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Lake Agassiz Final drainage event in the northwest North Atlantic

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[1] The 8.2 ka "climate" event recorded in Greenland ice cores is subject of debates with respect to causal linkage with a collapse of the Atlantic Meridional Overturning due to the drainage of the late-glacial lake Agassiz. Here, we present records from the NW North Atlantic, down-current the flood discharge route, showing that the 9.5–8 ka interval was marked by a succession of events. The drainage itself corresponds to a twin-layer of carbonate-rich turbidites deposited within the calibrated 8.35–8.5 ka interval. Proxies of sea-surface and deep-current conditions do not indicate significant concomitant changes in the NW North Atlantic. The dataset, however, supports the concept that the 8.2 ka "climate" event may represent one of the manifestations of climate instability during an interval with major changes of land drainage in NE America, due to the collapse of the Laurentide Ice Sheet, subsequent fast sea level rise and large scale reorganization of the North Atlantic thermohaline circulation pattern.
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1. Introduction

[2] In the scientific literature dealing with the Holocene, references to the "8.2 ka event" are frequent, but large uncertainties about its impact and timing remain [*Rohling and Pälike*, 2004]. Many papers have proposed links between the drainage of the Laurentide Ice Sheet (LIS) proglacial Lake Agassiz [*Barber et al.*, 1999], a significant reduction in the Atlantic Meridional Overturning (AMO) and climate excursions of variable age and duration in the 8.5–8.0 ka time frame, which were then correlated with the 8.2 ka event recognised in the Greenland ice cores that spans close to 160 years [*Thomas et al.*, 2007]. However, evidence for a significant reduction in the AMO or for a widespread contemporaneous change in sea-surface conditions over the northern North Atlantic is unclear, and model experiments of this event still require critical evaluation based on data [*Renssen et al.*, 2001; *LeGrande et al.*, 2006]. Recently, *Ellison et al.* [2006] proposed a decoupling of two short-lived cooling events, at ca. 8490 and 8290 years BP respectively, based on subpolar North Atlantic foraminiferal records that, despite possible interpretative biases, still suggest a more complex situation than the one proposed with the hypothesis of a freshwater "hosing" being responsible for a large-scale AMO decrease and related cooling. Here, we document the complexity of the events that took place during the time frame of the collapse of the LIS and drainage of Lake Agassiz, based on paleoceanographical records from the northwest North Atlantic, down-current from the flood discharge route through Hudson Strait (Figure 1).

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2. Labrador Sea Records

[3] The Labrador Sea is critically located to evaluate the impact of the Lake Agassiz drainage, because it constitutes a transitional basin between Hudson Bay and the open North Atlantic, and because of its importance with regard to the AMO. Regional winter convection currently occurs to produce the Labrador Sea Water (LSW), which overlies the North Atlantic Deep Water (NADW) forming a gyre carried by Western Boundary Undercurrent (WBUC) [*Clarke and Gaskard*, 1983].

[4] Illustrative sedimentary records from Labrador Sea margins (Figures 1 and 2) are presented vs. depth down-cores, in order to avoid misinterpretations arising from ^{14}C-age interpolations and because the drainage layer is a fast depositional unit (see auxiliary material).[1] This layer contains abundant fine detrital carbonates, which are the usual signature of reworked sediments from the Hudson Strait area, including in most Heinrich layers [*Stoner et al.*, 1996]. It is characterized by a double-peak structure indicating that the drainage occurred in two distinct phases (Figure 2). The reworking of glaciomarine sediment and till from the Hudson Strait by huge subglacial streams [*Clarke et al.*, 2003] probably accounted for turbid freshwater spreading and the dispersal of glacial-flour carbonates that were deposited along the Labrador shelf, slope and rise, as far south as the Newfoundland margin (sites P11, P19, MD2033; Figures 1 and 2).

