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Cave ice – the imminent loss of untapped mid-latitude cryospheric palaeoenvironmental archives

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Abstract: Cave hosted ice bodies have been reported to suffer significant mass loss worldwide. Although some successful achievements were reported recently to confirm the potential of stable isotope, pollen or trace element records in cave glaciers for climate and environmental reconstructions, these archives are still weakly studied. This brief paper is to be an invitation to the geoscience community to face this research need and devote more scientific attention to the complex research of cave ice deposits before accelerated melt will determine the complete loss of the unique palaeoenvironmental information stored in these deposits.

Key words: cryosphere, ice cave, ice loss, palaeoclimate

1. Introduction

Ice and snow in the seas, and above and below ground are collectively known as the cryosphere. It is almost a scientifically commonplace conclusion that the cryosphere is generally receding under recent climatic changes. Shrinking glaciers, decreasing sea ice extent and volume, and thawing permafrost are well known and frequently quoted evidence for this process in the scientific literature (Lemke et al., 2007, UNEP, 2007, Zemp et al., 2008) and public media.

Ice caves are lesser-known members of the cryosphere. An ice cave is a cave formed in bedrock which contains perennial accumulations of water in its solid phase (i.e., ice and snow) (Perşoiu and Onac, 2012). The ice masses primarily concerned here are those which accumulate in a cave entrance zone that functions as a physically closed depression acting as a 'cold sock' (sensu Wigley and Brown, 1976). Perennial ice accumulation in these caves can result from the diagenesis of snow accumulated during the winter season and/or from the freezing of infiltration water (congelation ice). The traditional nomenclature (Balch, 1900) refers to them as 'glacières'. Need to be emphasised that these deposits are distinct from the exceptional occurrence of relict ice masses originating from the surface (e.g., Coulthard Cave in the Canadian Rockies; see Marshall and Brown, 1974).

All ice caves together represent the smallest portion of the terrestrial cryosphere; the largest cave ice bodies barely exceeding 100,000 m^3. One might speculate that their minority status, compared to the enormous polar ice sheets and permafrost areas, condemns cave ice to negligence, or maybe that scientists involved in their study, both speleologists and glaciologists, regard cave ice as a “stepchild” in their discipline. For speleologists, calcareous speleothems are respected as valuable scientific targets for research, while ice is often seen as an annoying slippery decoration that should be avoided. For glaciologists, descending deeply into a dark abyss makes most of them shiver. Whatever the reason, the result is that the research effort dedicated to cave ice to date is very modest. Concluding sentence from Henderson (2006) perfectly mirrors the status quo: “For palaeoclimate, the past two decades have been the age of the ice core. The next two may be the age of the speleothem.” But what about ice cores from ice speleothems? Our aim is to give a brief but comprehensive literature review about main recent achievements from cave ice analysis, the foreseeable further contribution to mid-latitude environmental histories and to call the attention on how the recent and globally reported ice mass loss threatens these practically unexploited archives.

2. The potential of cave ice in palaeoenvironmetal studies

Ice caves can be found all around the world (Perşoiu and Onac, 2012). They usually occur at lower elevations than mountain glaciers, and generally in areas where surface glaciation is missing altogether. It means that such perennial ice masses can accumulate far outside of the boundaries of the conventional permafrost climatic zone which makes them especially vulnerable to any warming trend.

Based on the slowly increasing number of numerical age estimates ranging from centennial (Luetscher et al., 2007, Kern et al., 2009, Lauritzen et al., 2010, Hercman et al., 2010) to millennial (Citterio et al., 2005, Perşoiu and Pazdur, 2011, Belmonte Ribas et al., 2012) time-scales although regularly some degree of hiata are undeniably interspersed in their stratigraphic record.

