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A new high-precision furnace for paleomagnetic and paleointensity studies: Minimizing magnetic noise generated by heater currents inside traditional thermal demagnetizers

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[1] Although magnetic noise fields generated by heater currents in thermal demagnetizers have been noticed for a long time, no satisfactory tests have been conducted to quantify their effects. Toward this end, we have developed a new high-precision thermal demagnetizer that greatly reduces the magnetic noise field. We show the data quality generated by the new oven and the comparative results on several real samples that demonstrate the effects of the magnetic noise field due to heater currents. The properties of the spurious magnetization emanating from the heater currents critically depend on the decay rate of amplitude and its waveform of electric power which is delivered to oven coils at the end of the heating stage of thermal demagnetization. These results also illustrate the potential applications of this new instrument in paleomagnetism and paleointensity studies.

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Theme: Advances in Instrumentation for Paleomagnetism and Rock Magnetism
Guest Editors: M. Fuller, B. Goodman, J. Kirschvink, and K. Verosub

1. Introduction

[2] Bill Goree's extraordinary work and productive career have contributed enormously to paleomagnetic and rock magnetic studies and enabled many of the magnetic measurements we do today. Thermal demagnetization is one of the major lab measurements to recognize and remove secondary magnetization, and is routinely performed in paleomagnetic laboratories using thermal demagnetizers to heat specimens to a specified temperature and then cool them in a low magnetic field environment. Most commercial available thermal demagnetizers are made with a temperature-controlled electric furnace and Permalloy shield assembly. Direct current (DC) magnetic fields are attenuated by the shield assembly so that the instrument can be operated in a laboratory environment. It is vitally important to ensure that there are no DC magnetic stray fields operating over the specimens during thermal demagnetization, especially during the cooling procedure as the specimens would acquire a spurious moment proportional to and in the direction of the stray fields. New progress in Permalloy shielding techniques has reduced residual fields to a very low level, less than several tens of nanoteslas (nT) for almost all types of commercial thermal demagnetizers. However, researchers still often find noisy demagnetization results in many larger thermal demagnetizers, but much cleaner results in demagnetizers with smaller furnaces (e.g., eight-specimen-sized demagnetizers). Because shielding is generally not a major concern, it is imperative to examine the inner structures of these furnaces to understand what causes the differences. Here we report a new high-precision furnace in an effort to improve the situation. We will first document the existence of spurious remanent magnetization generated by heater currents, and then demonstrate important improvements of our new furnace in minimizing the magnetic noise field (hence the spurious magnetization) through measurements of actual rock samples.

2. Geometry of the Heating Coils

[3] One of the most critical aspects of a furnace design for thermal demagnetizers involves the geometry of the heating coils. Most thermal demagnetizers with large furnaces are constructed by spring-type wires arranged in opposite directions to mitigate the generation of alternating magnetic field during heating (Figure 1a). The number of the windings is limited because of the concern of avoiding electric shorts between them. Thermal demagnetizers with smaller furnaces, on the other hand, are made by single cable-type wires coiled into many turns in opposite directions around a cylindrical ceramic or quartz tube (Figure 1b). The spacing between the circles is shorter, thus, the alternating current (AC) magnetic field generated by heater currents in the smaller furnaces is much lower. On the other hand, improperly narrowing the space between the circles will sometimes also give rise to spurious magnetic noise due to occasional electric shorting of coils during heating. Figure 2 shows an example of sawtooth type noise along the axial direction of the oven tube during thermal demagnetization in a Taiheishoji furnace. The Taiheishoji small thermal demagnetizers were used in a few paleomagnetism laboratories in Japan about 2 decades ago, the last of which was repaired by one of us (Z.Z.) after we had found the problem mentioned above. It is this spurious phenomenon that greatly stimulated us to develop a new oven to understand and overcome the problem.

3. Power Delivery Mechanism

[4] Another aspect of the instrument design to consider is how the electric power is delivered to the oven coils. In particular, the decay rate of the power amplitude and waveform at the end of the heating cycle are the most important factors. All of the thermal demagnetizers employ some sort of power control circuit which cycles the oven power on and off during the heating cycle in an effort to elevate the sample temperature in a reasonable time frame while minimizing temperature overshoot. Some of the units employ a solid state relay to switch the AC power to the oven coils on and off abruptly ("on-off" mode), thus providing a quick decay rate of its amplitude at the end of the heating cycle. Other units use a mechanism in which solid state relay switches the power off after waiting until the amplitude of power has been ramped slowly down to zero ("ramp" mode). It would seem that switching the power to the coils off abruptly might create "noise" distinctly different from switching after the power has been ramped down to zero. Another source of possible noise is due to a component of asymmetric AC waveform, which is fairly often found in commercially available electrical power supplies. We will inspect the effects of

