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Compaction-induced inclination shallowing of the post-depositional remanent magnetization in a synthetic sediment

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Summary. A synthetic sediment comprised of kaolinite, distilled water and either equidimensional or acicular magnetite was given a post-depositional remanent magnetization (PDRM) by being stirred in a magnetic field. This sediment was compacted under pressures which varied continuously from 0 to 0.14 MPa in a water-tank consolidometer and to higher pressure steps (< 2.53 MPa) in a standard soil consolidometer. Compaction took place in the same magnetic field in which the sample was given its PDRM. The compaction caused shallowing of the sample's magnetic inclination.

This shallowing was found to be a function of the sample's initial magnetic inclination and the degree of sample compaction;

$$\tan (I_R) = (1 - a\Delta V) \tan (I_0),$$

where I_R is the remanent inclination after compaction, ΔV is the volume change, I_0 is the initial magnetic inclination, and a is an empirically derived constant. The data show a maximum inclination shallowing of 12° for an initial inclination of 54°, in good agreement with the maximum inclination shallowing predicted by the above equation.

We propose an electrostatic mechanism to be the cause of the inclination shallowing. In this model positively charged magnetite grains adhere to the surface of negatively charged clay grains with their long dimension parallel to the clay grain's surface. As the clay grains become reorientated due to compaction the easy axes of magnetization are rotated away from the axis of compression.

Alternating field demagnetization data reveal that our samples have shallower characteristic magnetizations than their post-compaction NRMs, implying that the smaller, higher coercivity grains are most affected by the compaction process. These data support our model since a surface charge mechanism for inclination shallowing would predict that the smallest magnetic grains would be preferentially affected.

Key words: compaction, inclination shallowing, PDRM, electrostatic effect

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Introduction

The first laboratory experiments investigating sedimentary remanence were redeposition experiments which resulted in large inclination errors (see Verosub 1977, for a review). These experiments suggested that detrital remanent magnetization (DRM) may have inherent problems recording the inclination of the Earth's magnetic field. However, when Irving & Major (1964) showed that the post-depositional realignment of magnetic particles was physically possible in a synthetic sediment, post-depositional remanent magnetization (PDRM) was studied by various workers (Khramov 1968; Kent 1973; Graham 1974; Lovlie 1974, 1976; Verosub, Ensley & Ulrick 1979) to determine its accuracy and mechanism. PRDM was and is viewed as a way to bring into agreement laboratory analogues of sedimentary remanence with the observation that natural sediments, in many cases, do not have an inclination error (Opdyke & Henry 1969; Stober & Thompson 1979).

Even though it is apparent that PDRM accurately records the ambient magnetic field (Verosub 1977; Stober & Thompson 1979), few workers have addressed the effects of a compaction-induced volume decrease on sedimentary remanence. In Pacific plate motion studies, discrepancies between palaeolatitudes determined from sediments and palaeolatitudes determined by other techniques (i.e. basalt remanence, seamount poles, skewness and relative amplitude of marine magnetic anomalies and the age of equatorial sediment facies; Jarrard & Cockerham 1975; Cockerham & Jarrard 1976; Clague & Jarrard 1973; Gordon & Cape 1981) suggest a shallowing of the sediment's magnetic inclination which may be due to burial compaction.

If compaction is the process causing the magnetic inclination shallowing observed in the above studies, the effect of compaction should be most noticeable in the longest cores. Thus, DSDP cores may exhibit more magnetic inclination shallowing than piston cores which only penetrate several metres. Whereas Hammond, Epp & Theyer (1979) and Prince, Heath & Kominz (1980) observed no inclination error in their piston-cored sediments, Hammond, Kroenke & Theyer (1975), Cockerham (1976) and Morgan (1977) inferred inclination shallowing in their longer DSDP cores. Morgan (1977) postulates that the shallowing may be due to compaction.

Several laboratory studies of the effect of compaction on the magnetization of a sediment have been performed (Vlasov, Kovalenko & Tropin 1961; Blow & Hamilton 1978; Hamano 1980; Otofuji & Sasajima 1980). However, Otofuji & Sasajima applied uniaxial compression perpendicular to the sediment's magnetization, and therefore no inclination shallowing was expected, nor was any seen. Hamano studied the acquisition of magnetic remanence as a function of sediment void ratio. He imposed a magnetic field at different void ratios as a sample was being compacted by a continuously increasing pressure. He then allowed the compaction to proceed in the presence of the field until a pressure of 0.15 MPa was reached. As he measured the sample only at the conclusion of an experimental run, it is quite difficult to tell whether inclination shallowing took place.

Blow & Hamilton's (1978) study did reveal an inclination shallowing, but their experiment used evaporative compaction as a model for burial compaction. Evaporation is clearly not the dewatering mechanism to which deep-sea sediments are subjected. In fact, Noel (1980) proposed that sediment drying may induce an inclination shallowing. Noel postulates that surface tension forces in partially filled sediment pore spaces may rotate the magnetic particles. These surface tension forces may also explain the inclination shallowing Henshaw & Merrill (1979) saw in their study of drying remanent magnetization.

Vlasov *et al.* (1961) observed a regular decrease in magnetic inclination with increased loading pressure. Their study suggested a dependence on magnetic grain size, but the dependence may have been masked by the different types of matrix material and different sizes of magnetite used.

One study which did attempt to model burial compaction revealed an inclination shallowing (Hall 1982). However, after application of an anhysteretic remanent magnetization (ARM), the samples were compacted in the Earth's field. Since the Earth's field was not parallel to the ARM, it is not clear whether compaction or a viscous magnetization (VRM) was the cause of the magnetic inclination shallowing. In addition, ARM is not the best analogue for a natural sediment's magnetization.

Our experiments were designed to study the effects of compaction on a PDRM. A synthetic sediment was used to simplify the system being studied. Two shapes of magnetic grains, acicular and equidimensional, were chosen to determine if grain shape contributes to the compaction effect. Stirring remanent magnetization, a laboratory analogue of bioturbation (Tucker 1980), gave an initial magnetization to the sediment. This method also permitted magnetization and compaction of the sample in the same magnetic field, thus ensuring greater experimental control. Furthermore, different magnetic field inclinations were used to determine whether the inclination shallowing is a function of the initial inclination of the sediment. The experiments show that compaction of our synthetic sediment does shallow magnetic inclination, and alternating field demagnetization does not remove this shallowing.

Methods

SAMPLE PREPARATION

The samples were made from a non-magnetic clay matrix, magnetite, and distilled water. Both acicular and equidimensional magnetite were used. The acicular magnetite has an average length of 0.45 μm along its long axis, with a length to width ratio of approximately 6:1 (Hall 1982). The equidimensional grains have an average diameter of approximately 0.5 μm (Pfizer SEM micrograph). Both types of magnetite were obtained from Pfizer Minerals and Pigments Division (MO-4232, MO-7029 respectively). The non-magnetic matrix, furnished by Spink's Clay Company, is kaolinite (commercially designated '1/2 Champion and 1/2 Challenger') with a mean particle size of 2.7 μm (Coulter Counter analysis, model TAII) and only 0.1 per cent of it larger than 63 μm (Hall 1982).

