to before and after (Fig. 1a, 1d). (2) Peltier (2005) argued that the Barents-Kara Ice Sheet also contributed to the event but this ice sheet had largely deglaciated by 19 ka (Svendsen et al., 2004). (3) Ocean models consistently demonstrate that the freshwater flux to the North Atlantic from a Northern Hemisphere source would have shut down the Atlantic meridional overturning circulation (AMOC), which did not occur (McManus et al., 2004). Aharon (2006) argued that benthic $\delta^{18}O$ records from the Gulf of Mexico support a substantial contribution from the LIS with minimal effect on the AMOC but Carlson (2009) showed that aspects of the model used by Aharon (2006) were incorrect.

In contrast, a substantial contribution from Antarctica explains why there is no significant reduction in the AMOC, and instead may explain why the AMOC abruptly resumed at this time (Weaver et al., 2003; Pahnke et al., 2008). In addition, an Antarctic source explains the geographic variation in far-field sea level records associated with the processes of glacial isostatic adjustment (Clark et al., 2002; Bassett et al., 2005).

In summary, the terrestrial record of past changes in global ice sheets places important constraints in identifying their contributions to the sea level rise of the last deglaciation. In particular, multiple ice sheets represent multiple reservoirs, each potentially behaving independently of each other in response to regional or hemispheric climate change. As is the case for modern ice sheets and future sea level change, disentangling these contributions is critical to fully decipher the sensitivity of sea level to climate change.

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A new chronology of sea level highstands for the penultimate interglacial

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A suite of submerged Italian speleothems constrain the timing of sea level highstands across the entirety of marine isotope stage 7 (~190-245 ka) indicating that sea level highstands were broadly in phase with insolation forcing.

Understanding the precise phase relationships of changes in sea level, temperature, and greenhouse gas concentrations during previous interglacials provides us with critical knowledge to evaluate the future response of the climate system to anthropogenic forcing. Absolutely dated sea level archives that document the response of ice sheets to changes in temperature and atmospheric CO_2 become increasingly rare as we look beyond the last interglacial (ca. 130 ka) due to the combined effects of alteration of suitable archives, physical superposition of multiple sea level oscillations, and challenges related to temporal limitations of geochronometers. This leads us to rely upon sea level reconstructions that are derived from deep-sea cores and models, which both lack direct age control. Because we seek to understand the phasing of orbital forcing and climate records relative to more continuous records of sea level change that are available from these models and deep-sea cores, we must first calibrate these against absolutely dated records of sea level response.

We have studied a suite of submerged stalagmites from Argentarola Cave (central west coast of Italy) collected across a depth range of -18 to -21 m, with the aim

