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UNDERWATER CAVE SYSTEMS IN CARBONATE ROCKS AS SEMI-PROXY INDICATORS OF PALEO-SEA LEVELS

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ABSTRACT - Underwater caves may yield valuable information on changes in sea level, as they can track the position of an ancient sea level to a variable degree of accuracy. Limestone caves, in particular, develop different morphologies as a function of oscillating sea levels. In carbonate settings, when true coastal caves including precise indicators of sea-level such as notches or beach deposits are lacking (which hold true as paleo-sea levels indicators for any type of lithology), ancient stillstand levels are approximated: 1) by determining a former groundwater level for continental karst processes (which subsequently experiences submersion) provided they acted sufficiently close to the coast; 2) by determining a mixing zone of different solutions leading to hyperkarst processes. The wide range of different typologies developed in the limestone coastal belt of the Tyrrhenian Sea (Italy), yields case-histories which can be taken as representative of the relationships between relative changes in sea levels and the evolution of karst systems. In particular, the occurrence of features related to hyperkarst processes can be reliable "semi-proxy" indicators of paleo-sea levels in absence of more precise markers.

RIASSUNTO - Le cavità sottomarine possono fornire importanti informazioni sulle variazioni del livello del mare ed in particolare possono essere considerate quali marker di antichi stazionamenti del livello del mare. Il grado di precisione nella determinazione dei paleolivelli marini è variabile in funzione del tipo di cavità e dunque dei processi speleogenetici. A tal scopo, viene fornita nei suoi tratti essenziali una classificazione dinamica delle cavità sottomarine, distinte in sommerse e marine s. s., queste ultime a loro volta suddivise in biogeniche, costiere e ipercarsiche. Le grotte sommerse (intendendo con questo termine grotte soggette a sommersione successiva alla loro genesi) si originano in ambiente continentale e vengono successivamente sommerse durante stazionamenti più alti del livello del mare. Tali cavità, sviluppate in particolare in rocce carbonatiche per processo dissolutivi (carsici), possono fornire informazioni su paleolivelli marini se la speleogenesi è avvenuta con un livello di base carsico prossimo all'antico livello del mare. Strutture idrogeologiche di dimensioni limitate forniscono una accuratezza dell'ordine della decina di metri. Le cavità biogeniche si rinvengono in presenza di biocostruttori in particolare nelle aree tropicali e la determinazione di paleolivelli può essere effettuata solo in congiunzione con analisi e datazioni assolute di altri indicatori morfologici associati. Le cavità costiere sono formate dal concorso di processi abrasivi, biologici e biochimici, accoppiati o no a quelli dissolutivi, e documentano un livello del mare con errore di pochissimi metri. Le cavità ipercarsiche si rinvengono in rocce carbonatiche e si originano per la miscelazione di acque a differente durezza. Tali cavità possono documentare paleolivelli marini con errore massimo della decina di metri. Le cavità presenti in rocce carbonatiche, ampiamente diffuse lungo le fasce costiere del Mar Tirreno, forniscono il più ampio spettro delle tipologie distinte e come tali rappresentano il setting lito-morfologico più favorevole per la determinazione di antichi livelli del mare, come documentano alcuni esempi discussi dalla Campania meridionale e dalla Sardegna orientale.

Key words: Underwater caves, Dynamic classification, Hyperkarst processes, Paleo-Sea levels
Parole chiave: Cavità sommerse, Classificazione dinamica, Ipercarsismo, Paleolivelli marini

1. INTRODUCTION

Caves in the coastal environment have been observed in a variety of geological settings, but, except for the sedimentary deposits they may host, they have not received much attention in studies aimed at reconstructing the geomorphological evolution of coastal belts. Even less research has been carried out on underwater caves due to the obvious difficulty of access. Additionally, studies on the speleological characteristics of coastal belts do not commonly take into account such evolutionary factors as tectonics and eustasy, which combine to determinate sea level oscillations. Changes in sea level do profoundly affect the development of cave systems either by the formation of coastal caves in abrasion/bioerosion controlled systems or by influencing the position of the base level for speleogenesis in dissolution-controlled systems.

One of the main problems in relating the speleogenetic evolution of a particular area to changes in sea level is the lack of a comprehensive characterization of sea-related caves, for which the number of detailed observations is still poor. Existing classifications of underwater and coastal caves have been commonly described on the basis of their morphology and lithology (e.g. Colantoni, 1976), and little attention has been devoted to tie the observed typologies to the speleogenetical processes.

Beside caves formed by processes operating at the coastline, which indicate precisely the position of the sea level at the time of their formation, we consider and mainly discuss in the present paper other morphological types which, even though less precise, can nevertheless provide an approximate gauge of sea level. These are represented by true karst systems at the groundwater level in coastal settings, which subsequently may have experienced submersion, and by caves formed by solution-mixing controlled hyperkarst processes. Such caves are fully developed in carbonate rocks and can offer important constraints to the sea level history of the coastal belt in addition to other, better known morphological indicators.

In this contribution, the reliability and limits of the various caves types mostly found in the underwater belt are reviewed. We outline a general classification of underwater and strandline caves based on the speleogenetical processes. Since limestone rocks widely outcrop in the Tyrrhenian coastal belt of Italy, we discuss the occurrence and significance of underwater caves in two different settings therein, namely Capo Palinuro and Capo M.te Santu to the eastern and to the western margin of the basin, respectively. These two case-histories are taken as representative of the relationships between karst evolution and changes in sea level, in light of detailed studies on the regional geomorphological evolution carried out therein.

2. A BRIEF OUTLINE ON UNDERWATER CAVES CLASSIFICATION

Underwater and strandline caves are distinguished as either submerged and marine caves *stricto sensu*. The latter class is further subdivided into primary caves formed in biogenic rocks, coastal caves, and solution mixing caves.

Submerged caves are those formed in the continental environment and subsequently submerged due to relative sea level rise. They are formed in all kinds of lithified rock, in rare cases in loosely cemented sediments, and exhibit a wide range of morphologies. However, only those formed in carbonate rocks by karst dissolution processes in close proximity to ancient coastlines are considered good indicators of paleo-sea levels, as discussed in a later section.

Among the marine caves s.s., the primary ones are formed by the differential growth of the organisms which consititute the bedrock. The best-known examples are found in the reef limestone (Stoddart, 1969; Garret et al., 1971) and rarely exceed few meters in diameter; however, some occurrences can reach dimensions of several meters and are mainly developed vertically, such as that shown in fig. 1. Their validity as sea level indicators depends on the depth of growth of the particular reef formation they are found within. It can be assumed with some safety that the base of interconnected voids represent a sea level base, since the reef started to grow from there upwards.

Coastal caves form at sea level by the combined action of mechanical abrasion of the sea, bioerosion and (bio-)chemical reactions, and are found in all lithified rocks (Colantoni, 1976). They display an elongated shape which tends to narrow toward the interior; the result is a short, wedge-shaped longitudinal section (i.e. normal to the coastline) and a triangle or trapezium-shaped section parallel to the coastline (fig. 2). The short dimension toward the interior is due to the fast decrease in abrasional energy.

For such caves when they occur in carbonate rocks, mechanically and biologically induced speleogenesis accompanies to karst dissolution at the coastline. Therefore they provide good indication of an ancient sea level, which corresponds to the levelled floor at the entrance, to the location of sea-level notches carved within and of beach deposits laid down into the cave, or to subhorizontal belts of bioerosion as in the case of *Lithophaga* borings (Carobene, 1972; Carobene and Pasini, 1982). Carobene and Pasini (1982) have shown along the coast of Sardinia (Italy) that "the altitude of the upper rim of marine wall grooves and of *Lithophaga* boring belt coincides with the altitude of the average high tide corresponding to the ancient sea-level stand during which the groove or belt was formed". Of course, these morphologies and deposits are not exclusive of caves albeit preferentially found therein due to their high preservation degree (low-energy environment). Therefore they will not be discussed longer in this paper.

