Preliminary Early Cretaceous paleomagnetic results from the Gansu Corridor, China

Gina Marie Frost a, Robert S. Coe a, Zifang Meng b, Zuolin Peng b, Yan Chen c, Vincent Courtillot c, Gilles Peltzer c, Paul Tapponnier c, Jean-Philippe Avouac c

a Department of Earth Sciences and Institute of Tectonics, University of California, Santa Cruz 95064, USA
b Lanzhou Institute of Geology, Gansu Province, People’s Republic of China
c Institut de Physique du Globe de Paris, 4 place Jussieu 75252, Paris Cedex 05, France

Received 27 July 1994; accepted after revision 17 November 1994

Abstract

We report results from our paleomagnetic study of Lower Cretaceous redbeds from the Gansu Corridor, northwestern China. The characteristic remanent magnetization (ChRM) resides in hematite, often at very high unblocking temperatures (> 660°C). The directions associated with this component exhibit only reversed polarities from locality A (Sunan area), but the samples from locality B (Lanzhou area, 480 km to the southeast) show roughly antipodal normal and reversed polarities. The combined sample directional data from both localities pass a fold test at the 99% confidence level. The mean paleomagnetic pole is located at 48.7°N, 199.7°E, with A 95 = 4.1°, which is discordant with poles of similar age elsewhere from neighboring regions in China. Although represented by relatively few samples (N = 21) this pole suggests that significant post-Cretaceous motion may have occurred between the Gansu Corridor and adjacent blocks. Relative to Eurasia or North China, the discordance corresponds to 28.1 ± 5.2° or 35.6° ± 9.7° clockwise rotation and 9.5° ± 4.5° or 9.8° ± 8.2° northward displacement respectively. The rotations support, but do not yet distinguish between, several neotectonic models assumed to have acted over the past 15–40 m.y. The displacement is not predicted by any of these models; if real, it may have occurred early in the history of the India–Asia collision, or even before.

1. Introduction

The literature now abounds with geologic and paleomagnetic evidence confirming the composite nature of China’s continent (Fig. 1a). Although a gross outline of the tectonic history has been well documented for some geologic time periods, the finer details of the timing and manner of amalgamation of these continental blocks to each other and to the Siberian craton remain to be clarified. Paleomagnetic data constrain the time of suturing of the North and South China Blocks (NCB and SCB) between the latest Permian and Cretaceous [1–3]. One model [3] envisions initial collision at the eastern end of the two blocks in the Early Triassic, followed by clockwise rotation of the SCB with respect to the NCB until final suturing was completed most likely during the Jurassic. These authors [1–3] and many others included in [1] conclude that the major tectonic blocks that comprise China (i.e., Tarim, NCB, SCB) have been arranged in approximately
their present relative configuration with Siberia since Cretaceous times.

Qaidam is nestled between Tarim, the NCB, and the Songpan–Ganzi (SG) accretionary complex, which forms a so-called ‘suture-knot’ between the SCB, eastern Qiangtang and Qaidam [4] (Fig. 1a). The Qilian Mountains (Qilian Shan) and the lower lying Gansu or Hexi Corridor trend northwestward along the northeast border of Qaidam. Both terminate at the NE-trending Altyn Tagh fault that forms the northwest margin of Qaidam. The corridor forms a transitional area between the uplifted Qilian Shan and the NCB. Paleomagnetic data for this transitional region are largely lacking and are badly needed to define the relationship over time between the Gansu Corridor and the adjacent Chinese blocks. We present some of the first paleomagnetic data from three localities of Lower Cretaceous red beds in Gansu Province, near Sunan, Lanzhou and Zhangye (Locality A (99.6°E, 39.0°N), Locality B (103.5°E, 36.0°N) and Locality C (100.1°E, 38.9°N) respectively; Fig. 1b).

2. Geologic setting and sampling

*Locality A: Sunan area:* Co-authors from the University of California at Santa Cruz and the Lanzhou Institute of Geology sampled Lower Cretaceous non-marine red clastic rocks of the Hekou Group from a section near Sunan in Gansu Province (Locality A: 99.6°E, 39.0°N; Fig. 1b). The strata are exposed along stream beds where they unconformably overlie Permian rocks. The Hekou Group is composed of sandstones, conglomerates and mudstones, and ranges in thickness from about 130 to 2000 m. It yields plant fossils (*Brachyphyllum spinosum, Classopollis–Schizaeoisporites* and Angiospermae), charophytes (*Aclistochara huiluibaensis, Mesochara stipitata* and *Sperochara verticillata*), gastropods (*Valvata transbaicalensis* and *Bithynia leachioides*), bivalves (*Unio* grabaui and *Nipponesia tertiensis*), estherids (*Yanjestheria kyongsangensis* and *Y. huanjenensis*), ostracods (*Cypridea yumenensis*, *C. vilimensis*, *C. kosukensis*, *Rhincoscalon turquenesis*, *Jingguella* spp. and *Djungarica* spp.), and fish (*Sinamia* sp.) [5]. The Hekou Group is assigned an Early Cretaceous age based on the above paleontologic assemblage, although some doubt remains as to the position of the Cretaceous–Jurassic boundary [5].