When preparing the samples, a small amount of magnetite was weighed, and distilled water was added to it. This mixture was then sonicated for at least 20 min to reduce

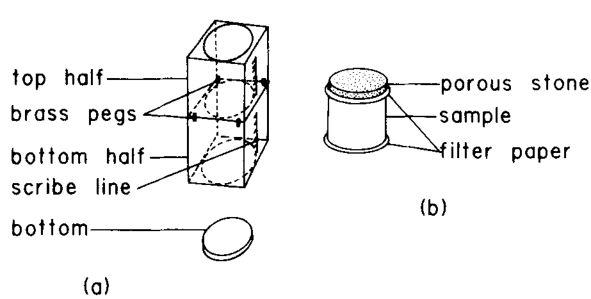

Figure 1. (a) Diagram of sample holder used in our experiments. Brass pegs hold the top and bottom together during compaction. Top half is removed to allow measurement of sample in bottom half. Scribe lines allow accurate orientation of sample in consolidometer and in magnetometer. Circular bottom is used to push sample from holder for alternating field demagnetization; (b) shows detail of sample, filter paper and porous plug.

clustering of the magnetite (Tucker 1979). Immediately following sonication, the kaolinite matrix was added. The samples were all prepared so that the initial water content was approximately 150 per cent by dry weight, and the magnetic fraction was less than 0.10 per cent by dry weight. The slurry was manually stirred until the sample appeared to be homogeneous. At this point, the slurry was thick, but pourable.

MAGNETIZATION PROCESS

After mixing, the slurry was immediately poured into an acrylic holder (2.22 cm I.D., 5.02 cm length; Fig. 1) which was designed to fit both into the low pressure compaction apparatus and the spinner magnetometer. This procedure minimized sample disturbance and orientation problems.

The holder and slurry were then placed into the consolidometer which was surrounded by two sets of 1 m square Helmholtz coils (Fig. 2). The coils (Parry 1967) were capable of maintaining a magnetic field with inclinations which ranged from 10° to 80° and an intensity of 0.05 mT. A PDRM was imparted to the slurry by stirring it in this field (Tucker 1980). A filter paper, stone and acrylic plug placed on to the slurry surface permitted the water to drain freely through the top of the sample holder during compaction, without allowing the sediment to escape (Fig. 1).

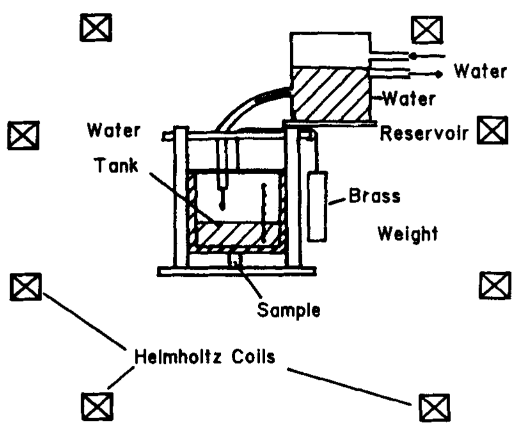

Figure 2. Diagram of water-tank consolidometer (Hamano 1980) used for low pressure consolidation. Apparatus is surrounded by square Helmholtz coils used to set up fields with different inclinations. The load is applied to the sample of water dripping slowly into the water tank.

COMPACTION PROCESS

Each sample was continuously compacted (after Hamano 1980) by slowly increasing the load applied to the sample. This was accomplished using an acrylic tank (Fig. 2), which was slowly filled with water, and resulted in a final pressure of 0.14 MPa after 6–8 hr. Most samples (low pressure compaction experiments) were removed from the water tank consolidometer (Hamano 1980) three to four times during the loading process for measurement of the sample's magnetic direction and intensity. After the final pressure was reached, the samples were left at this pressure for approximately 12 hr. Sample volume did not decrease further during this time period which suggested that our samples were not overpressured during compaction.

If the sample was to be compacted further (high pressure compaction experiments), a standard unidirectional (non-backpressured) soil consolidometer (Karol–Warner, model 350) replaced the water tank consolidometer in the centre of the Helmholtz coils. Each load could be applied with an accuracy of ±4.3 kg. The compaction process followed modified standard soil consolidation procedures (ASTM 1980). Each pressure was applied until primary consolidation was complete, i.e. when sample height remained constant as a function of log time. Generally, this took about 24 hr.

MEASUREMENT

Most samples were measured at Lehigh University using a slow spinner fluxgate magnetometer and a six-spin measurement routine. Four samples (stirring experiments and equidimensional magnetite sample 3; Table 1) were measured at Lamont–Doherty Geological Observatory with an ScT 2-axis cryogenic magnetometer. Most samples were measured at least three times so that a measurement error (Fisher 1953) could be determined.

ALTERNATING FIELD DEMAGNETIZATION

Following the final pressure step, the sample was removed from the acrylic holder and progressively alternating field demagnetized until less than 10 per cent of the sample's initial intensity remained. Orthogonal projection plots (Zijderveld 1967) were constructed

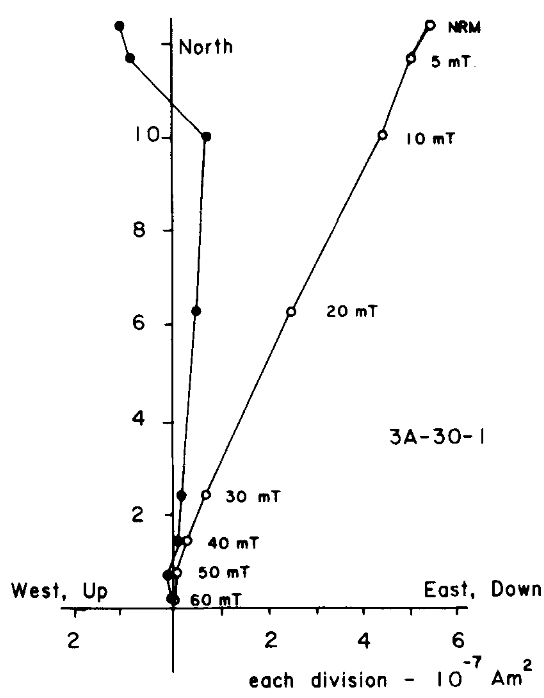

Figure 3. Alternating field demagnetization results for acicular magnetite sample 5. Note that vertical component shallows slightly during demagnetization. Characteristic directions are obtained by linear regression using four last demagnetization steps. These lines are tied to the origin. Open circles are vertical component, solid circles are horizontal component.

and characteristic magnetization directions were determined by linear regression in which the lines were tied to the origin (Fig. 3). The high quality of the demagnetization data suggested that this was the most reasonable technique for data analysis. Linear regression in which the origin was not an anchor gave similar results for each sample.

