Geophys. J. Int. (2002) **151,** 475–486

Laboratory depositional and compaction-caused inclination errors carried by haematite and their implications in identifying inclination error of natural remanence in red beds

Xiaodong Tan,[1,*] Kenneth P. Kodama[1] and Dajun Fang[2]

[1]*Department of Earth and Environmental Sciences, Lehigh University,* 31 *Williams Drive, Bethlehem,* PA 18015, *USA*
[2]*Department of Earth Sciences, Zhejiang University, Hangzhou, Zhejiang* 310027, *China*

Accepted 2002 May 29. Received 2002 May 1; in original form 2001 November 22

SUMMARY

Undetected depositional and/or compaction-caused inclination errors may result in an overestimation of tectonically caused latitudinal offset. Hodych & Buchan used a single-component isothermal remanent magnetization (IRM) acquired in a DC field at a 45° angle to the bedding to test for inclination errors in Silurian red beds. This approach was criticized by Stamatakos *et al.* We produced synthetic depositional and compaction-caused inclination errors to test Hodych and Buchan's approach. Red bed samples collected from the Eocene Suweiyi Formation, Tarim Basin (northwest China) were disaggregated using an ultrasonic cleaner and the sediments were mixed with distilled water to make a sediment slurry. The sediment slurry spontaneously separated into silt-dominated and clay-sized parts, so deposition and compaction experiments were conducted with three categories of slurries: coarse grained, the fine grained and a 1:1 volume ratio mixture of the coarse- and fine-grained slurries. During compaction clay-sized sediments experienced 17°–19° inclination shallowing at 58° magnetic field inclination, while coarser sediments showed little laboratory compaction-caused inclination error. Acquisition of IRM, coercivity spectra and unblocking temperature spectra reveal that the magnetic carrier for the fine-grained sample is dominated by pigmentary haematite. A deposition experiment was also conducted with the coarse-grained sediments, which showed a range of depositional inclination error, ∼0°–30°, carried by larger high unblocking temperature/coercivity particles. The intermediate unblocking temperature (or coercivity) component carried presumably by pigmentary haematite is an accurate record of the ambient magnetic field direction. Our data indicate that the single-component IRM method of Hodych & Buchan can be used to identify and correct for the compaction-caused inclination error of the fine-grained samples, while it failed to detect any depositional inclination error in the coarse-grained samples. Therefore, to better quantify the inclination error in red beds, it is suggested that multiple IRMs be measured in various directions.

Key words: compaction, deposition, inclination error, magnetic anisotropy, palaeomagnetism, red beds.

1 INTRODUCTION

The fidelity of sedimentary detrital remanent magnetization (DRM) in recording the geomagnetic field has been a major concern for over 30 years (see, e.g., Verosub 1977, for review). Inclination error in sedimentary rocks has been attributed to both depositional processes and post-depositional processes. Post-depositional realignment of magnetic particles may decrease or eliminate a depositional error, leaving compaction as the main cause of inclination error in sedimentary rocks (e.g. Verosub 1977; Arason & Levi 1990; Sun & Kodama 1992).

Compaction-caused inclination shallowing in magnetite-bearing sediments depends on non-magnetic grain size, clay content and electrochemical properties (Eh-pH) of the pore fluids (Anson & Kodama 1987; Deamer & Kodama 1990; Lu *et al.* 1990; Kodama & Sun 1992; Sun & Kodama 1992). Jackson *et al.* (1991) proposed a theoretical model to correct inclination error in sediments independent of the mechanisms causing the inclination error, assuming single-domain or pseudo-single-domain magnetite particles:

---

*Now at: IPGP, Laboratoire de Palaeomagnetisme, 4 place Jussieu, 75252 Paris Cedex 05, France. E-mail: tan@ipgp.jussieu.fr

$$\frac{\tan(I_{\mathrm{ChRM}})}{\tan(I_{\mathrm{field}})} = \frac{(a+2)\mathrm{ARM}_z - 1}{(a+2)\mathrm{ARM}_x - 1}, \tag{1}$$

where ARM_z and ARM_x are normalized minimum and maximum anhysteretic remanent magnetizations (ARMs) in the vertical and horizontal directions, respectively, in bedding coordinates, and '*a*' is the ARM anisotropy factor of individual magnetic grains. Since ARM is most easily applied to low-coercivity, ferrimagnetic grains, this correction is effectively only useful for magnetite-bearing rocks.

In contrast to magnetite-bearing sedimentary rocks, the correction for inclination error in haematite-bearing rocks has not been well studied. Although depositional inclination error has been observed in both modern fluvial deposits and laboratory redeposition experiments (e.g. Tauxe & Kent 1984; Lovlie & Torsvik 1984), little is known concerning the effect of compaction on the palaeomagnetic inclination of red beds. Tauxe *et al.* (1990) tried to measure the IRM anisotropy of the high-coercivity Siwalik red bed samples to determine the origin of remanence, but they were unsuccessful in obtaining a complete remanence anisotropy tensor from a single haematite-bearing sample. They found the 'memory effect' that the IRM acquired tended to be strongest in the first orientation, so that the resulting anisotropy tensor did not accurately measure the rock fabric. To avoid this problem, Hodych & Buchan (1994) measured a partial anisotropy of IRM in haematite-bearing samples by imparting IRM in increasingly greater magnetic fields at 45° to the bedding plane of the Silurian Springdale Group red bed samples from Newfoundland. Palaeomagnetic studies (Hodych & Buchan 1994; Potts *et al.* 1994) indicate that these rocks have anomalously shallow inclinations although the palaeomagnetic direction from volcanic rocks has large errors (Potts *et al.* 1994) probably caused by secular variations. In Hodych & Buchan (1994), eq. (1) reduces to

$$\frac{\tan(I_{\mathrm{ChRM}})}{\tan(I_{\mathrm{field}})} = \frac{\mathrm{IRM}_z}{\mathrm{IRM}_x} = \tan(I_{\mathrm{IRM},45^\circ}), \tag{2}$$

assuming an infinite '*a*' factor for haematite particles, and $I_{\mathrm{IRM},45^\circ}$ as the inclination of IRM acquired in a magnetic field that has a 45° inclination to the bedding plane. Although the general equation for inclination shallowing correction of red beds is different from the magnetite equation (Tan 2001; Tan & Kodama 2002a), for an infinite '*a*' factor for magnetite and haematite particles, the correction equation becomes the same as eq. (2). Stamatakos *et al.* (1994) have criticized Hodych & Buchan's approach because the magnetic field used did not saturate the magnetization of the sample so that not all the magnetic grains (including the characteristic remanent magnetization, ChRM-carrying particles) had been magnetically activated. The single-component IRM technique does not allow the anisotropy tensor to be determined.

Van der Voo *et al.* (1995) compared red bed palaeomagnetic inclinations with palaeomagnetic inclinations of coeval igneous rocks. Their data suggest that inclination shallowing is not important in natural red beds. However, owing to the low reliability and shallow inclination of some of the data sets, their results are not conclusive. In fact, anomalously shallow inclinations in red beds have been observed globally, e.g. in Newfoundland, Spain and the Alpine–Himalayan mountain belt ranging from Iberia to Parmir (Li *et al.* 1988; Pozzi & Feinberg 1991; Chen *et al.* 1992, 1993; Thomas *et al.* 1993; Bazhenov 1993; van der Pluijm *et al.* 1993; Bazhenov *et al.* 1994; Stamatakos *et al.* 1995; Garces *et al.* 1996; Gilder *et al.* 1996; Chauvin *et al.* 1996).

Particularly intriguing are red beds from central Asia ranging from Jurassic to Tertiary in age. Anomalously shallow inclinations have been observed in red beds from the Tarim basin, Fergana basin, Tadzhik basin, Kirgiz Tien Shan, the Ghissar Range (the westernmost part of the Tien Shan fold belt) and the Himalayan foreland basins (Li *et al.* 1988; Pozzi & Feinberg 1991; Chen *et al.* 1992, 1993; Butler 1992; Bazhenov 1993; Thomas *et al.* 1993; Bazhenov *et al.* 1994; Chauvin *et al.* 1996; Gilder *et al.* 1996; Rosler & Appel 1998; Gautam & Fujiwara 2000; Ojha *et al.* 2000). These rocks have inclinations 15°–30° shallower than the expected inclination from reference Eurasian palaeopoles (e.g. Besse & Courtillot 1991). Several explanations have been proposed, including continental shortening (e.g. Chen *et al.* 1993), a deflected non-axial geocentric dipole (Westphal 1993), a standing non-dipole field component (Chauvin *et al.* 1996), an undetected geological structure that may have accommodated the amount of northward transportation of the various continental blocks (Halim *et al.* 1998), and a non-rigid Eurasian plate (Cogne *et al.* 1999). There is a growing consensus that the inclinations of Cenozoic red beds from Central Asia are anomalously shallow, although there is no conclusive explanation for this observation (Butler 1992; Thomas *et al.* 1993; Chauvin *et al.* 1996; Gilder *et al.* 1996; Fang *et al.* 1997; Kodama & Tan 1997; Rosler & Appel 1998; Gautam & Fujiwara 2000; Ojha *et al.* 2000). Nevertheless, the rock magnetic effects on inclination shallowing should be fully explored before other hypotheses can be adequately evaluated.

