Reply [to “Comment on ‘Saw-toothed variations of relative paleointensity and cumulative viscous remanence: Testing the records and the model’ by L. Meynadier, J.-P. Valet, Y. Guyodo, and C. Richter”]

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Reply

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1. Introduction

Kok and Tauxe [1996 a, b] have developed a model of cumulative viscous remanence (CVR) that describes the time evolution of the magnetization intensity of an assembly of magnetic grains. They claim that the CVR model successfully duplicates the characteristics of the saw-tooth behaviour observed at ODP site 851 [*Valet and Meynadier*, 1993] (VM93).

We disagree with the basic assumptions inherent to their model because 1) the model concerns only a tiny fraction of the magnetization, 2) it does not conform the experimental data and 3) the only secondary component isolated in the experiments is a parasitic drilling magnetization with a very steep negative inclination. This component is very easily removed by alternating fields (af) at 10-15 mT and thus it did not affect the VM93 paleointensity signal. However, it is very resistant to thermal demagnetization and seem to contaminate the results shown by *Kok and Tauxe* [1996b]. Because we performed af demagnetization at 20 mT prior to our heating experiments, this parasitic remanence did not affect our results obtained at 300°C or 450°C.

2. Blocking Temperatures and Relaxation Times

The final sentence of *Kok and Tauxe*'s [This issue] conclusion is that "any distribution of relaxation times that contains a subset spanning from one to several dozens of millions of years can viscously relax to saw-toothed pattern as observed in VM93" [Valet and Meynadier, 1993]. We agree with Kok and Tauxe (KT) [This issue] that only grains with relaxation times (τ) between 1 Myr and dozens of millions of years can acquire a CVR. However, we disagree with the possibility that such a small subset of grains can have a significant effect on the remanent signal. Indeed, all sediments contain a very large magnetic grains distribution, and the largest contribution to the signal is due to grains with τ that are much longer than dozens of millions of years.

If we assume that Neel's theory correctly describes the time evolution of the grains, the distribution of relaxation times can be approximated from the distribution of unblocking temperatures. This has been done independently by both *Kok and Tauxe* [1996b] and *Meynadier et al.* [1998]. *Kok and Tauxe* [1996b, This issue] considered that the CVR is carried only by grains with unblocking temperatures between 150°C and 300°C. However, according to *Pullaiah et al.* [1975], grains with relaxation times between 1 Myr and 100 Myr are destabilized between ≈ 150°C and ≈ 200°C during a 45-min experiment. In spite of this, we can consider the larger temperature interval between 150°C and 300°C as used by KT [1996b, This issue]. In any case this means that significant CVR involves a narrow distribution of T_{ub}. Our major disagreement with KT is that their computed synthetic signal incorporates almost exclusively the fraction of grains carrying the CVR, i.e., the fraction of grains with T_{ub} between 150°C and 300°C. *Kok and Tauxe* [1996b] overlook that the natural remanent magnetization (NRM) measured above 150°C is the sum of the contribution of magnetic grains with unblocking temperatures between 150°C and 300°C plus the contribution of magnetic grains with unblocking temperatures between 300°C and 580°C. We understand that KT restrained their study to the computation of the CVR signal. In this case they should not compare the CVR signal with actual records of paleointensity.

The respective influence of the two fractions can be estimated either from the NRM demagnetization curves or from the thermoremanent magnetization (TRM) acquisition [see *Kok and Tauxe*, 1996b, Figures 3c-3d; *Meynadier et al.*, 1998, Figures 3 and 6]. Thermal demagnetization shows that the fraction with unblocking temperatures between 150°C and 300°C represents about one third of the total magnetization remaining after 150°C. The CVR computed by the KT model ($150°C<T_{ub}<300°C$) can produce a 80% long-term magnetization intensity decrease over a given polarity interval [*Kok and Tauxe*, 2000, Figure 1]. One must realize that in this case the total measured magnetic intensity would only be reduced by 27% at most. Indeed, one third of the signal can potentially be affected by a CVR, but the other two thirds have a stable magnetization with T_{ub} higher than 300°C ($2/3 \times 1 + 1/3 \times 0.2 = 0.73$). One could argue that a 27% decrease is significant, but this is far from the paleointensity record [*Valet and Meynadier*, 1993]. The respective influence of the two grain fractions can also be deduced from the TRM acquisition curves. In this case, it is clear that the fraction of magnetization carried by grains with blocking temperatures between 150°C and 300°C never exceeds 10% of the total signal acquired at 580°C. Thus the influence of the CVR can be considered as negligible

