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Palaeomagnetism of the (Upper Palaeozoic–Lower Mesozoic) Pyongan Supergroup, Korea: a Phanerozoic Link with the North China Block

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SUMMARY

The Upper Carboniferous–Lower Triassic Pyongan Supergroup is exposed in an E–W trending syncline comprising the Samcheok Coalfield in eastern South Korea; it borders the southern margin of a NE–SW trending (Okcheon) zone of Upper Jurassic–Lower Cretaceous deformation (Daebo Orogeny). Although a Recent field overprint widely recorded in Korean rocks is represented here, an ancient field component structure is recovered from the red bed facies in this Supergroup by detailed thermal demagnetization. A prominent Upper Jurassic–Cretaceous overprint is widespread ($D/I = 56.1/54.8°$, $\alpha_{95} = 9.6°$, palaeopole at 200.4°E, 46.7°N) and records the magnetic effect of the Daebo Orogeny within the Okcheon Belt. It is post-deformational in origin and appears to have been confined mainly to the Cretaceous Normal Superchron. It has been rotated clockwise since these times, in common with the main synclinal axis, as a consequence of dextral movements along the Tan Lu Fault System. Components predating this deformation are recovered from the Lower Triassic ($D/I = 1.1/19.4°$, $\alpha_{95} = 18.2°$, palaeopole at 306.1°E, 63.2°N), Permian ($D/I = 358.3/11.5°$, $\alpha_{95} = 6.3°$, palaeopole at 311.9°E, 58.7°N) and Upper Carboniferous ($D/I = 341.1/-9.2°$, $\alpha_{95} = 7.2°$, palaeopole at 335.7°E, 44.6°N) sediments.

Second-order small circle dispersions of site palaeopoles record unaccommodated tectonic rotations and are largest in the oldest beds below an Upper Carboniferous–Lower Permian unconformity. However, the presence of reversals, probably acquired before and after the Carboniferous–Permian Reversed Superchron, defines ancient field axes and identifies an Upper Carboniferous–Lower Triassic APW path. This path correlates with the contemporaneous path from the North China Block and is removed from the path from the South China Block; agreement with North China is enhanced when these results are corrected for the rotation indicated by the Cretaceous overprint. We therefore identify a first-order correlation between the Korean Peninsula and North China at least since Upper Palaeozoic times. Establishment of, and movements along, the Tan Lu Fault System since Mesozoic times have not obscured this palaeomagnetic correlation.

Key words: China, Korea, palaeomagnetism.

1 INTRODUCTION

Eastern Asia is a complex collage of terranes which have been assembled during a long history of tectonic emplacement commencing in Mesozoic times and continuing to the present day. Palaeomagnetic study provides the key tool for quantifying the component motions of this terrane assembly and has been an important focus of international effort during the last decade. These studies have succeeded in identifying early and middle Mesozoic times as an important period of relative movements followed by a general accretion into the present configuration of eastern

Asia by Cretaceous times (Enkin *et al.* 1992). Within individual terranes, however, there are frequently second-order complexities typified by a streaking of pole positions along small circles centred about the sampling locations; it therefore appears that the terranes are not strictly rigid but have undergone internal deformations. These deformations are often continuing at the present time as part of the extrusion of crustal blocks in eastern Asia resulting from indenting by the Indian subcontinent (Molnar & Tapponnier 1977).

The Korean Peninsula comprises the eastern part of this terrane assemblage and its affinities with the blocks to the west are a subject of much uncertainty. Traditionally this region has been incorporated with the North China Block (NCB) into a single Sino-Korean unit. More recent assessments of the geology of eastern Asia, however, have highlighted the importance of the Tan Lu Fault Zone as a possible terrane boundary (Fig. 1a). This fault has been the site of dextral movement extending from Central China north-east into the Sea of Okhotsk (Xu *et al.* 1987). Depending on the significance of these movements, it is possible that the Korean Peninsula was formerly located in proximity to the South China Block (SCB), a link which has been advocated by several workers (Lee, Besse & Courtillot 1987; Otofuji *et al.* 1989).

Within Korea a SW–NE trending zone, the Okcheon Belt, was a site of late Jurassic and early Cretaceous deformation (the Daebo Orogeny) and contains possible ophiolites (Lee 1987). This belt separates the previously stabilized Kyonggi Massif to the north from the Ryongnam Massif to the south (Fig. 1). To evaluate the origin of the Ryongnam Massif, the palaeomagnetism of a Carboniferous to Triassic sedimentary succession comprising the Pyongan Supergroup has been studied and the results are reported here. This succession is now exposed on both limbs of an E–W trending syncline, the Baekunsan Syncline, permitting routine application of the palaeomagnetic fold test (Graham 1949 and Fig. 1). This major structure is located close to the south-east margin of the Okcheon Belt, but is not considered to be a component of this belt (Lee 1987).

2 GEOLOGY AND SAMPLING

The outcrop of the Pyongan Supergroup comprising the Baekunsan Syncline forms the Samcheok Coalfield centred around the town of Changseong, Kangweon District. The succession in this area is summarized in Table 1 and unconformably overlies (Lower Cambrian to Middle Ordovician) rocks belonging to the Choseon Supergroup. It commences with red or drab detrital sediments of the Manhang Formation ranging from siltstones to fine-pebble conglomerates; samples from the red facies comprise an important component of this study (Table 1). The variety of lithologies in the succeeding Kuncheon Formation include coal measures but are considered generally unsuitable for palaeomagnetic study. Coal-bearing cyclothems also occur in the overlying rocks of the Changseong Formation which contains a Permian plant flora and is succeeded by the mainly arenitic sandstones of the Hambaeksan Formation. The Tosagok Formation red shales to pebble-bearing sandstones have been sampled for this study. In common with the overlying Kohan Formation, they include plant beds containing a Permian flora. The Kohan Formation is now preserved in the axial region of the synclinorium and is unconformably overlain by more restricted outcrops of the Tonggo Formation. The latter includes pink sandstones (sampled for this study); owing to the paucity of flora or fauna, the age is not well defined but is generally attributed to Lower or early Middle Triassic times.

Formation of the Pyongan Supergroup terminated later in Triassic times with the Songlim Disturbance, and sedimentation is therefore attributed to the interval between the middle of Upper Carboniferous times and early Triassic times (*c.* 300–240 Ma; Harland *et al.* 1990). The Songlim episode initiated the Baekunsan structure, which was subsequently further folded and overthrust during the Daebo Orogeny (late Jurassic–early Cretaceous). As a consequence of these latter movements, the northern limb of the structure is steeply deeping and partly overturned, and the axial plane dips towards the north. Nappe structures are a feature of the north-eastern extremity of the coalfield, but this region of more complex tectonics was avoided in the present study.

Distributed, short, 2.4 cm diameter cores were drilled in the formations noted above as summarized in Table 1 using a portable rock motor and oriented *in situ* employing sights on the Sun and/or magnetic bearings in conjunction with topographic sights. The distribution of sampling sites is shown in Fig. 1, and stratigraphic locations and orientations of each sampling site were noted during the course of the fieldwork. The field cores were trimmed into 2.2 cm long cylinders for subsequent palaeomagnetic analysis.

3 PALAEOMAGNETIC RESULTS

All samples were subjected to progressive thermal demagnetization and measured at each stage of treatment by cryogenic magnetometer. Heating steps were 100 °C to 300 °C, then in 50 °C steps to 500 °C, and subsequently in 20 °C steps up to the Curie points of the remanence carriers; the heatings were made by a Magnetic Measurements thermal demagnetizer and all experimental work was undertaken in a continuously monitored field free space provided by a set of large Rubens coils. The effects of thermal treatment were monitored at each stage of treatment by making susceptibility measurements; no significant chemical changes were identified in the samples (mostly red beds) yielding significant components of magnetization.

The total natural remanent magnetic (NRM) directions in these sediments are predominantly northerly positive similar to the present geomagnetic field direction (Fig. 2). A prominent overprint in the present field is a feature of most previous palaeomagnetic studies of Korean rocks (Shibuya *et al.* 1985; Ototfuji *et al.* 1986; Lee *et al.* 1987). Although this feature has been attributed to the alignment of magnetic grains in the rock interstices in Recent times (Otofuji *et al.* 1989), it is observed here that the NRM directions cluster more closely about the present-field direction in this region ($D/I = 352.6/52.4°$) than the mean axial dipole field ($D/I = 0/56.6°$; Fig. 2). It is therefore inferred that the NRMs are merely dominated by components of viscous origin.