[5] Along the Labrador margin, the drainage unit generally presents discrete erosional surfaces, notably near its base, and occasionally shows mm-thick sorted layers of small reworked shells of *Portlandia arctica* with frequent age reversals (Figure 2). This unit and older detrital-carbonate (DC) layers of the last glaciation show a typical terrestrial signature of the accompanying organic matter (see auxiliary material). On the shelf, in Cartwright Saddle (site P6), the drainage unit reaches nearly 3.5 m in thickness. A few ^{14}C-dates on benthic foraminifers or mollusc shells indicate a maximum calibrated age of 8.56 ka for its deposition, whereas an age reversal near its bottom confirms the presence of reworked fossils. The duration of the sedimentary event cannot be resolved from ^{14}C-measurements since the unit corresponds to a "^{14}C-plateau" within

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL030396.

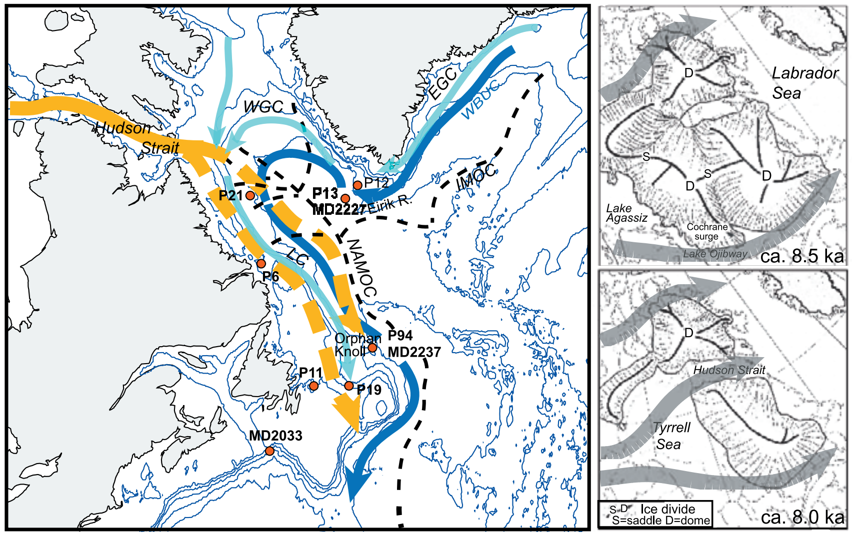


Figure 1. Maps of the study area. (right) Sketch of the configuration of the Laurentide Ice Sheet prior and after drainage, after *Dyke and Prest* [1987]. The grey arrows illustrate the main atmospheric paths as determined by the ice physiography. (left) The location of study sites and of important oceanographic features: Western Boundary UnderCurrent (WBUC, dark blue arrow), the East Greenland Current (ECG), West Greenland Current (WGC), and Labrador Current (LC) at the surface (light blue arrows). The orange arrows show the main dispersal pathways for detrital fine-grained carbonates from Hudson Strait Paleozoic source rocks, as determined from surface and gravity currents during the drainage of Lake Agassiz at ~8.4 ka BP. The dashed lines denote the deep channels, notably the Irminger Mid Ocean Channel (IMOC) and the Northwest Atlantic Mid-Ocean Channel (NAMOC).

^{14}C-dating uncertainties. It could well have been deposited within few years only, as suggested by *Clarke et al.* [2003]. The best estimate for the drainage unit is yielded by a calibrated age interval of 8.34–8.50 ka ($\pm 1\sigma$) from ^{14}C-data on planktic foraminifers from core P21, off Hudson Strait, which fits within error bars with the estimates of ~8.47 ka from *Barber et al.* [1999] and of 8.355–8.48 ka from *St-Onge et al.* [2003] (see auxiliary material for details on the ^{14}C-chronology uncertainties). The two drainage pulses that laid down the twin-detrital carbonate layers cannot be distinguished on ^{14}C grounds, since all ^{14}C-ages overlap within 1σ-error bar, but they unlikely match the twin-climate oscillations proposed by *Ellison et al.* [2006] since the last one (8290 BP) seems significantly younger.

