Seasonal Laurentide Ice Sheet melting during the "Mystery Interval" (17.5–14.5 ka)

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ABSTRACT

The last deglaciation in the Northern Hemisphere was interrupted by two major stadials, the so-called "Mystery Interval" (17.5–14.5 ka) and the Younger Dryas (12.9–11.7 ka). During these events, the North Atlantic region was marked by cold surface conditions, yet simultaneous glacier and snowline retreat. Rerouting of Laurentide Ice Sheet meltwater from the Gulf of Mexico to an eastern or northern spillway may have reduced meridional overturning circulation at the onset of the Younger Dryas. However, this hypothesis has not been tested for the Mystery Interval. Paired Mg/Ca and δ^{18}O measurements on foraminifera from laminated Orca Basin sediments in the Gulf of Mexico, constrained by 35 ^{14}C dates, document the timing of meltwater input with subcentennial resolution. Isolating the δ^{18}O of seawater (termed $\delta^{18}O_{GOM}$) reveals three major melting episodes from ca. 17.5 ka until 12.9 ka, followed by a rapid cessation, consistent with meltwater rerouting at the onset of the Younger Dryas. Conversely, inferred meltwater flow to the Gulf of Mexico during the Mystery Interval does not support a simple routing event, but is consistent with glacier and snowline retreat. We suggest that summer melting of Northern Hemisphere ice sheets during this stadial may have been an important mechanism for enhanced winter sea-ice formation, hypercold winter conditions, and enhanced seasonality in the North Atlantic region.

INTRODUCTION

One of the puzzling features of the last deglacial sequence is evidence for low δ^{18}O values in Greenland ice core records during Heinrich stadial 1 (17.5–14.5 ka) that suggest mean annual air temperatures colder than Last Glacial Maximum conditions (Rasmussen et al., 2006), despite simultaneous snowline retreat and major mountain glacier recession recorded in East Greenland, northern Europe, and North America. During this interval, Atlantic sea-surface temperatures (SSTs) exhibited extreme cooling (Bond et al., 1992; Bard et al., 2000) and meridional overturning circulation (MOC) was significantly reduced (McManus et al., 2004). In addition, high concentrations of ice-rafted debris found in northern North Atlantic sediments mark a rapid ice-calving event known as Heinrich Event 1 (H1) (centered ca. 16.8 ka) (Bond et al., 1992; Hemming, 2004).

However, atmospheric CO_2 and eustatic sea-level rise indicate deglacial warming throughout this interval (Fairbanks, 1989; Monnin et al., 2001). Modeling studies and continental proxy data, including temperature reconstructions inferred from fossilized beetle assemblages in the British Isles, suggest extreme seasonal conditions in northwest Europe that also included moderate summers (Atkinson et al., 1987; Renssen and Isarin, 2001). The abundance of seemingly contradictory climate records from the North Atlantic region may be reconciled by inferring that reduced mean annual temperatures were primarily driven by hypercold winter conditions and winter sea-ice formation, resulting in enhanced seasonality during what is often referred to as the "Mystery Interval" (17.5–14.5 ka) (e.g., Denton et al., 2005).

Previous research suggests that a decrease in MOC may be linked to a switch in Laurentide Ice Sheet (LIS) meltwater flow from the southern outlet through the Mississippi River system to an eastern or northern location into the North Atlantic and/or Arctic Oceans at the onset of abrupt cold events (Broecker et al., 1989; Clark et al., 2001; Tarasov and Peltier, 2005). This hypothesis raises the questions, to what degree was the LIS retreating during the Mystery Interval, and was the Mystery Interval caused by a switch in meltwater routing, as postulated for the Younger Dryas?

Deglacial LIS meltwater has been documented in the Gulf of Mexico as negative foraminiferal δ^{18}O excursions. *Globigerinoides sacculifer* from deep-sea sediment cores recovered in the western Gulf of Mexico exhibit low δ^{18}O values (<–2‰) during the Bølling-Allerød (Kennett and Shackleton, 1975). *G. ruber* (white) δ^{18}O data from the Orca Basin in the northern Gulf of Mexico (core EN32-PC6) closer to the Mississippi River outflow also revealed multiple negative excursions (Leventer et al., 1982). Paired Mg/Ca and δ^{18}O values from core EN32-PC6 exhibited anomalously low δ^{18}O of seawater ($\delta^{18}O_{SW}$) values suggesting glacial meltwater flow until the onset of the Younger Dryas (Flower et al., 2004). Negative δ^{18}O excursions in benthic and deep-dwelling planktic foraminifers from the upper Louisiana slope also support meltwater input to the Gulf of Mexico near the onset of the Bølling-Allerød in the form of hyperpycnal flows (Aharon, 2006).

