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Measuring the water retention curve of rock fragments: A novel repacked core methodology

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Abstract

We describe a novel suction plate experiment that uses large, repacked soil cores comprising clasts and a fine-textured matrix to accurately measure the water retention curve of rock fragments (RFs) of high and low porosity. The method incorporates a suction plate-core containment system that can be weighed as a unit, to overcome typical core size restrictions. The method relies on analysing the relationship between total core volumetric water content and RF concentration. Cores are packed with a mix of glass and RFs to maintain a uniform volumetric total clast proportion of 30% while RF concentration varies. A constant total clast volume improves accuracy and precision by ensuring the water-holding characteristics of the matrix varies as little as possible among cores.

1 Introduction

Soil hydraulic properties, such as the soil water retention curve (WRC), serve as key inputs in the quantitative assessment of water storage and drainage. Over the past decade, the WRC of soils incorporating rock fragments (RFs) has been considered, with the conclusion that RFs can store appreciable quantities of water (Parajuli et al., 2017; Robertson et al., 2021b). Thus, it is important to quantify the WRC of RFs so that models of water release of stony soils can be parameterised. The WRC of RFs is typically measured using suction plate analysis, on individual RFs (Parajuli et al., 2017; Tetegan et al., 2011), or multiple RFs in repacked cores with volumes <200 cm^3 (Schoeman et al., 1997; Wang et al., 2013). However, these methods may be prone to error as the volume of RFs used may be too small to determine the WRC of low porosity RFs. Additionally, measuring individual RFs may have

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restricted RF-suction plate contact which may inhibit drainage from parts of the RF. Repacked core methods are also prone to error by assuming fine earth porosity remains the same between cores with varying RF volumes (Baetens et al., 2009; Shi et al., 2012). Thus, this paper aims to prove a method of determining the WRC of RFs that overcomes the limitations described above, allowing RFs of any porosity to be measured.

2 Materials and Methods

The simplest potential solution to reducing relative errors is by increasing the volumetric proportion of RFs in the repacked cores (e.g. from 30% to >60%). However, a 30% volumetric proportion usually corresponds to the transition between a matrix-supported and a clast-supported state, where RFs are in contact (Milne et al., 1995). These contact points store water (Poesen and Lavee, 1994; Schoeman et al., 1997) and thus artificially increase the observed water retention of the RFs. Also, contact between RFs inhibits the ability to pack soils to specific bulk densities, making repacked cores with high RF proportions impractical (Naseri et al., 2019).

The second option would be to increase the volume of the repacked cores and in so doing, increase the absolute volume of RFs for volumetric proportions <30%. However, repacked cores are commonly constrained to a height and diameter of ~5 cm so that equilibration times are not excessive and because the weight of material in larger diameter cores can cause fissuring when cores are moved for weighing. A limited core height is preferable because it restricts the range of matric potential that occurs down a core (due to hydrostatic equilibrium) when it equilibrates with the underlying suction plate.

To use large diameter cores, we constructed a suction plate-core containment system that could be weighed as a unit, so the plate and core are never separated once the experiment begins. As a result, the core's diameter is only restricted by the size of the suction plate. The experimental system used 23 cm-square polyethylene suction plates (ecoTech Umwelt-Meßsysteme GmbH, Bonn, Germany) with a mean pore diameter of 0.45 µm, and an air entry value of -100 kPa. Each plate was placed in a container with a self-adhesive sealer around the lid to limit water loss from evaporation.

Suction from a vacuum pump was applied to the plates via air pressure. The piping network from the pump to plates included a manifold constructed of 100 mm outer diameter PVC pipe, to which all plates were connected to ensure the same pressure for all (Figure 1). Each core setup (plate, core and container) could be isolated individually from the vacuum by shutting a directional cut-off valve, after which the core set-up could be carefully transferred to a balance for weighing. After all core setups were weighed at a given suction, the vacuum system was returned to atmospheric pressure before the cores were reconnected via the shut-off valve. We initially used water-filled pipes to apply suction to the plates, but we found they quickly developed air plugs when the system was returned to atmospheric pressure at the core reconnection stage. We also experimented with pipe internal diameter and found the very low capillarity associated with an 8 mm internal diameter pipe prevented plugs from forming from water draining from the cores. Any water hanging in plugs creates pressure differentials along the pipe and inconsistent suctions across the plates, which differ from the suction applied at the pump. Incorporating the manifold and reducing the total length of pipe also served to minimise this problem.