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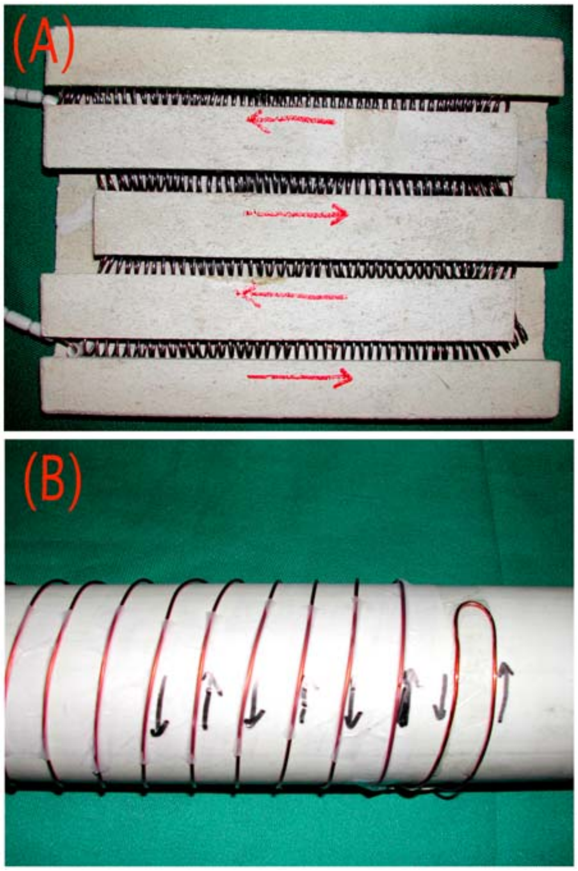

Figure 1. Schematics of wiring systems commonly used in commercial thermal demagnetizers. (a) Spring-type wires in large oven, arranged in opposite directions to reduce the generation of alternating magnetic field during heating. (b) Single-cable-type wires in smaller oven, coiled into many turns with opposite directions. Arrows indicate the directions of applied currents.

power supply to thermal demagnetization results by lab experiment runs on rock samples in section 6.

4. A New Thermal Demagnetizer: Sogo Fine-TD

[5] In order to minimize the magnetic noise field generated by heater currents, we have developed a new technique to shorten the safety distance between oppositely coiled wires to a minimum (about 5 mm) and successfully constructed a new thermal demagnetizer (Sogo Fine-TD, Figure 3). The oven chamber is 900 mm in length with a diameter of 50–90 mm. It can hold up to 10 specimens for paleointensity study, and 30 specimens for paleomagnetic directional study. The furnace is made by carefully selected nonmetallic materials that have recently become commercially available in the Japanese market. The temperature control and reproducibility are both less than 1°C. This oven can allow the acquisition of thermal remanent magnetization (TRM) in any applied field direction with field intensities up to 1000 μT. The magnetic shield of the oven is also specially designed so that any stray fields trapped inside the oven can be easily demagnetized by alternating field (AF) attachment coils. The other unique advantage of the instrument over the conventional oven is that it can control the cooling rate as slow as 0.01°C/min. The ability of the oven to cool slowly provides an opportunity to obtain blocking temperature spectra as close as possible to the true blocking temperature spectra of samples, and to evaluate the cooling rate effect on TRM acquisition [*Genevey and Gallet*, 2002].

5. Comparison of Magnetic Noise Field Generated by Heater Currents

[6] Table 1 compares magnetic fields due to heater currents inside various commercial thermal demagnetizers. These fields were measured near the central sample position with a fluxgate magne-

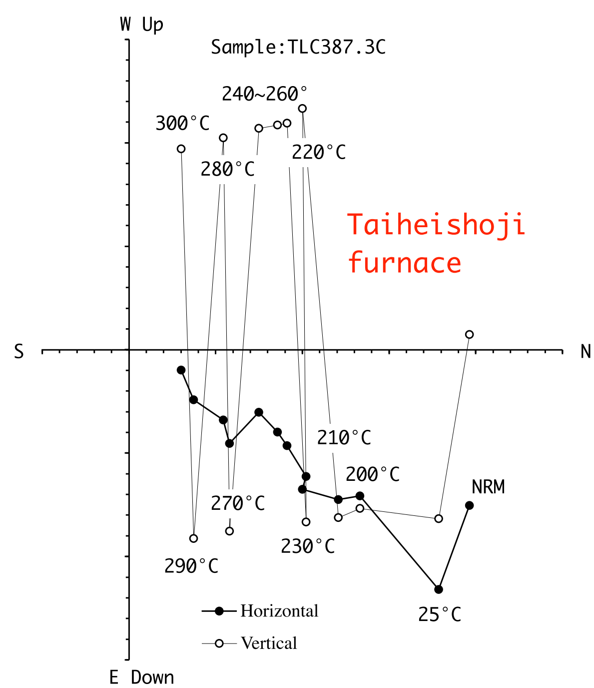

Figure 2. Vector plot of thermal demagnetization on a Pleistocene marine sediment sample from Taiwan. Due to electric shorting of windings during heating (Taiheishoji furnace), the vertical component of the sample, which is set parallel to the axis of the tube oven during thermal treatment, displayed a sawtooth pattern. Open and solid circles represent vertical and horizontal components, respectively. Subscale is 1 mA/m.

