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A 6000-year record of interaction between Hamilton Harbour and Lake Ontario: quantitative assessment of recent hydrologic disturbance using ^{13}C in lake sediment cellulose

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Abstract

Hamilton Harbour, a heavily urbanized and polluted embayment, has been selected for environmental remedy by an International Joint Commission. Ecosystem restoration efforts, however, require an understanding of harbour water balance and in particular the influence of recently enhanced exchange with the more dilute waters of Lake Ontario via the Burlington Canal. Here we provide a 6000-year quantitative reconstruction of hydrologic communication between Hamilton Harbour and Lake Ontario, based on the carbon isotope composition in the cellulose of the lake sediment, as a tracer of dissolved inorganic carbon. Results indicate that excavation of the canal has led to mixing levels 30–100% greater than the natural hydrologic state, conditions comparable to the Nipissing Flood when Upper Great Lakes drainage was diverted through Lakes Erie and Ontario roughly 5000 years ago. The effects of elevated exchange are clearly displayed by abrupt attenuation of anthropogenically driven eutrophication in the uppermost sediments from Hamilton Harbour. Thus, restoring the harbour water balance to pre-disturbance status would generate unfavourable environmental conditions in the harbour unless the effluent discharge to the harbour is eliminated entirely. © 2000 Elsevier Science Ltd and AEHMS. All rights reserved.

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1. Introduction

Urbanization over the past century has resulted in the direct discharge of untreated sewage and industrial effluent into Hamilton Harbour, a restricted embayment located at the extreme western end of Lake Ontario (Fig. 1). Hamilton Harbour is one of the most polluted sites in the Laurentian Great Lakes because of discharge of heavy metals (Nriagu et al., 1983; Poulton, 1987; Poulton et al., 1988), nutrients (OME, 1985) and organic and bacterial contaminants

(IJC, 1985; Rodgers, 1989). As a result, the harbour is the target of an intense multidisciplinary remedial action plan (Rodgers, 1989; RAP, 1989, 1991).

Effective ecosystem management in areas that have been altered by urban and industrial development, however, requires long-term data to: (1) establish reference, pre-disturbance conditions, thus providing a realistic target for restoration; (2) identify the magnitude of natural variability from which the impact of anthropogenic activities can be measured; and (3) provide an indication of possible future trends in the natural evolution of the ecosystem (Smol, 1992). The “multidisciplinary science of paleolimnology, which uses the physical, chemical, and

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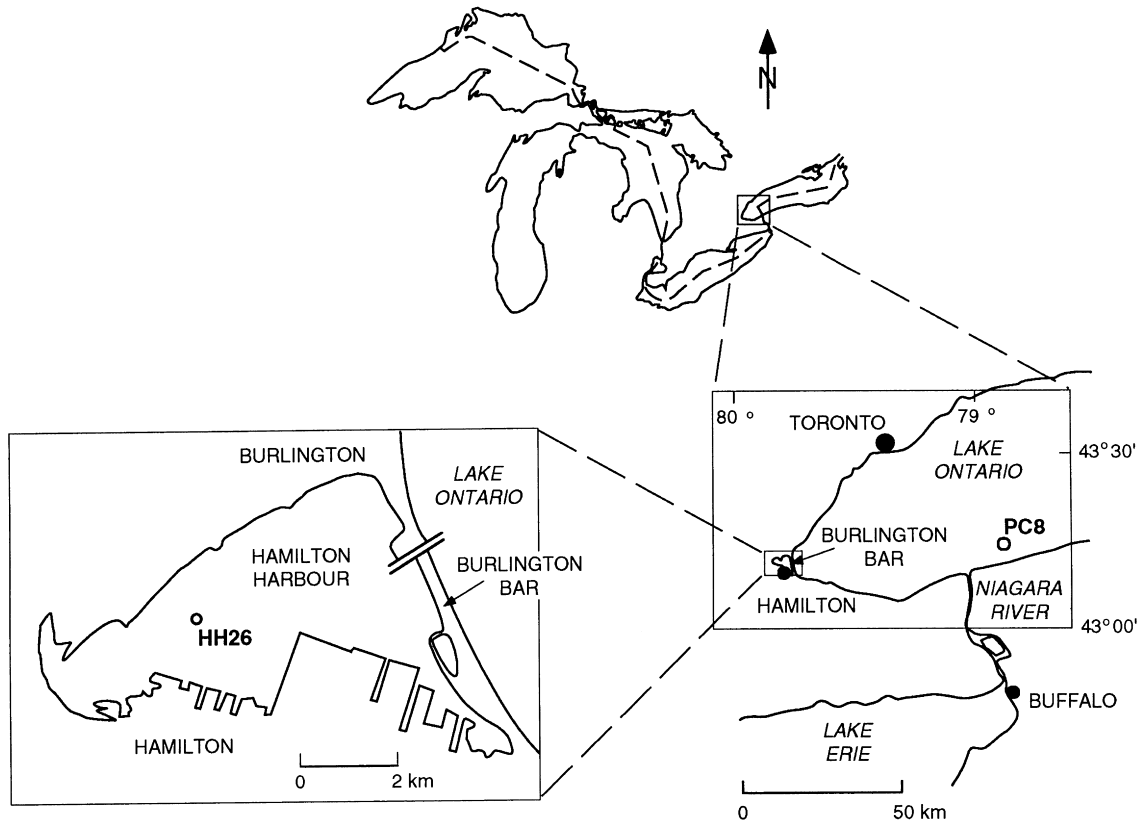


