ELSEVIER

Geodinamica Acta 15 (2002) 113–125

Geodinamica Acta

www.elsevier.com/locate/geoact

Phreatic overgrowths on speleothems: a useful tool in structural geology in littoral karstic landscapes. The example of eastern Mallorca (Balearic Islands)

Joan J. Fornós [a,*], Bernadí Gelabert [a], Angel Ginés [b], Joaquín Ginés [a], Paola Tuccimei [c], Pierluigi Vesica [d]

[a]Department Ciències de la Terra, Universitat de les Illes Balears. Cra. Valldemossa, km. 7.5, 07071 Palma de Mallorca, Spain
[b]Museu Balear de Ciències Naturals, Cra. Palma-Port de Sóller, km. 30, Sóller (Mallorca), Spain
[c]Dipartimento di Scienze Geologiche, Università 'Roma Tre', Rome, Italy
[d]Istituto per le Tecnologie Applicate ai Beni Culturali, Area della Ricerca di Roma del CNR, Monterotondo, Italy

Abstract

Along the eastern coast of Mallorca, many littoral caves partly filled with brackish waters occur. The most peculiar aspect of these caves is the presence of abundant phreatic overgrowths formed on pre-existing supports located at the underground pools' water table, which corresponds to the present sea level. Besides a specific geomorphological interest, these subaqueous speleothems provide an excellent record of Quaternary sea level stands. The clear relation between phreatic speleothem growth and the contemporary sea level allows the control of the tectonic evolution of an area, by comparing speleothems' ages and heights with the regionally established eustatic curves. In the studied region different altimetric positions of coeval phreatic speleothems suggest the existence of a recent tectonic activity. The characteristics and chronology of this tectonic event are the objectives of this paper, pointing out at the same time the potential of phreatic speleothems in structural geology investigations. Along the coastline of the studied area, alignments of phreatic speleothems attributed to high sea stands 5a, 5c and 5e are recorded at increasing elevations northwards. This is an evidence of a significant tectonic tilting that took place, at least partially, after substage 5a because phreatic speleothems of this substage are now located at different altitudes. Considering that tectonic tilting has been continuous from post-substage 5a (approximately 85 ka) until now, and that normal displacement is approximately of 1.5 m, the average minimum velocity of the tilting can be estimated about 0.02 mm/year in the southern part with respect to the north end. Data obtained from phreatic speleothems have been compared with other regional, stratigraphical, geomorphological and tectonic evidence that all together point to the same existence of the postulated tectonic tilting. Consequently, phreatic speleothem investigation results in a new method that allows the quantification of average velocities of tilting as well as other tectonic movements with high precision. This methodology can be extended to any littoral karstic landscape where phreatic speleothems are present. © 2002 Éditions scientifiques et médicales Elsevier SAS. All rights reserved.

Keywords: Western Mediterranean; Coastal karst; Phreatic speleothems; Tilting; Geomorphology; Neotectonics

1. Introduction

Karstic caves provide an excellent and sheltered environment for the identification of paleotectonic events if compared with the weathered and usually covered landscape outside. The simplicity of some karst speleothem assemblages—together with their dating possibilities using U-series disequilibrium, ^{14}C or paleomagnetism—allows the modeling of the different structural events experienced by a territory. Consequently, these deposits can be successfully used in tectonic and paleoseismic analyses [1–3].

Nowadays, the relationships between karst and structural processes have been increasingly investigated [4], mainly as regards the use of speleothems in the recognition of ancient seismic events [5] and their potential to evaluate the possible magnitude of an earthquake and the pattern of connected fractures [6–9]. Some contributions deal with the limits and validity of such methods [1].

Besides paleoseismicity investigations, other karst- related topics frequently discussed in the literature [4] are,

* Corresponding author. Tel.: +34-971-173-161; fax: +34-971-173-184.
E-mail addresses: joan.fornos@uib.es (J.J. Fornós), tuccimei@uniroma3.it (P. Tuccimei), datalab@mlib.cnr.it (P. Vesica).

© 2002 Éditions scientifiques et médicales Elsevier SAS. All rights reserved.
PII: S 0 9 8 5 - 3 1 1 1 (0 2) 0 1 0 8 3 - 5

among others: the role of structural control on both hydrogeological aspects and the genesis of cave systems [10], the recognition of neotectonic events [11–13] or, for instance, the evaluation of uplift rates and their influence in karst landform evolution [6,14].

Along the eastern coast of Mallorca, many littoral caves partly filled with brackish waters and heavily decorated with speleothems occur. The main peculiarity of these caves is the presence of conspicuous carbonatic phreatic overgrowths (POS) that are an excellent record of quaternary sea level stands. This kind of subaqueous speleothem is frequently found in the subterranean pools of Majorcan caves, in correspondence with the current level of sea waters [15]. Furthermore, a great number of phreatic crystallization deposits have been observed between +40 m above and –23 m below present-day sea level [16]. The formation of this particular kind of speleothem is related to paleolevels attained by the ground water table as a result of quaternary eustatic fluctuations [17,18], which are mainly controlled by abrupt climatic variations. U/Th dating of these speleothems has supplied an accurate reconstruction of Mediterranean eustatic oscillations during the last 300 ka BP [19–23].

The evident correlation between phreatic speleothem growth and the contemporary sea level allows the control of the tectonic evolution of an area, by comparing their datings and heights with the regionally established eustatic curves. Different altimetric positions of coeval speleothems suggest the occurrence of a recent tectonic activity that has affected the studied region. The characteristics and chronology of this tectonic event are the objectives of this paper, pointing out at the same time the potentials of phreatic speleothems in structural geology investigations.

2. Geological and geomorphological setting

The Balearic Islands are located in the middle of the western Mediterranean sea (Fig. 1). Mallorca, with its 3667 km^2, is the largest and the most central island of the archipelago. It is rhomboidal in shape and its vertices are oriented to the four cardinal points. The carbonatic lithologies, occurring almost continuously since the Middle Triassic [24] to the present, feature a geomorphological wide range of endo- and exokarstic morphologies. These lithologies have been extensively affected by a complex tectonic phase that acted from the Paleogene to the Middle Miocene, framed within the context of the western Mediterranean plate tectonics, which caused a strong orography.

The resulting structure [25] can be described [26] as a horst and graben system (Fig. 1). The horsts correspond to the ranges (Serres) which consist of an imbricate thrust sheet system, facing NW. The stratigraphic series of these thrust sheets range from Mesozoic to Lower Cenozoic. The steepest mountain range, known as Serra de Tramuntana, is located on the northwestern side of the island and is trending in a NE–SW direction. In the east, the Serres de Llevant shows a similar orientation and less rough topography due to the predominance of dolomitic and marly lithologies. The grabens correspond to the basins (El Pla and Migjorn) and are filled with deposits ranging in age from Upper Miocene to Quaternary. The El Pla and Migjorn areas, settled in the center and the south of the island, respectively, are mainly formed by Neogene tabular post-orogenic deposits. In the Migjorn area, Upper Miocene calcarenites predominate.

The boundary between the ranges and the basins are Upper Miocene normal faults. However, the differentiation between ranges and plains is not always so clear; they are frequently limited by Tertiary fractures, but occasionally their limits are angular discordances in which structures produced during the Mesozoic (normal faults) or in the Lower Cenozoic (mainly thrust) are buried by Tertiary and Quaternary deposits.

Along the eastern and southern coasts of Mallorca (Fig. 1), Upper Miocene reefal and oolitic calcarenites (Reef Unit and Santanyí Limestones [27,28]) crop out, exhibiting numerous and peculiar endokarstic forms [29]. They consist of caves originated as a network of solutional voids produced by mixing processes between fresh continental and sea waters in the littoral phreatic zone. During Pleistocene times, the cavities underwent successive wall and ceiling collapses which alternate and coexist throughout time with intense vadose stalagmitization phases and phreatic overgrowth deposition during the flooding periods in relation to the Mediterranean glacio-eustatic oscillations. The breakdown processes largely determine the present aspect of these caves and are also responsible for their opening to the exterior through collapsed entrances. Frequent infillings (POS and paleontological breccia) of great speleochronological and paleoclimatic value [30,31] have finally deposited in the caves.

3. Methods

Samples of phreatic overgrowths related to sea paleolevels were collected along a SW–NE profile in the eastern part of Mallorca, where investigated littoral caves are located (Fig. 1). A mineralogical and textural description of them was performed and their elevation with respect to the present sea level was measured. Samples were also U/Th-dated and analyzed by X-ray [23].