Existing Gulf of Mexico records lack the temporal resolution and age control to assess the detailed history of episodic LIS melting and its relationship with the Mystery Interval. Here, we present two independent reconstructions of ice-volume corrected $\delta^{18}O_{SW}$ with mean sampling resolution of 35 yr from 18.4 to 10.8 ka. Our data are not consistent with a simple "on-off" meltwater switch throughout the last deglaciation. Furthermore, we find evidence for two significant episodes of meltwater input during a period of extreme cooling in Greenland and the North Atlantic region. We suggest that summer meltwater input was linked to global deglacial warming and enhanced seasonality in the North Atlantic region, and that routing events were not the only drivers of deglacial MOC variability.

METHODS

The Orca Basin is located ~300 km southwest from the current Mississippi River delta, and has an anoxic brine pool (salinity >250) that preserves a laminated sediment record of Gulf of Mexico paleoceanography. High accumulation rates (40 cm/1000 yr) allow for high-resolution sampling, and abundant pteropod tests plus foraminifera with intact spines suggest negligible carbonate dissolution.

Core MD02–2550 (26°56.78′N, 91°20.75′W, water depth 2248 m) was sampled every 0.5 cm from 311 to 466 cm, and every 1 cm to 622 cm. Planktonic foraminifera *G. ruber* (white and pink, separately; >60 individuals from the 250–355 μm size fraction) were analyzed for Mg/Ca (Williams et al., 2010) and δ^{18}O using standard techniques (see Fig. DR1 in the GSA Data Repository[1]). Accelerator mass spectrometry ^{14}C dates (n = 35) from *G. ruber* (white and pink varieties) between 308 and 650 cm provide the chronological control (Fig. DR2; Williams et al., 2010). We isolate changes in $\delta^{18}O_{SW}$ by removing the effects of temperature (using Mg/Ca-SST) and global ice volume (Schrag et al., 2002; Stanford et al., 2010) from the *G. ruber* δ^{18}O record. Compounded error on resultant ice

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[1]GSA Data Repository item 2012265, methods, interpretation of $\delta^{18}O_{GOM}$ proxy, and Figures DR1–DR4, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY, October 2012; v. 40; no. 10; p. 955–958; Data Repository item 2012265 | doi:10.1130/G33279.1 |

volume-corrected $\delta^{18}O_{SW}$ (termed $\delta^{18}O_{GOM}$; GOM—Gulf of Mexico) is ±0.28‰ (see the Data Repository).

$\delta^{18}O_{GOM}$ RESULTS

G. ruber (white and pink) records display similar negative $\delta^{18}O_{GOM}$ excursions of 1‰-4‰ through the last deglaciation that suggest episodic LIS meltwater input (Fig. 1). At least three major negative excursions are seen in the *G. ruber* (white) $\delta^{18}O_{GOM}$ record, at 17.5–16.2 ka, 15.3–14.8 ka, and 13.7–13.0 ka (minimum values −1.25‰, −1.50‰, and −3.14‰, respectively). The *G. ruber* (pink) $\delta^{18}O_{GOM}$ records negative excursions at 17.0–16.3 ka, 15.6–14.8 ka, and 13.7–13.0 ka (minimum values −1.19‰, −2.14‰, and −3.10‰, respectively). Although the trend toward more negative values suggests peak meltwater flow during the Allerød (ca. 13.7 ka), this finding rests on the assumption of a constant LIS $\delta^{18}O$ end member (Mix and Ruddiman, 1984). *G. ruber* (pink and white) record a >4‰ increase in $\delta^{18}O_{GOM}$ to near modern values (+1‰; Fairbanks et al., 1992) at the Allerød–Younger Dryas transition (ca. 12.9 ka), termed the Cessation Event (Broecker et al., 1989).