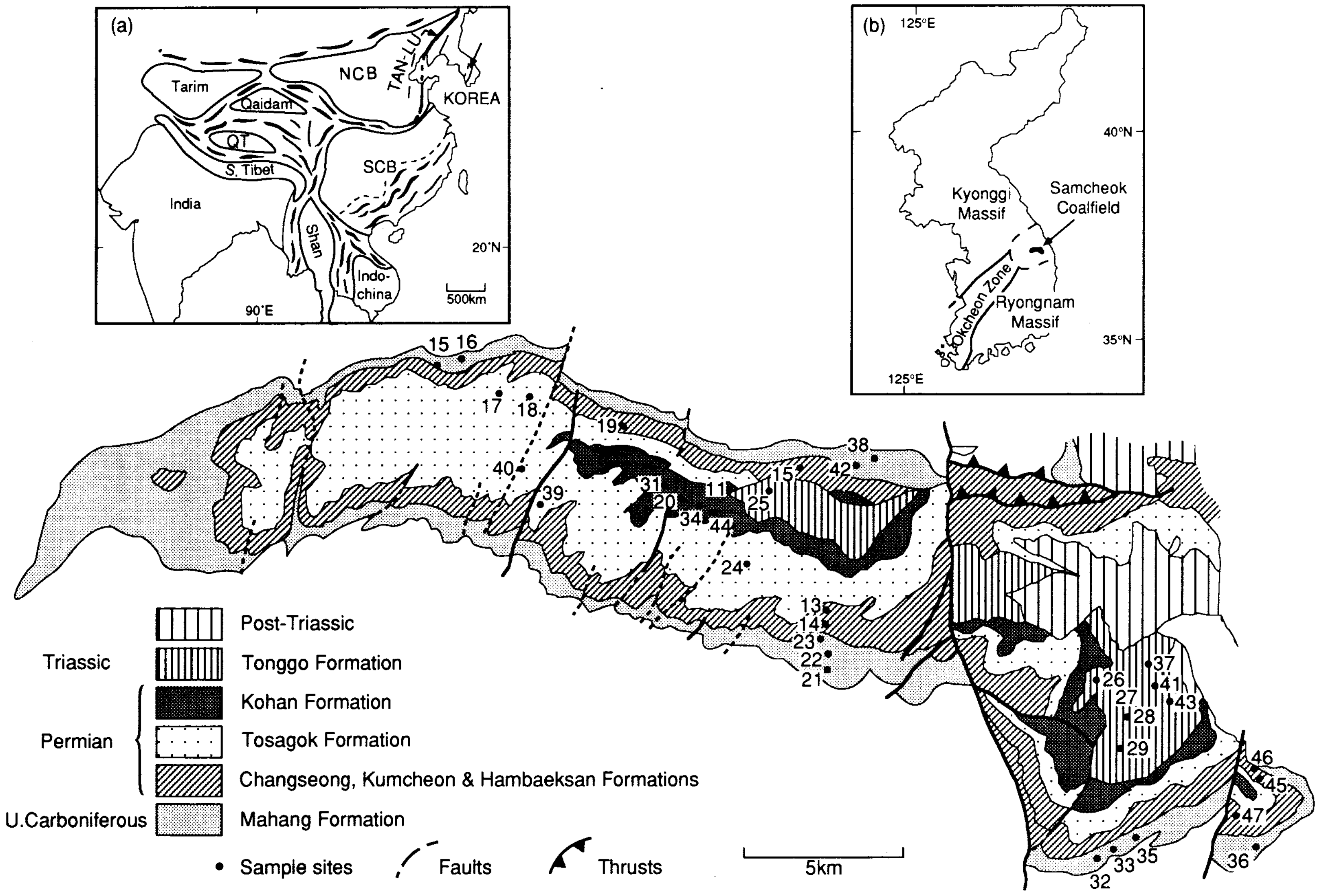

Figure 1. Simplified geological map of the Baekunsan Syncline, South Korea, showing the locations of the palaeomagnetic sampling sites of this study. Inset (a) shows the assemblage of terranes in eastern Asia and the location of the Tan Lu fault system; the abbreviations are NCB (North China Block), SCB (South China Block) and QT (Qiangtang Block). Inset (b) shows the regional setting of the Beakunsan Syncline (black) within the Samcheok Coalfield and the location of the Okcheon Belt separating the Pyongnam and Ryongnam Massifs.

Table 1. Stratigraphic succession of the Pyongan Supergroup exposed in the Baekunsan syncline (Samcheok Coalfield), Taebaek area, Korea.

Period	Epoch		Group	Formation	Thick. (m)	No. Sites
Triassic	Scythian to Tr2(?)		Hwangji	Tonggo	<400	8/7
----------	----------	----Unconformity----	----------	----------	----------	----------
	Zechstein	(Tartarian)		Kohan	300	6/4
		(Kazanian)		Tosagok	250	6/5
Permian		(Kunkurian)	Cheolam	Hambaeksan	200	4/0
	Rotliegendes	(Arlinskian)		Changseong	120	3/0
----------	----------	----Unconformity----	----------	----------	----------	----------
Carboniferous	Moscovian		Komok	Kumcheon	70	1/0
				Manhang	200	10/10

The sites column gives the number of sites sampled and the number of sites yielding significant palaeomagnetic results. Stratigraphic thicknesses are average estimates.

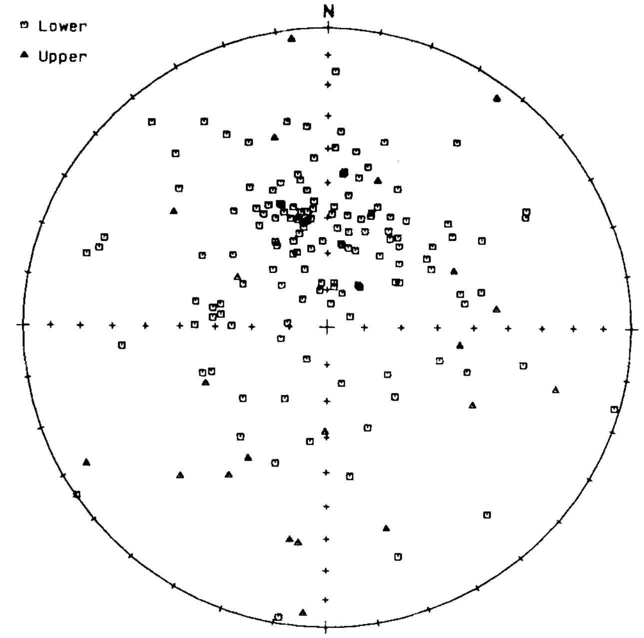

Figure 2. Total NRM directions from Upper Palaeozoic and Mesozoic sediments from the Baekunsan Syncline. Lower hemisphere plots are shown as squares and upper hemisphere plots as triangles. Equal area projections.

3.1 Triassic (Tonggo) Formation

A single site (28) in green sandstones of the Tonggo Formation was very weakly magnetized and yielded no significant palaeomagnetic results. The remaining seven sites (sites 25–27, 29, 37, 41 and 43) are in red sediments and yield a sequence of blocking-temperature components during progressive treatment. Two, and sometimes three, components are recorded in these rocks. Sample 25-5 (Fig. 3) is an example of three-component behaviour: the low blocking-temperature (lbt) component is a viscous acquisition in the present field and is removed by 500 °C; the second component is recovered over a narrow temperature range between 500 °C and the Curie point of magnetite (580 °C). The third convergent component is resident in haematite and subtracted by 660 °C. Sample 43-1 is an example of two-component behaviour with the first component of ancient (and probable Cretaceous, see below) origin subtracted by the Curie point of magnetite to isolate a single haematite-held component. In some samples the magnetite-resident component dominates the spectrum (sample 29-1). More complex behaviour is observed in a few samples; samples 37-4 and 41-4, for example, illustrate overlapping blocking temperature spectra and great circle migration of the direction during progressive treatment; sample 41-4 is an example of a very narrow high blocking-temperature (hbt) component close to the Curie point of haematite with a direction that cannot be accurately resolved by the thermal demagnetization.

It is apparent that the dominant viscous component in these rocks is successfully removed by thermal cleaning to isolate components of ancient origin. The first of these components is present in 55 per cent of the samples and resident in magnetite; it is normally magnetized and has a NNW positive direction (Fig. 4a). Grouping of these directions deteriorates with tilt adjustment (Table 2) and the pole position calculated at sample level from *in situ* directions corresponds to the apparent polar wander (APW) path for Korea in late Jurassic–Cretaceous times (Besse & Courtillot 1991). We therefore interpret this component as an overprint acquired during the Daebo Orogeny. Progressive untilting of this population yields an optimum grouping before adjustment, indicating that this component is essentially post-deformational in age.

