Sea level change at Capo Caccia (NW Sardinia) and Mallorca (Balearic Islands) during oxygen isotope substage 5e, based on Th/U datings of phreatic overgrowths on speleothems

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Sea level changes during Last Interglacial (substage 5e) have been documented in two sites of the Western Mediterranean area: Mallorca Island (Balearic Archipelago) and Capo Caccia area (NW Sardinia). Past sea stands have been recorded by overgrowths of phreatic crystallizations developing around previously formed vadose speleothems. These carbonate coatings have been U-series dated, mostly using multicollector inductively coupled mass spectrometry. Two high sea stands have been recognised along the eastern coast of Mallorca at about 1.5 - 3 metres a.p.s.l. from 135 to 109 ka B.P., with a rapid episode of regression around 125 ka. The average duration of the older high stand episode can be estimated at 9.5 ka and that of the younger at 12.8 ka. So far only the younger stand has been found in Capo Caccia area at 4.3 m a.p.s.l., with a minimum duration of 3 ka. The difference in elevation of late 5e high stand, recorded at Mallorca and Capo Caccia, can be only partly justified by neotectonic activity and is probably the result of different responses of the two areas, (owing to their different crustal thickness) to the change in the water loading characterising the glacial-interglacial cycles.
Keywords: *Mallorca, Sardinia, sea level change, speleothems, Th/U datings.*

CANVIS DEL NIVELL DE LA MAR A CAPO CACCIA (NW SARDENYA) I A MALLORCA (ILLES BALEARS) DURANT EL SUBESTADI ISOTÒPIC 5e, BASAT EN LES DATACIONS Th/U D'ESPELEOTEMES FREÀTICS. Els canvis del nivell de la mar durant el darrer interglacial (subestadi isotòpic 5e) han estat documentats en dues àrees de la Mediterrània occidental: l'illa de Mallorca (Illes Balears) i la zona de Capo Caccia, a l'Alguer (NW de Sardenya). A les coves costaneres d'aquestes illes, antigues estabilitzacions del nivell marí es troben enregistrades mitjançant sobrecreixements de cristal·litzacions freàtiques que es desenvoluparen al voltant d'espeleotemes vadosos preexistents. Aquests recobriments de carbonats s'han datat amb el mètode de les sèries de l'Urani, majoritàriament usant tècniques MC-ICPMS *(multicollector inductively coupled mass spectrometry)*. Al llarg de la costa oriental de Mallorca, ha estat possible reconèixer dos episodis transgressius que assoleixen 1,5 - 3 m per sobre de l'actual nivell marí, ocorreguts entre 135 i 109 ka BP, separats per una ràpida regressió al voltant dels 125 ka. La durada de la pulsació transgressiva més antiga pot ésser estimada en 9,5 ka, mentre que la duració de la més recent seria de 12,8 ka. Fins al moment, tans sols la transgressió més recent es troba documentada a l'àrea de Capo Caccia a +4,3 m amb una durada mínima de 3 ka. La diferència d'altitud de l'episodi transgressiu més recent dins el subestadi 5e, enregistrat a Mallorca i a Capo Caccia (Sardegna), pot ésser tan sols parcialment justificada per l'activitat neotectònica i és probablement el resultat de respostes diferents de les dues àrees (atribuïbles a les distintes gruixes de l'escorça continental) als canvis en la càrrega d'aigua marina que caracteritzen els cicles climàtics pleistocènics.

Paraules clau: *Mallorca, Sardenya, canvis del nivell de la mar, espeleotemes, datacions Th/U.*

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Introduction

In the major islands of the Western Mediterranean area, karst caves are a frequent occurrence at the existing limestone outcrops. Specifically, the littoral of eastern Mallorca (Balearic Islands, Spain), as well as that of Capo Caccia (north-western coast of Sardinia, Italy) lodges several coastal caves, that supply valuable information about the Quaternary sea level history in this basin.

The main interest in these littoral caves is the presence, inside them, of *Phreatic Overgrowths on Speleothems* (POS) generated at the surface of brackish cave pools (Ginés *et al.*, 1981b; Pomar *et al.*, 1979). These deposits consist in subaqueous crystalline coatings (calcite and/or aragonite, mainly), whose elevation is fully controlled by the sea level position. The resulting overgrowths define strictly horizontal bands that develop on cave walls or whatever suitable support, like conventional vadose speleothems (for example, stalactites) previously formed during low sea stands. Phreatic speleothems of this kind are nowadays growing at the surface of present-day cave ponds, which are clearly sea-controlled since they experience tidal and barometric daily fluctuations. As these subactual POS record the current sea level position, equally ancient crystallizations - situated both above and below ±0 metres a.s.l. (Fig.1) - are an excellent record of the elevation of past coast lines (Ginés *et al.*, 1981a; Pomar *et al.*, 1987). This geomorphical setting is well documented in Mallorcan caves (see a complete bibliographic revision in Ginés, 2000), where some Th/U dating programmes were performed, since the eighties, in order to correlate POS paleolevels with sea level fluctuations along Middle and Upper Pleistocene (Hennig *et al.*, 1981; Ginés and Ginés, 1989; Tuccimei *et al.*, 1997).