Eighteen cores were drilled from red beds spanning about 50 m of section, which represents the maximum available outcrop for this age in the sampling area. Dips were gentle, ranging between 6 and 16°NNW to NNE. These red beds represent fluvial crevasse-splay deposits, which may have initial dips of ~5°. Crevasse splay deposits are formed when flood waters cut breach channels through natural levees instead of occurring as sheet-like overflows onto the floodplain, where sediments are deposited as a tongue or fan of sand [6].

The samples were collected using a portable gasoline-powered drill and oriented with a magnetic compass. Laboratory procedures and analyses were carried out at the University of California, Santa Cruz (UCSC); some measurements were made at the Institute for Rock Magnetism, University of Minnesota. Most samples were thermally demagnetized in a custom-built shielded oven, which was calibrated to control temperature variations within 1° at an accuracy within 8° of the set temperature; ambient fields in the cooling chamber were less than 10 nT. Selected samples were demagnetized by alternating fields (AF) using a Schonstedt tumbling demagnetizer. Measurements were conducted using a 2G cryogenic magnetometer. This equipment is located in a shielded room at UCSC, where ambient fields are generally less than about 300 nT. Both
optical and scanning electron microscopy (SEM) were used to observe the magnetic phases in these rocks.

**Localities B and C: Lanzhou and Zhangye areas**\(^1\): Researchers at the Institut de Physique du Globe de Paris (IPG) sampled the same Lower Cretaceous Hekou Group in 1986 near Lanzhou (Locality B: 103.5°E, 36.0°N) and near Zhangye (Locality C: 100.1°E, 38.9°N) (both in Gansu Province, Fig. 1b). The Zhangye sampling area (Locality C) is only about 40 km from the Sunan area (Locality A). Both the Lanzhou and Zhangye sampling areas are significantly folded, with dips ranging from about 40°WNW–NNE to 12°NE and 14°SE at Lanzhou, and from about 50°SW to 70°NE at Zhangye. Six blocks were collected from Locality B and twelve blocks were collected from Locality C; all were oriented with a magnetic compass. Cores were drilled and analyzed in the laboratory at the IPG. Measurements and demagnetization of NRM were conducted using a CTF three-axis cryogenic magnetometer and a custom-built shielded oven, located in Meudon outside Paris.

**Structural Setting**: Sites A and B are located on opposite sides of the active left-lateral Haiyuan fault system in the Gansu Corridor (Fig. 1b). Site A is located near the northern margin of the Qilian Shan and Site B is close to the southeastern termination. Both sites lie near major active left-lateral faults [7] and, based on Landsat images, even closer to smaller active conjugate right-lateral faults with a component of thrust. There is a major regional unconformity between the Lower and Upper Cretaceous [8], and the entire Qilian Shan–Gansu Corridor region has been reactivated since the collision between India and Asia in the Eocene [9].

---

\(^1\) This was considered to be a pilot study to be used for future field work that has yet to be performed. Samples were only demagnetized up to 640°C and were subsequently lost when the laboratory was moved from Meudon to Paris. As a consequence, the results, which were obtained in 1986 by researchers at the IPG in Paris, were never published. It is felt that, in conjunction with the results from Locality A, they provide enough critical information to deserve inclusion in the present study.

---

Fig. 2. (a) Vector plot of thermal demagnetization behavior for a sample from Locality A (Sunan). Detail at high temperature is shown. The HTC was isolated by great-circle plane to six data points corresponding to temperatures of 500, 525, 550, 575, 600 and 620°C. A best-fit line, not through the origin, to four data points corresponding to 660, 670, 680 and 685°C gave a direction comparable to that obtained from the great-circle fit, but the MAD value was significantly higher (BFL: D = 221.0°, I = −53.2°, MAD = 21.76°; GC: best-estimated endpoint on great circle following [13], D = 232.9°, I = −55.5°, MAD = 5.86°; angle between directions = 7.3°). No goethite was observed in thin section in this sample, but fine- and coarse-grained hematite were observed. (b) Vector plot shows unstable high-temperature behavior for sample 88G-311A from Locality A (Sunan); X–Y plot shows decay of magnetization (normalized) with increasing temperature during thermal demagnetization (J/D vs. temperature). Equal-area stereonet plot of directions for the same sample shows great circle fit to five data points corresponding to temperatures of 500, 525, 550, 575 and 600°C. Vector plot of AF demagnetization behavior for companion sample (88G-311B) shows incomplete cleaning up to peak fields of 100 mT; X–Y plot shows decay of magnetization (normalized) with increasing peak applied field during AF demagnetization. X–Y plot of IRM experiments for a companion sample from the same core (88G-311C) is also shown. Goethite was observed in thin section in this sample: SEM–EDA revealed a detrital-looking Fe–Ti grain and abundant fine-grained iron oxides. (c) Vector plots of two samples with opposite polarities from Locality B (Lanzhou). Equal-area stereonet plot for sample 02-06A shows great-circle fit to data points corresponding to temperatures of 120, 250, 350, 450, 500, 550 and 600°C. Sample 02-03A provided the HTC from a best-fit line direction forced through the origin from data corresponding to 350, 450, 500, 550, 600, 620 and 640°C. (d) Vector plot of thermal demagnetization behavior for a sample from Locality A (Sunan). Detail at high temperature is shown. The HTC was isolated by best-fit line to three data points corresponding to temperatures of 660, 670 and 680°C.