The hbt components are isolated above 580 °C. Both polarities are represented (Fig. 4b). The total population (Table 2) is represented both by directions computed from discrete components defined as linear segments on orthogonal plots, and from intersecting great circles (McFadden & McElhinny 1988; see Table 2). The seven site mean directions conform most closely when fully tilt-adjusted; it then appears that three are normally magnetized (sites 26, 29 and 43) and four are reversely magnetized (sites 25, 27, 37 and 41; Table 2). The collective sites also pass a reversal test at the 95 per cent confidence level (Fig. 5a). The overall grouping of site mean directions is relatively poor ($\alpha_{95} = 20.5°$) because they are smeared along a swathe from SSW shallow to SE positive. We therefore suspect that components of unresolved local rotation contribute to this

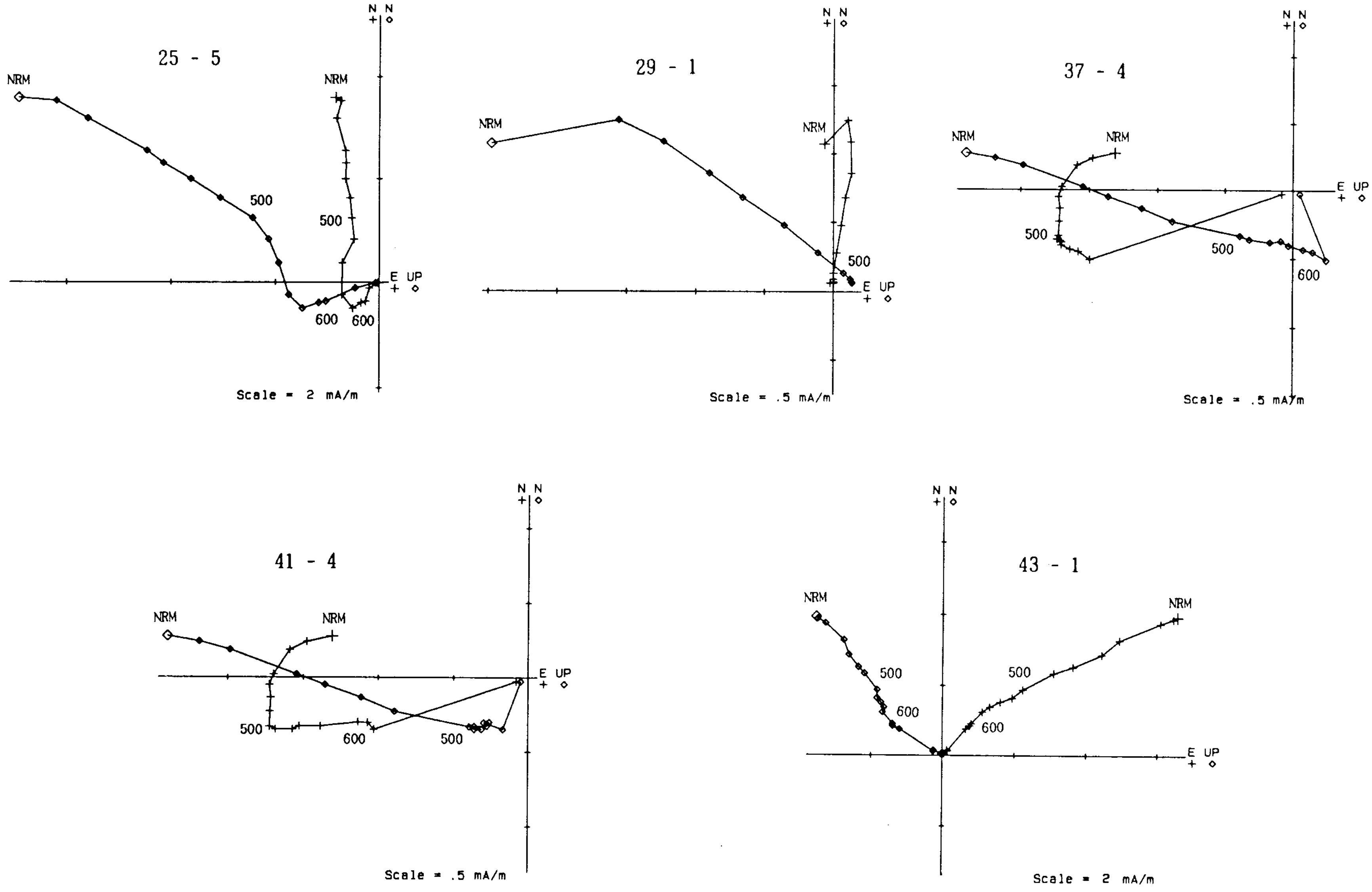

Figure 3. Demagnetization results from samples of the (Lower Triassic) Tonggo Formation, Baekunsan Syncline. The data are plotted as orthogonal plots *in situ*. Projections onto the horizontal plane are shown as crosses and the projections onto the vertical plane are shown as open squares. Temperature steps are listed in the text and representative stages are indicated here.

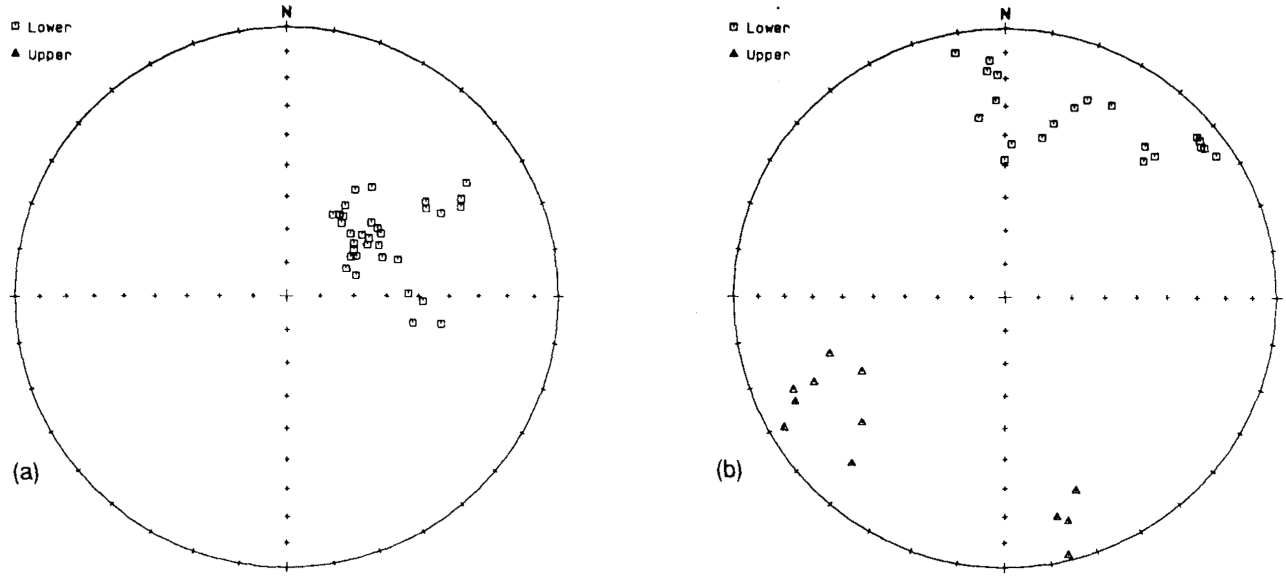

Figure 4. Ancient components of remanence isolated from the Tonggo Formation: (a) sample components of probable late Jurassic–Cretaceous origin (*in situ*) and (b) sample high blocking temperature components of probable Triassic origin (tilt adjusted), defined as linear segments on orthogonal plots.

dispersion, which are, however, not related to the large-scale distribution of the sites (*cf.* site 25 and the remainder in Fig. 1). Accordingly, data from sites 26, 37 and 41 at the extremities of the distribution are omitted, and a mean is calculated from the four sites defining a dipolar axis (sites 25, 27, 29 and 43; Table 2). These four sites pass the fold test (McElhinny 1964) at the 99 per cent confidence level. The corresponding pole position is at 306.1°E, 63.2°N; it is inferred to predate the late Jurassic–early Cretaceous deformation of these rocks and to be a post-depositional or early chemical diagenetic remanence of Lower–Middle Triassic age.

Table 2. Site and group mean palaeomagnetic results from Lower Triassic rocks from the Baekunsan syncline of the Taebaek area, South Korea.

Site	n/N	Dg	Ig	Ds	Is	k	α_{95}	PL.	
25	10/10	222.3	62.3	176.4	-4.5	16.3	12.6	2.3	D4, G6
26*	11/11	47.4	49.0	42.9	17.6	29.4	8.6	9.0	D11
27	6/8	183.7	-55.1	191.3	-21.2	242.8	5.6	11.0	G6
29	8/10	8.7	53.6	354.3	13.9	297.4	3.4	7.1	D4, G4
37*	10/10	254.0	-18.6	213.3	-34.5	125.5	4.8	19.0	G10
41*	9/12	252.1	7.5	241.1	-24.3	32.7	9.1	12.7	D9
43	6/7	42.2	59.9	3.2	37.8	59.8	8.7	21.2	D6
Ave.	4	22.5	38.4			2.1	86.4		
				1.1	19.4	26.4	18.2	(k_2/k_1=12.6)	
Overprinted components:									
25	4	59.0	34.9	94.8	3.1	20.8	20.6		
26	10	65.0	50.9	54.1	22.0	25.5	9.7		
29	4	62.7	68.3	3.6	41.5	505.4	4.1		
41	9	49.5	59.5	345.5	20.0	27.0	10.1		
43	6	57.7	60.9	8.1	44.6	246.3	4.3		
Ave.	33	58.8	55.5			24.7	5.1		
				18.6	33.2	7.4	9.9		

n/*N*: number of samples used in average/measured; *Dq* and *Ig*: *in situ* declination and inclination; *Ds* and *Is*: tilt-adjusted declination and inclination; *k*: Fisherian precision parameter (k_1: *in-situ*; k_2: tilt-adjusted); α_{95}: radius of cone of 95 per cent confidence interval; PL.: palaeolatitude; D and G: number of direct observations and great circles, respectively.
* Omitted in calculation of the mean (see text for explanation).