$\delta^{18}O_{GOM}$ shifts are too large to be explained by evaporation-precipitation and river water variability (Flower et al., 2004), and must reflect input of isotopically depleted (–25‰ to –35‰) meltwater (Fig. DR3; see the Data Repository). Glacial Lake Agassiz was a likely contributor to LIS meltwater flow after its inception at 11,810 ^{14}C yr B.P. (ca. 13.67 ka) until the southern outlet of Lake Agassiz was abandoned and lake levels dropped (maximum age: 10,675 ± 60 ^{14}C yr B.P.; ca. 12.7 ka; Fisher et al., 2008). As our *G. ruber* $\delta^{18}O_{GOM}$ records cannot distinguish Lake Agassiz water from LIS input, we interpret the $\delta^{18}O_{GOM}$ record as influenced by all freshwater flow to the Mississippi River drainage basin.

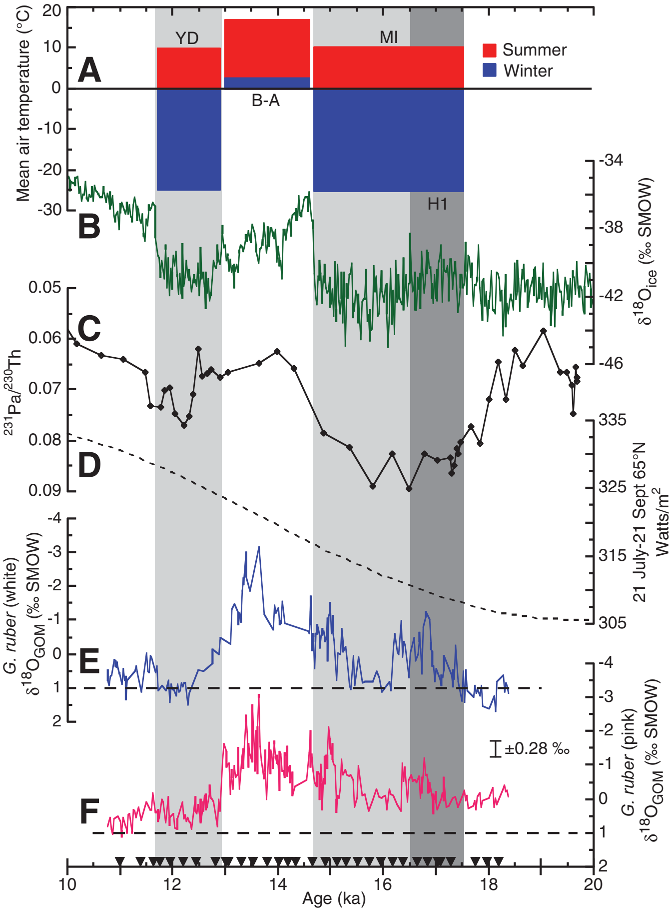

Figure 1. Proxy records indicate meltwater flow to Gulf of Mexico during so-called "Mystery Interval" (MI) prior to Bølling warming. YD—Younger Dryas; B-A—Bølling-Allerød; H1—Heinrich Event 1. A: Temperature reconstructions inferred from fossilized beetle assemblages (Atkinson et al., 1987). B: $\delta^{18}O_{ice}$ from North Greenland Ice Core Project (NGRIP) (Rasmussen et al., 2006). SMOW—standard mean ocean water. C: $^{231}Pa/^{230}Th$, proxy for meridional overturning circulation (MOC) (McManus et al., 2004) recalibrated with Marine09 calibration (Williams et al., 2010). D: Summer insolation at 65°N (Laskar et al., 2004). E: *Globigerinoides ruber* (white) $\delta^{18}O_{GOM}$ (this study) (GOM—Gulf of Mexico). F: *G. ruber* (pink) $\delta^{18}O_{GOM}$ (this study). Black triangles on *x*-axis indicate radiocarbon age control data points.

