeongseon, Yeongwol and Eumseong areas. Paleomagnetic pole positions of both remagnetized and unremagnetized rocks from the Okcheon Belt are plotted in Fig. 9b. The paleomagnetic poles of the remagnetized rocks fill a gap in the apparent polar wander path (APWP) of the Korean Peninsula where reliable poles for the period between the Late Cretaceous and the Miocene are otherwise absent. Moreover, these poles plot along a hairpin-curved path which obviously deviates from the trajectory of the APWP of the Korean Peninsula between the middle Early Cretaceous and the Miocene (Fig. 9a and b). The paleomagnetic pole of the Yeongdong Basin is closer to Late Cretaceous paleopoles than those of the other areas on the Korean hairpin-curved APWP (Fig. 9b), indicating that chemical remagnetization in the Yeongdong Basin predates the CRMs in the other areas. This result agrees well with the fluid-migration model suggested by Park et al. (2003) and with the timing constraint on the remagnetization in this study.

It is observed that paleopoles from the remagnetized component form a hairpin-curved portion of the middle Early Cretaceous to Miocene APWP of the Korean Peninsula (Fig. 9a and b). The paleolatitude calculated from the remagnetized component in the study area (Bakjisan Syncline) is about 41°N, which is slightly higher than Cretaceous and Miocene paleolatitudes and the present latitude (37–38°N). Although the latitude difference discussed here is very small, it is noteworthy that the inclination is steeper and not shallower than expected because inclination shallowing is widely observed in Mesozoic-Tertiary sedimentary rocks in central China (e.g. Dupont-Nivet et al., 2002; Gilder et al., 2003; Tan et al., 2003; Huang et al., 2004). Hence, this result indicates that the Korean Peninsula, including the study area, may have experienced latitudinal movement during the Early Tertiary. One plausible explanation for such latitudinal movement might be found by comparing the APWP of Korea with that of Eurasia, where it is observed that the Korean APWP, including the paleopoles of remagnetized component, is similar to the tight hairpin-curved APWP of Eurasia at about 50 Ma (Fig. 9a). Since changes in

