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## Tectonic implications of new Late Cretaceous paleomagnetic constraints from Eastern Liaoning Peninsula, NE China

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[1] A paleomagnetic study has been carried out in the east of the Tan-Lu fault, in Liaoning Province, NE China, to understand the timing of Tan-Lu fault activity. Samples aging from Early Paleozoic to Late Mesozoic from 51 sites have been analyzed. Paleozoic and Late Permian-Early Triassic rocks are remagnetized by the recent geomagnetic field; however, Late Cretaceous (between 118 and 83 Ma) red tuffaceous sandstone passes a positive fold test, shows no Present Earth Field characteristic remanent magnetization carried by both magnetite and hematite, presents a solo normal polarity, and thus provides the only reliable paleomagnetic data in this study. The paleomagnetic pole calculated from these rocks ( $\lambda_p = 59.4^\circ\text{N}$ ,  $\phi_p = 205.5^\circ\text{E}$ , and  $A_{95} = 7.3^\circ$ ) is statistically undistinguishable from all available Cretaceous paleomagnetic data from Eastern Liaoning-Korean Peninsula, indicating that these areas may belong to a single tectonic unit, here named the East Liaoning-Korea (ELK) Block, at least since the Late Cretaceous. Conversely, a significant discrepancy between the ELK Block and Chinese Block (i.e., North and South China Blocks) characterized by a differential rotation ( $22.5^\circ \pm 10.2^\circ$ ) with a negligible latitudinal displacement ( $0.8^\circ \pm 6.1^\circ$ ) is demonstrated. This result indicates, first, that the left-lateral displacement along the Tan-Lu fault, if any, must have occurred before the Late Cretaceous and, second, that the Korean Block can not be considered as a rigid part of North China Block. Sedimentological and structural evidence show that the Meso-Cenozoic triangle shaped plain, consisting of Songliao, Xialiaohe, Sanjiang, Zeya, and other smaller basins developing in northeast China and southeast Russia, south of the Mongol-Okhotsk Belt, experienced a heterogeneous rifting from the Late Jurassic to Tertiary. The variable amount of extension, larger in the northeast ( $\sim 300$  km) than in the southwest ( $\sim 80$  km), is probably related to the clockwise rotation of the ELK Block centered at the south of the Bohai Bay Basin. This result shows that a significant segment of the East Eurasian margin (more than 1000 km long) experienced differential rotation in Cenozoic times.

*INDEX TERMS:* 1518 Geomagnetism and Paleomagnetism: Magnetic fabrics and anisotropy; 1525 Geomagnetism and Paleomagnetism: Paleomagnetism applied to tectonics (regional, global); 1527 Geomagnetism and Paleomagnetism: Paleomagnetism applied to geologic processes; 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 8157 Tectonophysics: Plate motions—past (3040); *KEYWORDS:* paleomagnetism, rifting, continental margin Meso-Cenozoic geodynamics, Songliao Basin, northeastern China plain

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### 1. Introduction

[2] The main part of China landmass was formed by the welding of North China Block (NCB) and South China Block (SCB) as argued from geologic evidence [e.g., *Mattauer et al.*, 1985; *Sun et al.*, 1991; *Okay et al.*, 1993; *Xu et al.*, 1994], geochronology [e.g., *Li et al.*, 1993], metamorphic history [e.g., *Cong*, 1996], and paleomagnetic investigations [e.g., *Zhao and Coe*, 1987; *Enkin et al.*, 1992; *Gilder and*

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Courtillot, 1997]. However, the intracontinental deformation continues at different scales in Mesozoic and Cenozoic times [e.g., Chen, 1998]. Some phenomena such as the intrusion of numerous Cretaceous granitic plutons in southeast China [e.g., Jahn *et al.*, 1990] or the eastward extrusion of south China along the Qinling fault due to India-Eurasia collision [e.g., Peltzer *et al.*, 1985; Avouac and Tapponnier, 1993] are well documented. Moreover, some processes such as the evolution of the Tan-Lu fault are still hotly debated. On the basis of geologic correlation on the both sides of the fault, a left-lateral displacement of several hundred kilometers from the Late Jurassic to Early Cretaceous has been proposed [Xu *et al.*, 1987]. Paleomagnetic results from the Shandong and Anhui Provinces do not support any relative motion since the Late Cretaceous [e.g., Gilder *et al.*, 1999], this result complies with geological observations showing that during the Late Cretaceous the Tan-Lu fault was a brittle normal fault [e.g., Mattauer *et al.*, 1985; Faure *et al.*, 1999; Ratsbacher *et al.*, 2000]. Moreover, a paleomagnetic study from the Liaoning Province and South Korea, i.e., east of the Tan-Lu fault, suggests a left-lateral motion of nearly 800 km along the fault since the Late Cretaceous [Uchimura *et al.*, 1996; Uno, 2000]. In order to clarify these confusions a paleomagnetic study has been carried out in the Liaoning Province, NE China, from the Early Paleozoic to Late Mesozoic periods.

## 2. Geological Setting and Paleomagnetic Sampling

### 2.1. Geological Outline

[3] In eastern Asia, several continental blocks, namely, from north to south, Siberia, Mongolia, north China, and south China separated by orogenic belts and suture zones of Mongol-Okhotsk, Xing-Meng, and Qinling-Dabie, respectively, are well acknowledged (Figure 1). Other sutures (e.g., Amur suture in Sikhote Alin or in Japan) are interpreted as marks of microcontinent collisions [e.g., Faure and Natal'in, 1992; Natal'in, 1993; Ren *et al.*, 2002, and references therein]. Moreover, those ancient plate boundaries are cut at high angle by major faults such as Tan-Lu and its northern continuations in the Yilan-Yiton and Fushun-Mishan faults or the Shikhote Alin fault (Figure 1). In NE China, the Liaoning Province, geographically situated near the border with North Korea, is considered as the easternmost part of the North China Block [Bureau of Geology and Mineral Resources of Liaoning Province (BGMRLP), 1989; Bureau of Geology and Mineral Exploration and Development of Liaoning Province (BGMEDLP), 1997, and references therein]. There an Archean and Paleoproterozoic basement is overlain by a well-developed Neoproterozoic-Paleozoic-Early Mesozoic sedimentary cover. This lithostratigraphic pile is intruded by numerous Mesozoic granitic plutons and overlain by mainly continental Cretaceous-Tertiary basins filled by terrigenous and volcano-clastic deposits and intercalated by lava flows.

### 2.2. General Stratigraphy and Sedimentology of the Sampling Area

[4] In Liaoning Province, outcrops are generally well exposed with rock ages spanning from the Mesoproterozoic to Early Cenozoic [BGMEDLP, 1997]. Above the Archean metamorphic basement, the Paleoproterozoic series consists of weakly metamorphosed (i.e., greenschist facies) rocks,

dominantly volcanic rocks and Mg-rich detrital ones in the lower and upper parts, respectively. The Neoproterozoic series (sampled Qingbaikou group) is characterized by sediments of shallow marine environment. In the sampling area the rocks have experienced a low-grade (prehnite-pumpellyite facies) metamorphism with a stratigraphic thickness <100 m. The Early Paleozoic strata are also shallow marine sediments, and their lithology is essentially platform limestone. The thickness of this series varies from 1200 to 2600 m. Abundant characteristic fossils, such as trilobite, graptolite, cephalopoda, and conodont, are used to constrain the stratigraphic age. The Late Paleozoic series is marked by alternation of continental and shallow marine sedimentary facies. Typical fossils are of brachiopoda, corals, foraminifera, and plants. In the study area the Mesozoic and Cenozoic periods correspond to the time of an important development of continental rifting basins with a sedimentary thickness over >10 km.

### 2.3. Sedimentology of Sampling Sites

[5] Table 1 and Figure 2 show the paleomagnetic sites collected from this study. Three main age groups are distinguished, namely, (1) Paleozoic (essentially Middle Ordovician and Middle-Upper Carboniferous) limestone-sandstone and (2) Upper Permian to Lower Triassic coarse red sandstone (P<sub>2</sub>-Tr<sub>1s</sub>) and Late Cretaceous red tuffaceous sandstone (K<sub>2d</sub>).

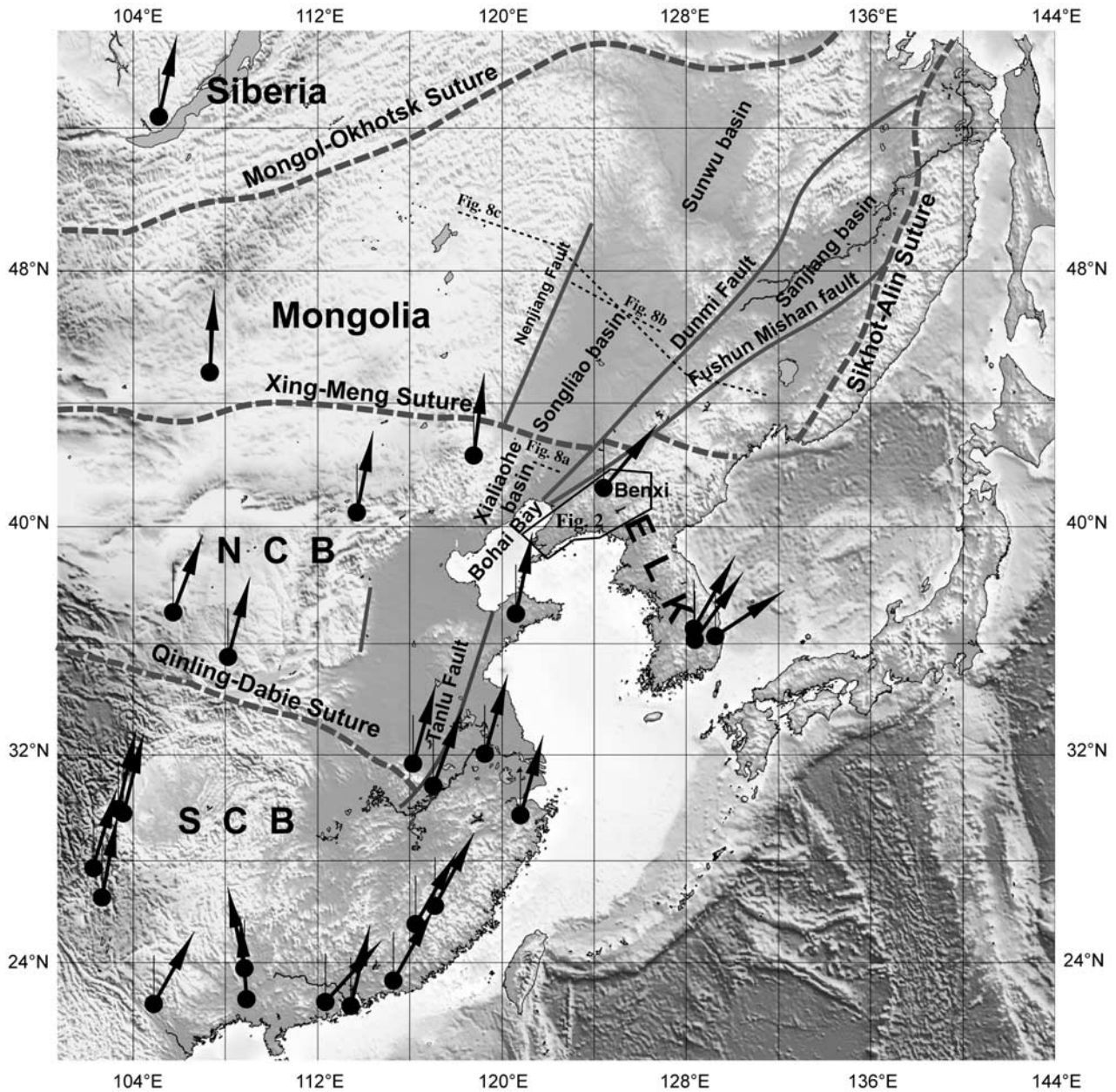
#### 2.3.1. Paleozoic Rocks

[6] In the Paleozoic rock group, three subgroups are differentiated on the basis of age and lithology: the Majiagou group of Middle Ordovician limestone (O<sub>2m</sub>), the Benxi group of Middle Carboniferous sandstone (C<sub>2b</sub>), and the Taiyuan group of Late Carboniferous limestone (C<sub>3t</sub>).