The isotopic investigations undertaken in the last years on the POS from Mallorca, represent a promising approach to Pleistocene paleoclimate and sea level change studies, as it is evidenced in several recent papers on this topic (Ginés *et al.*, 2003; Fornós, *et al.*, 2002; Vesica *et al.*, 2000). These tasks have been recently extended to some Sardinian caves (Tuccimei *et al.*, 2000), within a geomor-

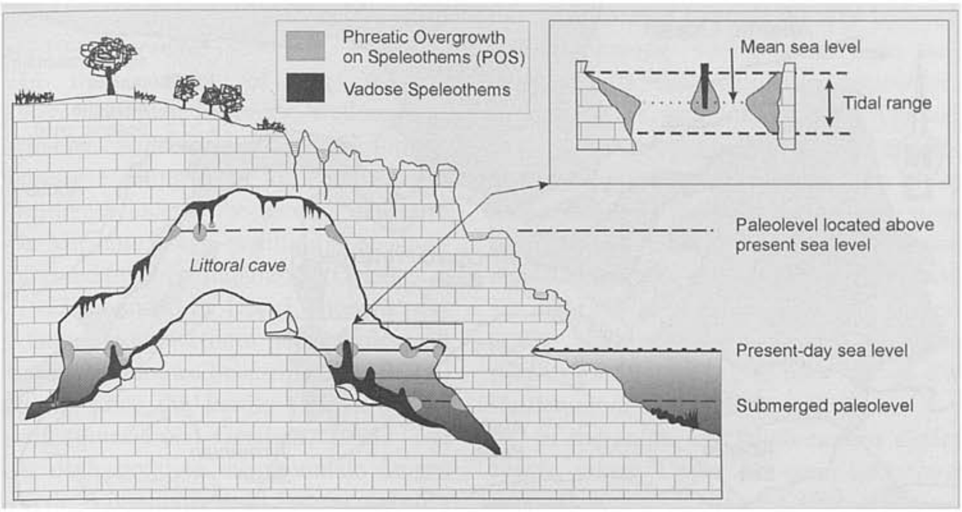

Fig. 1. Schematic representation of a littoral karst cave, outlined in an ideal cross section. Note the presence of phreatic overgrowths on speleothems related with present and past sea levels.
Fig. 1. *Representació esquemàtica d'una cova càrstica litoral, perfilada en una secció ideal. Notis la presència de sobrecreixements freàtics sobre els espeleotemes relacionats amb el nivell de la mar actual i pretèrits.*

phological framework similar to that of Mallorca. Th/U datings of POS from both geographical areas have supplied new informations about eustatic change during Last interglacial (isotopic substage 5e) and neotectonics, on the base of this remarkable karst record. The Phreatic Overgrowths on Speleothems prove to be a new source for Quaternary studies, complementary to more conventional indicators as fossil beaches or other evidences of past coast lines.

Geological and geomorphological setting

The Western Mediterranean is a triangular shaped (Fig. 2), almost continuous thrust and fold belt with a centrifugal sense of thrusting emplacement (Alpine Corsica, Apennines, Maghrebides, Rif, Betics and Balearic Promontory), which surrounds extensional basins partially oceanic (Liguro-Provençal, Algerian and Tyrrhenian) or with attenuated continental crust (Valencia trough and Alboran). The basins are separated by islands (Balearic Archipelago, Corsica and Sardinia) with a complex geological evolution because of the coeval extensional and compressional processes.

Mallorca

The islands of Mallorca (Balearic Archipelago) and Sardinia are located at both sides of this complex geological structure that is the Western Mediterranean, which results from the interaction between the European and the African plates with a set of small plates (Iberian and Apulian) trapped between them (Sàbat and Gelabert, 2003). This evolution started with the NE-SW Africa-Europe convergence, which originated the opening of the Valencia trough-Gulf of Lyon basin (30-20 Ma) and lead (20-10 Ma) to the differential eastward