[6] The distribution of the DC-layers linked to the drainage event suggests south-eastward transport from Hudson Strait, primarily both along the shelf (core P6), with some overflow downslope (core P19), and along a deep route (core P21). This dispersal along Labrador Current and WBUC pathways resembles the dispersal pattern of DC-layers during Heinrich events. Both DC-layers and the ~8.4 ka drainage unit are missing on the Greenland Rise in the eastern LS (sites P13 and MD2227), but sedimentological anomalies are present around 8.2 ka and 8.8 ka (Figure 3). Slight age reversals, lower biogenic carbonate content and lower $^{230}Th_{xs}$-values highlight these anomalies (Figures 3e and 3f). Such features are due to dilution of the biogenic micrite carried to the site with the WBUC, by carbonate-free detrital material [cf. *Hillaire-Marcel et al.*, 1994]. They relate to processes independent of the drainage of Lake Agassiz and linked to Greenland ice margin dynamics and/or to changes in the bathymetry or velocity of the WBUC, responsible for the advection of biogenic carbonates and $^{230}Th_{xs}$ at this site.

[7] The ^{14}C-based chronology cannot document precisely the duration of deposition of the drainage unit, except in providing a maximum value from calibrated ^{14}C-age ranges. Nevertheless, it allows interpolation of mean sedimentation rates, prior to and following the deposition, indicating analytical resolution in the critical time interval ranging from about 100 to 10 years (Figure 3). At sites with very high sedimentation rates, benthic biogenic mixing is negligible due to fast sediment accumulation and overall low productivity, which is also shown by the sharp isotopic excursions, for example downcore P21 (Figure 2). Therefore, proxies may indeed represent a time resolution as high as 10 years in some instances, and even a much better one during the deposition of the drainage layer itself. In contrast to the 1 to 2‰ shifts of δ^{18}O-values in planktic foraminifers observed during Heinrich events [*Hillaire-Marcel and Bilodeau*, 2000], the isotopic records of the drainage event are flat (Figures 3c, 3d, and 3f), suggesting a freshwater dispersal fast enough to leave no isotopic imprint in mesopelagic foraminifers. In addition, the isotopic composition of Lake Agassiz drainage waters (about −24‰ vs. VSMOW [*Hillaire-Marcel et al.*, 2006]) differed by a few per mil only from that of the modern "apparent" freshwater end-member in the NW North Atlantic (about −20‰). This corresponds to a shift from ^{18}O-salinity gradient of ~0.6‰/psu (modern) to a ~0.7‰/psu (drainage event). At site P21, at the outlet of the drainage pathway, only a brief light isotopic excursion is recorded near the top of the drainage layer. It might represent an instantaneous local event but may also result from the reworking of upslope planktic foraminifers (i.e., from a situation where lighter isotopic compositions would be expected). An abundance peak of sorted foraminifer shells matches this isotopic excursion and thus supports better the second interpretation. δ^{13}C-values

of planktic foraminifers also are practically constant throughout the critical interval (Figure 2), but increase afterwards. This indicates unchanged ventilation rates of intermediate waters and of overall productivity condition in the surface water layer before and during the drainage event, but a change towards a lesser stratification afterwards. This is consistent with sea-surface estimates from dinocysts indicating an overall increased salinity at all LS sites after ca. 8 ka BP (see Figure 3). From this point of view, the ca. 8.4–8.2 ka interval marks an important transition towards more open ocean conditions in LS surface waters, following their variable but generally low salinity conditions during late-glacial time, due to high melting rates of LIS and possibly Greenland ice [*Long et al.*, 2006]. Elsewhere, we have shown that LSW formation started rapidly after this transition, but did not occur before [*Hillaire-Marcel et al.*, 2001]. Estimates of winter vs. summer potential density in surface waters indicate that winter convection allowing LSW formation was most unlikely prior to ca. 7 ka BP (Figure 3b). Coupled models used to document the AMO-behaviour in response to freshwater pulses such as the 8.4 ka drainage event show a drastic response of the AMO to such a freshening [e.g., *Renssen et al.*, 2001; *LeGrande et al.*, 2006]. However, this response is largely due to the fact that these models start from a situation with LSW formation. Under such conditions, any major freshwater pulse in the Labrador Sea area would naturally shut off this component of the AMO.

[8] Sea-surface conditions were reconstructed from dinocysts in about 20 Holocene sequences from the northwest North Atlantic [*de Vernal and Hillaire-Marcel*, 2006]. Beyond salinity changes mentioned above, none of the record shows significant cooling feature (temperature or sea-ice) following the drainage event within the time resolution achieved. The only record with some significant change is that of site P21, in which a brief sea-ice peak is recorded within the drainage layer itself (Figure 3a). It could indicate some sea-ice spreading off Hudson Strait during the drainage event or could relate to reworking of upslope material, i.e., from a more proximal sea-ice margin position.