We solve for RF water content (WC) by analysis of a three-component mixing model where the proportions of two components vary but are known, and where we assume the water-holding behaviour of one component. The cores we constructed had a constant fines proportion (70%), and total clast content (30%) made up of RFs and glass fragments (GFs), we assumed the latter held no water within or as surface films. RF abundance ranged from 3 to 30%, and GFs varied as necessary to retain the 30% total clast content. The WC of the core (θ_T) is described by the following,

$$\theta_T = \mathrm{X}_{RF} \cdot \theta_{RF} + \theta_{FE}(1 - C) + (\mathrm{C} - \mathrm{X}_{RF})\theta_{GF} \qquad (1)$$

where θ_{RF}, θ_{FE} and θ_{GF} are the WCs of RFs, fine earth and GFs, respectively, X_{RF} is the volumetric abundance of RFs, and C is the proportion of clasts (0.3). Under the assumption θ_{GF}=0, eqn (1) reduces to

$$\theta_T = \mathrm{X}_{RF} \cdot \theta_{RF} + \theta_{FE}(1 - C), \qquad (2)$$

from which it is obvious that a plot of total core WC versus X_{RF} should yield a line with slope θ_{RF}.

We applied this new method in two experiments: 1) Low porosity RFs (indurated greywacke sandstone), sourced from the Canterbury Plains of New Zealand (Robertson et al., 2021a); and 2) High porosity pumice, sourced from Taupo, New Zealand (Gillespie, 2020). Case study 1 used RFs between 6-12 mm and a sandy soil matrix to construct the repacked cores (19.4 cm internal diameter by 4.9 cm high). Nine cores were constructed, each with a different RF content varying from 3-30%. Case study 2 used 6-20 mm RFs, with a silty sand tephra soil matrix (37% silt, 59% sand), in cores of 9.7 cm internal diameter by 5 cm high. Ten cores were constructed, with RF content varying from 2-22%.

All RFs were submerged in water for a minimum of four weeks. After the saturation period, the bulk density of the RFs was determined using the volume displacement method. The GFs were prepared by breaking 17-20 mm glass gemstones with a centre punch and hammer until dimensions were similar to the RFs. The density of the GFs (ρ_{GF}) was determined using the same method as for the RFs.

The fine earth was standardised at a gravimetric WC of 0.05, which is a suitable WC for packing sand as per the methods of Dane and Hopmans (2002).

The materials (fine earth, RFs and GFs) were thoroughly mixed within a watertight bag. A core was then placed on a thin aluminium baseplate (Figure 1) to keep the soil mixture supported during and after the packing process. The material was compacted into the core in two increments using a plastic tamper propelled by a hydraulic jack. Repacked cores (with the base plates) were then saturated with degassed water by partial immersion for four days.

Once saturated, cores (still supported by the baseplate) were removed from the water and allowed to drain for ~10 seconds. One edge of the core was then placed on a suction plate, before slowly removing the baseplate, allowing the core to be supported until it was in full contact with the plate, minimising disturbance to the soil. A 1 mm-thick layer of silica flour, formed to the same diameter as the core, ensured connectivity between the base of the core and the suction plate.

Core setup mass was measured at matric potential increments between -3 kPa and -80 kPa. After equilibrating at each matric potential (which took 7-12 days), water in the drainage vessel was emptied before the next matric potential was set. Throughout the experiment, some minor condensation built up on container lids. When cores equilibrated, condensation was removed with a paper towel, and then core setups were weighed, thus treating condensation like water drained from the core.

Once equilibrium was reached at -80 kPa, the core setups were weighed for a final time ($M_{core,80kPa}$). As the applied suction increased, some soil shrinkage occurred during the experiment. To quantify shrinkage, a layer of plastic wrap was laid over each core (following their final weight measurement) and pressed down until the surface of the soil in the core was covered. Water was then added until it was flush with the top of the core and the volume of water used was recorded (V_{H2O}). The soil/RF/GF material was then removed from the core, weighed ($M_{whole,80kPa}$), oven-dried at 105°C and weighed again ($M_{whole,OD}$). The whole soil bulk density at matric potential h ($\rho_{whole,h}$) was calculated assuming linear shrinkage between saturation and the final matric potential (h_{final}),

$$\rho_{whole,h} = \frac{M_{whole,OD}}{V_{core} - V_{H2O} * \frac{h}{h_{final}}} \quad (3)$$

The gravimetric WC of the whole soil at matric potential h ($W_{whole,h}$) was calculated by,

$$W_{whole,h} = \frac{(M_{whole,80kPa} - M_{whole,OD}) + (M_{core,h} - M_{core,80kPa})}{M_{whole,OD}} \quad (4)$$

where $M_{core,h}$ represents the mass of the soil core setup equilibrated at matric potential h. The gravimetric WC was then converted to volumetric WC ($\theta_{whole,h}$) by

$$\theta_{whole,h} = W_{whole,h}(\frac{\rho_{whole,h}}{\rho_w}) \quad (5)$$

in which ρ_w is the density of water, which was assumed to be 1.00 g cm^{-3}.