---

**3. Experimental results and analysis**

**Locality A: Sunan area**: Thin sections of three samples were examined using standard optical techniques (88G-304, 88G-311, 88G-313). One sample (88G-304) showed an abundance of fine-grained opaque oxides occurring as framework grains in a matrix of hematite cement; no goethite
was observed in this sample. In the other two samples (88G-311, 88G-313) goethite was observed in addition to hematite. It is interesting to note that stable endpoint line data defined the ChRM for the sample in which no goethite was observed (88G-304, Fig. 2a), whereas only great-circle analysis was able to determine the ChRM of the other two samples (88G-311, Fig. 2b; 88G-313) in which goethite was observed. Although the ChRM is reasonably well defined using best-fit lines for core 88G-304, in the final analysis we used the great-circle technique for this sample in the determination of the overall mean because the angular deviation of points from the circle was considerably less than that from the best-fit line (GC = 5.86 vs BFL = 21.76), although the difference in the directions obtained by the two methods was small (GC = 232.9, −55.5 vs. BFL = 221.0, −53.2; angle between directions = 7.3°).

SEM observation and energy dispersive analysis (EDA) of this same sample (88G-304) confirmed the presence of abundant iron oxide

<p>| Table 1 | Individual sample data for Localities A and B |</p>
<table>
<thead>
<tr>
<th>Sample #</th>
<th>Strike</th>
<th>Dip</th>
<th>Type</th>
<th>n</th>
<th>Range(°C)</th>
<th>Dir-In Situ</th>
<th>Dir-Tilt Corr.</th>
<th>Dir. Err.</th>
<th>MAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locality A: Sunan 99.6°E, 39.0°N</td>
<td>301</td>
<td>238</td>
<td>6NW</td>
<td>DirO</td>
<td>4</td>
<td>660-680</td>
<td>235.8</td>
<td>-84.4</td>
<td>230.0</td>
</tr>
<tr>
<td>302A</td>
<td>238</td>
<td>6NW</td>
<td>Dir</td>
<td>6</td>
<td>660-685</td>
<td>230.7</td>
<td>-43.3</td>
<td>225.2</td>
<td>-43.2</td>
</tr>
<tr>
<td>303A</td>
<td>238</td>
<td>6NW</td>
<td>DirO</td>
<td>6</td>
<td>660-685</td>
<td>231.3</td>
<td>-44.3</td>
<td>225.6</td>
<td>-43.3</td>
</tr>
<tr>
<td>304A</td>
<td>238</td>
<td>6NW</td>
<td>Gcn</td>
<td>4</td>
<td>500-620</td>
<td>24.4</td>
<td>-28.6</td>
<td>27.4</td>
<td>-31.8</td>
</tr>
<tr>
<td>305A</td>
<td>238</td>
<td>6NW</td>
<td>DirO</td>
<td>5</td>
<td>660-680</td>
<td>223.8</td>
<td>-49.3</td>
<td>217.3</td>
<td>-47.5</td>
</tr>
<tr>
<td>306A</td>
<td>324</td>
<td>6NE</td>
<td>Gcn</td>
<td>4</td>
<td>350-500</td>
<td>8.1</td>
<td>-39.4</td>
<td>4.2</td>
<td>-43.4</td>
</tr>
<tr>
<td>307A</td>
<td>324</td>
<td>6NE</td>
<td>Gcn</td>
<td>6</td>
<td>550-660</td>
<td>151.2</td>
<td>23.8</td>
<td>147.2</td>
<td>34.3</td>
</tr>
<tr>
<td>308A</td>
<td>324</td>
<td>6NE</td>
<td>Gcn</td>
<td>5</td>
<td>450-620</td>
<td>319.2</td>
<td>-5.7</td>
<td>318.6</td>
<td>-5.2</td>
</tr>
<tr>
<td>309A</td>
<td>324</td>
<td>6NE</td>
<td>DirO</td>
<td>6</td>
<td>660-685</td>
<td>222.4</td>
<td>-36.1</td>
<td>223.2</td>
<td>-30.2</td>
</tr>
<tr>
<td>310</td>
<td>324</td>
<td>6NE</td>
<td>Gcn</td>
<td>4</td>
<td>400-525</td>
<td>332.7</td>
<td>-23.3</td>
<td>330.1</td>
<td>-24.1</td>
</tr>
<tr>
<td>311A</td>
<td>279</td>
<td>16NE</td>
<td>Gcn</td>
<td>3</td>
<td>500-550</td>
<td>322.4</td>
<td>-22.4</td>
<td>328.9</td>
<td>-23.2</td>
</tr>
<tr>
<td>312A</td>
<td>279</td>
<td>16NE</td>
<td>Gcn</td>
<td>3</td>
<td>500-550</td>
<td>202.4</td>
<td>48.6</td>
<td>209.4</td>
<td>64.0</td>
</tr>
<tr>
<td>313B</td>
<td>279</td>
<td>16NE</td>
<td>Gcn</td>
<td>3</td>
<td>500-550</td>
<td>186.7</td>
<td>38.5</td>
<td>186.1</td>
<td>54.3</td>
</tr>
<tr>
<td>314A</td>
<td>279</td>
<td>16NE</td>
<td>Gcn</td>
<td>5</td>
<td>500-600</td>
<td>49.2</td>
<td>-32.1</td>
<td>58.0</td>
<td>-43.7</td>
</tr>
<tr>
<td>315A</td>
<td>279</td>
<td>16NE</td>
<td>Gcn</td>
<td>4</td>
<td>475-550</td>
<td>346.8</td>
<td>-35.8</td>
<td>160.4</td>
<td>50.2</td>
</tr>
<tr>
<td>317A</td>
<td>220</td>
<td>11NW</td>
<td>Gcn</td>
<td>4</td>
<td>500-525</td>
<td>228.8</td>
<td>77.5</td>
<td>244.5</td>
<td>54.3</td>
</tr>
<tr>
<td>318A</td>
<td>220</td>
<td>11NW</td>
<td>Gcn</td>
<td>5</td>
<td>500-575</td>
<td>14.4</td>
<td>-43.0</td>
<td>204.7</td>
<td>46.8</td>
</tr>
<tr>
<td>Locality A Mean</td>
<td>In Situ</td>
<td>n = 16</td>
<td>D = 225.8</td>
<td>1 = -44.0</td>
<td>a95 = 4.4</td>
<td>k = 75.55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tilt Corr.</td>
<td>n = 16</td>
<td>D = 221.9</td>
<td>1 = -39.0</td>
<td>a95 = 5.1</td>
<td>k = 55.77</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Locality B: Lanzhou 103.5°E, 36.0°N | 02-01A | 190 | 37NW | DirO | 6 | 450-640 | 252.7 | -12.8 | 239.6 | -40.5 | 0.8 |
| 02-02A | 203 | 39SE | DirF | 6 | 450-640 | 230.9 | -54.1 | 173.3 | -53.3 | 166.4 |
| 02-03A | 297 | 45NE | DirO | 7 | 350-640 | 309.2 | -68.9 | 237.2 | -42.5 | 2.7 |
| 02-04A | 53 | 14SF | DirF | 6 | 322.2 | -52.5 | 42.9 | 40.2 | 0.2 |
| 02-05A | 335 | 12NE | GC | 7 | 250-640 | 322.2 | 5.1 | 323.5 | 7.6 | 10.6 |
| 02-06A | 335 | 12NE | GC | 7 | 120-600 | 289.9 | 5.1 | 291.3 | 13.5 | 4.7 |

