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# Behavior of u-channels during acquisition and demagnetization of remanence: implications for paleomagnetic and rock magnetic measurements

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**Abstract**

We have examined the effects of translation speed on the acquisition and demagnetization of remanence in u-channels. The speed at which the u-channel moves through alternating and steady fields has a significant effect on the efficiency of remanence acquisition and demagnetization. Anhysteretic remanence (ARM) acquisition and alternating field (AF) demagnetization efficiency are inversely correlated with translation speed. ARM acquisition is most efficient at a track speed of 1 cm/s, whereas at higher speeds ARM reaches an apparent saturation at low peak fields and has a soft coercivity spectrum during subsequent AF demagnetization. The dependence of magnetization (acquired or removed) on translation speed through alternating or steady fields is explained by the number of alternating field half-cycles experienced as the sample is translated through the applied field and on the alternating field decay rate. At slow translation speeds a u-channel experiences a comparable number of alternating field cycles to that experienced by a stationary discrete sample. At fast translation speeds, the u-channel experiences a factor of 100 fewer alternating field cycles, and the conditions experienced by the u-channel sample can be comparable to the natural reorganization time of the magnetic moments within the sediment particles during remanence acquisition and demagnetization. At low decay rates the sample has more time in the blocking field and thus a more complete approach to equilibrium.


*Keywords:* u-Channel; Paleomagnetism; Rock magnetism; Anhysteretic remanent magnetization; Alternating field demagnetization; Relative paleointensity

## 1. Introduction

The first narrow access, long core cryogenic magnetometer was developed by 2G-Enterprises at the request of the paleomagnetic group in Gif-sur-Yvette in 1991. The small-access diameter allowed smaller pick-up coils to be placed closer to the sample. The new non-Helmholtz geometry of the pick-up coils proposed by the Gif-sur-Yvette group greatly enhanced the resolution of the system. In the last decade, the switch from radio frequency (RF) driven SQUIDs to DC biased SQUIDs further increased the sensitivity of the magnetometer. The standard u-channel system is now equipped with an in-line unit containing alternating field (AF) demagnetization coils and in-line anhysteretic remanent magnetization (ARM) and partial ARM (pARM) acquisition coils.

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Subsequent improvements include the 1.6 m solenoid impulse magnetizer for isothermal remanent magnetization (IRM) and saturation IRM (SIRM) acquisition. These features have increased the speed and ease with which magnetic measurements can be made on long sedimentary records. Reviews of the capabilities of these systems (2G model 755-R) are given by Nagy and Valet (1993), Weeks et al., 1993, Roberts et al., 1996 and Kissel et al., 1999.

Initial calibration tests at Gif-sur-Yvette (now the Laboratoire des Sciences du Climat et de l'Environment—LSCE) in 1991 revealed the sensitivity of the u-channel's magnetic signal to different translation speeds. Initial tests used deep-sea sediments with relatively uniform magnetic mineralogy, consisting of pseudo-single-domain (PSD) and multi-domain (MD) magnetite. The results of these tests determined the experimental parameters used for the acquisition and demagnetization of remanence in u-channel samples, which were input into the software and measurement routines written at LSCE. The experimental details of these tests have not been published. Briefly, the tests consisted of repeatedly AF demagnetizing a u-channel at a constant peak field, while gradually slowing down the u-channel translation speed. The goal was to find the translation speed at which AF demagnetization was most efficient, and beyond which there was no further loss of remanence even at slower translation speeds. The translation speed for AF demagnetization is 4 cm/s for the LSCE system. Similarly, u-channels containing deep-sea sediment were repeatedly subjected to ARM acquisition in a constant peak alternating field while gradually slowing down the u-channel translation speed. The goal was to find the translation speed at which ARM acquisition was the most efficient. The LSCE system uses a translation speed of 1.0 cm/s for the ARM acquisition. The LSCE values may differ from commercial software (Long Core v. 3.3 and 3.5 written for LabView), which allow the user to select translation speeds greater than 10 cm/s.