Bibliographic and field geomorphologic, stratigraphic and structural data observations were also obtained. A geomorphologic study of the coast was performed to detect differences in sea cliff alignments and describe the distinctive characteristics of bights (‘calas’) along the same section of the coast. A post-tectonic stratigraphic record along the eastern coast of Mallorca was obtained, and stratigraphic sections of the Upper Miocene were compared along the same sector of the coast. Drill cores were obtained from the incised valleys cut on Upper Miocene calcarenites where

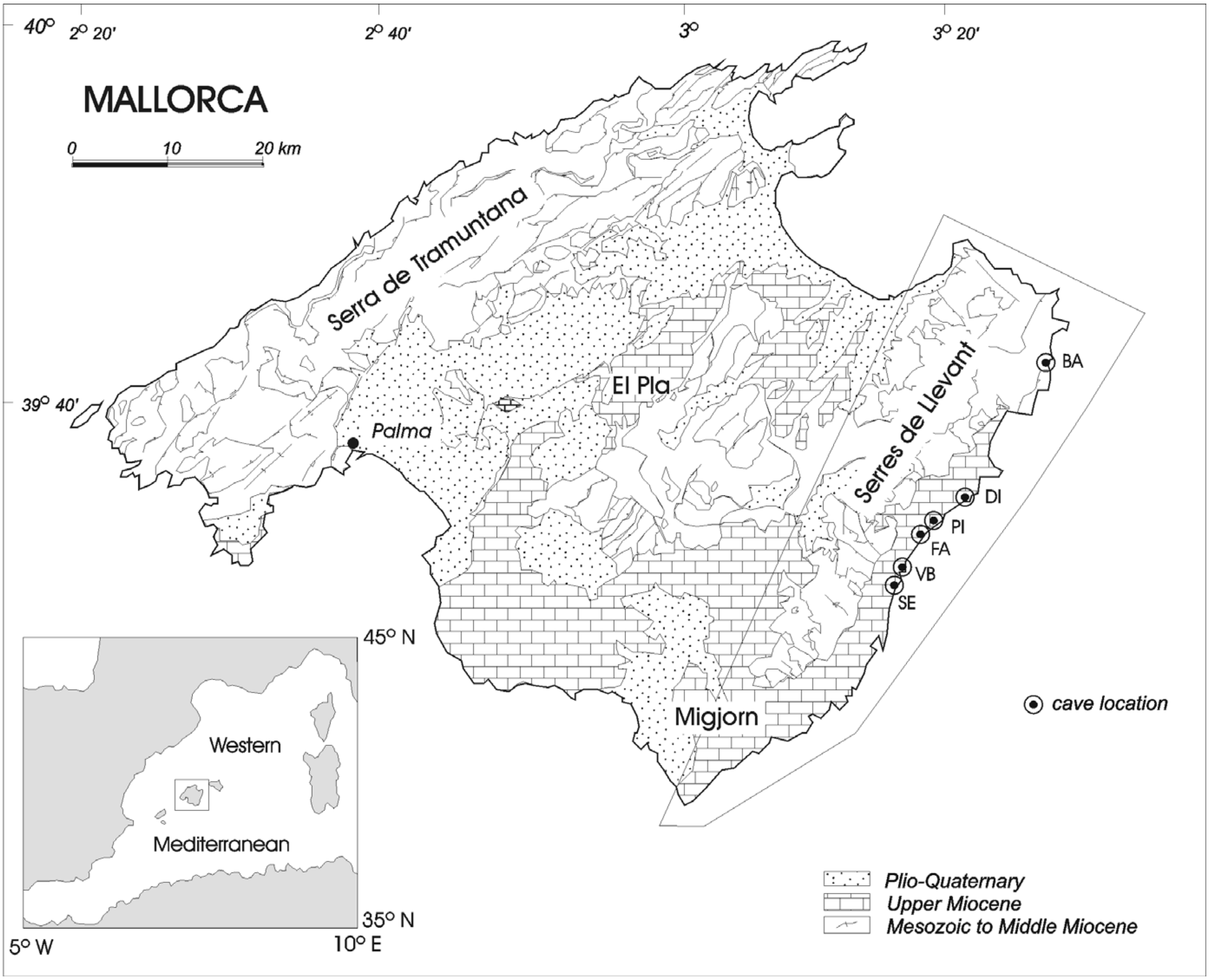

Fig. 1. Geological sketch of Mallorca Island with location of investigated caves (dots) containing POS. Cave located on Mesozoic limestones and dolostones: BA (Cova de na Barxa). Caves located on Upper Miocene limestones: DI (Cova del Dimoni), PI (Coves del Pirata), FA (Cova de Cala Falcó), VB (Cova de Cala Varques B), SE (Cova des Serral). Highlighted area is enlarged in Fig. 5.

Quaternary infillings were supposed to occur. The presence of quaternary dune and beach deposits was also taken into account. A structural analysis of main lineations and fractures was performed using aerial photographs.

Finally, the results of speleothem dating and their altimetric records were compared and related with the geomorphologic, tectonic, and stratigraphic data.

4. Sea level controlled phreatic speleothems

The karstic areas of Mallorca island show abundant littoral caves, partially drowned by brackish waters due to the post-glacial sea level rise. In such subterranean pools subaqueous speleothem deposition occurs, corresponding to the present-day level of sea waters [15]. The main interest in this carbonate precipitation process is represented by the horizontal alignments of phreatic speleothems which have recorded the past high and low stands of sea level, induced by Quaternary climatic fluctuations [17,18].

These crystalline deposits are similar to other subaqueous carbonate speleothems, but their morphological diversity is quite remarkable. Their formation takes place in the proximity of the ground-water table, developing over any suitable support like the cave walls or even previous vadose speleothems (stalactites and stalagmites). The phreatic speleothems usually consist of bulky carbonatic overgrowths whose thickness corresponds to the water table fluctuation range, which is in turn controlled by daily sea level fluctuations such as tides. These carbonatic coatings are disposed belt-like around ancient stalagmites or columns; in other cases, especially when the phreatic overgrowth affects