[7] The Middle Ordovician age of the Majiagou group is defined by trilobite (*Pseudouphus*), cephalopoda (*Stereoplasmoceras*, *Polydesmia*, *Orodosoceras*, *Wutinoceras* and *pseudoseptatum*), and conodont (*Erticodon tangshanensis*). This O<sub>2m</sub> stratum is essentially composed of thick limestone intercalated by dolomite. This group is in conformity with the underlying Lower Ordovician Liangjiashan group (O<sub>1l</sub>) and in parallel or weakly angular unconformity with the overlying Middle Carboniferous Benxi group (C<sub>2b</sub>). The total thickness of the Majiagou group is ~300–500 m in the sampling area. Eighteen sites are taken from this formation with variable bedding directions (Table 1 and Figures 2b and 2c).

[8] The Benxi group of the Middle Carboniferous (C<sub>2b</sub>) age consists mainly of continental facies thick yellow-green-gray coarse sandstone or micro conglomerate intercalated with shale and coal beds. The thickness of a single layer may reach 30 m. Numerous fossils have been identified in this formation, such as plants (*Sublepidodendron mirabile*, *Neuropteris gigantea*), Brachiopoda (*Linoproductus sp.*, *Burtunia cf. Juresanensis*). In the research area this 300-m-thick series, in which four sites are collected (Table 1), is conformably overlain by the Taiyuan group.

[9] The Upper Carboniferous Taiyuan group (C<sub>3t</sub>) lithologically belongs to marine and continental alternations of limestone intercalated by sandstone. Its thickness is variable from 60 to 230 m, and characteristic foraminifera fossils such as *Profusulinella*, *Eostaffella* are used to date this stratum. This series is in conformity with overlying and underlying neighboring strata. Eleven sites are drilled



**Figure 1.** Topographic map of East Asia with simplified tectonic sketch. NCB, SCB, and ELK stand for North China Block, South China Block, and Eastern Liaoning-Korea Block, respectively. The arrows are the Cretaceous magnetic declinations of East Asia calculated from the data listed in Table 3 at the geographic site of Benxi (41.3°N, 123.84°E).

from the Late Carboniferous Taiyuan group (Table 1 and Figures 2b and 2c).

### 2.3.2. P<sub>2</sub>-Tr<sub>1</sub> Shiqianfeng Group

[10] This group, of continental arid endoreic fluvial-lacustrine facies, is composed of dark red coarse-grained to conglomeratic sandstone with well-developed cleavage. It is conformably underlain by the Lower Permian Shihezi group and overlain by the Lower Triassic Linjia group with an angular contact. The thickness may reach to ~900 m. Some plants and bivalve fossils have been described for this formation, such as *Gigantonodechallai nicotianaefolia*, *Lobatannularia heianensis*. The bedding of this formation exposed in the western side of Benxi city varies very

slightly; therefore the five sampled sites will not offer a fold test (Table 1 and Figure 2b).

### 2.3.3. Late Cretaceous Dayu Group (K<sub>2d</sub>)

[11] This group consists of dark red to violet colored fine tuffaceous sandstone in the lower part and dark red to gray muddy sandstone on the top. The total thickness exceeds 1200 m. Few plant-type fossils are found in this formation, such as *Frenelopsis*. The age determination depends mainly on the stratigraphic relationship with the underlying formation and facies correlation with similar rocks. The Dayu group is unconformably underlain by the Xiaoling group. The age for the Xiaoling group is still in debate. A Late Jurassic-Early Cretaceous age was attrib-

**Table 1.** Paleomagnetic Sampling in Eastern Liaoning<sup>a</sup>

Site	Geographic Coordinates		N	Rock	Age	Formation	Bedding	
	Latitude, Longitude						Strike	Dip
1	41°23'11.7"N, 123°57'48.4"E		7	muddy limestone	Qn <sub>q</sub>	Qingbaikou	177.0	34.1
2	41°23'11.7"N, 123°57'48.4"E		7	muddy limestone	Qn <sub>q</sub>	Qingbaikou	172.3	38
3	41°20'53.1"N, 123°53'57.6"E		7	yellow sandstone	P <sub>1s</sub>	Shihezi	249.9	31.6
4	41°20'53.1"N, 123°53'57.6"E		8	yellow sandstone	P <sub>1s</sub>	Shihezi	217.1	15.6
5	41°20'53.1"N, 123°53'57.6"E		9	yellow sandstone	P <sub>1s</sub>	Shihezi	234.2	24.8
6	41°20'28.4"N, 123°54'18.7"E		6	microconglomerate	C-P <sub>s</sub>	Shanxi	242.7	22.5
7	41°17'17.7"N, 123°43'20.1"E		6	coarse red sandstone	P <sub>2</sub> -Tr <sub>1s</sub>	Shiqianfeng	95.7	11.0
8	41°17'17.7"N, 123°43'20.1"E		6	coarse red sandstone	P <sub>2</sub> -Tr <sub>1s</sub>	Shiqianfeng	86.8	15.5
9	41°17'17.7"N, 123°43'20.1"E		6	coarse red sandstone	P <sub>2</sub> -Tr <sub>1s</sub>	Shiqianfeng	106.0	16.0
10	41°17'17.7"N, 123°43'20.1"E		6	coarse red sandstone	P <sub>2</sub> -Tr <sub>1s</sub>	Shiqianfeng	87.7	24.0
11	41°17'17.7"N, 123°43'20.1"E		6	coarse red sandstone	P <sub>2</sub> -Tr <sub>1s</sub>	Shiqianfeng	95.7	14.5
12	41°20'38.8"N, 123°43'12.5"E		6	limestone	O <sub>2m</sub>	Majiagou	151.7	16.5
13	41°20'38.8"N, 123°43'12.5"E		6	limestone	O <sub>2m</sub>	Majiagou	148.7	21.0
14	41°20'38.8"N, 123°43'12.5"E		7	limestone	O <sub>2m</sub>	Majiagou	156.7	24.5
15	41°20'09.4"N, 123°42'50.3"E		7	yellow sandstone	C <sub>2b</sub>	Benxi	133.7	28.5
16	41°20'09.4"N, 123°42'50.3"E		6	yellow sandstone	C <sub>2b</sub>	Benxi	115.2	19.5
17	41°20'59.0"N, 123°42'28.6"E		5	brown sandstone	C <sub>2b</sub>	Benxi	266.7	37.0
18	41°21'06.0"N, 123°42'43.9"E		6	limestone	O <sub>2m</sub>	Majiagou	111.7	44.0
19	41°21'11.1"N, 123°42'55.5"E		6	limestone	O <sub>2m</sub>	Majiagou	133.4	34.0
20	41°21'11.1"N, 123°42'55.5"E		6	limestone	O <sub>2m</sub>	Majiagou	132.7	32.0
21	41°21'52.8"N, 123°42'48.1"E		5	limestone	O <sub>2m</sub>	Majiagou	124.4	30.8
22	41°21'02.2"N, 123°50'10.1"E		7	limestone	O <sub>2m</sub>	Majiagou	349.4	25.0
23	41°21'02.2"N, 123°50'10.1"E		6	limestone	O <sub>2m</sub>	Majiagou	6.0	24.0
24	41°24'41.6"N, 123°52'08.8"E		7	red shale and sandstone	C <sub>3t</sub>	Taiyuan	66.1	42.8
25	41°24'41.6"N, 123°52'08.8"E		7	gray-white sandstone	C <sub>3t</sub>	Taiyuan	109.7	21.0
26	41°24'08.4"N, 123°52'08.4"E		7	yellow-brown sandstone	C <sub>3t</sub>	Taiyuan	146.7 ~ 182.3	21 ~ 17
27	41°24'08.4"N, 123°52'08.4"E		7	yellow-brown sandstone	C <sub>3t</sub>	Taiyuan	182.3	22.0
28	41°20'54.9"N, 123°55'56.0"E		5	yellow sandstone	C <sub>2b</sub>	Benxi	127.0	42.2
29	41°18'17.7"N, 123°48'16.0"E		5	red tuffaceous sandstone	K <sub>2d</sub>	Dayu	344.9	29.6
30	41°18'17.7"N, 123°48'16.0"E		5	red tuffaceous sandstone	K <sub>2d</sub>	Dayu	15.7	13.5
31	41°18'17.7"N, 123°48'16.0"E		8	red tuffaceous sandstone	K <sub>2d</sub>	Dayu	296.7	22.0
32	41°18'17.7"N, 123°48'16.0"E		5	red tuffaceous sandstone	K <sub>2d</sub>	Dayu	16.7	22.0
33	41°18'17.7"N, 123°48'16.0"E		6	red tuffaceous sandstone	K <sub>2d</sub>	Dayu	307.7	19.0
34	41°18'17.7"N, 123°48'16.0"E		7	red tuffaceous sandstone	K <sub>2d</sub>	Dayu	303.7	18.0
35	41°18'17.7"N, 123°48'16.0"E		5	red tuffaceous sandstone	K <sub>2d</sub>	Dayu	312.7	19.0
36	39°24'28.4"N, 121°39'39.7"E		6	yellow-green sandstone	C <sub>3t</sub>	Taiyuan	197.0	8.0
37	39°24'28.4"N, 121°39'39.7"E		8	yellow-green sandstone	C <sub>3t</sub>	Taiyuan	193.7	9.0
38	39°24'28.4"N, 121°39'39.7"E		7	yellow-green sandstone	C <sub>3t</sub>	Taiyuan	193.7	6.0
39	39°22'37.3"N, 121°40'13.1"E		6	limestone	O <sub>2m</sub>	Majiagou	302.1	30.8
40	39°22'37.3"N, 121°40'13.1"E		6	limestone	O <sub>2m</sub>	Majiagou	333.7	23.0
41	39°22'37.3"N, 121°40'13.1"E		6	limestone	O <sub>2m</sub>	Majiagou	319.2	25.5
42	39°22'37.3"N, 121°40'13.1"E		6	limestone	O <sub>2m</sub>	Majiagou	297.2	19.0
43	39°22'37.3"N, 121°40'13.1"E		6	limestone	O <sub>2m</sub>	Majiagou	309.2	20.4
44	39°24'32.0"N, 121°39'50".0E		6	yellow-green sandstone	C <sub>3t</sub>	Taiyuan	321.4	27.8
45	39°10'20.4"N, 121°40'02.0"E		5	limestone	C <sub>3t</sub>	Taiyuan	225.5	40.5
46	39°10'20.4"N, 121°40'02.0"E		6	limestone	C <sub>3t</sub>	Taiyuan	207.7	42.0
47	39°10'20.4"N, 121°40'02.0"E		5	limestone	C <sub>3t</sub>	Taiyuan	228.7	52.3
48	39°09'46.5"N, 121°39'54.5"E		7	limestone	O <sub>2m</sub>	Majiagou	46.4	46.3
49	39°09'46.5"N, 121°39'54.5"E		6	limestone	O <sub>2m</sub>	Majiagou	50.2	58.9
51	39°11'24.3"N, 121°35'18.9"E		6	limestone	O <sub>2m</sub>	Majiagou	165.2	39.0
52	39°11'24.3"N, 121°35'18.9"E		5	limestone	O <sub>2m</sub>	Majiagou	155.7 ~ 74	42 ~ 20

<sup>a</sup>Latitude and longitude are present latitude and longitude of sampling site. N, number of sampled cores from the corresponding site.

uted to this formation [Zheng and Zhang, 1981; BGMRLP, 1989]. On the top, the Dayu group is unconformably overlain by Quaternary conglomerates. On the basis of the fossil composition, BGMEDLP [1997] proposed that these red beds of the Dayu group belong to the lower part of Upper Cretaceous. Seven sites are collected in the northern part of Benxi city with variable bedding orientations (Table 1 and Figure 2b).

