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## Time-domain magnetization of soils (VRM), experimental relationship to quadrature susceptibility

Michel Dabas\*, and John R. Skinner‡

### ABSTRACT

A comparison is made between measurements with a multichannel bipolar pulsed-induction meter (PIM) and measurements made with a phase-sensitive susceptibility bridge on more than 211 soil samples from a variety of archaeological sites in Europe. Eddy currents originating from the decay of viscous remanent magnetization (VRM) were measured with the PIM. The in-phase and out-of-phase ( $\kappa_q$ ) magnetic mass susceptibilities were measured with the susceptibility bridge.

Viscous remanent magnetization was measured through eight time sampling intervals on the pulsed-induction meter, and the linearity of VRM for selected samples was tested at various field strengths (200 to

2300  $\mu\text{T}$ ). It is believed that this extension of the reversible range indicates a high coercive strength of the magnetic grains in the soil samples involved.

Whatever the origin of the soil sample, a constant decay of VRM with time was observed between 56 and 417  $\mu\text{s}$ , after switching off the inducing field. This relation is shown to be a power law with exponent  $-1.4$ . This roughly agrees with a theoretical model that takes into account a finite-energizing time of the transmitter pulse and single-domain (SD) behavior of particles.

Finally, a comparison is made between VRM and quadrature susceptibility ( $\kappa_q$ ). This comparison is in accordance with well dispersed single-domain theory, and was found to be a linear relationship.

### INTRODUCTION

This study is a comparison between the measured time and frequency dependence of the response of magnetic particles in natural soils, which can be theoretically predicted from classical Néel theory, for noninteracting single domain particles. Previous studies have already showed that magnetic particles in soils are mainly superparamagnetic and single domain (Mullins, 1974). The volume of the magnetic particles being at most a few percent of the total volume of a soil, interactions between these particles are believed to be negligible.

A set of 211 samples have been selected and come from more than 50 archaeological sites throughout England, France, and Germany and are representative of most soil types encountered in these countries.

This study was carried out first to show that measurement of quadrature magnetic susceptibility is feasible using a

time-domain apparatus measuring the viscous remanent magnetization (VRM): the pulse induction meter.

The first mention of possible magnetic viscosity effects in archaeological soils was in 1966 by Colani and Aitken where, using a metal detector, they observed that the instrument is sensitive to nonmetallic features such as filled in pits and buried earths. They suggest that the response of the metal detector used (emission of repeated unipolar rectangular pulses and output voltage in the receiver coil sampled at a fixed time) is caused by magnetic viscosity. Confirmation that the observed response was due to magnetic viscosity was obtained by studying the time dependence of the voltage induced in the receiver coil. The voltage measured with this metal detector was shown to be roughly inversely proportional to the time. Consequently, the magnetic flux or momentum responsible for the observed voltage is proportional to  $\log(t)$ , a law which is predicted for single-domain (SD) particles. Any conductivity effect would have shown a

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$t^{-5/2}$  dependence. Moreover, drying of the sample shows no change in the measured voltage, indicating the absence of any conductivity contribution. It was also shown that, on a survey line, there exists a correlation between the magnetometer output and the metal detector output of Colani and Aitken (1966) indicating a possible correspondence between magnetic susceptibility and viscosity.

The pulse induction meter we have used operates on the same principles as the metal detector used by Colani and Aitken except that we can sample the decaying voltage through different channels. Therefore, we have used the PIM as a tool for measuring VRM. The quadrature susceptibility was measured with a phase sensitive susceptibility bridge (Walker, 1980).

Second, the consequence of this study is a better understanding of the effect of:

- 1) quadrature susceptibility in classical single-frequency electromagnetic surveys, and
- 2) VRM in TDEM surveys.

For example, using the frequency domain EM apparatus designed in our laboratory (SH3), anomalous conductivity responses have been observed while doing subsurface profiling on archaeological sites. The SH3, a classical Slingram-type apparatus, enables the separation of the in-phase response that is directly proportional to the real part of magnetic susceptibility and the out-of-phase response that is proportional to the electrical conductivity (Tabbagh, 1986). Taking into account the imaginary part of magnetic susceptibility (i.e., quadrature susceptibility  $\kappa_q$ ) results in a partial canceling of the response due to conductivity; the response due to quadrature susceptibility is opposite in sign to that of ground conductivity. For example, a quadrature susceptibility of  $10 \times 10^{-5}$  SI cancels the conductivity response for the SH3 with a height of the coils at 0.15 m (Tabbagh, 1986). As the ratio of the real to the imaginary part is approximately 5 percent (Dabas, 1989), the effect cannot be seen clearly for low susceptibilities. But in archaeological site surveying, very high susceptibilities—baked clays or slags for example—are often responsible for the anomalous decrease of the apparent measured conductivity of the soil. We have observed this phenomenon several times, and the charts of apparent resistivity in the case of high susceptibility areas closely correlate with the charts of apparent susceptibility. Knowledge of the response due to  $\kappa_q$  could allow the computation of the true conductivity of soils by multifrequency measurements, for example.