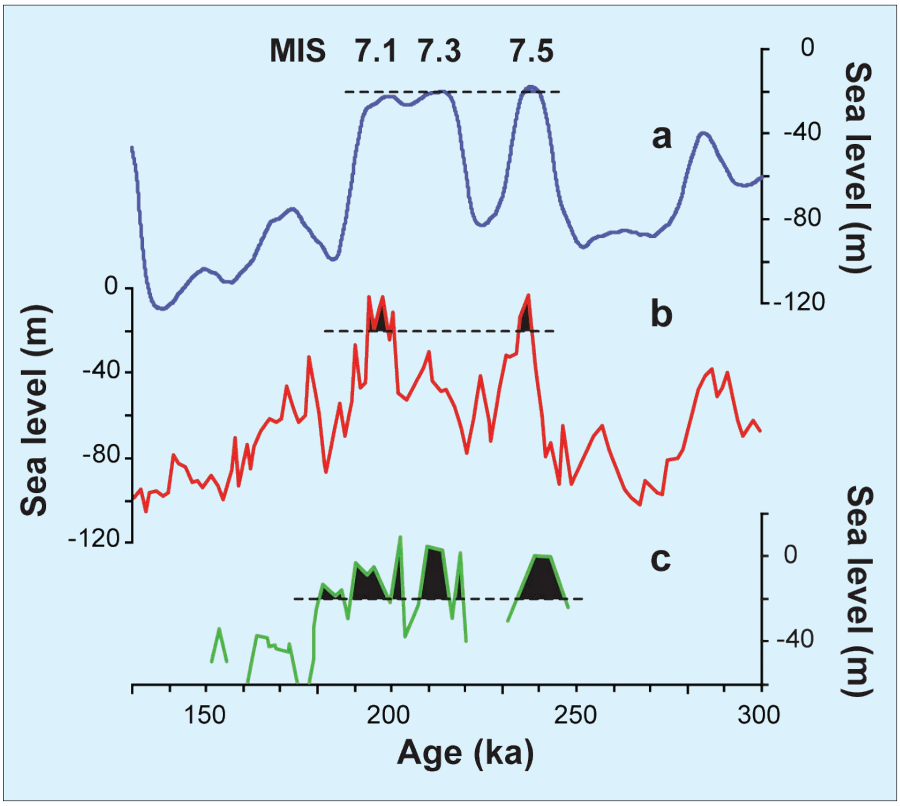

*Figure 1: Sea level curves shown for MIS 7, derived using three different methods: (**a**) model (Bintanja et al., 2008) driven by benthic oxygen isotope ($\delta^{18}O$) stack, (**b**) reconstruction of Red Sea seawater $\delta^{18}O$ (Siddall et al., 2003), (**c**) open system U-Th ages of corals (Thompson and Goldstein, 2005). Shading indicates periods of time that sea level rose above -20 m (dashed lines), the approx. depth of Argentarola Cave stalagmites. Note differences in the number of highstands predicted to exceed -20 m and the difference in elevation predicted for MIS 7.3 in particular. Figure modified from Dutton et al., 2009.*

of improving the absolute chronology of several sea level highstands during MIS 7 (190 to 245 ka), also referred to as the penultimate interglacial (Dutton et al., 2009). Our investigation provides benchmarks of the precise timing of sea level highstands during the penultimate interglacial that help to reconcile existing reconstructions of sea level across this time interval (Fig. 1). As previously reported, the spectacular feature of speleothems recovered from Argentarola Cave is the occurrence of alternating layers of biogenic calcite and inorganically precipitated spelean calcite that result from multiple sea level oscillations in the past (Bard et al., 2002; Antonioli et al., 2004). The biogenic layers are composed of serpulid worm calcite secretions that encase the speleothems during seawater submergence, while the spelean calcite growth only occurs when the cave is emergent, or above sea level. We have used U-series dating techniques to determine the precise timing of speleothem growth that brackets each serpulid calcite layer to ascribe a chronology to the sea level highstands. The combined record from three stalagmites, including one previously studied by Bard et al. (2002), captures the timing of sea level rise and fall past the cave during three successive peaks in sea level during MIS 7 (Fig. 2).

The timing of sea level highstands at Argentarola Cave accurately represents the timing of eustatic sea level oscillations because the time difference between local sea level reaching -18 m at Argentarola and the calculated timing of -18 m eustatic sea level (ice-equivalent volume) is very small (estimated at <0.1 ka) relative to the precision of the U-Th ages (1.5 to 3.0 ka) (Dutton et al., 2009). It is also important to recognize that these data provide maximum estimates for the duration of the highstand above the elevation of the cave because the U-Th ages are measured on samples of spelean calcite that grew before and after the sea level highstand.

In a broad sense, the overall timing of these highstands encompasses, and in some cases is almost centered on, the timing of maximum Northern Hemisphere insolation (Fig. 3). We note that the absolute chronology of the Argentarola record is also in good agreement with other absolutely dated archives of sea level and interglacial conditions during MIS 7. However, a closer look at some of the more subtle differences in timing may reveal critical insight to the timing and nature of ice sheet response to insolation forcing. For instance, if we compare the timing of sea level rise past -18 m at Argentarola to the timing of maxima in Northern Hemisphere insolation, we see that during MIS 7.5 and 7.1, speleothem growth at -18 to -18.5 m terminates a few thousand years before insolation maxima are reached. In contrast, during the onset of the MIS 7.3 highstand there is no difference, within our analytical error, between the timing of sea level rise past -21 m and the insolation maximum. So this intervening highstand, MIS 7.3, is delayed in a relative sense when compared to the timing observed for the other two highstands.