Once it forms, cave ice preserves the frozen information with the same fidelity as aboveground ice bodies; it has the potential to be an useful complementary alternative to mid- and low-latitude glaciers in deciphering comparable palaeoenvironmental information (for a detailed review about Alpine ice cores see Schwikowski and Eichler, 2010), especially over the historical times. The potential suitability of the cave ice deposits for palaeo studies stems from two specialities. Firstly, as mentioned above, ice caves occur generally in areas where surface glaciation is missing; consequently cave ice is the only available cryospheric archive. Secondly, they can contribute some useful complementary information in those mid-latitude regions where ‘classical’ alpine ice cores are available. Thus at the typical altitude of Alpine glaciers, air masses from the polluted boundary layer are diluted with cleaner free tropospheric air (Schwikowski and Eichler, 2010). Air quality monitoring results also pointed out that mountain stations standing above the mixing boundary layer are practically decoupled from the pollution sources situating at the lowlands during winter conditions (Gehrig and Buchmann, 2003, Emili et al., 2011). Therefore in the winter season the high elevation belt, inevitably including the ‘classical’ ice core drill sites, cannot record the atmospheric conditions prevailing below the boundary layer, whereas the low elevation ice cave sites have better chance to record the polluted near-surface conditions. In this situation one can expect that cave ice derived pollution records provide a complementary data to the dominantly large-scale pollution history preserved and obtained from classical ice cores extracted from the cold firn zone of the alpine glaciers.

Exploring the extent to which such underground frozen water archives might hold past environmental and climate information is an open issue, but studies have intensified in the recent past (Laursen, 2010).

Stable isotopes are the most intensively studied parameters from cave ice profiles (Fórizs et al., 2004, Luetscher et al., 2007, Perşoiu et al., 2007, 2011, Kern et al., 2009, 2011a, May et al., 2011). Kinetic fractionation definitely acts during ice formation from liquid water (Jouzel and Souchez, 1982), hence the stable isotopic composition of cave ice is shifted from the original composition of the parent water and thus lay a certain degree of uncertainty on its use as a palaeoclimatic indicator. However, recent investigations managed to reconstruct the original composition of water before freezing (Perşoiu et al., 2011) and this innovative method could be adopted for other ice caves where annual ice layers develop by the freezing of seepage water.

The glaciochemical signal in cave ice deposits is almost completely unexplored. Only a handful of studies have investigated the chemistry of cave ice profiles (Citterio et al., 2004, Claussen et al., 2007) and have shown that particular trace elements have the potential to preserve the history of aboveground atmospheric composition (Kern et al. 2011b). Consequently, where these ice bodies are situated much closer to inhabited and industrialized regions and exposed more directly to local-scale historical anthropogenic pollutant emissions, compared to high-latitude or high-elevation glaciated areas, they could offer one of the best sources of information on palaeo-air pollution.

Fossil remains can also be excavated from cave ice deposits. The earliest palaeoenvironmental study based on cave ice samples targeted just pollen grains from two Romanian ice caves (Pop and Ciobanu, 1950). This pioneering work lacked independent age estimates, so a recent reinvestigation was conducted on one of the studied profiles, refuting the former putative age estimate owing to the solid support of numerical radiocarbon data (Feurdean et al., 2011). However, the reinvestigation validated the early observations on the excellent preservation of plant microfossils in the ice and the collected data (floristic micro- macrofossils, micro- and macrocharcoal) provided an accurate picture with very high temporal resolution of the vegetation dynamics of the past 1000 years at both local and regional scale, with a clear signals of human impact (Feurdean et al., 2011).

In another study, cave ice accumulation rates, determined by dating the intercalated plant macrofossils by means of radiocarbon and dendrochronological methods, provided a clear link between underground ice accumulation and large-scale atmospheric dynamics (Stoffel et al., 2009).

These examples demonstrate that this field has moved beyond ‘potential’ use to actual application.