[9] Deep-water conditions, in particular the velocity of the WBUC, can be documented from $^{230}Th_{xs}$ on the upper Greenland Rise (Figures 3e and 3f). At this site, $^{230}Th_{xs}$ is not a simple function of water depth [*McManus et al.*, 2004], but is laterally advected and focussed below the high velocity axis of the WBUC [*Veiga-Pires and Hillaire-Marcel*, 1998]. Data illustrate an increasing trend of carbonate and $^{230}Th_{xs}$ fluxes during the early Holocene, which probably corresponds to intensification of the WBUC with enhanced production of Denmark Strait Overflow Water (the bottom component of NADW). Data also show a major shift of $^{230}Th_{xs}$ at ca. 8.8 ka in core MD2227 despite flat ^{18}O records (Figures 3d, 3e, and 3f), which illustrates the

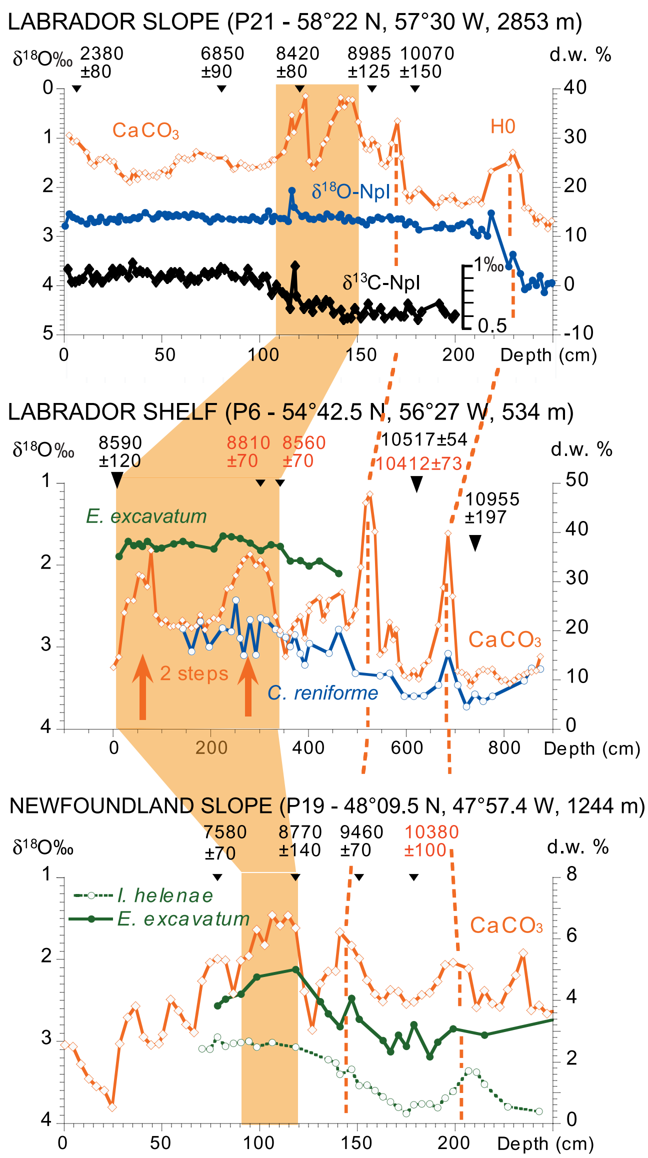
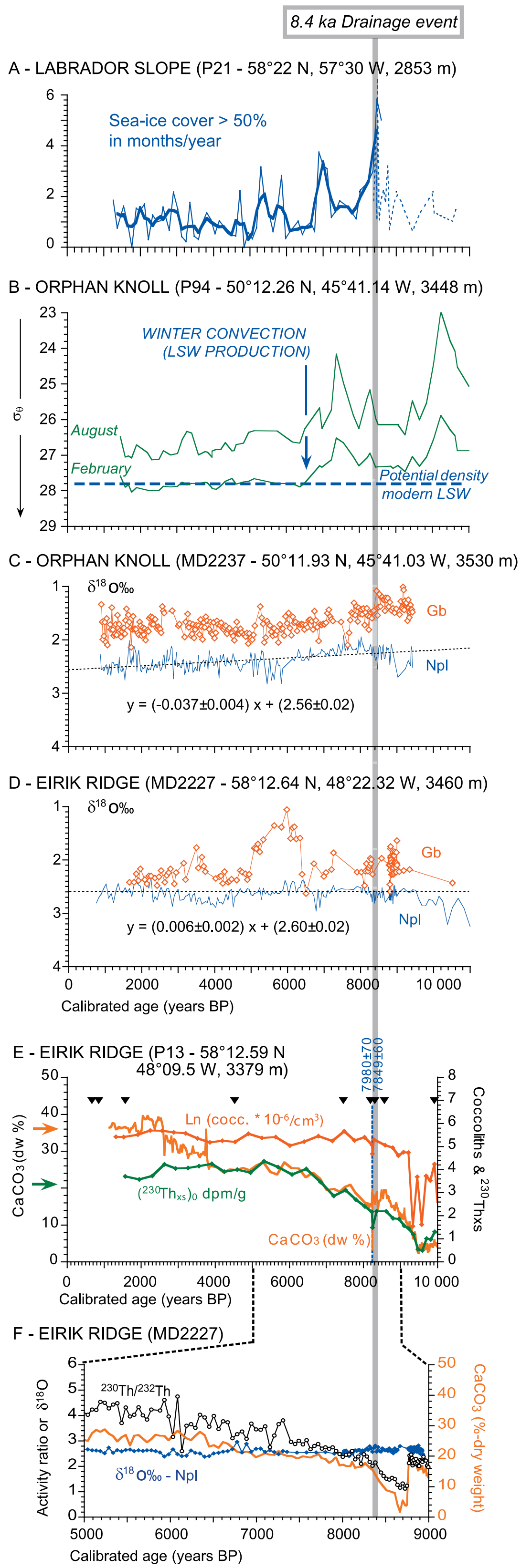