For the prevailing mechanical processes, the levelled floor at the entrance is taken to represent the mini-

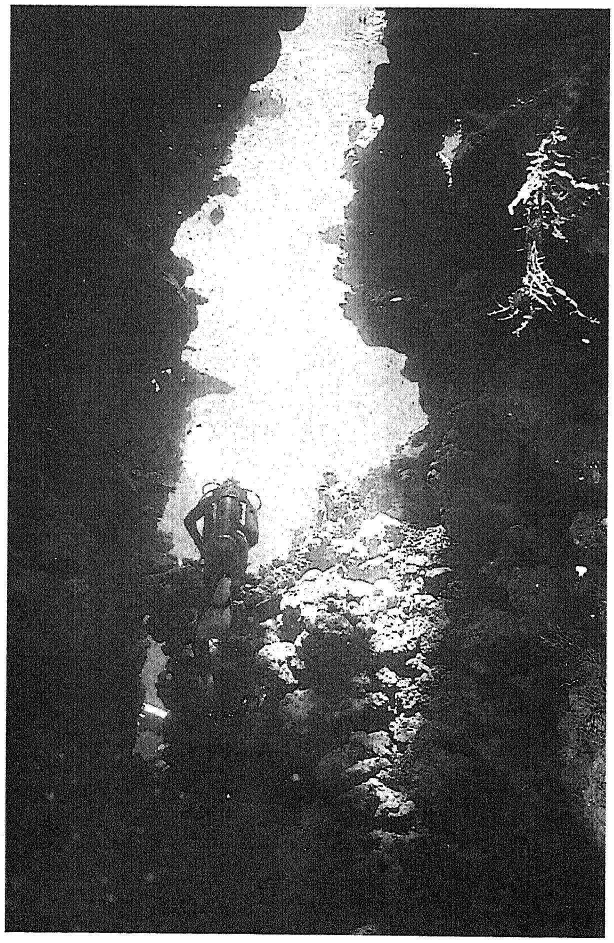

Fig. 1 - Primary cave in reef limestone, Jackfish Alley, Ras Mohammed, Red Sea. Base of cave is about 20 m deep.

Cavità primaria in scogliera carbonatica, Jackfish Alley, Ras Mohammed, Mar Rosso. Il pavimento della cavità è ubicato alla profondità di circa 20 m.

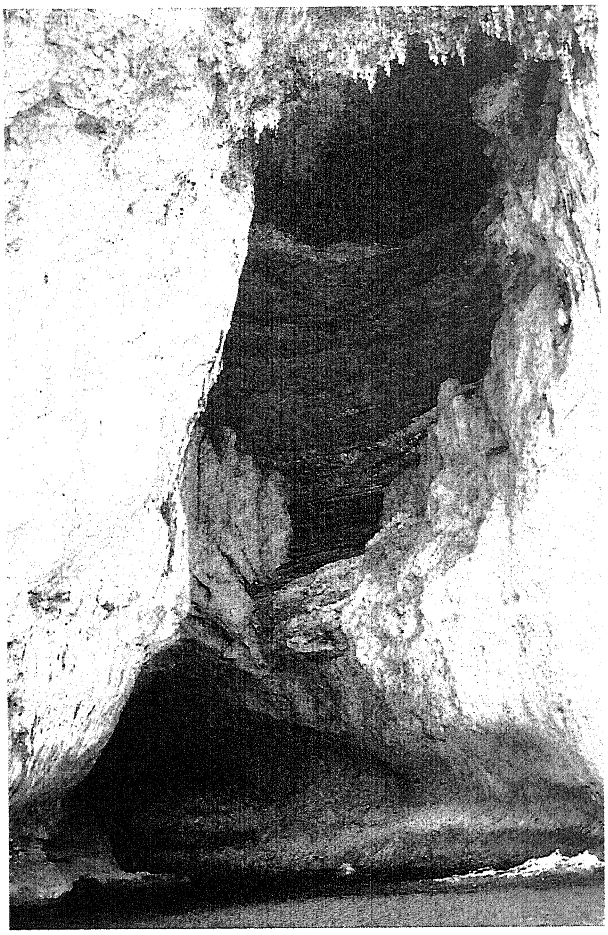

Fig. 2 - Grotta Bianca (below) and Grotta Vascio o' Funno (above), the latter filled with volcanoclastic eolianite. The Grotta Vascio o' Funno was formed by karst-dissolution processes and shows abundant concretions, whereas the Grotta Bianca displays features typical of coastal caves, such as the shape wedging toward the interior, a triangular section at the entrance and a lack of speleothems. Island of Capri, Campania, Tyrrhenian Sea.

Grotta Bianca (sotto) e Grotta Vascio o' Funno (sopra), quest'ultima riempita di eolianite vulcanoclastica, Isola di Capri (Campania). La Grotta Vascio o' Funno si è formata per processi di dissoluzione carsica e mostra abbondante concrezionamento, mentre la Grotta Bianca mostra caratteri tipici delle cavità costiere, quali la sezione longitudinale a cuneo rastremato verso l'interno, la sezione trasversale all'ingresso a triangolo, e la mancanza di speleotemi.

mum level of marine wave action, which is found few meters below the surface, depending on the local vertical drop in marine energy. Often, an "abrasion" notch is associated to the levelled floor of coastal caves and may or may not correspond to a true sea-level notch. These caves are more easily analysed in rocks where dissolution-dominated speleogenetic processes are lacking, such as basalts, and the simple physical erosion can be fully developed; on the contrary, they are more difficult to distinguish in carbonate rocks since dissolution processes compete with abrasion in determining cave morphology. Moreover, quite similar cave morphologies can derive from rockfall or subaerial erosion along vertical surfaces of weakness, such as a fault. This convergence in character can lead in some cases to an erroneous interpretation of paleo-sea level position.

Caves formed by mixing of different solutions develop as a result of hyperkarst processes (Forti, 1991; 1993) and are found in rocks subject to dissolution, such as evaporite and limestone. The peculiar morphotypes range in scale from the "alveolar" karst landscapes to large cave systems resulting from fluid mixage (e.g. Gregor, 1981; Back et al., 1984; Chiesi and Forti, 1987). As a rule, such caves mark the mixing zone, which in some cases (i.e. coastal "ponors") can correspond to the zone not far below the sea level. As stated before, however, more confident attributions can only be assessed with the aid of other sea level markers (notch, marine terraces, or beach deposits).

3. INFLUENCE OF LITHOLOGY

The bedrock lithology is of a fundamental importance in determining the different classes of caves and hence morphologies which are hypothesized to indicate a paleo-sea level.

For exemple, columnar basalts in the coastal environment can easily lead to the development of vertically elongated coastal caves, such as the long-celebrated Fingall Cave in the Hebrides of Scotland. Obliquely dipping volcanogenic rocks and interlayered lava flows develop coastal caves along the interlayer surfaces of weakness, and the resulting wedge-shaped cave depart in orientation from the perfect vertical triangle (fig. 3, where the effects of marine abrasion are amplified by solution-mixing processes on the carbonate interlayered with the lava-flows: Colantoni et al., 1994). In such cases the levelled mouth indicative of a paleo-sea level may form with a stair-case profile, indicating a sea level rise along an inclined surface. This profile constitutes an excellent indicator of paleo-sea level. More massive lithologies such as lava breccias may instead form the ideal vertical wedge profile, although the cliff-parallel profile is more obtuse rather than triangular due to homogeneous lateral abrasion and rockfall (fig. 4).

Caves in limestone display by all means the wider range of morphologies. They form the largest occurence of submerged caves, but in most cases complex morphologies deriving from several processes are found. Thus, more than one paleo-sea level can be present in these rocks and are documented by different classes of cave types (from pure coastal to fluid mixage).

4. HYPERKARST PROCESSES AND SEA LEVEL

In the continental environment, dissolution of carbonates below the phreatic table can occur as a result of mixing of two (or more) $CaCO_3$-saturated solutions with different and commonly low concentrations, according to the well-known "Boegli effect" (Boegli, 1975).

In the marine environment, particularly when hydrothermal waters are present, the mixing of waters at different $CaCO_3$ concentrations, one of which being at high salt content (high ionic strenght) lead to an increase in dissolution processes at or below the sea level ("hyperkarst", Forti, 1991). The hyperkarst processes are controlled by the diffusion of carbonatic into chloride-rich waters (Forti and Perna, 1986).