We have never used time-domain electromagnetic methods (TDEM) in archaeological surveying, but authors like Buselli (1982) report that some effects are due to near-surface superparamagnetic material. The advent of the Sirotem with its high sensitivity ( $0.1 \mu\text{V}/\text{A}$ ) has enabled the measurement of anomalous transients especially for late delay times and close loop configurations: low apparent resistivities are derived from late channels where it is known from geology that the resistivity should increase. Buselli explains this paradox by the superposition of the magnetic viscosity effect ( $t^{-1}$  time dependence) and the conductive effect ( $t^{-5/3}$  time dependence). For late time delay, the magnetic viscosity effect could become very important and

could even overcome the conductivity effect. Laboratory measurement on soil samples were made, and a response proportional to  $t^{-1.08}$  was measured close to the one observed during the field survey. Again, this time dependence indicates the presence of magnetic viscosity.

#### EQUIPMENT AND SAMPLES

Measurements of VRM were made with a pulsed induction meter (PIM). This instrument is capable of sampling the received signal at ten logarithmically spaced time intervals called channels. The width of these channels are given in Table 1, along with the time at the center of each interval. The time width spans from 12  $\mu\text{s}$  for the first channel to 270  $\mu\text{s}$  for the tenth channel. A fixed-delay time of 50  $\mu\text{s}$  exists after shut-off of the transmitter pulse. The first channel is centered on time  $t = 56 \mu\text{s}$ , taking the time of shut-off of the transmitter as the origin. The instrument generates a 12-volt bipolar transmitter pulse, 500  $\mu\text{s}$  in duration (Corbyn, 1980). The duration between pulses is 2000  $\mu\text{s}$  at which time the received information is monitored, see Figure 1 (Colani, 1966; Foster, 1968). The transmitter and receiver coils are solenoids and coaxially aligned. The receiver coil is inside the transmitter coil. The diameters of the two coils are such that a 1.5 cm gap exists between them to reduce the effects of intercoil capacitance. Although the PIM is capable of measuring ten sample intervals, only eight were used in this study (this limitation comes from the scanner of the automatic data acquisition system used).

Susceptibility measurements were made with a phase-sensitive, nonbalanced susceptibility bridge designed by Walker (1980). This bridge is capable of measuring both in-phase and quadrature mass susceptibility and both measurements were used in conjunction with the PIM. This instrument operates at a frequency of 1806 Hz, and has a sensitivity of  $1.2 \times 10^{-6}$  SI.

Two hundred and eleven samples were processed with both instruments. The samples were dried, sieved, and weighed. Granular samples weighed 50 g, while the clay rich samples varied from 25 to 50 g.

#### FIELD DEPENDENCE OF VRM FOR SOILS

Previous workers (Le Borgne, 1960) have observed that the acquisition or decay of viscous magnetization (viscous induced, VIM, and viscous remanent magnetization, VRM) is linearly related to the inducing field only in a specific range

Table 1. PIM sampling intervals (in  $\mu\text{s}$ )

channel	sample width	central time
1	12	56
2	17	70.5
3	24	91
4	34	120
5	48	161
6	68	219
7	96	301
8	136	417
9	190	580
10	270	837

for single-domain (SD) noninteracting grains and for times ranging from 15 to 9000 s. In that range of fields and times, the ratio of magnetization to the inducing field is a constant (coefficient of viscosity). It is therefore important to test if the field generated by the PIM lies in this linear region.

This procedure used in determining linearity in the time domain is as significant as that used in the frequency domain: the ratio of magnetization to the inducing field is constant only in a range of field and frequency—the Rayleigh domain (reversible susceptibility). Moreover, this procedure is es-

sential in relating measurements between different instruments, which very often operate at different field strengths.

Le Borgne quoted an upper limit of 2000  $\mu\text{T}$  for the domain of linearity of VRM. Under this limit, the VIM or VRM  $J(A/m)$  at time  $t$  in an inducing field  $h_0$  could be written as:

$$J(h_0, t) = J(h_0, t_0) + S h_0 \log \frac{t}{t_0}, \quad (1)$$

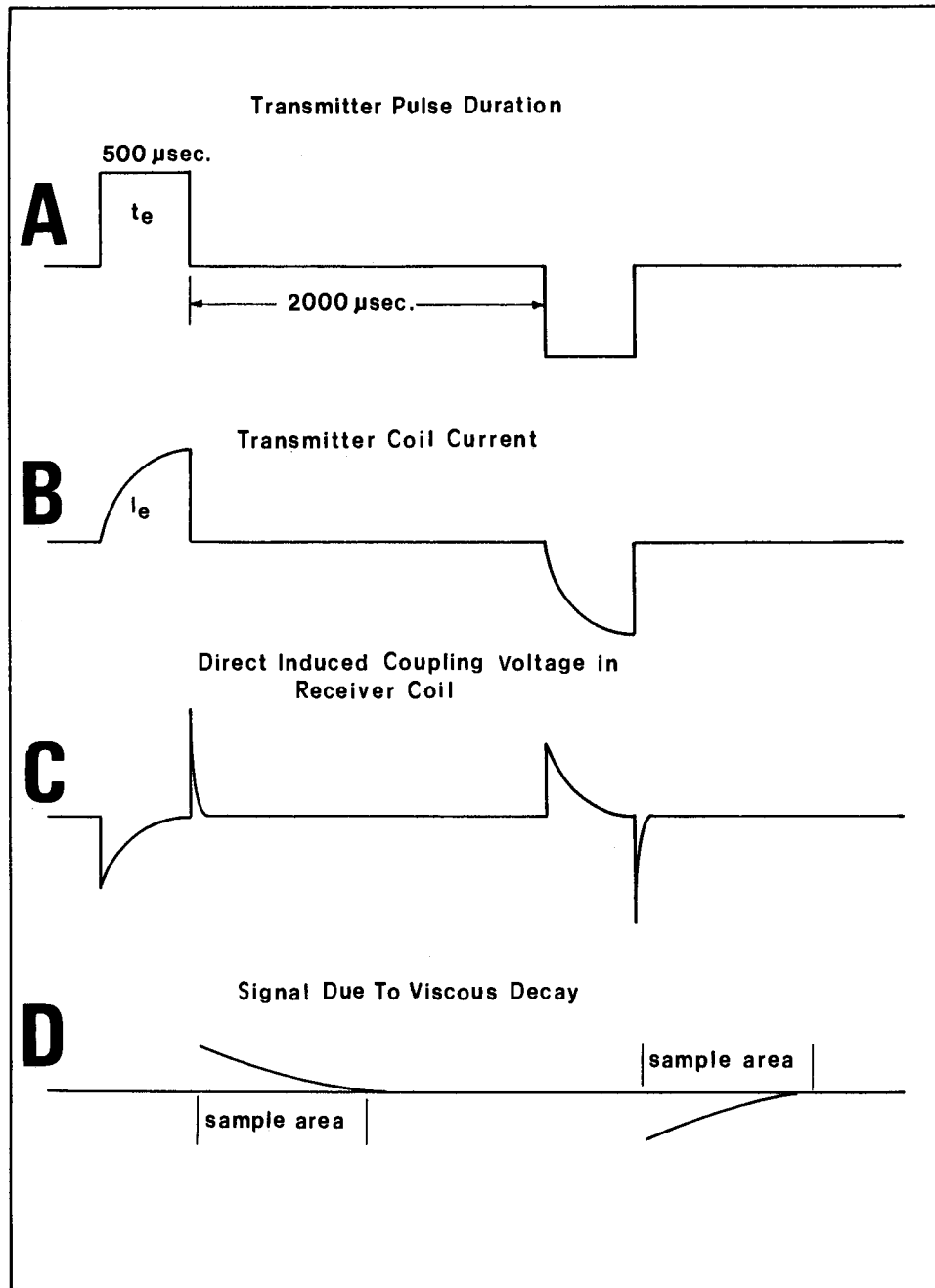


FIG. 1. Plot of the timing of the transmitter pulse for one period (A), the corresponding current driven into the transmitter coil (B), the current induced into the receiver coil (direct air coupling) (C) and the measured voltage due to the VRM of the sample (D) which has a longer period of decay than the direct coupling signal. Arbitrary vertical units.

where  $J(h_0, t_0)$  is the initial magnetization when the field is switched off ( $S < 0$ ) or switched on ( $S > 0$ ) at  $t = t_0$ .  $S$  is a constant that has an absolute value that is equal for the switch on and off (equality of VIM and VRM).

Between 2000  $\mu\text{T}$  and 6000  $\mu\text{T}$ , the magnetization  $J$  is no longer linearly related to the inducing field; however, the log  $t$  dependence is still valid:

$$J(h_0, t) = J(h_0, t_0) + S(h_0) \log \frac{t}{t_0}. \quad (2)$$

Induced and remanent magnetization are no longer equal.  $S$  is dependent on the inducing field.

To establish the peak value of the generated field in the PIM, an accurate measurement of the current in the transmitter coil was accomplished. The electrodynamic constant (ratio of the flux  $\Phi$  to moment  $M$ ) was defined through theoretical application and practical experimentation. Both results have allowed the calculation of a maximum field intensity of 2300  $\mu\text{T}$ .