Figure 3. Newly constructed Sogo Fine-TD thermal demagnetizer. With accuracy of temperature control and reproducibility to less than 1°C and with an extraordinarily low AC field (~2 μT) inside the oven during heating, this thermal demagnetizer enables very high resolution investigations of paleomagnetism and rock magnetism on rocks.

tometer by applying direct currents to the heater. It is well known that magnitude difference between magnetic fields generated by AC and DC currents is generally small as long as the electric induction within the oven is small. Large thermal demagnetizers, such as ASC TD48 (capable of heating up to 48 samples in a single batch) and MMTD80 (80 samples thermal demagnetizer), are constructed with powerful spring-type wires. On the other hand, eight-specimen-sized small furnaces (e.g., Natsuhara and Sogo Fine-TD) use single cable-type wires (Figure 1b). The spring-type heater of ASC TD48 was coiled in the same way as the small furnaces. However, for the big furnace of MMTD80, only a few of spring-type heating elements were arranged in opposite directions along the axial of tube furnace. As shown in Table 1, the measured magnetic noise fields are almost linearly

Table 1. Magnetic Field due to Furnace Currents Inside Thermal Demagnetizers Measured at Central Sample Position[a]

	Sogo Fine-TD (nT)			Natsuhara, JP (nT)			ASCTD48, USA[c] (nT)			MMTD80, UK (nT)		
Current[b] (A)	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
0.00	0	16	16	7	−3	8	40	30	10			
0.10	18	7	15				900	80	60	69,000	400	−2,000
0.20	36	26	18				1,700	190	40	90,000	400	−1,500
0.30	59	31	15	820	270	510	2,280	280	40	107,100	300	−900
0.40	83	44	7	1,060	360	640	2,950	390	20	>128,500[d]	300	−700
0.50	104	51	9	1,310	460	790	3,590	480	20	>128,500	100	100
0.60	125	65	9	1,540	550	910	4,580	580	20	>128,500		
0.70	147	60	10				6,230	730	150			
0.80	170	60	4				7,350	890	270			
0.90	192	76	4									
1.00	213	83	3									
1.10	235	85	3									
1.20	255	94	2									
1.30	277	99	2									
1.40	303	111	1									
10	2.3 uT[e]			32 uT[e]			72 uT[e]			~5 mT[e]		

[a]X, axial; Y, horizontal; Z, vertical.
[b]A direct current was applied to the heater, as it is well known that there is insignificant difference between fields generated by AC or DC currents as long as electric induction within the oven is small. The generated field was measured near the central sample position by a fluxgate magnetometer at the following laboratories: Sogo Fine-TD furnace at Sogokaihatsu Co., Ltd., by the first author (Z.Z.); Natsuhara furnace at Tokyo University by Z.Z.; and ASCTD48 at the Chinese Academy of Earth Sciences in Beijing also by Z.Z. Data from MMTD80 at Academia Sinica in Taipei were obtained by the 3rd author (C.-S.H.).
[c]Between the three sets of heater elements of the ASCTD48, only the middle one (longest heater) was given electric currents.
[d]The maximum value a fluxgate magnetometer can measure is 128,500 nT.
[e]Extrapolated.

proportional to heater currents, and the magnetic noise field (along the axial direction of the tube oven) varies greatly among these ovens. When linearly extrapolated to cases of applying 10 A currents, which is the typical working condition for thermal demagnetizers, the magnetic noise field would be ~2.3 μT for the Sogo Fine-TD furnace, ~32 μT for the Natsuhara oven, ~72 μT for ASCTD48, and ~5 mT for MMTD80 (Table 1). It is clear that proper design of oven winding configurations, such as the Sogo Fine-TD furnace, can greatly mitigate the magnetic noise field when the ovens are undergoing normal heating during thermal demagnetization experiments.

6. Laboratory Tests for Spurious Magnetization and Comparison of Power Control Methods

[7] How do these magnetic "noise" fields emanating from the oven coil act in combination with elevated temperatures to produce spurious components of magnetization on samples? To examine this problem, we applied various alternating fields through the field coil installed for TRM work on our new oven as an analog for the "noise" that would emanate from the oven winding set. We also used a variac as an analog of a solid state relay to switch the alternating field off abruptly as in "on-off" or "ramp" mode.

[8] Figures 4 and 5 show representative thermal demagnetization results conducted on several geologic samples with laboratory alternating field switched off in "on-off " mode at the end of heating procedure. The samples are from Pleistocene marine sediments of the Tsailiao-chi (TLC) section, southwestern Taiwan [*Horng et al.*, 1998]. A total of four samples (TLC383.4A, 387.3C, 394.3B and 397.1B) were selected to elucidate the behavior of AC magnetic noise fields generated by the heater currents. To sensitively detect the spurious components of magnetization, a tiny laboratory field (1 μT) was first applied to the horizontal direction of the sample to obtain a weak TRM (600°C, 1 μT) when the samples were cooled down from 600°C to room temperature. Four laboratory AC magnetic fields (0 μT, 100 μT, 500 μT, and 1000 μT) were each subsequently applied to the vertical direction of the samples throughout the entire heating stage of each stepwise thermal demagnetization experiment and switched off abruptly before the start of the cooling stage of the experiment. To obtain the same polarity of TRM in the oven's residual DC magnetic field during cooling (typically ~30 nT), the vertical directions of the samples were set along the same axial direction of the tube oven until the highest temperature step, and each sample was also kept in the same position in the oven throughout all the experiment runs to avoid fluctuation due to temperature gradient in the oven. To evaluate the maximum residual TRM, at the highest temperature step 620°C, an additional step was taken when the vertical direction of the sample was set in the opposite axial direction of the tube oven to acquire an opposite polarity of full residual TRM during accessory cooling (labeled as R620°C in Figures 4–7). The magnetization measured in room temperature after each thermal demagnetization step is composed of the following three components: (1) the remaining part of the lab-induced weak TRM (600°C, 1 μT), (2) residual TRM (T_i, 30 nT) acquired during cooling from elevated temperature (T_i) to room temperature in the oven's residual DC magnetic field (~30 nT), and (3) the noise magnetization due to applied laboratory AC magnetic fields. It should be noted that if a sample's coercivity force is greater than the AC magnetic fields, then only components 1 and 2 would be observed.