Before exploring the reason for the different behavior of the MIS 7.3 highstand, we first turn to an unexpected finding made during this study regarding the relative elevation of these highstands. Due to differences in the number of serpulid calcite layers preserved in stalagmites from different depths and evidence of dissolution that occurred in the halocline, we were able to determine that the elevation of sea level peaked at approx. -18 m during the MIS 7.3 highstand and was between -18.5 and -21.0 m during the MIS 7.2 lowstand. In contrast, peak sea level during MIS 7.5 and 7.1 was somewhere above our highest reference point in the cave (-18 m). Our observation of lower peak sea level during MIS 7.3 relative to MIS 7.5 and 7.1 is in agreement with sea level reconstructions of Lea et al. (2002) and Siddall et al. (2003) that are based on seawater $\delta^{18}O$ determinations but are not in keeping with reconstructions that are based in whole or in part on benthic $\delta^{18}O$ records (e.g., Waelbroeck et al., 2002; Bintanja et al., 2005) that imply similar peak elevations for all three highstands. This finding suggests that the benthic $\delta^{18}O$ record may be biased by temperature influence during the MIS 7.3 highstand, possibly as a consequence of strong peaks in insolation in both the Northern and Southern Hemispheres during this time interval (Fig. 3).

Having noted the unusual nature of the MIS 7.3 highstand with respect to both timing and elevation, we now return to the issue of understanding the delayed timing of sea level rise past Argentarola cave relative to the two other highstands. The preceding sea level lowstand, MIS 7.4, has been associated with cold temperatures and ice volumes that approach the full glacial conditions of MIS 8 (e.g., Roucoux et al., 2006; Jouzel et al., 2007; Martrat et al., 2007). The transition from MIS 7.4 to MIS 7.3 has even been likened to a full glacial termination (Huybers and Wunsch, 2005). Both the delayed timing and dampened amplitude of MIS 7.3 may be a consequence of MIS 7.4 glaciation that was extensive but according to Bintanja et al. (2008) was not enough to cause coalescence of the two Cordilleran and Laurentide Ice Sheets in North America. The merging of these two ice sheets has been postulated as a key factor in initiating rapid retreat of the ice sheets during termination events (e.g., Bintanja et al., 2008).

Our chronology of sea level highstands during the penultimate interglacial from Argentarola Cave provides precise and accurate ages that are critical benchmarks in determining the phasing of insolation forcing and climate relative to sea level response. The findings summarized here and more fully developed in Dutton et al. (2009) also underpin the importance of cryosphere state as a critical factor de-