Results

STIRRING EXPERIMENTS

Since our samples had been too watery to measure in our spinner magnetometer directly after stirring, the assumption had been made that the samples acquired a magnetization parallel to the field in which they were stirred. This assumption is consistent with observations made by Tucker (1980) and Kent (1973). Several experiments were conducted at Lamont–Doherty Geological Observatory using a cryogenic magnetometer to check this assumption. The cryogenic magnetometer allowed measurement of very high water content samples.

Slurries composed of kaolinite and either acicular or equant magnetite were stirred in a 'zero' field (< 1 nT intensity), a 0.091 mT field with a 30° inclination, a 0.066 mT field with a 45° inclination, and a 0.056 mT field with a 76° inclination. Immediately following the stirring, the samples were measured. The 'zero' field and 76° field experiments were conducted with the same samples, and, therefore, exactly the same amount of magnetite. The results indicate that the magnetization of samples stirred in a 'zero' field is at least two orders of magnitude weaker than when stirred in a 0.056 mT field. The samples stirred in fields with 30°, 45°, and 76° inclinations exhibited interesting and similar behaviour (Fig. 4). In each one, the remanent inclination was 6°–10° steeper than the field inclination. Directional agreement (within experimental error) was found between samples containing acicular- and equant-shaped magnetite.

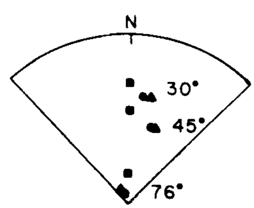

Figure 4. Equal area net showing the results of the stirring experiments. Circles are results from equidimensional magnetite. Triangles are results from acicular magnetite. Squares show fields (30°, 45° and 76° inclinations) in which the samples were stirred. Samples acquired magnetizations with inclinations steeper than the field in which they were stirred; however, in each case acicular and equidimensional magnetite results agree within measurement error. Solid symbols are lower hemisphere.

LOW PRESSURE COMPACTION EXPERIMENTS

Most of the inclination change we observed took place while the load was being applied to the sample in the water-tank consolidometer (Hamano 1980). This was also when the greatest volume change occurred. To study this behaviour in detail 24 samples only were subjected to compaction in the water-tank consolidometer (Hamano 1980). Fourteen samples contained acicular magnetite and 10 contained equant magnetite. These samples were removed and measured two to three times during loading from 0 to 0.14 MPa. The experiments were conducted in fields with inclinations ranging from as shallow as 20° to as steep as 80°. The intensity of the field was 0.05 mT.

Table 1. Results of the low pressure compaction experiments. Field inclination is the field applied during PDRM acquisition and compaction. Applied field declination is $D = 0°$. Characteristic magnetization is from alternating field demagnetization after the final pressure is applied. M is moment in 10^{-7} Am^2.

A. Acicular Magnetite

Sample	Field Incl.	ΔV	Remanence I	Remanence D	Remanence M	Characteristic Magnetization I	Characteristic Magnetization D
1	20°	0.36	16.8	357.0	13.9		
		0.44	16.1	357.5	12.4		
		0.51	14.7	356.7	11.6		
		0.59	11.0	352.7	12.0	11.0	357.0
2	20°	0.32	15.4	1.4	36.3		
		0.40	15.7	0.4	33.7		
		0.46	15.5	0.5	32.5		
		0.54	14.5	0.9	30.3	14.0	2.7
3	22°	0.29	14.8	359.5	5.4		
		0.49	18.2	0.0	3.8		
		0.61	16.6	1.6	3.2	13.0	9.6
4	30°	0.25	31.7	3.3	11.6		
		0.30	33.4	5.2	9.7		
		0.35	27.8	4.9	8.4		
		0.54	27.3	4.5	6.7	22.0	8.3
5	30°	0.28	29.0	357.2	18.3		
		0.31	28.1	357.9	15.8		
		0.46	26.2	358.9	14.6		
		0.56	24.3	357.9	13.8	16.0	4.8
6	35°	0.27	33.2	0.1	16.6		
		0.35	33.6	0.1	15.4		
		0.44	31.4	0.4	14.3		
		0.54	28.3	0.6	12.6	29.0	358.0
7	45°	0.50	35.4	1.0	12.3	31.0	357.0
8	45°	0.31	41.1	4.5	16.5		
		0.41	40.0	4.2	14.9		
		0.47	37.8	3.9	13.7		
		0.55	36.2	4.0	12.4	29.0	13.6
9	54°	0.30	45.8	0.9	13.0		
		0.39	44.8	1.1	11.6		
		0.48	42.5	0.8	10.0		
		0.58	39.2	0.9	9.1	33.0	2.9
10	60°	0.26	62.4	357.9	14.6		
		0.36	62.0	357.8	13.0		
		0.44	59.3	357.8	11.1		
		0.58	56.1	358.0	9.2	44.0	345.0
11	70°	0.53	61.6	358.3	21.3		
		0.58	59.8	358.3	19.6	61.0	356.0
12	70°	0.58	59.9	356.4	15.2	58.0	359.0
13	70°	0.28	64.3	359.2	18.4		
		0.44	61.3	356.8	13.9		
		0.50	59.4	357.1	10.7		
		0.56	58.2	356.0	9.2	60.0	356.0
14	80°	0.27	74.9	0.5	4.1		
		0.37	74.7	0.6	3.0		
		0.54	71.7	0.9	4.2	75.0	356.0

B. Equidimensional Magnetite

Sample	Field Incl.	ΔV	Remanence I	Remanence D	Remanence M	Characteristic Magnetization I	Characteristic Magnetization D
1	20°	0.33	19.9	357.1	5.9		
		0.42	20.1	359.8	5.1		
		0.52	18.5	0.1	4.3		
		0.59	16.1	0.3	4.2	15.0	359.0
2	30°	0.30	29.5	3.4	1.2		
		0.45	27.6	4.0	1.7		
		0.57	24.7	5.2	1.7	20.0	4.0
3	45°	0.00	40.1	356.0	3.9		
		0.04	41.1	350.3	4.1		
		0.42	30.7	348.1	3.2		
		0.51	28.0	345.9	3.0		
		0.51	26.9	340.8	3.0		
		0.53	29.2	342.3	2.8	34.0	2.4
4	45°	0.52	37.4	351.4	6.4		
		0.57	37.0	351.1	5.8	37.0	350.0
5	45°	0.30	37.3	3.9	2.7		
		0.37	39.1	5.0	2.4		
		0.49	37.2	5.4	1.9		
		0.55	35.4	5.3	1.9	34.0	2.8
6	54°	0.37	51.9	354.6	6.3		
		0.49	47.3	353.8	4.5		
		0.56	45.7	353.9	4.0	45.0	353.0
7	70°	0.49	63.1	355.5	8.7		
		0.53	62.4	355.1	8.2	60.0	1.0
8	70°	0.30	65.7	8.6	3.0		
		0.40	63.7	14.0	2.3		
		0.50	61.3	11.5	2.7		
		0.56	62.4	12.5	2.4	60.0	13.0
9	75°	0.57	74.1	349.9	2.7	73.0	351.1
10	80°	0.32	79.3	4.9	5.5		
		0.42	78.5	3.8	3.6		
		0.44	78.3	2.2	2.5		
		0.54	76.7	6.1	1.8	76.0	0.0