[9] When 0 μT and 100 μT AC magnetic fields were applied, all the samples used in this experiment showed good demagnetization behavior (Figure 4). The demagnetization is characterized by a linear decay of TRM (600°C, 1 μT) and an increasing weak residual TRM in the vertical direction. The maximum residual TRM was less than 10% of TRM (600°C, 1 μT), which is consistent with the direct measurement of about 30 nT residual DC field in the oven. With application of 500 μT AC magnetic field, three specimens still displayed stable demagnetization behavior, but one specimen (TLC394.3B) exhibited noise behavior with a "sawtooth" pattern of vertical component (Figure 5, top). When a 1000 μT magnetic field was applied, all the samples displayed significant magnetic noise of uniform polarity within the same demagnetization step (Figure 5, bottom), uniquely characterized by the sawtooth type curve of vertical component (i.e., parallel to applied AC magnetic field direction but in random polarity between different steps, such as the data points for 250°C, 400°C, 450°C, and 500°C treatments in Figure 5). For the same sample, these spurious magnetizations are of random polarities in each experiment (note sample TLC383.4A in Figure 5 (bottom) versus Figure 6b). However, their magnitudes are strongly proportional to the strength of applied AC field

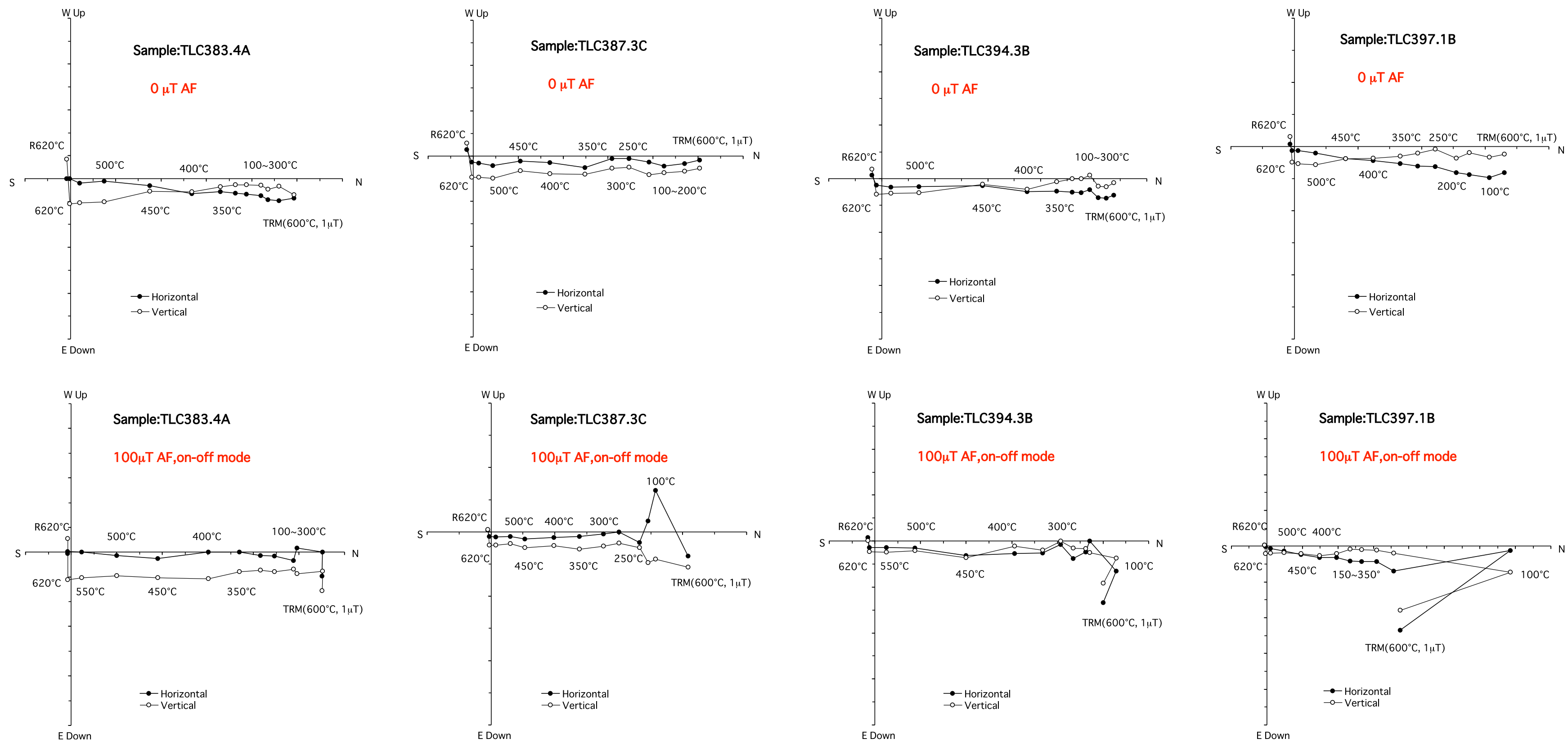

Figure 4. Vector plots of thermal demagnetization experiments on the 4 test samples from Pleistocene marine sediments when (top) no laboratory AC field (0 μT) and (bottom) 100 μT AC field were applied. AC magnetic fields were each subsequently applied to the vertical direction of the samples throughout the entire heating stage of the stepwise thermal demagnetization experiment and were switched off abruptly before the start of the cooling stage. No significant spurious thermoremanent magnetization noise was acquired for weak AC magnetic fields (less than 100 μT). Open and solid circles signify vertical and horizontal components, respectively. Subscale is 5 mA/m.