The linearity of the amplitude of VRM was tested at time = 56  $\mu\text{s}$  (channel 1) and at time = 417  $\mu\text{s}$  (channel 8) for several inducing fields varying from 200 to 2300  $\mu\text{T}$  (Figures 2 and 3). In this test, four different natural soil samples were selected to cover the ordinary VRM values of soils (diamonds, triangles, crosses, and stars on Figures 2 and 3). Observations of these samples confirmed that the hypothesis of linearity was not contradicted.

Despite the difference in the time scale of this study ( $10^{-4}$  s) to that of paleomagnetism ( $>10^5$  s), the range of linearity for the time dependence of VRM is the same as the one quoted by Le Borgne. It is believed that this result is a consequence

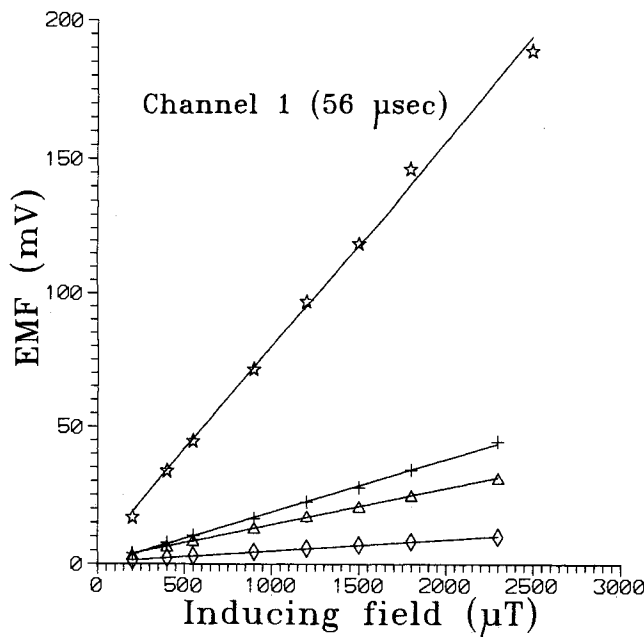


FIG. 2. Field dependence of the viscous signal for four selected samples (diamonds, triangles, cross, and stars) covering the whole range of emf observed, and for the first channel (56  $\mu\text{s}$ ). The observed linearity (straight lines) has been checked up to 2300  $\mu\text{T}$  and for the eight channels (not represented).

of the high coercive strength of single-domain grains involved in these viscous magnetizations ( $> 10\,000 \mu\text{T}$ ).

#### TIME DEPENDENCE OF VRM FOR SOILS

By using the first eight channels, it was possible to derive a decay relationship for VRM between 56 and 417  $\mu\text{s}$ . Because of instrument design limitations, it was not possible to get a response time earlier than 56  $\mu\text{s}$ . The VRM of a sample generates an electromotive force (emf) in the secondary coil that is integrated over the entire window length (see Table 1). To obtain an averaged emf, the integrated emf must be divided by the window length. The result is, arbitrarily, at the center of the window. The decay of more than 211 samples has been studied. Figure 4 shows the decay of VRM through the eight channels for one of the samples (119). It was not possible to derive an absolute value for VRM, as the instrument has not yet been calibrated.

We have matched an equation of the type  $e = kt^\beta$  to the data,  $e$  being the voltage measured in the receiver coil proportional to the VRM at time  $t$ . The power exponent  $\beta$ , along with the standard deviation and the square of the coefficient of correlation, has been calculated for the whole sample set. All exponents occupy a very narrow interval between  $\beta = -1.3$  and  $-1.5$ . The mean exponent is  $-1.40$  with a standard deviation of 0.03 for a population of 211 soil samples (see Figure 5 for the normal law derived from the data).

#### INTERPRETATION

It is believed that the very high uniformity observed reflects the uniformity in the distribution of magnetic particles. It is well known from classical Néel theory of well dispersed, noninteracting single-domain grains, that the theoretical relationship of:

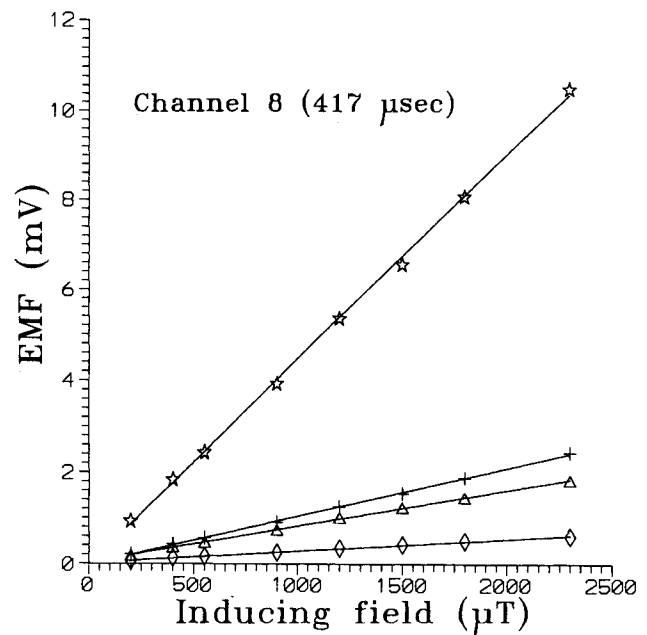


FIG. 3. Same as Figure 2 but for channel 8 (417  $\mu\text{s}$ ).