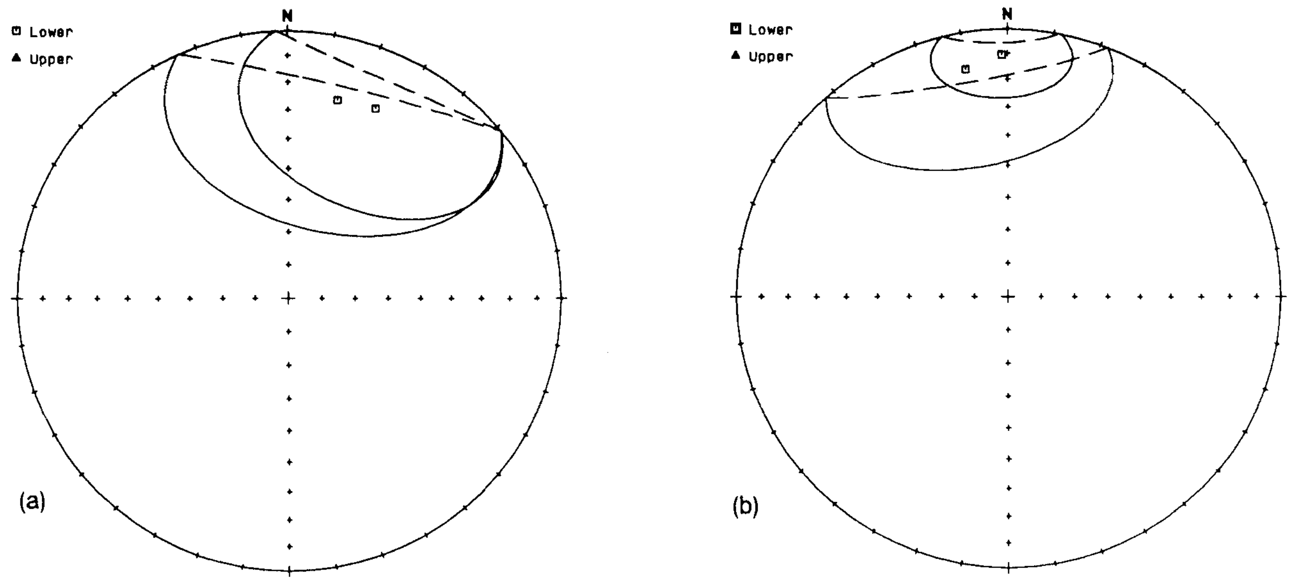

Figure 5. Reversal tests applied to selected site mean directions (see text) from the (a) Triassic and (b) Permian Formations. The mean of each polarity population is calculated and one population is reversed for comparison with the other; 95 per cent confidence circles are shown.

3.2 Permian Formations

Sites 11 and 48 in dark grey shales of the Kohan Formation yielded magnetizations that were too weak to resolve their component structures. The remaining sites (sites 20, 31, 34 and 44) are in red shales and mostly have two components with overlapping blocking-temperature spectra in addition to a small viscous contribution (e.g. samples 31-2 and 34-1 in Fig. 6). Hence most component directions from this formation are resolved from analysis of great circles by the method of McFadden & McElhinny (1988; see Table 3). They are uniformly reversed and have southerly shallow directions after tilt adjustment. Because tilt is similar at all sites, no fold test is possible, but the tilt-adjusted direction is considered likely to be applicable to these beds because the remanence then corresponds most closely to the other Upper Palaeozoic–Lower Mesozoic results of this study; the *in situ* direction only corresponds to the reversed Tertiary field direction, a time period during which there is no obvious case for remagnetization.

In the Tosagok Formation (as in the Kohan) the grey shales yielded no significant palaeomagnetic information (site 17). The remaining five sites in red shales and sandstones yield mostly two-component structures (Fig. 6) although three components are present in some with a poorly defined lbt component. Otherwise the lbt component is either an overprint acquired in the present Earth's field (sample 18-1 in Fig. 6) or during the late Jurassic–Cretaceous remagnetization event (sample 39-2). There are variable degrees of overlap with the hbt component and the directions of these latter components are derived in part from remagnetization circles (Table 3). Both polarities are represented; the grouping improves, and the site mean directions become more closely anti-parallel, when fully adjusted for tilt. These sites also pass a reversal test at the 95 per cent confidence level (Fig. 5b).

Sites 18, 30 and 39 in the Tosagok Formation identify a dipole axis with comparable mean direction to three sites (sites 20, 31 and 34) in the Kohan Formation. Sites 24, 40 and 44 have similar inclinations but aberrant declinations; this may have a tectonic cause but we can identify no specific one. These sites are excluded from the calculated mean derived from the remaining sites in the Kohan and Tosagok and listed in Table 3.

The Tosagok Formation is dated as Kazanian (Lee 1987) and was therefore probably deposited slightly before the end of the Carboniferous–Permian Reversed (CPR) Superchron. The concensus of present evidence places the end of this superchron between Lower and Upper Tartarian times, or within the Upper Tartarian stage (Molina-Garza, Geissman & Van der Voo 1989; Harland *et al.* 1990). Hence the presence of reversals in the hbt (haematite-resident) components of the Tosagok Formation is indicative of remanence acquisition somewhat later than deposition, and implies a post-depositional or early diagenetic origin.

No significant palaeomagnetic information was derived from grey sandstones of the Hambaeksan Formation (sites 13, 19, 45 and 47) and the Changseong Formation (sites 12, 14 and 46).

3.3 Carboniferous Formations

The Permian rocks unconformably overlie the Carboniferous Kumcheon Formation where a single site (site 15) in grey sandstones yielded no significant information. The underlying red sandstones and shales of the Manhang Formation, however, possess up to three discrete components. The lbt fraction includes a component of late Jurassic–Cretaceous origin in some samples (sample 23-3 in Fig. 7), but has a composite origin in other samples (e.g. sample 22-5) with a present-field component also, or alternatively, present. The directions of these components are steep NE to E positive and rotated clockwise from the present-field direction although there is some smearing towards shallow easterly directions (Fig. 8a). The hbt component is typically a discrete convergent one subtracted