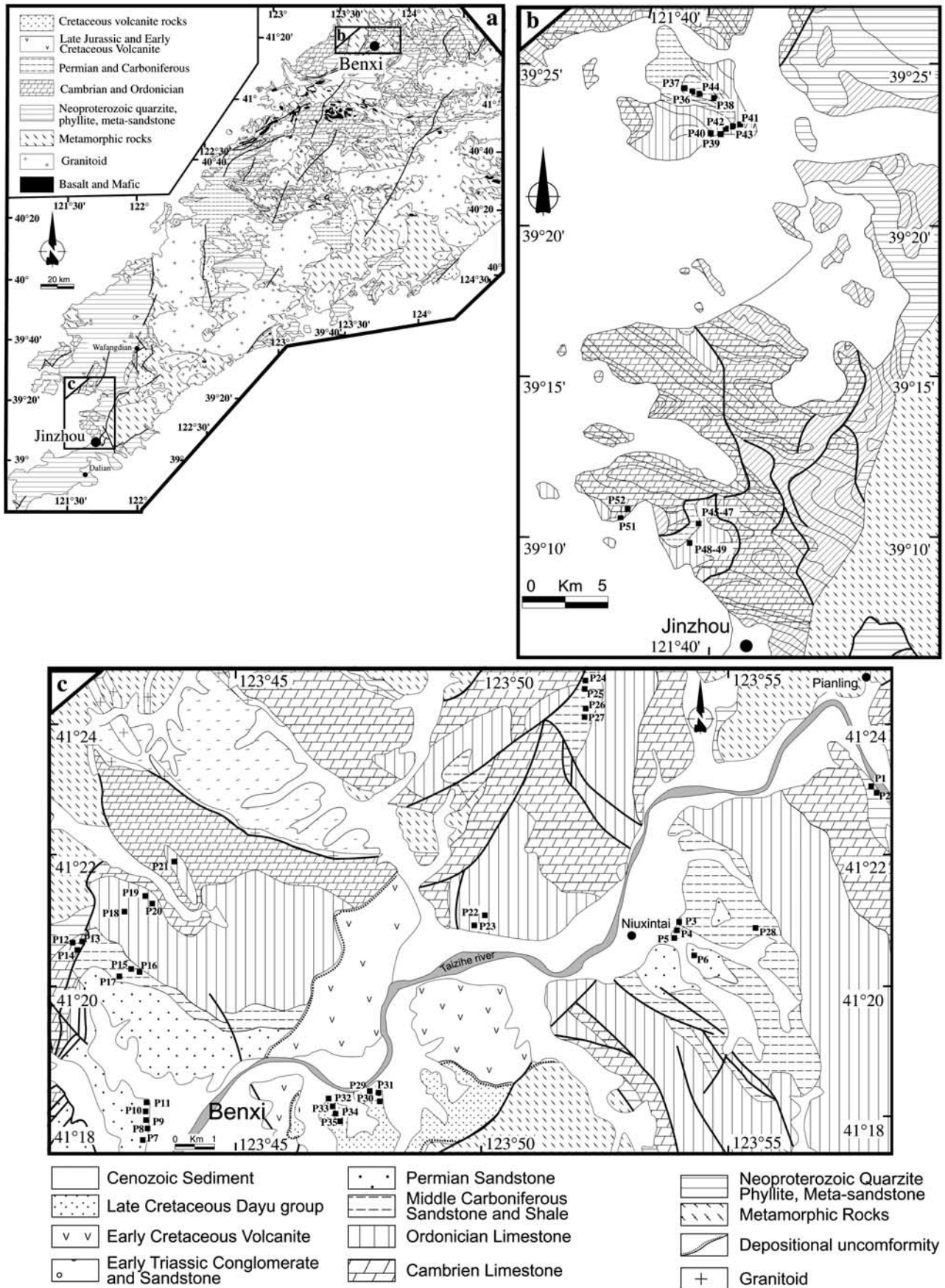
[12] Paleomagnetic sampling was carried out with a gasoline powered drill. Five to eight cores were taken in each site presenting a stratigraphic thickness of 5–10 m. Both magnetic and Sun compasses, when it was possible, were used for the core orientation. The average of difference between these two azimuths is about  $8.3^\circ \pm 3.3^\circ$ , and this

value is applied to the correction for the cores that do not possess solar measurements as well as bedding strikes.

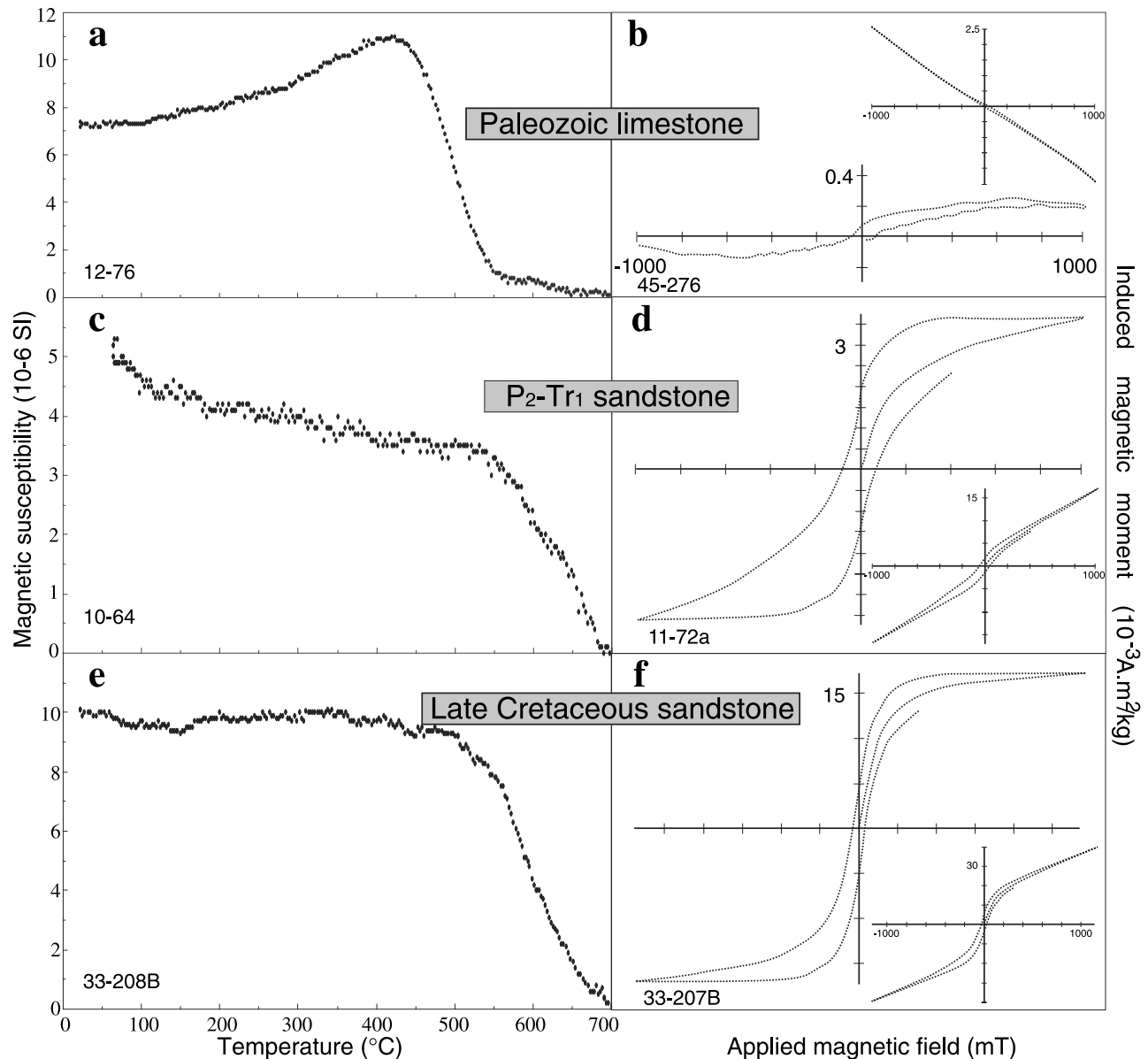
### 3. Paleomagnetic Results

#### 3.1. Laboratory Measurement and Directional Analytic Techniques

[13] In the laboratory, cores are prepared into standard specimens with 2.5 cm in diameter and 2.2 cm in length. Thermomagnetic experience is carried out by KLY3 kappa-bridge coupled with CS3 furnace. Magnetic hysteresis curves are obtained by a magnetic inductometer at Paleomagnetic Laboratory of Saint Maur (Paris), the anisotropy of magnetic susceptibility (AMS) was measured by KLY3



**Figure 2.** Simplified geological and paleomagnetic sampling maps of (a) Liaoning Province, (b) Benxi, and (c) Jinzhou areas, respectively. Solid squares represent sampling sites.



**Figure 3.** Magnetic mineralogical measurements. (a), (c), and (e) Thermomagnetic experiences and (b), (d), and (f) magnetic hysteresis curves for three age groups. The larger (smaller) curves show diamagnetic or paramagnetic reduced (bulk) measurements, respectively.

kappabridge. All sandstone and most limestone are subjected to progressive thermal and alternative field (AF) demagnetizations by about 12 to 16 steps with temperature intervals from 200°C to 10°C and 2 to 20 mT, respectively. The magnetic remanence is measured by JR5 magnetometer at the Laboratoire de Magnétisme des Roches d'Orléans for all sandstone and by 2G cryogenic magnetometers at the Institut de Physique du Globe de Paris for partial limestone. Magnetic directions are isolated by the principal component analysis [Kirschvink, 1980] and mean magnetic directions are calculated by the spherical analysis [Fisher, 1953]. Watson and Enkin [1993] method is applied to fold test.

[14] Because the number of sites for some geologic periods, such as the Neoproterozoic Qingbaikou group (two sites) and the Carboniferous-Permian Shanxi group

(one site), is too small to provide reliable paleomagnetic data, we present the results from 45 out of 51 sites for three main geologic periods: limestone-sandstone of the Paleozoic including O<sub>2m</sub>, C<sub>2b</sub>, C<sub>3t</sub>, coarse red sandstone of the P<sub>2</sub>-Tr<sub>1s</sub> and tufaceous red sandstone of K<sub>2d</sub>.

### 3.2. Paleozoic Limestone and Sandstone

[15] A generally weak natural remanent magnetization (NRM) was observed with a mean intensity of  $1.24 \pm 0.9 \times 10^{-3}$  A/m for all Paleozoic limestone and yellow-gray-green-white sandstone. Though thermal magnetic experience from limestone presents a relatively important susceptibility drop from 450°C to 550°C, indicating that the magnetite is probably the principal remanence carrier (Figure 3a), the magnetic hysteresis curve shows a diamagnetic mineral dominance for the limestone (Figure 3b).