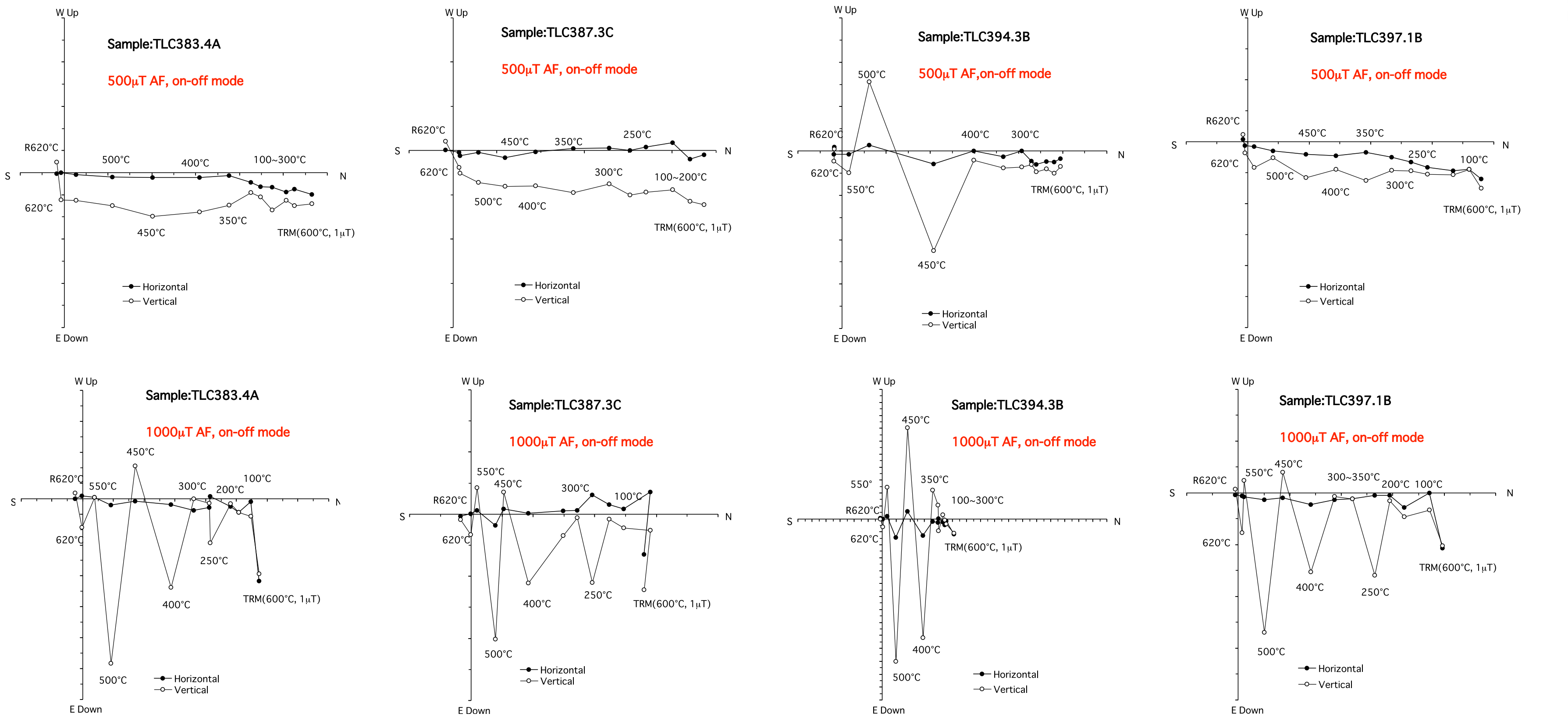

Figure 5. Vector plots of thermal demagnetization experiments on the same four test samples from Pleistocene marine sediments when (top) 500 μT AC field and (bottom) 1000 μT AC field were applied. With application of 500 μT AC magnetic field, three specimens still displayed stable demagnetization behavior, but one specimen (TLC394.3B) exhibited noisy behavior with "sawtooth" pattern of vertical component. When 1000 μT magnetic field was applied, all the samples displayed the sawtooth type curve of vertical component with uniform polarity within same demagnetization steps. Open and solid circles represent vertical and horizontal components, respectively. Subscale is 5 mA/m.