Locality B Mean | In Situ | n = 5 | D = 237.1 | 1 = -48.6 | a95 = 38.7 | k = 5.28 |
| | Tilt Corr. | n = 5 | D = 239.1 | 1 = -44.1 | a95 = 10.0 | k = 68.97 |

Sample # = Sample identification; Strike−Dip = bedding attitude; Type = analysis method (Dir = best-fit line not forced through origin; DirF = Fisher average; DirO = best-fit line forced through the origin; GCn = great-circle fit weighted by intensity; GC = great-circle fit not weighted; HD = direction determined by vector differences [18] n = number of data points used in analysis; Range = temperature range in degrees Celsius of data points used in analysis; Dir-In Situ (Dec,Inc, Long,E, Lat,N) = declination and inclination of best-fit line or HD sample direction, or longitude and latitude of pole to best-fit great circle to directional data in situ; Dir-Tilt Corr. = declination and inclination of best-fit line or HD sample direction, or longitude and latitude of pole to best-fit great circle to directional data in tilt corrected Dir. Err. (MAD) = error angle associated with Dir-Tilt Corr. (maximum angular deviation) k = Best estimate of precision parameter  " = Sample direction not used to calculate mean. Mean directions calculated following [11]
phases, which occurred both as finely disseminated microcrystals less than 2 μm in diameter and as very large pseudohexagonal grains up to 50 μm across. Ti-oxide grains were also identified, and contained no trace of Fe. SEM observation and EDA of another sample (88G-311) revealed abundant microcrystalline iron oxides occurring mostly as grain coatings; only one large Fe-Ti rich detrital-looking grain was observed.

Magnetic properties confirm the presence of both hematite and goethite in core 88G-311. AF demagnetization was ineffective at isolating the ChRM; only ~25% of the NRM was lost after 100 mT AF treatment (Fig. 2b). Thermal demagnetization indicated the presence of goethite by a loss of about 50% of the NRM by 200°C thermal treatment and of hematite by unblocking temperatures of saturation IRM up to 685°C (Fig. 2b). IRM acquisition experiments in applied fields to 1000 mT indicated the presence of only very high coercivity phases such as hematite and goethite. In addition, the IRM acquisition curve near the origin was convex away from the vertical axis, which argues against any magnetically significant fraction of magnetite or maghemite in these samples [10]. Little indication of goethite (there is a slight change of slope at 200°C), however, was observed in the plot of thermal decay of IRM (see Fig. 2b), possibly because IRM acquisition was applied along only one axis to a previously untreated sample so that the significantly larger contribution to \( J_{rs} \) from hematite may have obscured that from goethite [11]. Similar IRM behavior was observed in core 88G-303.