More than 60 specimens are demagnetized in the pilot study by both thermal and AF methods. Few sandstone samples show stable magnetic remanence (Figure 4a), and all limestone ones display a solo normal polarity (Figures 4b and 4c). The mean direction of these samples is more clustered in the geographic coordinates than that in stratigraphic ones:  $D_g = 5.5^\circ$ ,  $I_g = 60.7^\circ$ ,  $\kappa_g = 75.5$ , and  $\alpha_{95g} = 2.7^\circ$ ;  $D_s = 341.6^\circ$ ,  $I_s = 63.3^\circ$ ,  $\kappa_s = 6.0$  and  $\alpha_{95s} = 10.5^\circ$  (Figure 5a). The negative fold test is concluded [Watson and Enkin, 1993]. The mean direction in geographic coordinates is close to the Present Earth Field (PEF)(the dipolar direction,  $D = 0^\circ$  and  $I = 58.9^\circ$ ; the IGRF direction,  $D = 351.8^\circ$  and  $I = 58.9^\circ$ ; Figure 5a).

### 3.3. P<sub>2</sub>-Tr<sub>1</sub> Coarse Red Sandstone

[16] The average of NRM intensity for these coarse red sandstones is  $\sim 9.18 \pm 3.86 \times 10^{-3}$  A/m. The Curie temperature experience displays two possible susceptibility drops at from 480 to 580 and 600 to 680, respectively (Figure 3c). The magnetic hysteresis curves present the dominance of paramagnetic minerals with magnetic induced saturation at  $3.6 \times 10^{-3}$  A m<sup>2</sup>/kg and magnetic coercive force at 32.3 mT (Figure 3d). Thus the hematite could be considered as the main remanence carrier with a weak proportion of magnetite. Most thermal demagnetization reveals only a single component ranging from 20°C to 680°C (Figure 4d). Only a few specimens present a well-isolated and no originward “lower” temperature component with a tendency of another component at higher temperature (Figures 4e and 4f). Because of the small number of specimens and weak magnetic remanent intensity, no stable and reliable directions would be isolated and computed from the latter component. Fisher statistics of directions isolated from single, and sometimes “lower” temperature, component gives a slight better cluster distribution of directions in geographic coordinates than those in stratigraphic one:  $D_g = 359.9^\circ$ ,  $I_g = 66.4^\circ$ ,  $\kappa_g = 510.5$  and  $\alpha_{95g} = 3.4^\circ$ ;  $D_s = 353.7^\circ$ ,  $I_s = 82.4^\circ$ ,  $\kappa_s = 216.4$  and  $\alpha_{95s} = 5.2^\circ$  (Figure 5b and Table 2). The fold test is negative according to Watson and Enkin [1993] method and the in situ mean direction is close to PEF (Figure 5b).

### 3.4. K<sub>2d</sub> Fine-Grained to Muddy Sandstone

[17] This age group of fine-grained to muddy sandstone presents a higher proportion of soft magnetic minerals with respect to two former groups with a higher NRM intensity of  $38.8 \pm 13.2 \times 10^{-3}$  A/m. Magnetic hysteresis curves confirm this observation with higher magnetic induced saturation at  $17.1 \times 10^{-3}$  A m<sup>2</sup>/kg and magnetic coercive force at 14.9 mT (Figure 3f). Curie temperature determination shows a stable susceptibility until nearly 500°C and a continuous drop from about 500°C to 680°C (Figure 3e). The above observations indicate that both magnetite and hematite may be the main magnetic remanence carriers. Some specimens present both lower- and higher-temperature components varying from 20°C to 300°C and 300°C to 680°C, respectively (Figure 4g). The remaining shows just a single component (Figure 4h). Both of them are of normal polarity, i.e., northeastward declination and downward inclination. The lower-temperature component shows scattered directions probably due to the magnetic viscosity. The higher-temperature component is interpreted as char-

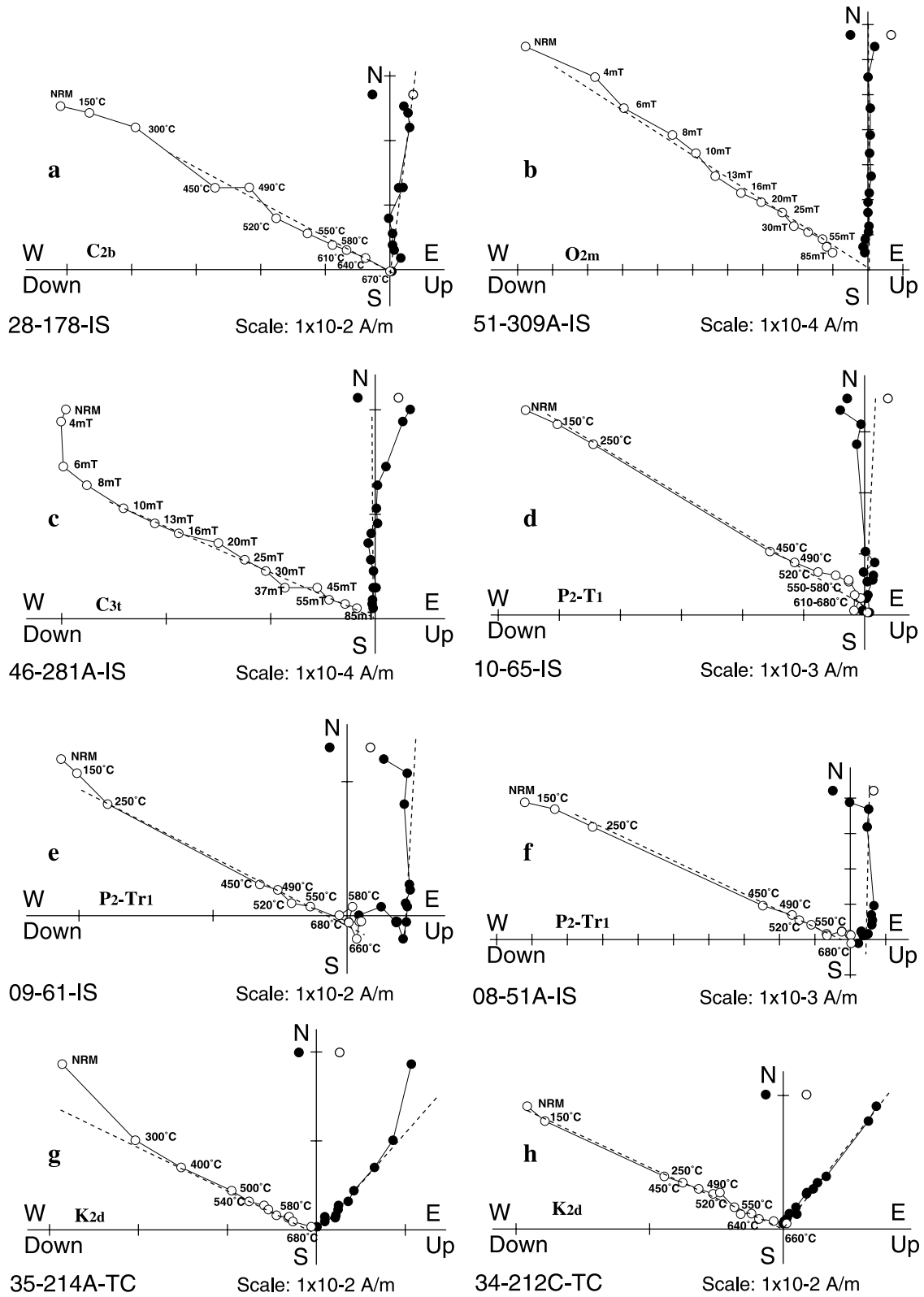
acteristic remanent magnetization (ChRM). The ChRM presents a better clustered distribution of directions in stratigraphic coordinates ( $D_s = 40.1^\circ$ ,  $I_s = 57.9^\circ$ ,  $\kappa_s = 70.1$ , and  $\alpha_{95s} = 7.3^\circ$ ) than those in geographic ones ( $D_g = 39.6^\circ$ ,  $I_g = 75.4^\circ$ ,  $\kappa_g = 42.5$ , and  $\alpha_{95g} = 9.4^\circ$ ; Figure 5c), giving a positive fold test with a maximum grouping of directions at 83.7% unfolding (with statistic uncertainties ranging from 68.7 to 95.1 [Watson and Enkin, 1993]). Thus a paleomagnetic pole is calculated:  $\lambda_p = 59.4^\circ$ N,  $\phi_p = 205.5^\circ$ E and  $A_{95} = 7.3^\circ$  (Table 3).