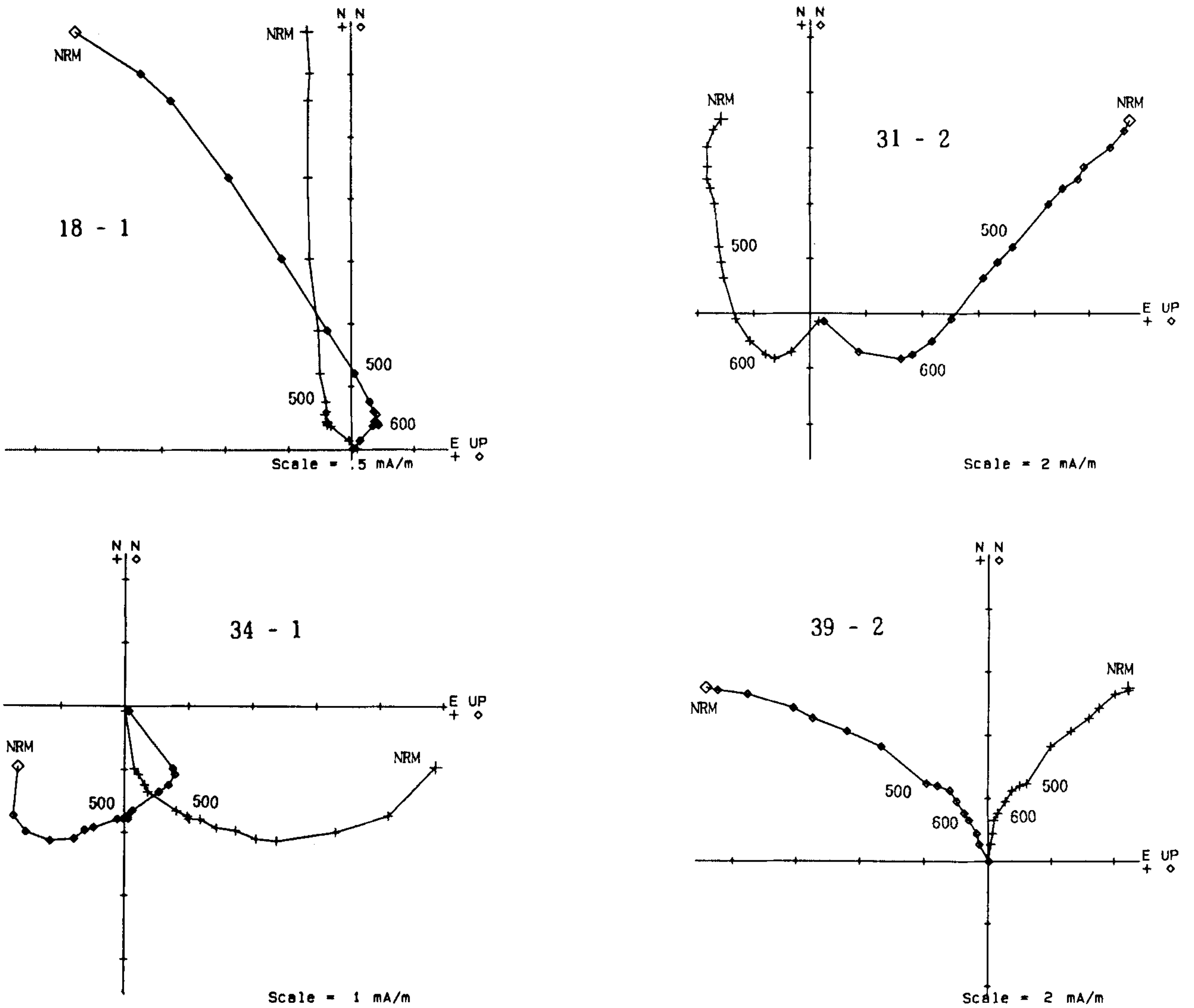

Figure 6. Typical results of thermal demagnetization of samples from the (Permian) Kohan and Tosagok Formations. The symbols are as for Fig. 3.

Table 3. Site and group mean palaeomagnetic results from Permian rocks from the Baekunsan syncline of the Taebaek area, South Korea.

Site	n/N	Dg	Ig	Ds	Is	k	α_{95}	PL.	
i) Kohan Formation									
20	6/6	171.0	-52.4	174.6	-5.7	23.8	16.5	2.9	D1, G5
31	6/8	174.2	-58.8	176.9	-11.8	82.3	9.6	6.0	G6
34	8/8	174.9	-59.4	177.3	-1.5	70.8	7.7	0.8	G8
44*	7/9	152.8	-52.6	156.6	-4.0	22.5	15.7	2.0	G7
ii) Tosagok Formation									
18	5/7	182.8	-3.9	176.0	-19.6	393.4	5.7	10.1	G5
24*	4/5	323.3	41.9	323.5	11.9	459.9	5.0	6.0	D2, G2
30	7/7	9.1	47.1	2.8	13.3	127.7	5.6	6.7	D5, G2
39	9/9	5.8	20.1	2.6	16.9	31.2	9.8	8.6	D4, G5
40*	7/7	213.4	-19.8	213.2	-18.0	26.7	12.4	9.2	D4, G3
Ave	6	180.8	-40.8			12.1	20.0		
				178.3	-11.5	113.6	6.3	($k_2/k_1=9.4$)	

n/N: number of samples used in average/measured; *Dg* and *Ig*: *in situ* declination and inclination; *Ds* and *Is*: tilt-adjusted declination and inclination; *k*: Fisherian precision parameter (k_1: *in-situ*; k_2: tilt-adjusted); α_{95}: radius of cone of 95 per cent confidence interval; PL.: palaeolatitude; D and G: number of direct observations and great circles, respectively.

* Omitted in calculation of the mean (see text for explanation).

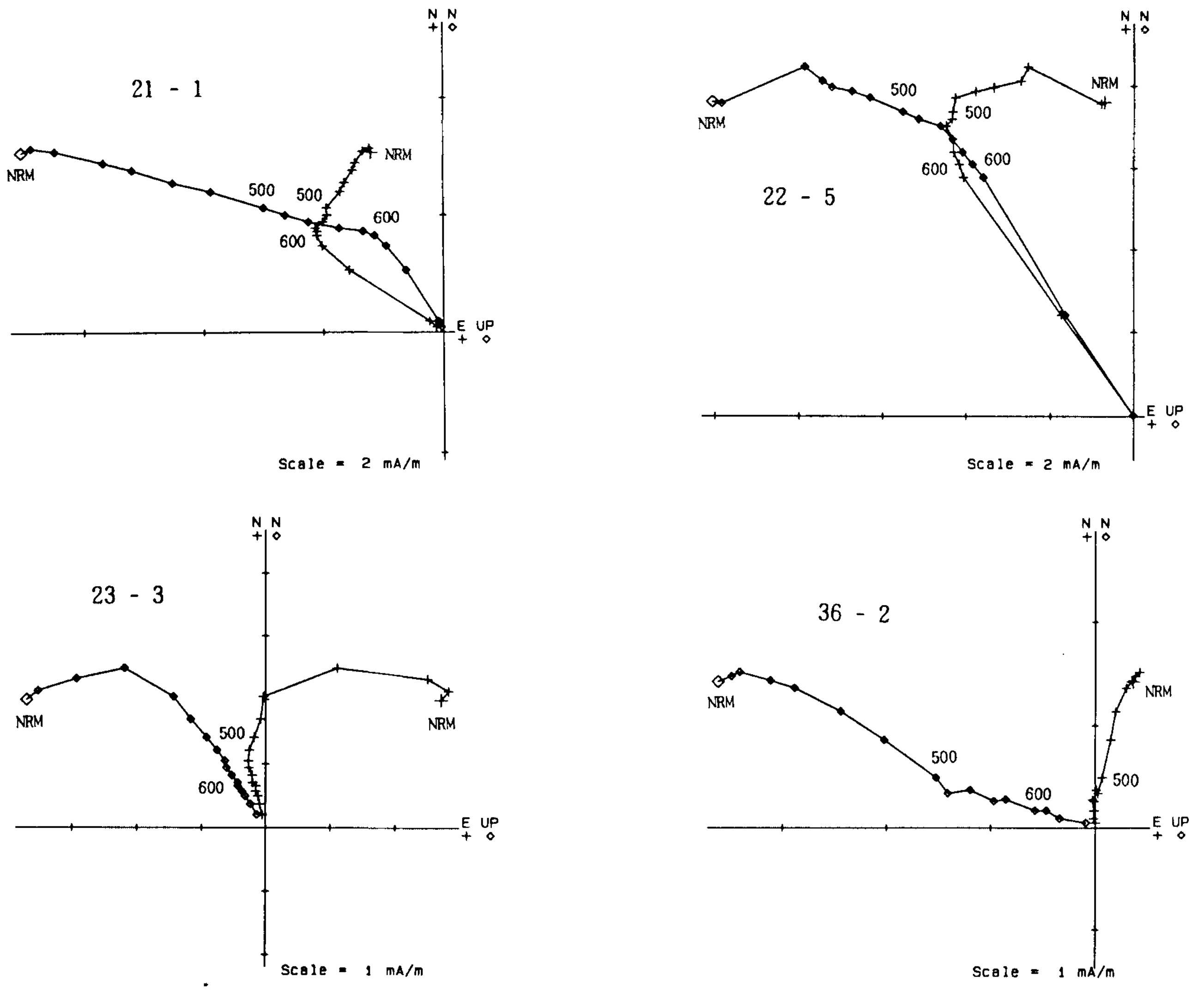

Figure 7. Representative thermal demagnetization results from samples of the (Carboniferous) Manhang Formation. The symbols are as for Fig. 3.

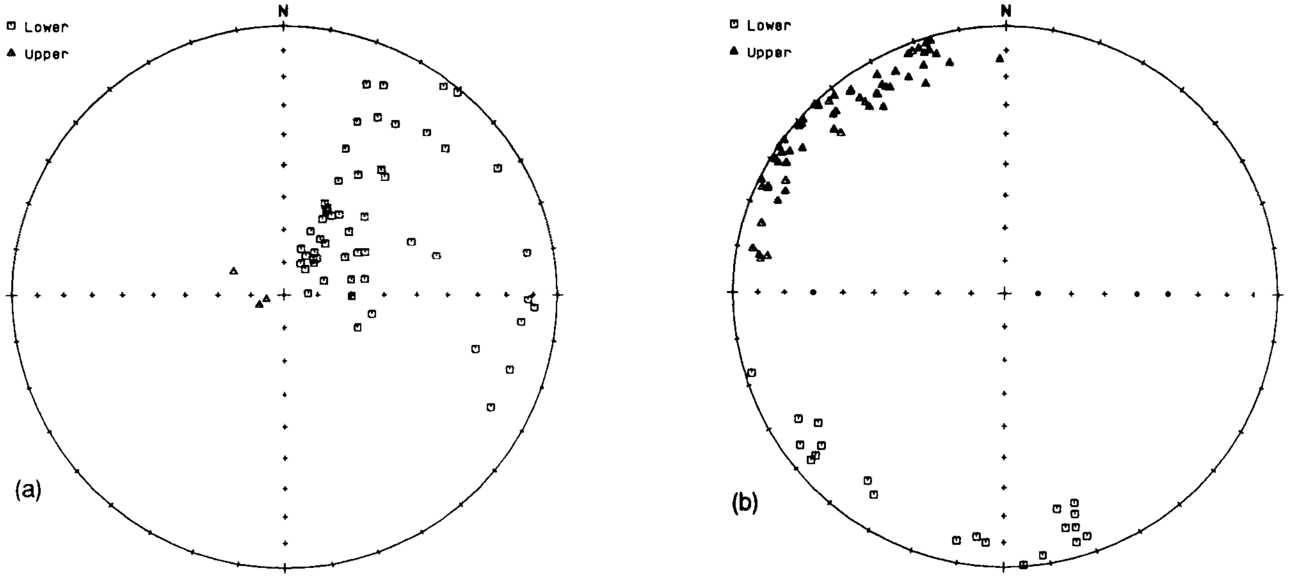

Figure 8. Components of magnetization identified in the Manhang Formation: (a) lbt components *in situ* and (b) hbt components adjusted for tilt.