Fig. 1. Location map showing Hamilton Harbour and Lake Ontario and the respective locations of cores HH26 and PC8. Hamilton Harbour is connected with Lake Ontario by a 107 m-wide and 9.5 m-deep ship canal originally constructed in 1823 (Campbell, 1966).

biological information preserved in sedimentary profiles to reconstruct past environmental conditions” (Smol, 1995), is an effective tool for meeting these objectives (see reviews by Smol, 1992, 1995; Charles and Smol, 1994; Charles et al., 1994).

Previous paleoenvironmental investigations in Lake Ontario and Hamilton Harbour have focused mainly on reconstructing postglacial water level history (Karrow et al., 1961; Sly and Prior, 1984; Anderson and Lewis, 1985; Flint et al., 1988; McCarthy and McAndrews, 1988; Coakley and Karrow, 1994). Anderson and Lewis (1985) provided the most comprehensive compilation, based on numerous cores and radiocarbon dates, showing that water level change in Lake Ontario has been controlled largely by differential isostatic uplift of the outlet following retreat of the Laurentide Ice Sheet, punctuated by capture of Upper Great Lakes

drainage at about 5000–4000 radiocarbon years before present (5–4 ka BP).

To complement these studies, Duthie et al. (1996) undertook a multidisciplinary stratigraphic analysis of a lake sediment core to reconstruct the paleolimnology of Hamilton Harbour. Profiles of siliceous microfossils, stable isotopes, and major organic elements revealed an 8300-year chronicle of change consistent with the main elements of the Lake Ontario water level history constructed by Anderson and Lewis (1985). The two most significant limnological events during this period were the establishment of permanent connection with Lake Ontario at about 6.2 ka BP and the striking environmental degradation within the past three centuries related to human activity. The latter event was also investigated in a short-core study by Yang et al. (1993).

In spite of these efforts, only qualitative

understanding exists of the changing hydrological relationship between Hamilton Harbour and Lake Ontario over the past 6000 years or of the extent to which the hydrology has been affected by human activity (Coakley and Karrow, 1994; Duthie et al., 1996). Present-day interaction with Lake Ontario is aided by an artificially deepened ship canal through the Burlington Bar (Fig. 1) and several studies have attempted to quantify the present hydrologic exchange (e.g. Dick and Marsalek, 1973; Palmer and Poulton, 1976; Kohli, 1979; Harris et al., 1980; Klapwijk and Snodgrass, 1985; Harvey et al., 1997). Recent estimates suggest that lake inflow via the canal accounts for 72–87% of the harbour's daily water budget (Versteeg et al., 1995). Consequently, inflow from the lake plays an important role in diluting and dispersing contaminants within the harbour. Here, we compare the anthropogenically enhanced interaction that currently exists between the harbour and the lake with natural hydrologic change that has occurred during the past 6000 years. Our quantitative reconstruction is based on comparison of carbon isotope data obtained from sediment cellulose from two cores, one from within the harbour and one from offshore in Lake Ontario. Apparently, similarly high levels of hydrologic mixing have occurred in the recent geological past, driven by changes in Lake Ontario water level, but current conditions deviate profoundly from the likely natural hydrologic state.