Sea water alone is not able to cause karst dissolution, since it is commonly oversaturated in bicarbonate. However, the mixing of chloride-rich sea water with sulfate-carbonicate meteoric water is responsible for the contemporaneous occurrence of the Boegli and the "solvent" effect (Lohmann, 1988).

Forti (1991) has summarized the main morphological features resulting from hyperkarst processes. In the upper layer of mixing they are typified, going from the less to the most relevant features, by: the enlargment of porosity and fracture networks; the development of short conduits, either dead-end or anastomosed, without any relationship with the external physical system (Gregor, 1981; Back et al., 1984); the formation of overhanging rock "pendants", flared ogival roofs and "dissolution" notches (at sea level); condensation domes and chambers (extending few meters above/below sea level) (Chiesi and Forti, 1987). Convective motions induced by hydrothermal temperature differences, which are conveyed into preexisting tubes and develop phreatic conduits, may sum to the diffusion processes. Within the whole mixing zone, continuous mixing leads to the formation of large hyperkarstic marine caves, whose dimensions and internal development are proportional to the amount of mixed waters, respectively (Forti, 1991). Typically, in hyperkarst marine caves there is lack of spelothems in the underwater portion of the cave and an abundance of rock pendants simulating speleothems.

To sum up, the fundamental result of hyperkarst processes in which one phase is formed by the sea-water, is the formation of caves at or immediately below the sea level. Solution mixing caves may open inside the rock mass often without any relationship with physical sea-water motion outside. As such they differentiate from the coastal cave type, but track the water mixing zone at or close to the sea level.

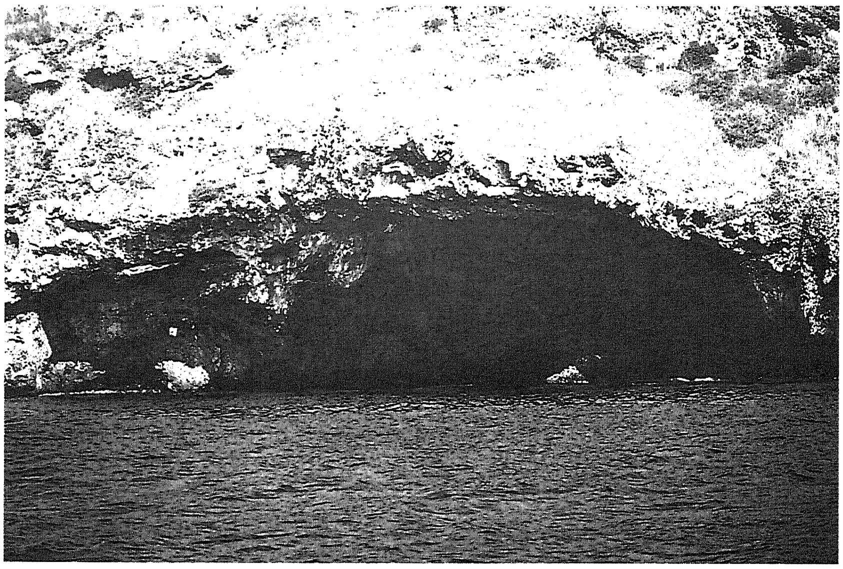

Fig. 3 - Grotta di S. Francesco, showing a lenticular-shaped entrance due to abrasion along oblique interlayered carbonate-cemented sills and volcanic rocks. Layering dipping due left. Island of Ustica, Eolian Archipelago, Tyrrhenian Sea.
Grotta di S. Francesco, Isola di Ustica, Arcipelago delle Eolie. La grotta mostra una sezione trasversale lenticolare all'ingresso dovuta all'abrasione marina lungo rocce vulcaniche con intercalazioni di sills a cementazione carbonatica. Il layering immerge verso sinistra nella foto.

5. RECORDING PALEO-SEA LEVEL IN LIMESTONE CAVES FROM THE PERI-TYRRHENIAN AREA. TWO CASE HISTORIES

As outlined in the previous sections, the carbonate rocks can develop different classes of cave types as a response to changing sea levels. Some morphologies are more precise indicators of sea level, while others provide solely a general indication or a depth-interval.

Carbonate rocks are widespread along the coast of the Tyrrhenian Sea, where they form fault-bounded promontories alternating to recent coastal planes, and host a large number and variety of caves.

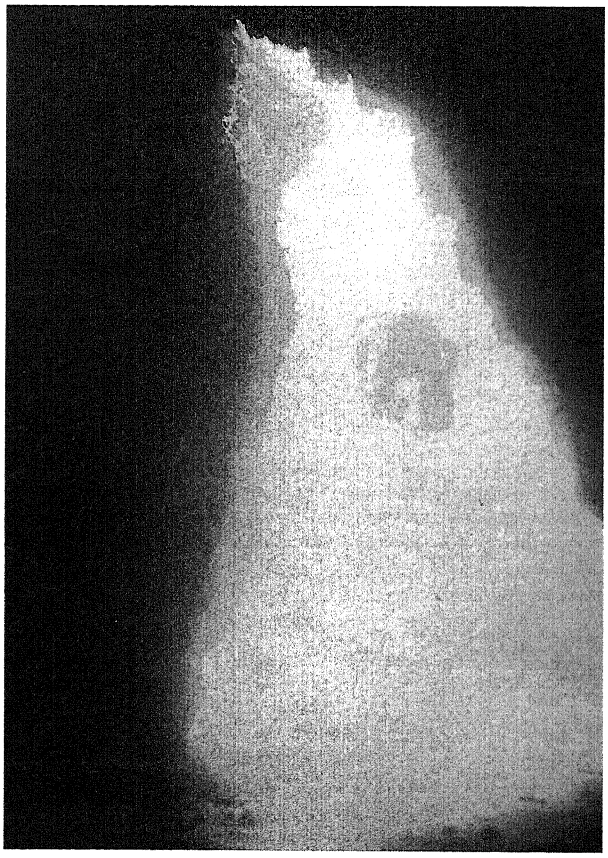

Fig. 4 - Grotta Grande delle Formiche, showing the upside-down V-shaped section at the entrance, typical of coastal caves. Ischia Channel, Gulf of Naples, Tyrrhenian Sea.
Grotta Grande delle Formiche, Canale d'Ischia, Golfo di Napoli. La grotta mostra la sezione trasversale all'ingresso a V rovescia, tipica delle cavità costiere.