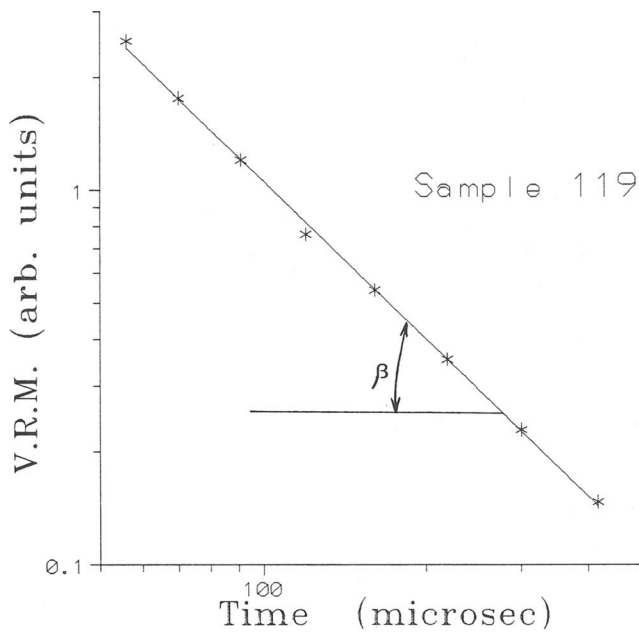


FIG. 4. Observed VRM response for one sample through the eight channels (56 to 417  $\mu\text{s}$ ). Arbitrary vertical units. A best fitting law (straight line on the log-log plot) has been calculated indicating a power law decay (exponent  $\beta = -1.4$ ) of the VRM response with time.

$$\frac{\partial J_r}{\partial t} = kt^{-1} \quad (J_r \text{ remanent magnetization}) \quad (3)$$

[the constant of proportionality  $k$  being  $Sh_0$  according to (1)] is predicted for the decay of VRM. Thus we should have obtained  $\beta = -1$  if SD theory is valid for our sample set.

If, however, the finite-energizing time of  $t_e = 500 \mu\text{s}$  is considered (i.e., with an inducing function expressed as a rectangular function and not a Heaviside's function), equation (3) should become:

$$\frac{\partial J_r}{\partial t} = \frac{k_1}{t} - \frac{k_2}{t + t_e}, \quad (4)$$

with  $k_1$  and  $k_2$  as constants, which are equal in SD theory [a ratio  $k_1/k_2$  of 2 is often quoted in multidomain (MD) theories].

It should be stressed that if compatibility between results of different studies is required, the time  $t_e$  for these studies should be of the same order, along with the intensity of the inducing field. The second term of equation (4) is generally omitted in paleomagnetism studies because if  $t \ll t_e$  the asymptotic term is a function of  $t^{-1}$ . But, if the energizing time  $t_e$  is small compared to  $t$ , the asymptotic term is now a function of  $t^{-2}$ . Figure 6 is the result of a numerical simulation, taking into account a variation of the energizing time between 1 and 16 000  $\mu\text{s}$  [equation (4)]. The slopes have been estimated between the time corresponding to channel 1 and channel 8. For  $t_e = 500 \mu\text{s}$ , the slope corresponding to this model is  $-1.24$ , which is slightly higher than the observed slope.