These samples experienced inclination shallowing, a magnetization intensity decrease and a volume decrease with increasing pressures (Table 1). After alternating field demagnetization the characteristic magnetization directions diverged from the post-compaction NRM directions by more than 3° in nine of the 24 samples.

HIGH PRESSURE COMPACTION EXPERIMENTS

A set of compaction experiments was performed to determine the effects of higher pressures (> 0.14 MPa) on the slurry. Four samples containing acicular magnetite and four samples containing equidimensional magnetite were compacted in the water-tank consolidometer (Hamano 1980) in a 45° inclination field. They were then measured and transferred to the soil consolidometer for loading to higher pressures. After application of the desired pressure, the samples were removed and remeasured. Two of these samples were subjected to a final pressure of 2.53 MPa (Fig. 5, Table 2), corresponding to a burial depth of about 360 m (Hamilton 1959). Directly after the water-tank consolidation (0.14 MPa), the samples' inclinations were already 10°–17° shallower than the 45° field in which they were stirred and compacted, as discussed in the previous section (Fig. 5, Table 2). Application of pressures greater than 0.14 MPa resulted in only 0.8°–2.8° further shallowing of the inclination. After alternating field demagnetization (Table 2) the inclinations of the characteristic magnetizations were within 3° of their post-compaction NRMs.

The samples' intensity of magnetization is observed to decrease by up to 10 per cent during compaction in the soil consolidometer (Table 2).

Table 2. Results of the high pressure compaction experiments. Pressure is applied in discrete steps. All other notes as in Table 1.

A. Acicular Magnetite

Applied Field Inclination = 45°

Sample	Pressure(MPa)	ΔV	Remanence I	Remanence D	Remanence M	Characteristic Magnetization I	Characteristic Magnetization D
1	0.14	0.58	34.3	357.6	8.62		
	0.29	0.62	33.5	357.2	8.23	31.0	358.0
2	0.14	0.57	31.9	1.1	12.8		
	0.61	0.63	30.9	1.5	12.0	33.0	2.0
3	0.14	0.56	29.7	353.7	17.4		
	1.24	0.64	27.9	354.2	16.0	31.0	359.0
4	0.14	0.55	32.4	359.2	0.55		
	2.53	0.64	29.6	359.1	0.64	27.0	2.0

B. Equidimensional Magnetite

Applied Field Inclination = 45°

Sample	Pressure(MPa)	ΔV	Remanence I	Remanence D	Remanence M	Characteristic Magnetization I	Characteristic Magnetization D
1	0.14	0.59	31.5	1.2	5.64		
	0.29	0.61	30.8	0.4	5.43	30.0	0.3
2	0.14	0.59	32.0	355.8	5.53		
	0.61	0.62	31.7	356.2	4.98	32.0	359.0
3	0.14	0.45	32.0	357.3	7.27		
	1.24	0.64	31.7	358.3	6.59	31.0	1.0
4	0.14	0.56	35.0	355.0	-		
	2.53	0.63	33.3	354.6	-	33.0	357.0

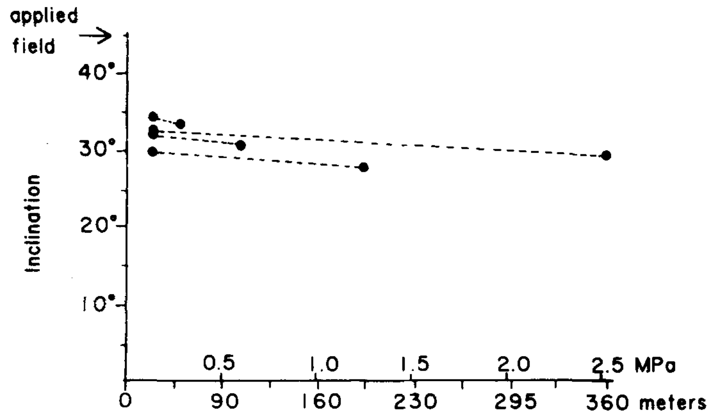

Figure 5. Magnetic inclination as a function of pressure (MPa) and depth below sediment–sea water interface (metres) for high pressure consolidation experiments. Depth relationship is calculated by a technique outlined by Hamilton (1959). The lowest pressure point for each sample (0.14 MPa) is from measurement after compaction in the water-tank consolidometer (Hamano 1980), all other points are from compaction in the Karol–Warner soil consolidometer. Note that most of the inclination shallowing occurs by the 0.14 MPa pressure step. These samples were stirred and compacted in a 45° inclination field.

ADDITIONAL EXPERIMENTS

Experiments were conducted to determine the importance of three parameters hypothesized to affect the results of our compaction experiments; the length of time that a sample took to reach the first pressure step (0.14 MPa), the direction the water drained during sample loading and the salinity of the interstitial fluid.

In one experiment a sample (Table 3) was stirred in a 45° inclination field and compacted by the technique used in the low pressure consolidation experiments, except that the loading rate was seven times slower. Its inclination change was similar to that observed in samples compacted using our standard technique. Therefore, the duration of the loading did not appear to affect the inclination shallowing observed.

In another set of experiments the effect of drainage direction was tested (Table 3). Four samples were allowed to drain through the bottom of the acrylic sample holder, rather than through the top. Three of the four samples had post-compaction inclinations which were shallower than their PDRM acquisition fields. The magnitude of the shallowing is similar to that observed in samples which drained through their tops. The fourth sample experienced a steepening of inclination with respect to its PDRM acquisition field but the stirring experiments suggest that this result does not necessarily imply compactive steepening; therefore, the results from this sample are ambiguous. Overall, the data indicate that drainage direction was not a factor in causing the inclination shallowing effect.