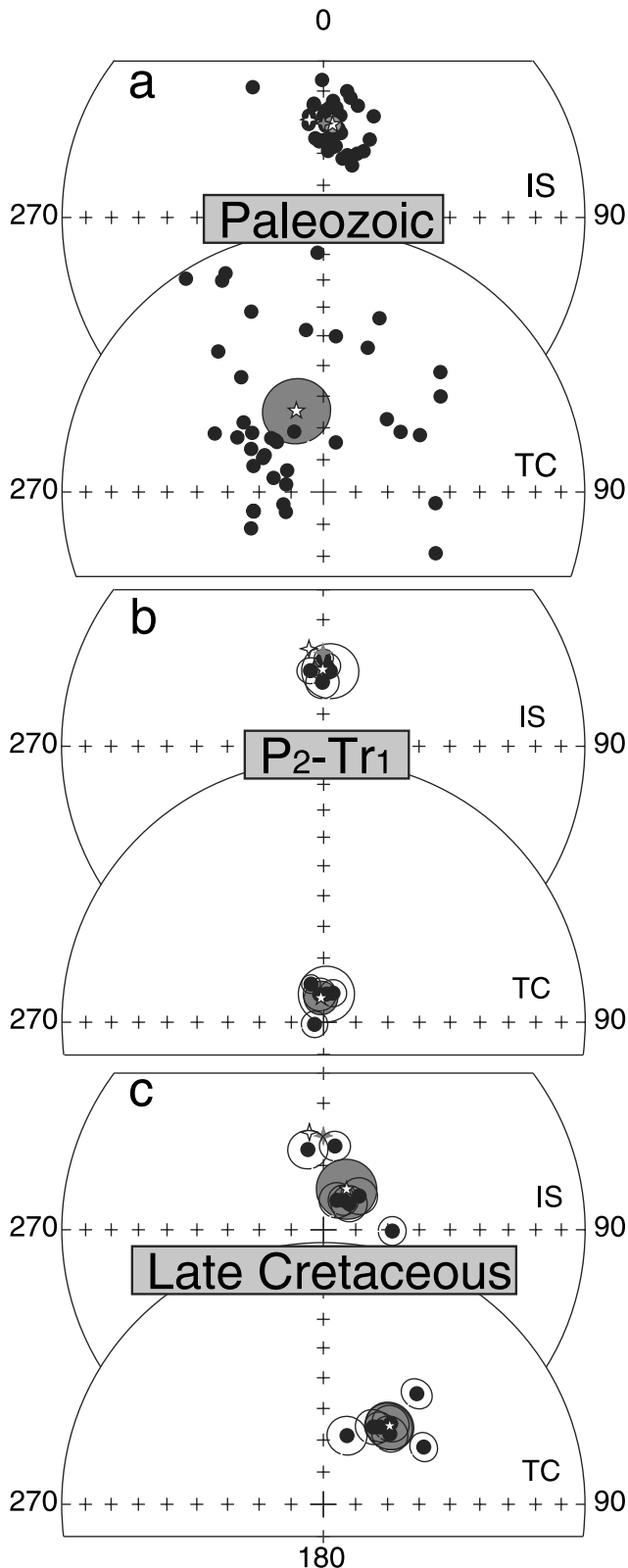
## 4. Interpretation and Discussion

### 4.1. Evidence for Clockwise Rotation of the ELK Block

[18] Three age groups have been paleomagnetically analyzed: Paleozoic limestone/yellow-gray sandstone, Permo-Triassic coarse red sandstone, and Late Cretaceous fine-grained to muddy red tuffaceous sandstone. The former two show better clustered magnetic directions in geographic coordinates, being undistinguishable from PEF, than those in stratigraphic ones and indicating a remagnetization. The Paleozoic limestone is well fractured, folded, and, sometimes, overturned. The fractures are often filled with secondary mineral crystallizations. The brittle deformation likely enhances fluid circulations that may produce a chemical remagnetization. In order to characterize the sedimentary fabrics of the P<sub>2</sub>/Tr<sub>1s</sub> coarse red sandstone, a study of the anisotropy of magnetic susceptibility (AMS) has been carried out on the rocks. The AMS measurements show a good cluster of the vertical axes of foliation poles ( $K_3$ ) with a scattered distribution of maximum and intermediate axes,  $K_1$  and  $K_2$ , respectively (Figure 6a). The mean values for the shape parameter,  $T$ , about 0.4, and for the anisotropy degree,  $P'$ ,  $\sim 1.025$ , are typical of sedimentary origin (Figure 6a) [Tarling and Hrouda, 1993]. This AMS observation implies that the P<sub>2</sub>/Tr<sub>1</sub> red sandstone did not experience a significant tectonic deformation; therefore the remagnetization of the P<sub>2</sub>/Tr<sub>1</sub> rocks could be either of chemical and/or thermal origins. In the study area the important Mesozoic and Early Cenozoic thermal events have been evidenced in widespread zones but with few Quaternary ones mostly concentrated in the Changbaishan mountain at the boundary between China and North Korea [Cheng, 1990; Liu, 1988] and in the northern part of research area [Liaoning Bureau of Geology and Mineral Resources-Kuandian, 1967]. The isolated direction from this coarse red sandstone, being consistent with PEF, should be a record of the recent geomagnetic field for following reasons: (1) if the remagnetization age was older than the Late Cretaceous, these rocks should have suffered the same rotation as K<sub>2d</sub> sandstone because of the geographic proximity between these two localities, and (2) the apparent polar wander path (APWP) of the Eurasian landmass predicts a significantly different paleoposition and a relatively rapid latitudinal drift of the studied area during the Tertiary [Besse and Courtillot, 2002]. Therefore the chemical origin of the remagnetization could be considered as main factor for these coarse red beds.

[19] The characteristic remanent magnetization (ChRM) of K<sub>2d</sub> red tuffaceous sandstone carried by both magnetite and hematite and presenting a positive fold test probably





**Figure 5.** Equal-area projections of mean directions (a) at sample level for Paleozoic rocks and at site levels for (b)  $P_2$ - $Tr_{1s}$  and (b)  $K_{2d}$  rocks. IS and TC stand for in situ (geographic) and tectonic corrected (stratigraphic) coordinates. Solid (open) diamond presents dipolar (actual) geomagnetic field of sampling areas. Star stands for the age mean direction.

**Table 2.** Paleomagnetic Results From  $P_2$ - $Tr_{1s}$  and  $K_{2d}$  Age Groups<sup>a</sup>

Site	<i>n</i>	Geographic coordinates		Stratigraphic coordinates		$\kappa$	$\alpha_{95}$ , deg
		D, deg	I, deg	D, deg	I, deg		
<i>P<sub>2</sub>-Tr<sub>1s</sub> Coarse Red Sandstone</i>							
7	5	359.6	70.4	352.1	81.3	225.3	5.1
8	6	2.8	65.2	18.0	80.5	250.1	4.2
9	6	0.6	62.8	341.7	77.5	253.1	2.9
10	6	350.5	66.4	256.7	87.1	273.6	4.1
11	6	5.7	66.7	5.7	81.2	60.6	8.7
Mean <sup>b</sup>	5	359.9	66.4			510.5	3.4
Results <sup>c</sup>				353.7	82.4	216.4	5.2
<i>K<sub>2d</sub> Red Tuffaceous Sandstone</i>							
29	5	7.8	63.5	40.2	43.8	270.5	4.7
30	3	349.0	64.4	19.0	67.3	409.7	6.1
31	8	24.4	79.9	32.9	61.1	103.1	5.5
32	5	91.0	68.5	60.3	53.5	304.9	4.4
33	6	33.8	78.9	36.2	59.9	207.8	4.7
34	5	46.6	74.7	39.8	56.9	179.8	5.7
35	5	44.5	78.6	43.4	59.6	190.5	5.6
Mean <sup>b</sup>	7	29.6	75.4			42.5	9.4
Results <sup>c</sup>				40.1	57.9	70.1	7.3

<sup>a</sup>*D*, *I*,  $\kappa$ , and  $\alpha_{95}$  are magnetic declination, inclination, Fisher [1953] statistic precision parameter, and uncertainty at 95% confidence level, respectively.

<sup>b</sup>Statistical results before bedding correction.

<sup>c</sup>Statistical results after bedding correction.

shows a primary origin of magnetic remanence. Furthermore, the weak anisotropy degree of AMS (1.021) and the well-grouped but quasi-horizontal inclination of  $K_1$  axes imply that these  $K_{2d}$  sandstones have not experienced important deformation since their diagenesis (Figure 6b). The solo normal polarity may indicate that the remanence age is comprised in the Cretaceous Long Normal Superchron (CLNS) between 118 and 83 Ma.

[20] More and more paleomagnetic data become available for both NCB and SCB, particularly for the Cretaceous age, with a relatively good geographic cover. Several paleomagnetic syntheses on their geodynamic history have been therefore proposed [e.g., Enkin *et al.*, 1992; Gilder and Courtillot, 1997; Yang and Besse, 2001]. One of their main conclusions is that these two continents did not experience a paleomagnetically observable relative displacement since the Early Cretaceous. This conclusion is illustrated in Figure 7b by all available Cretaceous poles from both NCB and SCB listed in Table 3. The angular difference computed from the polar averages of these two continents is statistically insignificant ( $3.2^\circ \pm 6.7^\circ$ ). Thus a mean paleomagnetic pole with  $\lambda_p = 77.7^\circ\text{N}$ ,  $\phi_p = 205.9^\circ\text{E}$ , and  $A_{95} = 3.7^\circ$  (Table 3) can be calculated for the whole NCB and SCB (hereinafter this single landmass will be called ‘‘Chinese Block’’).

[21] On the basis of geological correlation on both sides of the Tan-Lu fault, Xu *et al.* [1987] argued for a relative left-lateral motion of several hundreds of kilometers along the Tan-Lu fault during the Late Triassic to Early Cretaceous period. Several models based on this large sinistral wrenching have been then proposed to account for the geodynamics of eastern Asia [e.g., Kimura *et al.*, 1990; Yin and Nie, 1993; Xu and Zhu, 1994; Li, 1994]. Gilder *et al.* [1999] published paleomagnetic results from Shandong and Anhui Provinces on the both sides of Tan-Lu fault with

**Table 3.** Available Cretaceous Paleomagnetic Poles From North China Block (NCB), South China Block (SCB), Eastern Liaoning-Korea Block (ELKB), and Eurasian Reference<sup>a</sup>

Age	Coordinates		<i>N</i>	$\lambda_p$	$\phi_p$	$A_{95}$	References
	Lat, °N	Long, °E					
<i>North China Block (NCB)</i>							
$K_1$	42.0	119.2	6	82.9	249.5	5.7	Zhao <i>et al.</i> [1990]
$K_1$	35.0	108.0	10	75.8	208.7	7.5	Ma <i>et al.</i> [1993]
$K_1$	37.0	120.7	11	81.3	217.3	5.9	Gilder <i>et al.</i> [1999]
$K_1$	45.4	107.6	3	87.3	247.6	21.6	Pruner [1992] <sup>b</sup>
$K_1$	39.9	97.7	9	75.5	169.9	7.7	Chen <i>et al.</i> [2002]
Mean $K_1$			5	81.7	206.8	6.7	
$K_{1-2}$	37.2	105.0	10	74.5	203.4	8.2	Wu <i>et al.</i> [1993]
$K_{1-2}$	31.6	116.0	10	74.5	201.0	4.7	Gilder and Courtillot [1997]
$K_2$	40.1	112.9	4	79.6	170.1	5.8	Zheng <i>et al.</i> [1991]
Mean $K_{1-2}$			8	79.8	200.6	4.5	
<i>South China Block (SCB)</i>							
$K_1$	29.7	120.3	7	77.1	227.6	5.5	Lin [1985]
$K_1$	22.2	114.2	12	78.2	171.9	10.6	Chan [1991]
$K_1$	30.0	102.9	23	77.9	244.5	3.2	Enkin <i>et al.</i> [1991]
$K_1$	25.9	101.7		64.6	199.6	3.3	Otofuji <i>et al.</i> [1998]
$K_1$	26.8	102.5	7	69.0	204.0	4.3	Huang and Opdyke [1992]
$K_1$	22.7	108.7	8	86.5	26.4	6.8	Gilder <i>et al.</i> [1993]
$K_1$	18.8	109.4	6	83.2	143.0	9.8	Li <i>et al.</i> [1995]
$K_1$	27.9	102.3	11s	77.4	196.2	14.5	Zhu <i>et al.</i> [1988]
Mean $K_1$			8	78.8	202.1	7.1	
$K_2$	25.0	116.4	20	67.9	186.2	9.2	Hu <i>et al.</i> [1990]
$K_2$	32.0	119.0	19	76.3	172.6	10.3	Kent <i>et al.</i> [1987]
$K_2$	23.0	115.0	43s	66.0	221.5	3.4	Hsu [1987]
$K_2$	26.0	117.2	5	66.9	221.4	5.4	Zhai <i>et al.</i> [1993]
$K_2$	30.8	117.5	4	83.8	200.2	14.6	Gilder <i>et al.</i> [1999] <sup>b</sup>
$K_2$	30.0	102.9	16	74.8	250.8	6.6	Enkin <i>et al.</i> [1991]
$K_2$	26.5	102.3	18	81.9	220.9	7.1	Huang and Opdyke [1992]
$K_2$	26.0	117.3	20	65.1	207.2	5.0	Gilder <i>et al.</i> [1993]
$K_2$	23.1	113.3	19	56.2	211.5	3.9	Gilder <i>et al.</i> [1993]
$K_2$	23.7	108.7	9	79.4	7.1	10.0	Gilder <i>et al.</i> [1993]
$K_2$	26.6	102.4	20s	78.9	186.6	5.5	Zhu <i>et al.</i> [1988]
Mean $K_2$			11	75.2	210.7	7.5	
Mean $K_{1-2}$			19	76.7	207.6	5.0	
Mean $K_{1-2}$	NCB + SCB	27	77.7	205.9	3.7		
<i>Eastern Liaoning-Korean Block (ELKB)</i>							
$K_2$	41.3	123.8	5	59.3	202.6	6.0	Uchimura <i>et al.</i> [1996]
$K_2$	41.3	123.8	7	59.4	205.5	7.3	this study
$K$	36.0	128.5	65	64.0	195.0	6.4/8.4	Otofuji <i>et al.</i> [1986]
$K_1$	35.9	128.5	19	67.6	205.1	5.8	Lee <i>et al.</i> [1987]
$K_1$	35.9	128.6	15	68.7	199.0	8.9	Zhao <i>et al.</i> [1999] <sup>b</sup>
$K_1$	37.1	129.0	14	46.7	200.4	9.6	Doh and Piper [1994]
Mean $K_{1-2}$			6	61.0	201.3	6.8	
<i>Eurasia</i>							
$K$ 110 ± 10 Ma			18	79.9	181.9	3.9	Besse and Courtillot [2002]