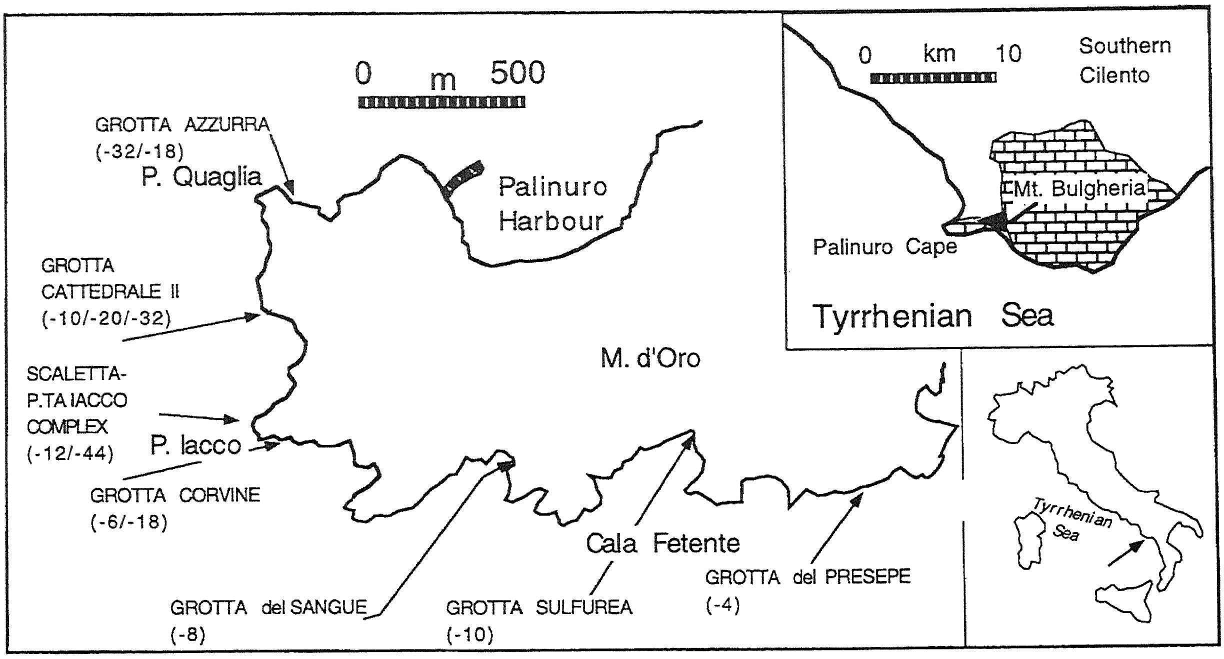

Fig. 5 - Map of Capo Palinuro, indicating the main submerged cave systems quoted in the text and the depth of their entrances. Bigger inset shows location of the Capo Palinuro-M.te Bulgheria system in Southern Cilento. Also indicated is the hydrological relationship inferred to be existing up to Middle Pleistocene between Capo Palinuro and the larger M.te Bulgheria block (arrows point to fresh water paleo-flow direction) as proposed in Antonioli et al. (1994). Smaller inset shows location of Capo Palinuro-M.te Bulgheria on the eastern Tyrrhenian coast.

Carta di Capo Palinuro, con localizzazione delle principali cavità sommerse discusse nel testo e indicazione della loro profondità all'ingresso. L'inserto più grande localizza il sistema Capo Palinuro-M.te Bulgheria nel promontorio del Cilento e mostra le interconnessioni idrogeologiche esistenti fra Capo Palinuro ed il più esteso blocco del M.te Bulgheria fino al Pleistocene medio (la freccia indica il senso del paleoflusso), come proposto in Antonioli et al. (1994). L'inserto più piccolo localizza il sistema Capo Palinuro-M.te Bulgheria sulla costa tirrenica orientale.

5. 1 Capo palinuro, Campania (Eastern Tyrrhenian Sea)

Capo Palinuro, on the southern part of Cilento Peninsula, includes a remarkable density of both subaerial and underwater caves (Muscio e Sello, 1993; Alvisi et al., 1994a; Ferranti and Antonioli, in press), a large part of which pre-date the final shaping of the cliff (fig. 5). They include galleries formed in continental conditions and subsequently foundered under the sea (submerged cave type). In some cases, during submersion, their entrance has been profoundly reworked and enlarged by the sea after the final shaping of the cliff (fig. 6, 7), thus representing a mixed cave type.

Many such caves are presently submerged at various depth, and only their levelled floor at the mouth (coastal part of the mixed cave type) and related notches document the existence of ancient sea levels (e.g. fig. 6, 7), which are found at about -30 m, -18/22 m, -12/14 m and -7/8 m below the present one (Antonioli et al., 1994; in press; Alvisi et al., 1994a). Other minor caves of variable shapes (arches, niches, enlarged fractures) are scattered at various depths and in some cases give a proxy evidence of ancient sea levels (coastal caves *stricto sensu*).

In addition to coastal caves *stricto sensu*, other evidence points to the existence of well definite ancient base levels. These evidences are represented either by karst base-levels formed close to the coastline, or by hyperkarst morphologies formed at the fresh thermal and sea water mixing zone few metres below the sea level (e. g. fig. 6a, Grotta Azzurra). In the following we discuss some of these examples.

It has been observed in some cases that the initial gallery of a presently submerged cave is formed by narrow phreatic conduits without coastal reworking; as such it should not document ancient sea levels. However, a recurrent depth for such conduits is found at -4/6 m b.s.l. ("window" in fig. 6a, 8 and 9), suggesting that the base-level, corresponding to the fresh and sea water mixing zone, could have been very close. We conclude that the phreatic conduits at -4/6 m are close indicators of a paleo-sea level; we further suggest it might correspond to the -7/8 m sea level separately detected in the area by means of other markers (such as true notches, terraces, pot-holes and coastal caves), and referred to the substage 5.5 of the oxygen isotopic curve (Antonioli et al., 1994; in press)

Fossil levels of cave springs have been recorded at -11, -5, +1 m a/b s.l. (Muscio & Sello, 1993). Entrance conduits with hydromorphic sections found in some caves (Grotta delle Corvine, Grotta la Cattedrale II, fig. 8), the "eyes" or "windows" at some entrances that represent the remnant of earlier tubes (fig. 6a, Grotta Azzurra; fig. 8, Grotta la Cattedrale II; fig. 9, Grotta del Presepe), and the sulphureous-sea water boundary (Grotta Viola) are aligned at about -4/-6 m b.s.l. and can be related to the previously mentioned ancient base

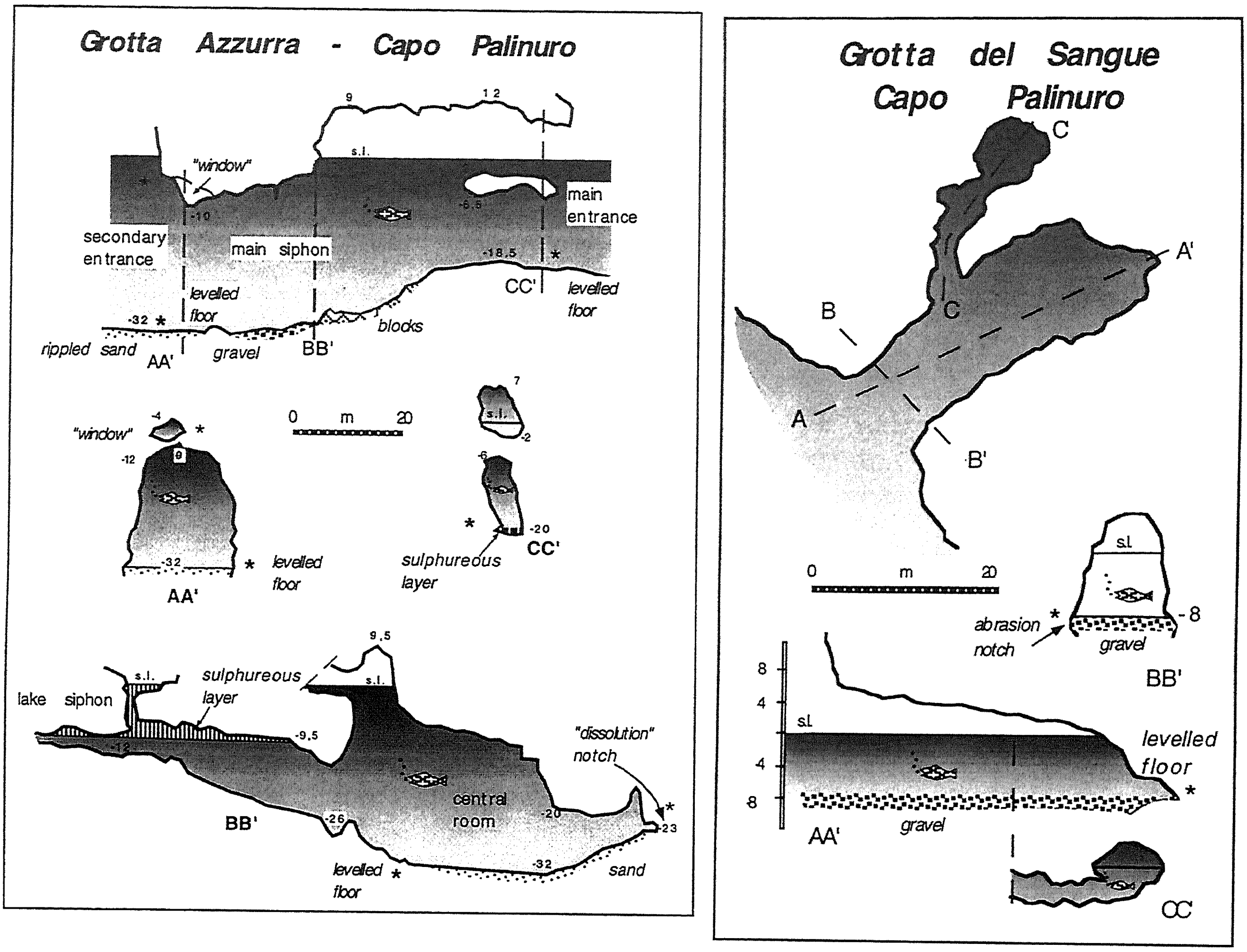

Fig. 6 - Map and sections of a) Grotta Azzurra (modified from Alvisi et al., 1994b) and b) Grotta del Sangue (modified from Antonioli et al., 1994), Capo Palinuro, eastern Tyrrhenian Sea. See Fig. 5 for cave location.