It is well documented that clays have a different consolidation behaviour in salt water than in fresh water (Rieke & Chilingarian 1974), and, therefore, the effect of interstitial fluid salinity was also tested (Table 3). A sample was prepared using an interstitial fluid with a salt concentration of 0.598 M, comparable to the salt concentration in sea water (Gross 1982). The salt used was NaCl, since that comprises 88 per cent of the salt in ocean water (Gross 1982). The magnitude of this sample's inclination shallowing was in agreement with other studies made with acicular magnetite, 45° inclination fields, and in distilled water (Table 1). This result is consistent with Blow & Hamilton's (1978) redeposition experiment in which sea water was used as the interstitial fluid.

Table 3. Results of additional experiments. Experiment A is for loading over 48 hr instead of 6 hr. Experiment B are four samples drained through their bottoms instead of tops. Experiment C is for a sample with saline interstitial fluid.

A. Low Pressure Compaction 0–0.14 MPa
Applied Field Inclination = 45°
Total Loading Time = 48 hours

I = 31.6° D = 359.6° M = 25.0 x 10^{-7} Am^2 ΔV = 0.56

B. Low Pressure Compaction 0–0.10 MPa
Samples Drain through Bottom

1. Applied Field Inclination = 45°
   a. Acicular Magnetite
   I = 34.8° D = 350.0° M = 25.6 x 10^{-7} Am^2 ΔV = 0.52

   b. Equidimensional Magnetite
   I = 39.7 D = 0.6° M = 7.8 x 10^{-7} Am^2 ΔV = 0.54

2. Applied Field Inclination = 70°
   a. Acicular Magnetite
   I = 75.5 D = 324.5 M = 33.7 x 10^{-7} Am^2 ΔV = 0.48

   b. Equidimensional Magnetite
   I = 62.8 D = 351.1 M = 9.3 x 10^{-7} Am^2 ΔV = 0.54

C. Low Pressure Compaction 0–0.14 MPa
Applied Field Inclination = 45°

Saline Interstitial Fluid

ΔV	I	D	M(X10^{-7} Am^2)
0.35	39.1	4.0	16.7
0.46	36.5	3.9	14.2
0.51	34.5	4.1	13.4
0.54	33.1	3.6	12.5

Discussion

RELEVANCE OF RESULTS TO NATURAL SEDIMENTS

A striking feature of the data is the large volume decrease (50 per cent) experienced by the samples at relatively low pressures (0.14 MPa, Table 1). This volume decrease corresponds to a porosity decrease from about 77 per cent to 45 per cent after application of the 0.14 MPa pressure. Using the techniques of Hamilton (1959), the calculated depth of burial corresponding to this low pressure is only about 40 m. However, examination of porosity logs from DSDP sites 388 (Bensen & Sheridan *et al.* 1978), 305 (Larson & Lowrie 1975), 316 (Schlanger & Jackson 1976), 366 (Lancelot & Siebold *et al.* 1977), and 354 (Perch-Nielson & Supko *et al.* 1977) shows that in these natural systems the porosity is approximately 70 per cent at the seafloor but does not decrease to 40–50 per cent until burial depths of 300–500 m are reached.

One explanation for the difference in porosity versus pressure behaviour between our synthetic sediment and that observed in DSDP cores is that natural systems have many more components than our simple kaolinite/magnetite synthetic sediment and, thus, exhibit different compaction behaviour. The clay mineral suites in the cores are usually a mixture of illite, montmorillonite and kaolinite in which the proportions vary according to the climate of the provenance area (Blatt, Middleton & Murray 1972; Kennett 1982). Since kaolinite has a larger grain size (1–2 μm; Blatt *et al.* 1972; Grim 1953) and a greater electrostatic charge than illite and montmorillonite (Rieke & Chilingarian 1974), it has the smallest void ratio when compared with these other clay minerals during consolidation experiments (Rieke & Chilingarian 1974). This behaviour would explain the large volume decrease observed at relatively low pressures for our kaolinite sediment when compared with more complicated mixtures of clays in deep-sea sediments. The inclination shallowing we observed experimentally at pressures of 0.14 MPa probably does not occur in natural sediments until burial depths of 300–500 m. Since natural deep-sea sediments are observed to be totally consolidated at 300–500 m depths (B. Carson, private communication), the total volume decrease that our experiments model is reasonable, but we have reached it with much lower pressures than occur in natural systems.

MODELS FOR COMPACTION SHALLOWING

Blow & Hamilton (1978) propose the following model for inclination shallowing;

$$\tan(I_R) = (1 - \Delta V)\tan(I_0), \quad (1)$$

where I_R is the remanent inclination of the sample after compaction, ΔV is the degree of compaction and I_0 is the initial inclination of the sample. This model suggests that $\tan(I_R)$

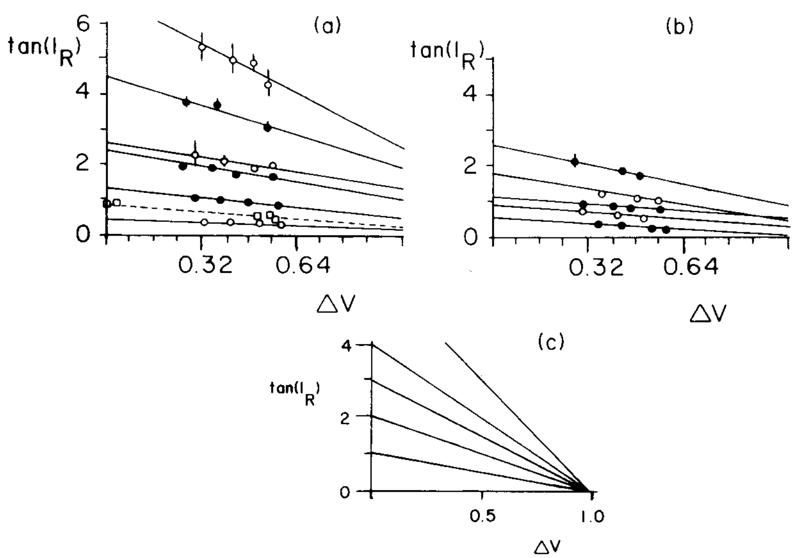

Figure 6. Linear segments resulting from linear regression on $\tan(I_R)$ as a function of ΔV, where I_R is the post-compaction inclination and ΔV is the degree of compaction. Solid circles are acicular magnetite samples; open circles are equidimensional magnetite samples. (a) and (b) show that there is a linear relationship for these quantities in our data and that the slope of these lines is less than slope predicted by Blow & Hamilton's (1978) compaction equation (c). Dashed line in (a) shows sample measured on a cryogenic magnetometer at $\Delta V = 0$. Error bars are $\alpha - 95$ for measurement error. When error is smaller than circle, error bars are omitted.