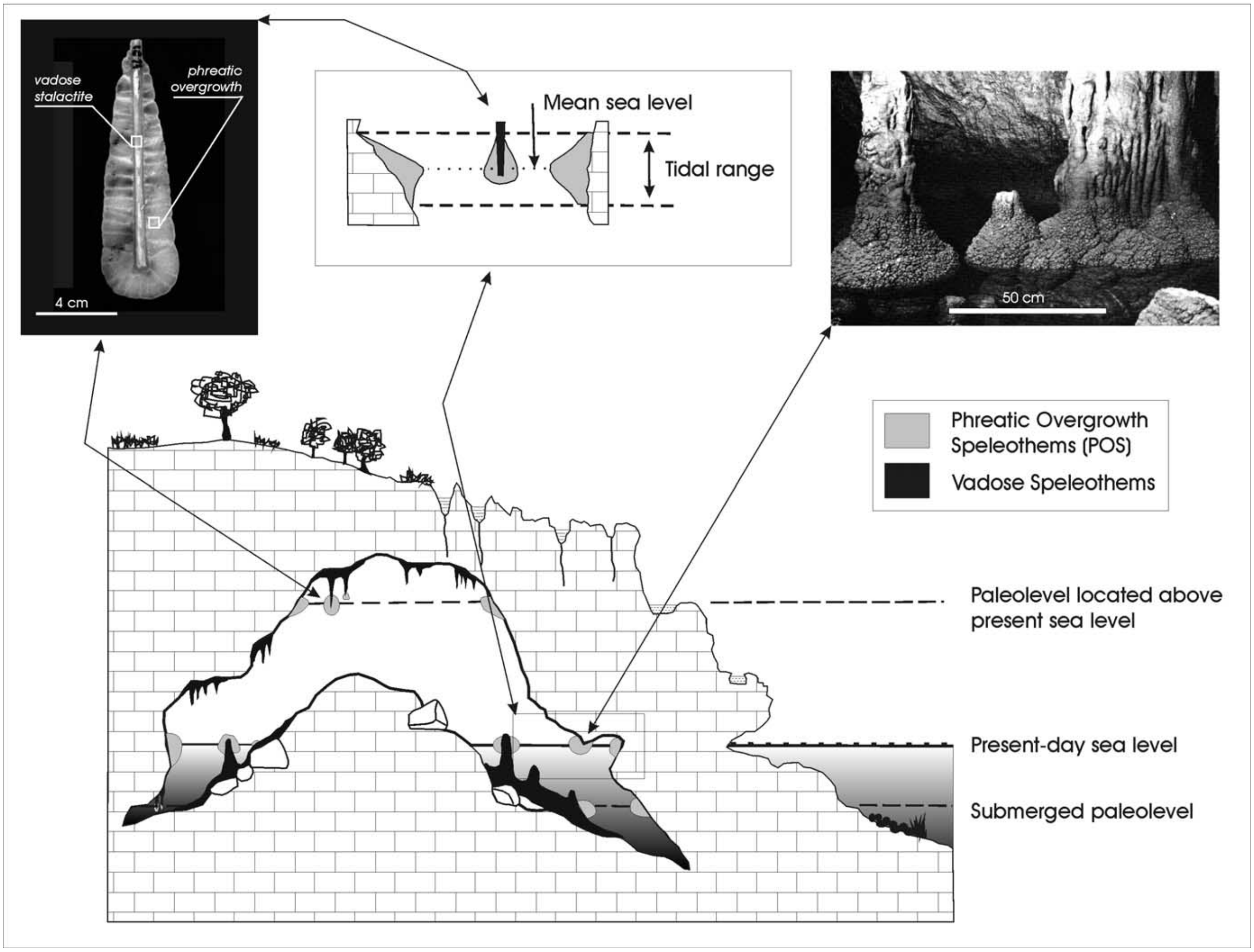

Fig. 2. Schematic representation of littoral karst in Mallorca outlined in an ideal cross-section. Note the presence of POS related to past and present sea levels, as well as the detailed morphology due to the tidal and atmospheric oscillation of the coastal water table.

the tips of stalactites, the original speleothem morphology can be greatly modified (Fig. 2). Frequently, floating calcite rafts are trapped between the growth layers of these coatings.

Although a lot of work remains to be done on the geochemistry of the coastal aquifers where this kind of carbonate precipitation occurs, it appears certain that these phreatic speleothems originate mainly along the oscillation range, usually 50 cm in height, of the surface of such subterranean pools [15]. Some localities may prove that these coatings can be produced even several decimeters below the water table. In both cases the proximity to the pool surface favors the precipitation process, as the carbon dioxide degassing is enhanced near the water surface.

Phreatic crystallizations from Majorcan caves offer a great textural and mineralogical variability as shown in several publications [32,33], being mainly present calcite and aragonite as well as low Mg-calcite and high Mg-calcite or even dolomite. The combination of various factors (mineralogy, crystal size and habit, and fabrics of the mineral deposit) conditions the external morphology of phreatic speleothems [16]. The resulting appearance can include smoothed rounded surfaces, small coralloid-like projections and very spectacular macrocrystalline formations. The last-mentioned papers pointed out the paleoclimatic significance of phreatic speleothem mineralogy by relating the presence of aragonite to warm events—particularly Oxygen Isotope Stage (OIS) 5—which, in marine sediments, results in the appearance of malacological thermophile fauna typical of the Eutyrrhenian [34–36].

A great number of phreatic speleothems paleolevels have been recognized between +40 m above current sea level and –23 m below [16], in caves located along the whole coast of the island. In some papers [37] the possibility has been considered of altimetrically correlating these deposits with past coast lines, corresponding to the Middle and Upper Pleistocene, also identified by fossil raised beaches in Mallorca [38].

In order to assess this, two radiometric dating programs (Th/U method) of phreatic speleothems collected in Majorcan littoral caves were performed during the last decades

[16,19–23,39]. The obtained results (see next section for a detailed discussion) clearly support the previous geomorphological assumptions and confirm that the higher paleolevels (>30 m a.s.l.) must belong presumably to the Middle Pleistocene, since they bring forward ages over 300 ka BP.

The possibilities that derive from the geochronological study of phreatic speleothem alignments are quite promising, especially regarding the better knowledge of both the Quaternary in Mallorca and the sea level history in the western Mediterranean basin.

5. Th/U datings of phreatic speleothems in coastal caves of Mallorca

About 40 samples of phreatic speleothems from 14 caves located along the eastern coast of Mallorca have been analyzed using the Th/U method in order to reconstruct the Mediterranean sea level history during the Late Quaternary [16,19–23,39]. The obtained ages range from 3.9 ka BP—in the case of post-glacial samples located at the current sea level—to more than 350 ka that are referred to speleothems occurring higher than +30 m a.s.l. and belonging at least to OIS 9 or 11.

Speleothems ranging in age between 60 and 150 ka BP are the most frequent [16,22]. On their basis a very accurate reconstruction of the Mediterranean sea level history during the last interglacial period (OIS 5) has been proposed (Fig. 3). At least three high sea stands (only a few meters above the current marine level) have been recognized within this complex climatic event. They were separated by very dramatic sea level falls, more than 18 m in only a few thousand years in response to cold climatic pulsations. The rates of sea level shift have been deduced, obtaining mean values of 4 m/ka [22], similar to those reported for the last interglacial in other geographical environments [40].

Phreatic speleothems formed during the high sea stands referable to OIS 5 deserves special attention (Table 1 and Fig. 3). They have recorded at heights ranging from +1.4 to +2.5 m a.s.l. several stands of the Mediterranean sea corresponding to warm substages 5a, 5c and 5e. Phreatic speleothem paleolevels belonging to substage 5e are very well-documented, with ages ranging between 111.9 and 130.4 ka BP. Th/U dating of 5e speleothems allows to recognize two different high sea stands at 112–125 and 130–135 ka BP [22]; these warm climatic pulsations have been also suggested from marine Tyrrhenian deposits of Mallorca [41] as well as on the basis of geological evidence from other geographical areas such as the Bahamas [42].

Finding coeval samples at diverse elevations, in different caves along the eastern coast of the island, is illustrative of a tectonic deformation of the studied area, as discussed later. Referring first to phreatic speleothems attributed to substage 5e—which are well-documented, with a total of six U-series datings—this past sea level is represented at about +1.5 m

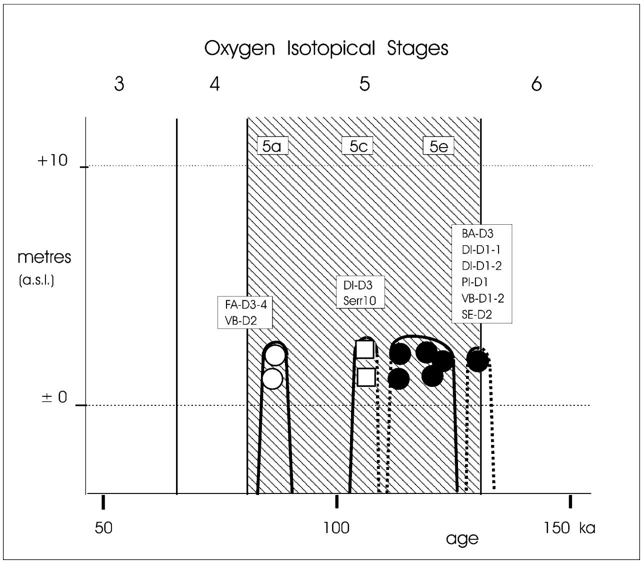

Fig. 3. Partial eustatic curve of the last interglacial period in Mallorca. Phreatic speleothem samples used in this study are represented as open dots (OIS 5a), open squares (OIS 5c), and black dots (OIS 5e). Solid lines represent sea level fluctuations documented by more than one dating [22].

in the southern part of Migjorn area (Cova des Serral), but records of the same substage are found at progressively higher positions in caves located north-eastwards: in Coves del Pirata it is present at +2.1 m, whereas in Cova de na Barxa (the northernmost investigated cave, in Serres de Llevant area) it has been recognized at about +2.4 m a.s.l. These data demonstrate that the height of phreatic speleothems formed during substage 5e is progressively increasing from SW towards NE (Fig. 4).

The same setting is documented by speleothems correlated to other substages: OIS 5c and 5a. Speleothems attributed to substage 5c were collected (from SW to NE) in Cova des Serral at +1.5 m and in Cova del Dimoni at +2.5 m a.s.l. Samples pertaining to OIS 5a occur at +1.4 and +1.9 m, respectively, in Cova de Cala Varques B and in Cova de Cala Falcó. In all cases there is a change in the elevation of contemporary deposits that increases more than 1 m towards NE, reaching the highest elevations in the Serres de Llevant area.