Figure 2. Sedimentary record of the Lake Agassiz drainage in sequences collected along the Labrador shelf and slope, i.e., along the shallow and deep dispersal trajectories of drainage waters into the Labrador Sea. The drainage layer, highlighted with an orange vertical stripe, consists of a characteristic twin-layer of fine detrital carbonates originating from the Hudson Strait area. Calibrated ^{14}C ages (with $\Delta R = 0$ using Calib 5.02; see auxiliary material) are from planktic foraminifers (core P21), benthic foraminifers (black numbers, either *Cassidulina reniforme* or *Islandiella helenae*) or from shells of *Portlandia arctica* (red numbers) in cores P6 and P19. In the Labrador Sea, cores are easy to correlate based on detrital carbonate layers (dashed orange lines), notably those assigned to H0 and to a more recent event (dated at ca. 9.5 ka BP), which possibly correlates with the Cockburn ice advance of the LIS over Hudson Strait [*Miller et al.*, 2005]. Glacio-marine sediments, dated at 8.6 to 8.4 ka BP in Hudson Strait cores and assigned to the "Noble Inlet" ice advance by *Jennings et al.* [1998], are possibly correlative of the drainage layer described here. The twin-carbonate peak drainage layer was rapidly deposited and age reversals are frequent, suggesting reworking of fossils from the sediment source area, in Hudson Strait and westward. Note the flat oxygen and carbon isotope profiles in foraminifers, except for a short excursion at a depth of ∼120 cm in core P21.

high sensitivity of the western flank of Eirik Ridge to minor changes in the sedimentary regime controlled by the WBUC fluctuations, and to proximal sedimentary supplies linked to ice retreat over Greenland. The drop in biogenic carbonate production and $^{230}Th_{xs}$ at about 8.8 ka is seen in many upper-rise records from deep LS below WBUC high-velocity core, notably near Orphan Knoll [e.g., *Hillaire-Marcel and Bilodeau*, 2000]. This event marks an oceanographical change, but it occurred well before the drainage of Lake Agassiz and may be related to late deglacial events involving the LIS, the Inuitian or Greenland ice sheets, or even the vanishing Scandinavian Ice Sheet.