Table 4. Site and group mean palaeomagnetic results from Upper Carboniferous rocks from the Baekunsan syncline of the Taebaek area, South Korea.

Site	n/N	Dg	Ig	Ds	Is	k	α_{95}	PL.	
16*	6/9	258.2	16.9	246.4	5.8	50.3	12.4	-2.9	G6
21*	17/17	306.6	19.7	312.2	-6.0	38.1	5.9	-3.0	D13, G4
22*	12/12	324.1	29.6	323.6	-10.3	85.1	4.7	-5.2	D12
23	7/7	336.1	22.3	336.6	-7.5	155.1	4.9	-3.8	D7
32	9/9	190.4	-47.7	165.4	11.1	86.2	5.6	-5.6	D9
33*	10/10	235.1	17.0	230.9	10.8	48.1	7.0	-5.4	D10
35*	20/20	273.1	71.2	299.5	-4.9	30.1	6.1	-2.5	D16, G4
36	7/8	359.6	74.6	341.4	-9.0	48.8	8.7	-4.5	D7
38*	4/7	282.8	-12.9	288.9	-6.9	38.6	15.0	-3.5	D4
42*	9/9	196.2	-45.5	189.2	9.7	301.3	3.2	-4.9	D3, G6
Ave.	3	351.8	49.3			7.9	47.1		
				341.1	-9.2	296.2	7.2	(k_2/k_1=37.5)	
Overprinted Components:									
21	8	32.4	65.5	19.5	16.9	13.0	16.0		
22	11	56.4	52.6	12.8	40.7	6.4	19.6		
23	6	84.9	12.0	77.3	16.1	7.2	26.7		
32	5	37.4	60.9	337.4	7.6	97.9	7.8		
33	7	48.1	48.0	69.4	52.5	7.1	24.4		
35	8	48.3	56.9	344.7	12.3	7.7	21.4		
36	5	54.7	66.3	358.3	0.5	18.2	18.4		
38	4	268.0	-77.0	342.7	-55.6	64.9	11.5		
42	3	36.5	36.3	27.3	-10.5	67.5	15.1		

n/*N*: number of samples used in average/measured; *Dq* and *Ig*: *in situ* declination and inclination; *Ds* and *Is*: tilt-adjusted declination and inclination; *k*: Fisherian precision parameter (k_1: *in-situ*; k_2: tilt-adjusted); α_{95}: radius of cone of 95 per cent confidence interval; PL.: palaeolatitude; D and G: number of direct observations and great circles, respectively.
* Omitted in calculation of the mean (see text for explanation).

close to the Curie point of haematite (samples 21-1, 22-5, 23-3 and 36-2 in Fig. 7); they are of uniformly shallow inclination when adjusted for tilt (Fig. 8b).

Site mean directions derived from the hbt components are listed in Table 4; sample components from individual sites are of uniform polarity and well grouped. Collectively, however, they are dispersed both *in situ* and when tilt adjusted (Figs 9a and b). These components most probably predate the deformation because the aberrant *in situ* directions from sites 35 and 36 move to positions grouping with, or anti-parallel to, other sites in this population. Furthermore, when tilt-adjusted, the site mean directions move to occupy a great circle path that is not evident in the *in situ* orientation. This distribution of near-horizontal magnetization about a vertical axis (Fig. 9b) implies that tilt adjustment about local strike directions have failed to correct for more regional block rotations (MacDonald 1980). This is also implied by the positions of the site palaeomagnetic poles; these show an arcuate distribution along a circle with a pole located at 129.4°E, 40.2°N (Fig. 9c), which is close to the sample location (128.8°E, 37.2°N). In these circumstances the closest estimate of the regional magnetization recorded by these rocks is probably represented by the anti-parallel population comprising sites 23, 32, and 36, where site 32 is accurately reversed with respect to sites 23 and 36 (Table 4). There are two reasons for believing that this selection is the valid one. First, these sites are located remote from one another and will not therefore have undergone a common tectonic rotation. Secondly, the coincidence of these poles with the APWP of the North China Block (Section 4) implies that there are no hidden rotations which are unaccommodated here.

The Manhang Formation is dated as Lower Moscovian in age (Lee 1987) and was therefore most probably deposited during the CPR Superchron. There are two uncertainties that may explain the occurrence of the normal polarities identified here. First, the palaeomagnetic material is from the red beds in the undated basal part of the formation that may be older than the higher horizons dated by plant flora. Secondly, it is possible that reversals continued into Westphalian 'B' times (Khramov 1987) which are equivalent to the Lower Moscovian (Harland *et al.* 1990). Otherwise the haematite-held remanence in these beds would be of much younger, but still pre-deformational, age.

4 DISCUSSION

The Pyongan Supergroup has previously been sampled across the Baekunsan Syncline by Otofuji *et al.* (1989). These authors resolved only a Recent field overprint and their demagnetization results (see their Fig. 3) show a component with this direction subtracted by 300–400°C implying a remanence dominated by pyrrhotite. The sampled lithologies are not stated but we note that all

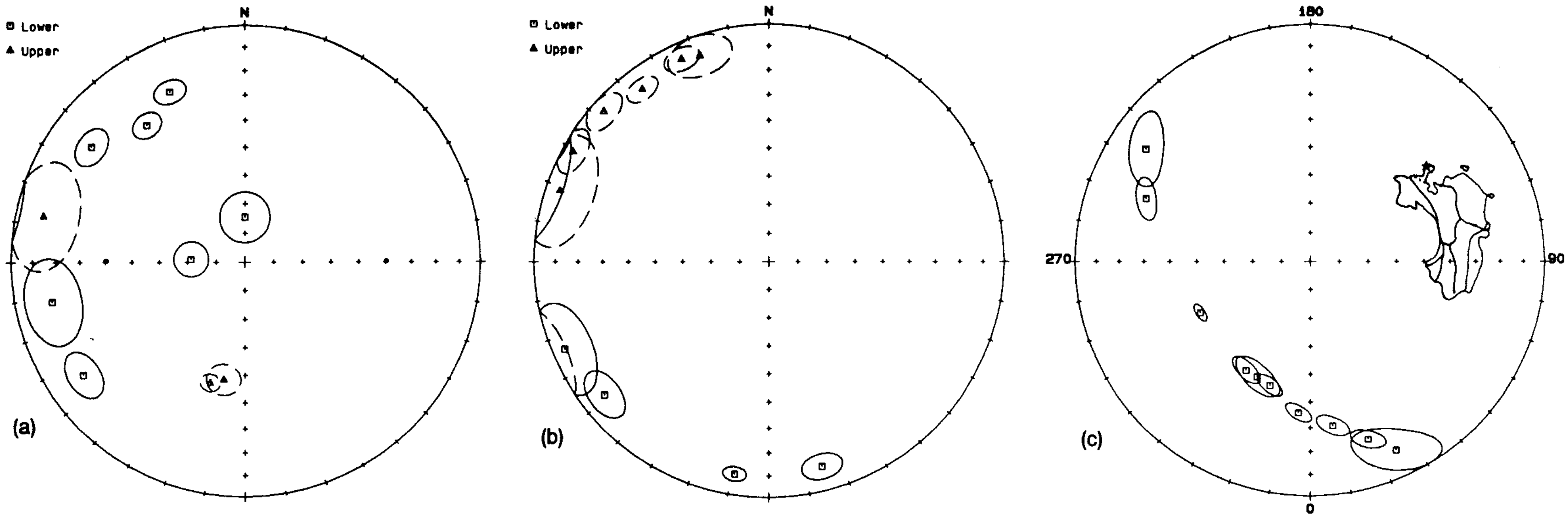

Figure 9. (a) *In situ* site mean directions and 95 per cent confidence circles from the Manhang Formation (Carboniferous). (b) Tilt-adjusted site mean directions. (c) Pole positions from the Manhang Formation showing the arcuate distribution and the location of the sampling district (star).