2. Carbon isotopes in lake sediments

Recent studies suggest that the carbon-isotope composition of fine-grained cellulose ($\delta^{13}\text{C}_{\text{cell}}$, the values which represent the $^{13}\text{C}/^{12}\text{C}$ ratio (R), expressed as deviations in per mil (‰) from the PDB standard, such that $\delta^{13}\text{C}_{\text{cell}} = 1000((R_{\text{sample}}/R_{\text{PDB}}) - 1)\text{‰}$) contained within the organic fraction of lake sediments is a useful tracer of biogeochemical processes in freshwater lakes (e.g. MacDonald et al., 1993; Duthie et al., 1996; Wolfe et al., 1996, 1999). Although $\delta^{13}\text{C}$ in the bulk organic matter has also been used for paleolimnologic investigations (e.g. Oana and Deevey, 1960; Schelske and Hodell, 1991, 1995; Meyers and Horie, 1993), mixing of terrestrial and aquatic source material and changes in the relative proportion of organic constituents having

differing isotopic compositions can complicate interpretation (e.g. Spiker and Hatcher, 1984; Aravena et al., 1992). In contrast, cellulose deposited in offshore lake sediments is frequently aquatic in origin and is well-preserved, perhaps owing to rapid deposition and burial of phytoplankton in zooplankton fecal pellets with little chance for oxidation (Edwards, 1993).

The carbon isotope composition of aquatic cellulose is determined primarily by the $\delta^{13}\text{C}$ of ambient dissolved inorganic carbon (DIC), which is controlled by a number of processes including isotopic exchange with atmospheric CO_2 , input of DIC from runoff, ^{13}C -enrichment deriving from preferential uptake of ^{12}C by phytoplankton during photosynthesis and recycling of ^{13}C -depleted carbon from the decay of organic matter in the water column and bottom sediments. Changes in primary productivity are often the major cause for variation in $\delta^{13}\text{C}$ values of organic matter in sediment cores (McKenzie, 1985; Schelske and Hodell, 1991, 1995; Dean and Stuiver, 1993; Meyers et al., 1993), although alteration of the carbon balance arising from hydrologic changes may also be important (Wolfe et al., 1996, 1999).

3. Methods

Several long piston cores have been retrieved from Hamilton Harbour, all displaying similar sediment stratigraphy. Offshore sediment deposited since confluence with Lake Ontario is composed of both massive and laminated silty clay. These sediments are underlain by gyttja that accumulated in the small 'perched' lake that occupied the harbour during the early-Holocene lowstand in the Ontario basin. The present investigations are based on data obtained from core HH26, a composite core described previously by Coakley and Karrow (1994) and Duthie et al. (1996). The core was collected at a centrally located site in a water depth of 21 m (see Fig. 1).

The dominant lithology of the upper 4.92 m of Lake Ontario core PC8 is silty clay, which was deposited during the past 6 ka (Weatherly, 1993). Core PC8 was collected in 50 m depth of water off the southern shore of Lake Ontario (Fig. 1).

Cellulose was extracted from the $<150\ \mu\text{m}$ fraction of acid-washed sediment from both cores using methods similar to the wood cellulose purification

