Quaternary Science Reviews 173 (2017) 92–100

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A stalactite record of four relative sea-level highstands during the Middle Pleistocene Transition

Paolo Stocchi [a,*], Fabrizio Antonioli [b], Paolo Montagna [c], Fabrizio Pepe [d], Valeria Lo Presti [b], Antonio Caruso [d], Marta Corradino [d], Gino Dardanelli [e], Pietro Renda [d], Norbert Frank [f], Eric Douville [g], François Thil [g], Bas de Boer [h], Rosario Ruggieri [i,j], Rosanna Sciortino [e], Catherine Pierre [k]

[a] NIOZ Royal Netherlands Institute for Sea Research, Department of Coastal Systems (COS), and Utrecht University, P.O. Box 59, 1790 AB Den Burg, Texel, The Netherlands
[b] ENEA National Agency for New Technologies, Energy and Environment, Via Anguillarese 301, 00060, S. Maria di Galeria, Rome, Italy
[c] ISMAR-CNR, Via Gobetti 101, 40129 Bologna, Italy
[d] Dipartimento di Scienze Della Terra e Del Mare, Via Archirafi, 22, Università di Palermo, Palermo, Italy
[e] Dipartimento di Ingegneria Civile, Ambientale, Dei Materiali (DICAM), Università di Palermo, Viale Delle Scienze, Ed. 8, 90128 Palermo, Italy
[f] Universität Heidelberg, Im Neuenheimer Feld 229, 69120 Heidelberg, Germany
[g] LSCE/IPSL, UMR 8212 CNRS-CEA-UVSQ, 91198, Gif-sur-Yvette, France
[h] IMAU, Utrecht University, Utrecht, The Netherlands
[i] CIRS Centro Ibleo di Ricerche Speleo-Idrogeologiche, Via Torrenuova 87, 97100, Ragusa, Italy
[j] University of Nova Gorica, SI-5000, Nova Gorica, Slovenia
[k] LOCEAN, Jussieu, Paris Cedex, France

ARTICLE INFO

Article history:
Received 15 March 2017
Received in revised form
15 July 2017
Accepted 7 August 2017

Keywords:
Interglacial(s)
Pleistocene
Sea level changes
Western Europe
Speleothems
Corals
Stable isotopes
U-Th dating
$^{87}Sr/^{86}Sr$ ages

ABSTRACT

Ice-sheet and sea-level fluctuations during the Early and Middle Pleistocene are as yet poorly understood. A stalactite from a karst cave in North West Sicily (Italy) provides the first evidence of four marine inundations that correspond to relative sea-level highstands at the time of the Middle Pleistocene Transition. The speleothem is located ~97 m above mean sea level as result of Quaternary uplift. Its section reveals three marine hiatuses and a coral overgrowth that fixes the age of final marine ingression at 1.124 ± 0.2, thus making this speleothem the oldest stalactite with marine hiatuses ever studied to date. Scleractinian coral species witness light-limited conditions and water depth of 20–50 m. Integrating the coral-constrained depth with the geologically constrained uplift rate and an ensemble of RSL scenarios, we find that the age of the last marine ingression most likely coincides with Marine Isotope Stage 35 on the basis of a probabilistic assessment. Our findings are consistent with a significant Antarctic ice-sheet retreat.

1. Introduction

Changes in solar radiation due to orbital forcing and variations in the concentrations of atmospheric greenhouse gases led to a succession of glacial and interglacial periods during the Pleistocene (Bintanja et al., 2005; De Boer et al., 2013; Rohling et al., 2014). Large fluctuations in ice volumes on both hemispheres resulted in significant sea-level changes that can be inferred from proxy records such as benthic and planktonic foraminiferal $\delta^{18}O$ from deep-sea sediment cores (Rohling et al., 2014; Lisiecki and Raymo, 2004; Grant et al., 2014). However, $\delta^{18}O$ time series lack direct age control and require numerical iteration to decouple the convolved deep-water temperature and global ice mass signal (Bintanja et al., 2005; De Boer et al., 2014). Relative sea-level (RSL) changes can be permanently recorded by coastal geomorphological markers that are linked to coastal uplift (Ferranti et al., 2006; Antonioli et al.,

* Corresponding author.
E-mail address: Paolo.Stocchi@nioz.nl (P. Stocchi).

http://dx.doi.org/10.1016/j.quascirev.2017.08.008
0277-3791/

2015). A common approach in constraining Pleistocene ice-sheet fluctuations is to date RSL markers such as shallow karst cave speleothems and measure their elevations with respect to modern mean sea level. The subaerial growth of speleothems inside caves that are connected to the sea is interrupted during marine floodings. Successive marine inundations appear as series of concentric hiatuses within speleothem sections and can be converted into RSL changes (Dutton et al., 2009; Richards et al., 1994). While paleo sea-level markers such as fossil beaches from the Pliocene have been identified worldwide (Rovere et al., 2014), speleothems that can be used as reliable RSL indicators that are older than 1 million years are extremely rare because of cliff retreat due to coastal erosion and active tectonics (Breitenbach et al., 2005; Artyushkov, 2012).

In this work we reconstruct the conditions and the chronology of the events that led to the occurrence and preservation of four marine ingressions that are recorded by a stalactite that is located inside the uplifted Rumena karst cave (RKC) in Custonaci, North West Sicily (NWS; Figs. 1 and 2). The descriptive work of Ruggieri and De Waele (2014) provides information on the RKC morphology as well as a tentative minimum age of 1200 ka for the cave based solely on the age of the corals encrustation as provided by Antonioli et al. (2012, 2014).