The natural remanent magnetization (NRM) of red beds can be either a detrital (depositional or post-depositional) remanence or a chemical remanence (CRM). Burial mechanical compaction can only affect red bed remanence if it is a DRM or a CRM that was acquired early in the post-depositional history of the sediment. Some workers have suggested that red bed remanence is acquired chemically over long periods of time (Walker *et al.* 1981; Larson *et al.* 1982); others have suggested that haematite-bearing sedimentary rocks carry a DRM (Elston & Purucker 1979; Tauxe *et al.* 1980; Steiner 1983; Maillol & Evans 1992; Garces *et al.* 1996). While a CRM red bed remanence could be acquired long after deposition, some palaeomagnetic studies of red beds suggest that a chemical remanence was acquired before burial by only 1 m of overburden (Liebes & Shive 1982). In this case even a CRM could be reoriented to shallow inclinations by subsequent burial compaction. Deposition of haematite-bearing sediments occurs in many modern depositional environments. Recent measurements of AMS carried by haematite particles in the Carboniferous Mauch Chunk Formation (Tan & Kodama 2002b), Cretaceous Kapusaliang Group (Tan *et al.* 2002) and Triassic Passaic Formation (our unpublished data) all showed depositional fabrics, suggesting that DRM in red beds is more common than CRM.

To test the possible effects of compaction on depositional remanence in red beds, three groups of compaction experiments were conducted with sedimentary slurries made from disaggregated material from the Eocene red beds of the Suweiyi Formation, Tarim basin, northwest China. The results reported here indicate that the compaction-caused inclination error depends on the sediment grain size, and that clay-sized haematite-bearing sediments may suffer significant inclination shallowing. The compaction-caused inclination shallowing of fine-sand and silt-sized sediments is shown to be negligible, but the coarse-grained red beds may suffer significant depositional inclination error. Finally, use of the single-component IRM method (Hodych & Buchan 1994) to test inclination error in red beds is not always successful.

2 SAMPLE DESCRIPTION

Samples were collected from a road cut in the Kuche river section located in the Kuche depression near the northern boundary of the

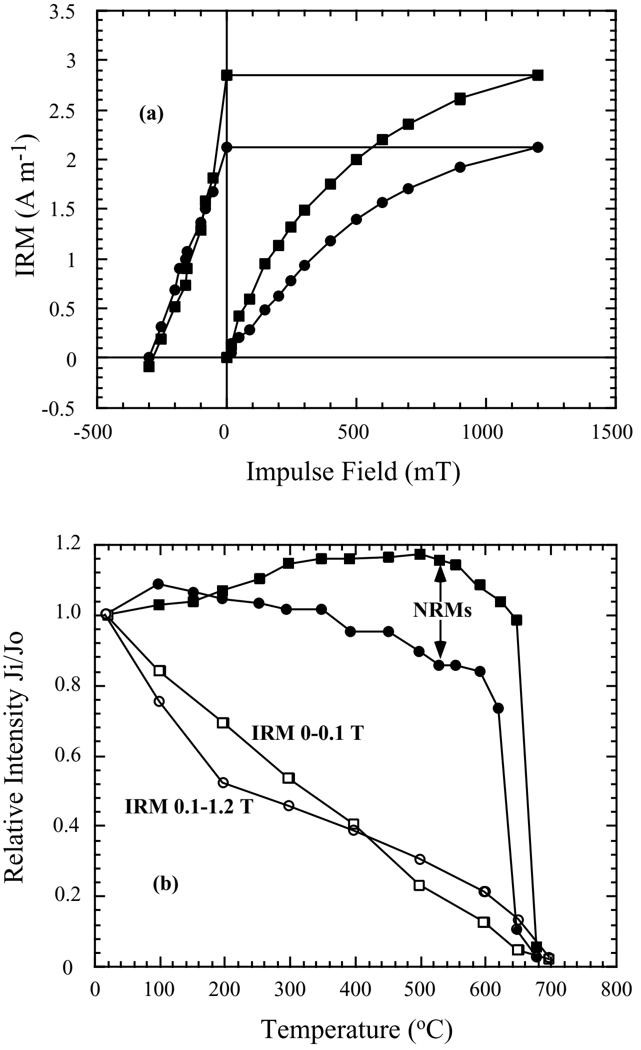

Figure 1. (a) IRM acquisition and back field demagnetization of the Suweiyi Formation red bed samples and (b) thermal demagnetization of NRMs and IRMs acquired in a 1.2 T field indicate haematite is the dominant magnetic mineral.

Tarim basin. The Kuche depression formed during Neogene thrusting in the Tian Shan caused by the Indo–Eurasian collision and contains exposures of Mesozoic and Cenozoic fluvial and alluvial deposits. The Suweiyi Formation is among the youngest strata of the Late Jurassic to Early Tertiary fluvial red bed sequences. Detailed palaeomagnetic study and inclination correction for the natural rock samples of the Suweiyi Formation will be presented elsewhere.

The narrow unblocking temperature spectrum at 640–680°C (Fig. 1), suggests that the natural remanence of the red beds is carried exclusively by haematite. The unblocking temperature spectra of two-component IRMs are distributed over a wide temperature range, up to 700°C (Fig. 1). Acquisition of IRM does not reach saturation at the field of 1.3 T, and the back field to remove the IRM acquired at the highest field is greater than 0.2 T. The high-saturation field (>1.3 T) and high coercivity also suggest that haematite is the dominant magnetic mineral in the samples.

Samples of the Suweiyi Formation were crushed into small fragments ~5 mm in size and disaggregated using an ultrasonic device. Extreme care was taken to avoid any contamination of the samples during the fragmentation and disaggregation processes. The grain shape and the character of the silt and fine-sand grains were checked frequently under an optical microscope to determine whether the grains were completely liberated from the matrix of the rock. A sediment slurry was made using distilled water and the disaggregated particles. The slurry spontaneously separated into clay-sized and silt-sized fractions (Fig. 2), and the laboratory redeposition and compaction experiments proceeded using three different slurries: a fine-grained slurry, a coarse-grained slurry, and a one-to-one volume mixture of the fine- and coarse-grained fractions. The mixture had less coarse-grained material than the grain size distribution of the original sample; therefore the slurry mixture does not represent the character of the original sediment. The study, however, should provide insights into the compaction behaviour of red beds, and more importantly, the methodology for checking and correcting any inclination error.

3 DEPOSITION AND COMPACTION EXPERIMENTS

3.1 Compaction-caused inclination shallowing

3.1.1 Redeposition and DRM/pDRM acquisition

The sediment slurries were poured into a 15.8 mm diameter acrylic cylindrical sample holder in a magnetic field with a 58° inclination controlled by Helmholtz coils. The intensity of the magnetic field was 80 μT, which is slightly stronger than the present Earth's surface magnetic field. Filter papers and porous stones with very weak remanent magnetizations ($<5 \times 10^{-10}$ A m^2) were placed under and on the top of the slurry sample to allow water to drain during compaction (Anson & Kodama 1987). Remanent magnetizations were measured using a CTF two-axis cryogenic magnetometer. The slurries initially acquired magnetizations with inclinations 5°–6° shallower than the laboratory field. After approximately an hour, the magnetization reoriented to be nearly parallel to the laboratory field, presumably caused by post-depositional realignment of fine haematite particles.

3.1.2 Compaction

After the slurries had acquired their magnetization parallel to the ambient magnetic field, they were compacted using a water tank consolidometer (see Hamano 1980; Anson & Kodama 1987). The magnetic field was kept constant during compaction. The pressure on the slurry was increased at a rate of 0.008 MPa h^{-1}, which was controlled by adjusting the drip rate of water into the water tank. The volume and remanent magnetization of the sample were measured ten times at various stages of compaction.