Carta e sezioni della Grotta Azzurra (modificato da Alvisi et al., 1994b) e della Grotta del Sangue (modificato da Antonioli et al., 1994), Capo Palinuro. Localizzazione in Fig. 5.

level. Also the well recorded boundary of sulphureous and sea-waters between -17 and -22 m (Alvisi et sl., 1994a, b), accompanied by peculiar "dissolution" notches could be related to an earlier base level (fig. 6a, Grotta Azzurra).

Evidence of a more definite base level is found at greater depths (between about -45 and -60 m. b.s.l.) in the western/southwestern portion of the Cape, and is represented by a consistent transition between upper vertical shafts formed in vadose conditions and a basal network of subhorizontal phreatic conduits. The latter represent a downward limit of the bulk karst deepening (e. g., Scaletta-P.ta lacco complex, fig. 10). Conceivably, deeper and probably older (Messinian? see Perna, 1996) karst systems are speculatively present in the carbonate blocks presently foundered beneath the Tyrrhenian Sea offshore Capo Palinuro. The areal extent and lateral correlability of the subhorizontal network in the -45/60 depth range, possibly formed at the vadose-phreatic boundary, suggest the existence of a former groundwater level at these depths. This base level existed until the Middle Pleistocene, before the downcutting of gorges between Capo Palinuro and the M. Bulgheria, a large coastal carbonate block in southern Cilento Peninsula (fig. 5), shunt off the water supply from the latter acquifer to Capo Palinuro (Antonioli et al., 1994; in press). Therefore the deep karst system documents the existence of a prolonged lowstand which is to be ascribed either to the earliest middle Pleistocene or to older times (Antonioli et al., 1994; in press). If we suppose true the first chronological attribution, the evidenced groundwater level is a good, albeit imprecise indicator of the sea level position at that time, since the latest significant episode of block-faulting in the area had already occurred during latest early Pleistocene to early middle Pleistocene (Ascione et al., 1995). Thus, we have a rough estimation of the position for this major lowstand, occurring supposedly at the beginning of the middle Pleistocene. However, this position is relative to other and younger paleo-sea levels detected in the area, and does not take into account later uplift.

More precise chronological estimates can be made for younger and shallower paleo-base levels indicating (roughly) paleo-sea levels. The mentioned shallower levels of springs and related vadose-phreatic boundary

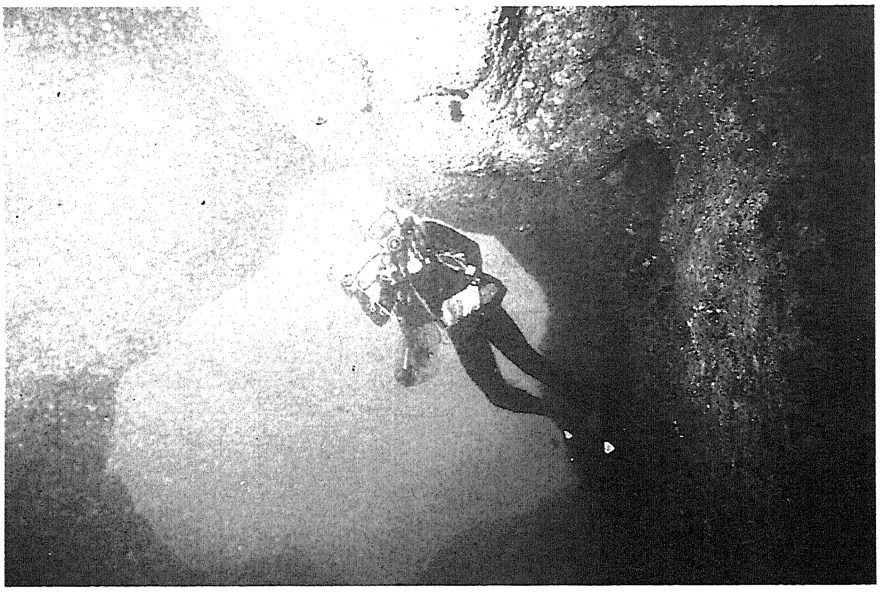

Fig. 7 - Grotta della Scaletta (location in fig. 5), Capo Palinuro, eastern Tyrrhenian Sea. Note the levelled floor at the mouth of the cave (-12 m b.s.l) which was carved by the sea onto a preexisting karst system

Grotta della Scaletta (ubicazione in Fig. 5), Capo Palinuro, caratterizzata da un pavimento livellato all'ingresso (-12 m di profondità), scolpito dal mare sul preesistente complesso carsico.

systems (-4/6, -11, -17/22 m b.s.l.) were active after the promontory had acquired a morpho-structural configuration very similar to the present one (Antonioli et al., 1994; in press). Therefore these speleogenetic episodes, which should yield more precisely the position of paleo-sea levels, are not older than the middle Pleistocene.

In addition to the "normal" karst processes, the effects of hyperkarst processes can give similar indications.

Hyperkarst processes at Capo Palinuro are a result of the mixing of water with different chemical-physical characteristics. At present, different waters are found within the first 5 metres b.s.l. flowing out of the bedrock already mixed with sea-waters. Cold and warm (about 27°C) fresh waters and sulphureous waters are thought to have different sources and follow different circuits (Muscio & Sello, 1993), but their emergence marks a base level which, in the present case, is coincident with the mixing zone with sea-waters near the surface. The mixing of different type of waters with increasing dissolution effects ("mixing hyperkarst", Forti, 1991), amplified in the case of the concourse of hydrotermal waters, could have been responsible in the past for the development of a number of cave features such as small development, homogeneous dimensions and rounded morphologies of terminal room following in the interior the entrance conduits, and the existence of anastomosing channels departing from a large central room. Such features are frequently observed at -4/-6 m b.s.l., where a paleo-sea level has been independently supposed as outlined above. Expanding upon this base, we speculate that the alignment of such features observed also at