Evidence suggests that high salinities (S > 35) may elevate *G. ruber* Mg/Ca-SST values by 4%–27%, which may skew $\delta^{18}O_{GOM}$ results (Lea et al., 1999; Arbuszewski et al., 2010). However, meltwater input during the deglacial sequence likely decreased surface salinity, minimizing its effect on Mg/Ca (Williams et al., 2010). Our data exhibit no correlation between Mg/Ca values and $\delta^{18}O_{GOM}$ values. In fact, two large increases in $\delta^{18}O_{GOM}$ centered ca. 12.9 ka and 15.8 ka are not accompanied by an SST increase in *G. ruber* (white or pink) (Fig. 2).

Recent research suggests that *G. ruber* (white and pink) are seasonally decoupled in the northern Gulf of Mexico (Williams et al., 2010; Richey et al., 2012). Plankton tows and sediment trap studies suggest that while *G. ruber* (white) lives year round, *G. ruber* (pink) is a nonwinter species (Tolderlund and Bé, 1971). Zero-age core top *G. ruber* (white) from the nearby Pigmy Basin yield Mg/Ca-SST values of 25.4 °C, equivalent to modern Gulf of Mexico mean annual temperatures. In contrast, *G. ruber* (pink) Mg/Ca-SST values (27.0 °C) exhibit a summer-dominated signal (Richey et al., 2012).

MELTWATER ROUTING DURING THE EARLY DEGLACIATION

One stratigraphic test of the meltwater routing hypothesis (Broecker et al., 1989) is to compare the timing of meltwater cessation in the Gulf of Mexico to the onset of stadial conditions during the last deglacial sequence. Numerous ocean circulation proxies including $^{231}Pa/^{230}Th$, Cd/Ca, and $\delta^{13}C$ indicate major MOC reductions during the Younger

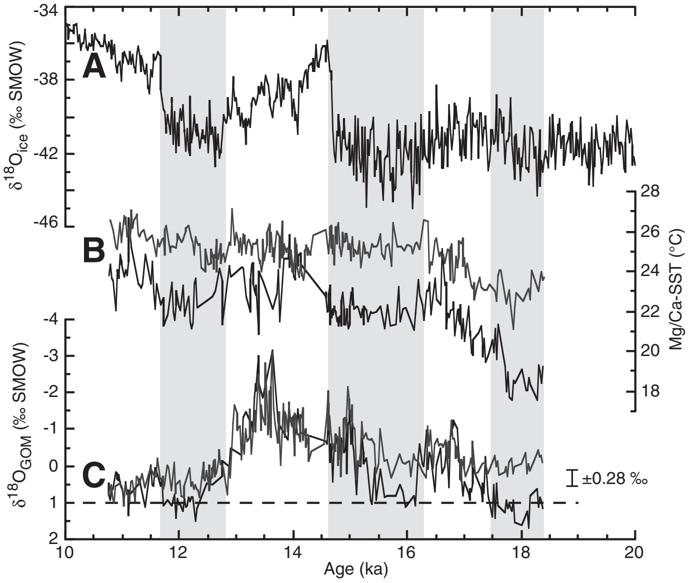

Figure 2. Intervals of intensified seasonal conditions, inferred from *Globigerinoides ruber* (white and pink) records. SMOW—standard mean ocean water. A: North Greenland Ice Core Project (Rasmussen et al., 2006). B: Core MD02–2550 *G. ruber* (white—black line, pink—gray line) Mg/Ca-SST (sea-surface temperature, °C) (Williams et al., 2010). C: Core MD02–2550 (this study) *G. ruber* (white—black line, pink—gray line) $\delta^{18}O_{GOM}$ (GOM—Gulf of Mexico). Horizontal dotted line represents modern $\delta^{18}O_{GOM}$ (~+1‰). Shaded areas indicate increased contrast between *G. ruber* (pink and white) records.

Dryas and Mystery Interval (Fig. 1; Boyle and Keigwin, 1987; McManus et al., 2004). Although subtle differences between records exist, this agreement is striking given the secondary controls that complicate each proxy (Keigwin and Boyle, 2008). As an example, we compare our $\delta^{18}O_{GOM}$ meltwater records to a rapid MOC decrease, inferred from high $^{231}Pa/^{230}Th$ values during the Younger Dryas (McManus et al., 2004); $^{231}Pa/^{230}Th$ is closely associated with high $\delta^{18}O_{GOM}$ values, consistent with meltwater routing away from the Gulf of Mexico. Furthermore, $\delta^{18}O_{GOM}$ values reach the modern $\delta^{18}O_{SW}$ value of +1‰; this is interpreted as a complete cessation of meltwater to the Gulf of Mexico.