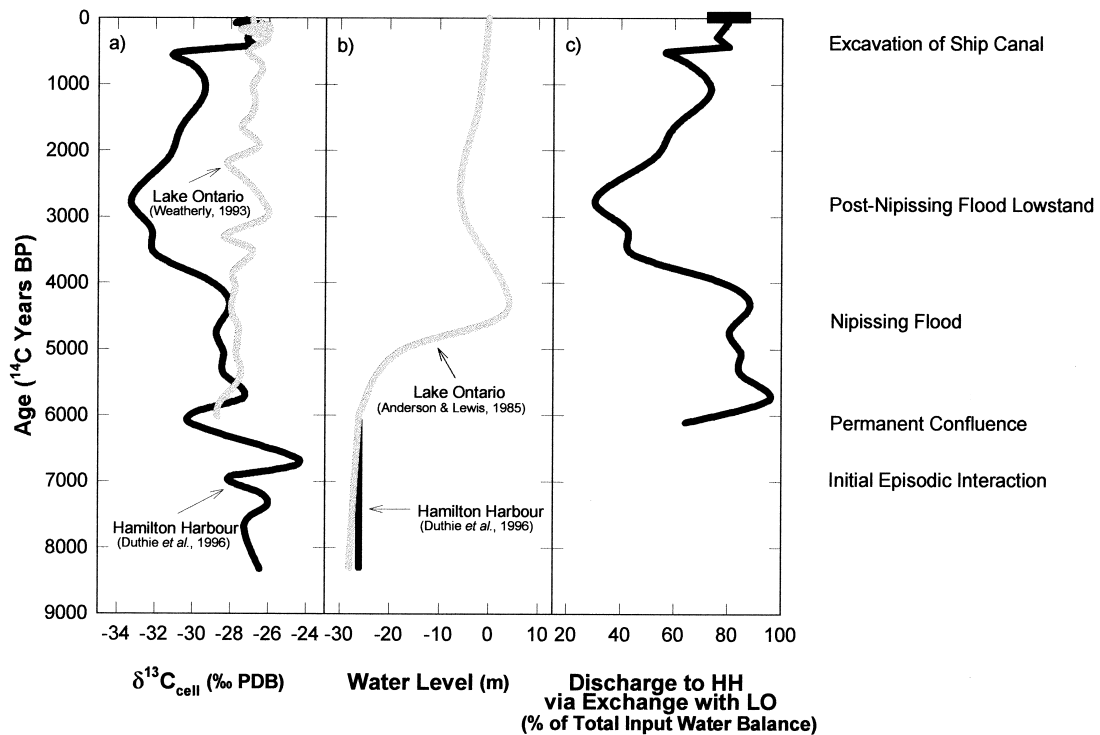


Fig. 2. (a) The $\delta^{13}\text{C}_{\text{cell}}$ records from Hamilton Harbour (Duthie et al., 1996) and Lake Ontario (Weatherly, 1993). Sediment core chronologies are based on radiocarbon dates on bulk organic matter in both cores plus correlation using ^{210}Pb dating and pollen markers in HH26 (Weatherly, 1993; Duthie et al., 1996). Influence from influx of terrestrial cellulose on the isotopic records appears to be minor in both cores, including during the period of forest clearance (Weatherly, 1993; Duthie et al., 1996). Note the historical shift in the Hamilton Harbour $\delta^{13}\text{C}_{\text{cell}}$ record that appears to occur at about 500 BP is likely an artifact of poor dating control in this part of the core and more likely corresponds to the initial effects of cultural eutrophication in the latter part of the 1700s; (b) Sketch of Lake Ontario and Hamilton Harbour Holocene lake level history (from Anderson and Lewis, 1985; Duthie et al., 1996); (c) Inferred discharge of water to Hamilton Harbour (HH) via exchange with Lake Ontario (LO), 6–0 ka BP, expressed in percentage relative to total input water balance. See text for explanation.

procedure of Green (1963). Carbon isotope ratio determination was performed on CO_2 gas prepared by conventional closed-tube combustion (Boutton, 1991) at the Environmental Isotope Laboratory, University of Waterloo. Analytical uncertainties are $\pm 0.3\text{‰}$ based on repeated analyses of natural samples.

4. Data and discussion

Fig. 2a shows the $\delta^{13}\text{C}_{\text{cell}}$ profile from core HH26 (Duthie et al., 1996) compared with the $\delta^{13}\text{C}_{\text{cell}}$ profile from core PC8 (Weatherly, 1993). The profiles reveal similar $\delta^{13}\text{C}$ values ca. 6–4 ka BP and over the past few hundred years, but diverge markedly in the

intervening period. Lake Ontario $\delta^{13}\text{C}_{\text{cell}}$ exhibits rather consistent values in the range -28 to -26‰ , whereas Hamilton Harbour $\delta^{13}\text{C}_{\text{cell}}$ becomes substantially more negative from about 4 ka BP, with values as low as -33‰ near 3 ka BP. As noted by Weatherly (1993), the inferred $\delta^{13}\text{C}$ of DIC ($\delta^{13}\text{C}_{\text{DIC}}$) in Lake Ontario has changed little over the past 6000 years, in contrast to widely varying inferred $\delta^{13}\text{C}_{\text{DIC}}$ in the waters of Hamilton Harbour.