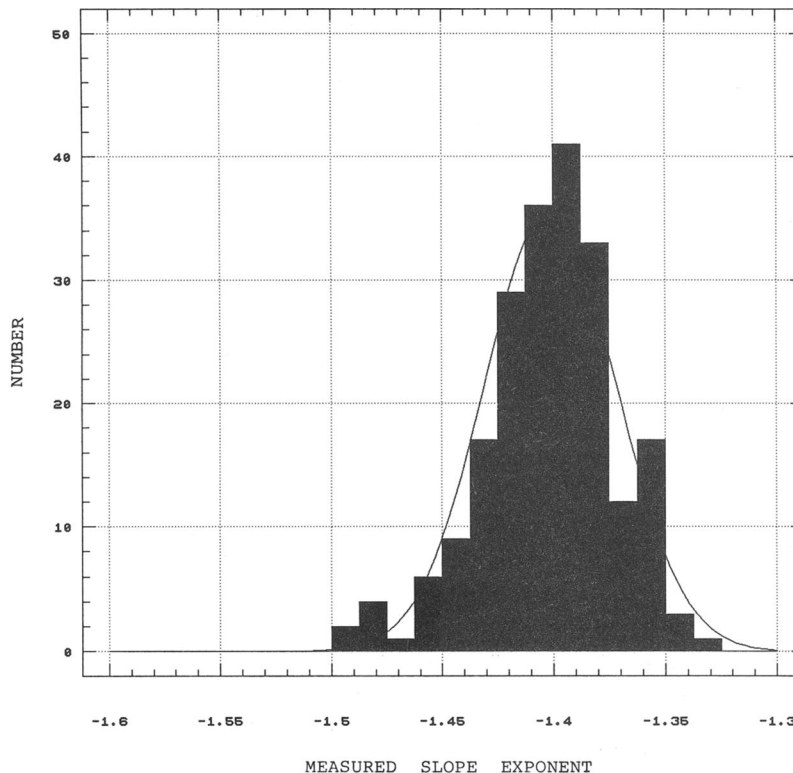


FIG. 5. Histogram of the exponent of the power law decay  $\beta$  (see Figure 4) for 211 different soil samples. Vertical axis: number of samples. All calculated exponents span in a very narrow band between  $-1.50$  and  $-1.33$  and centered on  $-1.40$ . Standard deviation was found to be equal to  $0.029$ .

Equation (4) is only valid for an excitation function which is rectangular. A more realistic theory should take into account the real shape of the inducing field (see Figure 7) and especially the finite-rising and decay time of the pulse by using the response of a single Heaviside's function, and, assuming linear field effects, the response at switch off can be derived as a superposition of a series of Heaviside functions. Considering that the induced and remanent viscosity coefficients are equal, for a well dispersed single domain grain population, the response at the initial current rise can also be calculated as a series of Heaviside functions. The two contributions are then subtracted.

Let  $s(t)$  be the response to a Heaviside's function and  $f(t)$  be the pulse-induced field of duration  $T$  (from  $t = -T$  to  $t = 0$ ). The measured emf at  $t$  (taking the origin of time at the break off) is given as:

$$k = T/\delta t$$

$$\sum_{k=1} f(-T + k\delta t)[s(t + T - k\delta t) - s(t + T - (k-1)\delta t)]$$

(5)

As in the definition of a Riemann integral, equation (5) is a series that converges to an upper bound as  $\delta t \rightarrow 0$ . Similarly, we have computed the other series that converges to a lower bound (by replacing the function  $f(\ )$  of equation (5) by  $f(-T + (k-1)\delta t)$ ). Between 56 and 417  $\mu\text{s}$  a best fitting power law is  $-1.60$  and  $-1.64$ , which has been derived by

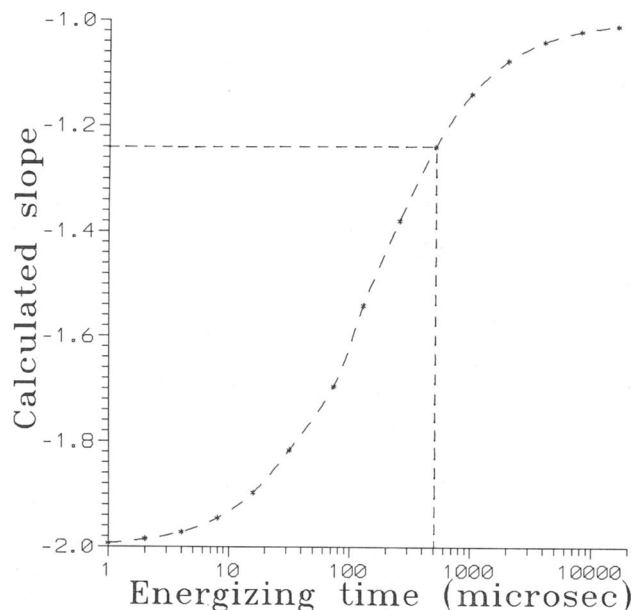


FIG. 6. Simulation of the variation of  $\beta$  taking into account a finite-energizing time  $t_e$  of a transmitted rectangular pulse according to equation (4) (stars). For large  $t_e$ , the calculated slope is very near  $-1$ , indicating a  $1/t$  dependence of the response, but for short energizing time, the slope is asymptotic to  $-2$ , indicating a  $1/t^2$  response. For the fixed energizing time used in our PIM, this model predicts a value of  $-1.24$  for  $\beta$  (dots) which is a slight discrepancy to the one observed in Figure 4.

considering the finite-rise time of the transmitter pulse with the two series previously quoted. The dotted line on Figure 7 represents a graphic representation of this solution. The solid line represents the solution for a perfect rectangular function of 500  $\mu\text{s}$  duration (power  $-1.24$ ). As expected in the higher channels, both solutions converge to the same values.

Trials with slightly different pulse shapes and durations exhibit scatter in the power law exponent ranging over a value 0.3. This could lead to the observed value of  $\beta$  ( $-1.4$ ).