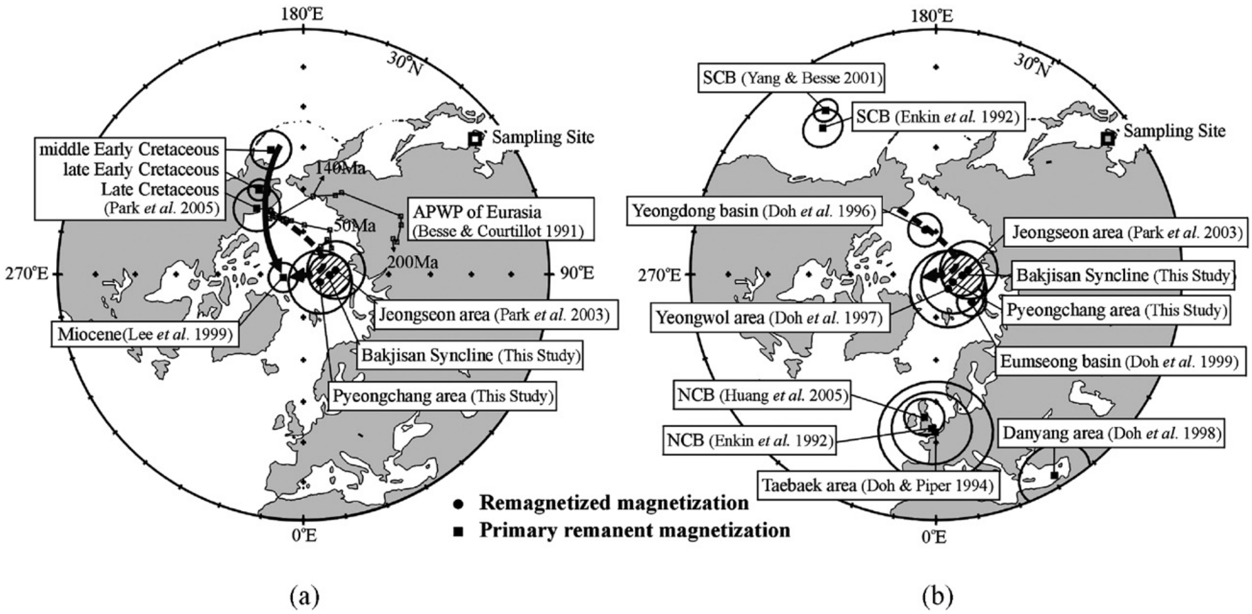

Fig. 9. (a) Paleomagnetic poles calculated from the remagnetized component of the Pyeongan Supergroup in the Bakjisan Syncline compared to the middle Early Cretaceous to Miocene paleopoles obtained in Korea. The apparent polar wander path (APWP) of Eurasia since 200 Ma (Besse and Courtillot, 1991) is also shown for the comparison. (b) Paleomagnetic poles of remagnetized areas (Bakjisan Syncline, Yeongwol area, Eumseong Basin and Yeongdong Basin) shows that the remagnetization in the Yeongdong Basin possibly predates to that in the other areas. Early Triassic paleopoles obtained from unremagnetized areas (Taebaek and Danyang areas) within the Taebaeksan Basin are also shown as solid squares for the comparison with those of the North China Block (NCB) and the South China Block (SCB) (see ref. Doh and Piper, 1994; Doh et al., 1998; Lee et al., 1999).

APW direction are the signature of change in Euler pole of rotation of the continent, the cusps in APW paths have been attributed to continental collision or break-up (Irving and McGlynn, 1981; Evans, 2003). The continental collision between India and Asia is a possible tectonic event that could have caused the hairpin-curved APWP of Eurasia and the Korean Peninsula at about 50 Ma. This collision may, in turn, have been responsible for latitudinal movement of the Korean Peninsula during the Early Tertiary suggested by the small paleolatitude discrepancy noted above.

6.3. Spatial distribution of remagnetized and unremagnetized areas in the Taebaeksan Basin and its implications

The distribution of remagnetized and unremagnetized areas in the Taebaeksan Basin is shown in Fig. 10b. Complete remagnetization occurred in the northwestern part (Yeongwol, Jeongseon and Pyeongchang areas) of the basin, whereas the primary remanent magnetization has been retained in the southeastern part (Taebaek and Danyang areas). This aspect is consistent with the classical concept of bioprovinces in the Taebaeksan Basin. From paleontologic study of the early Paleozoic Joseon Supergroup of the Taebaeksan Basin (Kobayashi, 1953), the Supergroup has been divided into the Duwibong-type sequence with North China Cambrian biofacies to the east and the Yeongwol-type sequence with Yangtze (South China) Cambrian biofacies to the west. The presumable boundary between these two sequences is the Gakdong thrust (Choi, 1998, Fig. 10b). The Gakdong thrust has been proposed as an extension of the strike-slip shear belt between the North China Block (NCB) and the Yangtze Craton (the South China Block, SCB) (Cluzel et al., 1991). The significant difference of paleontologic facies between the southeastern and northwestern sides of the Gakdong thrust is also observed in the late Paleozoic Pyeongan Supergroup as well as in the early Paleozoic Joseon Supergroup (Cheong, 1982). Cheong (1982) found Sakmarian fusulinids only on the northwestern side of the Gakdong thrust, indicating that a hiatus occurred during the Sakmarian on the southeastern side of the thrust. He also noted that structural trends in the northwestern region have a NS direction, while those in the southeastern region trend NE–SW and ENE–WSW. Choi et al. (1992) further showed that the fossil assemblages and directions of deformation of each side are quite different, and argued that the northwestern region could have experienced much stronger structural