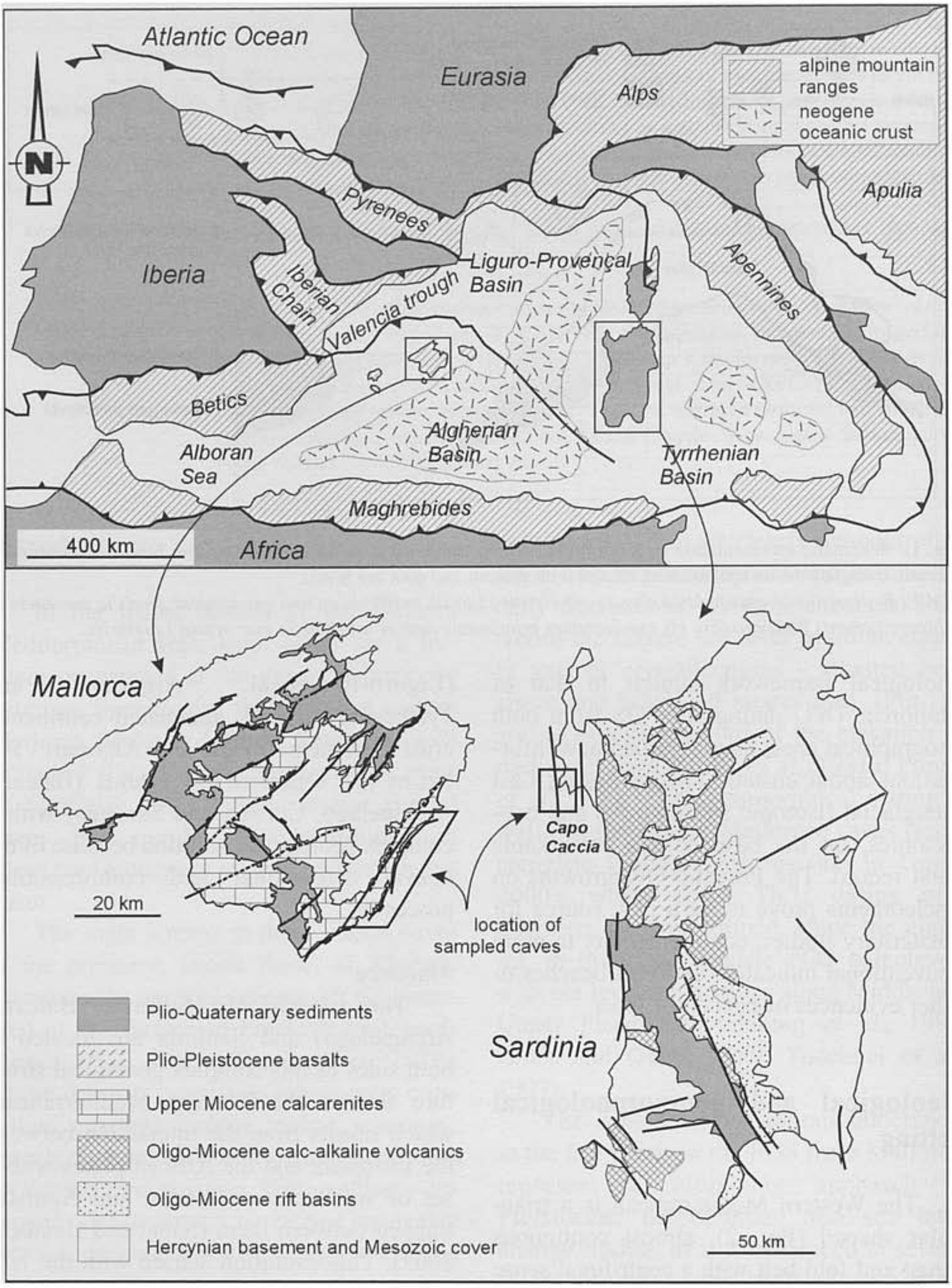

Fig. 2. Simplified tectonic map of the Western Mediterranean and geological sketch maps of Sardinia and Mallorca islands with the location of the sampled caves.
Fig. 2. *Mapa tectònic simplificat del Mediterrani occidental i mapes geològics esquemàtics de les illes de Sardenya i Mallorca on es mostra la localització de les coves que s'han mostrejat.*

migration of Corsica and Sardinia (Gueguen *et al.*, 1997; Séranne, 1999).

In the context of the Western Mediterranean plate tectonics, Mallorca was affected by two tectonic phases: the former, compressive acting from the Paleogene to the Middle Miocene, the second, extensive Upper Miocene in age, resulting in an structure formed by horst and graben (Gelabert *et al.*, 1992) bounded by Upper Miocene normal faults. Both tectonic phases affect all carbonate lithologies occurring almost continuously since the Permo-Triassic to the Present (Fornós and Gelabert, 1995). The horsts correspond to the mountain ranges (Serra de Tramuntana and Llevant) and consist of an imbricate thrust sheet system facing NW. The grabens correspond to the basins (Pla and Migjorn) filled with tabular postorogenic sediments, mainly Upper Miocene to Quaternary in age.

Sediments deposited after the Middle Miocene are considered post-orogenic and do not present evident compressive structures. Consequently, Mallorca must be considered stable since the Upper Miocene.

Most of the evidences of recent tectonic activity in Mallorca are located in the centre of the island (Giménez, 2003) and are related with NE-SW normal fault neogene structures (Gelabert, 1998), due to the opening of the Valencia Trough (Giménez *et al.*, 2002), and fault-propagation folds trending NW-SE, perpendicular to the normal faults (Rohdenburg and Sabelberg, 1973). The coeval occurrence of distensive and compressive structures, means that neogene extension has finished and the Plio-Quaternary regime is closer to a strike-slip field (Giménez, 2003).

Nevertheless some evidences of weak tectonic movements must be considered. Fornós *et al.* (2002) point out a general tectonic tilting with a progressive lowering of the areas located towards the SW by comparing phreatic speleothems ages and heights with the regionally established eustatic curves, supported by other regional, stratigraphical, sedimentological, tectonic and geomorphologic evidences. The tilting was continuous from oxygen isotope stage (OIS) 5a until now, and originates a normal displacement that can be estimated in about 1.5 m of the northeastern part with respect to the southwestern end. This tilting is roughly parallel and agree with the NE-SW shortening direction mentioned above.