Extension of the routing hypothesis to the early deglacial interval predicts meltwater routing away from the Gulf of Mexico during the Mystery Interval when MOC was also reduced (Fig. 1). However, simultaneous meltwater input to the Gulf of Mexico from 17.5 to 16.2 ka (this study) and North Atlantic at H1 (Bond et al., 1992) indicates that simple routing events cannot explain all deglacial MOC changes. Rather, we speculate that meltwater flow to both the Gulf of Mexico and the North Atlantic from the LIS and other Northern Hemisphere ice sheets was necessary for MOC reduction. Multiple records based on northern North Atlantic sediments provide evidence for melting episodes originating from the Barents Sea, Fennoscandian, and Laurentide ice sheets before the onset of the Bølling (Bond et al., 1992; Fairbanks et al., 1992). Furthermore, meltwater input to the Gulf of Mexico spanning H1 (this study) supports the idea that low-salinity meltwater preconditioned the North Atlantic for MOC changes via the Gulf Stream system (Otto-Bliesner and Brady, 2010). Although a sharp positive $\delta^{18}O_{GOM}$ excursion from 16.2 to 15.3 ka raises the possibility that meltwater flow stopped or was briefly routed away from the Gulf of Mexico during the coldest part of the Mystery Interval following H1, existing data are insufficient to resolve a brief MOC change during this interval of reduced MOC (McManus et al., 2004).

A recent modeling experiment showed that a nearly instantaneous stoppage of meltwater to the North Atlantic at 14.67 ka is required to produce a rejuvenation of MOC and rapid temperature increase in Greenland ice core records at the onset of the Bølling-Allerød (Liu et al., 2009). Our *G. ruber* $\delta^{18}O_{GOM}$ data provide no evidence for a sudden onset of meltwater flow to the Gulf of Mexico ca. 14.67 ka, which would be expected in a southward routing event. Instead, continuous meltwater input is seen to the Gulf of Mexico from at least 15.3 ka through the Bølling. There is evidence for a brief pulse of terrigenous input ca. 14.55 ka based on sedimentology data (Meckler et al., 2008) during an interval of low foraminiferal abundance in core MD02–2550. However, the lack of a clear on-off switch between North Atlantic and Gulf of Mexico meltwater flow indicates that the linkage between abrupt climate change and routing events is not simple.

SEASONAL LIS MELTING AND ENHANCED SEASONALITY

Our *G. ruber* (white and pink) $\delta^{18}O_{GOM}$ records indicate two significant episodes of LIS melting during the Mystery Interval, centered ca. 16.6 ka and 15.1 ka, which suggests that temperatures were sufficiently high to allow for summer melting of the LIS well before the onset of the Bølling-Allerød warm period. We speculate that Northern Hemisphere ice sheet melting was driven by rising solar insolation, likely amplified by greenhouse gases. In addition, warming of the tropics may have contributed to early ice sheet melting and sea-level rise (Rodgers et al., 2003).

Summer melting of circum–North Atlantic ice sheets likely produced a freshwater lens, which may have led to the expansion of winter sea ice, derived in part from meltwater input the previous summer. Northern North Atlantic climate was likely intensified by higher albedo due to the sea ice and reduced oceanic influences, which amplified seasonal conditions and produced extremely cold winters. These hypercold winters were further intensified by reduced MOC through positive feedbacks associated with winter sea-ice cover, including increased continentality and isolation of Greenland. It is interesting that seasonal melting caused by deglacial warming may have contributed to extreme stadial conditions during the Mystery Interval.