The volume loss as a function of pressure is shown in Fig. 3(a) for all three groups of sediments. For half of the samples, compaction did not start until the friction between the filter paper and plunger was overcome at pressures greater than 0.03 MPa. For the remaining samples approximately half of the total volume loss occurs at a pressure of around 0.04 MPa. As the pressure increases, incremental volume loss decreases and reaches zero at the highest pressures. The total volume loss for a sample is proportional to the initial water content (the weight ratio of water to dry sediment) and inversely proportional to the sediment grain size. The fine-grained samples containing 270 per cent water content experienced a total volume loss of 75 per cent, while the coarse-grained sample with 35 per cent initial water content only experienced a total volume loss of

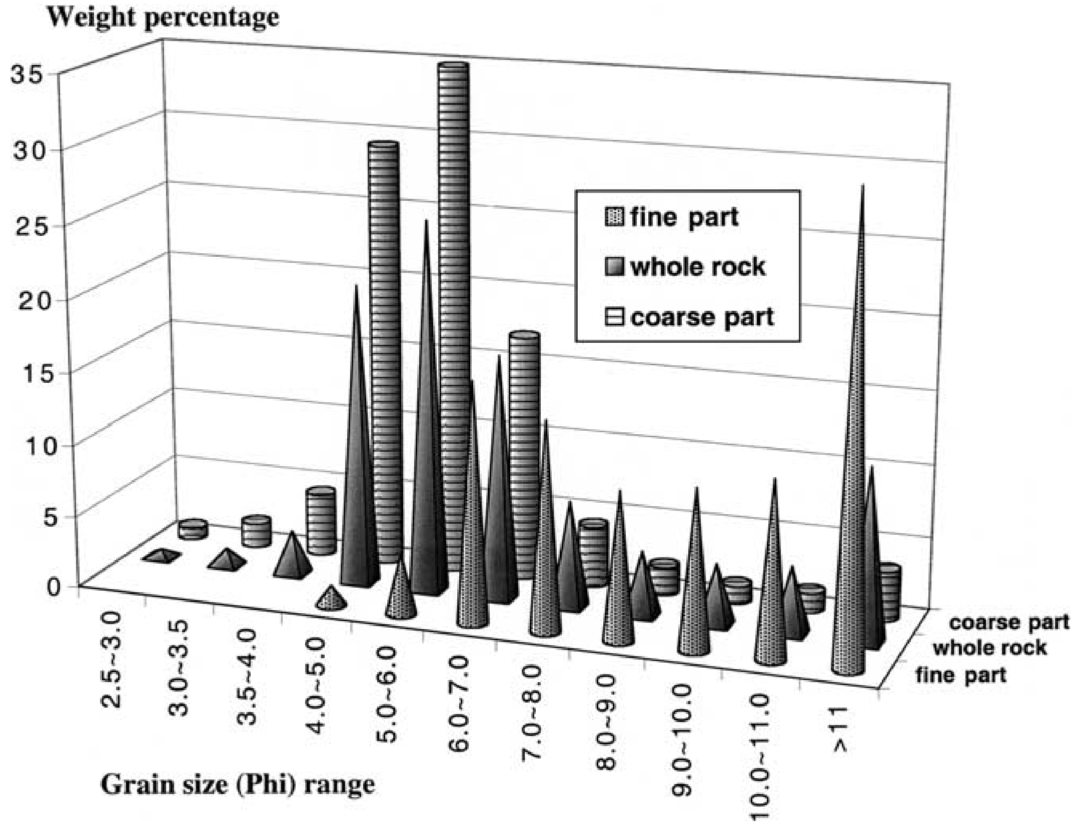

Figure 2. Grain size distributions of the disaggregated whole rock samples, the fine (clay-sized) and the coarse part of the slurries. Grain size (mm) $(\frac{1}{2})^{\Phi}$.

12 per cent. The mixture of coarse- and fine-grained sediments, which had an initial water content of 65 per cent, lost 35 per cent of their volume.

The amount of inclination shallowing of remanent magnetization is proportional to the volume loss and pressure (Figs 3b and c). A significant amount of inclination shallowing may occur at low pressures and volume loss; however, inclination shallowing does not seem to stop at the highest pressures. For all three groups of sediments, the inclination shallowing is more significant at the volume losses that occur at the final stages of compaction.

Sediment grain size is a critical factor controlling the amount of compaction-caused inclination shallowing. For the fine-grained samples, inclination shallowing can be as great as 17°–19° when the initial inclination is ~58°. Inclination shallowing of the coarse-grained sample is only 3°. The mixture of one-to-one (by volume) coarse- and fine-grained slurries only experienced 6° inclination shallowing at a total volume loss of 35 per cent. In summary, our laboratory compaction experiments indicate that significant inclination shallowing of the haematite-bearing sediments occurs only in the clay-sized sediments at high-volume losses (>50 per cent).

3.2 Depositional inclination shallowing

Although the coarse-grained slurry showed little compaction-caused inclination shallowing, it could have suffered from a significant depositional inclination shallowing, as suggested by previous studies of modern river deposits and laboratory redeposition experiments (Tauxe & Kent 1984; Lovlie & Torsvik 1984; Rosler & Appel 1998). Remanence carried by haematite particles (pigmentary and specularite) in modern fluvial deposits is indeed a DRM (e.g. Tauxe & Kent 1984; Rosler & Appel 1998). The coarse-grained slurry was used in a series of redeposition experiments. In these experiments, the slurry was poured into the top of a 7.5 cm high water column in a cylindrical sample holder (the same one used in the compaction experiment). The particles settled by gravity to the bottom of the sample holder in the same magnetic field as used in the compaction experiment. The amount of inclination shallowing observed depended on the sediment accumulation rate, which ranged from 5 to 0.5 mm min^{-1}. The inclination measured after deposition ranged from 28° to 65° (Table 1). The highest depositional rates caused the greatest inclination error. Samples were then compacted to remove most of the water in the column. The inclinations were subsequently shallowed by only 0°–2° caused by compaction. After being air-dried in the same magnetic field, samples were coated with water glass (40 per cent sodium silicate (Na_2SiO_3) solution). During drying and coating, samples experienced only a few degrees of variation in magnetization direction, indicating that the drying process and/or water glass coating only slightly affected the orientation of the magnetic particles. After the water glass coating was dried, samples were subjected to either thermal (using a TSD-1 thermal demagnetizer) or alternating field (AF) (using a GSD-5 AF demagnetizer) demagnetization.

4 MAGNETIC STABILITY OF SYNTHETIC REMANENCE

Kodama & Davi (1995) have shown that the remanent magnetization of their laboratory redeposited and compacted magnetite-bearing samples from the Cretaceous Pigeon Point Formation consisted of two components, one of which was a large viscous

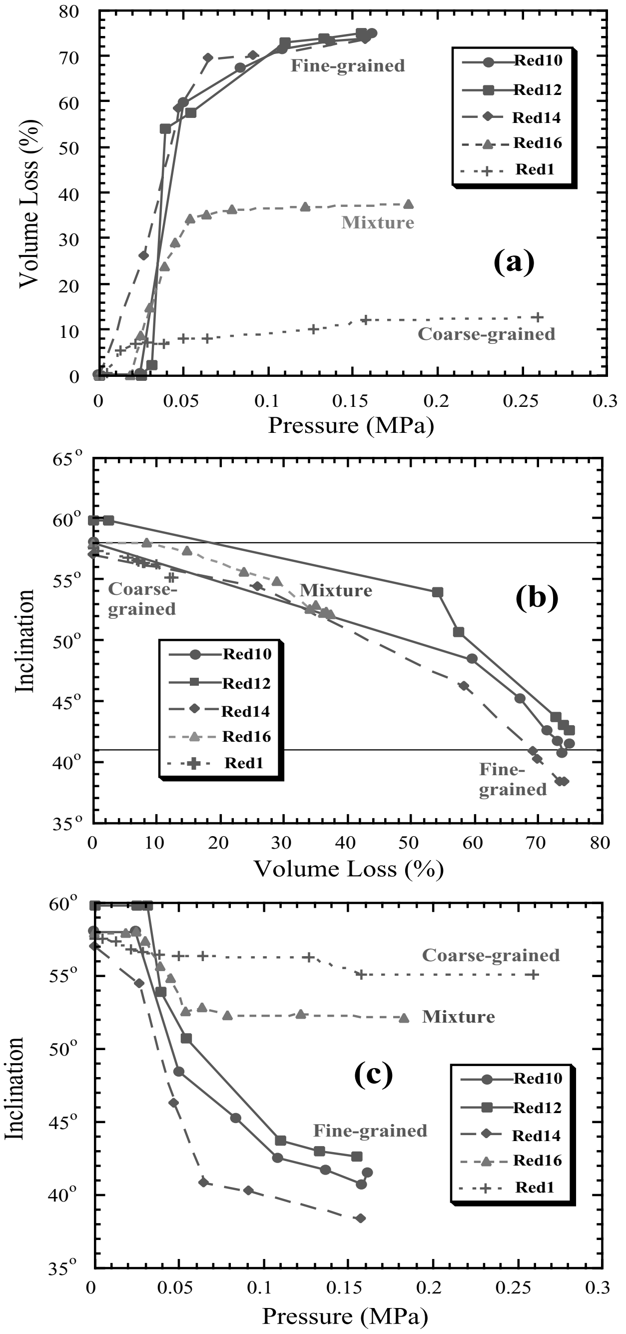

Figure 3. (a) Curves showing the relationship between volume loss and pressure. Most of the volume loss occurs at a pressure below 0.05 MPa. At higher pressures, incremental volume loss decreases to zero. Volume loss is a function of sediment grain size and water content of the sediments. The fine-grained sediments (sample Red10, Red12, Red14) experienced 75 per cent volume loss, while the coarse-grained sediments (sample Red1) experienced only 12 per cent volume loss. The mixture (sample Red16) of fine- and coarse-grained sediments lost 35 per cent of their volume. (b) Inclination variations of three groups of sediments (symbols as in (a)). Inclination shallowing depends on the volume loss of a sediment. For fine-grained sediments, inclination shallowing can reach up to 17°–19° when the initial inclination was ∼58°. Inclination shallowing of coarse-grained sediments is a maximum of 3°. The mixture of coarse- and fine-grained sediments shows 6° inclination shallowing at 35 per cent volume loss. (c) Inclination shallowing versus pressure curves, indicating that significant inclination shallowing occurs at low pressure, yet shallowing does not stop at high pressures as long as compaction continues.

magnetic overprint. We conducted AF and thermal demagnetization of our fine- and coarse-grained samples after compaction to determine whether they had also acquired a large secondary overprint during compaction. Demagnetization should also be able to isolate the contributions of fine- and coarse-grained haematite particles to the observed depositional inclination error, and reveal some features of depositional error, which may be useful for recognizing natural depositional inclination error in red beds.