Since the confluence was established with Lake Ontario at 6.2 ka BP, variations in the water level in Hamilton Harbour have been coupled directly to those in the lake (Duthie et al., 1996; see Fig. 2b). As noted above, long-term shifts in lake level are controlled by gradual isostatic rebound of the outlet to the Saint Lawrence River in the east, which is rising faster

than the western end of the lake basin. Superimposed on this monotonic rise was the Nipissing Flood, an episode of elevated water levels spanning about 5–4 ka BP, associated with major readjustment of the water balance of Lake Ontario, resulting from re-routing of drainage from the Upper Great Lakes as a consequence of differential isostatic uplift of Lake Huron outlets (Anderson and Lewis, 1985). Because of the relatively restricted channel connecting the harbour and the lake, these changes in water level must have strongly influenced the degree of inflow from Lake Ontario to the harbour. Indeed, Duthie et al. (1996) addressed this issue qualitatively by considering microfossil and geochemical data from core HH26. For example, the initial transitory connection with Lake Ontario at about 7 ka BP was inferred from a sharp rise in the abundance of euplanktonic diatoms in Hamilton Harbour and a shift in the inferred oxygen isotope composition of the harbour water. Subsequent changes in microfossil assemblages and the relation between the carbon isotope compositions of bulk organic matter and cellulose were used as indicators of limnologic changes likely related to the shifting hydrologic balance of the harbour. However, the carbon isotope profiles shown in Fig. 2a suggest that these data can also support a more direct, quantitative assessment of the varying degree of Lake Ontario inflow to Hamilton Harbour, based on the use of $\delta^{13}\text{C}_{\text{cell}}$ as a tracer for $\delta^{13}\text{C}_{\text{DIC}}$.

The $\delta^{13}\text{C}_{\text{DIC}}$ of surface waters in the Laurentian Great Lakes is mainly controlled by CO_2 exchange with the atmosphere, which provides a ^{13}C -enriched source of CO_2 to the DIC pool (Weiler and Nriagu, 1978; Yang et al., 1996). Lake Ontario $\delta^{13}\text{C}_{\text{DIC}}$ is typically about -1‰ , which is slightly more negative than expected for complete isotopic equilibrium with the atmosphere (ca. $+2.5\text{‰}$), because catchment-derived runoff contributes ^{13}C -depleted CO_2 (Weiler and Nriagu, 1978). The balance of these two main carbon pathways in Lake Ontario waters, though strongly weighted to the former, appears to have been relatively constant over the past 6000 years judging by the $\delta^{13}\text{C}_{\text{cell}}$ record from core PC8 (Fig. 2a).

In contrast, a more complex record of carbon dynamics is suggested by changes in the $\delta^{13}\text{C}_{\text{cell}}$ profile from the Hamilton Harbour sediment core. In addition to CO_2 exchange with the atmosphere and catchment-derived runoff, additional important

controls on the $\delta^{13}\text{C}_{\text{cell}}$ record from Hamilton Harbour include biological effects of varying primary productivity and inflow DIC from Lake Ontario. For instance, between 8.3 and 7.0 ka BP, high $\delta^{13}\text{C}_{\text{cell}}$ values may be due to productivity-driven ^{13}C -enrichment of DIC, an interpretation consistent with conditions in the shallow, mesotrophic water body that existed during this time (Yang, 1994; Duthie et al., 1996). The marked $\delta^{13}\text{C}_{\text{cell}}$ oscillations between 7.0 and 6.2 ka BP probably reflect the episodic interaction with the lake and environmental variability suggested by microfossil evidence, prior to the establishment of more hydrologically stable conditions after permanent confluence with Lake Ontario. Most of the variation over the past 6000 years, however, can be explained by straightforward mixing between ^{13}C -depleted DIC from local runoff and ^{13}C -enriched DIC from Lake Ontario, driven by water level fluctuations.