In the south and south-eastern cliffed coasts, where Upper Miocene limestones and calcarenites crop out (Pomar *et al.*, 1990), a wide set of endokarst features are remarkable (Ginés, 1995) in the form of solutional voids and caves originated in the littoral phreatic zone by mixing of fresh and sea waters. The caves act as a register of the complex Pleistocene sea level history (Ginés and Ginés, 1995) showing several phases of infillings, collapse and breccia formation and several periods of deposition of both vadose and phreatic speleothems.

Capo Caccia area

Sardinia is a large rectangular island located in the Western Mediterranean Sea off the coast of Italy. It stands on the eastern margin of the Provençal basin, which represents the southern part of a regional rift system active in western Europe during the Cenozoic (Le Pichon *et al.*, 1971; Burrus, 1984; Casula *et al.*, 2001). According to Burrus and Audbert (1990), the Sardinian margin underwent about 100 m of subsidence associated with cooling of the lithosphere since the end of the Messinian, which correspond to an average rate of 2 cm/ka.

Capo Caccia area is located in the NW edge of Sardinia and is made up with limestone, Cretaceous in age, dissected by sys-

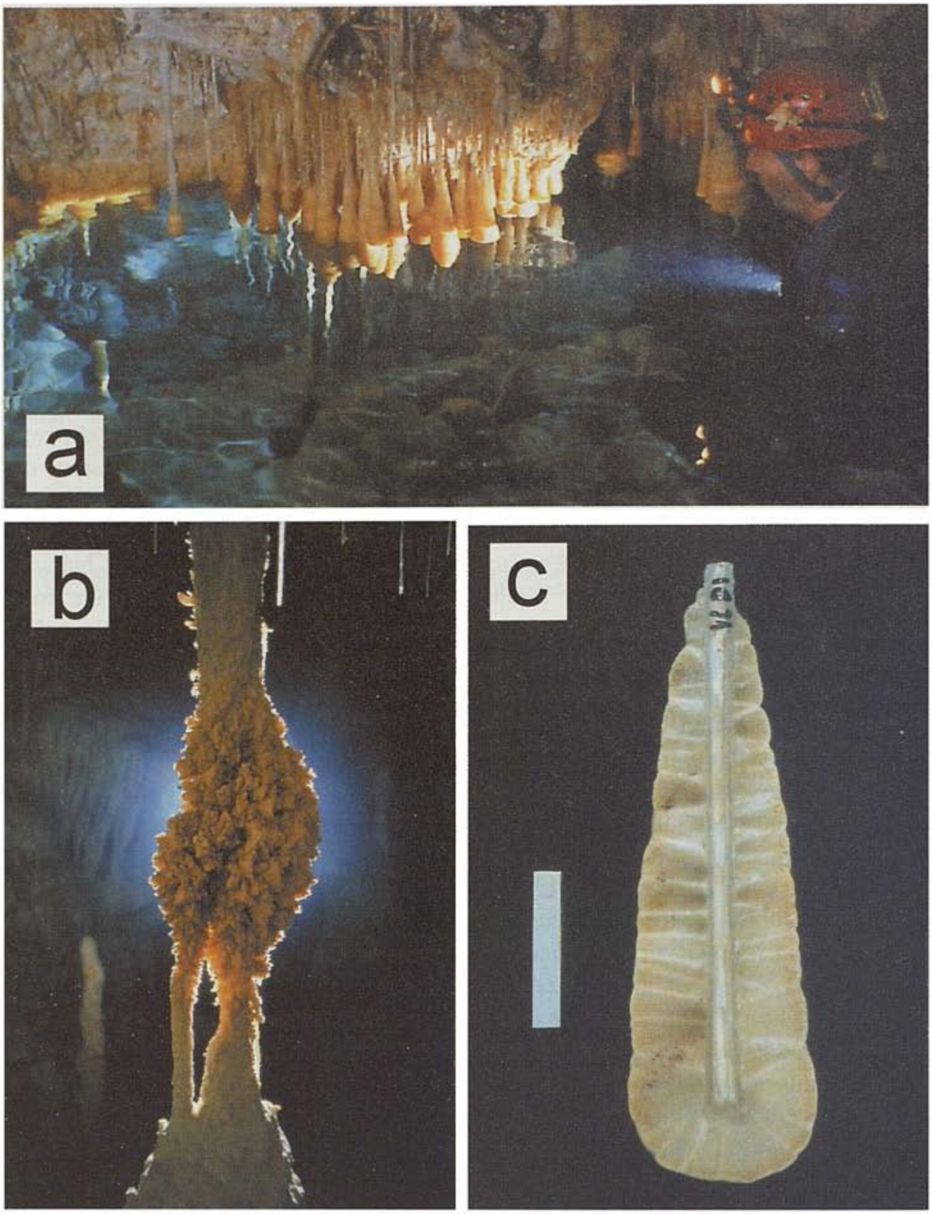

Fig. 3. a) Morphology of present-day phreatic overgrowths in a littoral cave pool from eastern Mallorca, in a low tide situation (photo: K. Downey); b) detail of a calcite overgrowth on a column corresponding to a past sea high stand (note the maximum thickness of the POS corresponding to the coeval mean sea level -photo: A. Merino); c) section of an aragonite overgrowth showing the vadose stalactite that acts as a support of the POS (scale bar: 5 cm).
Fig. 3. *a) Morfologia d'un sobrecreixement freàtic actual en una llac d'una cova litoral de l'est de Mallorca, en una situació de mar baixa (Foto: K. Downey); b) detall d'un sobrecreixement de calcita sobre una columna que correspon a un nivell de mar elevat pretèrit (notis el màxim espessor del POS que correspon al nivell mig de la mar corresponent - foto: A. Merino); c) secció d'un sobrecreixement d'aragonita mostrant com l'estalactita vadosa actua de suport del POS (escala de la barra: 5 cm).*

Table 1 - U-series data of phreatic overgrowths on speleothems (POS) from Mallorca Island and Capo Caccia area

Sample	Cave	Elevation (m)	ppb U	($^{234}U/^{238}U$)	($^{230}Th/^{232}Th$)	($^{230}Th/^{234}U$)	Age (yr)	($^{234}U/^{238}U)_{initial}$