There are nearly 20 u-channel magnetometer systems in operation around the world. Each lab uses its own set of instrument parameters and experimental procedures that best suit its specific research needs. While the same is true for other instruments that analyze single specimens, the effect of variable translation speed on u-channel measurements magnifies this effect. The effects of instrument settings and experimental procedure on magnetic measurements (both stationary discrete samples and u-channels) was recently explored in a series of inter-laboratory cross-calibration experiments (Sagnotti et al., 2003). Significant differences were observed in the intensity of ARM acquired by a standard material analyzed in multiple laboratories on multiple instruments (Sagnotti et al., 2003). The differences were partially attributed to variable AF decay rates used in the ARM acquisition process, as well as the ARM acquisition procedure (single-axis or three-axis) (Sagnotti et al., 2003). The differences were particularly striking when comparing the ARM acquired by a stationary sample (a single discrete cube or cylindrical core) and the ARM acquired by a moving sample measured on a pass-through magnetometer (e.g. a 1.5 m long core section, 1.5 m u-channel, or a tray of widely spaced discrete samples carried through the sensing region on a conveyor belt). These effects can complicate the use of magnetic parameters as quantitative environmental proxies. This is true even in the simple case of dimensionless ratios such as ARM normalized by SIRM (ARM/SIRM) and susceptibility of ARM normalized by magnetic susceptibility ($k_{\mathrm{ARM}}/k$). Bias in one or both parameters will skew the ratio and cause errors in particle size interpretations based on the calibrated Banerjee plot and King plot (Banerjee et al., 1981; King et al., 1982). Furthermore, incomplete ARM and SIRM acquisition and demagnetization can lead to errors in relative paleointensity normalization. It is important to call attention to these potential sources of discrepancies, particularly as new users from outside the magnetism community increasingly collect u-channel samples and use common rock-magnetic parameters for rapid down-core analyses.

In this article, we examine the response of u-channel samples to alternating and DC fields as a function of translation speed, a topic that has not yet been addressed in the literature. We have built upon the initial LSCE calibration tests via a study of well-described sediments from Lake Pepin, Minnesota (Brachfeld and Banerjee, 2000), which were sampled both with u-channels and discrete paleomagnetic cubes, and with synthetic standards of 2 μm magnetite dispersed in calcium carbonate. We demonstrate the importance of u-channel translation speed on remanence acquisition and demagnetization, which we explain in terms of the number of half-cycles experienced by the sample and by the relaxation time of magnetic moments in the presence of the applied field.

## 2. Alternating fields

ARM is imparted to a u-channel sample as it passes through a region in which both an AF and a DC field are applied. The effects of translation speed on ARM acquisition were revealed when a u-channel sample containing lacustrine sediment with fine PSD magnetite was sent through the ARM acquisition unit at the maximum speed of 36 cm/s. The sample reached apparent saturation at just 60 mT (Fig. 1a), and the intensity of ARM acquired was only 38% of the ARM imparted to a duplicate stationary discrete sample measured using a Schonstedt AF demagnetizer and ARM unit. We repeated stepwise ARM acquisition on the u-channel sample using a slow translation speed of 1.0 cm/s, resulting in a factor of 2.2 increase in the intensity of ARM acquired, with saturation achieved between 90 and 100 mT (Fig. 1a).

To systematically investigate the effect of track speed on ARM acquisition and demagnetization we prepared a standard sample of 2 μm magnetite (Pfizer 3006) dispersed in calcium carbonate. We performed stepwise ARM acquisition at four track speeds: 12, 6.5, 1.0, and 0.2 cm/s. The results are shown in Fig. 1b. At fast track speeds of 6.5 and 12 cm/s, apparent ARM saturation was reached in fields of 60–70 mT. The two data sets acquired at fast translations speeds are nearly identical. At slow track speeds of 0.2 and 1.0 cm/s ARM saturation was reached in fields of ~90 mT. The two data sets acquired at slow translations speeds are nearly identical.