3. Conclusion

[10] The drainage of Lake Agassiz has left a clear sedimentological signature off Hudson Strait, along the Labrador Shelf and Slope, with a double-peak, detrital carbonate-rich unit, dated within the calibrated 8.34–8.50 ka interval.This event occurred at a time when the Labrador Sea was still under deglacial influence with large amounts of freshwater released from the vanishing LIS. The event did not significantly modify surface conditions, with the possible exception of a very brief sea-ice spread off Hudson Strait. In the western North Atlantic, there is no indication of contemporary changes in the deep currents carrying the NADW masses, at the time resolution achieved here. The drainage might possibly have had a remote impact on the AMO, but linkages are unclear. Alternatively, the concomitant re-organisation of the hydrography along the northeast American margins, with a change of the main drainage pathway from the St. Lawrence River to the Hudson Strait [*St-Onge et al.*, 2003], could have played some role in the North Atlantic circulation. Moreover, the sudden dislocation of the residual LIS with a collapse of its altitude [*Dyke and Prest*, 1987] possibly led to reorganisation of atmospheric trajectories (Figure 1) and certainly

Figure 3. Selected Holocene paleoceanographic records from the Labrador Sea. (a) Sea-ice cover at site P21 off Hudson Strait estimated from dinocysts (full lines show data from the gravity core and the thick line is 3-points running average; dashed line shows data from the piston core [*de Vernal and Hillaire-Marcel*, 2006]). (b) Potential density (σ_θ) of surface waters at Orphan Knoll reconstructed from dinocyst data showing that winter convection and LSW formation likely started only at about 7 ka BP. (c, d) Selected high resolution ^{18}O records in planktic foraminifers (*Neogloboquadrina pachyderma* left-coiling, Npl; *Globigerina bulloides*, Gb) at Orphan Knoll (Figure 3c) and off southern Greenland (Figure 3d), which do not show any isotopic excursion during the drainage event (shaded stripe) from the analyses of epipelagic (Gb) and deeper dwelling (Npl) foraminifers. (e, f) Tracers of sedimentary regime changes on the Greenland Rise, below the high-velocity core of the WBUC carrying the North Atlantic Deep Water masses into their deep gyre in the Labrador Sea. In core 2237 (Figure 3f), a sharp decrease in biogenic carbonates and 230Th-excess advection is seen at ~8.8 ka BP while $\delta^{18}O$-record remains unchanged (Figure 3f). In core P13 (Figure 3e), a younger event (~8.2 ka) is recorded by a drop in biogenic carbonates and ^{230}Th-excess due to their dilution by proximal detrital sources (which incorporate reworked material as illustrated by a small ^{14}C-age reversal).

impacted the regional albedo and related feedbacks, as also suggested by isotopic records in Greenland Ice cores [*Siggaard-Andersen et al.*, 2007]. Finally, the drainage event itself and the accelerated LIS retreat recorded afterwards [*Hillaire-Marcel et al.*, 1981] resulted in fast sea-level rise, possibly coeval of the elusive Termination 1C [*Fairbanks*, 1989; *Törnqvist et al.*, 2004] that could also account for some of the paleoclimate and paleogeographical events described in literature during this episode. Thus, prior to and following the drainage event, but distinguished with difficulties from each other due to uncertainties in ^{14}C chronologies, several climatic events related to late-glacial LIS paleogeography are recorded, leading to some confusion when attempting to correlate North Atlantic paleoclimate sequences [*Rohling and Pälike*, 2004]. Because of the complexity of the ∼8.4 ka drainage event that was accompanied with major changes in orography, land surface, and hydrology at subcontinental scale, climate model simulation of the so-called 8.2 ka event should include changes in boundary conditions and initial conditions in addition to freshwater forcing. Furthermore, in view of the chronological resolution required to identify unequivocally a "8.2 ka event" from data records and because of the spatial heterogeneity of the climate and ocean responses to a given forcing, meaningful model-data comparison could only be achieved through regional scale modelling in such key areas.

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