Our chronological and altimetrical data are in general agreement with those corresponding to marine terraces, with full thermophile fauna, attributed vaguely to OIS 5. These deposits are usually found at heights between +1 and +3 m along the coastline of Mallorca, as established by Cuerda and Butzer mainly [34,38,43]. In particular, the best-known last interglacial marine site in the island—Camp de Tir, in Palma bay—yielded ages of 117 and 135 ka BP, referred to two different beach deposits, the oldest culminating at +3 m a.s.l.; this height is consistent with the more accurate data supplied by phreatic speleothems from the eastern coast of Mallorca.

Table 1
U-series data of POS used in this study. Data from Vesica et al. [23]. Data referred to sample Serr10 from Hennig et al. [39]

Locality	Sample	Height a.s.l. (m)	U (ppb)	$^{234}U/^{238}U$	$(^{234}U/^{238}U)_0$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	Age (ka)
Cova de na Barxa	BA-D3[a]	+2.4	423 ± 19	1.430 ± 0.070	1.612 ± 0.103	∞	0.715 ± 0.045	124.7 ± 14[d]
Cova del Dimoni	DI-D1-1[a]	+2.5	2640 ± 77	1.185 ± 0.013	1.255 ± 0.018	257.3 ± 25.4	0.660 ± 0.020	112.9 ± 5.8[d]
	DI-D1-2[a]	+2.5	1273 ± 48	1.090 ± 0.018	1.126 ± 0.025	∞	0.676 ± 0.032	119.7 ± 10[d]
	DI-D3[a]	+2.5	1887 ± 45	1.108 ± 0.015	1.147 ± 0.020	∞	0.638 ± 0.020	107.9 ± 5.7[d]
Coves del Pirata	PI-D1[a]	+2.1	262 ± 9	1.663 ± 0.062	1.959 ± 0.092	∞	0.745 ± 0.035	130.4 ± 14[d]
Cv. de Cala Falcó	FA-D3-4[b]	+1.9	542 ± 5	1.378 ± 0.003	1.528 ± 0.037	112.3 ± 0.2	0.554 ± 0.023	83.9 ± 5.0[d]
Cv. C. Varques B	VB-D1-2[b]	+1.4	252 ± 4	1.519 ± 0.081	1.71 ± 0.08	∞	0.632 ± 0.020	111.9 ± 5.7[d]
	VB-D2[b]	+1.4	228 ± 10	2.113 ± 0.099	2.41 ± 0.13	∞	0.567 ± 0.025	83.4 ± 5.1[d]
Cova des Serral	Serr10[a]	+1.5	233 ± 5	1.487 ± 0.025	–	733.3 ± 733.3	0.663 ± 0.015	109.0 ± 4.0[c]
	SE-D2[a]	+1.5	200 ± 4	1.453 ± 0.032	1.639 ± 0.046	240 ± 45	0.705 ± 0.019	121.3 ± 5.6[d]

[a] Alpha counting.
[b] Mass spectrometry.
[c] $\pm 1\sigma$.
[d] $\pm 2\sigma$.

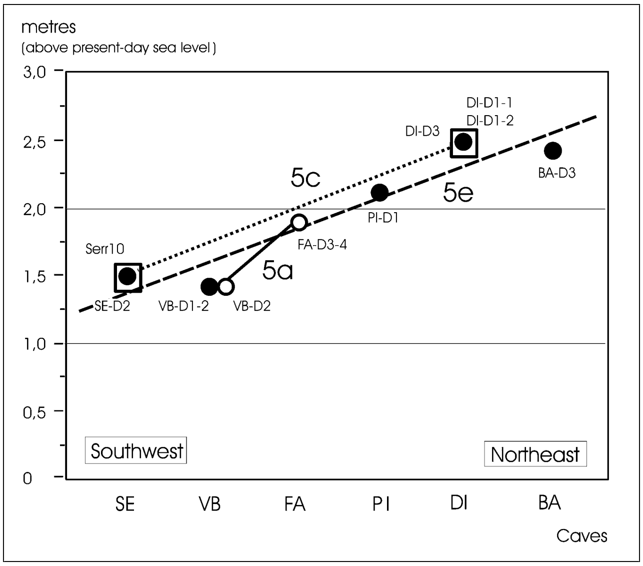

Fig. 4. Present-day elevation of the phreatic speleothems referred to the last interglacial period (OIS 5). Height differences of coeval samples are attributed to neotectonic movements. Note the general tilting with a subsidence towards the southwest represented by lines. Latitudinal distribution of caves not to scale. Name and location of caves are reported in Fig. 1. White dots, samples corresponding to OIS 5a; squares, samples corresponding to OIS 5c; black dots, samples corresponding to OIS 5e.

6. Stratigraphical, geomorphological and structural proofs

The general tilting of the studied area is also demonstrated by stratigraphical, geomorphological and tectonic data, as well as by other microtectonic imprints. Although none of them can be considered as conclusive, all of them point in the same direction.

Among them, those referred to the geological mapping (Upper Miocene to Holocene outcrops), the stratigraphy (Pleistocene alluvial and dune deposits, as well as Holocene infillings), the geomorphology (especially the littoral and fluvial features) and the structural geology (distensive fracturation) will be considered.

6.1. Regional stratigraphy and geological mapping

The structured deposits that build up the Serres de Llevant are surrounded by post-orogenic deposits (mainly Upper Miocene in age) along the eastern and southern part of Mallorca Island (Fig. 1).

From a simple examination of the Mallorca geological map [44] it appears that the older materials outcrop more extensively northeastwards (Fig. 5). In particular, post-orogenic stratigraphic levels pertaining to the basal levels of the Upper Miocene Reefal Unit [28] crop out in the northeastern end of the area. Moving southwestwards, the Santanyí Limestones [27] of the Upper Miocene appear and finally, Plio-Pleistocene calcarenitic dunes occur in the south, without significant changes in the topographical height of the area.

A more detailed examination of the Santanyí Limestones shows the same structural trend. The Santanyí Limestones consist of a constant sequence made up of four different levels that can be distinguished and recognized [45] as follows: in the southwestern part of the studied area, all the four main facies described [45] are represented, attaining maximum thickness (nearly 40 m); moving northeastwards (Port de Manacor) the thickness of the outcropping sequence decreases and the upper levels disappear (Fig. 5). The lack of such levels are due to the erosive processes that have affected the northern end of the zone, because it is known that all the Santanyí Limestone sequence has been deposited in the whole area [46].

6.2. Geomorphological aspects

The eastern coast of Mallorca can be divided into two structural domains: a first one formed by mesozoic structured deposits, located in the NW and corresponding to the Serres de Llevant, and a second domain consisting of calcarenitic post-orogenic deposits, Upper Miocene in age, occupying the southern part of the studied area. These two sectors show a general sloping surface with heights decreasing progressively southwards (Fig. 5).

An irregular coast with cliffs, mainly controlled by the tectonic alpine structure, developed on the mesozoic rocks featuring a mountain relief that hosts only a few beaches accumulated in the coastal sheltered parts.

From a physiographical point of view the post-orogenic Miocene rocks show the same topographical trend described above. The northeastern area has a higher elevation, with coastal cliffs 20–30 m in height. Moving southwestwards the topography goes down gently, with mean cliff heights of only a few meters arriving to the meridional tip of the island.

Upper Miocene rocks are sporadically cut by the incision of small creeks that mainly run southwards (Fig. 6A). The interaction between the coast with cliffs and the fluvial incisions results in a particular morphology, locally called 'cala' [47].

According to Rosselló-Verger [48], the term, 'cala' (bight, cove, pocket bay) refers to marine indentations in the coastline related to the eustatic flooding of ancient, often non-functional, stream-valleys. This author distinguishes between high 'calas' with steep-sided flanks and a canyon-like morphology, and low 'calas' that merely are drowned fluvial valley systems.