After ARM acquisition at the 100 mT level the standard sample was subjected to stepwise AF demagnetization. The track speed during AF demagnetization was kept constant at 4.0 cm/s for all four sets of measurements. The spectra diverge after the 10 mT step where two groupings emerge. The ARM acquired at the two faster speeds have softer demagnetization spectra, and ARM acquired at the two slower speeds have harder spectra (Fig. 1c). These observations have important implications for relative paleointensity normalization based on ARM measurements. Incomplete ARM acquisition would result in an artificially soft

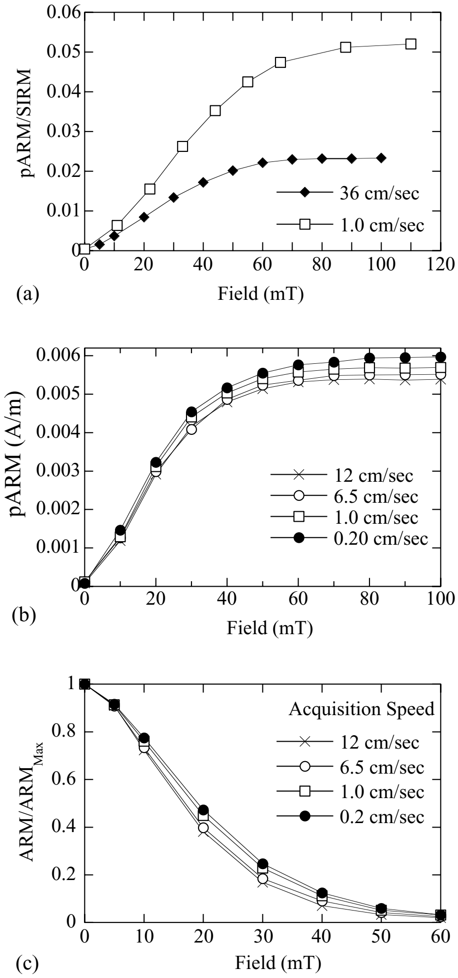


Fig. 1. (a) ARM acquisition for lacustrine sediment at u-channel translation speeds of 1 and 36 cm/s. Both data sets are normalized by SIRM. The u-channel translated at 1.0 cm/s has a higher value of saturation ARM, and saturates in a higher field (after Brachfeld, 1999). (b) ARM acquisition at four track speeds performed on a standard sample of 2 μm magnetite dispersed in $CaCO_3$. (c) AF demagnetization of the ARM imparted in (a), with AF demagnetization translation speed of 4 cm/s.

coercivity spectrum and the value of the NRM/ARM normalization would depend on the demagnetization level chosen for normalization.

We attribute these observations to the u-channel translation speed, which determines the number of alternating field cycles experienced by the u-channel sample and determines the AF decay rate experienced by the magnetic particles within the sample. In the case of the u-channel magnetometer, the sample experiences a variable AF decay rate as a function of position in the AF demagnetization unit, and experiences many fewer half-cycles than a stationary discrete sample demagnetized at the same peak alternating field level. Each of these variables is discussed below.

The track speed determines the total number of half-cycles experienced by the u-channel sample, and the time it spends in the field. The total number of half-cycles during an AF demagnetization step is given by

$$\#\text{half-cycles} = \left(\frac{d}{v}\right) \times 2\omega \tag{1}$$

where $d$ is the half-length of the demagnetizer (36 cm), $v$ is the track speed, and $\omega$ is the field frequency (250 Hz). This value is a constant for a u-channel at a given track speed, and is independent of the peak alternating field value. For a translation speed of 1 cm/s, the u-channel sample experiences ∼18,000 half-cycles. For a translation speed of 36 cm/s, the u-channel experiences only 500 half-cycles. In contrast, a stationary discrete sample experiences an increasing number of half-cycles as the peak field increases, and is given by the peak field divided by the (constant) decay rate. For ARM acquired in a peak field of 100 mT, the stationary sample experiences 40,000 half-cycles, which is higher than but still comparable to the conditions experienced by the u-channel sample at the slowest translation speed. However, it is obvious that u-channel sample translated through the field at the highest speed will not experience the full range of AF cycles required for efficient acquisition of remanence.

To consider the effects of translation speed on AF decay rates, it is instructive to visualize the geometry of the u-channel sample inside the AF demagnetization unit. A u-channel moves through a field that decays in space rather than with time. The alternating field is ramped up to its peak value and held constant while the u-channel passes through. The three mutually perpendicular axes are each demagnetized in a separate pass through the field. The axial ($Z$) coil on the LSCE system is a solenoid that is 12 cm long and 22 cm in diameter. The length of these solenoids has been reduced to 8.9 cm on more recent systems (B. Goree, pers. commun.). The transverse coils ($X$ and $Y$) are pancake pairs that are each 3.2 cm thick with a 24 cm diameter and 3.8 cm bore. The pairs are spaced 4.5 cm apart (B. Goree, pers. commun.). The axial coil has the simplest geometry and is also the coil used for both acquisition and demagnetization of the ARM. Therefore, we use the specifications of this coil to calculate AF decay rates.