should be a linear function of the degree of compaction, ΔV. Simple regression analysis shows that a linear relationship does exist in our data (Fig. 6a, b). Assuming that this linear relationship holds over the entire range of ΔV the initial inclination for our samples may be calculated from the ordinate intercept. This assumption is clearly supported by the results from equidimensional magnetite sample 3 (Table 1). This sample was compacted in the water-tank consolidometer and measured in five steps from $\Delta V = 0$ to $\Delta V = 0.53$ with a cryogenic magnetometer. If a straight line is fit to the data for the $\Delta V = 0.42$, 0.51 and 0.53 pressure steps the ordinate intercept will predict the measured I_0 for this sample within 1°

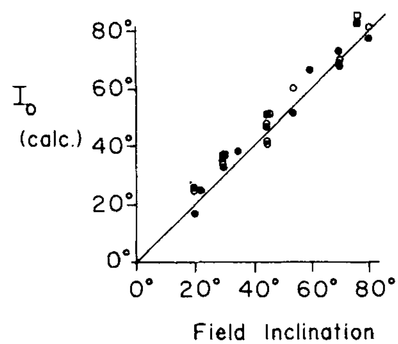

Figure 7. Initial inclinations, I_0, calculated from ordinate intercepts of tan (I_R) versus ΔV plots (Fig. 6a and b) and plotted as a function of PDRM acquisition field inclination. Solid symbols are acicular magnetite samples. Open symbols are equidimensional magnetite samples. Squares indicate actual I_0 measurements with a cryogenic magnetometer. Points above solid line are steeper than PDRM field.

indicating that tan (I_R) is a linear function of ΔV over the entire range of ΔV (Fig. 6a). Additional support for this assumption comes from the initial inclinations, I_0, calculated from the ordinate intercepts. Thirteen of the 21 initial inclinations calculated were steeper than their PDRM acquisition field in direct agreement with the stirring experiments conducted with a cryogenic magnetometer (Fig. 7).

However, even though our data show that tan (I_R) is a linear function of the degree of compaction, ΔV, the slope of these lines is not as steep as that predicted by Blow & Hamilton's (1978) model (equation 1) (see Fig. 6c).

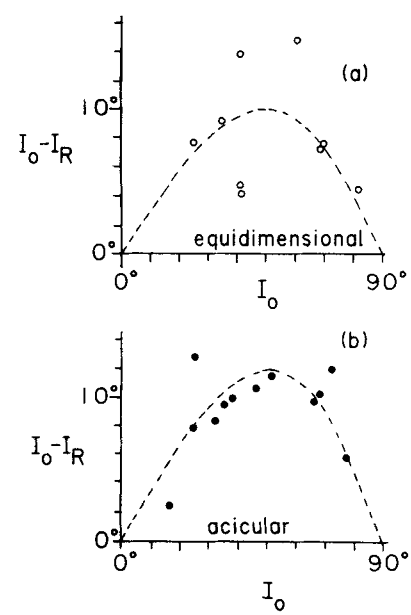

Figure 8. Change in inclination ($I_0 - I_R$) as a function of initial inclination I_0 for equidimensional magnetite (a) and acicular magnetite (b) samples. Theoretical curves (dashed lines) are based on equation (2), the value of a for each sample group (see text), and a ΔV of 0.55. Note that the acicular magnetite samples fit their theoretical relationship more closely than the equidimensional magnetite samples.

The data, instead, suggest the functional form;

$$\tan (I_R) = (1 - a\Delta V) \tan (I_0), \qquad (2)$$

where a is the factor by which the amount of compactive shallowing is decreased when compared to equation (1). All other parameters are as in (1). Our experiments yield $a = 0.54 \pm 0.18$ for equidimensional magnetite samples and $a = 0.63 \pm 0.18$ for acicular magnetite samples. Using these values the relationship between initial inclination, I_0, and inclination shallowing, $\Delta I = I_0 - I_R$, may be plotted and compared with the data (Fig. 8). The acicular magnetite samples agree more closely (non-linear correlation coefficient = 0.72) with the theoretical relationship than the equidimensional magnetite samples (n.c.c. = 0.51). This point will be addressed in the next section.

AN ELECTROSTATIC MECHANISM FOR COMPACTION SHALLOWING

The synthetic sediment used in these experiments is a slurry of distilled water, kaolinite and magnetite. The long, flat faces of the kaolinite grains are negatively charged due to isomorphic substitutions in the clay structure (Swartzen-Allen & Matijevic 1974; Yariv & Cross 1979). The net charge on the surface is compensated by available ions in the water, resulting in an electric potential difference occurring across the clay–water interface. The placement of compensating ions in the water forms an electric double layer of positive and negative charges (Yariv & Cross 1979). This electric double layer is composed of an inner Helmholtz layer of preferentially orientated water molecules directly next to the clay surface, an outer Helmholtz layer consisting of the closest approach of fully hydrated cations, and finally the outermost Gouy–Chapman diffuse layer where the cations' concentration decreases with increasing distance from the clay particle (Yariv & Cross 1979). The result of this double layer is that the area adjacent to the clay flake acts as a plane capacitor with an electric field orientated perpendicularly to the clay flake's surface (Fig. 9). The thickness of the electric double layer is controlled by the concentration of ions in solution. The greater the cation concentration, the thinner the double layer.

The presence of particle-generated electric fields will have an effect on magnetite grains. Since magnetite is a relatively insoluble oxide, it will acquire a surface charge density which is a function of the ion concentration (pH) of the surrounding liquid (Parks 1965). A negatively charged clay grain will cause a concentration of positive ions (low pH) in the region adjacent to the clay surface. If a magnetite particle is in this region, its surface will become positively charged. The motion of the magnetite grain will be controlled by the interaction of its positive surface charges and the electric field from the negatively charged clay flake. The magnetite particle will translate towards the clay flake. When it comes in contact with the clay grain, the magnetite particle will pivot around its first point of contact and rotate so its long dimension will lie parallel to the clay grain's surface (Fig. 9). This rotation will only occur if the electric torque is strong enough to overcome the magnetic torque aligning the magnetite with the ambient magnetic field. The feasibility of this process is shown by a simple calculation (see Appendix) in which it is assumed that the magnetic field is orientated at 45° to the clay flake's negatively charged surface and that the positive charge is uniformly distributed on the surface of an acicular magnetite grain, which is magnetized along its long axis. The total charge needed on the magnetite to create an electric torque equal to the maximum magnetic torque is 1.23×10^{-16} esu. Since one monovalent ion has a charge of 4.80×10^{-10} esu it is perfectly reasonable to expect surface charges on the magnetite to have a misaligning influence.