A detailed study of this coastline's morphological features puts forward a certain variability in the resulting landscapes, depending on the relative location along the studied area. In light of this, the northernmost Migjorn region (Fig. 5E) is characterized by the presence of cliff-sided 'calas', like those of Port de Manacor or Cala Virgili. Towards the southwest, the fluvial valley systems end more frequently in gentle coves, often complex in shape, like the Mondragó locality (Fig. 5C). Most of these 'calas' exhibit

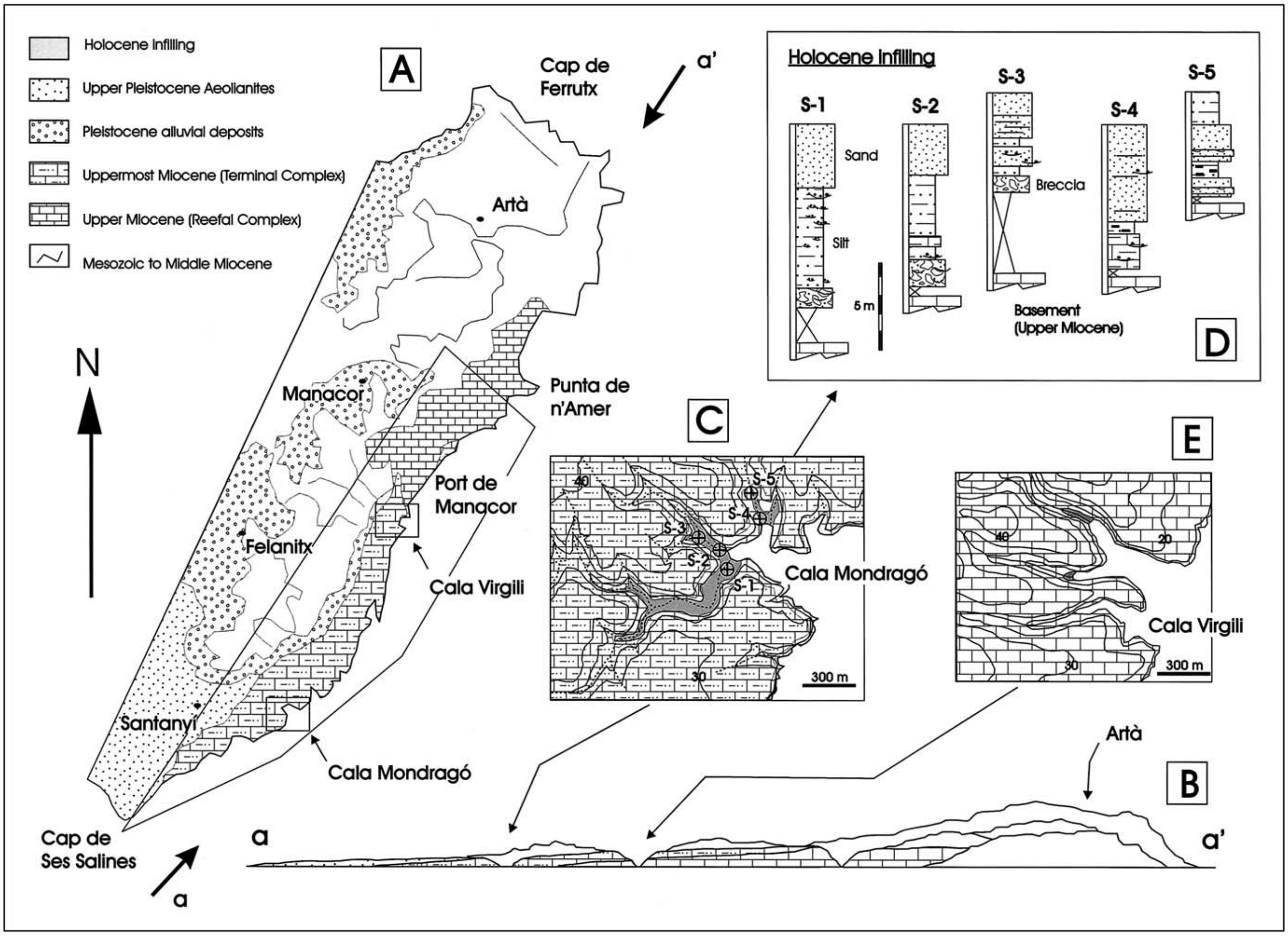

Fig. 5. (A) Detailed geological map of the eastern coast of Mallorca (see location in Fig. 1) with the distribution of different post-orogenic units. Highlighted area is enlarged in Fig. 6. (B) SW–NE geological sketch section. Note the presence of older units outcropping northwards. (C) Detailed geological and geomorphological map of Cala Mondragó. Note the complex morphology of the coast resulting from the flooding and successive sediment infilling during Holocene times. (D) Detailed sedimentological logs of the Holocene infillings corresponding to littoral facies. (E) Detailed geological and geomorphological map of Cala Virgili. Notice the fluvial geomorphological differences with Cala Mondragó as well as the minor presence of Holocene deposits.

flat bottoms in correspondence with their end portions revealing, in some cases, important sedimentary holocene infillings.

These geomorphological data give support to the occurrence of recent tectonic deformations, postulated on the basis of evidence both from phreatic speleothem study and the regional stratigraphy of eastern Mallorca.

6.3. *Incised valley infillings*

A general feature of Mallorca are the incised valleys cut in the Upper Miocene calcarenitic deposits [49]. These valleys are some 10 m high with steep walls and a flat ground, especially evident at the end of the fluvial or creek systems (at the 'cala') where it may reach several hundred meters in width. The flat area represents the depositional surface of littoral deposits accumulated during the last high sea stand (Holocene times). The thickness of these deposits usually reaches more than 20 m in relative depocenters [50]. Dated as Holocene [51], these deposits directly onlap the eroded Upper Miocene calcarenitic platform with no presence of Plio-Pleistocene sediments.

The valley morphology, as well as the valley's infillings, changes along a NE–SW trend (Fig. 5). In the NE, valleys are narrower with quasi-vertical walls (Cala Virgili, Cala Falcó, Cala Anguila, etc.) and do not show any kind of sediment infilling except for the most recent, that are scarce and usually correspond to coarse fluvial material reworked by littoral processes. Moving southwestwards (Cala Mondragó, Portocolom, Portopetre) the valleys have fewer vertical walls (in the areas located in the proximity of the sea) and the Holocene infillings are always present. (Fig. 5C, D). Such infillings exhibit a complex geometry with alternances of black silts, white bioclastic sands, red silts and clays, microconglomerates and breccias. All these deposits are unconsolidated and were deposited in littoral environments (marsh, lagoon, beach and dunes). They record Holocene fluctuations of sea level and the continental influence on this littoral area.