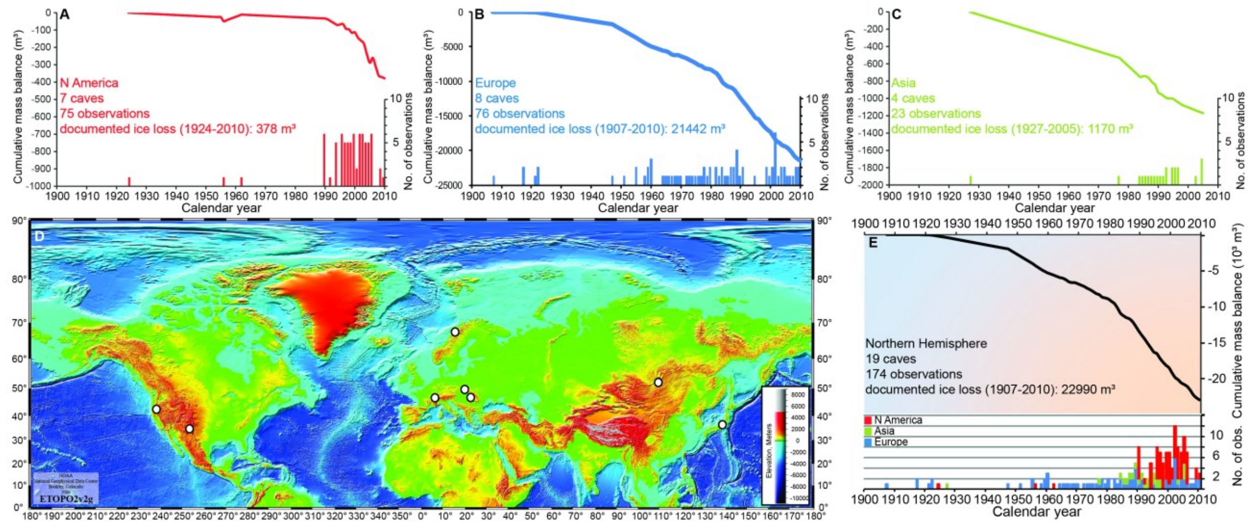

Fig. 1. Decline in ice volume of Northern Hemispheric perennial cave ice deposits. Upper plots show the cave ice history for the three continents: North America (A), Europe (B) and Asia (C). Circles indicate corresponding ice cave locations in the hemispheric relief topography (D). The hemispheric sum for cumulated mass balance and observation records are shown with colored background (E). Curves display the ice mass balance record and bar charts show the observations in each graph.

3. Melting ice is a hot question

Present-day climatic changes are deteriorating the stability of conditions for underground as well as surface glaciers. These underground ice bodies have been documented to suffer significant mass loss worldwide. Historical ice volume information has been collected by a comprehensive literature survey from 19 perennial ice caves of the Northern Hemisphere's mid-latitudes. Records are detailed in the Appendix. The first ice cave records that offer potential volume references date back as early as 1907 in Europe, 1924 in North America, and 1927 in Asia. All but one of the available multidecadal cave ice volume histories shows a steady decreasing trend (Fig. A1). Historical ice volume information summarized for 19 perennial ice caves of three continents of the Northern Hemisphere documented ca. 23,000 m^3 cave ice loss until 2010 (Fig. 1). In comparison with the present-day loss rates of surface ice, this value for cave ice loss seems to be extremely small if not negligible. However, this means ~15% when we compare the lost ice volume to the earliest total ice mass of those caves where ice volume estimates are available (Tab.S1).

This widely observed ice degradation process seriously threatens cave ice deposits by total melting of the perennial ice, as has already been reported from some former ice caves (e.g. Luetscher et al. 2005, Trofimova, 2007, Behm et al., 2009). However, non-complete melting also causes serious problems. In the case of Scărişoara Ice Cave, for instance, the ice loss at the surface (thus mainly due to climatic changes) might look small (~3.34%) compared to the total estimated volume of ice (~100,000 m^3, Holmlund et al., 2005), but important is the fact that this volume translates in more than 1 meter of ice, which corresponds to some 150 years of ice accumulation (Perşoiu, 2011), thus making impossible to calibrate any potential palaeoclimatic signal recorded in the ice against the instrumental record. This example nicely illustrates that multidecadal ablation leads to the loss of significant ice-stored environmental history. As this multiannual negative mass balance severely affects the most recent, uppermost part of the ice sequence, deposited during times when advanced instrumental climate and air quality datasets provide opportunities for direct calibration of the preserved cave ice environmental signal, the possibility to quantitatively deduce climate and environmental reconstructions of past conditions could irreversibly be lost.