In a sediment which has not undergone compaction the long axes of the magnetite particles will tend to align parallel to the clay flakes' surfaces but the clay particles will be

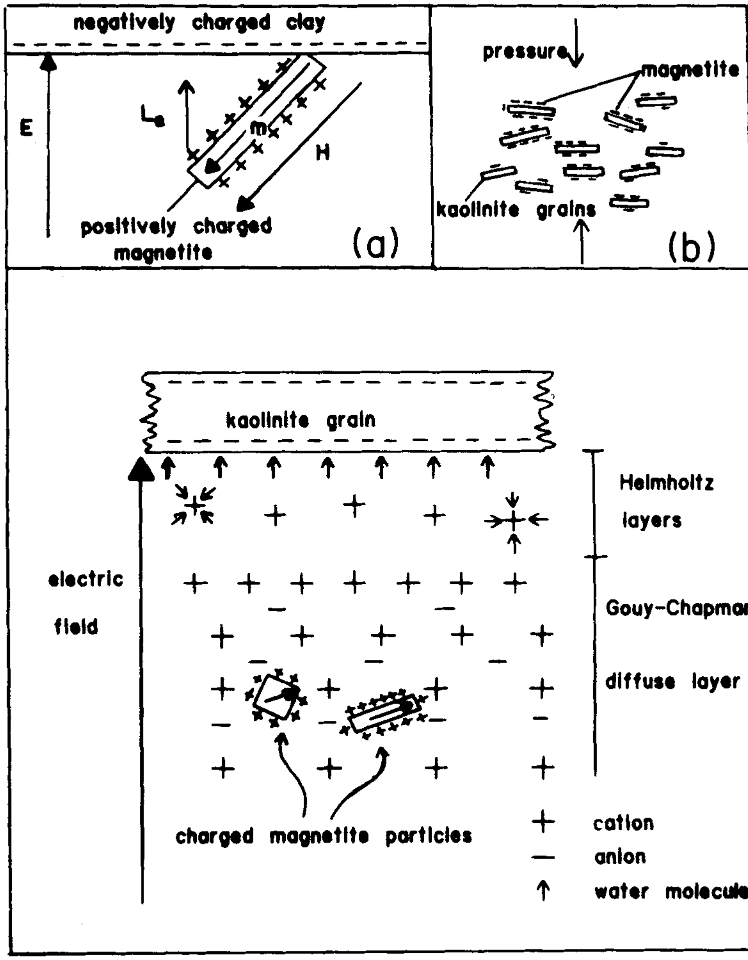

Figure 9. Sketch of electric double layer formed at surface of kaolinite grain (from Yariv & Cross 1979). The double layer creates an electric field perpendicular to the flat surface of the clay grain. Magnetite particles near to the clay flake acquire positive surface charges due to the relatively high concentration of positive ions caused by the double layer. Charged magnetite grains will translate toward charged clay surface. Inset (a) shows pivoting of acicular magnetite particle around first point of contact. $\mathbf{L_e}$ is electric torque on charged grain due to electric field, **E. H** is ambient magnetic field (see Appendix for simple calculation of the magnitude of $\mathbf{L_e}$.) Inset (b) shows magnetite grains (not to be confused with negative charges) adhering electrostatically to kaolinite grains. Pressure causes preferred alignment of clay flakes, thus causing rotation of easy axes of magnetization away from the compression axis.

randomly orientated. Statistically the overall orientating bias for the magnetite particles will be the ambient magnetic field. However, as the sediment is compacted the clay grains will take on a preferred orientation with their flat surfaces perpendicular to the axis of compression. Since the magnetite grains are orientated with their long dimensions parallel to the flat surfaces of the clay particles the preferred alignment acquired by the clay during compaction will push the magnetite particles' easy axes of magnetization away from the compression axis. The acicular magnetite grains in our experiments have a more clearly defined long dimension than the equant magnetite grains, therefore the electrostatic mechanism outlined here should affect acicular grains more readily than equidimensional grains. This is supported by the results plotted in Fig. 8.

Studies show that preferred alignment of clay flakes takes place at pressures comparable to those in our experiments. Experiments with kaolinite slurries indicate that a pressure as low as 0.1 MPa will produce an easily observable orientation of the clay grains perpendicular to the applied pressure (Rieke & Chilingarian 1974). Faas & Crocket (1983) noted similar behaviour in a natural deep-sea sediment. At the top of DSDP core 515A they saw that the clay grains were nearly randomly orientated. With increasing depth in the core, they documented the development of a horizontal planar fabric due to parallel alignment of clay minerals. This suggests that the preferred alignment of clay flakes, a necessary mechanism in our model, does indeed take place.

By examining the morphology of the kaolinite grains, a physical interpretation for the parameter as in equation (2) becomes apparent. Kaolinite has a constant negative surface charge along its broken bond edges (van Olphen 1963). Therefore, the electric double layer created by the broken bond edges would create an electric field parallel to the flat faces of the clay flake. This field will rotate magnetite particles parallel to the axis of compression as the clay particles become aligned. Because the large flat surfaces of the kaolinite account for a much higher proportion of their total surface area, the net effect is still an overall rotation of the magnetization away from the axis of compression. The broken bond edges of the kaolinite grains will affect only a fraction of the magnetite particles. The parameter a in (2) can be considered to be the proportion of magnetic grains affected by the kaolinite's broken bond edges with respect to those affected by the larger, flat surfaces of the clay flakes or, more simply, it is the ratio of clay edge area to face area. The experimentally determined value for a of about 0.6 agrees reasonably well with the average thickness to length ratio of 0.5 for kaolinite (Grim 1953).

EXPERIMENTAL SUPPORT OF THE ELECTROSTATIC MODEL

In a simple mechanical model in which decreasing pore size causes inclination shallowing, the largest magnetite grains would experience the greatest rotation. They would come in contact with the walls of their pore space early in the compaction process and would be subject to mechanical reorientation by the non-magnetic fabric throughout most of the compaction. The smallest magnetite grains would be able to constantly realign parallel to the ambient magnetic field until their pore spaces became very small, after the sediment had undergone a significant amount of compaction. However, in the electrostatic model, the smallest magnetic grains would be greatly affected by the electric field of the clay flakes and closely follow the reorientation of the non-magnetic fabric. Larger magnetic grains comparable in size to the clay grains would not be able to align parallel to the clay grains' flat surfaces as easily.

Alternating field demagnetization may be used to isolate the magnetic signal of the smallest (most coercive) magnetic grains (Parry 1965). Since the electrostatic process should cause a larger degree of rotation, and therefore inclination shallowing, for the smallest (highest coercivity) grains, alternating field demagnetization should result in a shallower characteristic magnetization than the sample's post-compaction NRM. If the smallest magnetic grains are not preferentially affected, a statistically equal number of samples should have characteristic magnetizations shallower or steeper than their post-compaction NRMs after alternating field demagnetization. A chi-square test was performed comparing the number of characteristic magnetizations shallower or steeper than the samples' post-compaction NRMs. The hypothesis of equal proportions was rejected at the 95 per cent significance level. Out of 34 samples compacted and demagnetized, 23 had shallower characteristic directions than their post-compaction NRMs. These demagnetization data support our model of an electrostatic mechanism for inclination shallowing.