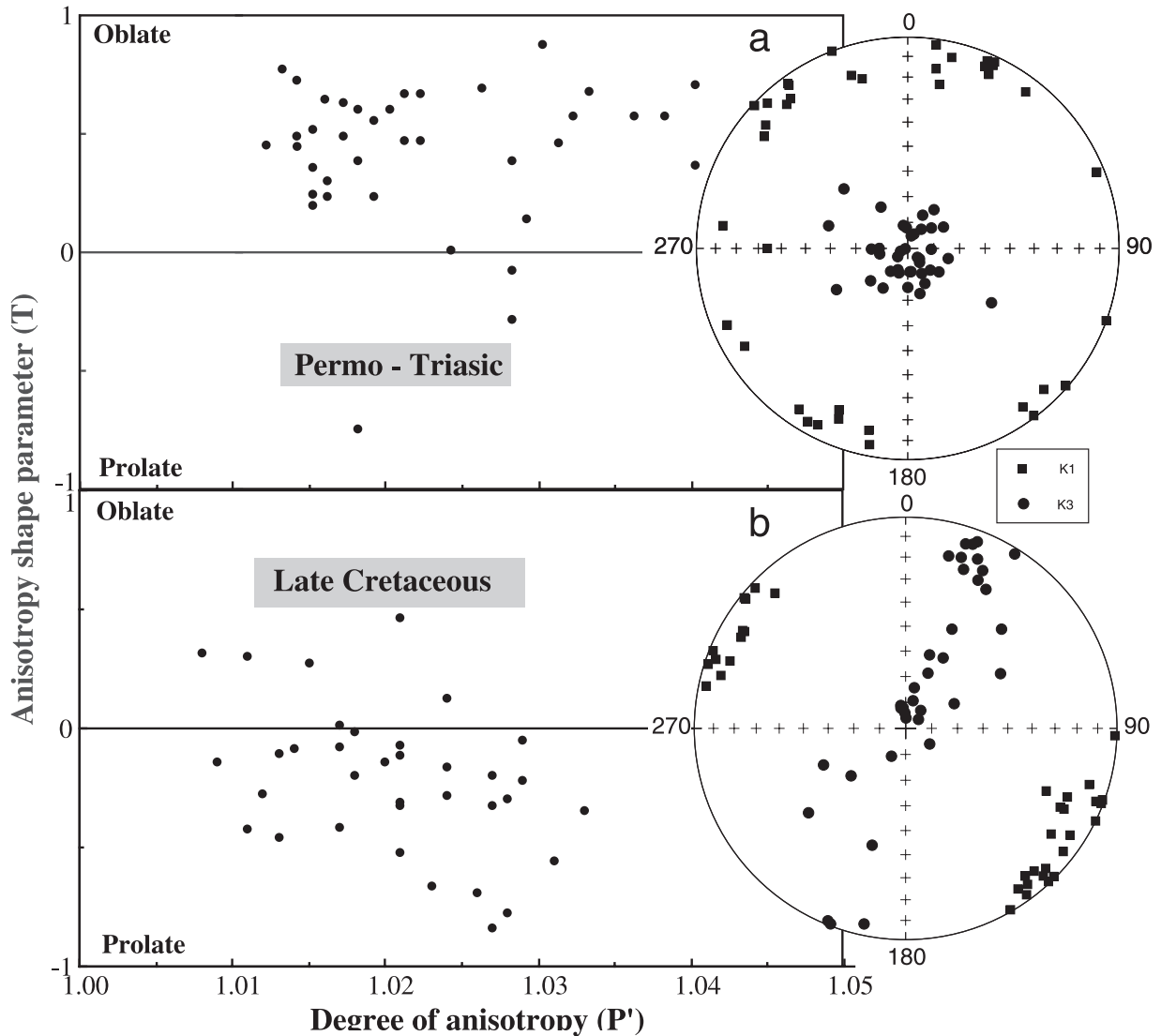
<sup>a</sup>Lat and Long symbolize the geographic coordinates in latitude and longitude of corresponding study area; *N* (*s*) stands for the number of sites (samples);  $\lambda_p$ ,  $\phi_p$  and  $A_{95}$  present polar coordinates and uncertainty at 95% confidence level, respectively.

<sup>b</sup>Pole recalculated from original paper.

rock ages spanning from the Late Triassic to Early Cretaceous. The significant difference among the data older than Late Cretaceous from two sides of the fault and a good coherence among younger data led the authors to conclude that the relative motion along the fault, if there was any, should have occurred before the Late Cretaceous. If the Benxi area belonged to the Chinese Block at the age of the studied rocks (Figure 1), i.e., in the Late Cretaceous, this conclusion should also be sound for it. In other words, the Late Cretaceous paleomagnetic data from the Benxi area should be statistically consistent with those of the Chinese Block. However, the significant discrepancy of the Benxi area with Chinese Block by an angular difference of  $18.5^\circ \pm$

$8.2^\circ$  indicates that Benxi area has significantly moved with respect to the Chinese Block.

[22] To clarify if this relative motion corresponds either to a local one, as post-Cretaceous tectonics are not negligible in the study area, or to a continental-size block displacement, a review of previous paleomagnetic data from surrounding areas is necessary. In fact, a paleomagnetic study has been carried out on Paleozoic and Upper Cretaceous rocks near our sampling area [Uchimura *et al.*, 1996]. Though Uchimura *et al.* mentioned that the Paleozoic data are too scattered to give some tectonic explanation (probably due to remagnetization), the Upper Cretaceous paleomagnetic data are compatible to ours with an angular

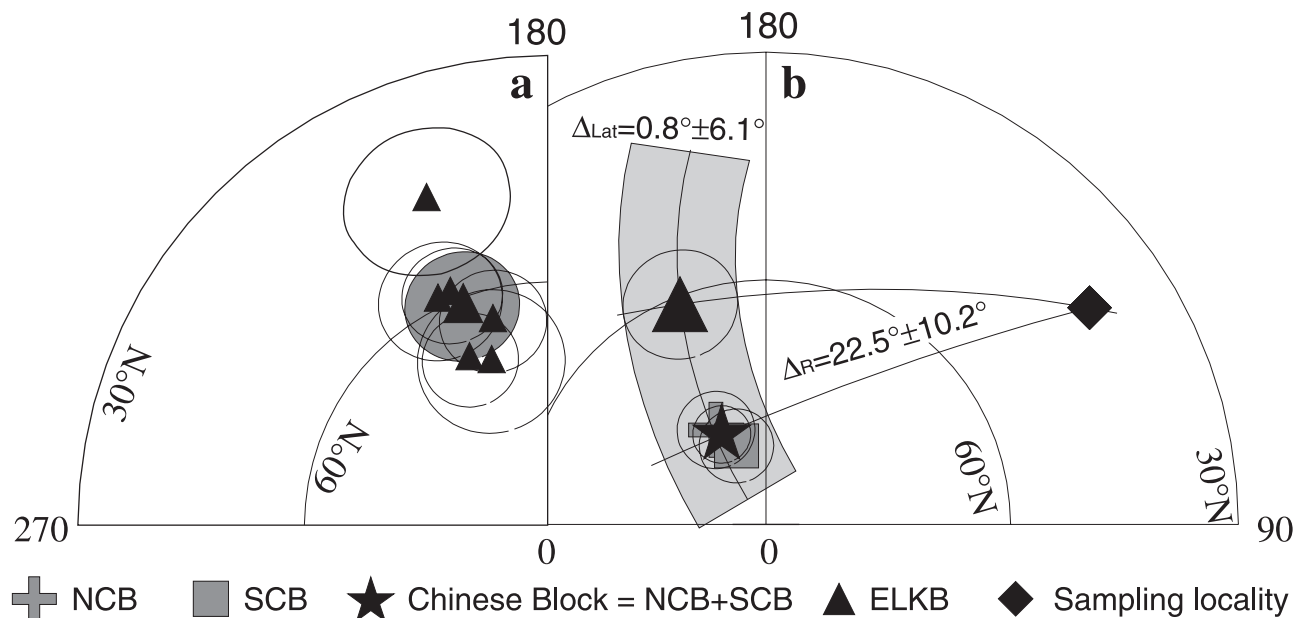


**Figure 6.** Anisotropy degree ( $P'$ ) against shape parameter ( $T$ ) and equal-area projection of maximal ( $K_1$ ) and minimal ( $K_3$ ) axes of the anisotropy of magnetic susceptibility for  $P_2$ - $Tr_{1s}$  and  $K_{2d}$  age groups.

$$(P = \exp \sqrt{[(\ln K_{\max} - \ln K_{\text{mean}})^2 + (\ln K_{\text{int}} - \ln K_{\text{mean}})^2 + (\ln K_{\min} - \ln K_{\text{mean}})^2]} \text{ with } K_{\text{mean}} = (K_{\max} + K_{\text{int}} + K_{\min})/3; T = [2 \ln (K_{\text{int}}/K_{\min})/\ln(K_{\max}/K_{\min})] - 1 \text{ [Jelinek, 1981]}.$$

difference of  $1.5^\circ \pm 9.4^\circ$  (Table 3). *Zhao et al.* [1999] presented three apparent geomagnetic poles from the Taegu region (Ryongnam massif) in South Korea and argued that the Korean Peninsula has rotated clockwise by  $34.3^\circ$ ,  $24.9^\circ$ , and  $-0.9^\circ$  with respect to Eurasia during Early, Middle, and Late Aptian, respectively. As the uncertainty at 95% confidence level for the Cretaceous pole of the Eurasian reference is relatively small ( $3.9^\circ$  [Besse and Courtillot, 1991]), the relative rotations are significant. However, if these three poles are projected in a same plot, their uncertainties overlap each other; in other words, they are not significantly different at 95% confidence limits. Moreover, because the Middle Aptian data resulted from three volcanic flows, it would be suspect whether the secular variation has been averaged out. If the relative rotations present a geological reality, a simple calculation of the possible rotation ( $35.2^\circ$ ) on the maximal Aptian duration (5 Ma [Odin,

1994]) gives an average rotation velocity of  $7^\circ/\text{Myr}$ , which seems too fast for this region as no important tectonic events have been documented for this period. On the basis of above reasons, we recalculate a mean pole from all sites of *Zhao et al.* [1999] (Table 3). Figure 7a presents all Cretaceous paleomagnetic data from different zones and types of rocks from East Liaoning and South Korea. Apart from that of *Otofujii et al.* [1986], the other five independent data are statistically consistent (Table 3). This observation leads us to suggest that Eastern Liaoning and Korea Peninsula may constitute a tectonically single and coherent unit, which is called the East Liaoning-Korea (ELK) Block in the following, at least since the Late Cretaceous. This paleomagnetic conclusion complies with geological evidence that in the Late Cretaceous the whole Korea Peninsula behaved as a unique continental mass. Therefore a mean pole for the ELK Block has been computed (Table 3).



**Figure 7.** (a) All available magnetic poles from Eastern Liaoning and Korea Block (small triangles) with the corresponding average (large triangle). (b) Equal-area projection of mean paleomagnetic poles from NCB, SCB, and ELKB with the sampling locality of this study. Cross, square, star, triangle, and diamond show the mean poles from NCB, SCB, NCB + SCB, ELKB, and sampling locality, respectively.  $\Delta_R$  and  $\Delta_{\text{Lat}}$  show the relative difference in rotation and latitudinal displacement, respectively, between NCB + SCB and ELKB.

[23] The comparison of the ELK Block pole with that of the Chinese Block shows a statistically significant difference:  $16.9^\circ \pm 7.6^\circ$ . This angular difference presents a relative latitudinal motion of  $0.8^\circ \pm 6.1^\circ$  and a relative rotation of  $22.5^\circ \pm 10.2^\circ$  between these two tectonic units at the geographic reference of  $41.3^\circ\text{N}$  and  $123.8^\circ\text{E}$  (the sampling locality of this study). This calculation indicates that the relative motion between the ELK Block and the Chinese Block is essentially in the relative rotation instead of in the latitudinal displacement. In other words, the 800-km strike-slip motion along the northern continuity of Tan-Lu fault in Liaoning Province estimated by *Uchimura et al.* [1996] is not supported by our data. This conclusion is consistent with field observation. In several places in Jiangxi, Anhui, and Shandong Provinces, the Tan-Lu fault appears as a normal fault that controls the opening and sedimentary infill of Cretaceous continental red beds [e.g., *Mattauer et al.*, 1985; *Gilder et al.*, 1999; *Faure et al.*, 1999; *Ratsbacher et al.*, 2000; *Lin et al.*, 2000, also Polyphase deformation in the Feidong-Zhangbaling Massif (eastern China) and its place in the collision between North China and South China Blocks, submitted to *Tectonophysics*, 2002].