NRM intensities range from 3 to 20 mA/m (typically ~10 mA/m). NRM directions generally cluster near the geocentric axial dipole (GAD) field direction at the sampling area. Progressive thermal demagnetization to 685°C, however, revealed two components of magnetization.

A lower unblocking temperature component (LTC) was isolated in all samples by best-fit lines to demagnetization data between 100 and 575°C. Most samples lose more than 30% of their remanence by 200°C, consistent with the observation of goethite discussed earlier. The LTC is exhibited at very low temperatures (100–200°C) and persists until high temperatures (<600°C). The direction of the LTC is indistinguishable from the GAD field direction at the sampling area before tilt correction and is distinct from the GAD field direction after tilt correction. In addition, the LTC fails a fold test at the 95% confidence level [12], indicating a magnetization acquired after tilting.

A very high unblocking temperature component (HTC) was isolated between 660 and 685°C in five samples (Table 1). The ChRM directions associated with this HTC was determined by best-fit lines to vector plots of demagnetization data (e.g., see Fig. 2d). The remaining twelve samples measured from this locality were analyzed for this component using great circles (e.g., see Fig. 2a and b and Table 1). Results from eleven samples (one rejected due to its large great-circle error, see Table 1) were included in the calculation of the mean for both localities using the combined analysis of remagnetization circles and best-fit line data [13].

The ChRM was observed to reside in the very highest unblocking temperature grains, isolated between 660 and 685°C in those samples from the Sunan area for which best-fit line data was obtained (see Table 1). A similar observation holds true for many studies of redbeds by our and other groups (e.g., [14–16]). In the present study, petrographic and rock magnetic observations provide a clue as to the reason for this phenomenon.

Two populations of hematite were petrographically observed, finely crystalline hematite-coated and cemented larger grains, and larger hematite grains occurring as part of the framework. Thermal demagnetization of saturation IRM indicated the presence of hematite with a distributed range of unblocking temperatures up to 625°C separated by a sharp change in slope between 625 and 680°C (Fig. 2b). We interpret this change in slope as reflecting differences in grain-size distributions associated with the observed framework and cement hematite-grain populations. We associate the ChRM with framework hematite grains (perhaps detrital?) and the LTC with finely crystalline hematite that coated and cemented other grains.

Locality B: Lanzhou area: The six samples from Locality B exhibited two components of magnetization. The LTC makes up about 10% to
more than 50% of the NRM and is removed after 120–250°C in the reversed samples, and after 450–600°C in three samples that exhibit normal polarity. The HTC (ChRM) was determined by best-fit lines to six or seven data points in two samples, by an average [17] of six data points in one sample, and constrained by great circles in two samples. In the normal polarity samples the HTC was exhibited by 640°C, but it was not described by enough data points. In one sample (02-04A) there was evidence of a third, even higher temperature component; in this case, the ChRM was determined by successive vector differences and the intersection of the two great circles on which these differences lay [18]. The results from Locality B are listed in Table 1 and examples are illustrated in Fig. 2c. One direction (02-02A) is a clear and unexplained outlier (whose in-situ direction appears to be close to the bedding-corrected direction of the other samples) and was not included in the determination of the overall mean. The other five directions yield a positive fold test at the 99% confidence level and the two polarities are roughly antipodal.

**Locality C: Zhangye area:** The results from Locality C were noisy and components were difficult to isolate. Best-fit line directions could be determined, usually between 120 and 640°C, for nine samples, and great circles were used for three samples. Four of the best-fit line directions and the three great circles yielded a clearly negative fold test with a mean in-situ direction close to the GAD field direction. Two other best-fit line directions were similar, but rotated clockwise by 20–40° from north. The remaining data appear to be outliers, both in-situ and after tectonic correction. Because of the negative fold test and the observation that the mean in-situ ChRM direction was close to the GAD field direction at the sampling locality, the results from Locality C

---

![Fig. 3. Equal-area stereonet plots of mean directions and associated 95% confidence circles in-situ (a) and tilt-corrected (b) based on combined directional data from both localities (A = Sunan, B = Lanzhou). Great circle is best fit to individual sample poles-to-great circles. See Table 1 for sample data and locality means and Table 2 for overall mean (shaded). The fold test is positive at the 99% confidence level [12]. Also shown are the separate locality means.](image-url)
Table 2
Overall means for LTC and HTC based on combined sample directions from Localities A and B

<table>
<thead>
<tr>
<th></th>
<th>Direction</th>
<th>Pole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Coord.</td>
</tr>
<tr>
<td>LTC</td>
<td>21</td>
<td>in-situ</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>tilt-corr</td>
</tr>
<tr>
<td>HTC</td>
<td>21</td>
<td>in-situ</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>tilt-corr</td>
</tr>
</tbody>
</table>

Comp. = LTC or HTC component; n = number of samples used to calculate means; D, I = Long.°E, Lat.°N = declination and inclination/longitude and latitude of the mean direction/pole; k = precision parameter for direction/pole; α95/K95 = 95% confidence limit about the mean direction/pole

were not included in the calculation of the mean direction for the Hekou Group and are not considered further.