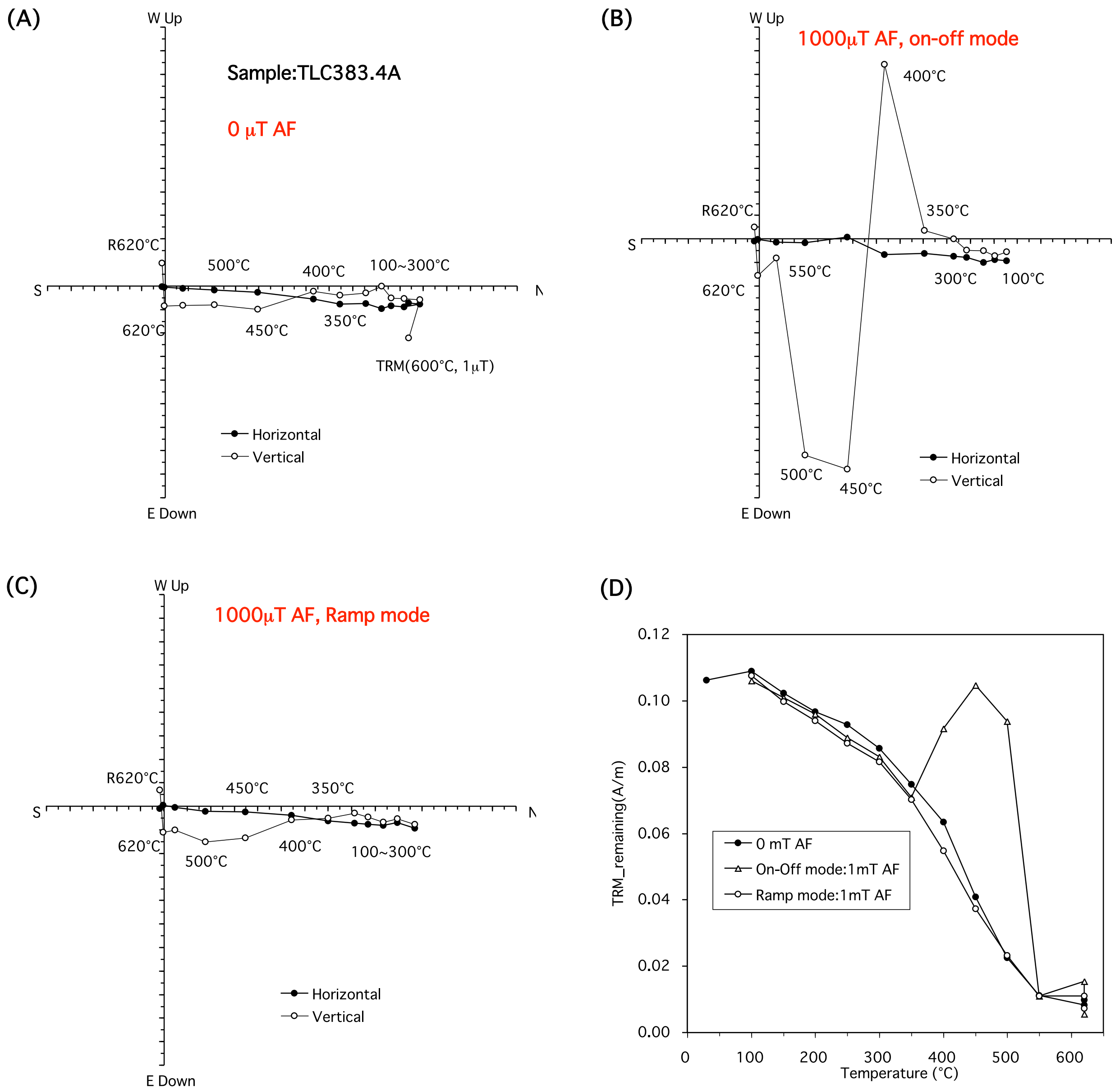

Figure 6. Comparison of different delivery modes of electric power to oven coils. At each thermal demagnetization step, three thermal demagnetizations were performed under different AC field deliveries. (a) Excellent thermal demagnetization result run in zero AC field. (b) A sawtooth type curve of vertical component was observed when a uniform 1000 μT AC magnetic field was applied and was switched off abruptly at the end of heating stage. (c) Excellent AF demagnetization was observed: the magnetization "noise" acquired in the second run was almost completely removed when the AC field was switched off after it had been ramped down to zero slowly in about 60 s. (d) The magnetization thermal decay curve of second run ("on-off" mode) has a significant "noise" component. Subscale is 5 mA/m.

(e.g., sample TLC394.3B in Figure 5). These results clearly suggest that for the thermal demagnetizers with "on-off" mode switches, thermal demagnetization results on the samples for this study are seriously affected when the oven's magnetic noise field is greater than 500–1000 μT. Our new oven has noise field less than 3 μT at normal working condition. Thus, it should not affect the demagnetization properties even if an "on-off" switch had been installed in the oven.