A linear regression analysis was then performed using X_{RF} as the independent variable and θ_T as the dependent variable. The slope of the regression relationship and its standard error represents θ_{RF} and associated uncertainty. As an indication of regression stability, the slope's standard error at each matric potential was calculated sequentially while decreasing the number of cores used in the regression. This test calculates the standard error for all possible combinations of cores that can occur within the regression. For instance, in case study 1 when all nine cores are used, only one combination of cores is possible; however, when eight cores are used, nine combinations are possible and so on. Mean standard errors of the slope were then calculated for regression combinations with the same number of cores used in the analysis. If the mean standard error of the slope changes drastically for regressions using fewer cores, this indicates the results are sensitive to the layout of the experiment, while if the mean standard error of the slope does not change, this indicates the estimation process is stable.

To complete the WRC, the RF WC at thirteen matric potentials between -100 and -1700 kPa were measured. The range of matric potentials was achieved by air-drying thirteen samples of saturated 2-6 mm RFs for varying lengths of time (between 50 and 75 minutes) at a constant temperature (25°C) and humidity (60%). A WP4C Dewpoint Potentiameter was used to determine the matric potential of the RFs. After weighing, the air-dried RFs ($M_{2.6,h}$) were then oven-dried at 105°C ($M_{2.6,OD}$) and the volumetric WC ($\theta_{2.6,h}$) at matric potential h was determined,

$$\theta_{2.6,h} = \frac{M_{2.6,h} - M_{2.6,OD}}{M_{2.6,OD}}\left(\frac{\rho_{RF}}{\rho_w}\right) \quad (6)$$

The greywacke WRC (-3 to -1700 kPa) was fit to the van Genuchten model (van Genuchten, 1980) using SWRC Fit (Seki, 2007).

3 Results and Discussion

Results show that the measurement method was accurate enough to elucidate the WRC of both low and high porosity RFs (Figure 2). Compared to other methods of measuring RF WRCs, the standard errors of our calculated WCs were relatively small (Table 1). Brouwer and Anderson (2000) measured the volumetric WC of nonmagnetic ironstone gravel at -20 kPa using small, repacked cores and a suction table. The average standard error measured on the ironstone gravels (0.027) was over three times greater than what was measured for the greywacke in this study at -20 kPa (0.007) but was >25%

less than what was measured for the pumice (0.043). Still, the relative standard error between RFs was almost the same (11%, 15% and 10%, respectively), while previous research into pumice has shown that its bulk density and water retention properties could be prone to high natural variability (Dal Ferro et al., 2014; Flores-Ramírez et al., 2018; Parajuli et al., 2017). Cousin et al. (2003) measured individual RFs of calcareous origin with a pressure plate apparatus. At -1 kPa, the standard error was 0.12 and relative error >100%, which exceeds any error calculated within this study. Though not direct comparisons of method performance, the above results indicate that the method developed in this study performed well.

High numerical precision notwithstanding, our assumption that GFs do not retain water is a potential source of error, especially as Fiès et al. (2002) found <6 mm GFs had volumetric WCs of 0.02 and 0.04 at -3 and -5 kPa, respectively. However, Fiès et al. (2002) used cores with 100% GFs, which maximises the number of GF contact points and thereby the amount of water that the GFs would retain at high matric potentials. As clast proportion was maintained at 30% for this study (which minimises clast contact points), the water retention of GFs in this study is likely to be much lower than was measured by Fiès et al. (2002). Robertson et al. (2021b) found 2-20 mm greywacke RFs had a volumetric WC of 0.07 when measured from *in situ* soils at an average matric potential of -4.8 kPa. Using the fitted van Genuchten equation (Figure 2), the greywacke measured in this study also had a VWC of 0.07 at -4.8 kPa, justifying our inert GF assumption and demonstrating our results apply to field soils.

The number of cores used for the regression might hinder the method's ability to be used routinely in an operational way. Calculating the slope's standard error as cores were removed from the analysis indicated the sensitivity of precision to the number of cores. The mean standard error of the slope varied little (<0.04) with the number of cores used in the regression, indicating that the estimation process is reasonably stable. As such, the process of estimation does not seem to depend on having nine cores, with fewer cores capable of producing satisfactory results.

4 Conclusions

This study demonstrates that the RF WRC of low and high porosity RFs can be determined precisely using large, repacked cores with RF and GF mixtures. When compared to the results of other measurement methods, errors in WCs were either similar or lower, indicating that the method performed well.