	MALLORCA							
GL-D7 *	Cova de sa Gleda	-13.5	272 ± 2	1.667 ± 0.003	42 ± 1	0.661 ± 0.022	107,400 ± 2,800	1.903 ± 0.008
DI-D1-1 *	Cova del Dimoni	+2.5	2531 ± 7	1,273 ±0,002	236 ± 2	0.654 ± 0.004	109,900 ± 1,100	1.372 ± 0.003
DI-D3 *	Cova del Dimoni	+2.5	2050 ± 6	1.192 ± 0.001	2834 ± 55	0,664 ± 0.003	114,200 ± 900	1.265 ± 0.001
DI-D1-2 *	Cova del Dimoni	+2.5	1254 ± 5	1.087 ± 0.001	5231 ± 62	0.670 ± 0.003	118,400 ± 900	1.122 ± 0.014
PO-D2 *	Cova des Pont	+2.1	347 ± 1	1.381 ± 0.003	529 ± 9	0.704 ± 0.006	122,700 ± 1,900	1.539 ± 0.005
VB-D5 *	Cova de Cala Varques B	-16.5	786 ± 2	1.822 ± 0.003	891 ± 11	0.730 ± 0.003	124,700 ± 900	2.169 ± 0.005
VB-D3 °	Cova de Cala Varques B	-14	680 ± 2	1.881 ± 0.020	320 ± 14	0.735 ± 0.007	125,000 ± 2,000	2.256 ± 0.028
OX-D1 *	Cova de s' Ònix	+3	254 ± 1	1.443 ± 0.002	37 ± 0,5	0.727 ± 0.008	128,500 ± 2,500	1.637 ± 0.005
SE-D2 *	Cova des Serral	+1.5	198 ± 1	1.521 ± 0.009	591 ± 5	0.736 ± 0.005	130,200 ± 1,600	1.752 ± 0.013
PI-D1 *	Coves del Pirata	+2.1	300 ± 1	1.649 ± 0.006	1681 ± 20	0.751 ± 0.006	133,000 ± 1,900	1.945 ± 0.01
GE-D1 *	Cova Genovesa	+2	179 ± 1	1.102 ± 0.003	59 ± 0,9	0.729 ± 0.007	138,000 ± 2,800	1.151 ± 0.004
GL-D2 *	Cova de sa Gleda	-14	505 ± 1	1.968 ± 0.004	242 ± 2	0.796 ± 0.005	143,400 ± 1,600	2.45 ± 0.009
GE-D2 *	Cova Genovesa	-13	244 ± 1	1.233 ± 0.005	38 ± 0,4	0.756 ± 0.012	143,600 ± 4,600	1.349 ± 0.009
	SARDINIA							
GN-D3-1§, #	Grotta di Nettuno	+4.20	271 ± 10	1.050 ± 0.03	95 ± 21	0.690 ± 0.02	125,000 ± 7,000	1.07 ± 0.04
GN-D3-2 °	Grotta di Nettuno	+4.30	212 ± 2	1.203 ± 0.004	100 ± 5	0.677± 0.045	117,000 ± 2,000	1.283 ± 0,007
GN-D4 °	Grotta di Nettuno	+4.30	175 ± 3	1.160 ± 0.013	170	0.682 ± 0.007	120,000 ± 2,000	1.225 ± 0.018
GN-D6 #	Grotta di Nettuno	+4.30	226 ± 5	1.130 ± 0.02	75 ± 28	0.680 ± 0.03	120,000 ± 9,000	1.18 ± 0.03

* stands for MC-ICPMS, ° refers to TIMS analyses, # stands for AC

§ vadose speleothem

Table 1. U-series data of phreatic overgrowths on speleothems (POS) from Mallorca Island and Capo Caccia area. Errors are quoted as 2 sigma.
Taula. 1. *Dades de la sèrie del U de sobrecreixements freàtics a espeleotemes (POS) de la illa de Mallorca i de l'àrea del Capo Caccia (Sardenya). Error expressat com a 2 sigma.*

tems of normal faults with a downthrow westward and south-westward. Along these structural features karst phenomena developed and a large number of littoral caves occur. Inside the caves, POS around cave walls or pre-existing supports are observed.