One may wonder why the characteristics of the NRM demagnetization do not mimic those of the TRM acquisition. We show below that a parasitic magnetization acquired during drilling affects a large spectrum of blocking temperatures. Thus it is incorrect to extract any distribution of blocking temperatures from the NRM demagnetization curves. Actually, only the TRM acquisition curves can be used. They which indicate that quite a negligible contribution of grains potentially carries CVR.

Of minor importance, but still significant, is the problem we have with the low end of the distribution used by KT [1996b] [also *Kok and Tauxe*, This issue, Figure 1], which includes grains with τ as small as 3000 years ($10^{16.5-5.5}$ s =

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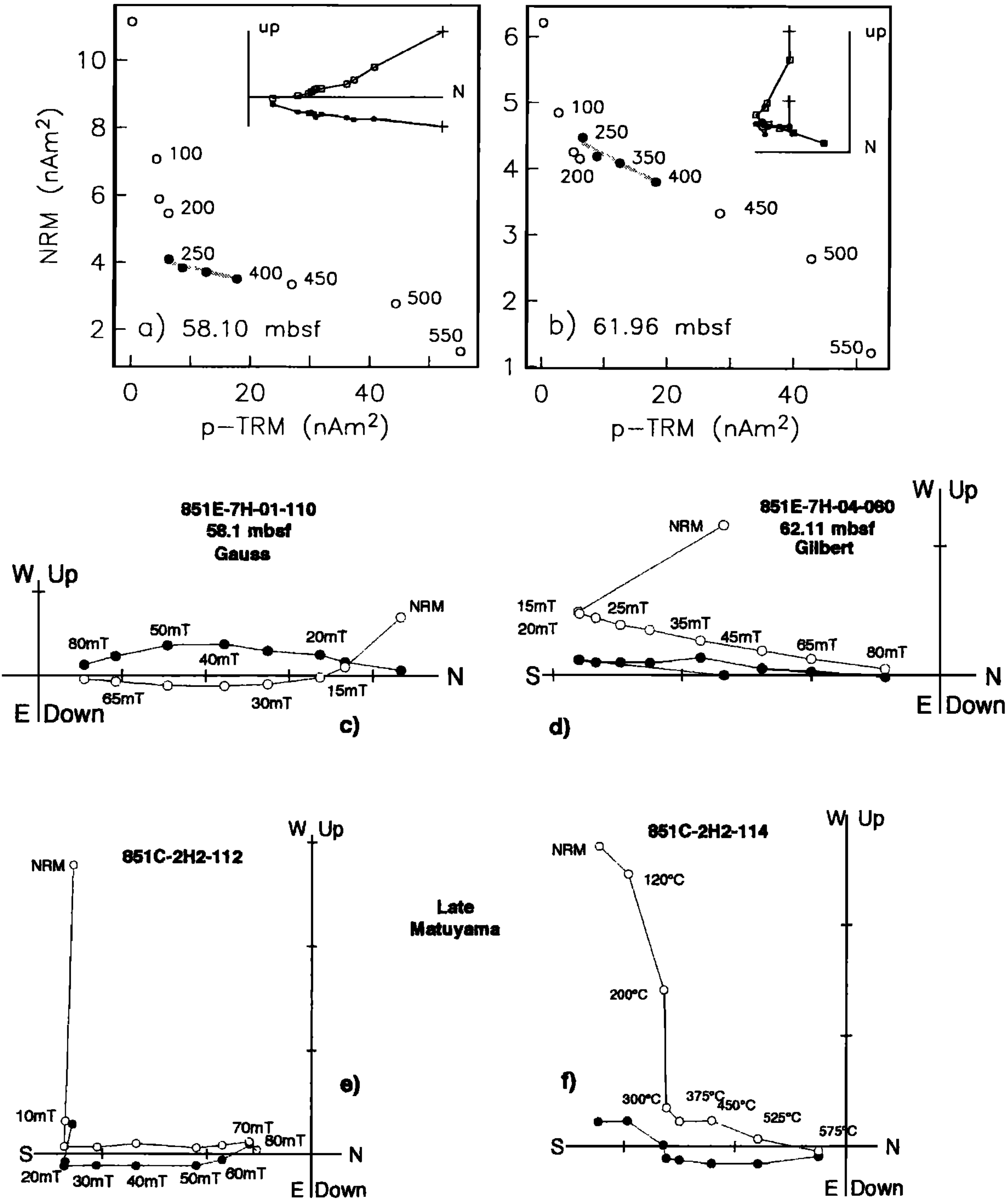