4.1 Stability of compaction-shallowed inclination

For samples that suffered significant compaction-caused inclination shallowing, the direction of remanent magnetization remains nearly unchanged during stepwise AF and thermal demagnetization while the remanent intensity decays gradually (Fig. 4). The inclination appears to steepen at the highest-temperature demagnetization steps (600, 650, 700 °C), but this is an artefact of the low-magnetic intensity and large measurement error. In addition, AF demagnetization reveals that particles over a range of coercivities carry the same shallow direction. These results indicate that all the magnetic grain sizes in the sample have experienced approximately the same magnitude of inclination error.

The presence of relatively low coercivities and unblocking temperatures revealed by demagnetization could suggest the presence of magnetite, yet acquisition of IRM, back field demagnetization and thermal demagnetization of two orthogonal components of IRM indicate that the contribution of magnetite to the remanent magnetization of a sample is negligible (Fig. 5). Introduction of magnetite during laboratory procedures can also be ruled out. The distributed IRM unblocking temperature and coercivity spectra are typical of pigmentary haematite, which has also been observed in modern river deposits (e.g. Tauxe & Kent 1984). The patterns of unblocking and coercivity spectra are probably caused by the gradual diffusion of defect moments in the pigmentary haematite (Dunlop 1972; Dekkers & Linssen 1989). For the natural samples, most of the intensity of ChRM was removed between ∼620 and 680 °C (Fig. 1), suggesting that large-grained haematite (specularite) is present in the rock samples (Collinson 1974; Dekkers & Linssen 1989). Thermal demagnetization also shows that large haematite particles are present in the coarse-grained part of the redeposited slurry (Fig. 6). Experiments on the Cretaceous Ladd Formation (Tan & Kodama 1998), the Triassic Daye Formation (Tan *et al.* 2000), the Mauch Chunk Formation (Tan & Kodama 2002), the Kapusaliang Group (Tan *et al.* 2002) and the Passaic Formation (our unpublished data) have shown that in both magnetite-bearing and haematite-bearing samples the induced remanence (ARM and IRM) and artificial remanence (i.e. redeposited and compacted remanence) generally have more distributed unblocking temperature spectra than the ChRM or NRM of the corresponding natural samples. Thus, one would not necessarily expect the same unblocking spectra for the artificial remanence as for the NRMs. If the intermediate temperature component is mainly carried by pigmentary haematite, the fact that direction does not change during demagnetization could indicate either a detrital origin or very early formation of the pigmentary haematite. Formation of haematite late in the post-depositional history could be ruled out since laboratory experiments have shown late-stage haematite can carry multicomponent CRMs even though the ambient field remained unchanged (Heider & Dunlop 1987; Stokking & Tauxe 1990). NRM of red beds is often not as complicated as the laboratory-produced CRM, implying either a single generation of CRM or simply a DRM or a pDRM.

Table 1. Magnetic components of the laboratory depositional remanent magnetization isolated by principal-component analysis (Kirschvink 1980).

Sample	Component	Dec (deg)/Inc (deg) (MAD deg)	Inc0 (deg)	Inc1 (deg)	Inc2 (deg)
Redep-1	200°C–origin	11.6/28.9 (3.6)	32.4	42.7	43.2
	400–630°C	345.3/32.7 (4.6)			
Redep-3	630°C–origin	348.4/18.9 (4.8)	30.4	44.6	–
	300–660°C	12.8/54.6 (4.1)			
Redep-5	630°C–origin	7.8/37.0 (4.1)	57.0	43.6	44.1
	200–630°C	357.1/66.3 (2.4)			
Redep-7	630°C–origin	17.0/55.8 (4.0)	65.6	43.9	44.5
	0–630°C	354.9/52.4 (4.2)			
Redep-8	630°C–origin	356.9/34.8 (4.3)	54.7	44.4	45.0
	0–60 mT	355.2/33.4 (4.6)			
Redep-2	60 mT–origin	359.0/20.2 (3.5)	28.7	42.1	43.4
	0–100 mT	349.4/57.3 (2.6)			
Redep-4	60 mT–origin	357.1/39.6 (3.3)	55.3	43.9	44.5
	0–100 mT	346.6/63.0 (2.7)			
Redep-6	60 mT–origin	3.1/49.4 (2.5)	60.3	44.1	44.6

Note: Inc0 is the inclination of DRM (resultant of all components); Inc1 is the inclination of saturation IRM (SIRM) acquired at 45° field inclination; Inc2 is the inclination of the high unblocking temperature component of SIRM. Samples are listed in the order of decreasing deposition rate in the thermal demagnetization and AF demagnetization sections, respectively.

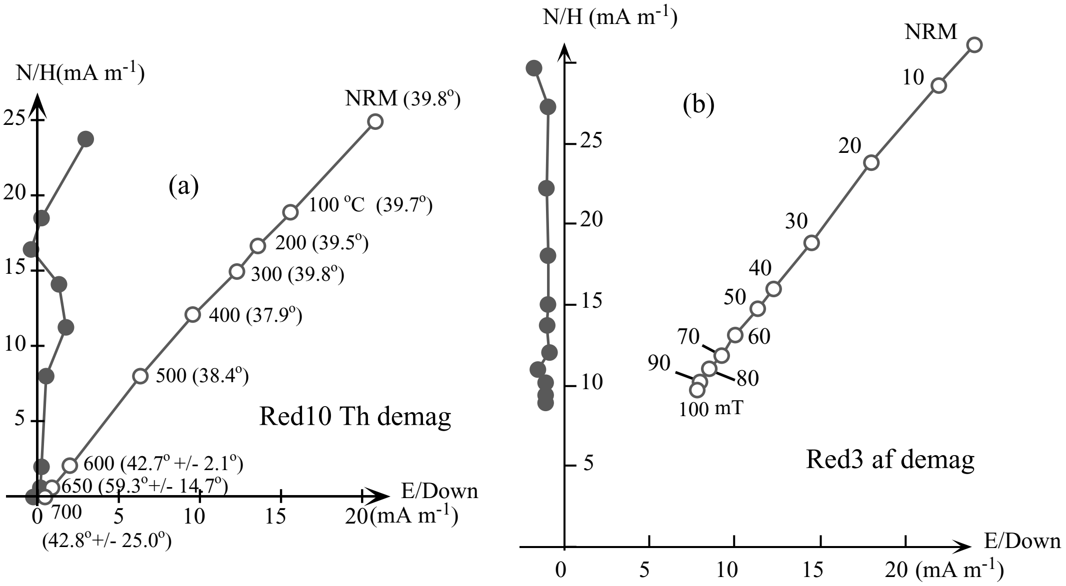

Figure 4. Hyperbolic orthogonal vector end point projections of remanent magnetizations after stepwise thermal demagnetization for the fine-grained sediment sample Red10 (a), and alternating field demagnetization for sample Red14 (b), which showed 17°–19° inclination shallowing after compaction. The solid circles represent the vector projections on to the horizontal plane, the open circles show projection on to a vertical plane. Inclinations are also noted in (a); the errors of inclination are less than 1°, unless otherwise indicated.

The stable directional demagnetization behaviour of the compacted samples indicates that clay-sized red sediments could carry a remanent magnetization that may have experienced significant burial compaction-caused inclination shallowing if the pigmentary haematite formed before significant compaction occurred.