4. Discussion

Overall means for each component were determined by combining the sample directions from both localities. The LTC fails a fold test at the 95% confidence level [12]. In addition, the lower unblocking temperatures, the observation of abundant secondary magnetic mineral phases, and the occurrence of only normal polarity directions whose mean is indistinguishable from the GAD field direction in geographic coordinates and distinct from the GAD field direction after tilt correction all indicate that the LTC is a late (probably Brunhes) chemical remanent magnetization (CRM) aligned with the GAD field direction at the sampling locality. We interpret the LTC to reside in both goethite and hematite for samples from the Sunan area, consistent with the petrographic and magnetic observations discussed.

Fig. 4. Stereographic plot showing mean Early Cretaceous paleomagnetic poles for Chinese blocks with associated A95. Sampling localities in China: A = Sunan, B = Lanzhou. See Table 3 for data and references.
above. The same interpretation likely holds true for the Lanzhou area as well.

Combined directions from both localities pertaining to the HTC are shown in Fig. 3 and listed in Table 2, both prior to and after unfolding. The HTC probably represents a near-primary remanence, for the following reasons: (1) The combined data pass a fold test at the 99% confidence level [12] (these Early Cretaceous beds were folded before deposition of Late Cretaceous strata in the Gansu Corridor [8]), (2) normal polarity directions observed in three samples from locality B are roughly antipodal to the reversed polarity directions from the same locality, (3) the polarity is dominantly reversed, which is compatible with an Early Cretaceous primary magnetization acquired prior to Chron M0 and incompatible with a Recent field magnetization, (4) similar results were obtained from separate localities located about 480 km apart, and from separate laboratories, and (5) the HTC direction (ChRM) is unlike any known for neighboring Chinese regions since Early Cretaceous time.

The mean paleomagnetic pole of the HTC was based on the combined analysis of great circles and best-fit lines to directional data [13]. This pole lies at 48.7°N, 199.7°E (A95 = 4.1°, Table 2) and is illustrated in Fig. 4 along with Early Cretaceous paleomagnetic poles for the NCB, Tarim, Western Tibet and Eurasia (EUR) (see Table 3 for data and references). Three very striking features in this figure are (1) progressive relative northward displacement of each of the major blocks (i.e., Western Tibet relative to Tarim and Tarim relative to EUR), (2) significant northward displacement of the Gansu Corridor with respect to the NCB and EUR, and (3) significant clockwise rotation of the Gansu Corridor with respect to the other blocks.

We are well aware that our Gansu Corridor pole is based on a small number of samples and sites. However, the dearth of any results from this tectonically important and poorly understood area and the fact that two laboratories obtained consistent results with a positive fold test and opposing normal and reversed polarities from two localities some 480 km apart in our opinion warrants at least a preliminary interpretation of the data. It is possible that systematic errors (e.g., magnetic anisotropy, inclination error, initial dip) rather than tectonic displacement could account for the somewhat shallow inclination observed from the Gansu Corridor relative to blocks to the north (i.e., EUR, NCB, Tarim). In addition, both sites are close to small active right-lateral faults [7] that could be responsible for the observed clockwise rotations, which thus might be of only local importance. These rotations could also be related

Table 3
Displacements and rotations of the Gansu Corridor with respect to different blocks comprising Eurasia, calculated for a site mid-way between Locality A (Sunan) and Locality B (Lanzhou) at 102°E, 37.5°N