Figure 1. Thermal demagnetization of two samples from (a) the Gauss Chron and (b) the Gilbert Chron; reproduced from Kok and Tauxe [1996b]. (c) and (d) Alternating field (af) demagnetization diagrams of two samples taken at the same levels as those of Kok and Tauxe [Valet and Meynadier, 1993]. (e) and (f) Comparison between af and thermal demagnetization of two adjacent samples from the late Matuyama [Meynadier et al., 1998]. All samples come from ODP Leg 138 Site 851.

Compare Figure 1a with Figure 1c, Figure 1b with Figure 1d, Figure 1e with Figure 1f. All demagnetization diagrams show a steep upward overprint, which is probably induced by coring. This component is erased after the first step of af treatment. (10- 15 mT), whereas it is not properly demagnetized by heating. A small fraction of the overprint remaining at high temperatures biases the inclinations towards negative values. The inclination obtained after af demagnetization are in much better agreement with the value of ±5° expected at the site latitude.

10^{11} s) and thus T_{ub} lower than 150°C. These grains have very large influences on the CVR computation because they attained their equilibrium magnetization over a short period of time, and thus their contribution to the CVR signal can increase up to 30-fold after deposition Such grains, if deposited at the end of the Matuyama chron, would rapidly acquire a normal magnetization so that their total contribution would be large enough to counterbalance the other grains with reverse polarity. This process can artificially create normal polarity before the last reversal. It would be interesting to see the entire CVR signal produced by the KT [1996b] distribution of τ over 4 Myr and the CVR signal across the Gauss-Gilbert reversal after truncating the distribution at T_{ub} = 150°C.

3. Summary of the Experiments

Kok and Tauxe consider that most of the saw-toothed signal relies on a unique af demagnetization at 15 mT. This is not correct. The U channels measured in the upper part of the record (<1 9 Ma) were subjected to stepwise demagnetization up to 90 mT [*Valet and Meynadier*, 1993, *Meynadier et al.*, 1995]. The 20 mT step was selected after confirming that the demagnetization vectors decreases linearly toward the origin beyond 10-15 mT and that the paleointensity signal remained unchanged at each demagnetization step. There was also no change in using either anhysteretic remanent magnetization, low-field susceptibility, or isothermal remanent magnetization (IRM) as normalization parameters. The other cores were demagnetized at 15 mT, and more than 500 single samples were stepwise demagnetized between 7 and 11 steps up to 80 mT. Again, beyond the 10 mT step the demagnetization diagrams were characterized by a univectorial component that decreases linearly toward the origin. The whole core measurements at 15 mT match nicely the discrete samples at all steps between 15 and 65 mT. Finally, *Meynadier et al.* [1998] performed thermal demagnetization of U channels located at critical positions across the reversal boundaries in order to check the possibility that a CVR would have resisted af demagnetization. These U channels were af demagnetized at 20 mT and then thermally demagnetized at 300°C and 450°C. The two signals (300°C-450°C) well reproduced the signal derived from the af experiments (VM93).