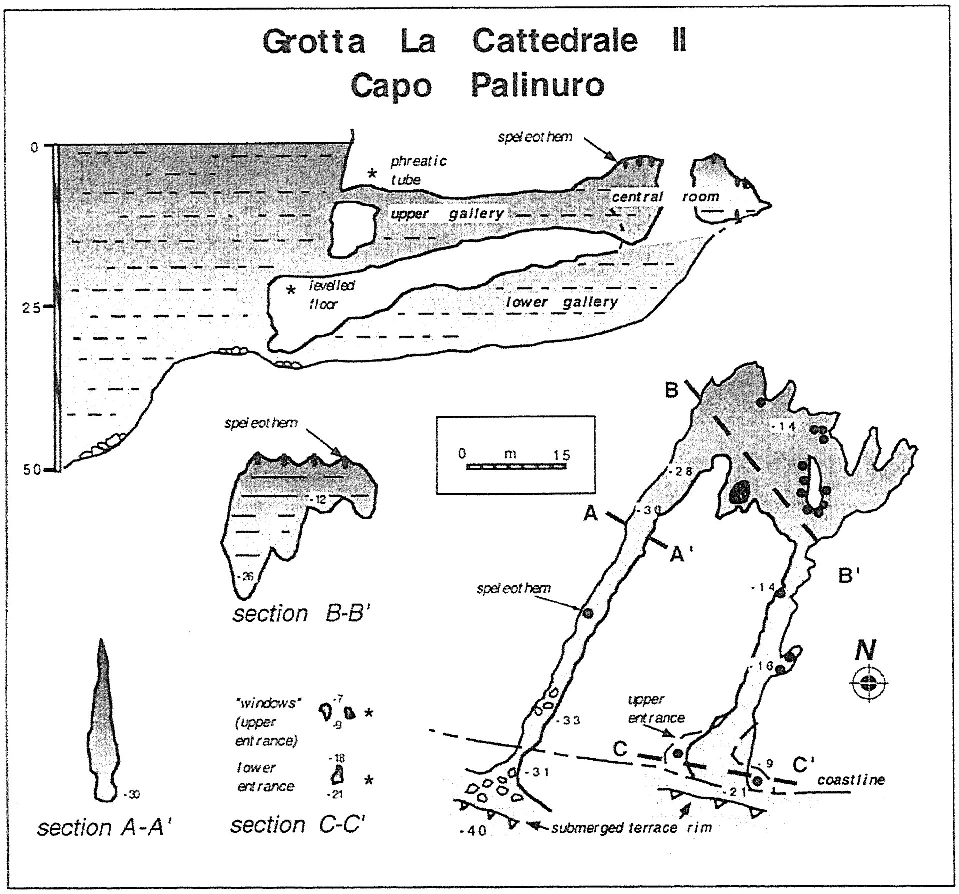

Fig. 8 - Grotta della Cattedrale II (location in fig. 5), Capo Palinuro, eastern Tyrrhenian Sea. The entrance of the cave has been profoundly reworked by marine abrasion, but internal galleries still retain their primary karst morphology. Asterisks indicate supposed paleo-sea levels.

Grotta della Cattedrale II (ubicazione in Fig. 5), Capo Palinuro. L'ingresso della cavità è stato profondamente rielaborato dall'abrAsione marina; tuttavia le gallerie interne conservano ancora la loro morfologia carsica primaria. L'asterisco indica paleolivelli marini ipotizzati.

other depths, such as -11 and -17/-22 m, marks ancient base levels which are taken to represent paleo-sea levels. As stated above, paleo-sea levels have been independently documented at -7/8 m, -18/22 m and -12/14 m b.s.l. (Antonioli et al., 1994, in press).

More problematic evidence of ancient base levels are found in the case of a larger and more complex cave system found at Capo Palinuro, whose formation is difficult to relate only to that of fresh-water discharge. The combination of karst and hyperkarst dissolution, marine abrasion, and coastal bio-corrosion can be very difficult to resolve, as in the case of the Grotta Azzurra and Grotta Sulfurea.

The Grotta Azzurra, the most famous and studied cave of Capo Palinuro (Alvisi *et al.*, 1994b), forms a wide and articulated system (fig. 6a). It

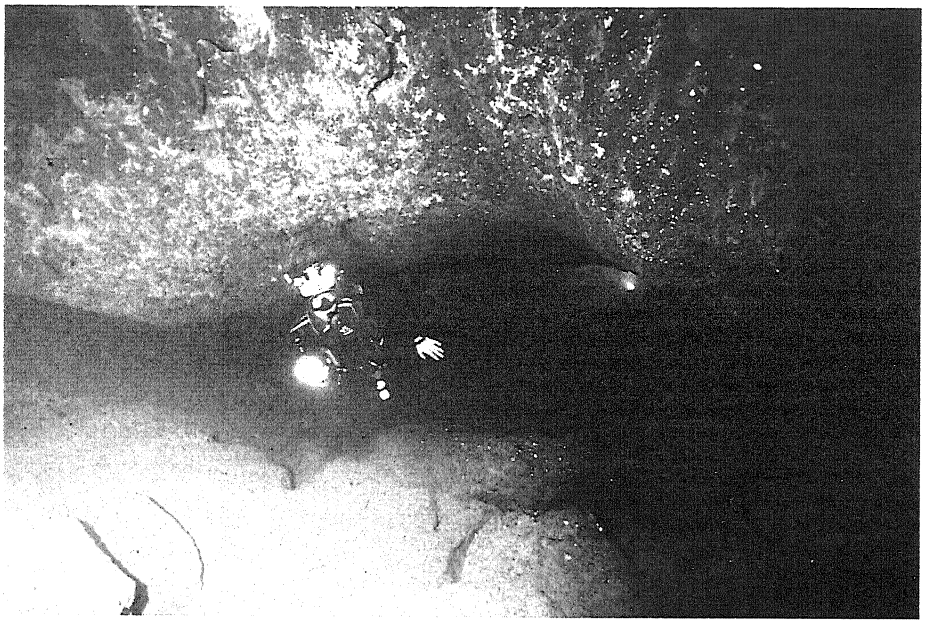

Fig. 9 - Grotta del Presepe (location in fig. 5), Capo Palinuro, eastern Tyrrhenian Sea. Phreatic conduit at -4 m b.s.l. was formed very close to the coastline after the final shaping of the promontory. It has not been reworked by the sea during subsequent foundering and submersion of the cave.

Grotta del Presepe (ubicazione in fig. 5), Capo Palinuro. Il condotto freatico a -4 m di profondità si è formato in prossimità della linea di costa successivamente al modellamento finale del promontorio. Questo condotto non è stato rielaborato dal mare durante i successivi sprofondamenti e allagamenti della grotta.

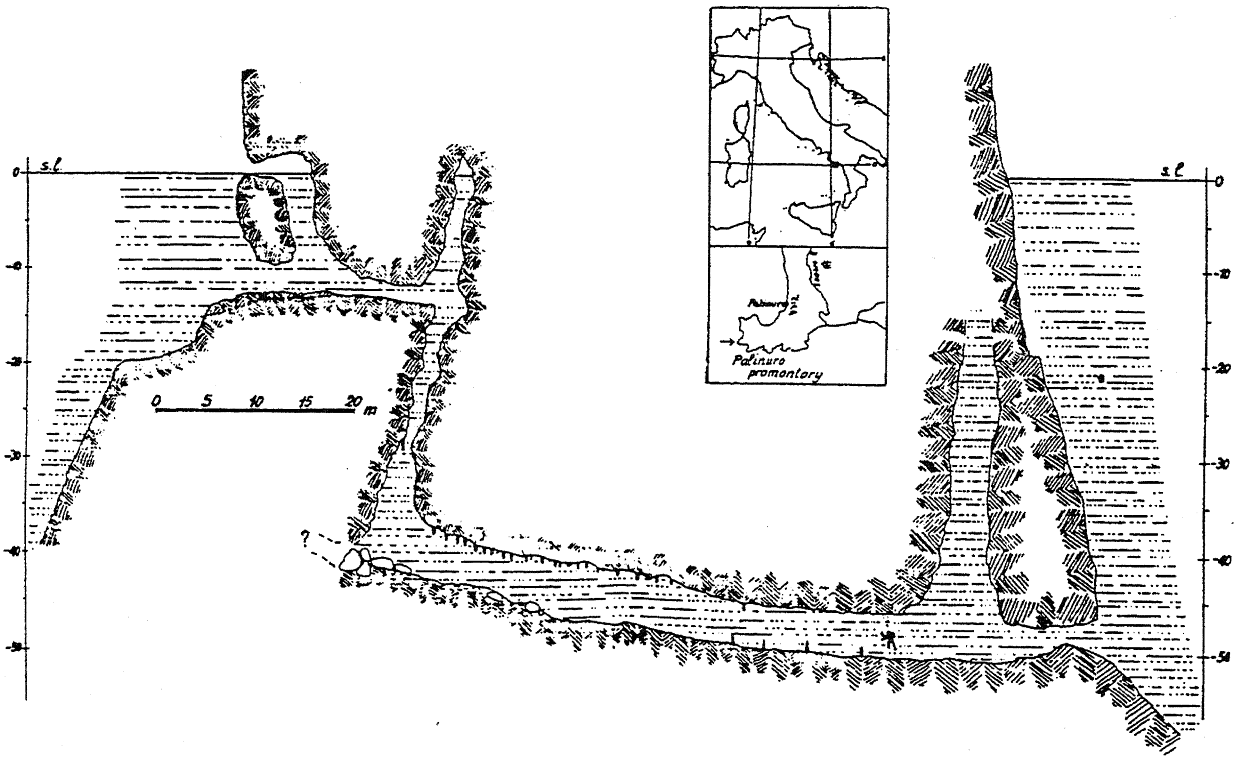

Fig. 10 - P.ta Iacco-Scaletta cave complex (location in fig. 6), Capo Palinuro, eastern Tyrrhenian Sea. Note the quite abrupt transition between vertical shafts and subhorizontal galleries, which is taken to represent the vadose-phreatic bouindary and hence a former groundwater level close to the coastline (from Antonioli et al., in press). See text for details.