<table>
<thead>
<tr>
<th>Block</th>
<th>Age (Ma)</th>
<th>Pole (°E, °N)</th>
<th>Pole A95</th>
<th>Pole N</th>
<th>Pole R</th>
<th>Dec, Dec Obs</th>
<th>Inc, Inc Exp(1)</th>
<th>Rot(2)</th>
<th>Plat Obs(2)</th>
<th>Plat Exp(2)</th>
<th>Displ(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gansu Corr.</td>
<td>102°E, 37.5°N</td>
<td>199.7, 48.7</td>
<td>4.1</td>
<td>21</td>
<td>20.8</td>
<td>45, 39.6</td>
<td>22.8 ± 3.2</td>
<td>32.3 ± 1.2</td>
<td>9.5 ± 4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EUR [21]</td>
<td>130-98 Ma</td>
<td>207.5, 75.2</td>
<td>4.0</td>
<td>10</td>
<td>9.9</td>
<td>16.9, 51.7</td>
<td>28.1 ± 5.2</td>
<td>32.3 ± 1.2</td>
<td>9.5 ± 4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCB [20]</td>
<td>K1</td>
<td>222.0, 80.9</td>
<td>9.5</td>
<td>-</td>
<td>-</td>
<td>9.4, 52.0</td>
<td>35.6 ± 9.7</td>
<td>32.6 ± 7.6</td>
<td>9.8 ± 8.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W. Tibet [19, 30]</td>
<td>K1</td>
<td>245.0, 66.2</td>
<td>5.3</td>
<td>14</td>
<td>13.8</td>
<td>14.8, 32.3</td>
<td>30.2 ± 5.7</td>
<td>17.5 ± 4.2</td>
<td>5.3 ± 5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tarim [19, 30]</td>
<td>K1</td>
<td>223.8, 69.1</td>
<td>3.8</td>
<td>5</td>
<td>5.0</td>
<td>19.5, 42.8</td>
<td>25.5 ± 4.9</td>
<td>24.8 ± 1.0</td>
<td>2.0 ± 4.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gansu Corridor: Results from this study (see Table 2) EUR: 130–98 Ma Eurasian pole [21], no Chinese poles included NCB: North China Block pole [20] W. Tibet: Western Tibet pole [19,20,34] Tarim: Tarim pole [19,30] Age (K1) – Early Cretaceous Pole (°E, °N) – Longitude and latitude of paleomagnetic pole; Pole A95, Pole N and Pole R = 95% confidence limit, number of studies and resultant vector, respectively, for the paleomagnetic pole Dec, Inc Obs = Observed declination and inclination of the Gansu Corridor based on data from this study Dec, Inc Exp = Expected declination and inclination of the Gansu Corridor based on the respective poles for the different blocks Rot = Rotation and error associated with the expected and observed directions Plat Obs = Observed paleolatitude of the Gansu Corridor based on data from this study Plat Exp = Expected paleolatitude and associated error of the Gansu Corridor based on the respective poles for the different blocks Displ = N–S displacement and associated error of the Gansu Corridor based on the respective poles for the different blocks. (1) Calculated according to [50,51]; (2) calculated according to [52] with C = 0.8 [51]; (3) this study (see Table 2)
more directly to Cenozoic strain in the major Haiyuan fault system (Fig. 1b). However, the internal consistency of our results suggests that paleolatitudes and rotations might have a larger scale meaning. With this in mind, we will now discuss the broader implications of the data depicted in Fig. 4.

Progressive relative northward displacement of Chinese terranes: Enkin et al. [1], Chen [19] and Chen et al. [20] have noted that many of the Cretaceous poles from Chinese blocks were systematically far-sided with respect to the EUR reference pole [21] and distributed along a great circle that cuts through central Asia in a north-northeast direction. These authors interpreted the streaking (i.e., systematic far-sidedness) to indicate small (up to 10°) relative northward displacements between these blocks. Our results from the Gansu Corridor, after removing the effect of rotation, are consistent with systematic northward displacement of the Chinese terranes with respect to EUR (Fig. 4).

Northward displacement of the Gansu Corridor with respect to the NCB and EUR: Kinematic models based on earthquake data from the past century predict internal shortening of Eastern Tibet at rates of 15 km/m.y. in a NNE direction [7] or allow northward displacements of about 30 km/m.y. across the Gansu–Ningxia region relative to the SCB and presumably EUR or the NCB [22,23]. These rates correspond to displacements of between 300 and 1200 km over the past 20–40 m.y. or roughly 3–12° in latitude. The paleolatitude difference predicted from paleo-

Fig. 5. Schematic reconstruction of Early Cretaceous paleogeography of Asia modified from [19,20]. Black star = paleolatitude and associated 95% error bar of the Gansu Corridor determined from this study; white star = expected paleolatitude of the Gansu Corridor based on the NCB pole (see Table 3). INC = Indochina; JUN = Junggar; KAZ = Kazakhstan; KUN = Kunlun; LH = Lhasa; MAR = Markam; MON = Mongolia; NCB = North China Block; QA = Qaidam; QI = Qiangtang; SCB = South China Block; ST = Shan–Thai; TAR = Tarim.
magnetic results between the Gansu Corridor (this study) and EUR or the NCB is 9.5 ± 4.5° or 9.8 ± 8.2° respectively, which indicates a northward displacement of the Gansu Corridor with respect to each of these blocks (Table 3). We conclude that the sense and order of magnitude of the displacement estimated by paleomagnetism is comparable to that predicted by these models, but the large uncertainty precludes distinguishing between them.

In contrast, several other kinematic models based on Quaternary data [24–29] predict movement no larger than a small fraction of the approximately 10° implied by our paleomagnetic data between the Gansu Corridor and the major blocks located to the north (NCB and EUR). Note, however, that the Tarim pole [30] is roughly on the same small circle, centered between Sunan and Lanzhou at 37.5°N, 102°E, as our pole (Fig. 4). This suggests that the Gansu Corridor and Tarim may have experienced similar amounts of latitudinal displacement relative to EUR or the NCB since the Cretaceous. Significant cumulative shortening north of our study area, perhaps in the Altai Mountains and even farther north, would be required to accommodate this convergence. Extrapolation of neotectonic interpretations for areas north and east of the Gansu Corridor, characterized by E–W strike-slip faulting and minor crustal shortening across the Gobi–Altai [31] and E–W extension on N–S normal faults around the Ordos Basin [32], would not support such large northward displacements. However, further to the northwest Chen et al. [33] suggested that significant shortening could have occurred between Junggar and Siberia. It is interesting that the paleolatitude of about 23°N, which we find for our Gansu Corridor localities, would place the Gansu Corridor in the immediate vicinity of Qaidam in the Cretaceous reconstruction of Chen et al. [20] and not in its present position relative to the NCB (Fig. 5). Therefore, the paleomagnetic data could be interpreted in terms of a post-Cretaceous component of N–S displacement between a western block comprising Junggar, Tarim, Qaidam, the Gansu Corridor and the Tibetan blocks and an eastern block comprising the NCB, SCB and EUR. If real, our paleomagnetically inferred displacement may have occurred early in the history of the India–Asia collision, or even before.