Thus, the occurrence of similar $\delta^{13}\text{C}_{\text{cell}}$ values for both Hamilton Harbour and Lake Ontario ca. 6–4 ka BP corresponds to the period of progressively rising lake level before and during the Nipissing Flood, when DIC from Lake Ontario was the dominant influence. Subsequent departure of Hamilton Harbour $\delta^{13}\text{C}_{\text{cell}}$ to more negative values as water levels declined following the Nipissing Flood is consistent with decreasing importance of ^{13}C -enriched DIC from the lake, with this trend reversing after about 3 ka BP, as water levels again began to rise. An intriguing feature of the HH26 record is the sharp curtailment of the 4‰ increase in $\delta^{13}\text{C}_{\text{cell}}$ associated with the onset of human disturbance of the harbour. This positive shift most likely reflects intense productivity-driven ^{13}C -enrichment of DIC in the harbour water owing to eutrophication (Duthie et al., 1996; see also Schelske and Hodell, 1991), abruptly cut off by the increased degree of exchange with the more dilute waters of Lake Ontario upon excavation of the ship canal.

This conceptual model can be readily transformed into a quantitative description of the changing hydrologic interaction between Hamilton Harbour and Lake Ontario, based on simple two-component mixing between the main sources of DIC. As mentioned above, $\delta^{13}\text{C}_{\text{DIC}}$ of modern surface waters in Lake Ontario averages about -1‰ and the $\delta^{13}\text{C}_{\text{DIC}}$ record from core PC8 suggests that this is a good approximation for the past as well. Based on modern isotopic

measurements of DIC in streams in southwestern Ontario (Yang et al., 1996), a $\delta^{13}\text{C}_{\text{DIC}}$ value of -10‰ is a reasonable estimate for catchment runoff. Hence, assuming only minor influence from productivity-driven ^{13}C -enrichment (and other confounding factors), aquatic cellulose in Hamilton Harbour sediments can be expected to show $\delta^{13}\text{C}$ variations inherited from DIC within a maximum range of about 9‰ , potentially spanning 0–100% inflow from Lake Ontario. This mass balance model can be roughly calibrated using the range of modern lake inflow percentage to the harbour reported by Versteeg et al. (1995) to transform the $\delta^{13}\text{C}_{\text{cell}}$ record from HH26 into a quantitative characterization of inferred past changes in Lake Ontario influence on harbour water balance, yielding the curve shown in Fig. 2c.

Although substantial uncertainties (conservatively, of the order of $\pm 10\text{--}20\%$) surround this inferred record, it suggests that inflow from the Lake Ontario to Hamilton Harbour during the peak of the Nipissing Flood were likely similar to those that are now artificially maintained, and two- to three-fold greater than the minimum reached around 2.8 ka BP during the post-Nipissing Flood lowstand. Inflow from the lake to the harbour was apparently declining perhaps toward an ultimate level only half to two-thirds that of the present-day, when human activity began to affect the water balance.

5. Implications and conclusions

Carbon isotope data from the lake sediment cellulose has provided the basis for a 6000-year quantitative reconstruction of changing Lake Ontario influence on Hamilton Harbour. These data show unequivocally the existence of considerable anthropogenic perturbation of the harbour water and carbon balance. While this is clearly not unexpected, given the abundant evidence from other paleolimnological indicators and historical and observational records, the isotopic data also provide a quantitative guide to the magnitude of these effects in relation to the probable natural state of the harbour in the absence of human influence. Interestingly, our results emphasize that artificial alteration of the water balance in the harbour by the excavation of the ship canal helped to mitigate (perhaps inadvertently) the effects of the

initial cultural eutrophication of the harbour, by enhancing exchange with Lake Ontario. An important implication of this observation is that restoration of the natural hydrologic balance of Hamilton Harbour would clearly not be a particularly desirable goal unless coupled with complete elimination of effluent discharge. These investigations, built on the foundation provided by Duthie et al. (1996), have reinforced the value of using a multidisciplinary paleolimnological approach to reconstruct long-term environmental history, as an aid in distinguishing the impacts of natural and anthropogenic ecosystem change. This is especially important in the Laurentian Great Lakes because of the dynamic nature of hydrologic change in this recently glaciated region. Incorporation of isotopic tracers has proven to be particularly useful in these studies, providing access to quantitative information not readily available from other data.

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