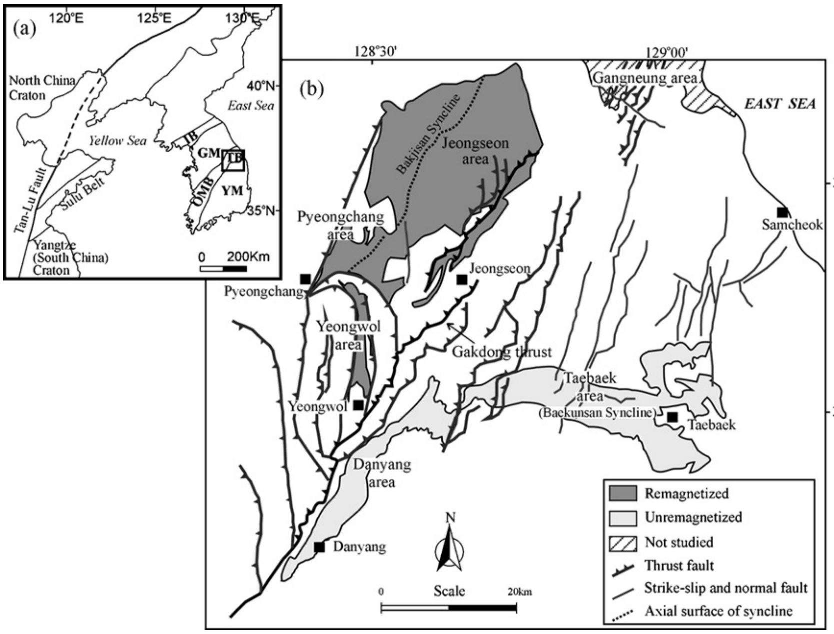

Fig. 10. (a) Simplified tectonic map of the East Asia. IB, Imjingang Belt; GM, Gyeonggi Massif; YM: Yeongnam Massif; OMB: Okcheon Metamorphic Belt; TB: Taebaeksan Basin. (b) Simplified geologic map of the Taebaeksan Basin, the unmetamorphosed northeastern subzone of the Okcheon Belt, showing distribution of the remagnetized and unremagnetized areas.

deformation with respect to the southeastern region since the late Permian. Based on these observations, the two regions are considered to separated and have experienced different geotectonic evolutions. On the other hand, it is observed that Early Triassic paleomagnetic poles from the southeastern unremagnetized region (Taebaek and Danyang areas) are much closer to the contemporaneous poles from the NCB as compiled by Enkin et al. (1992) and Huang et al. (2005), rather than to those of the SCB as compiled by Enkin et al. (1992) and Yang and Besse (2001) (Fig. 9b). Thus, our data reinforce the hypothesis that the southeastern part of the Taebaeksan Basin was connected to the NCB throughout the interval of deposition of the Lower Triassic strata. However, in the case of the northwestern region of the Taebaeksan Basin, its affinity with the SCB is not established because reliable primary remanent magnetizations have not yet been resolved.

6.4. *Role of the thrust system in chemical remagnetization: barrier or pathway?*

The reason that complete remagnetization occurred selectively on the northwestern side of the Gakdong thrust is unclear at present. The distribution of the thrust fault system including the Gakdong thrust in the Okcheon Belt may provide an important clue to the reason for the selective remagnetization established by this study. It is also known that intra-cratonic fault zones typically have long histories of recurrent activity that may span hundreds of millions of years, whereas fault zones in actively deforming mountain belts usually have relatively short-lived histories although they maybe rooted in deeper more ancient lineaments (Marshak and Paulsen, 1996; Ramsey and Onasch, 1999). The major thrust systems in this region, including the Gakdong thrust within the Okcheon Belt, were initiated by the Triassic Songrim Orogeny and later reactivated during the late Jurassic (the Daebo Orogeny) and the Cretaceous. The Cretaceous reactivation of the thrust system as the strike-slip fault formed several Cretaceous basins (e.g. the Yeongdong, Eumseong, Gongju and Poongam basins) along the boundaries of the Okcheon Belt. In this context, there are at least two alternative explanations for the relationship between the thrust fault system and the remagnetization: namely the barrier model and the pathway model.

The barrier model proposes that the remagnetizing fluids originated from the northwestern area of the Taebaeksan Basin, and migrated southeastward across the Gakdong thrust. In this case, the Gakdong thrust acted as a barrier to the passage of fluids to the southeast. Accordingly, the northwestern side of the thrust was extensively affected by fluid-mediated chemical remagnetization, whereas the southeastern side of the thrust was less influenced by these fluids. However, the degree of remagnetization is not found to vary with distance from the thrust on the southeastern side. Furthermore, Late Cretaceous–Tertiary igneous rocks as sources of the remagnetizing fluid are not exposed on the northwest of the Taebaeksan Basin, although this is a key element of the barrier hypothesis. Hence, the barrier model seems unlikely at present.

The pathway model is based on the observation that there are many thrusts on the northwestern side of the Gakdong thrust, while there are only smaller numbers of thrusts on the southeastern side (Fig. 10b). Also, many thrusts in the northwestern region extend southwestward to the central part of the Okcheon Belt. The migrating fluids along the Gakdong thrust from southwest to northeast might penetrate more easily and pervasively into the northwestern side by utilizing this already well-developed thrust system. The northward or northeastward migration of fluids inferred from the comparison of paleopoles of the remagnetized areas within the Okcheon Belt (Fig. 9b) favors the pathway hypothesis. In addition, the pathway model agrees well with recent structural investigation by Kim et al. (2001) suggesting that most NE–SW-trending thrust faults including the Gakdong thrust in the Taebaeksan Basin were reactivated as left-lateral strike-slip faults during the Late Cretaceous–Early Tertiary. Based on the observations described above, the pathway model is therefore preferred at present. We hope that our interpretation of this study may induce further detailed studies, including the structural syntheses, geochemical analyses and systematic absolute age determinations for veins in the thrust belts, to give a better resolution of the fluid migration under the tectonic settings in the Okcheon Belt.

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