Clockwise rotation of the Gansu Corridor with respect to the other blocks: A streaked distribution of Cretaceous paleomagnetic poles from individual studies in China is noted by Enkin et al. [1]. Because the distribution was fit reasonably well by a small circle centered on China (35°N, 110°E), these authors [1] interpreted the streaking in terms of local block rotations about vertical axes resulting from the India–Asia collision. A streaked distribution of Cretaceous poles for Tibet that were fit reasonably well by a small circle centered on Tibet was also noted [19,20,34], which was interpreted to reflect oroclinal bending after collision [19,20,34]. Our results from the Gansu Corridor are also consistent with rotation relative to the Eurasian reference pole [21] and to the mean poles for the major blocks comprising China. They correspond to 25.6 ± 10.7° and 28.1° ± 5.2° of clockwise rotation, relative to the NCB and EUR respectively, since the Early Cretaceous (Table 3). Comparison with Tarim [19,30] and Western Tibet [19,34] yields similar clockwise relative rotations in the 25–35° range.

As we have seen, crustal deformation of the greater Tibetan region (Tibet, Qaidam and the Qilian Shan) caused by the India–Asia collision has been the focus of much interpretation, analysis and modeling (e.g., [9,16,19,20,29,34–49]). The Gansu Corridor lies at (or just beyond) the northeastern extremity of that region, with the result that the effect of the collision on our sampling localities is not unambiguously predictable by these studies. In some models [22,23,37,38] clockwise rotation of northeastern Tibet is generally predicted, which, by extrapolation, may apply to the Gansu Corridor as well.

Cumulative clockwise rotations of 5–20° in 40 m.y., depending on the rheological model, are implied across the Gansu–Ningxia region by numerical experiments [37,38], which employed simplifying continuum assumptions for deformation of the lithosphere. Larger rotations have been inferred either from the geometry and kinematics of major active faults [24–28] or from the summation of seismic moment tensors of earthquakes in
the region during the last century [22,23]; these rely on data spanning 10,000–100,000 years in the former case (measured offsets of glacial features) and 100 years at most in the latter case. Rotations in the Gansu Corridor are also consistent with interpretations of satellite images and laboratory studies on the deformation of plasticine by a rigid-body indenter [29,44,46,47], which advocate dominantly lateral extrusion of eastern Tibet and South China toward the southeast. All these models emphasize the importance of major arcuate strike-slip fault systems that trend NW–SE through eastern Tibet and divide it into elongate blocks (Fig. 1b). Indentation by the northward movement of India causes these blocks to rotate clockwise, accommodated by left-lateral offset on their bounding faults. The main differences involve the extent to which in each model clockwise rotation is accompanied by eastward extrusion of blocks, which is not directly testable by our data.

Some of these models [22–25,28] are also gratifyingly consistent in predicting clockwise rotation rates relative to EUR of between 1 and 2°/m.y. If these rates held constant, our paleomagnetically observed rotation would have been accomplished in 15–30 m.y. Many lines of evidence suggest the Miocene as the time of major uplift and denudation associated with the formation of the Tibetan Plateau [35,36,39–41,47,48]. More specifically for northeastern Tibet, Meyer [7] has argued that the present kinematics was established probably less than 20 m.y. ago, and that most of the deformation took place in the last 10 m.y. He also showed that about 6° clockwise rotation of the Qaidam block is accounted for by lateral variation in crustal shortening absorbed by thickening in the Qilian Shan. This is only 20% of the paleomagnetically observed rotation of the Gansu Corridor, indicating that other mechanisms must be involved if our roughly 30° rotation is interpreted to reflect regional rather than local tectonics.

In conclusion and with due reference to the caveats outlined in this paper, the correspondence between our paleomagnetic results and some of the predictions made by various kinematic models is better than expected considering the limitations of our study and the uncertainties in applying neotectonic rates to large parts of the history of the India–Asia collision. Firm tectonic conclusions, however, will require additional data from elsewhere in the Gansu Corridor.

Acknowledgements

We thank many friends and colleagues at the Lanzhou Institute of Geology of Academia Sinica for their help in making this project possible. We also thank B. Meyer for help in the field. Support was provided in part by NSF grants EAR-8707376 and EAR-9018360, in part by the Academia Sinica of the PRC, and in part by the INSU (DBT contribution 710). We gratefully acknowledge help and support provided by the Institute for Rock Magnetism at the University of Minnesota. This is manuscript 194 of the Institute of Tectonics at the University of California, Santa Cruz and IPGP contribution 1333. [PT]

References