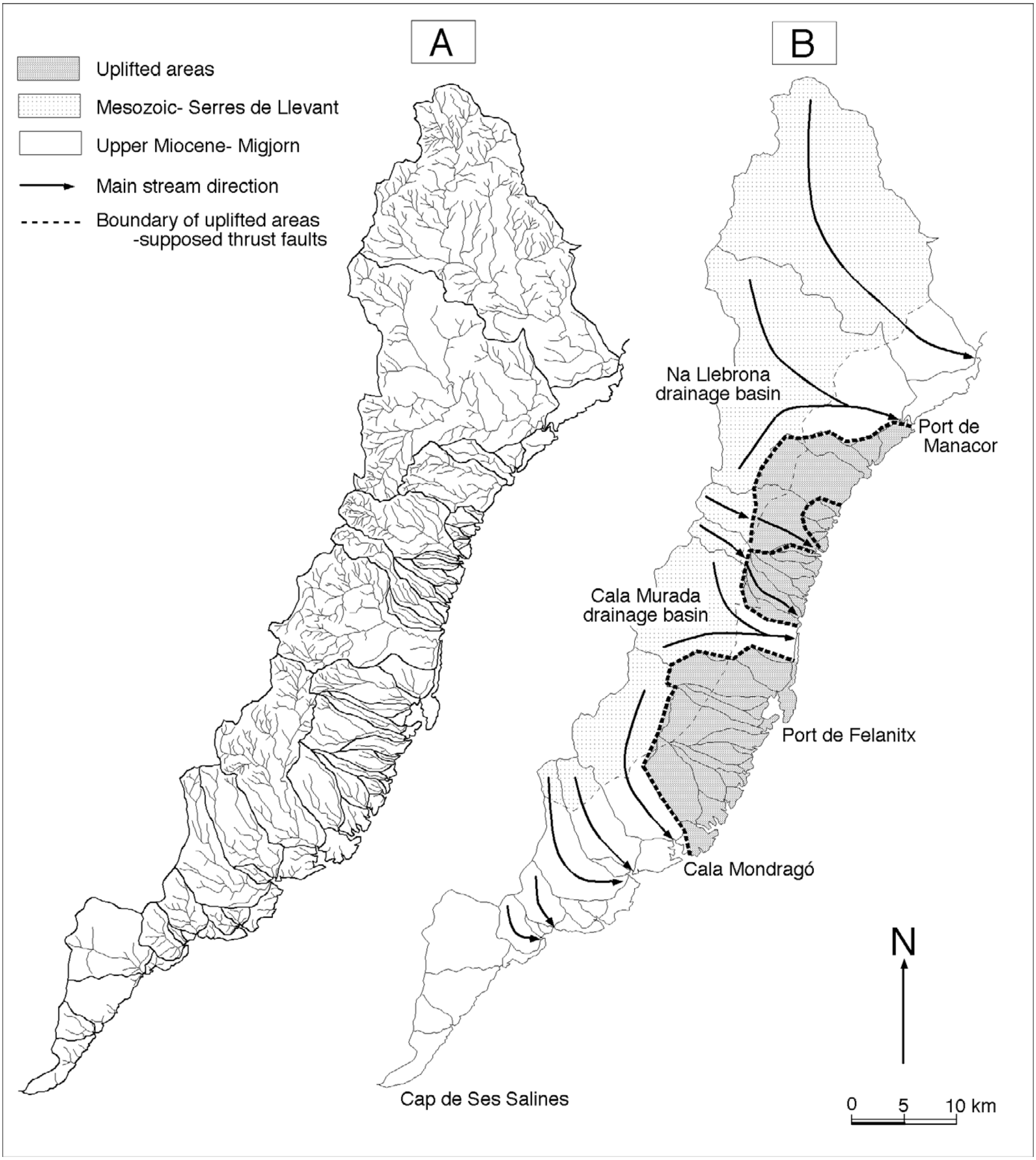

Fig. 6. (A) Map of the drainage basin system of the Migjorn area (see location in Fig. 5). (B) Main stream direction in the area. Stream courses are running to the SE, except for the south of Na Llebrona and Cala Murada drainage basins, because of the presence of two uplifted blocks, in which drainage basins are smaller and stream courses are running to the ESE.

Southwards the Miocene rocks are submerged under the sea, resulting in a flat low-lying coast covered by Pleistocene to Holocene dunes and alluvial deposits.

A pre-Holocene tectonic tilting (of the eastern part of Mallorca) towards the SE is suggested because the valley infillings are absent in the northern area (caused by subaereal exposure). The thickness of the sedimentary infilling increases southwestwards indicating a major accommodation space for sedimentary reception.

6.4. Tectonics

The geological structure of Mallorca is the result of a complex evolution involving three main phases: (1) the Mesozoic extension, (2) the Late Oligocene–Early Miocene compression due to the Africa–Iberia–Europe continental collision and, (3) Neogene–Recent extension. All these phases, depending on their duration, intensity and age, are reflected in the geological structure of the island.

Compressive processes have been quantified [26], while Late Miocene to Recent extensional processes have been treated in a very general way [26] in Sa Pobla basin. One of the goals of this paper is to quantify the amount and the average velocity of the tectonic tilting produced in recent times in the eastern part of Mallorca.

The main structures developed during the last stage of Mallorca's evolution basically consist of kilometric normal faults, trending NE–SW, and fault-propagation folds trending NW–SE, perpendicular to the normal faults. Normal faults are listric, affect even the ranges (see for example, Bunyola and Alaró faults intersecting the Tramuntana range, Fig. 7) and can display more than 1 km of normal displacement (Alaró and Bunyola normal faults) [26]. Compressive structures are essentially the above-mentioned fault-propagation folds trending NW–SE: these are the cases of the Santa Maria and Santa Eugènia anticlines [52] and the Penyes Rotges anticline [53]. All these structures agree with a NE–SW main shortening direction, which is roughly parallel to the tectonic tilting mentioned. In the light of this data, we suppose that the tilting is produced because of this shortening.

The tectonic tilting seems to also affect the Serres de Llevant mountains: the highest topography is located in the NW (Artà surrounding areas) and these ranges are covered by Late Miocene tabular calcarenites in the SW (near Santanyí).

Relationships between tectonics and the surface fluvial drainage pattern are also evident. Fig. 6 is a detailed map of the drainage basin system of the Migjorn area. Stream courses of major drainage systems run from N to S in the western areas and progressively from WNW to ESE further east, describing a loop. This is the expected orientation and direction of the drainage system if we assume a gentle tectonic tilting acting along a NE–SW direction, with the open sea (the base level) in the east. This general orientation is not respected in two cases: in the Na Llebrona and Cala Murada drainage basins, where the stream courses are running from SW to NE and also from W to E. The Na Llebrona and Cala Murada drainage systems surround minor drainage basins where stream courses run from

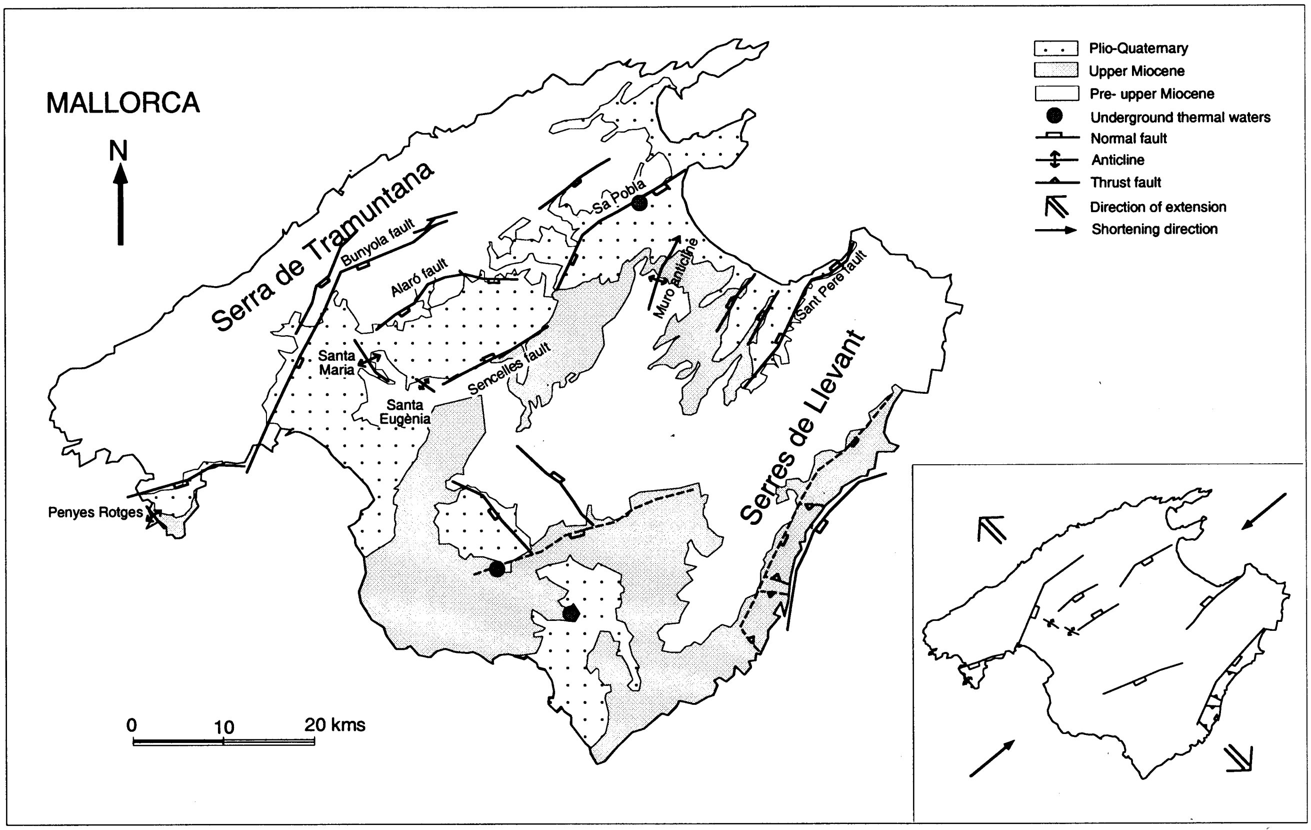

Fig. 7. Mallorcan tectonic map of Upper Miocene to Holocene structures, showing the main extension and shortening direction.