In the Gulf of Mexico, three distinct intervals of contrast between *G. ruber* (pink and white) $\delta^{18}O_{GOM}$ and SST values during the late glacial (ca. 18.4–17.5 ka), part of the Mystery Interval (16.2–15.3 ka), and Younger Dryas (12.9–11.7 ka) provide further insight to the importance of seasonal melting (Fig. 2; this study; Williams et al., 2010). Although *G. ruber* (white) $\delta^{18}O_{GOM}$ reaches modern values of 1‰, suggesting a nonsummer cessation of meltwater input, the *G. ruber* (pink) record suggests continued summer LIS melting. These three intervals of summer melting seem to correspond only to the coldest phases of stadials in the North Greenland Ice Core Project (NGRIP) record. In contrast, *G. ruber* (white and pink) $\delta^{18}O_{GOM}$ values were nearly identical during a subtle warming in NGRIP temperatures ca. 17.5–17 ka, as well as the Bølling-Allerød and early Holocene (Rasmussen et al., 2006). We speculate that melting was less restricted to summer months during the latter periods. Summer meltwater of the LIS during stadials is consistent with the seasonality hypothesis of Denton et al. (2005) and may have provided a mechanism to enhance seasonality in the North Atlantic region by fostering winter sea-ice formation and reducing MOC (Fig. DR4).

SUMMARY AND CONCLUSIONS

$\delta^{18}O_{GOM}$ data sets, derived from paired *G. ruber* (white and pink, separately) $\delta^{18}O$, and Mg/Ca-SST analyses and combined with excellent AMS ^{14}C age control, provide the first detailed assessment of meltwater flow to the Gulf of Mexico spanning the Mystery Interval and the Younger Dryas. Low $\delta^{18}O_{GOM}$ values from ca. 17.5–14.5 ka indicate LIS melting during the Mystery Interval, when nearby Greenland air temperatures and North Atlantic SSTs were cold.

Thus, stadial summers were sufficiently warm for the generation of meltwater, which may have enhanced winter sea-ice formation, reduced MOC, and fostered hypercold winters. Inferred meltwater input from the LIS is consistent with snowline retreat and mountain glacier recession in East Greenland, northern Europe, and North America, and supports the hypothesis of enhanced seasonality in the northern North Atlantic region during the Mystery Interval. Simultaneous meltwater input to the North Atlantic and Gulf of Mexico spanning H1 (ca. 17.5–16.5 ka) suggests that simple on-off routing events are not the only drivers of MOC changes and that both routes may be required for major MOC reduction. Overall, glacial meltwater played an important role in MOC variability, North Atlantic climate, and the genesis and seasonality of millennial-scale climate changes during the last deglaciation.

ACKNOWLEDGMENTS

We thank the IMAGES (International Marine Past Global Changes Study) program, Viviane Bout-Roumazeilles, Yvon Balut, and Laurent Labeyrie for a productive cruise on the R/V *Marion Dufresne* in 2002. This work was supported by the Gary Comer Science and Education Foundation (CP-18 to Flower and Hastings) and National Science Foundation grants OCE-0318361 and OCE-0903017. Radiocarbon analyses were performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory (contract W-7405-Eng-48). We also thank Ethan Goddard for invaluable expertise in stable isotope ratio mass spectrometry sample preparation and analysis; Wallace Broecker, George Denton, Thomas Lowell, Richard Alley, Jessica Spear, Julie Richey, and the University of South Florida PaleoLab members for useful comments and discussions; Eckerd College interns for help in sample preparation; and anonymous reviewers for constructive criticism.

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Manuscript received 7 February 2012
Revised manuscript received 20 April 2012
Manuscript accepted 24 April 2012

Printed in USA

Statement of Ownership, Management, and Circulation

(Required by Title 39 U.S.C. 4369)

Geology (Publication No. 0091-7613) is published monthly by The Geological Society of America, Inc., (GSA) with headquarters and offices at 3300 Penrose Place, Boulder, Colorado 80301, U.S.A., and mailing address of Post Office Box 9140, Boulder, Colorado 80301-9140, U.S.A. The Publisher is Jon Olsen; the Managing Editor is Lyne Yohe; their offices and mailing addresses are the same as above. The annual subscription prices are: GSA Members $85; GSA Student/K-12 Teacher Members $45; non-members $875. The publication is wholly owned by The Geological Society of America, Inc., a not-for-profit, charitable corporation. No known stockholder holds 1-percent or more of the total stock. There are no known mortgagees or holders of other securities. The purpose, function, and non-profit status of The Geological Society of America, Inc., has not changed during the preceding twelve months. The average number of copies of each issue during the preceding twelve months and the actual number of copies published nearest to the filing date (September 2012 issue) are noted at right.

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