[10] To further evaluate the effect of electric power delivery on demagnetization results, we further compared the differential behavior of "on-off" mode and "ramp" mode. At each thermal demagnetization step, three thermal runs were performed in different AC field conditions on these four

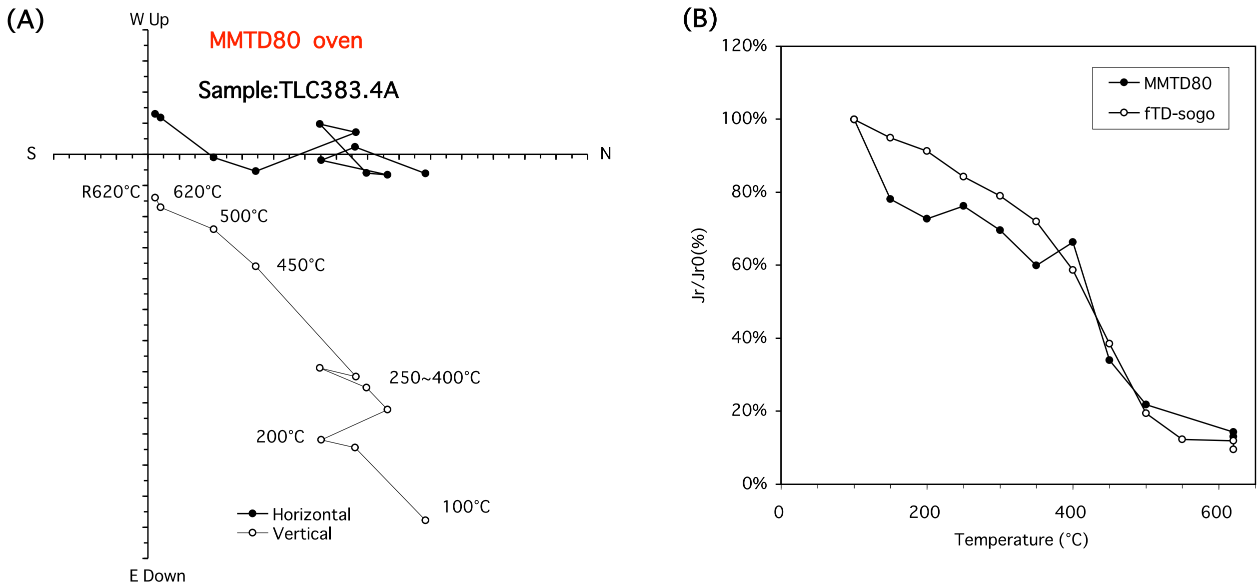

Figure 7. (a) Representative orthogonal plot of thermal demagnetization of the TLC samples by using MMTD80 furnace. (b) The result from the Sogo Fine-TD furnace was also plotted in the magnetization thermal decay curve for comparison. The power control circuit of MMTD80 appears to have provided excellent AF demagnetization behavior; no significant spurious magnetization "noise" was observed. Open and solid circles represent vertical and horizontal components, respectively. Subscale is 5 mA/m.

samples: (1) the first run in zero AC field as a normal demagnetization, (2) the second run with a uniform 1000 μT laboratory AC magnetic field applied to the samples and then switched off abruptly before the start of cooling stage, and (3) the third run with the 1000 μT AC field switched off after waiting for the amplitude of AC field to ramp down to zero slowly (in about 60 s). The comparative results from representative sample TLC383.4A are plotted in Figure 6. The magnetization "noise" components acquired during the second run (Figure 6b) were almost completely removed when the AC field was switched off after ramping down to zero slowly in about 60 s (Figure 6c). It is clear that the "ramp mode" method, which decreases the spurious harmonic waveforms gradually like in the case of AF demagnetization treatment on the sample, can help yield excellent demagnetization behavior and achieve magnetization directions almost as good as those during the first normal run (Figure 6a versus Figure 6c).

[11] We conducted a routine thermal demagnetization experiment on the MMTD80 oven with the same four samples for a comparative test. The MMTD80 oven would produce the largest "noise" magnetic field in comparison with other ovens (see Table 1). The experiment was conducted in Taiwan by the third author (C.-S.H.) following the same sample position procedure in the oven as in the case of the Sogo oven. Figure 7 shows representative results for sample TLC383.4A. It is interesting to discover that somewhat "noisy" data for the MMTD80 oven existed over the temperature range between 100 and 400°C (Figure 7b), and slightly improved data after 400°C. It seems that the power control circuit in MMTD80 oven functions superbly to produce good demagnetization behavior even though it has the largest magnetic "noise" signal from heater currents (Table 1).

7. Discussion and Conclusions

[12] Using recently available nonmetallic materials and making the spacing between oven windings only ~5 mm, we have made a new thermal demagnetizer that has a minimum magnetic noise field at its normal working condition. To quantitatively model the effect of magnetic noise field on samples during heating procedure, we have analyzed four weakly magnetized samples from Taiwan. As shown in Table 1 and Figures 4–6, the results obtained from our new thermal demagnetizer illustrate that the magnetic noise field in our instrument has been greatly reduced compared with most commercial available thermal demagnetizers.

Higher quality of demagnetization work thus can be achieved with this new instrument (Figure 4, top).