Kok and Tauxe [1996b] performed Thellier-Thellier measurements across the Gilbert-Gauss boundary on single samples. Their results are different from VM93, but even more surprisingly, they also differ from the thermal demagnetization of the U channels at 300°C-450°C within the same interval [*Meynadier et al.*, 1998]. There are three differences in the experimental procedure. In our case, the U channels were af demagnetized at 20 mT before thermal treatment, and heating was performed in a neutral atmosphere to avoid oxidation. The thermal demagnetizations performed by KT were included within the Thellier-Thellier procedure.

4. Origin of the Secondary Component

The most critical observation is that no demagnetization diagram [*Kok and Tauxe*, 1996b, This issue; *Meynadier et al.*, 1995; *Valet and Meynadier*, 1998; *Meynadier et al.*, 1998] reveals the existence of a secondary component with an inclination close to 5° that would be expected with viscous overprint acquired at the latitude of the site. In contrast, the unique secondary component present in the samples has a very steep negative inclination (Figure 1), [also *Kok and Tauxe*, 1996b, Figures 3a-3b; *Meynadier et al.*, 1998, Figures 4 and 6], typical of a drilling-induced magnetization [*Meynadier et al.*, 1998]. Removal of this parasitic magnetization was easily achieved by applying 10 mT peak alternating fields. This overprint is much more resistant to thermal demagnetization than af and does not seem to be totally removed by heating at 400°C in the experiment performed by KT. This is suggested by the two demagnetization diagrams shown in Figure 3 of *Kok and Tauxe* [1996b], which we have reproduced in Figure 1 of this paper. The sample at 58.1 m below sea floor (mbsf) belongs to the Gauss normal polarity interval and should have a positive inclination. The demagnetization diagram (Figure 1a) shows a steep upward component, which was not removed completely before the last heating steps. The other sample from 61.96 mbsf (Figure 1b) is affected by a similar steep upward overprint that could be responsible for the persistence of a rather steep inclination (-18° instead of -5°) up to the last steps. Our af demagnetization results of the samples from the same interval (Figures 1c-1d) were not affected by this problem and the inclination are in satisfactory agreement with the expected values at that site. The same resistance to heating persists over the entire record as shown in Figures 1e-1f by the af and thermal demagnetization plots of two adjacent samples from the upper part of the core. This steep negative overprint could have an influence on the magnetization intensities measured by KT. If it is not removed properly, this upward component can increase (decrease) the magnetization of samples with reverse (normal) magnetization and thus change the shape of the records. Another aspect to consider is a possible alteration of the NRM during the Thellier-Thellier experiments. Kok and Tauxe did not perform any pTRM-check, and the segment used to calculate the paleointensity involves a surprisingly small fraction of the NRM. These potential problems did not affect our U channels measurements because the drilling related overprint was erased by 20 mT af demagnetization performed prior to the thermal treatment which was not performed in presence of field. The demagnetization characteristics of this overprint suggest that this is an IRM. There is no indication that any viscous overprint with an inclination close to 5° remained unremoved by af demagnetization and caused the saw-toothed shape of the record.

Finally, we note that the four most detailed volcanic records [*Prévot et al.*, 1985, *Chauvin et al.*, 1990; *Bogue and Paul*, 1993; *Valet et al.*, 1999] that are long enough to document the field intensity variations exhibit systematically larger field strength after the transition. Whether or not such intense recovery is followed by a long-term decrease during the following polarity interval is more difficult to detect because of the existence of both short-term and large-amplitude fluctuations. *Guyodo and Valet* [1999] have shown recently that volcanic records are inappropriate to test these kinds of variations because of the sporadic character of the eruptions. Accumulation of detailed records from homogeneous sediments clearly remains the best approach.

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