4. Conclusion

A strong research effort is needed to exploit the available physical, chemical, isotopic and biological records from the untapped cryospheric archives known as 'ice caves'. Due to the extremely special character of these deposits, interdisciplinary cooperation between experts from various disciplines of the Earth sciences (e.g. speleologists, geophysicists, and glaciologists) is necessary not only to interpret research results but also to conduct additional field work. It is important to face this research need and devote more scientific attention to the complex study of cave ice, in order to read and rescue the endangered and untapped palaeoenvironmental information stored in these deposits.

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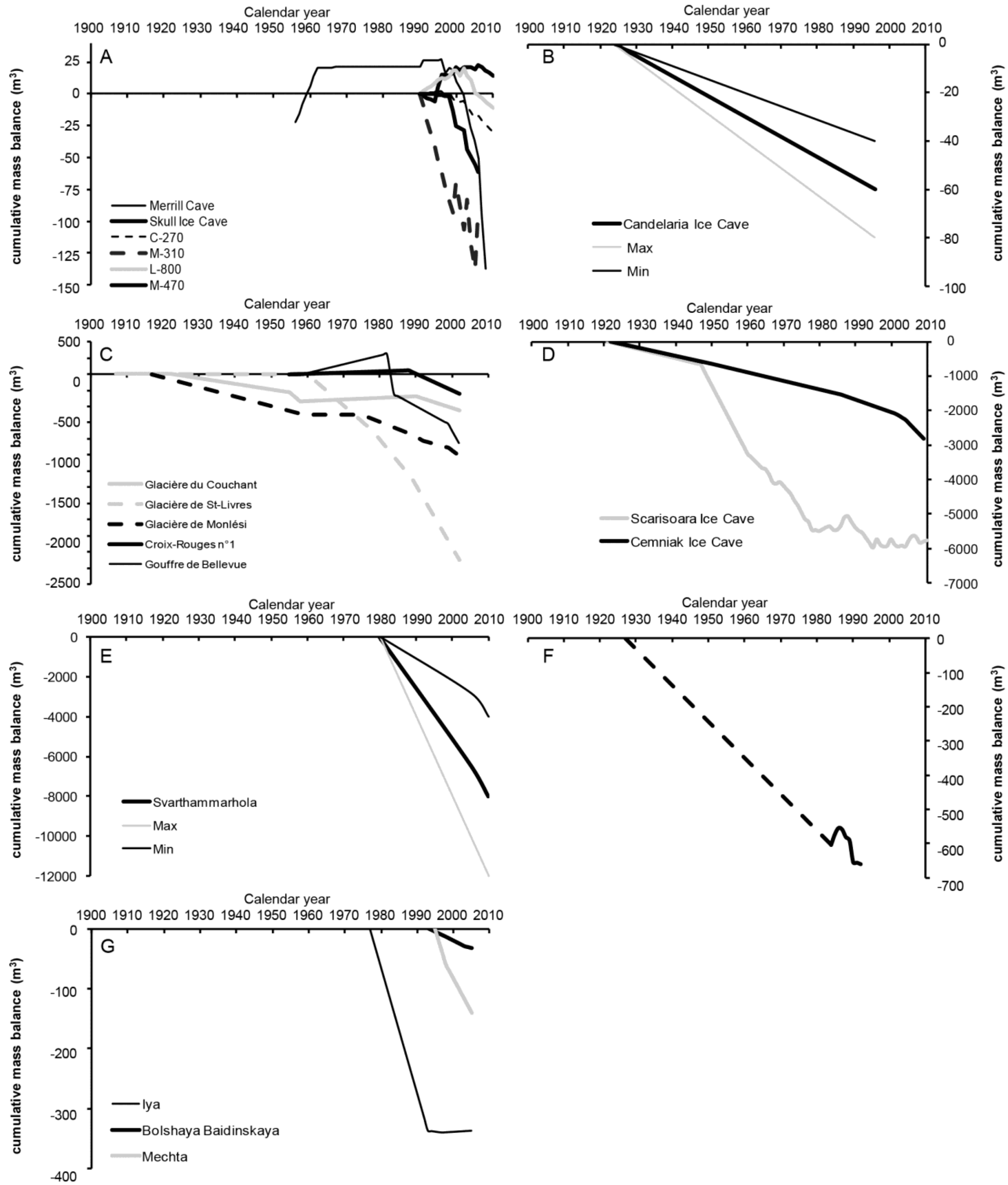