WNW to ESE and are rectilinear. Within a single basin, an asymmetric drainage net is observed: the northern part is much more developed (except for the two mentioned basins) than the southern, as expected from the NE–SW tilting.

On this basis, we suggest that the observed patterns in the drainage basins are due to a general tilting southwestwards acting simultaneously with recent uplifting of minor blocks (shaded areas in Fig. 6). These blocks represent an obstacle to stream courses from the Serres de Llevant, making them bend and run parallel to the northern margin of the uplifted block. Inside the uplifted blocks minor drainage basins develop because of the smaller drainage area.

A careful interpretation of the age and altimetric values obtained from POS recording past high sea stands (Table 1) allows the quantification of recent tectonic movements. In this sense, when a single marine paleolevel is recorded in some caves at different elevations, this altitude is always higher in caves located in the north, as reported in Fig. 4 for phreatic speleothems attributed to substages referred to OIS 5a, 5c and 5e.

This is evidence of a major tectonic tilting that took place, at least partially, after substage 5a, because phreatic speleothems of this substage are now located at different altitudes. Considering that the tectonic tilting has been continuous from post-substage 5a (approximately 85 ka) until recent times (there is no more precise information), and that the differential (among N and S) displacement is approximately of 1.5 m, the southern part sinks at an average minimum velocity of 0.02 mm/year with respect to the northern part. These values are about 1/10 of those calculated for the listric normal faults that bounds the Tramuntana range from the Sa Pobla basin [26].

7. Conclusions

In the coastal caves of Mallorca (western Mediterranean) phreatic carbonatic overgrowths form at the surface of brackish pools. Their occurrence directly identifies the height of the sea level at the time of the carbonate deposition, because such pools are physically connected with the sea. POS resulted in an excellent tool for structural geology studies in order to prove and quantify tectonic movements with a precision of 1 m and also better.

In the eastern coast of Mallorca several POS have been dated using the Th/U method making it possible to determine the position of the sea level during Upper Pleistocene and Holocene times. Comparison of coeval speleothems located at diverse heights has permitted to describe and evaluate the tectonic tilting affecting the area.

POS-related data have been discussed in the light of other geomorphological, structural and stratigraphical evidence. This interdisciplinary approach has put in evidence a general tectonic tilting of the eastern part of Mallorca, with a progressive lowering of the areas located in the south-west.

Because different samples of phreatic speleothem overgrowths corresponding to substages 5a, 5c and 5e are now located at different altitudes, it has been possible to calculate the average velocity of the tectonic tilting as 0.02 mm/year.

As described in the Introduction, speleothems (mainly stalagmites) have been used in literature to show the effects of earthquakes and related paleoseismicity using the change of their growth axis and other changes in their morphological aspect. The breakdown or bending of speleothems and the occurrence of new overgrowths on them clearly give evidence of movements connecting punctual events easily dated by radiometric techniques. These kinds of methods are now enhanced and bring new possibilities because of the information given by the POS. Thus, the POS, which are controlled by the sea level variations during Pleistocene times in littoral areas, can be used as a good tool in structural geology for recent times.

Data reported by POS has been, until now, the only method that allows us to quantify average velocities of tilting in the eastern part of Mallorca. This methodology can be used in other littoral karstic terrains where the phreatic speleothems are present.

Acknowledgements

This paper is part of the projects: DGICYT PB94-1175 and DGESIC PB98-0132. Thanks to Alfredo Barón and S.G.O.P. of M.O.P.U. for providing the Holocene drill cores, and to Dr. Miquel Seguí, Dr. Eric Gilli and Dr. Francis Lemeille for the comments that have improved the final text.

References

[1] D. Postpischl, S. Agostini, P. Forti, Y. Quinif, Palaeoseismicity from karst sediment: the 'Grotta del Cervo' cave case study (central Italy), Tectonophysics 193 (1991) 33–44.

[2] H. Morinaga, T. Yonezawa, Y. Adachi, H. Inokuchi, H. Goto, K. Yaskawa, The possibility of inferring paleoseismicity from paleomagnetic dating of speleothems, western Japan, Tectonophysics 230 (1994) 241–248.

[3] T. Camelbeeck, Speleothems as palaeoseismic indicators: the point of view of a seismologist, in: Y. Quinif (Ed.), Karst and Tectonics. Contributions to the International Symposium on Karst and Tectonics. Relations Between Tectonics, Karst and Earthquakes, Speleochronos hors-série, 1998, pp. 23–24.

[4] Y. Quinif (Ed.), Karst and Tectonics. Contributions to the International Symposium on Karst and Tectonics. Relations Between Tectonics, Karst and Earthquakes, Speleochronos hors-série, 1998, pp. 1–196.

[5] E. Gilli, Evidence of palaeoseismicity in a flowstone of the Observatoire cave (Monaco), Geodinamica Acta 12 (1999) 159–168.

[6] P.Y. Jeannin, Neotectonique dans le karst du nord du lac de Thoune (Suisse), Eclog. Geol. Helvet. 83 (1990) 323–342.

[7] C.A. Davenport, Karst as a record of Palaeoseismicity, in: Y. Quinif (Ed.), Karst and Tectonics. Contributions to the International Symposium on Karst and Tectonics. Relations Between Tectonics, Karst and Earthquakes, Speleochronos hors-série, 1998, pp. 41–44.

[8] P. Forti, Seismotectonic and paleoseismic studies from speleothems: the state of the art, in: Y. Quinif (Ed.), Karst and Tectonics. Contributions to the International Symposium on Karst and Tectonics. Relations Between Tectonics, Karst and Earthquakes, Speleochronos hors-série, 1998, pp. 79–81.

[9] F. Lemeille, M. Cushing, D. Carbon, B. Grellet, T. Bitterli, Ch. Flehoc, Ch. Innocent, Co-seismic ruptures and deformations recorded by speleothems in the epicentral zone of the Basel earthquake, Geodinamica Acta 12 (1999) 179–191.

[10] J.M. Thery, M. Pubellier, B. Thery, A. Butterlin, A. Blondeau, C.G. Adams, Importance of active tectonics during karst formation. A Middle Eocene to Pleistocene example of the Lina Mountains (Irian Jaya, Indonesia), Geodinamica Acta 12 (1999) 213–221.

[11] P. Fenart, N.N. Cat, C. Drogue, D. Van Canh, S. Pistre, Influence of tectonics and neotectonics on the morphogenesis of the peak karst of Halong Bay, Vietnam, Geodinamica Acta 12 (1999) 193–200.

[12] A. Bini, Y. Quinif, O. Sules, A. Uggeri, Les mouvements tectoniques récents dans les grottes du Monte Campo dei Fiori, Karstologia 19 (1992) 23–30.

[13] E. Gilli, Néotectonique dans la grotte des Deux Gourdes, Karstologia 8 (1986) 50–52.

[14] P.W. Williams, Speleothem dates, Quaternary terraces and uplift rates in New Zealand, Nature 298 (1982) 257–260.

[15] L. Pomar, A. Ginés, J. Ginés, Morfología, estructura y origen de los espeleotemas epiacuático, Endins 5-6 (1979) 3–17.

[16] J. Ginés, El karst litoral en el levante de Mallorca: una aproximación al conocimiento de su morfogénesis y cronología, Ph.D. thesis, Universitat de les Illes Balears, Palma de Mallorca, 2000, pp. 1–595.

[17] A. Ginés, J. Ginés, L. Pomar, Phreatic speleothems in coastal caves of Majorca (Spain) as indicators of Mediterranean Pleistocene paleolevels, Proceedings of the Eighth International Congress of Speleology, Bowling Green, vol. 2, 1981, pp. 533–536.

[18] L. Pomar, A. Rodriguez-Perea, J.J. Fornós, A. Ginés, J. Ginés, A. Font, A. Mora, Phreatic speleothems in coastal caves: a new method to determine sea-level fluctuations, in: C. Zazo (Ed.), Late Quaternary sea-level changes in Spain, Museo Nacional de Ciencias Naturales, vol. 10, C. S. I. C. Trabajos sobre Neógeno-Cuaternario, Madrid, 1987, pp. 197–224.

[19] A. Ginés, J. Ginés, Absolute dating of phreatic speleothems from coastal caves of Mallorca (Spain), Proceedings of the Tenth International Congress of Speleology, Budapest, vol. 1, 1989, pp. 191–193.