Here we adopt a multidisciplinary and quantitative approach by combining geodetic measurements, dating techniques, geological and paleoecological observations and reconstructed RSL curves that are based on proxy data and numerical modelling. We aim at pinpointing the elevation of the uplifting stalactite in time and with respect to the fluctuating sea level. Our main goal is to correlate the marine ingressions that are observed within the stalactite section to the RSL changes that characterize the proxy-based sea-level curves. We evaluate the bathymetric conditions during the last flooding event with respect to present-day local sea level.

2. Geological settings and quaternary uplift rate

NWS is a segment of the Early Miocene to present-day Sicilian-Maghrebian Fold and Thrust Belt (Fig. 2). The latter consists of a thin-skinned, south-verging fold and thrust system formed by Mesozoic–Tertiary carbonates, siliciclastic and evaporites, locally overlain by late orogenic clastic deposits (Catalano et al., 2000). Quaternary extensional and strike-slip faults deformed the nappe pile and formed structural ridges and intervening basins (Mauz et al., 1997). Post Middle-Pleistocene coastal terraces are presently distributed around the NWS at elevations up to 160 m above modern mean sea level (msl) (Di Maggio et al., 2009), thus demonstrating that vertical uplift occurred as a consequence of deep-seated processes. A swarm of NW-SE and N-S/NNE-SSW trending faults accommodates the structural separation between the Rocca Rumena Ridge, where the cave karst formed, and the Castelluzzo and Cornino coastal plains (Fig. 2; Catalano et al., 2006). Close to Custonaci, eolian deposits (Fig. 3a and b) and shallow marine depositional systems (Fig. 3c and d) are preserved above Mesozoic-Paleogene carbonates at an elevation of 120 ± 10 m above msl in close proximity to the RKC (see Fig. 2; Di Maggio et al., 2009). Although index fossils in these deposits are lacking, based on regional stratigraphic correlations, it has been proposed that they formed during the transgressive depositional cycle of the Early Pleistocene Calabrian Stage (Ruggeri et al., 1979), which comprises the Marine isotope Stages (MIS) 53–35 (Milli et al., 2013). The absolute age of 1.48 (±0.10) Ma inferred for the oldest deposits (Ruggeri et al., 1979) suggests a long-term linear uplift rate of 0.081 ± 0.014 mm yr^{-1}. The latter is consistent with a shorter-term estimate of ~0.08 mm yr^{-1} that is based on MIS 5e (~125,000 years ago and assuming an elevation of ~6.0 m above msl paleo sea level) elevated coastal terraces that lie approximately 1 km to the west at ~16 m above msl (Antonioli et al., 2002; Lambeck et al., 2004).

3. Materials and methods

Here we describe our multidisciplinary approach that incorporates instrumental geodetic measurements of the stalactite elevation, laboratory analytical dating techniques for the age of speleothem and fossil corals and numerical modelling of RSL change.

3.1. Orthometric height of the stalactite

The orthometric height of the stalactite is the result of two integrated different geodetic surveying techniques: tacheometric and GNSS methods (Dardanelli et al., 2009). A static GNSS survey was conducted on several control points close to the RKC with the following acquisition parameters: 10 km baseline distance, observation time 4 h for each point, cut-off angle 10° and rate 5 s. The goal of the survey was the estimation of geoid undulation within the investigated zone. The data were calculated relative to the reference station TRAP (Trapani) of the UNIPA NRTK GNSS permanent GNSS network (Dardanelli et al., 2009); the geodetic undulation is approximately 43.52 m. A triple-difference analysis was performed by means of Network Deformation Analysis software package, which makes ionospheric and tropospheric corrections. The modelling of the tropospheric delay was carried out by using the ideal gas law refractivity model published by (Saastamoinen, 1972; Niell, 1996), while the modelling of ionospheric error was performed using the Total Electron Content (Klobuchar, 1996) with daily parameter values supplied by the Center for Orbit Determination in Europe of the Astronomical Observatory of the University of Bern. In addition, the ocean loading correction and the zenith troposphere delay estimation (which affects the baseline coordinates) were based on a hydrodynamic model (Schwiderski, 1980). We also performed a correction of antenna phase center position using precise ephemeris. To fix the phase ambiguity, we used the LAMBDA method associated with a secondary test on the "ratio" (Teunnisen et al., 1995), inserting the parameters of rotation of the Earth (Earth Orientation Parameters) and the values of the ocean tides to obtain an accurate result. The difference in elevation between the stalactite and the known points was derived by means of tacheometric levelling. Using the backward intersection method, we connected the tacheometric survey inside the cave to the GNSS survey.

3.2. U/Th dating

Two small pieces of carbonate (~200 mg) were extracted from the innermost and outermost layers of the stalactite (Fig. 1f) using a diamond-studded blade. The fragments were mechanically cleaned using the diamond blade to remove any visible contamination, leached with 0.1 HCl and dissolved with diluted HCl. The solution was equilibrated with a mixed $^{236}U/^{233}U/^{229}Th$ spike, and the U and Th fractions were separated using UTEVA resin (Eichrom Technologies, USA). U and Th separation and purification followed a procedure slightly modified from Douville et al. (2010). Uranium and thorium isotopes were analysed using a ThermoScientific NeptunePlus MC-ICP-MS at the Laboratoire des Sciences du Climat et de l'Environnement in Gif-sur-Yvette. Mass bias was corrected using an exponential mass fractionation law (normalized to the natural $^{238}U/^{235}U$ isotopic ratio) and the standard/sample bracketing technique (using a mixture of our triple spike and HU-1). For more details on the analytical procedure see Pons-Branchu et al. (2014).