Complesso Punta Iacco-Scaletto, Capo Palinuro (ubicazione in Fig. 5). Il brusco passaggio da pozzi verticali a gallerie suborizzontali è considerato rappresentativo del limite vadoso-freatico e pertanto l'evidenza di un antico livello di base formatosi in prossimità della linea di costa (da Antonioli et al., 1996).

displays a large central room with two submerged vaulted entrances, whose bottom is at -18/-20 and -32 m b.s.l. Smaller and shallower entrances are found at shallower depth and are formed by a half-emerged gallery between +7 and -3 and by a subhorizontal, phreatic conduit between -5/-9 depth. The emergent portion of the cave is a vaulted gallery at +12 m of height, which continues above sea level through concretioned rooms leading to a lake-siphon. The submerged part is a large and rounded vain with complex networks of lateral galleries. Here, warm (t=24°C) sulphureous springs flow out between -17/-23 m depth and are responsible for sulphobacteria growth, water whitening, and a marked thermal inverse stratification (Muscio and Sello, 1993; Alvisi et al., 1994b).

The morphological analysis of the Grotta Azzurra reveals different components which can be related to different processes, base-levels and paleo-sea levels (Antonioli et al., 1994). The sulphureous spring alignment, water stratification band, and likely "dissolution" notch obserbed between at -17/-23 m b.s.l., could represent the remnant of a mixing zone, which was responsible for the accelerated erosion, rounded morphology and large dimensions of the central room, and the anastomosing gallery pattern associated to the spring zone (solution mixing cave component). The mixing zone and concentrated spring flow were probably formed with a lower sea level relatively to the present one. The phreatic conduits at -5/-9 m b.s.l. ("window" in fig. 6a) are a remnant of a post-middle Pleistocene episode of relatively minor speleogenesis, which we already discussed as possibly related to the 5.5 isotopic substage or slightly older (a 5.5 substage notch is carved into the conduits, Antonioli et al., 1994). In their present position they represent a secondary submerged cave type component. Finally, the tunnel arcades with levelled floor at -18/-20 and -33 m depth (fig. 6a left) are the result of coastal abrasion superposed on the primary karst morphology (coastal cave type component) and more directly indicate a paleo-sea level (the shallower one has been ascribed to the stage 3 of the oxygen isotopic curve reaching a similar depth in the Tyrrhenian Sea: Antonioli and Ferranti, 1996).

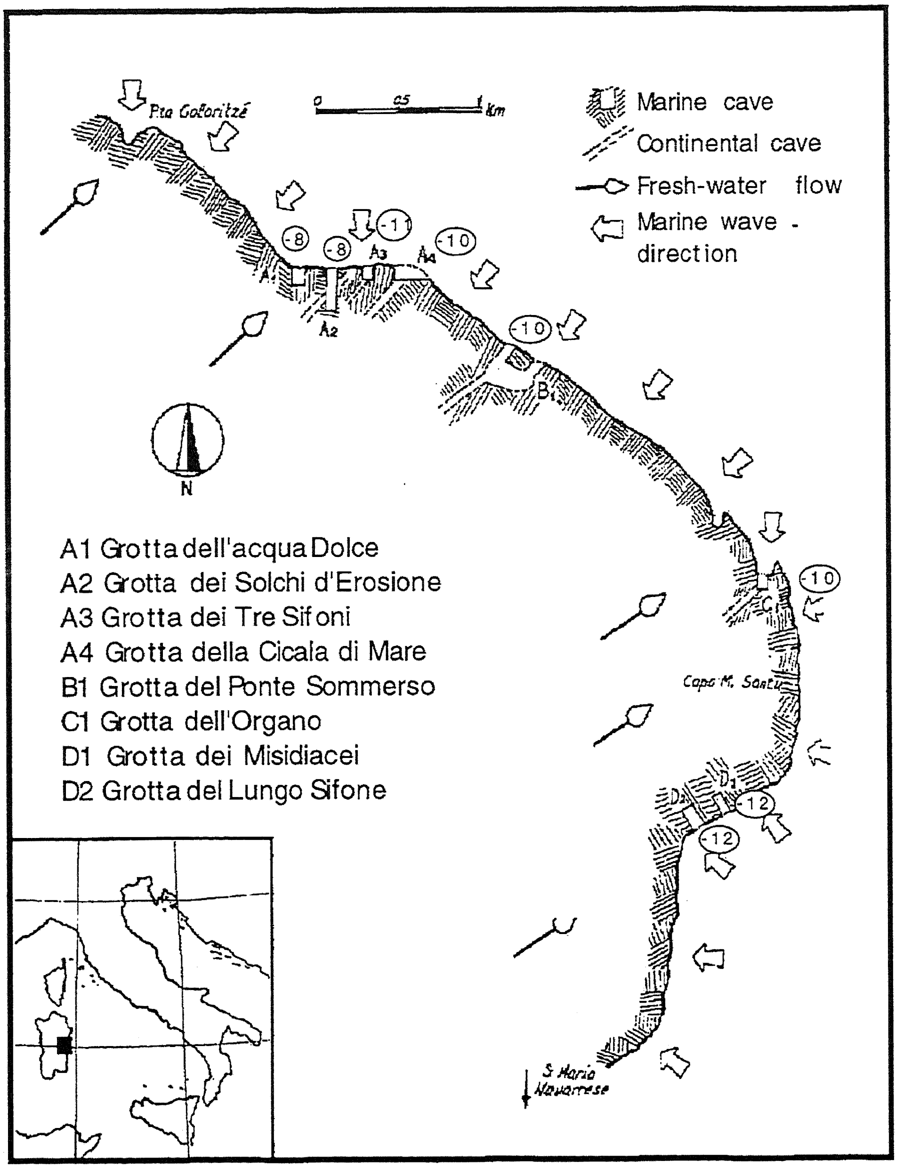

Fig. 11 - Map of Capo M.te Santu, Sardinia, western Tyrrhenian Sea, indicating the submerged caves and the depth of paleo-sea levels detected in the area (adapted after Antonioli and Ferranti, 1992). The two sets of arrows shows the orientation of marine wave-direction and fresh-water flow which concurr in shaping the submerged cave.

Carta di Capo Monte Santu, Sardegna, con indicazione delle cavità sommerse e della profondità dei paleo-livelli marini rinvenuti nell'area (da Antonioli e Ferranti, 1992). I due tipi di frecce mostrano rispettivamente direzione e senso del moto ondoso e del flusso di acque dolci che interagiscono nella speleogenesi delle cavità sommerse.

5.2 Capo M.Te Santu, Sardinia (Western Tyrrhenian Sea)

The Capo M.te Santu, located in the central part of eastern Sardinia, is formed by a limestone plateau, which is bordered seaward by one-two hundred meters high cliffs. In this block, several underwater caves are found aligned at well defined depth ranges (Alvisi and Forti, 1987), suggestive of their correlation with ancient base-levels (fig. 11). The caves have generally a subhorizontal trend and mostly develop toward the interior for some hundreds to thousands metres (Pappacoda and Fercia, 1991). Many of these caves (e. g. Grotta dell'Organo, C1, fig. 12), share a common morphology, with a narrow entrance leading to a rounded, often half-emerged room (e.g. "central room" in cave C1, fig. 12) from which anastomosing conduits branch to the interior (Antonioli and Ferranti, 1992). They are interpreted as solution mixing cave types developed at the fresh-sea water mixing zone.