Fig. A.1. Ice volume evolution of the 19 Northern Hemispheric mid-latitude caves. Lava Beds (A), Candelaria Ice Cave (B), Swiss Jura Mts. (C), Carpathians (D), Svarthammarhola (E), Fuji Wind Cave (F) and Baikal Area (G) Note the different vertical scales!

Appendix

To avoid any potential bias due to seasonal cave ice occurrence, only caves with more than 10 years of documented ice cover were regarded. As a conservative approach, ice volume was assumed to change with a constant linear rate between reference dates.

The southernmost cave in this collection is Candelaria IC, New Mexico, USA (34.98°N, Dickfoss, 1996) while the northernmost is Svarthammarhola, Norway (67.20°N, Lauritzen et al., 2010). For details see Tab. S1. The earliest reference datum dates back to 1907 from the Glacière du Couchant, Swiss Jura (Luetscher et al., 2005). We were also aware of methodological biases. Those caves where serious risk could be suspected that the real ice volume change between certain periods is overwhelmed by the improved precision of ice volume estimates owing to some technical advance or some cave management intervention are not included in this compilation. These are the reasons why the famous Eisriesenwelt, Dobsina IC and Kungur IC, for instance, are disregarded in this collection. Altogether, 174 cave ice observations were collected. The records allow a first preliminary evaluation of the regional and global cave ice history over the last ca. 100 yrs.

North America

Lava Beds National Monument, California, USA

Intensive monitoring of cave ice levels started in 1990 in Lava Beds. Based on multiple observations available from numerous ice caves in the area, the usual ice phenology of the region can be characterized by March-May high stands and November low stands. To eliminate the seasonal ice level changes and emphasize the long-term ice evolution trend, only late autumnal ice level records were used in our calculations (Fig. A1a). Six caves had observation histories longer than 10 years for late autumn ice levels. To estimate ice volume changes from these ice level records, ice covered areas were measured on cave maps.

Historical ice level changes can be extended back to 1956 at Merrill IC by ice level estimations based on stratigraphic (Sowers and Devereaux, 2000) and archival photographic (Fuhrmann, 2007) records.

It is important to note the exceptional behaviour of Skull IC. Intra-annual ice level changes do not show any characteristic seasonal cycle in this cave, however, the really odd character is that this is the only cave where multidecadal cumulated ice mass balance is positive out of the 18 studied ice caves distributed over the Northern Hemisphere.

Candelaria Ice Cave, New Mexico, USA

Dickfoss (1996) estimated minimum/maximum ice volume for Candelaria IC for 1924 and 1996 as 130/363 m^3 and 90/283 m^3, respectively. Although the total ice volume estimation shows a large uncertainty, the ice volume changes derived from either minimum or maximum volumetric approximations – 40-80 m^3 – agree fairly well between them. We used the mean value, 60 m^3, for calculations (Fig. A1b).