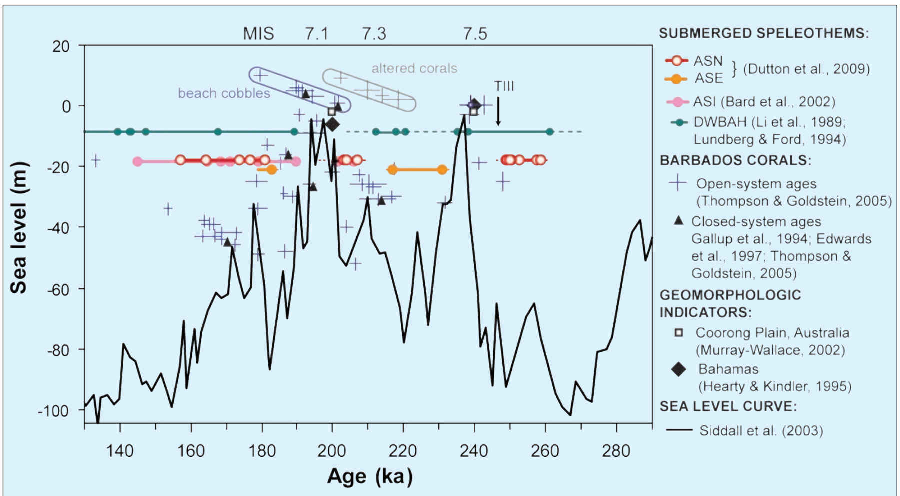

Figure 2: Comparison of Argentarola submerged stalagmite data (Agentarola stalagmite N, E, and I: ASN, ASE, ASI) with other relative sea level records across MIS 7. Speleothem U-Th data represent growth periods and should be above the sea level curve, whereas coral data should be just below the curve; ***Solid lines*** *connecting these U-Th ages represent periods of uninterrupted growth. Error bars for samples next to hiatuses are shown as* ***dashed lines****. Peak MIS 7.5 coral data were assumed to sit at modern sea level (Thompson and Goldstein, 2005). The remainder of the Barbados coral elevations are calculated assuming constant uplift rates, which introduces some error into the elevation estimates.* ***Gray*** *data points are heavily altered corals ($\delta^{234}U_{initial}$ > 330‰);* ***blue*** *data points in circle are beach cobbles. Closed-system ages are shown for corals with $\delta^{234}U_{inital}$ within 2‰ of seawater. TIII = Termination III. Figure modified from Dutton et al., 2009.*