It is important to stress that the promontory of Capo Caccia is cut at about 4-5 m a.p.s.l. by a wave-cut notch attributed to substage 5e. The notch is recorded at decreasing elevations northward, from 5.40 to about 3.45 m a.p.s.l. This is an evidence of a descendent metric tilting from E to W (Antonioli *et al.*, 1998) with an average rate of about 0.02 mm/yr.

Sampling

Among the very abundant littoral caves found in both geographical areas (Mallorca and NW Sardinia), the sites containing POS - in the form of horizontal alignments of subaqueous crystallizations - were firstly identified (Fig. 3); as it has been exposed before, these deposits are clear indicators of ancient sea levels. The exploration of the cavities required the use of conventional caving techniques, together with specialized scuba-diving in the cave ponds for sampling regressive paleolevels. The recognized POS alignments were sampled collecting preferentially those zenital speleothems (phreatic overgrowths coating vadose stalactites) which are of easier recollection (Fig. 3c); the detailed sampling methodology is described in Ginés (2000).

Samples have been always collected as close as possible to the upper limit of the subaqueous overgrowth, being them -in this manner- unequivocally indicative of the maximum elevation attained by the sea-controlled phreatic level at the moment of the speleothems deposition. The elevation of sampled POS alignments was topographically determined inside the subaerial part of the caves (estimated error ±0.10 meters). In the submerged sections, the depth was measured with the pressure depth-meter used by the divers. In both cases, the elevation of POS paleolevels is referred to the current mean sea level, being the obtained figures rounded to 0.5 meters for the submerged samples.

Thirteen POS specimens from 8 different caves in eastern Mallorca and four speleothems from Grotta di Nettuno (NW Sardinia) have been collected. The elevation of these samples range from +2.5 to -16,5 meters a.p.s.l. in Mallorcan sites (table I), whereas the sampled POS from Sardinia have an elevation of +4.3 metres. These samples are included in an extensive POS study programme that has investigated more than 20 caves in both islands, furnishing a lot of Th/U datings ranging from 3.9 ka to >350 ka BP (Ginés *et al.*, 2003; Hennig et al., 1981; Tuccimei *et al.*, 1997; Vesica *et al.*, 2000). In this paper the attention is focused to speleothems ranging in age from about 150 to 100 ka BP and belonging to the Last Interglacial.

The speleothems were sectioned in the laboratory and samples of the POS extracted with a table micro-drill for mineralogical and isotopical investigations. All the samples were obtained avoiding any existing altered or recrystallizated area. When possible, several sub-samples of the main different growing layers have been identified and dated (Tuccimei *et al.*, 2006).

Analytical procedure

Thirteen samples from Mallorca Island and four from Sardinia were U-series dated using mostly multicollector inductively-coupled mass spectrometry (MC-ICPMS - twelve speleothems), secondarily thermal ionisation mass spectrometry (TIMS - three POS) and alpha-counting (AC - two samples). Data referred to samples from Mallorca are from Tuccimei *et al.* (2006). U-series data of speleothems from Capo Caccia area are new data.

As far as samples analysed by MC-ICPMS are concerned, aliquots of 200 mg were spiked with about 0.1 g of a mixed ^{236}U + ^{229}Th spike solution and dissolved in 7.5 N HNO_3. ^{236}U and ^{229}Th concentrations in the tracer solution were equal to 4.84 and 0.0457 pmol/g, respectively. The sample solutions were directly loaded onto anion exchange columns (Dowex 1x8) to separate U from Th. After washing out matrix elements (Ca, Mg etc.), uranium was eluted with 7.5 N HNO_3 and thorium with 0.5 N HNO_3. U and Th fractions were dried and redissolved with about 0.5 mL of nitric acid.

U and Th solutions were measured at the Laboratory for Isotope Geology (Institute of Geological Sciences), University of Bern (Switzerland) on "Nu Plasma", an inductively coupled plasma double focusing magnetic sector multicollector mass spectrometer, designed and manufactured by Nu Instruments Ltd.

The program measures ^{234}U, ^{235}U, ^{236}U and ^{238}U in static mode. ^{234}U and ^{236}U are