In particular, it has been very difficult to measure the finite-decay time of the pulse at switch off (less than 2  $\mu\text{s}$ ), and therefore has not been incorporated into  $f(\ )$  in equation (5). A 2  $\mu\text{s}$  duration switch off could lead to the observed value of  $\beta$ .

All these simulations show the importance of the knowledge of the real shape of the energizing pulse. Moreover, the measured value of  $\beta$  is in total accordance with these simulations taking the SD theory as a basis.

#### COMPARISON OF QUADRATURE SUSCEPTIBILITY AND VRM

Finally, a comparison between the raw data of the PIM (emf integrated over the window length) and quadrature susceptibility measurements made on the phase-sensitive bridge was done for the 211 soil samples (Figure 8). This comparison shows an extremely linear relationship, regardless of the origin of the soil samples, remaining very linear through a series of eight time intervals measured (56 to 417  $\mu\text{s}$ ).

It has been demonstrated (see Mullins, 1974; Dabas et al., 1991) that the link between time and frequency-domain

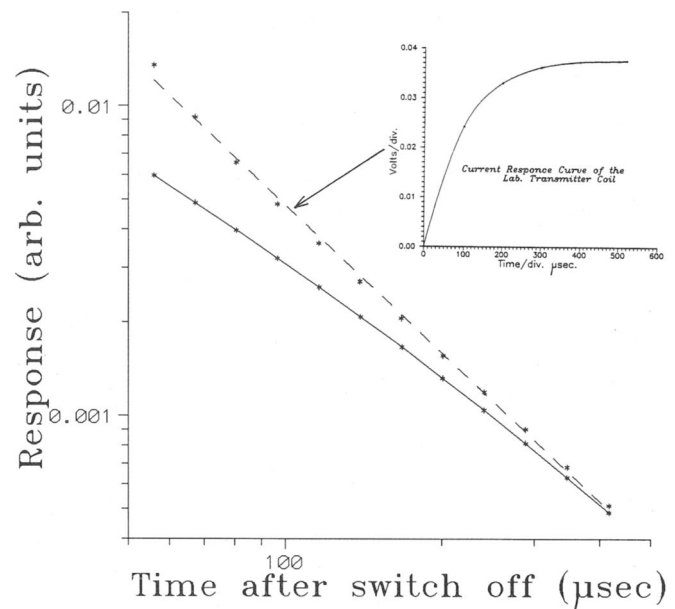


FIG. 7. Simulation of the decay of VRM response when considering a rectangular energizing pulse (solid line) and for the real PIM energizing pulse (digitized on scope) using equation (5) (dashed line). Coefficient  $\beta$  (slope of the lines) is equal to  $-1.24$  with the first model (case of Figure 6) and is equal to  $-1.6$  with the second model.