The decay rate experienced by an element of a u-channel sample as it moves through the field is given by

$$R = \left(\frac{\mathrm{d}H}{\mathrm{d}x}\right)\frac{v}{2\omega} \tag{2}$$

where $R$ is the decay rate in μT per half-cycle, $\mathrm{d}H/\mathrm{d}x$ is the spatial gradient of the field in μT/cm, $v$ is the speed of the track in cm/s, and $\omega$ is the frequency of alternating field in Hz. The field in μT at a point on the axis of the solenoid is given by

$$H(x) = \frac{40\pi ni}{L} \times \left[\frac{L+2x}{2\sqrt{D^2+(L+2x)^2}} + \frac{L-2x}{2\sqrt{D^2+(L-2x)^2}}\right] \tag{3}$$

where $n$ is the number of turns, $i$ is the current, $L$ is the solenoid length, $D$ is the solenoid diameter, and $x$ is the distance from the center of the solenoid (Cullity, 1972). This function and its first derivative, $\mathrm{d}H/\mathrm{d}x$, are shown in Fig. 2. The field is nearly uniform over

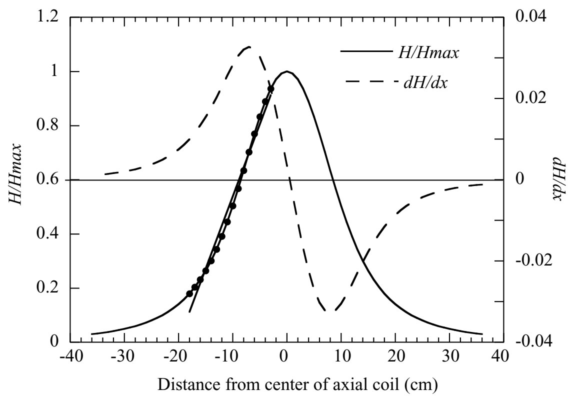


Fig. 2. Normalized field intensity (solid line) and spatial field gradient (dashed line) for the axial demagnetization coil (after Brachfeld, 1999). The horizontal axis denotes distance in centimeter from the center of the axial coil. Solid symbols denote the $H(x)$ data over the interval 3–18 cm. A line fit to the data from this interval is used to calculate an average $\mathrm{d}H/\mathrm{d}x$, which determines the decay rate experienced by the u-channel.

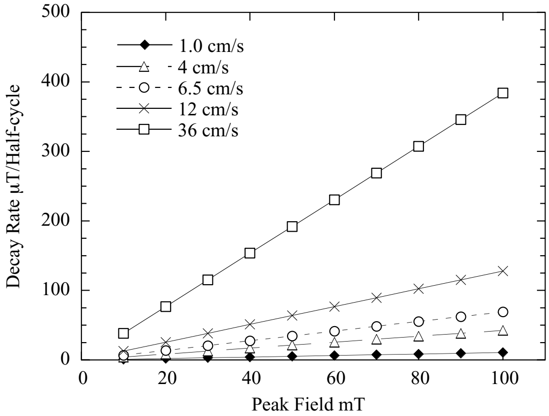


Fig. 3. Decay rates for the u-channel demagnetization unit as a function of track speed and peak alternating field (after Brachfeld, 1999). Single specimen demagnetization units typically use decay rates less than 5 μT per half-cycle.

the central 4 cm of the solenoid. The decay rate experienced by the u-channel sample changes as a function of position. A representative decay rate has been calculated by fitting a line to the function $H(x)$ over the interval 3–18 cm. The slope of this line is used as $dH/dx$. Over this interval the alternating field decays to 18% of its peak value and the regression coefficient is 0.99182. Representative decay rates in μT per half-cycle rate as a function of peak field and track speed are shown in Fig. 3. The decay rates calculated for the slow track speeds are nearest to those produced in single specimen demagnetizers such as the Schonstedt units, which generate decay rates of 0.1–5 μT per half-cycle. Decay rates at the fast track speeds are two orders of magnitude higher than those produced in single specimen demagnetizers.