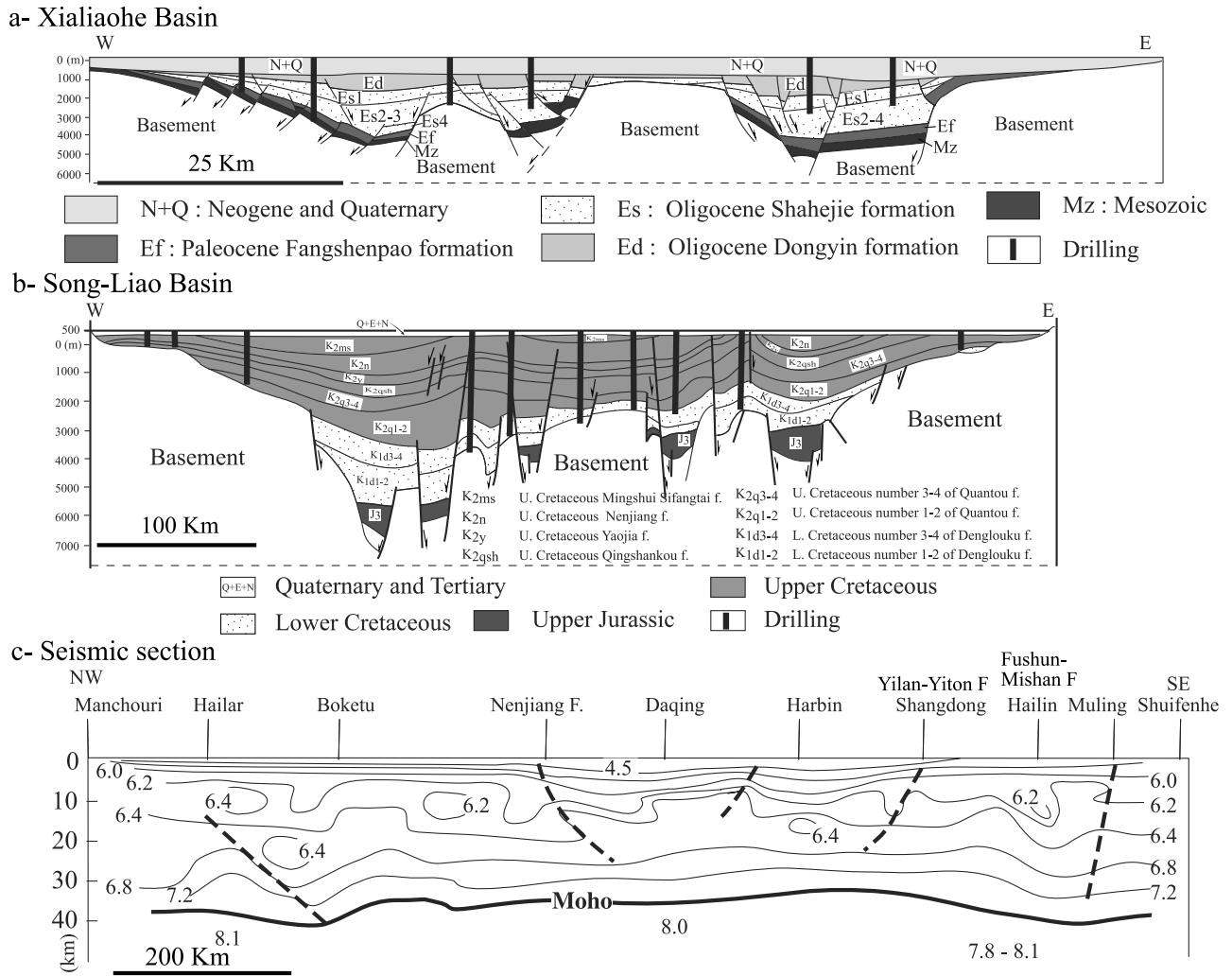
[24] Conversely to a classic tectonic explanation that would relate the clockwise rotation of ELK Block to the strike-slip motion along the Tan-Lu fault, we would like to propose here an alternative interpretation in which this discrepancy of paleomagnetic data between the Chinese and ELK Blocks is the result of the rifting of the Songliao and other basins of NE China.

#### 4.2. Rifting of the NE China Basins

[25] The northeastern (NE) China plain consists of two major Meso-Cenozoic basins: the Xialiaohu and Songliao

basins in the south and north, respectively (Figure 1). The Zeya basin in Russia is the northern continuation of the Songliao one, and other basins (Sanjiang, Boli, and Jixi) crop out east of the Yilan-Yitong fault (Figure 10a). It is worth noting, even from the topography, that this area which comprises the Meso-Cenozoic basins of NE China forms a triangular shape with a progressive width increase from the southwest to the northeast (Figure 1). A good understanding of the rifting history of these basins may bring new insights for the tectonic relationships between the ELK and Chinese Blocks.

[26] In the northern portion of the Bohai Bay basin, the Xialiaohu basin (Figure 1), started to rift in Paleocene and ended its extension in the Oligocene [Yu, 1989; Allen et al., 1998]. The small amounts of Late Jurassic and Early Cretaceous volcanic rocks and coal-bearing sediments indicate an early but limited rifting episode (Figure 8a). The Songliao basin is a Late Mesozoic extensional basin (Figures 1 and 8b). The Late Jurassic fluvial and lacustrine sediments intercalated with volcanic rocks were preserved only in the deepest parts of the trough. The Early Cretaceous was the initial rifting period when the Dengloulou formation ( $K_1$ ) accumulated in 20 NNE trending grabens in which the fluvial and lacustrine sedimentary thickness is more than 2000 m (Figures 8b and 9). During Late Cretaceous, fluvial and lacustrine sediments more than 3000 m thick, corresponding to the Quantou to the Nenjiang formations ( $K_2$ ), were deposited in a starved basin with an area of almost 7 times of that of previous grabens (Figure 8b). Numerous characteristic fossils, such as *Asterisporites radiata* and *A. stellate*, are frequently found in the upper portion of the Quantou formation. Angiospermous pollen, such as *Cranwellia stiatella* and *Lythraidites debilis*, occurred at a ratio of



**Figure 8.** Cross sections through (a) the Xialiaohe basin and (b) the Songliao basin [Chen et al., 1999]. (c) A structural reinterpretation of a seismic section at the crustal scale [after Yu, 1989]. All sections are located in Figure 1.

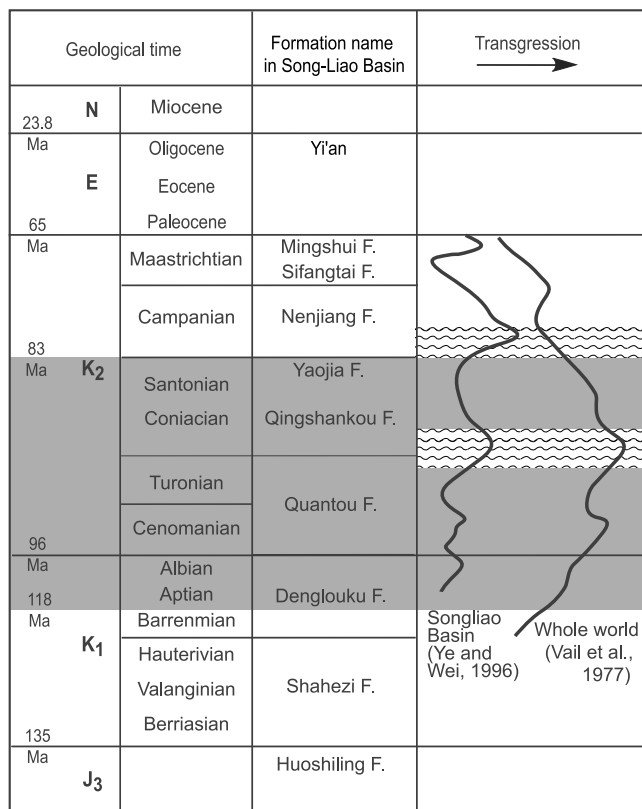
9–30% in the Quantou formation ( $K_2$  [Li, 2001]). Therefore the age of the Quantou formation is confidently assigned to the Turonian and Cenomanian (Figure 9). Marine transgressions that occurred in the upper portion of the Qingshankou formation ( $K_2$ ) and the lower portion of the Nenjiang formation ( $K_2$ ) are evidenced by brackish to seawater fossils, glauconite, as well as calcareous nannofossils in condensed sections (Figure 9) [Ye and Wei, 1996]. The Latest Cretaceous Sifangtai and Mingshui formations composed of fluvial sediments are preserved only in the western part of the Songliao basin, in agreement with a westward migration of the depocenter at the end of Mesozoic time. The Oligocene deposited unconformably on slightly folded Cretaceous strata.

[27] Recent geochemical and geochronological studies of the volcanic rocks in the Songliao basin provided evidences for a subduction-related tectonic setting for a part of the Cretaceous magmatism [e.g., Wang et al., 2002, and references therein]. Wang et al. relate this magmatism to a southward subduction along the Mongol-Okhotsk Belt (Figure 1). However, such an interpretation is not supported

by geologic observations since the Mongol-Okhotsk Belt trends E-W along several hundred kilometers, whereas the Songliao volcanic rocks develop along a NNE-SSW trend, that is to say, nearly perpendicular to the Mongol-Okhotsk Belt to the inferred subduction zone. It is worth noting that a geochemical calc-alkaline signature of volcanic rocks does not preclude extensional tectonics. Indeed, in Cretaceous time the subduction zone along the eastern margin of Asia was located ~1000 km east of the Songliao basin. Therefore the development of the Songliao basin can be considered as a rift basin mainly opened in Late Cretaceous-Cenozoic times within a Cretaceous magmatic arc.

[28] To the east of the Yilan-Yitong fault, the Sanjiang basin is a superimposed basin, in which Cretaceous lacustrine sediments are unconformably overlain by 3000-m-thick Tertiary dark colored mudstone [Guo and Liu, 1989]. In the Boli and Jixi basins (Figure 10a), only thick Cretaceous or Eocene sediments with thickness of 4000 m and 3000 m, respectively, are preserved.

[29] Regional seismic investigations show that the Songliao basin is characterized by a relatively thin con-



**Figure 9.** Comparison of the world transgression [after Vail et al., 1977] to that of the Songliao basin [after Ye and Wei, 1996] characterizing the local basin evolution during the Late Cretaceous. The shaded zone presents the possible magnetic remanence age within the Cretaceous Long Normal Superchron (CLNS).