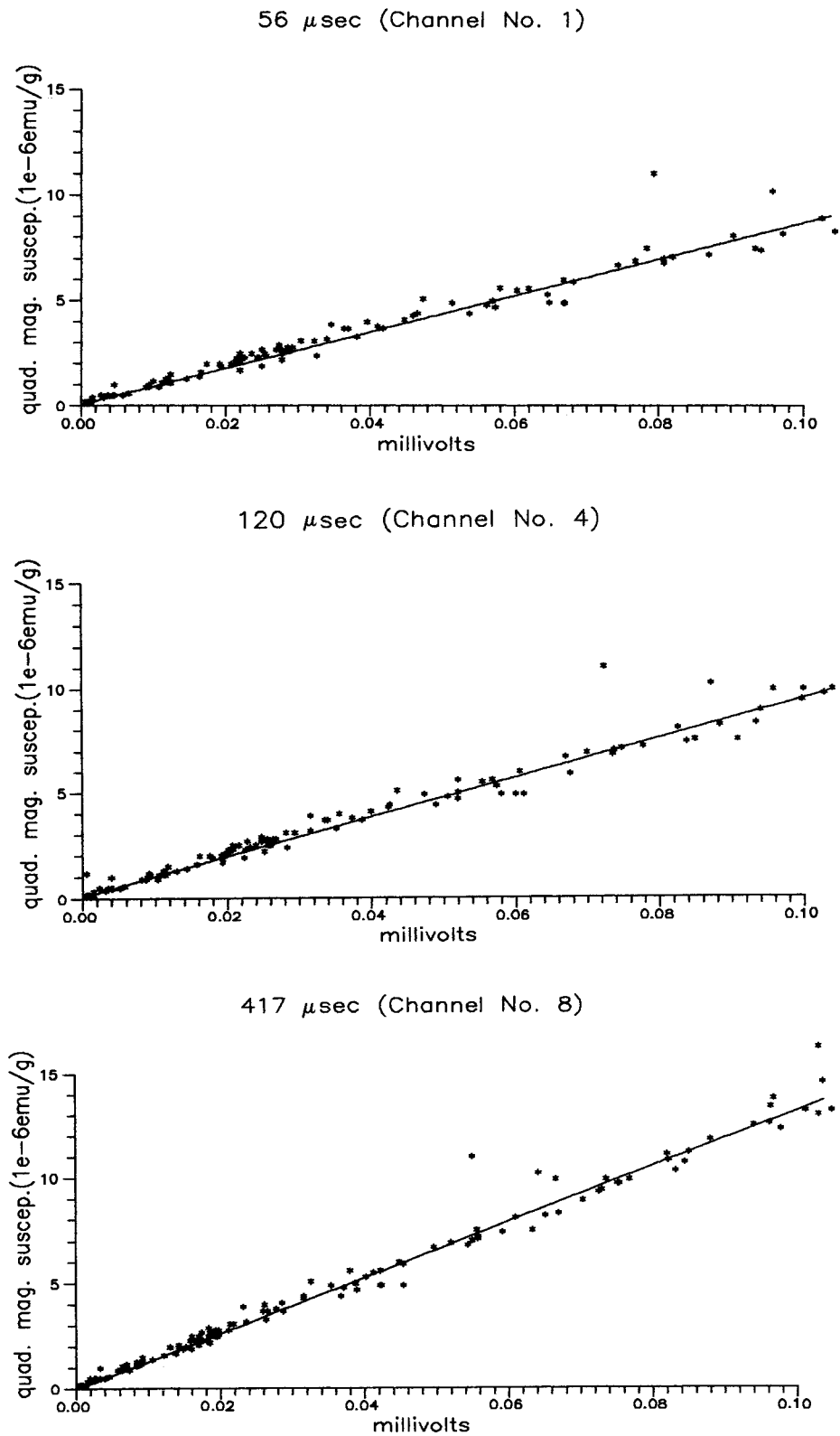


FIG. 8. Plot of the quadrature mass susceptibility versus the VRM responses for the 211 different soil samples and for channel 1 (56  $\mu$ s), channel 4 (120  $\mu$ s) and channel 8 (417  $\mu$ s)—a linear relationship is observed as predicted by SD theory [equation (7)].



responses for SD grains with no interactions can be written as:

$$\frac{2K_q}{\pi} = \frac{1}{h_0} \frac{\partial J_r}{\partial \ln t},$$

where  $J_r$  is remanent magnetization and  $K_q$  is the out-of-phase susceptibility per unit volume.

From equation (1), it follows that  $K_q$  is a constant:

$$K_q = S \frac{\pi}{2}. \quad (6)$$

The emf ( $e$ ) measured with the PIM is proportional to the rate of decay of the volume magnetization. If  $G_s$  is the electrodynamic constant of the secondary coil and  $V$  the volume of the sample, the measured emf  $e$  is using equation (3):

$$e = -G_s V \frac{\partial J_r}{\partial t} = -G_s V h_0 \frac{S}{t}.$$

The emf is directly proportional to the volume susceptibility using equation (6)

$$e = -G_s V h_0 \frac{2K_q}{\pi t},$$

and finally:

$$e \cdot t = [G_s h_0 2/\pi] V \rho \kappa_q, \quad (7)$$

where  $\rho$  is density.

The terms in the brackets of Equation (7) depend only on the geometrical dimension and current in the coils used. As a result, a linear relationship can be expected between PIM measurements and those of mass susceptibility, as measured on a bridge. The results observed in this study are consistent with SD theory. The value of the slope as shown in Figure 8 is  $12.8 e - 6$  ( $m^3/kg * Volt * s$ ).

As calibration is still being carried out on the PIM, ( $G_s$  and an accurate correlation between gain size and  $e$ ), comparison with the theoretical slope is not yet possible.

### CONCLUSIONS

In summary, for soils it can be said:

- 1) VRM is linearly dependent for the inducing field used (less than  $2300 \mu T$ );
- 2) A similar law of decay of VRM for all the soil samples with time is observed. For the PIM used, this law could be approximated by a power law of  $-1.40 + -0.03$  between 56 and 417  $\mu s$ ;
- 3) The power law observed could be interpreted within the frame of SD grain theory;
- 4) A linear relationship is observed between quadrature susceptibility and the PIM readings;
- 5) This relationship is also predicted by the SD theory.

From these conclusions, we see that it is now possible to measure the quadrature susceptibility with a time-domain

apparatus using fields up to  $2300 \mu T$ . Improvements in experimental data are dependent upon a precise knowledge of the shape of the induced field with the coils used.

As a consequence of this, it should be pointed out that:

- 1) in time-domain electromagnetics (TDEM), a correction could be applied to take into account the "soil magnetism" effect for the latest time. This would allow a better separation of the responses, especially for eddy currents flowing in conducting targets.
- 2) in frequency-domain electromagnetics a correction could be applied between responses due to conductivity and quadrature susceptibility. As quadrature is only a few percent of the in-phase susceptibility this correction is valid only for low conductivities or in high susceptibility areas.

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