4.2 Stability of depositional inclination error

In contrast to the single-component, fine-grained samples, most of the coarse-grained redeposition samples, except one, carry at least two remanence components (Fig. 6, Table 1). For most of the samples, the demagnetization trajectory can be fitted to a line, but this line does not pass through the origin (Fig. 6). In fact, the inclination becomes shallower when demagnetization proceeds at higher temperatures. To make an estimate of the ChRM direction, the last several steps were used to fit the characteristic directions (Table 1). The demagnetization behaviour indicates that for the highest unblocking temperature, presumably the coarsest haematite particles suffer the most depositional inclination error, probably owing to the gravitational force causing the basal plane of particles to settle nearly horizontally. For the five slowly deposited samples (Redep-4 to 8), their initial remanent magnetization before demagnetization and the intermediate temperature component are closer to the laboratory magnetic field. Yet, their ChRMs can suffer a significant

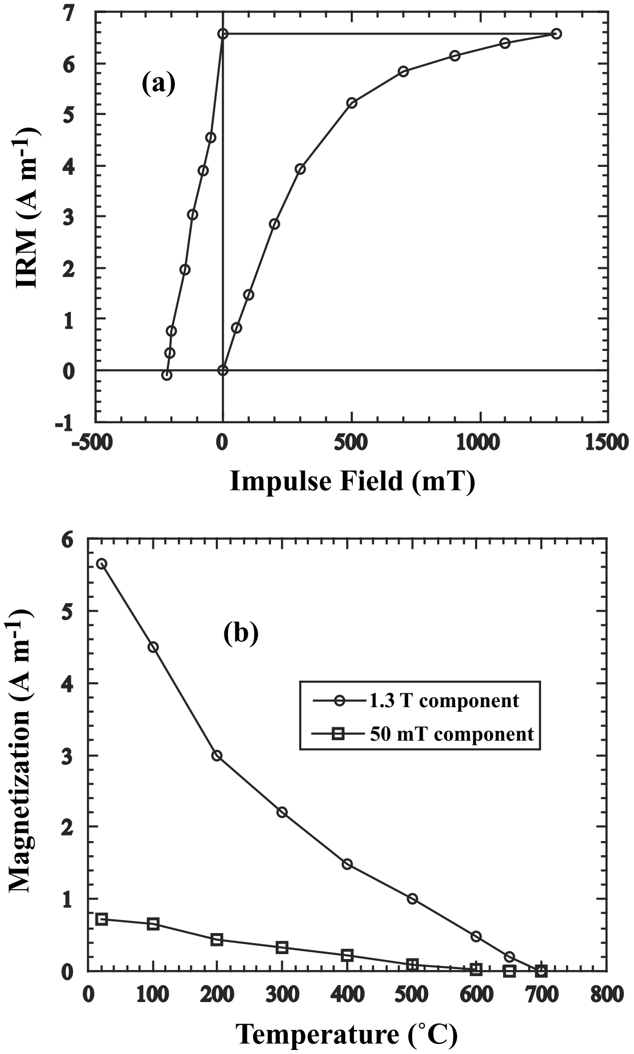

Figure 5. (a) Acquisition of IRM and back field demagnetization curves for a fine-grained sample. IRM is not saturated at the highest impulse field of 1.3 T. The coercivity of remanence is greater than 200 mT. (b) Thermal demagnetization of two orthogonal IRM components acquired in 1.3 T and 50 mT in bedding parallel and bedding perpendicular directions, respectively. These characteristics indicate that pigmentary haematite is the dominant magnetic mineral, although the NRM demagnetization data (Fig. 1) may also indicate the presence of high-unblocking temperature specularite grains.

depositional inclination error, up to 23°. Apparently, the finer haematite particles are able to orient parallel to the Earth's magnetic field during relatively slow deposition. Without demagnetization, no depositional inclination shallowing would be observed, and these samples would be considered to be accurate recorders of the Earth's magnetic field. After demagnetization, the intermediate temperature component is, in fact, a good proxy for the ambient magnetic field direction.

Depositional inclination shallowing probably depends on the ability of magnetic particles to orient or reorient parallel to the Earth's magnetic field. The larger haematite grains are less capable of orienting and reorienting parallel to the Earth's magnetic field during and after deposition, and therefore suffer greater inclination shallowing. The faster deposition rate reduces the duration when sediments remain at the water–sediment interface and decreases the chance of orientation/reorientation of haematite particles. Therefore, sediments carrying specularite particles formed in a fast depositional environment may experience significant inclination shallowing.

5 RELEVANCY TO NATURE

Our depositional inclination error is produced in conditions comparable to low-energy alluvial/fluvial deposition environments, in which sediments are settled mainly by gravity on to a more or less flat surface. A considerable depositional inclination error, typically ~15°–30°, has been observed in nature (e.g. Tauxe & Kent 1984; Rosler & Appel 1998). In some sites of the Cretaceous Kapusaliang Group red beds from the Tarim basin, China, fine-grained haematite particles carry an accurate palaeomagnetic inclination (Tan *et al.* 2002), similar to the second laboratory deposition experiment in which the fine-grained haematite particles (Table 1, the lower stability component) carry the real magnetic field direction. Sedimentary deposition rates for real strata are often extremely underestimated, because fluvial and alluvial deposition happens in pulses and during much of the time period of a section there is no deposition at all. Modern fluvial and alluvial depositions occur mainly during the rainy and flood seasons of a year. The DRM produced by laboratory redeposition is probably a good analogue to nature. Therefore, in nature, the depositional inclination error carried by fluvial deposits may be more prevalent than previously thought. However, our compaction experiment is only analogous to shallow (<100 m) burial compaction early in the post-depositional history of sediments. In nature, intergranular pressure solution may cause viscous compaction for sand and silt-sized sediments during deep (>1 km) burial that could cause further inclination shallowing (e.g. Tada & Siever 1989). Pressure solution becomes more important at burial depths greater than 1 km, with increases in pressure, temperature and burial time (e.g. Tada & Siever 1989). Although no compaction-caused inclination shallowing for sandstones has been produced in the laboratory, one can imagine that progressive flattening of sedimentary beds will cause a flattened distribution of prolate and/or oblate magnetic particles, in a way similar to mechanical compaction of clays (e.g. Sun & Kodama 1992). Therefore, compaction-caused inclination error may be more important for older and more deeply buried sedimentary rocks. In summary, our laboratory-produced depositional inclination error may be relevant to natural DRM carried by fluvial red beds, while the experimental compaction behaviour represents the behaviour of sediments after shallow burial for a short time period.

6 CORRECTION FOR INCLINATION ERROR

Anisotropy of remanent magnetization can be used to measure the deviation of remanent magnetization from the ambient geomagnetic field (e.g. Jackson *et al.* 1991). The anisotropy of anhysteretic remanent magnetization (AAR) has been used successfully to correct the magnetization of sediments and sedimentary rocks containing low-coercivity ferrimagnetic minerals (e.g. Hodych & Bijaksana 1993; Kodama 1997; Tan & Kodama 1998).

To measure magnetic remanence anisotropy in our haematite-bearing samples, we applied an impulse DC magnetic field (using an ASC impulse magnetizer) at 45° to the horizontal plane of the vertically compacted samples. This approach is similar to the technique used by Hodych & Buchan (1994). Our samples either have a compaction-induced inclination shallowing or experienced virtually no inclination shallowing during compaction; thus we can