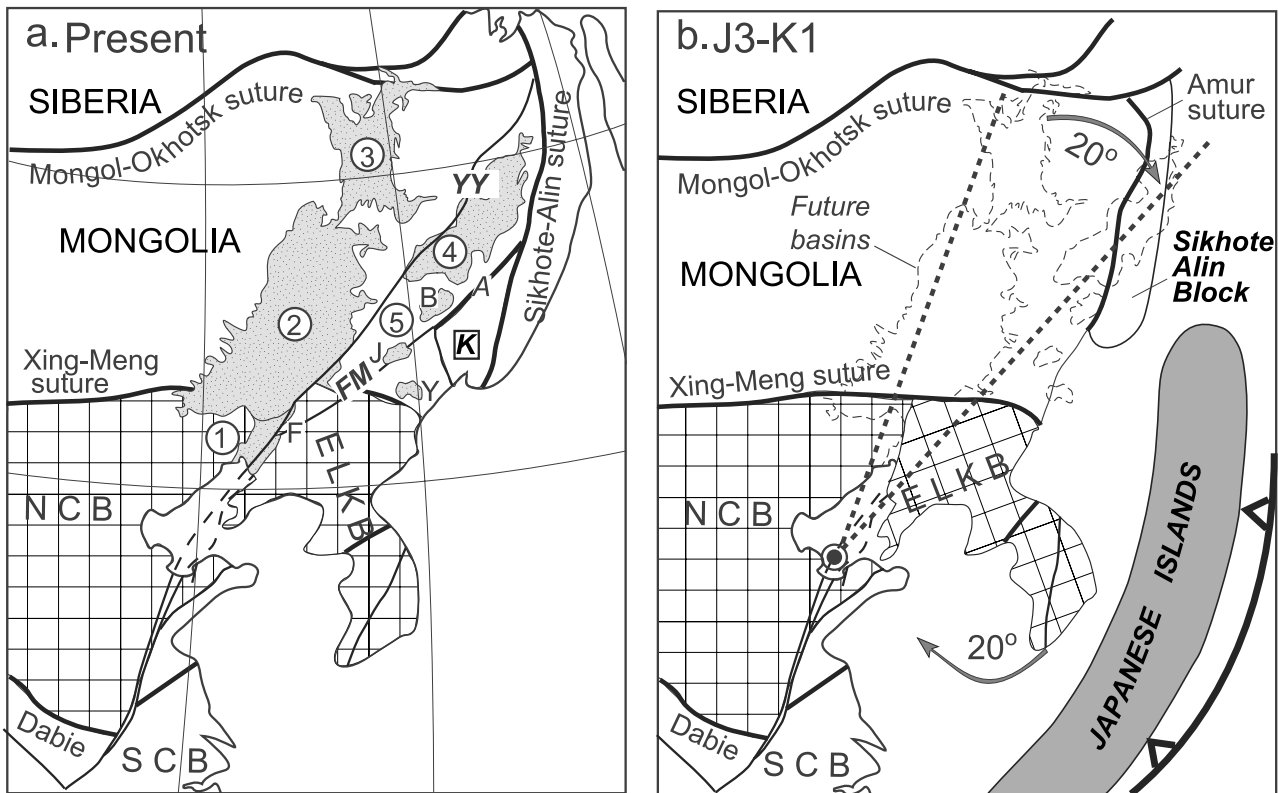
tinental crust and lithosphere with high heat flow [Ma, 1987; Yu, 1989; Yang et al., 1997; Menzies and Xu, 1998]. The thickness of the crust varies from 29 to 35 km from the center to margin of the basin, respectively (Figure 8c) (In the Songliao basin surroundings, the crust reaches a 35–40 km thickness, and the lithosphere thickness ranges from 60 to 80 km, which is much thinner than those in the surrounding areas.) Thus geophysical observations suggest that the Songliao basin was developed in an extensional tectonic regime.

[30] The above mentioned evolution of the sedimentary basins in this region clearly reveals an inhomogeneous rifting history. In fact, all Late Jurassic to Early Cretaceous sediments in the region are coal measures, deposited in intramontane basins in west and south and paralic basins in northeast [Li et al., 1983; Bureau of Geology and Mineral Resources of Heilongjiang Province, 1993]. The Late Cretaceous extension happened in an area much larger than the Songliao basin alone since the Xialiaohe basin in the south and the Sanjiang basin in the east also experienced the rifting event. The triangle-shaped rifting shows that this region experienced a differential extension from the north to the south. It seems clear that the extension is more important in the northern part than in the southern part. However, to the north, the extended area seems to be limited by the Mongol-Okhotsk suture, which has been reactivated as a

left-lateral transfer fault in Late Cretaceous times [Natal'in, 1993]. In the south, the Xialiaohe basin stopped rifting in Early Cretaceous, although its activity became renewed again in the Eocene. Most of the Cretaceous strata have been eroded with only Lower Cretaceous rocks still preserved (Figure 8a). However, these emersion and erosion phenomena do not seem directly related to regional tectonics. As shown by the comparison between the sea level curves of the Songliao basin and the whole world (Figure 9), the Cretaceous erosion is likely related to global eustatic positive motions. The Songliao basin seems to end its extension at the end of the Cretaceous (Figure 8b). To the east of the Yilan-Yitong fault, the extension might stop also in the Cretaceous in the south, such as the Yanji basin (Figure 10a), and thick Eocene sediments developed only in its northern region (such as the Sanjiang basin). However, in the south of the NE China plain, the extension continuously lasted until at least to the Oligocene (Figure 8a), and coeval the sedimentary basin developed progressively from north to south.

[31] The heterogeneous rifting responsible for the rotation forms the triangle-shaped NE China plain may be related to the clockwise rotation of the ELK Block with respect to the Chinese Block. The ELK Block is separated from the NE China plain by the Fushun-Mishan fault (Figure 10a). In fact, the Fushun-Mishan fault is composed of two normal faults that make up a half graben basin. The normal fault on the west controls the sedimentary center of the Fushun basin (Figure 10a). The Neogene sediment in the basin is ~2000 m [Wu et al., 2001], indicating that the main extension period is of Neogene. Similar to the Fushun-Mishan fault, the Yilan-Yitong fault system, situating at the east of Songliao basin, was also composed of two boundary faults that make up half grabens (Figure 10a). The west boundary fault is a growing fault facing to the east and controls the Neogene deposits of the graben. The sedimentary strata overlap to the east with maximum thickness >5000 m in the depocenter [Liu et al., 1993].

[32] If taking into account 15 km for the difference between the initial and thinned crust thickness [Kirillova, 1995], the  $\sim 20^\circ \pm 10^\circ$  clockwise rotation of the NE China plain centered nowadays in the south of the Bohai Bay (Figure 10b) would correspond to an extension amount of about  $300 \pm 150$  km in the north part of the plain. This paleomagnetic estimation complies with the tectonic reconstructions showing that the present basin with of ~700 km results of the stretching of a segment with an initial width of ~500 km. In fact, this extension affected an area wider than 800 km in north (i.e., the Songliao basin plus the basins east of the Yilan-Yitong fault), whereas the width of the extended domain in the south (i.e., the Xialiaohe basin, Figure 8a) is <80 km. Geological data indicate that the rifting might begin before the early Late Cretaceous. In addition, sinistral strike-slip motion along the Yilan-Yitong fault and the Fushun-Mishan fault, as well as faults within the Songliao basin [Li and Li, 1999], might also have absorbed parts of the rotation. Therefore the proposed rotational rifting accounts for the amount of extension of the northern termination of the basins. The sedimentological study shows that the oldest sediments in the bottom of these basins are of Late Jurassic age, indicating that the rifting started at that time. Since a relatively important rate of



**Figure 10.** Reconstruction of the rotational rifting in NE China. (a) Present view of NE Asia. Basins are (numbered circles) 1, Xialiaohe basin; 2, Songliao basin; 3, Zeya basin; 4, Sanjiang basin; 5, relic basins east of Yilang-Yitong fault with B, Boli basin; J, Jixi basin; Y, Yanji basin. Faults are A, Amur suture; YY, Yilan-Yitong fault; FM, Fushun-Mishan fault. K in square indicates the Khanka massif. (b) A Jurassic-Cretaceous reconstruction by counterclockwise rotation of  $\sim 20^\circ$ . The rotation pole is fixed in the southern termination of the Xialiaohe basin.

sedimentation is observed for the Late Jurassic-Early Cretaceous period (Figures 8a and 8b), it is reasonable to think that the ELK Block suffered a larger rotation since the Jurassic time. A tentative reconstruction of the eastern Eurasia margin in Late Jurassic-Early Cretaceous times taking into account the  $20^\circ$  clockwise rotation of the ELK Block and the coeval opening of the Songliao and other rift basins is proposed in Figure 10b. Some microcontinents such as Sikhote-Alin and Japanese islands are represented according to *Faure and Natal'in* [1992].

[33] One may argue that the Cenozoic basins in the south of Bohai, such as Jizhong and Subei basins, should be also considered in this kinematic model as they are probably be “coeval” and/or formed by the same geodynamic cause [e.g., *Allen et al.*, 1997, 1998]. Because of the structural complexity and the great width of the area involved in this large-scale tectonics, since the area ranges from  $30$  to  $50^\circ\text{N}$  and  $114$  to  $130^\circ\text{E}$  in latitude and longitude, respectively, the development of these basins is controlled by different (reactivated) structural systems. The seismic profiles from the Songliao and Xialiaohe basins show rather similar tectonic structures: the NNE-SSW oriented normal faults are parallel to major faults, such as the Tan-Lu, Yilan-Yitong, and Nenjian faults (Figure 8). It is not the case for the southern basins. For example, Bohai basin is essentially controlled by two groups of normal faults in NNE-SSW and ENE-WSW directions. The latter is almost orthogonal to the

major structures. This basin has meanwhile experienced two styles of deformation: extensional and partial compressional in the northern and southern parts, respectively [*Qian and Han*, 2001]. These two different styles of deformation within the same basin have been also shown in other southern basins, such as the Subei basin: with extension in the south and compression in the north [*Chen et al.*, 2001]. As the analysis of deformation styles and kinematic history is beyond this study, we will not discuss them in detail here. Additional paleomagnetic studies in these areas may offer more opportunities to this debate.

[34] From the geodynamic point of view, several hypotheses may explain the clockwise rotation of the ELK Block. Basically, two kinds of models involve either asthenospheric or lithospheric layers. Mantle upwelling related to asthenospheric convection widely developed below east Asia has been proposed to account for the petrology and geochemistry of mantle xenoliths scavenged by Cenozoic volcanics [e.g., *Menzies and Xu*, 1998]. Other models consider NE China rifting to be linked to the subduction of the Pro-Pacific Ocean below the eastern margin of Eurasia [e.g., *Ren et al.*, 2002, and references therein]. In the present state of knowledge a detail discussion of these models is beyond the scope of this paper, which is restricted to the kinematic aspects. In order to provide stronger constraints on these models, more paleomagnetic, structural, geochemical, and geochronological surveys involving larger

temporal and spatial spans have to be carried out in near future.

## 5. Conclusions

[35] In Eastern Liaoning Province, Paleozoic and Late Permian-Early Triassic rocks are unfortunately remagnetized by the recent geomagnetic field; however, Late Cretaceous red tuffaceous sandstone passes the positive fold test, shows no PEF ChRM carried by both magnetite and hematite, presents a solo normal polarity, and thus provides the only reliable paleomagnetic data in this study. The good coherence between all available Cretaceous paleomagnetic data from Eastern Liaoning-Korean Peninsula indicates that this zone belongs to a single tectonic unit since that time, namely, the East Liaoning-Korea (ELK) Block. A significant difference in magnetic declination has been evidenced between the ELK Block and NCB plus SCB (the Chinese Block). This difference may be interpreted as a differential rotation ( $22.5^\circ \pm 10.2^\circ$ ) with a negligible latitudinal displacement ( $0.8^\circ \pm 6.1^\circ$ ) between these two tectonic units. This observation indicates that left-lateral displacement along the Tan-Lu fault, if there was any, should have occurred before the Late Cretaceous. Moreover, the Korean Block cannot be considered as a rigid part of NCB. A Mesozoic rifting model has been documented to illustrate this relative rotation. The triangle-shaped NE China plain has experienced heterogeneous rifting from the late Jurassic to the Oligocene-Miocene, forming several basins. Its larger extension in the north may be accommodated with a clockwise rotation of the ELK Block centered at the south of the present Bohai Bay. This model may be tested by more paleomagnetic constraints spanning from the NE China plain and Korea.

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