Europe

Swiss Jura Mts.

Historical ice volume estimations are available from five caves (Luetscher et al., 2005). To eliminate uncertainties in total ice volume, estimations arose from missing knowledge on below ice topography; ice volume differences were calculated from the original ice volume data (Fig. A1c).

Ciemniak Ice Cave (Ladowa Jaskinia w Ciemniaku), Poland

The earliest cave map sufficiently detailed for ice volume estimation is available from 1922 from Ciemniak IC (Rygielski et al., 1995). Historical ice volume estimations calculated by Rachlewicz and Szczucinski (2004), updated recently by Szukała (2010), were used to represent the long-term ice volume evolution of this Carpathian ice cave (Fig. A1d).

Scărişoara Ice Cave (Gheţarul de la Scărişoara), Romania

The first scientific visit to Scărişoara IC occurred as early as 1857, while the first intensive studies begun in 1921 (Racoviţă, 1927). Since 1963, the ice level changes were monitored on a monthly basis, during three intervals (1963 – 1968, 1982 – 1992, 2001 – 2012) (Racoviţă, 1994, Perşoiu and Pazdur, 2011). The ice surface lowered by 75 cm between 1947 and 1960, and 100 cm between 1960 and 2012 (Şerban et al., 1967, Perşoiu and Pazdur, 2011). A figure which, correlated with the above information gives a total lowering of the surface of the ice block of about 78 cm between 1947 and 2012. The upper face of the ice block is estimated to be 3000 m^2, which gives a total ice mass loss, at the surface of the ice block, of about 2340 m^3. Further, a third of the upper face of the block lost another 100 cm of ice between 1921 and 1960 (Şerban et al., 1967), which adds another ~1000 m^3 to the total ice loss, raising the figure to ~3340 m^3. Between 1947 and 2012, basal melting resulting in the loss of an additional ~2900 m^3 of ice (Fig. A1d).

Svarthammarhola, Norway

The ice floor surface area is 4000 m^2. There are clear evidence that 30-50 cm have been lost from the top surface since 2005, and paintmarks suggest that a total of 1-3 m might have been lost since about 1980 (Laurizten et al., 2010). We used the mean value, for calculations (Fig. A1e).The total volume is not far from 20,000 m^3 but very uncertain as the ice deposit has basically a wedge shape that drapes over a slope (Lauritzen, pers. com.).

Asia

Fuji Wind Cave (Fuji Fuketsu), Japan

To calculate the annual ice volume changes for Fuji Wind cave, the annual mean net balance data have been used from 1986 to 1992 (Tab. 2 in (Ohata et al., 1994)). Considering that the area of the main floor ice was 1100 m^2 in 1986, and decreased by ca. 5% (about 1045 m^2) by 1992 (Ohata et al., 1994), a constant linear decrease was presumed for the ice covered area between 1986 and 1992 and increased at the same rate between 1984 and 86.

Historical ice level changes can be extended to 1927. Considering that Ohata et al. (1994) stated (based on historical cave photographs) that the difference in ice level between 1927 and the latter half of 1980s is probably less than 1 m, we assumed that the 1927 ice level was 0.5 m higher than the mid-1980s ice level maximum. A minor increase of the ice covered area (1110 m^2) was also assumed to have been accompanied by higher ice levels; however, it must be emphasized that this is probably a very conservative estimate as the assumed 10 m^2 aggradation is hardly more than the annual areal decrease computed above for the 1986–1992 period (9.17 m^2/a). To visualize the uncertainty (underestimated ice loss) of the pre-1984 period, the estimated ice loss trend is shown as dashed line (Fig. A1f).

Baikal Region, Russia

Although earliest report on cave glaciation dates back to 1927 in the Baikal Region, the first qualitative historical cave ice data are available only from 1977 and ice volume estimates were available for four caves (Trofimova, 2006, 2007). Three of them provided a longer history than the applied 10 year-long threshold (Fig. A1g).

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