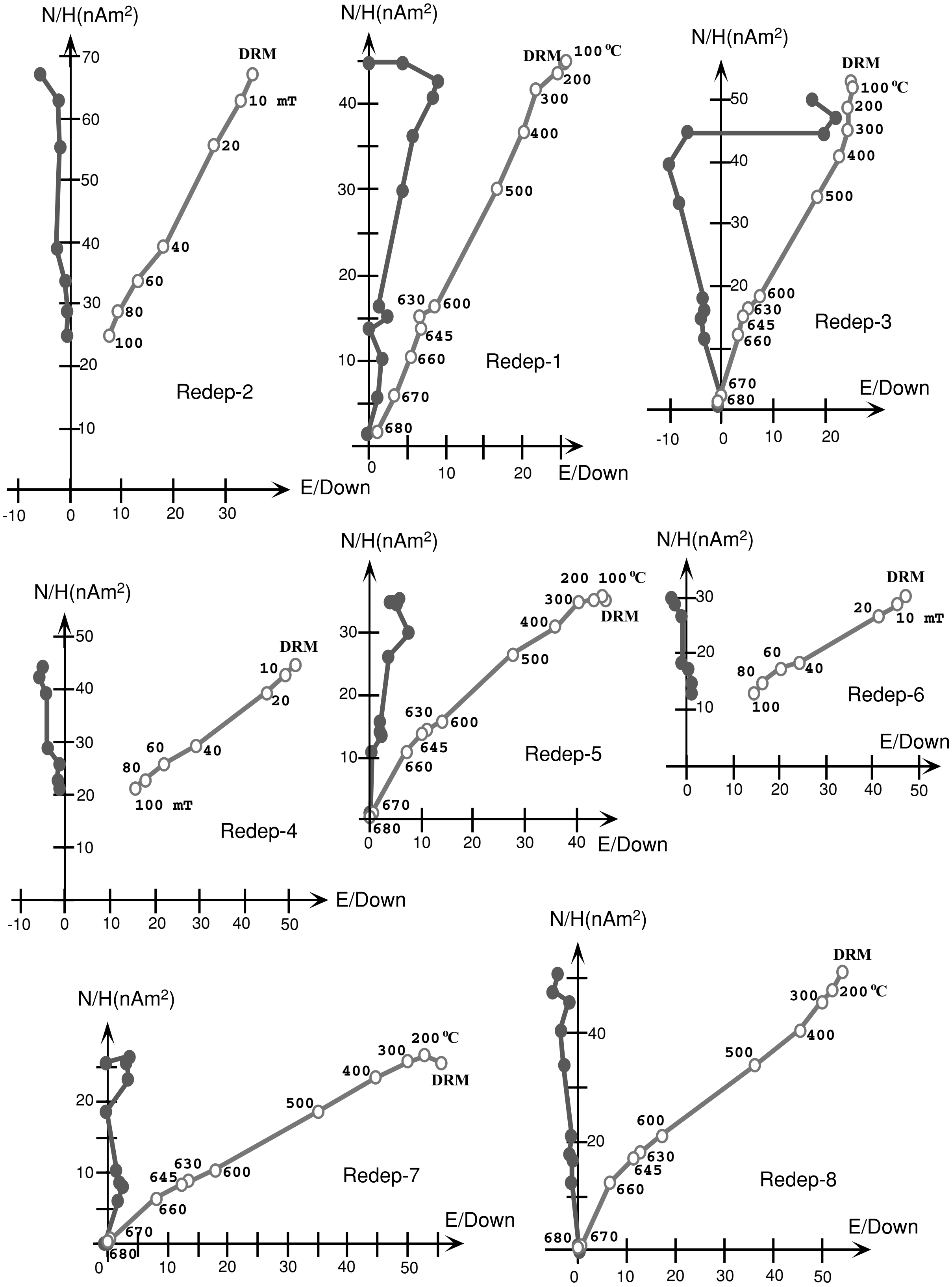

Figure 6. Hyperbolic orthogonal demagnetization trajectories of the laboratory redeposited coarse-grained samples. Solid (open) circle represents projection of remanent magnetization on to horizontal (vertical) plane.

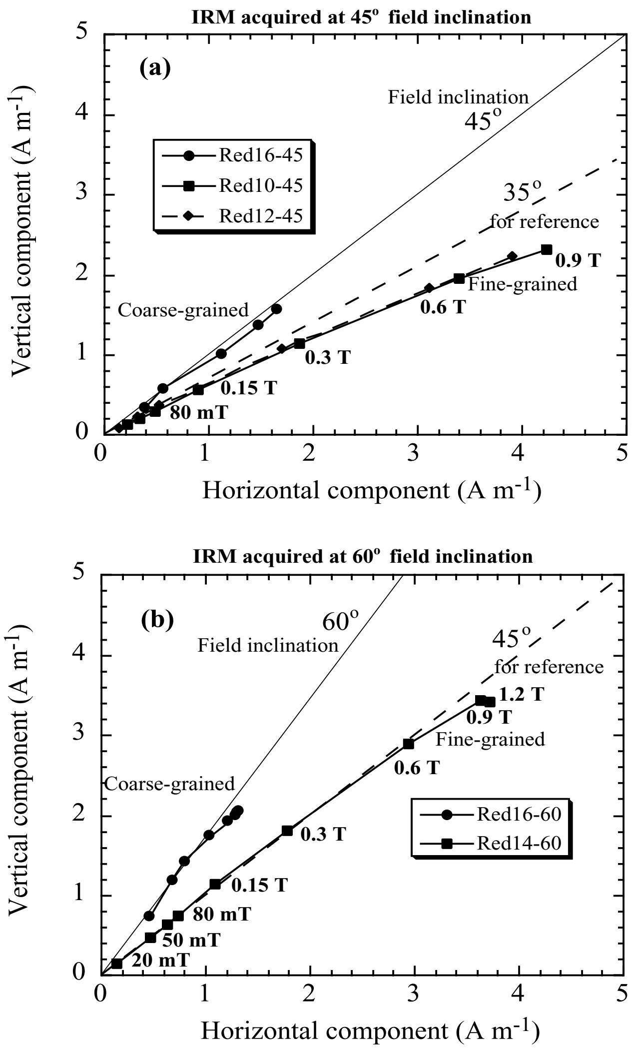

Figure 7. (a) IRM acquisition at a 45° angle to the bedding of the sample to test whether IRM can identify inclination shallowing. A fine-grained sample that showed significant compaction-induced inclination shallowing in our compaction experiments acquired its IRM at an angle 10°–13° shallower (closer to bedding) than the angle at which the field was applied (45°). Sample Red16, which showed 6° experimental compaction-induced inclination shallowing, acquired its IRM only 2° from the angle at which it was applied. The results show the usefulness of IRM acquisition as a method for identifying the importance of compaction-caused inclination shallowing in natural sediments. (b) IRM acquisition at 60° to the bedding plane of the samples. For sample Red16, the difference between the angle at which the field was applied and that the IRM acquired is small, similar to the amount of inclination shallowing observed in our compaction experiments. For the fine-grained sample Red14, the IRM acquisition experiments reveal a 15°–18° difference between the field applied and the IRM acquired, similar to the amount of compaction-induced inclination shallowing. It also shows that this angular difference remains constant for a range of IRM acquisition fields, so the highest field (1.3 T) may be enough to indicate the compaction-induced inclination shallowing.

assume that the magnetic anisotropy is greater in the samples that suffered a greater amount of inclination shallowing. Fig. 7(a) indicates the inclination of IRM acquired at increasingly higher field intensities from 20 to 900 mT. Two observations may be made. The fine-grained samples, which have experienced significant laboratory compaction-caused inclination shallowing, also show significant (>10°) errors in the inclination of the IRM acquired. The coarse-grained sample, however, which experienced only 3° compaction-caused inclination shallowing, acquired IRM inclinations with a deviation of less than 2° from the applied field. In addition, the IRM inclination error tends to increase slightly as the applied field increases. The IRM inclination error increases from 10° when the field applied is 20 mT to 13° at the highest field intensity, 900 mT. These results suggest that a single-component IRM may be used as a first-order measure of remanence anisotropy in haematite-bearing sediments.

We then used two independent measures to determine whether the partial anisotropy of a single-component IRM could adequately identify and correct inclination error. First, we imparted a magnetic field at 60° to the horizontal plane of the sample to see whether the IRM inclination shallowing is similar to the amount of compaction-induced shallowing observed for the ChRM inclination. Fig. 7(b) shows the inclination as the applied DC field strength increases from 20 to 1200 mT. The IRM of the coarse-grained sample accurately records the inclination of the applied field, while the IRM inclination of the fine-grained sample is 15° shallower than the applied field at low field strength (50–800 mT), and at the highest fields, it shallows to 43°. The inclination of the compacted ChRM for the same sample was 38°, and thus, the IRM inclination error is in reasonably close agreement with the ChRM inclination shallowing if the 2° inclination difference between IRM acquisition and laboratory compaction fields and other errors, such as orientation and measurement errors (2° orientation, 1° measurement, and 2° maximum angular deviation, MAD for the least-square-fitted ChRM), are taken into account. Secondly, we applied eq. (2) to correct the inclination for the two compacted ChRMs of the fine-grained samples. Table 2 shows that the corrected inclination is ~4° shallower than the laboratory field inclination during deposition, which is 58°, when the low-field IRM inclination is used and the difference decreases to nearly zero when the high-field IRM inclination is used in eq. (2). Although IRMs acquired in fields well below saturation causes a slight undercorrection of the ChRM inclination, higher fields closer to IRM saturation can be used to accurately correct the inclination of haematite-bearing sediments. Apparently, single-component IRMs rather than the complete IRM anisotropy tensor may provide accurate corrections and, in general, can be used to assess the importance of compaction-caused inclination shallowing in a haematite-bearing sediment.

Similarly, we applied the 45° single IRM component approach to those coarse-grained redeposited samples that experienced from 0° to 40° of depositional inclination shallowing. The inclination of the saturation IRM (Inc1 in Table 1) does not deviate significantly from the 45° field inclination despite the wide range in inclination shallowing of laboratory DRM. The inclination of the high unblocking temperature IRM component (Inc2 in Table 1) is even closer to the 45° inclination of the magnetic field. Since the larger haematite particles suffer greater depositional inclination shallowing, if the single IRM component is capable of detecting remanent anisotropy, Inc2 should be much shallower than Inc1, and deviate even further from 45°. Apparently, the single-component IRM fails to identify any depositional inclination errors.

For the single IRM component technique, it is assumed that the individual particle anisotropy of magnetic particles is infinite. While the IRM anisotropy of large crystalline haematite particles is approximately two (Neel 1953), the successful correction of compaction-caused inclination shallowing by the single-component IRM approach and eq. (2) may suggest that the fine-grained haematite behaves magnetically like an infinitely anisotropic particle. One

Table 2. Correction of compacted ChRM inclination by a single IRM direction (see text).