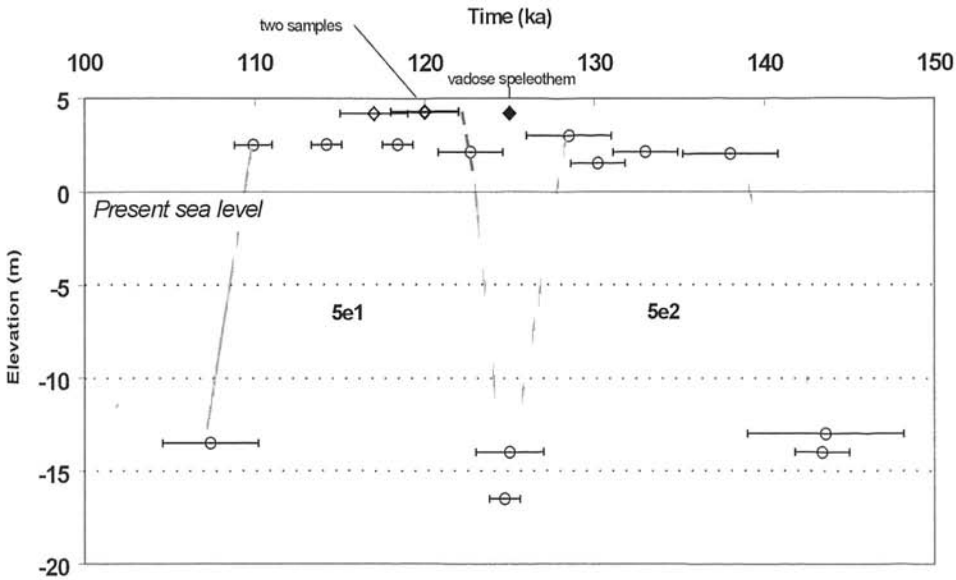

Fig. 4. Last Interglacial high sea stands at Mallorca (Balearic Archipelago) and Capo Caccia area (NW Sardinia) based on Th/U datings of phreatic overgrowths on speleothems. Open circles and solid lines refer to POS from Mallorca, open squares and dashed lines to POS from Capo Caccia and the single closed square to a vadose support in Grotta di Nettuno, Sardinia, (GN-D3-1) around which POS GN-D3-2 formed. The error bar of the vadose speleothem, ± 9 ka (2 sigma), is not reported.

***Fig. 4.** Nivells màxims del nivell de la mar a Mallorca (Arxipèlag Balear) i àrea del Capo Caccia (NW de Sardenya) basats en datacions Th/U de sobrecreixements freàtics a espeleotemes (POS). Els cercles i línies contínues corresponen als POS de Mallorca; els quadrats i les línies discontínues als POS del Capo Caccia, i el rombe al suport vadós dins la Grotta di Nettuno, Sardenya (GN-D3-1), sobre el qual va crèixer el POS GN-D3-2. La barra d'error de l'espeleotema vadós, ± 9 ka (2 sigma), no s'indica.*

measured in ion counters. The $^{235}U/^{238}U$ ratio is used for fractionation correction. Ion counters gain calibration is done using the U050 standard (NIST). In order to cancel out any memory effect, a 5-10 minute wait between individual runs is required during which the system is flushed with clean 0.5 N nitric acid.

For Th runs, the $^{235}U/^{238}U$ ratio is used for fractionation correction and U960 must be added to the sample. The program has two cycles in which ^{229}Th and ^{230}Th are alternatively measured in ion counter #1. In order to prevent damage to the electron multipliers due to the high ^{232}Th beam, the $^{230}Th/^{232}Th$ ratio is not measured directly, but is calculated via ^{238}U. Gain calibration is done using a standard, Th from MOSS, best diluted 1:50 in 0.5 N HNO_3. It has a $^{230}Th/^{232}Th$ ratio of 1.560 (± 0.003) x 10-4 (1 standard deviation, 24 runs). If samples with little ^{232}Th are run after such a gain calibration run, it is important to allow time to let the ^{232}Th memory die down. This mostly takes at least 10 minutes and can be helped by nebulizing some 2N HCl for a while.

The two samples analysed by TIMS were prepared and measured according to the analytical procedures described in Edwards et al. (1986-1987) and in Tuccimei et al. (2004).

AC dated samples were prepared following the procedure described in Bishoff et al. (1988).

The age and the initial ($^{234}U/^{238}U$) activity ratios of all samples were calculated by means of ISOPLOT, a plotting and regression program designed by Ludwig (1994) for radiogenic-isotope data. U-series data are reported in Table 1. Errors are always quoted as 2 ?.

Last Interglacial high stands

Timing of Last Interglacial period (known as substage 5e) has been controversial. Some studies suggest a relatively short duration that is orbitally forced (CLIMAP Project Members, 1984; Martinson *et al.*, 1987) and others indicate a long duration that is at most only partly related to orbital forcing (Lorius *et al.*, 1985; McManus *et al.*, 1994; Winograd *et al.*, 1992, 1997; Jouzel *et al.*, 1993; Szabo *et al.*, 1994; Kukla *et al.*, 1997). In addition, Maslin and Tzedakis (1996) report evidence of a sudden, short-lived (< 1 ka long) chill, during oxygen isotope substage 5e, at about 122 ka B.P. Other authors indicate that a short low sea stand episode has occurred during OIS 5e in the mediterranean region (Hearty *et al.*, 1986; Hearty, 1987; Hillaire-Marcel *et al.*, 1996; Zazo *et al.*, 1997; Vesica *et al.*, 2000; Dai Pra and Ozer, 1984; Riccio *et al.*, 1999; Hearty, 2002; Jedoui *et al.*, 2003), as well as in other areas of the world (Chen *et al.*, 1991; Zhu *et al.*, 1993; Neumann and Hearty, 1996; Hearty, 1998; Israelson and Wohlfarth, 1999).