Additional experimental support for our model comes from Payne & Verosub (1982). In an experiment designed to determine the mobility of different magnetic grain sizes as a function of water content, they concluded that the least mobile fraction of the magnetic carriers were the most coercive. This result is consistent with our demagnetization data.

The results from one sample containing a saline pore fluid were hoped to provide a test of our electrostatic model (Table 3). According to double layer theory, increasing the cation concentration of the interstitial fluid should reduce the thickness of the electric double layer (Yariv & Cross 1979; Rieke & Chilingarian 1974). This should cause a smaller electrostatic effect and reduce the amount of inclination shallowing. However, the results from the saline sample show an inclination shallowing of 14.9° which is 2.9° more inclination shallowing than our theoretical relationship (2) predicts. This result may be due to a change in compaction behaviour for our sediment. By reducing the size of the electric double layer, which tends to keep grains apart, the sediment will compact more easily (Rieke & Chilingarian 1974). Since we have been unable to keep compaction behaviour the same while varying the thickness of the double layer, these results are inconclusive. Another technique must be developed to vary the strength of the double layer's electric field.

INTENSITY DECREASE DURING COMPACTION

Our data also suggest a 20–30 per cent intensity decrease during compaction (Table 1). Other workers have observed an intensity decrease associated with a volume decrease (Henshaw & Merrill 1979; Hamano 1980; Hall 1982). One possible explanation is that as the sample is consolidated the magnetic grains must move closer together and magnetic interactions between the grains become increasingly more important. Hamano (1983) has treated the problem of magnetic interactions for low concentrations (< 0.1 per cent by volume) of magnetic particles and shown both experimentally and theoretically that a significant decrease in intensity will occur in this low concentration range as interactions increase. If it may be assumed that the moments of all the grains in the sediment are at least subparallel, as may be expected in a PDRM, then the magnetic field from a neighbouring grain would tend to oppose the magnetization of a grain. If the grains are multidomain then the domain walls would move to decrease the grain moment. If the grains are monodomain the moment would be rotated away from the easy axis. In either case the overall moment of the sediment would be decreased.

Conclusions

We conducted experiments in which a synthetic sediment was given a PDRM by being stirred in a known magnetic field. The sediment was then compacted in the same field with a pressure that varied continuously from 0 to 0.14 MPa and then was applied in discrete steps up to 2.53 MPa. The sediment lost 50 per cent of its volume by the 0.14 MPa pressure step and only an additional 3–9 per cent at the higher pressures. The sediment experienced an inclination shallowing which was directly related to the volume decrease.

We observed that the sediment's degree of compaction, ΔV, its initial inclination, I_0, and its post-compaction inclination, I_R, are related by;

$$\tan(I_R) = (1 - a\Delta V)\tan(I_0),$$

where the coefficient a is probably the edge to face surface area ratio of the kaolinite grains.

We propose an electrostatic mechanism which causes the inclination shallowing. In our model, positively charged magnetite grains are pulled towards negatively charged clay flakes. When they come in contact with the surface of the clay the magnetite grains rotate to have their long dimension parallel to the clay's surface. As the clay fabric is orientated by compaction the magnetite grains adhering to the clay grains are rotated with the fabric. This effect will pull the easy axes of magnetization of the magnetite away from the axis of compression which causes the compaction. Alternating field demagnetization data support this interpretation since the highest coercivity (smallest) magnetite grains appear to be most affected by compaction-induced inclination shallowing.

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Appendix: Electric charge needed to overcome magnetic alignment

Assume an acicular (length = 0.45×10^{-4} cm, aspect ratio 6:1) magnetite grain aligned with ambient magnetic field. The magnetic torque tending to align the grain is

$$L_m = mH \sin\phi$$

where

ϕ = angle of grain with magnetic field

m = magnetic moment of single grain [from Stacey (1972) $J = 0.1$ emu cm^3, given volume of grain = 1.99×10^{-15} cm^3]

$\therefore m = 1.99 \times 10^{-16}$ emu

$H = 0.5$ oersted

Counteracting this magnetic aligning torque is an electric torque due to the electric field from a nearby clay flake acting on the surface charges of the magnetite particle. This electric torque is

$$L_e = \int_0^R \lambda Er \cos\theta \, dr,$$

where

θ = angle of magnetite axis with clay flake surface

λ = charge/unit length on magnetite

r = distance of charge element from pivot point

$E = 2\pi\sigma$, σ = surface charge density on clay flake

$R = 0.45 \times 10^{-4}$ cm

$$\therefore L_e = \frac{\lambda E R^2}{2} \cos\theta$$

But $\lambda = Q/R$ for uniform distribution of total charge, Q

$$\therefore L_e = \frac{QER}{2} \cos\theta = \pi Q \sigma R \cos\theta.$$

To find σ on a clay flake follow the treatment of van Olphen (1977):

(a) 1 mol kaolinite is 516.3 g;

(b) each unit cell has 45.835×10^{-16} cm^2 surface area on each side;

(c) cation exchange capacity of kaolinite is
15 meq/100 g or $(15 \times 10^{-3})(6.02 \times 10^{23}) = 9.03 \times 10^{21}$
monovalent cations in 100 g;

(d) total surface area in 100 g

$$= (100\text{ g}/516.3\text{ g})(6.02 \times 10^{23})(45.835 \times 10^{-16}\text{ cm}^2) = 1.069 \times 10^{9}\text{ cm}^2;$$

(e) ions/surface area $= (9.03 \times 10^{21}\text{ ions}/1.069 \times 10^{9}\text{ cm}^2) = 8.45 \times 10^{12}\text{ ions cm}^{-2}$;

(f) $\sigma = (4.803 \times 10^{-10}\text{ esu ion}^{-1})(8.45 \times 10^{12}\text{ ions cm}^{-2}) = 4.059 \times 10^{3}\text{ esu cm}^{-2}$;

To deflect a magnetite grain from aligning with the magnetic field requires

$$L_e = L_m$$

Assume the magnetite is at 45° to the clay flake,

$$\therefore \theta = \pi/4 - \phi$$

The total charge, Q, needed to provide a counteracting electric torque is

$$Q = \frac{mH \sin(\pi/4 - \theta)}{\pi\sigma R \cos\theta} = \frac{0.225\, mH}{\sigma R}(1 - \tan\theta)$$

$$= 1.23 \times 10^{-16}\text{ esu} \quad \text{for } \theta = 0^\circ$$

$$\ll 4.80 \times 10^{-10}\text{ esu},$$

the basic unit of charge. Hence, the magnetic aligning torque is easily overcome.