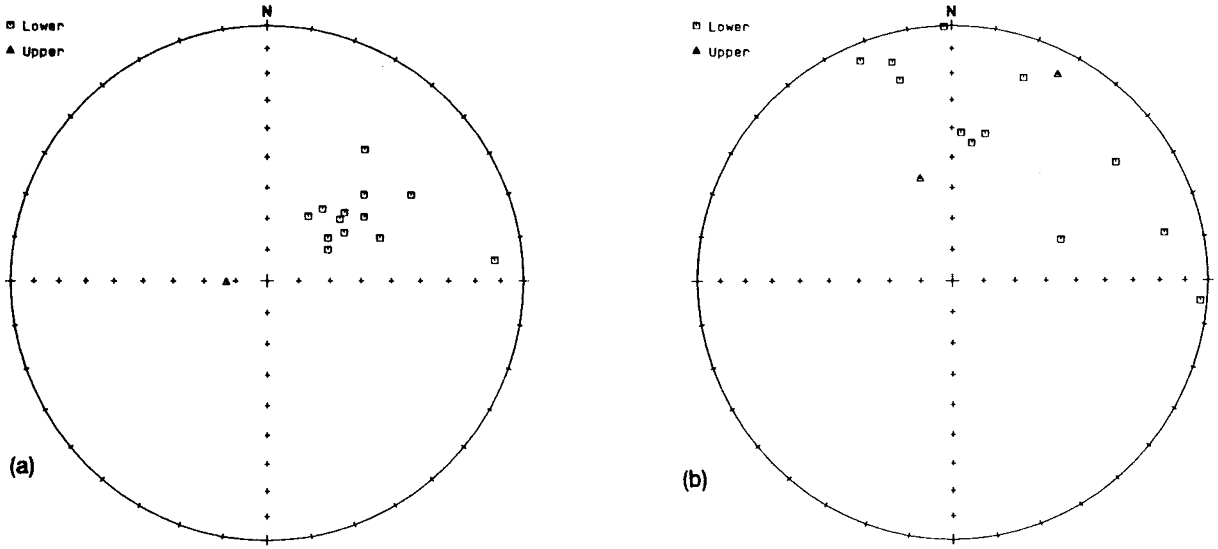

Figure 10. Site mean directions of magnetization for overprints of presumed ancient origin (a) *in situ* and (b) tilt adjusted.

Table 5. Summary of palaeomagnetic poles from this study.

Age of Pole	Samples/sites	Pole Position °E	Pole Position °N	A_{95}	Fold Test	Reversal Test
Overprint (?L. Cretaceous)	90/14	200.4	46.7	9.8	negative	
Lower Triassic	30/4	306.1	63.2	12.6	99%	pass
Upper Permian	41/6	311.9	58.7	4.1	99%	pass
Upper Carboniferous	23/3	335.7	44.6	6.9	99%	pass

The poles positions from the inferred primary magnetizations are moved to 0°E, 52.4°N (Lower Triassic), 358.3°E, 47.4°N (Permian) and 7.3°E, 28.2°N (Upper Carboniferous) when mean directions are adjusted for 30° of clockwise rotation recognized in the Mesozoic overprint (see Fig. 12).

drab-coloured samples in the present study possessed only weak remanence and no components of apparent ancient origin. However, red beds belonging to each Series are found to possess a two- or three-component structure of ancient origin. These components yield estimates of the ancient palaeofield direction and corresponding palaeopoles as summarized in Table 5.

The mean directions calculated for the Triassic, Permian and Carboniferous formations are each supported by a fold test significant at the 99 per cent confidence level and by a reversal test at the 95 per cent confidence level. The non-Recent overprints calculated at site mean level are plotted in Fig. 10. Although relatively dispersed, it is apparent that the *in situ* distribution is circular with approximately the same spread in declination as in inclination; hence unaccommodated components of tectonic rotation are not evident here. Furthermore, this distribution is dispersed when adjusted for tilt and the fold test is negative at the 95 per cent level. The mean direction ($D/I = 56.1/54.8°$, $\alpha_{95} = 9.6°$) corresponds to a pole position at 200.4°E, 46.7°N. This pole is not positively distinguishable from the collective pole positions from the NCB, SCB and Korea of Upper Jurassic and Cretaceous age but plots at the eastern limit of their distribution (see Enkin *et al.* 1992, and Fig. 11) suggesting that it may have experienced clockwise rotation. It is also rotated clockwise with respect to the contemporaneous Eurasian APW path (plotted in Fig. 11). The NE declination is consistent with the declinations of magnetizations resolved from Upper Triassic and Jurassic granites and sediments of the Ryongnam Massif in South Korea by Kim & Van der Voo (1990). These authors recognize a clockwise rotation of vectors in Jurassic granites within the Okcheon Belt although the geographic spread of the present sampling is not sufficiently large to detect this.

Hence we regard this NE positive overprint as a magnetic signature of the Daebo Orogeny but note that it is post-deformational in origin. With the exception of data from a few isolated samples, all of these overprints have normal polarity. Since the late Jurassic–early Cretaceous (pre-Barremian) geomagnetic field was characterized by frequent reversals with roughly equal time periods spent in the normal and reversed states (e.g. Harland *et al.* 1990), this suggests that the period of overprinting was mainly concentrated within the succeeding Cretaceous Normal Superchron (*c.* 118–83 Ma).

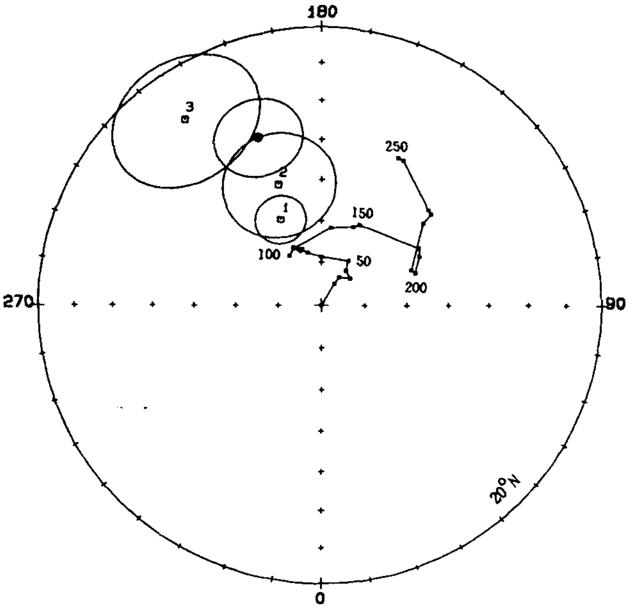

Figure 11. Apparent polar wander path for Eurasia from Permian times (250 Ma) to present (solid squares) after Enkin *et al.* (1992) with the pole position derived from the Cretaceous overprint of this study (solid circle). Also shown are the pole positions derived from Upper Triassic (open squares, 3)–Jurassic (2) granites and sediments by Kim & Van der Voo (1990) and the pole of Lee *et al.* (1987) derived from Cretaceous (1) sediments in the south-east part of the Korean Peninsula. See text for explanation and interpretation.

Magnetizations with comparable direction and uniform normal polarity are resolved by Kim & Van der Voo (see Figs 5 and 12 in Kim and Van der Voo 1990) from granites of the (late Triassic) Songlim Orogeny in the Ryongnam Massif dated as Triassic and Jurassic in age (e.g. Choo 1971, 1986). The characteristic remanence in these granites is removed from the pre-folding remanence isolated from the Lower Triassic sediments in this study which, however, is in general accord with a dual polarity magnetization identified by Kim & Van der Voo (1990) from a small number of samples in Triassic red beds (sampled from the Tonggo Formation of this study) bordering the Okcheon Belt. We therefore interpret the magnetizations in these granites as Cretaceous in age. They appear to record the same overprinting event as the one recognized in the Samcheok Coalfield (and more widely in eastern Asia by Lee *et al.* 1987); it is therefore implied that the radiometric ages on these granites are unrelated to their magnetizations.

The Daebo Orogeny was accompanied by the emplacement of syn-orogenic granites (Lee 1987) and two possible causes for the subsequent remagnetization event can be identified:

(i) a regional heating linked to granite magmatism and/or
(ii) migration of a fluid front from the Okcheon Zone motivated by stacking of nappes and lithosphere loading to the north (e.g. Oliver 1986).

The former would be recorded as a partial thermoremanence whilst the latter would be a chemical remanence likely to result from the growth of authigenic haematite mediated by the orogenic fluids. The observation that the Cretaceous overprint is magnetite-held tends to favour the former mechanism as the predominant one.