The time spent in the field controls the sample's approach to equilibrium, be it demagnetization or remanence acquisition. For a monodomain grain with uniaxial anisotropy, the relaxation time is given by

$$\frac{1}{\tau} = f_0 \exp\left(-\frac{E}{\kappa T}\right) \quad (4)$$

where $f_0$ is typically $10^9\ \mathrm{s}^{-1}$ and $E$ is the energy barrier to irreversible magnetization changes and is equal to the product of the anisotropy constant ($K_u$) and the grain volume ($V$). In the presence of a field, the energy barrier for rotation of the magnetization into the field direction is lowered and is given by

$$E = K_u V \left(1 - \frac{H_{AF}}{H_c} - \frac{H_{DC}}{H_c}\right)^2 \quad (5)$$

where $H_{AF}$ is the peak alternating field (zero for the case of IRM acquisition), $H_{DC}$ is the steady field (zero for the case of AF demagnetization) and $H_c$ is the coercive force equal to $2K_u/\mu_0 Ms$ (O'Reilly, 1984). Substitution of this expression into Eq. (4) gives the relaxation time as a function of applied field. At constant temperature and grain volume, the relaxation time will be short in a strong field and equilibrium will be reached quickly. In a weak field the relaxation time will be longer, and more time in the field is needed to significantly affect the magnetization. The concept of a blocking field can be invoked, analogous to blocking temperatures and volumes, where thermal fluctuations are comparable to the heights of the energy barriers and where the magnetic moments behave viscously. Therefore, slow decay rates of the applied field give the assemblage more time in the blocking field, and a more complete approach to equilibrium.

Egli and Lowrie (2002) recently presented a comprehensive theoretical treatment of ARM in an assemblage on non-interacting fine particles. Their model predicted that the dependence of ARM intensity on the AF decay rate is on the order of 30% when the AF decay rate varies over three orders of magnitude. The dependence of ARM intensity on the AF decay rate was linked to the atomic reorganization time of stable-single domain particles, the switching mode for thermal activation, and the time during one AF cycle. In this study, we observed variations in ARM intensity on the order of 50–60% when the AF decay rate varied over two orders of magnitude (Figs. 1a and 3). In this study, we cannot separate the effects of AF decay rate and the effects of the number of half-cycles experienced. The number of half-cycles experienced by the u-channel sample may in fact be the main control on ARM intensity.

### 2.1. Steady DC and impulse fields

The behavior of u-channel samples during DC demagnetization was investigated by comparing values of coercivity of remanence ($H_{cr}$) measured on a u-channel magnetometer with vibrating sample magnetometer (VSM) measurements of discrete samples removed from the u-channels. We note that the quantitative calibration of $H_{cr}$ is extremely challenging due to the complex nature of natural assemblages of interacting particles (see Dunlop and Özdemir, 1997; Fabian and von Dobeneck, 1997; Tauxe et al., 2002). Our purpose here is not to attempt quantitative calibration of $H_{cr}$ data, but rather to highlight the need for extra steps in u-channel sample treatment.

$H_{cr}$ can be measured on a u-channel sample by imparting a SIRM to the u-channel along one-axis, and then applying gradually increasing backfields until the magnetization along that axis changes sign. This experiment was carried out on a u-channel using a 1.6 m impulse magnetizer that magnetizes along the axis ($Z$-direction) of the u-channel. For the purpose of this experiment, we deliberately used only one pulse at each applied field level in order to assess the magnitude of potential errors. The u-channel sample $H_{cr}$ values were calculated by fitting a line to the field-remanence data points over the range of 32–45 mT and taking $H_{cr}$ as the field ($H$)-intercept of this line. Discrete samples taken from the u-channel were measured on a VSM. $H_{cr}$ values obtained from the u-channel sample are 5–17 mT higher than $H_{cr}$ measured on discrete samples using a vibrating sample magnetometer (Fig. 4). The general shape of the two curves is very similar and both the u-channel sample data and the VSM data show substantial variations that likely reflect relative grain-size changes. In the absence the discrete sample data, a user might be tempted to interpret the u-channel data as reflecting finer particle sizes or reflecting a magnetic mineral with a high degree of anisotropy. Both interpretations would be incorrect due to any of the following complicating factors.