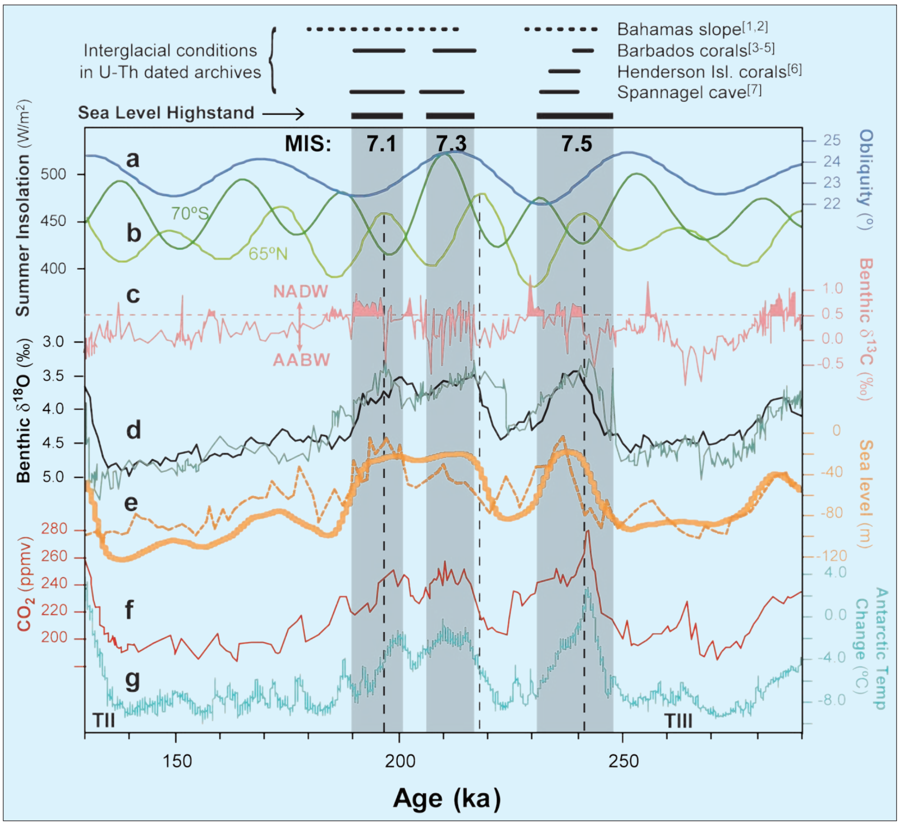

*Figure 3: Sea level and climate reconstructions during MIS 7. Sea level highstands at Argentarola denoted by vertical gray bars. (**a**) Obliquity, and (**b**) summer insolation curves at 65°N (JJA) (maxima shown by dotted lines in MIS 7) and 70°S (DJF) (Laskar, 1990), (**c**) Iberian Margin benthic carbon isotope ($\delta^{13}C$) data (Martrat et al., 2007) highlights the unusual nature of MIS 7.3, (**d**) benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005: black) and benthic $\delta^{18}O$ from the Iberian Margin (Martrat et al., 2007: blue), (**e**) sea level reconstructions (Siddall et al., 2003; Bintanja et al., 2008: dashed and solid orange lines, respectively), (**f**) compiled Antarctic ice core CO_2 (Lüthi et al., 2008), (**g**) EPICA Dome C temperature change (Jouzel et al., 2007). TII and TIII = Terminations. Data sources as follows: [1] Henderson et al., 2006; [2] Robinson et al., 2002; [3] Gallup et al., 1994; [4] Edwards et al., 1997; [5] Thompson and Goldstein, 2005; [6] Andersen, 2006; [7] Spötl et al., 2008; [8] Dutton et al., 2009. Figure modified from Dutton et al., 2009.*

termining the sensitivity of sea level response to insolation forcing. While records from submerged speleothems such as this are rare, they are archives that have enormous potential to shed light on the dynamics of climate and sea level in the past, and also to inform us about the interplay of these variables as we head into the future.

Acknowledgements

We would like to thank T. Esat, K. Lambeck and M. McCulloch for their contributions to the work discussed here, and also J. Desmarchelier, L. Kinsley and G. Mortimer for analytical assistance.

Data Information

Data are available in online supplemental material associated with Dutton et al. (2009) *Nature Geoscience*, at http://dx.doi.org/10.1038/NGEO470

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Tempo of global deglaciation during the early Holocene: A sea level perspective

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High-resolution early Holocene sea level records are essential to aid predictions of future sea level change. However, our current understanding about the nonlinear response of sea level to rapid climate changes during this critical time interval is still in its infancy.

Sea level change is the result of complex interactions among the Earth's lithosphere, hydrosphere, atmosphere and cryosphere as a function of time. Geophysically, this change is defined as the vertical shift of the geoid, an equipotential surface of the Earth's gravitational field that coincides with the ocean surface, due primarily to variations in ocean mass and volume (Farrell and Clark, 1976; Mitrovica and Milne, 2003). This in turn leads to a complex spatio-temporal sea level response (Lambeck and Chappell, 2001). Therefore, studying past sea level changes from different time intervals and geologic settings can not only provide direct information about the dynamics of global ice volume (e.g., Peltier, 2004), but also about the physics of the Earth's interior that cannot be inferred seismologically (e.g., Kaufmann and Lambeck, 2002).

High-resolution sea level records also constitute an important knowledge base for predicting the behavior of future sea level, given the threat that global warming poses to low-lying coastal communities in terms of accelerated sea level rise. However, the predicted magnitude of sea level rise by the end of the 21st century (e.g., 0.26-0.59 m (IPCC, 2007) and 0.5-1.4 m (Rahmstorf, 2007)) remains highly uncertain. This uncertainty lies primarily in our poor understanding of the dynamic response of ice flow to climate change (Alley et al., 2005; Oppenheimer et al., 2007). For example, transient processes that may lead to non-linear sea level responses were not considered in the IPCC Fourth Assessment Report (IPCC, 2007), and the model of Rahmstorf (2007) includes neither ice sheet physics nor makes use of any longer sea level records. Such longer, high-resolution sea level records have the potential to address these issues. Rather than giving answers, here we raise some key questions that may help guide the next wave of investigations.