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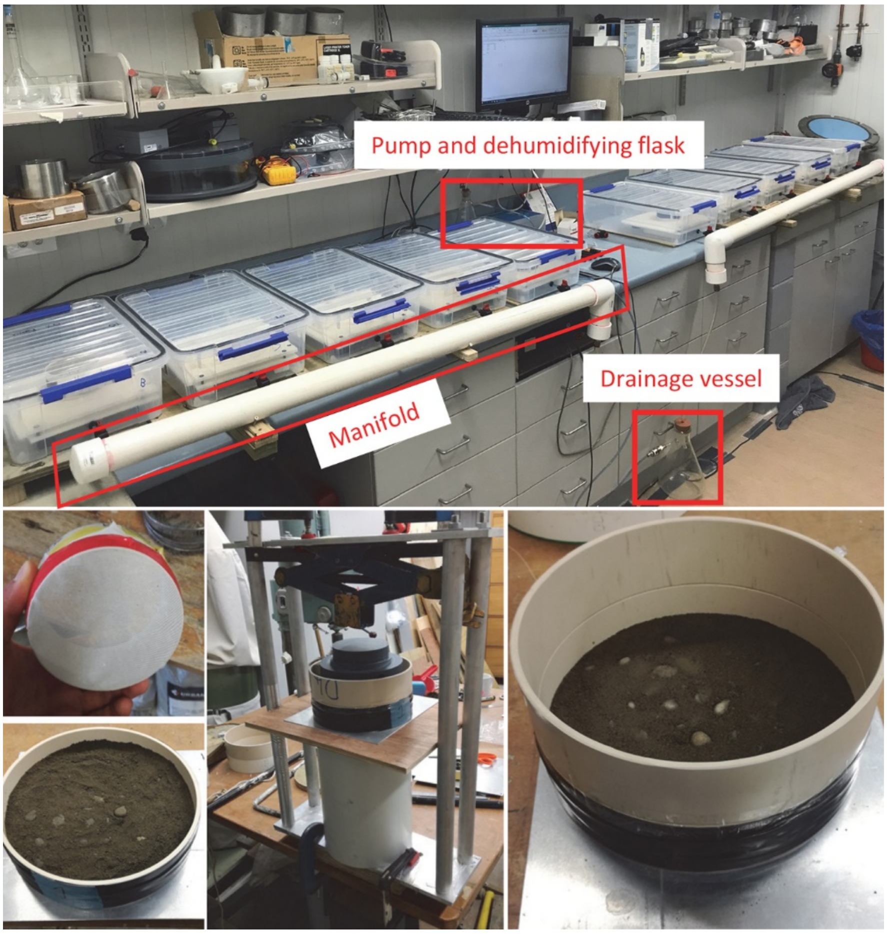

Figure 1 Photoplate of the vacuum system and compaction process.