[20] J. Ginés, A. Ginés, Dataciones isotópicas de espeleotemas freáticos recolectados en cuevas costeras de Mallorca (España), Endins 19 (1993) 9–15.

[21] P. Tuccimei, J. Ginés, A. Ginés, J.J. Fornós, P.L. Vesica, Dataciones Th/U de espeleotemas freáticos controlados por el nivel marino, procedentes de cuevas costeras de Mallorca (España), Endins 22 (1998) 99–107.

[22] P. Tuccimei, J. Ginés, C. Delitala, L. Pazzelli, A. Taddeucci, B. Clamor, J.J. Fornós, A. Ginés, F. Gràcia, Dataciones Th/U de espeleotemas freáticos recolectados a cotas inferiores al actual nivel marino en cuevas costeras de Mallorca (España): aportaciones a la construcción de una curva eustática detallada de los últimos 300 ka para el Mediterráneo occidental, Endins 23 (2000) 59–71.

[23] P.L. Vesica, P. Tuccimei, B. Turi, J.J. Fornós, A. Ginés, J. Ginés, Late Pleistocene paleoclimates and sea-level change in the Mediterranean as inferred from stable isotope and U-series studies of overgrowths on speleothems, Mallorca, Spain., Quat. Sci. Rev. 19 (2000) 865–879.

[24] J.J. Fornós, B. Gelabert, Lithology and tectonics of the majorcan karst, in: A. Ginés, J. Ginés (Eds.), Karst and caves in Mallorca, Endins, 20/Mon. Soc. Hist. Nat. Balears 3 (1995) 27–43.

[25] B. Gelabert, F. Sàbat, A. Rodríguez-Perea, An structural outline of the Serra de Tramuntana of Mallorca (Balearic Islands), Tectonophysics 203 (1992) 167–183.

[26] B. Gelabert, La estructura geológica de la mitad occidental de la Isla de Mallorca, ITGE, Colección Memorias, Madrid, 1998, pp. 1–129.

[27] J.J. Fornós, L. Pomar, Mioceno Superior de Mallorca: Unidad Calizas de Santanyí (Complejo Terminal), El Terciario de las Baleares. Guía de las Excursiones del X Congreso Nacional de Sedimentología, Menorca, 1983, pp. 177–206.

[28] L. Pomar, A. Rodríguez-Perea, F. Sàbat, J.J. Fornós, Neogene stratigraphy of Mallorca Island, in: J. Agustí, R. Domènec, R. Julià, J. Martinell (Eds.), Iberian Neogene Basins, Field Guidebook. Paleontología i Evolució (Mem. Esp.), vol. 2, 1990, pp. 271–320.

[29] J. Ginés, Mallorca's endokarst: the speleogenetic mechanisms, in: A. Ginés, J. Ginés (Eds.), Karst and caves in Mallorca, Endins, 20/Mon. Soc. Hist. Nat. Balears 3 (1995) 71–86.

[30] A. Ginés, J. Ginés, On the interest of speleochronological studies in karstified islands. The case of Mallorca (Spain), Com. Ninth Congress International Speleology, Barcelona, vol. 1, 1986, pp. 297–300.

[31] J. Ginés, A. Ginés, Speleochronological aspects of karst in Mallorca, in: A. Ginés, J. Ginés (Eds.), Karst and caves in Mallorca, Endins, 20/Mon. Soc. Hist. Nat. Balears 3 (1995) 99–112.

[32] L. Pomar, A. Ginés, R. Fontarnau, Las cristalizaciones freáticas, Endins 3 (1976) 3–25.

[33] J. Ginés, A. Ginés, L. Pomar, Morphological and mineralogical features of phreatic speleothems occurring in coastal caves of Majorca (Spain), Proceedings of the Eighth International Congress of Speleology, Bowling Green, vol. 2, 1981, pp. 529–532.

[34] K.W. Butzer, J. Cuerda, Coastal stratigraphy of southern Mallorca and its implications for the Pleistocene chronology of the Mediterranean sea, J. Geol. 70 (1962) 398–416.

[35] K.W. Butzer, Pleistocene littoral-sedimentary cycles of the Mediterranean basin: a Mallorquin view, in: K.W. Butzer, G.L. Isaac (Eds.), After the Australopithecines: stratigraphy, ecology and culture change in the Middle Pleistocene, Chicago, 1975, pp. 25–71.

[36] C. Zazo, Interglacial sea levels, Quat. Int. 55 (1999) 101–113.

[37] A. Ginés, J. Ginés, Consideraciones sobre los mecanismos de fosilización de la Cova de Sa Bassa Blanca y su paralelismo con formaciones marinas del Cuaternario, Boll. Soc. Hist. Nat. Balears 19 (1974) 11–28.

[38] J. Cuerda, Los tiempos cuaternarios en Baleares, Instituto de Estudios Baleáricos, Palma de Mallorca, 1975, pp. 304.

[39] G.J. Hennig, A. Ginés, J. Ginés, L. Pomar, Avance de los resultados obtenidos mediante datación isotópica de algunos espeleotemas subacuáticos mallorquines, Endins 8 (1981) 91–93.

[40] R.S. Harmon, Paleoclimatic information from isotopic studies in speleothems: a review, in: W.C. Mahaney (Ed.), Quaternary Paleoclimate Geo Abstracts Ltd. Norwich, 1980, pp. 299–318.

[41] C. Hillaire-Marcel, C. Gariépy, B. Ghaleb, J.L. Goy, C. Zazo, J. Cuerda, U-series measurements in Tyrrhenian deposits from Mallorca. Further evidence for two last-interglacial high sea levels in the Balearic islands, Quat. Sci. Rev. 15 (1996) 53–62.

[42] A.C. Neumann, P.J. Hearty, Rapid sea-level changes at the close of the last interglacial (substage 5e) recorded in Bahamian island geology, Geology 24 (1996) 775–778.

[43] L. Pomar, J. Cuerda, Los depósitos marinos pleistocénicos en Mallorca, Acta Geol. Hispànica 14 (1979) 505–513.

[44] IGME, Mapa Geológico de España. Escala 1:50,000, Instituto Tecnológico Geominero de España, Madrid, 1991.

[45] J.J. Fornós, Estudi sedimentològic del Miocè Terminal de l'Illa de Mallorca, Tesi de Llicenciatura, Universitat de Barcelona, Inédita, 1983, pp. 228.

[46] J.J. Fornós, La Unitat Calcàries de Santanyí (Miocè superior) a la zona de Cala Murta (Marina de Llevant, Mallorca), Boll. Soc. Hist. Nat. Balears 34 (1991) 33–40.

[47] A. Penck, Morphologie der Erdoberfläche, Engelhorn, Stuttgart, 1894.

[48] V. Rosselló-Verger, Les cales, un fet geomòrfic epònim de Mallorca, Boll. Soc. Hist. Nat. Balears 38 (1995) 167–180.

[49] J. Pardo, A. Rodríguez-Perea, J.J. Fornós, F. García, T. Cervera, Caracterización de los fondos de las calas y los barrancos menorquines mediante sondeos eléctricos, Dinámica Litoral-Interior, Actas XV Congr. de Geógr. Españoles, vol. 1, 1997, pp. 191–203.

[50] J.J. Fornós, P. Fumanal, G.X. Pons, A. Barón, A. Fornés, J.E. Pardo, A. Rodríguez-Perea, V.M. Rosselló, F. Segura, J. Servera, Rebliment holocènic a la vall incisa del Barranc d'Algendar (Cala Galdana, Sud de Menorca, Mediterrània Occidental), Boll. Soc. Hist. Nat. Balears 41 (1998) 173–189.

[51] E.I. Yll, R. Pérez-Obiol, J. Pantaleon, J.M. Roure, Palynological evidence for climatic change and human activity during the Holocene on Minorca (Balearic Islands), Quat. Res. 48 (1997) 339–347.

[52] M. Grimalt, A. Rodríguez-Perea, Unidades morfológicas del Llano de Palma (Mallorca), in: J. Arnáez-Vadillo, J.M. García-Ruiz, A. Gómez Villar (Eds.), 'Geomorfología en España' III Reunión Nacional de Geomorfología, Logroño, Sociedad Española de Geomorfología, vol. 2, 1994, pp. 403–412.

[53] H. Rohdenburg, U. Sabelberg, Quartäre Klimazyklen im Westlichen Mediterraneangebiet und ihre Auswirkungen auf die Relief und Bodenentwicklung, Catena 1 (1973) 71–180.