Also the true coastal cave type is present and displays mostly a lenticular rather an upside-down V-shaped section, in relation to the subhorizontal stratification of the plateau (Colantoni, 1968). A recurrent alignment of simple coastal caves (or coastal caves superposed on an earlier vadose morphology) is observed at the present depth of between -8 and -11 m b.s.l. (depth of the levelled floor of trapezoidal sections, e.g. cave A2, fig. 12). In the example of cave A2, the coastal morphologies are carved into a preexisting karst system which displays transition between vertical vadose conduits and subhorizontal phreatic tubes, and likely formed as local groundwater table close to the present-day coastline (see sections of cave A2, fig. 12). A difference in orientation is observed often within the same cave between the karst galleries (which are trending northeast-southwest parallel to the main fracture trend of the plateau) and the coastal cave morphologies (which are trending parallel to the sea-wave direction and almost perpendicular to the coastline). This, besides the morphology, has allowed Antonioli and Ferranti (1992) to differentiate, within such mixed cave types, the karst and the true coastal components, respectively (fig. 11). This recurrent level of coastal and/or water-mixing caves at -8/-11 m b.s.l. is a direct indicator of a paleo-sea level, which is also substantiated by the finding of submerged marine terraces and related beach deposits at similar depths elsewhere along the cliffs of the carbonate block (Antonioli and Ferranti, 1992). On the basis of morphostratigraphic relationships, this ancient coastline has been ascribed to a stillstand occurred between the isotopic stages 5 and 2 (Antonioli and Ferranti, 1992), and is likely to represent the substage 5.5 of the oxygen isotopic curve.

This chronological-depth attribution can be well compared to the Capo Palinuro area on the eastern flank of the Tyrrhenian Sea, as discussed in the previous chapter, since both blocks on either sides of the basin reached their tectonic stability during the stage 5 (Antonioili and Ferranti, 1992; Antonioli *et al.*, 1992; Antonioli and Ferranti, 1996).

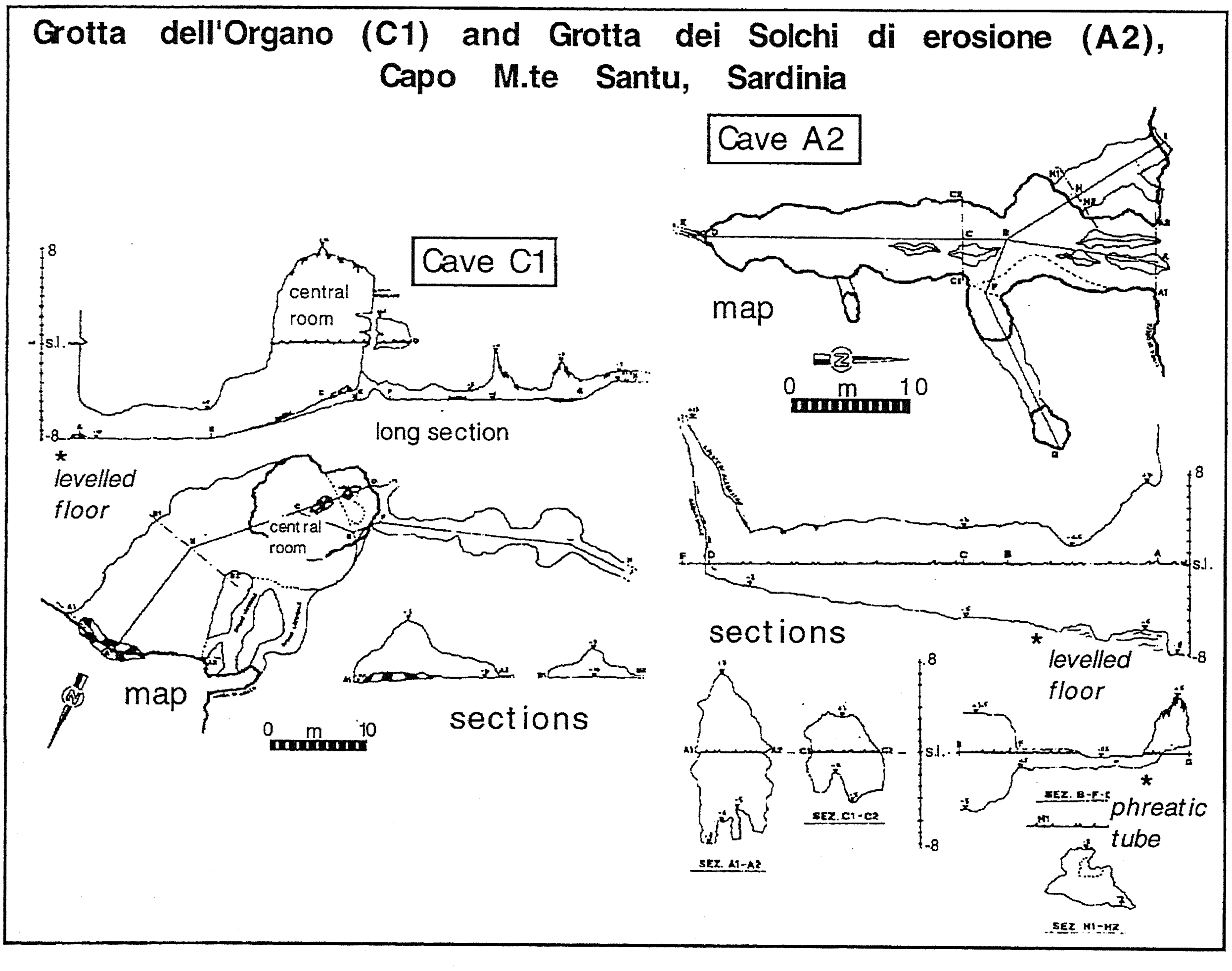

Fig. 12 - Map and sections of caves C1 and A2 (see fig. 10 for location) at Capo M.te Santu, Sardinia.
Carta e sezioni delle cavità C1 e A2 (ubicazione in Fig. 10) a Capo Monte Santu (Sardegna).

6. CONCLUSIONS

The geomorphological analysis of underwater and coastal caves provides informations on ancient still-stands of the sea level. Different cave types formed under different processes at or close to the coastline are distinguished on the ground of their morphological features and of the characteristics of their whole speleogenetic system. Attention has been focused on carbonate rocks which yield a wide *spectrum* of cave types with a variable degree of reliability as paleo-sea level indicators. The end-members, which in natural exemples are actually present in mixed systems, are represented by:

- coastal caves formed by abrasional/bioerosional/biochemical processes, which indicate the sea level or a depth immediately below (commonly between 0-3 m);
- base-level karst systems in carbonate settings close to the coastline, which provide evidence of still-standing some metres below their smoothed horizontal distribution (on the order of 10 m depending on the wideness and relative proximity of the cave to the coastline). Such estimates are further complicated by the existence of hydraulic paleo-gradients of the groundwater which varies the height of the fresh-water table above the sea level, by the primary oscillation of the groundwater, and by the wedging of the sea water beneath the lighter fresh water which causes uplift of the latter one. All these factors must be accounted when considering the spatial distribution of observed morphologies. In small-scale settings however, either the groundwater dip and the sea water wedging are low and introduce variations of very few metres (Celico, 1968). Presently submerged karst systems are a result of relative sea level rise;
- solution-mixing caves which suggest the existence of a sea level few meters above them (between few and 10-20 m as a function of morphotype development).

Theoretical studies on solution-mixing caves (Forti, 1991; 1993) and the investigation of natural examples which occur in the Tyrrhenian Sea (Antonioli et al., 1994; Alvisi et al., 1994a; Colantoni et al., 1994) has recently revealed the importance of this type of cave in limestone, which is here stressed as a possible although not precise indicator of paleo-sea level. In fact, the occurrence of features related to hyperkarst processes can be a valuable semi-proxy indicator of paleo-sea levels in absence of more precise markers.

The case-histories discussed from the western and eastern Tyrrhenian sea suggest that the study of morphological evidences of ancient sea levels in caves need to be accompanied by accurate geomorphological analysis to restore the relative positions of paleo-sea levels, to establish the timing of cessation of tectonic movement, and to fit the observed levels into existing sea level curves.

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