This section is focused on sea level changes during Last Interglacial in two sites of the Western Mediterranean, Capo Caccia area (NW Sardinia) and Mallorca (Balearic Islands), based on U-series dating of phreatic overgrowths on speleothems.

Mallorca

At Mallorca U-series ages indicate two high sea stands during the Last Interglacial (Tuccimei *et al.*, 2006) that may have occurred from 135 to109 ka (Fig. 4):

-a first stand at 1.5-3 metres above present sea level (a.p.s.l.), with an earlier possible beginning at 140.8 and a later start at 135.2 ka B.P. The conclusion of this episode can be set from 131 to 126 ka, resulting in a possible duration of a minimum of 4.2 ka and a maximum of 14.8 ka (average value = 9.5 ka);

-a second stand apparently longer than the first, at 2.5 metres a.p.s.l., with an earlier possible beginning at 124.6 ka and a later start at 120.8 ka B.P. The end of this stand fall from 111 to 108.8 ka, lasting a minimum of 9.8 ka and a maximum of 15.8 ka (average value = 12.8 ka);

The two high stands are separated by a low stand at a maximum depth of 16.5 m around 125 ka.

Two high sea stands during oxygen isotope substage 5e have been found in beach deposits from Mallorca Island also by Hearty (1986), Hearty et al. (1987) and Hillaire-Marcel *et al.* (1996). Th/U measurements by TIMS on mollusc shells from unconformably superimposed indurated littoral conglomerates and beach-rocks yielded ages of 135 and 117 ka (Hillaire-Marcel *et al.*, 1996).

Capo Caccia

In Capo Caccia area (NW Sardinia), only an episode of high sea stand has been recorded at 4.3 m a.p.s.l. According to the ages of POS (120 - 117 ka), a minimum duration of 3 ka can be been estimated for this episode. It can be correlated with the late substage 5e found at Mallorca (5e1 in Fig.4). The age of 125 ka obtained for a vadose speleothems (GN-D3-1) representing the support of POS GN-D3-2 and located at 4.3 m a.p.s.l. suggests that around that age the sea level was lower than 4.3 m a.p.s.l. The large error (± 9 ka) associated with this age does not allow any further temporal consideration.

On the basis of the collected data, there are no evidences of the early 5e high sea stand (5e2 in Fig. 4) in the area of Capo Caccia, but it is not possible to exclude that this is due to a lack of sampling. Consequently only the data referred to the more recent high stand will be discussed.

Discussion

On the basis of the data available so far (Fig. 4) the high sea stand referred to late substage 5e is recorded at higher elevation on the north-western coast of Sardinia with respect to the eastern coast of Mallorca. The two sites can be considered substantially stable, even if minor post-120 ka tilting phenomena have affected similarly both sites (Fornós *et al.*, 2002; Antonioli *et al.*, 1998). In both cases, the sea level change can be considered to follow, in a first approximation, the eustatic sea level fluctuations in the Western Mediterranean, since Sardinia and Mallorca are located sufficiently far from former Penultimate Glacial Maximum ice sheets and are not significantly affected by glacial unloading. Further away from the ice sheets, regional differences in sea level changes are mainly controlled by the unloading and the loading of the seafloor as ocean volumes change (Lambeck and Bard, 2000). The small difference in elevation, from a maximum of 3.3 to a minimum of about 1 m (Fornós *et al.*, 2002; Antonioli *et al.*, 1998) recorded for the Last Interglacial sea stand at Mallorca and Capo Caccia could be due, besides to tectonics, to the different responses of the two sites to the uplift and subsidence processes induced by changes in the loading of the central basin of the Western Mediterranean seafloor during the last two glacial-interglacial cycles Lambeck and Bard (2000, Figure 10) report a map of predicted sea level in the Western Mediterra-nean at the time of Last Glacial Maximum (based on EO earth model parameters). The EO earth model describes the mantle as a three spherical layer, compressible body, comprising a lithosphere (with a given elastic thickness), an upper mantle and a lower mantle (with given different average effective viscosities). By changing the value of the elastic lithospheric thickness, different predictions of sea level come out. This means that a different lithospheric thickness can induce different responses to changes in the water loading.

In the above mentioned map, the eastern coast of Mallorca is approached by a -120 m contour line and Capo Caccia area is crossed by a -115 m line. In addition, the two sites are characterised by a different crustal thickness. Mauffret *et al.* (1996) show that the Moho depth is about 25 km along the eastern margin of the Provençal Basin where Mallorca is located, but the contour line of 25 km in the Capo accia area is locally displaced westward, suggesting that a thicker crust is present in NW Sardinia. These findings could justify the different responses of Mallorca and Capo Caccia area to the water loading that followed the Last Glacial Maximum, with a stronger subsidence of Mallorca, where the crustal thickness is lower, with respect to Capo Caccia.

If similar processes were active also during previous glacial-interglacial cycles, they could also justify the lower elevation of late 5e high sea stand at Mallorca with respect to Capo Caccia area.

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