In common with the result of Lee *et al.* (1987), the Upper Mesozoic result from this study (interpreted above as acquired during the Cretaceous Normal Superchron) is rotated clockwise with respect to the combined results of this age from the NCB and SCB (Fig. 11 and Enkin *et al.* 1992). This clockwise rotation is evident in most poles derived from the east of the Tan Lu Fault System with respect to poles from the NCB and SCB to the west (Enkin *et al.* 1992; see also Kim & Van der Voo 1990). It specifically applies to the data from Korea south-east of the Okcheon Belt where there is evidence for differential rotations consequent upon distributed deformation across this block. Thus the mean declination calculated from the combined Deagu and Andong sections of Lee *et al.* (1987) in south-east Korea is 28.1° and yields a pole position close to the contemporaneous Eurasian path (Fig. 11). The mean declination of the overprint of this study is 56.1°. The difference of ~30° is close to the rotation of the axis of the Baekunsan Syncline from the main Okcheon Belt (Lee 1987; see also Fig. 1). It therefore appears likely that this belt was folded in parallelism with the Okcheon zone during the climactic Upper Jurassic–Lower Cretaceous deformation and has been progressively rotated clockwise since the Cretaceous overprinting. Similar regional tectonic implications will apply to the results of Kim & Van der Voo (1990) from close to the margin of the Belt which are also evidently subject to variable clockwise rotations (Fig. 11).

The palaeopoles derived from pre-folding components (Table 5) are each defined by fold and reversal tests and resident in hbt haematite components; they are therefore inferred to be essentially of primary (probably post-depositional) origin. Palaeofield axes can be defined by the presence of reversals; the dispersion of site mean directions along small circle lines centred about the sampling locality observed here is a second-order complexity and is widely noted in studies in eastern Asia (Enkin *et al.* 1992). It is most marked in the lowest (Upper Carboniferous) Manhang Formation and highlights the probable tectonic significance of the unconformity between the Upper Carboniferous and the Upper Permian (Table 1).

The palaeolatitudes are: Carboniferous (5°S), Permian (6°N) and Triassic (10°N). Hence this sector of the Korean Peninsula appears to have occupied equatorial latitudes throughout the interval of deposition of the Pyongan Supergroup; the coal facies which persist through the Upper Carboniferous–Upper Permian section are equatorial in origin in common with contemporaneous examples in Europe and eastern North America.

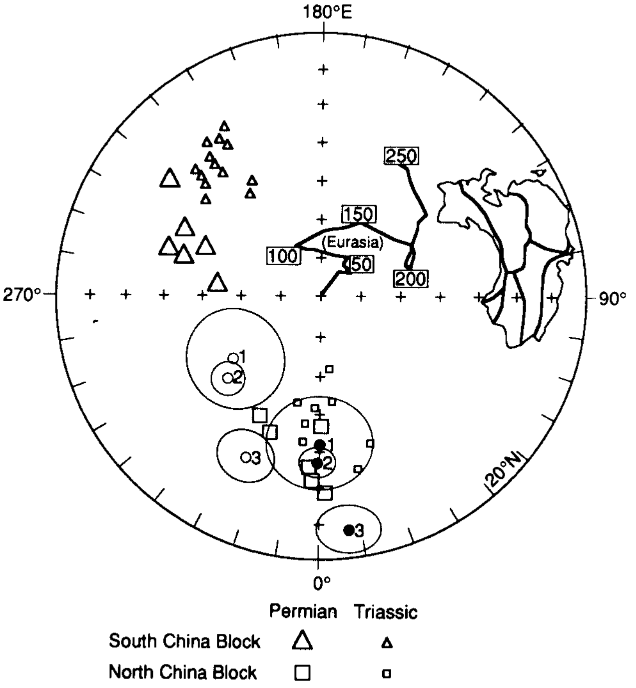

Figure 12. Palaeopoles for the North and South China Blocks of Upper Permian (NCB, large open squares; SCB, large open triangles) and Lower Triassic (NCB, small solid squares; SCB, small solid triangles) results as defined by quality selected poles (Enkin *et al.* 1992) and compared with the contemporary APW path for Eurasia. The latter is shown as a continuous bold line calculated from overlapping time windows of palaeomagnetic poles and 50 Ma intervals are indicated (Piper 1987). The Upper Carboniferous–Lower Triassic poles of this study are plotted both adjusted for local tilt (open circles: 1, Lower Triassic; 2, Permian; 3, Upper Carboniferous) and corrected for the regional clockwise rotation (solid circles) recognized from the Cretaceous overprint.

Collectively the Upper Palaeozoic–Lower Mesozoic palaeopoles are shown in Fig. 12 plotted with the palaeopoles for the NCB and SCB of Upper Permian and Lower Triassic and the contemporaneous apparent polar wander path for Eurasia. These are the first pre-Jurassic pole positions derived from the Korean Peninsula. Even without correction for clockwise rotation since Cretaceous times, it is clear that they correspond only with the Late Palaeozoic poles from the NCB; they are removed from the contemporary poles from the SCB. Thus the large APW motion evident between Lower and Upper Triassic poles from the NCB is replicated in the Korean results.

If the results of this study are corrected for the 30° clockwise rotation deduced from the Cretaceous overprint, the directions and corresponding pole positions are changed to: Lower Triassic ($D/I = 331.1/19.4^\circ$, palaeopole at 0°E, 52.4°N), Permian ($D/I = 148.3/-11.5^\circ$, palaeopole at 358.3°E, 47.4°N) and Upper Carboniferous ($D/I = 311.1/-9.2^\circ$, palaeopole at 7.3°E, 28.2°N). This adjustment achieves a precise correlation with the Permian–Lower Triassic poles from the NCB (Fig. 12). The Korean Peninsula has therefore been an eastward extension of this tectonic block since at least Upper Palaeozoic times. It is also apparent that the Mesozoic and later movements along the Tan Lu Fault System (see Fig. 1) have not been large enough to obscure this essential palaeomagnetic correlation.

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REFERENCES

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

Choo, S.H., 1971. Isotopic age determination on the rocks of the Korean Peninsula, *Geol. Ore Deposit,* **14,** 1–45.

Choo, S.H., 1986. A study on age determination of Ryongnam Massif by Rb/Sr method, III, Korean Inst. *Energy Resour.*, KR-86-17, 1–28.

Enkin, R.J., Yang, Z., Chen, Y. & Courtillot, V., 1992. Palaeomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the present, *J. geophys. Res.*, **97,** 13 953–13 989.

Graham, J.W., 1949. The stability and significance of magnetism in sedimentary rocks, *J. geophys. Res.*, **54,** 131–167.

Harland, W.B., Armstrong, W.L., Cox, A.V., Graig, L., Smith, A.G. & Smith, D.G., 1990. *A Geologic Time Scale 1989,* Cambridge University Press, Cambridge.

Khramov, A.N., 1987. *Palaeomagnetology,* Springer-Verlag, New York.

Kim, K.H. & Van der Voo, R., 1990. Jurassic and Triassic palaeomagnetism of South Korea, *Tectonics,* **9,** 699–717.

Lee, D.S., 1987. *Geology of Korea,* Kyohak-Sa Publishing, Seoul.

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

MacDonald, W.D., 1980. Net tectonic rotation, apparent tectonic rotation and the structural tilt correction in palaeomagnetic studies, *J. geophys. Res.*, **85,** 3659–3669.

McElhinny, M.W., 1964. Statistical significance of the fold test in palaeomagnetism, *Geophys. J. R. astr. Soc.*, **8,** 338–340.

McFadden, P.L. & McElhinny, M.W., 1988. The combined analysis of remagnetization circle and direct observation in palaeomagnetism, *Earth planet. Sci. Lett.*, **87,** 161–172.

Molina-Garza, R.S., Geissman, J.W. & Van der Voo, R., 1989. Palaeomagnetism of the Dewey Lake Formation (Late Permian), northwest Texas; end of the Kiaman Superchron in North America, *J. geophys. Res.*, **94,** 17 881–17 888.

Molnar, P. & Tapponnier, P., 1977. Relation of the tectonics of eastern China to the Indian–Eurasian collision: application of strike-line field theory to large-scale continental tectonics, *Geophysics,* **5,** 212–216.

Oliver, J., 1986. Fluids expelled tectonically from orogenic belts: Their role in hydrocarbon migration and other geologic phenomena, *Geology,* **14,** 99–102.

Otofuji, Y., Katsuargi, K., Inokuchi, H., Yaskawa, K., Kim, K.H., Lee, D.S. & Lee, H.Y., 1989. Remagnetisation of Cambrian to Triassic sedimentary rocks of the Paegunsan Syncline of the Okch'on Zone, South Korea, *J. Geomagn. Geoelectr.*, **41,** 119–135.

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

Piper, J.D.A., 1987. *Palaeomagnetism and the Continental Crust,* John Wiley, New York.

Shibuya, H., Min, K.D., Lee, Y.S., Sasajima, S. & Nishimura, S., 1985. Some palaeomagnetic measurements in the Korean Peninsula, in *Physical Geology of Central and Southern Part of Korea,* pp. 41–83, eds Nishimura, S. & Min, K.D., Kyoto University Press, Kyoto.

Xu, J., Zhu, G., Tong, W., Cui, K. & Liu, Q., 1987. Formation and evolution of the Tancheng–Lujiang wrench fault system: a major shear system to the northwest of the Pacific ocean, *Tectonophysics,* **134,** 273–310.