Sample Red-10				Sample Red-14			
Field (mT)	I_{IRM} (deg)	I_{ChRM} (deg)	I_{corr} (deg)	Field (mT)	I_{IRM} (deg)	I_{ChRM} (deg)	I_{corr} (deg)
40	30.4	42	55.9	20	32.1	43	56.1
80	31.7	42	55.6	50	33.8	43	54.3
150	32.2	42	55.0	100	34.3	43	53.9
300	31.5	42	55.8	300	32.4	43	55.8
600	29.8	42	57.5	600	30.5	43	57.7
900	28.8	42	58.6	900	29.7	43	58.6

Note: The laboratory magnetic field inclination is 58°. I_{IRM}, I_{ChRM} and I_{corr} are the IRM inclinations acquired at fields of increasingly high strength and with an inclination of 45° to the bedding, the ChRM inclination of compacted samples and the corrected ChRM inclination by applying eq. (2), respectively.

possibility is that the pigmentary haematite particles were transformed from goethite by dehydration or from single-domain magnetite by oxidation. We have been able to measure the complete remanent anisotropy tensors of the Passaic and Mauch Chunk formations red bed samples, which show 10 and 20 per cent depositional and/or compactional fabrics, respectively (Tan 2001; Tan & Kodama 2002b, and our unpublished data). Since the thermal demagnetization approach was used to measure the complete tensor of IRM anisotropy, the 'memory effect' was avoided. In addition, the measured degree of anisotropy was confirmed by multiple subsamples drilled from bedding parallel and bedding perpendicular directions, and hence the effect of mineral alteration caused by heating is negligible. While for the Mauch Chunk Formation samples, the single-component IRM does identify a significant remanent anisotropy, it fails to show measurable anisotropy for the samples from the Passaic Formation. Whether the single-component IRM is able to identify significant anisotropy probably also depends on the domain stability and the shape and anisotropy of individual haematite particles. If the domain structure of haematite particles can be modified by a high DC magnetic field or the *a* factor is as small as reported by Neel (1953), the inclination of the single IRM component will not deviate much from the 45° field inclination. The single-component IRM technique may be used as a simple test to identify significant anisotropy and inclination error. However, failure to show significant deviation of IRM from the applied field direction does not necessarily indicate a small anisotropy between bedding parallel and bedding perpendicular planes, and, hence, little inclination shallowing. To evaluate remanent magnetic anisotropy and correct for inclination shallowing in red beds, we strongly recommend that multiple IRM components in different directions should be measured.

7 CONCLUSIONS

Our experiments demonstrate that mechanical compaction-caused inclination shallowing depends on the grain size of haematite-bearing sediments. While coarse-grained sediments show little inclination shallowing during compaction, the clay-sized sediments show significant compaction-caused inclination shallowing. Most of the inclination error occurs at high volume loss and at large burial depths. The NRM of red beds can be of detrital and/or of chemical origin. If CRM acquisition occurred early enough in the post-depositional history of sediments, the fine-grained red beds (e.g. mudstones) may also have experienced significant inclination shallowing. The coarse sediments may suffer a depositional inclination error. Depositional inclination error is greater for larger haematite particles and at a faster sediment accumulation rate. Samples deposited slowly may consist of multicomponent magnetizations, in which the intermediate unblocking temperature/coercivity component carried by finer haematite particles may accurately record the Earth's magnetic field direction. Although a single-component IRM approach may be used to recognize inclination shallowing for very fine-grained samples, in some cases significant remanent anisotropy in coarse-grained samples is not detected by the method. Therefore, several IRM components in various directions should be determined to identify even a partial anisotropy of rock samples and to correct inclination error.

ACKNOWLEDGMENTS

This study was partially supported by the National Natural Science Foundation of China (grant 49334050) and the US NSF (grant EAR-9315778). XT was also supported by Lehigh University's Kingsley Fellowship. We thank Dr Bobb Carson for his generous supply of ultrasonic equipment.

REFERENCES

Anson, G.L. & Kodama, K.P., 1987. Compaction-induced inclination shallowing of the post-depositional remanent magnetization in a synthetic sediment, *Geophys. J. R. astr. Soc.,* **88,** 673–692.

Arason, P. & Levi, S., 1990. Models of inclination shallowing during sediment compaction, *J. geophys. Res.,* **95,** 4481–99.

Bazhenov, M.L., 1993. Cretaceous palaeomagnetism of the Fergana basin and adjacent ranges, central Asia: Tectonic implications, *Tectonophysics,* **221,** 251–267.

Bazhenov, M.L., Perroud, H., Chauvin, A., Burtman, V.S. & Thomas, J.C., 1994. Palaeomagnetism of Cretaceous red beds from Tadzhikistan and Cenozoic deformation due to India–Eurasia collision, *Earth planet. Sci. Lett.,* **124,** 1–18.

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

Butler, R.F., 1992. Palaeomagnetism: magnetic domains to geologic terranes, Blackwell, Boston.

Chauvin, A., Perroud, H. & Bazhenov, M.L., 1996. Anomalous low palaeomagnetic inclinations from Oligocene-Lower Miocene red beds of the south-west Tien Shan, Central Asia, *Geophys. J. Int.,* **126,** 303–313.

Chen, Y., Cogne, J.-P. & Courtillot, V., 1992. New Cretaceous palaeomagnetic results from the Tarim basin, Northwestern China, *Earth planet. Sci. Lett.,* **114,** 17–38.

Chen, Y., Courtillot, V., Cogne, J.P., Besse, J., Yang, Z. & Enkin, R., 1993. The configuration of Asia prior to the collision of India: Cretaceous palaeomagnetic constrains, *J. geophys. Res.,* **98,** 21 927–21 941.

Cogne, J.P., Halim, N., Chen, Y. & Courtillot, V., 1999. Resolving the problem of shallow magnetizations of tertiary age in Asia; insights from palaeomagnetic data from the Qiangtang, Kunlun, and Qaidam blocks (Tibet, China), and a new hypothesis, *J. geophys. Res.,* **104,** 17 715–17 734.

Collinson, D.W., 1974. The role of pigment and specularite in the remanent magnetism of red sandstone, *Geophys. J. R. astr. Soc.,* **38,** 253–264.

Deamer, G.A. & Kodama, K.P., 1990. Compaction-induced inclination shallowing in synthetic and natural clay-rich sediments, *J. geophys. Res.,* **95,** 4511–4529.

Dekkers, M.J. & Linssen, J.H., 1989. Rock magnetic properties of fine-grained natural low-temperature haematite with reference to remanence acquisition mechanisms in red beds, *Geophys. J. Int.,* **99,** 1–18.

Dunlop, D.J., 1972. Magnetic mineralogy of unheated and heated red sediments by coercivity spectrum analysis, *Geophys. J. R. astr. Soc.,* **27,** 37–55.

Elston, D.P. & Purucker, M.E., 1979. Detrital magnetization in red beds of the Moenkopi Formation (Triassic), Gray Mountain, Arizona, *J. geophys. Res.,* **84,** 1653–1665.

Fang, D., Tan, X. & Kodama, K.P., 1997. New palaeomagnetic data of Cretaceous and Tertiary red beds from the northern Tarim Basin, northwest China provide more evidence for anomalously shallow inclinations, *EOS, Trans. Am. geophys. Un.,* **78,** Fall Meet. Suppl., F174.

Garces, M., Pares, J.M. & Cabrera, L., 1996. Further evidence for inclination shallowing in red beds, *Geophys. Res. Lett.,* **23,** 2065–2068.

Gautam, P. & Fujiwara, Y., 2000. Magnetic polarity stratigraphy of Siwalik Group sediments of Karnali River section in western Nepal, *Geophys. J. Int.,* **142,** 812–824.

Gilder, S., Zhao, X., Coe, R., Meng, Z., Courtillot, V. & Besse, J., 1996. Palaeomagnetism and tectonics of the southern Tarim basin, northwestern China, *J. geophys. Res.,* **101,** 22 015–22 031.

Halim, N. *et al.*, 1998. New Cretaceous and early Tertiary palaeomagnetic results from Xining-Lanzhou Basin, Kunlun and Qiangtang blocks, China; implications on the geodynamic evolution of Asia, *J. geophys. Res.,* **103,** 21 025–21 045.

Hamano, Y., 1980. An experiment on the post-depositional remanent magnetization in artificial and natural sediments, *Earth planet. Sci. Lett.,* **51,** 221–232.

Heider, F. & Dunlop, D.J., 1987. Two types of chemical remanent magnetization during the oxidation of magnetite, *Phys. Earth planet. Inter.,* **46,** 24–25.

Hodych, J.P. & Bijaksana, S., 1993. Can remanence anisotropy detect palaeomagnetic inclination shallowing due to compaction? A case study using Cretaceous deep-sea limestones, *J. geophys. Res.,* **98,** 22 429–22 441.

Hodych, J.P. & Buchan, K.L., 1994. Early Silurian palaeolatitude of the Springdale Group red beds of central Newfoundland: a palaeomagnetic determination with a remanence anisotropy test for inclination error, *Geophys. J. Int.,* **117,** 640–652.