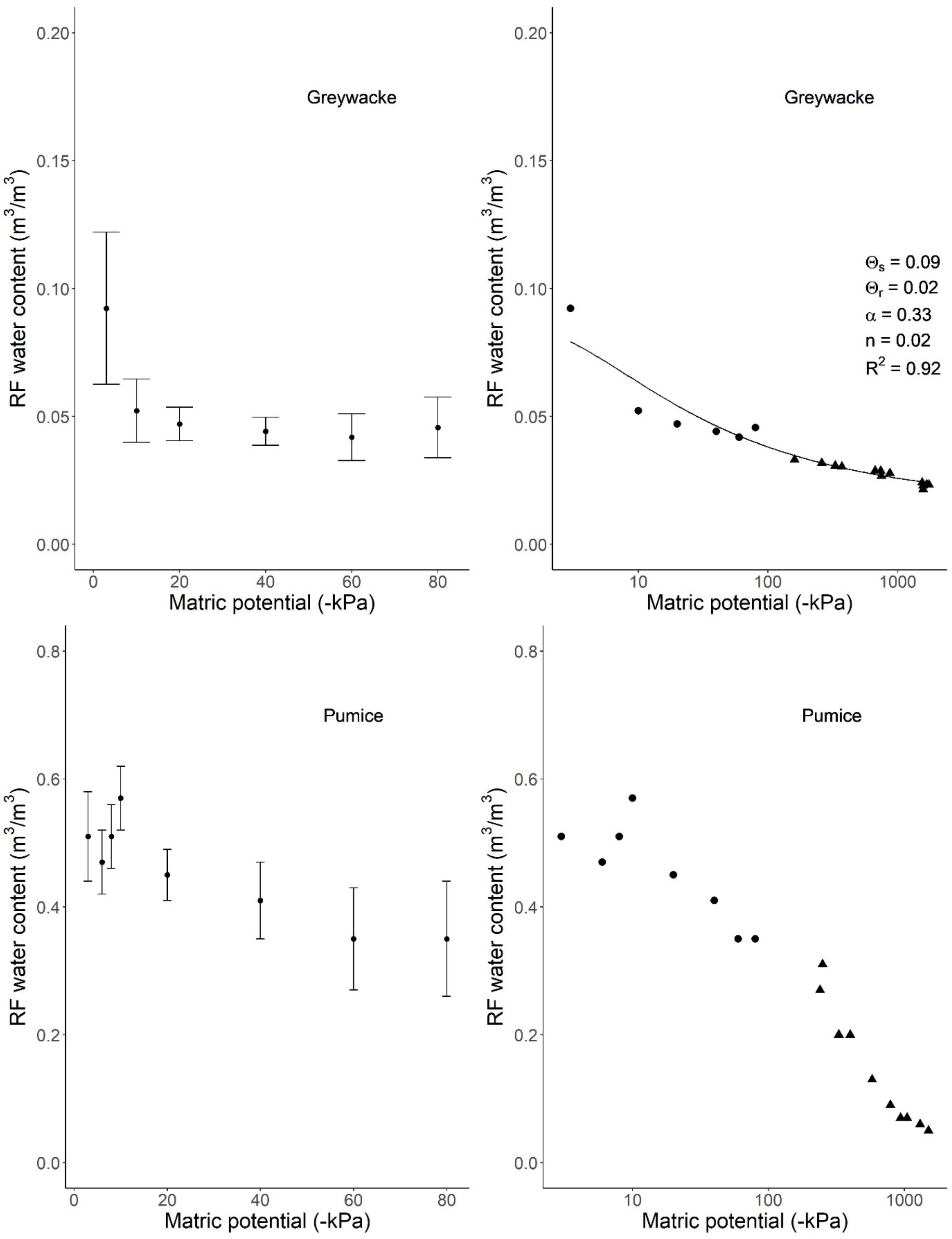

Figure 2 Water retention curve of greywacke RFs and pumice. Dots represent regression averages from soil core experiment with standard error bars (on left); triangles represent point measurements using the dew point potentiameter (on right). The curve (top right) represents the fitted van Genuchten model, which is displayed with associated model parameters and R^2.

Table 1 Regression of whole soil WC at selected matric potentials, where the slope is equal to the volumetric WC (VWC) of RFs.

RF	Dependent variable	Regression equation	R^2	SE* of the slope	SE*%
Greywacke	3 kPa VWC	$\theta_{whole,h} = 0.092\chi_{RF} + 0.175$	0.58	0.030	33%
Greywacke	10 kPa VWC	$\theta_{whole,h} = 0.052\chi_{RF} + 0.042$	0.72	0.012	23%
Greywacke	20 kPa VWC	$\theta_{whole,h} = 0.047\chi_{RF} + 0.034$	0.88	0.007	15%
Greywacke	40 kPa VWC	$\theta_{whole,h} = 0.044\chi_{RF} + 0.029$	0.90	0.006	14%
Greywacke	60 kPa VWC	$\theta_{whole,h} = 0.042\chi_{RF} + 0.017$	0.75	0.009	21%
Greywacke	80 kPa VWC	$\theta_{whole,h} = 0.046\chi_{RF} + 0.010$	0.68	0.012	26%
Pumice	3 kPa VWC	$\theta_{whole,h} = 0.508\chi_{RF} + 0.328$	0.86	0.072	14%
Pumice	6 kPa VWC	$\theta_{whole,h} = 0.470\chi_{RF} + 0.283$	0.93	0.046	10%
Pumice	8 kPa VWC	$\theta_{whole,h} = 0.509\chi_{RF} + 0.248$	0.92	0.053	10%
Pumice	10 kPa VWC	$\theta_{whole,h} = 0.566\chi_{RF} + 0.225$	0.93	0.053	9%
Pumice	20 kPa VWC	$\theta_{whole,h} = 0.448\chi_{RF} + 0.162$	0.93	0.043	10%
Pumice	40 kPa VWC	$\theta_{whole,h} = 0.411\chi_{RF} + 0.101$	0.84	0.062	15%
Pumice	60 kPa VWC	$\theta_{whole,h} = 0.354\chi_{RF} + 0.076$	0.72	0.078	22%
Pumice	80 kPa VWC	$\theta_{whole,h} = 0.349\chi_{RF} + 0.069$	0.68	0.085	24%

*SE means standard error.

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