[13] It is well known that the magnetic properties of grains at high temperatures are rather different from that at room temperature. When thermal demagnetization temperature reaches near the sample's Curie point, the coercivity of the sample reduces quickly to the order of the Earth's magnetic field. This is one of the reasons we often observed a sharp increase in susceptibility in thermomagnetic curves at temperatures just before reaching the Curie point (known as the Hopkinson effect). When more grains are caught in the direction of an applied weak magnetic field at such high temperatures, the accumulated magnetic moment of the grains can overpower the weakening of spontaneous magnetization, thus resulting in susceptibility increases. A similar effect could potentially occur on magnetic grains during thermal demagnetization: the higher unblocking temperature grains of lower coercivity are disturbed by the AC magnetic field caused by the heater current, so the properties of the "noise" magnetization depend critically on the decay rate of amplitude and the waveform of electric power which is delivered to the oven coil at the end of the heating stage of thermal demagnetization. If the field is shut off abruptly or a pulse component is present in the commercial power supply, a high-temperature weak-field isothermal remanence (TIRM) could be acquired along the last polarity of AC waveform field, as shown in Figures 2, 5, and 6b. This is why the spurious component was in one polarity sometimes and the opposite polarity at other times (the "sawtooth" pattern). However, if the field is slowly ramped down, the net effect would be like AF demagnetization rather than acquisition of a "noise" component (Figure 6c). If a weak constant DC field is added into the AC field (as when imparting a pTRM in a controlled cooling rate paleointensity experiment when an electric current is delivered to the oven during a cooling stage), or if an asymmetric AC waveform is supplied to the demagnetizer, a complete AF demagnetization effect cannot be expected, but a high-temperature anhysteretic remanent magnetization (TARM) will be acquired. The spurious TIRM, TARM, as well as the AF demagnetization effect discussed in this study that would arise from the apparent difference in AF-assisted unblocking temperature spectra and purely thermal blocking temperature spectra can also be a serious problem in paleointensity investigation. The best method of mitigating the problem is to keep the magnetic noise field due to the heater current to a reasonably low level.

[14] The study of Earth's past magnetic field intensity (paleointensity) is important for our understanding of the geodynamo and the complex linkages among the different parts of the Earth system, such as the origin of marine magnetic anomalies, rates of seafloor spreading and oceanic crust formation, episodic mantle convection, plume activity, production of large igneous provinces and continental flood basalt, and mass extinctions. Interest in paleointensity determination during the past several years has surged dramatically. However, it is becoming increasingly recognized that thermal alteration will almost certainly occur in laboratory heating experiments, especially when it reaches a high temperature such as the Curie point, thus resulting in unreliable paleointensity estimates. The so-called nonideal behavior for the Thellier-Coe paleointensity experiment is mostly due to such alteration and also to strong magnetic grain interactions [*Zheng et al.*, 2005; *Zheng and Zhao*, 2006] and other unstable characteristics of multidomain grains during heating. The dedication required to conduct proper paleointensity determinations on rocks has limited the number of investigations and hence the overall number of absolute paleointensities presently available.

[15] As we reported previously [*Zheng et al.*, 2005; *Zheng and Zhao*, 2006, 2008], the challenge of selecting suitable rocks for paleointensity study requires that techniques be developed to surmount these difficulties. Our new method with the application of this thermal demagnetizer can clearly distinguish whether or not samples are suitable for paleointensity determination and rescue and extend paleointensity results that would not normally fulfill the rigid requirements of absolute paleointensity determination. The key instrument to implement the new measurements described above is a thermal demagnetizer. With accuracy of both temperature control and reproducibility as high as less than 1°C and an extraordinarily low AC field (~2 μT) inside the oven during heating, our oven can allow the acquisition of TRM in any cooling rate and applied field direction with field intensities up to 1000 μT. The magnetic shield of the oven is also specially designed so that any stray fields trapped inside the oven can be easily demagnetized by AF attachment coils. With this new instrument, very high resolution investigations of paleomagnetism and rock magnetism in rocks are now practical. An example

of this type of work that can be carried out with this instrument is our new analyses of ordinary rocks from the Ocean Drilling Program Leg 192, which yielded paleointensity estimates that agreed within error with those from single plagioclase magnetic inclusions which are less susceptible to experimental alteration [*Riisager et al.*, 2003]. These results illustrate the promising potential of the new thermal demagnetizer for paleomagnetic and paleointensity studies.

[16] To sum up, our study demonstrates that because of the geometry of the heating coils used in larger thermal demagnetizers, AC currents can generate relatively strong local "noise" from alternating fields (up to a few mT) produced during heating. By making the spacing between windings only ~5 mm, such as in our new oven, the magnetic noise field can be greatly reduced at its normal working condition. The "noise" alternating fields acting in combination with elevated temperatures can produce spurious components of magnetization (e.g., TIRM), which can be a serious problem and prevent magnetic cleaning during thermal demagnetization. Our comparative results also suggest that the "ramp" mode of power control with slow decay rate of the amplitude of electric power delivered to oven coils at the end of the heating stage of demagnetization can have the effect of AF demagnetization that helps remove the spurious magnetizations.

Acknowledgments

[17] This work is dedicated to the memory of Bill Goree, who inspired us in conducting experimentation in paleomagnetism and rock magnetism. We thank Mike Fuller and John Tarduno of the theme editorial board for providing useful advice and encouragement and Michael Jackson of the Institute for Rock Magnetism and Craig Amerigian of ASC Scientific for constructive review. We are extremely grateful to Rob Coe and Walter Schillinger for their comments and English corrections that greatly improved the manuscript and to Zenyu Yang for assistance in measuring magnetic field in an ASCTD48 oven. The construction of the new thermal demagnetizer was supported by Sogokaihatsu Co., Ltd. This article was supported by U.S. National Science Foundation grant EAR-0633891 (to X.Z.). This paper is also contribution 505 of the Paleomagnetism Laboratory and Center for the Study of Imaging and Dynamics of the Earth, Institute of Geophysics and Planetary Physics at the University of California, Santa Cruz.

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