Jackson, M.J., Banerjee, S.K., Marvin, J.A., Lu, R. & Gruber, W., 1991. Detrital remanence, inclination errors and anhysteretic anisotropy: quantitative model and experimental results, *Geophys. J. Int.,* **104,** 95–103.

Kirschvink, J.L., 1980. The least-square line and plane and the analysis of palaeomagnetic data, *Geophys. J. R. astr. Soc.,* **62,** 699–718.

Kodama, K.P., 1997. A successful rock magnetic technique for correcting palaeomagnetic inclination shallowing: Case study of the Nacimiento Formation, New Mexico, USA, *J. geophys. Res.,* **102,** 5193–5206.

Kodama, K.P. & Davi, J.M., 1995. A compaction correction for the palaeomagnetism of the Cretaceous Pigeon Point Formation of California, *Tectonics,* **14,** 1153–1164.

Kodama, K.P. & Sun, W.W., 1992. Magnetic anisotropy as a correction for compaction-caused palaeomagnetic inclination shallowing, *Geophys. J. Int.,* **111,** 465–469.

Kodama, K.P. & Tan, X., 1997. Central Asian inclination anomalies: possible inclination shallowing in red beds?, *EOS, Trans. Am. geophys. Un.,* **78,** Fall Meet. Suppl., F174.

Larson, E.E., Walker, T.R., Patterson, P.E., Hoblitt, P.R. & Rosenbaum, J., 1982. Palaeomagnetism of the Moenkopi Formation, Colorado Plateau: basis for long term model of acquisition of CRM in red beds, *J. geophys. Res.,* **87,** 1081–1106.

Li, Y., Zhang, Z., McWilliams, M.O., Sharps, R., Zhai, Y., Li, Y.A., Li, Q. & Cox, A., 1988. Mesozoic palaeomagnetic results of the Tarim Craton: tertiary relative motion between China and Siberia?, *Geophys. Res. Lett.,* **15,** 217–220.

Liebes, E. & Shive, P.N., 1982. Magnetization acquisition in two Mesozoic red sandstones, *Phys. Earth planet. Inter.,* **30,** 396–404.

Lovlie, R. & Torsvik, T., 1984. Magnetic remanence and fabric properties of laboratory-deposited haematite-bearing red sandstone, *Geophys. Res. Lett.,* **11,** 229–232.

Lu, R., Banerjee, S.K. & Marvin, J., 1990. Effects of clay mineralogy and the electrical conductivity of water on the acquisition of DRM in sediments, *J. geophys. Res.,* **95,** 4531–4538.

Maillol, J.M. & Evans, M.E., 1992. Magnetic intensity variations in red beds of the Lodeve Basin (southern France) and their bearing on the magnetization acquisition process, *Geophys. J. Int.,* **111,** 281–290.

Neel, L., 1953. Some new results on antiferromagnetism and ferromagnetism, *Rev. Mod. Phys.,* **25,** 58–63.

Ojha, T.P., Butler, R.F., Quade, J., DeCelles, P.G., Richards, D. & Upreti, B.N., 2000. Magnetic polarity stratigraphy of the Neogene Siwalik Group at Khutia Khola, far western Nepal, *Geol. Soc. Am. Bull.,* **112,** 424–434.

Potts, S.S., van der Pluijm, B.A. & van der Voo, R., 1994. Discordant Silurian palaeolatitudes for central Newfoundland: new palaeomagnetic evidence from the Springdale Group, *Earth planet. Sci. Lett.,* **120,** 1–12.

Pozzi, J.-P. & Feinberg, H., 1991. Palaeomagnetism in the Tajikistan: continental shortening of the European margin in the Parmirs during India Eurasian collision, *Earth planet. Sci. Lett.,* **103,** 365–378.

Rosler, W. & Appel, E., 1998. Fidelity and time resolution of the magnetostratigraphic record in Siwalik sediments: high-resolution study of a complete polarity transition and evidence for cryptochrons in a Miocene fluviatile section, *Geophys. J. Int.,* **135,** 861–875.

Stamatakos, J., van der Voo, R., van der Pluijm, B.A., Potts, S. & Torsvik, T., 1994. Comment on: 'Early Silurian palaeolatitude of the Springdale Group red beds of central Newfoundland: a palaeomagnetic determination with a remanence anisotropy test for inclination error' by Hodych, J.P. & Buchan, K.L., *Geophys. J. Int.,* **119,** 1009–1013.

Stamatakos, J., Lessard, A.M., van der Pluijm, B.A. & Van der Voo, R., 1995. Palaeomagnetism and magnetic fabrics from the Springdale and Wigwam red beds of Newfoundland and their implications for the Silurian palaeolatitude controversy, *Earth planet. Sci. Lett.,* **132,** 141–155.

Steiner, M.B., 1983. Detrital remanent magnetization in haematite, *J. geophys. Res.,* **88,** 6523–6539.

Stokking, L.B. & Tauxe, L., 1990. Multicomponent magnetization in synthetic haematite, *Phys. Earth planet. Inter.,* **65,** 109–124.

Sun, W. & Kodama, K.P., 1992. Magnetic anisotropy, scanning electron microscopy, and X ray pole figure goniometry study of inclination shallowing in a compaction clay-rich sediment, *J. geophys. Res.,* **97,** 19 599–19 615.

Tada, R. & Siever, R., 1989. Pressure solution during diagenesis, *Ann. Rev. Earth planet. Sci.,* **17,** 89–118.

Tan, X., 2001. Correcting the bias toward shallow palaeomagnetic inclinations in haematite-bearing sedimentary rocks: theory, experiments, and applications, *PhD dissertation,* Lehigh University, Bethlehem, USA.

Tan, X. & Kodama, K.P., 1998. Compaction-corrected inclinations from Southern California Cretaceous marine sedimentary rocks indicate no palaeolatitudinal offset for the Peninsular Ranges terrane, *J. geophys. Res.,* **103,** 27 169–27 192.

Tan, X. & Kodama, K.P., 2002a. An analytical solution for correcting palaeomagnetic inclination error, *Geophys. J. Int.,* submitted manuscript.

Tan, X. & Kodama, K.P., 2002b. Magnetic anisotropy of the Mississippian Mauch Chunk Formation red beds suggests significant paleomagnetic inclination shallowing, *J. geophys. Res.,* in press

Tan, X., Kodama, K.P., Wang P. & Fang, D., 2000. Paleomagnetism of Early Triassic limestones from the Huanan Block, South China: no evidence for separation between the Huanan and Yangtze blocks during the Early Mesozoic, *Geophys. J. Int.,* **142,** 241–256.

Tan, X., Kodama, K.P., Chen, H., Fang, D., Sun, D. & Li, Y., 2002. Paleo- and rock magnetic study of the Cretaceous Kapusaliang Group red beds from the Tarim Basin, Northwest China: inclination shallowing rather than continental shortening, *J. geophys. Res.,* in press

Tauxe, L. & Kent, D.V., 1984. Properties of a detrital remanence carried by haematite from study of modern river deposits and laboratory redeposition experiments, *Geophys. J. R. astr. Soc.,* **76,** 543–561.

Tauxe, L., Kent, D.V. & Opdyke, N.D., 1980. Magnetic components contributing to the NRM of Middle Siwalik red beds, *Earth planet. Sci. Lett.,* **47,** 279–284.

Tauxe, L., Constable, C., Stokking, L. & Badgley, C., 1990. Use of anisotropy to determine the origin of characteristic remanence in the Siwalik red beds of Northern Pakistan, *J. geophys. Res.,* **95,** 4391–4404.

Thomas, J.-C., Perroud, H., Cobbold, P.R., Bazhenov, M.L., Burtman, V.S., Chauvin, A. & Sadybakasov, E., 1993. A palaeomagnetic study of Tertiary formations from the Kirgiz Tien Shan and its tectonic implications, *J. geophys. Res.,* **98,** 9571–9589.

van der Pluijm, B.A., Van der Voo, R., Potts, S.S. & Stamatakos, J., 1993. Early Silurian palaeolatitude for Central Newfoundland from palaeomagnetism of the Wigwam Formation: discussion, *Can. J. Earth Sci.,* **30,** 644–645.

Van der Voo, R., Stamatakos, J. & van der Pluijm, B.A., 1995. No evidence for prevalent inclination shallowing in red beds, *EOS, Trans. Am. geophys. Un.,* **76,** Spring Meet. Suppl., S96.

Verosub, K.L., 1977. Depositional and post-depositional processes in the magnetization of sediments, *Rev. Geophys. Space Phys.,* **15,** 129–143.

Walker, T.R., Larson, E.E. & Hoblitt, R.P., 1981. Nature and origin of haematite in the Moenkopi Formation (Triassic), Colorado Plateau; a contribution to the origin of magnetism in red beds, *J. geophys. Res.,* **86,** 317–333.

Westphal, M., 1993. Did a large departure from the geocentric axial dipole hypothesis occur during the Eocene? Evidence from the magnetic polar wander path of Eurasia, *Earth planet. Sci. Lett.,* **117,** 15–28.