There are several possible complications when using an impulse magnetizer on discrete samples or u-channel samples. The short duration of the pulsed field may cause incomplete IRM acquisition due to the time-dependent blocking field process described earlier, particularly in weak fields where the relaxation time is longer. The calibration of impulse magnetizers is the most robust at high charging voltages. However, weak fields used for DC demagnetization are generated at very low voltages where the field calibration is less robust. Therefore, fitting a line to the magnetization versus field data will introduce error into the calculation of $H_{cr}$. Impulse magnetizers may overshoot zero when they ramp back down from the peak voltage, applying a small field in the opposite direction and effectively erasing a part of the backfield remanence that was just induced. Higher applied backfields would be necessary to achieve dc demagnetization. This scenario would be manifested as an artificially high $H_{cr}$, as observed in our u-channel samples. The 1.6 m solenoid may also heat up and change resistance if repeated pulses are generated, resulting in the peak current being less for the same voltage (B. Goree, pers. commun.). Even with these complications, the 1.6 m solenoid is preferable to manually passing the u-channel between the pole pieces of an electromagnet. As this latter process is not automated, local maxima and minima can result during IRM acquisition if the user changes the rate at which the u-channel is translated through the field. These conflicting effects have been reconciled at

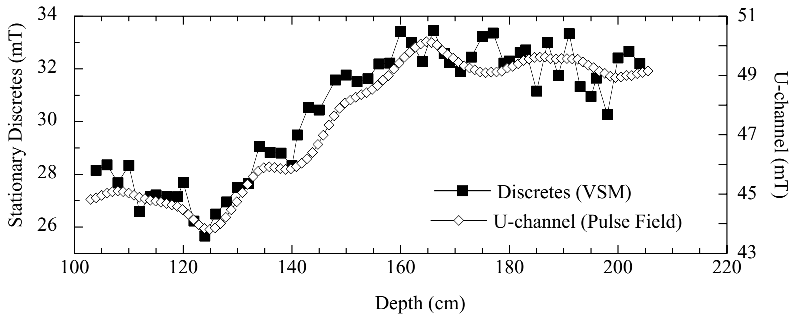


Fig. 4. Comparison of $H_{cr}$ values determined for lacustrine sediment. Discrete sample $H_{cr}$ was measured on a vibrating sample magnetometer. $H_{cr}$ was measured on a u-channel sample via DC demagnetization using a solenoid impulse magnetizer. While the $H_{cr}$ profile is similarly shaped in the two data sets, the u-channel values are much higher. This discrepancy can be caused by a combination of factors including viscous effects in the sample and less robust impulse magnetizer calibration at weak applied fields.

LSCE by systematically investigating the number of repeated pulses required to fully saturate a u-channel sample (LSCE, unpublished data). LSCE now applies two pulses at each desired field level, with the application of the pulses separated by ∼10 s.

## 3. Conclusions

A comparison of discrete sample and u-channel sample behavior during acquisition and demagnetization of remanence shows that u-channel translation speed has a significant effect on the intensity of remanence acquired and on the subsequent AF and dc demagnetization behavior. At slow translation speeds a u-channel sample experiences on the order of $10^4$ alternating field half-cycles, which is comparable to the conditions experienced by stationary discrete samples. Slow track speeds yield slower decay rates, permitting the sample to spend more time in its blocking field range and make a more complete approach to equilibrium. ARM acquisition at speeds ∼1 cm/s gives the maximum remanence and hardest demagnetization spectrum. At faster translation speeds, u-channel systems have AF decay rates that are inherently much greater than those produced in stationary single specimen systems, and result in the specimen experiencing a factor of 100 fewer AF cycles. This results in an inefficiently (de)magnetized sample, and any subsequent treatments, for example, AF demagnetization of an incomplete ARM, will be artificially soft. These are basic effects that are easily overcome and corrected. However, they are also non-negligible, and must be kept in mind as the magnetism community works towards the construction of quantitative environmental proxies and rigorous inter-laboratory cross-calibrations (Sagnotti et al., 2003). The effects of translation speed on u-channel measurements suggest that standardization of procedures should be explored, and translation speeds routinely reported when publishing u-channel data sets.

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