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Cover photo : Keir Vaughan-Taylor on Lake 2, Koonalda Cave, Nullarbor Plain. (Photo by Kevin Moore)

Back Cover : The Khan and Beagum in Kubla Khan Cave Tasmania (Photo by Garry K. Smith)

Flank Margin Caves In Telogenetic Limestones In Italy

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Abstract

Almost 20% of Italy is characterized by the outcropping of carbonate massifs ranging in age from Cambrian to Quaternary. Coastal karst is present in many Italian regions: from North-East to South and West: the Gulf of Trieste, the Conero (South of Ancona, Marche), the Adriatic coast of Apulia including Gargano, Murge and Salento, Maratea in Basilicata, Cilento in Campania, Circeo and Gaeta in Latium, Argentario and Giannutri Island in Tuscany, the southernmost part of the Ligurian Alps, Palermo Mts., San Vito Lo Capo, Syracuse coast and Marettimo Island in Sicily, and, especially, in Sardinia, which has carbonate rocks touching the sea along the coast of Balai near Porto Torres, Capo Caccia-Punta Giglio (Alghero), Sinis and Buggerru along the western litoral, Capo Teulada and Capo Sant'Elia at Cagliari, Capo Figari, Tavolara Island and the Gulf of Orosei along the eastern mountainside.

Recent researches have revealed several coastal cave systems that have a clear origin by mixing corrosion, in which the aggressive solution derives from the mixing between saline and fresh water at the watertable interface (the so-called flank margin caves). Glacioeustasy and tectonic movements can control the position of sea level with respect to coastal carbonate outcrops. For this reason these coastal caves represent useful records of sea-level stillstands. These caves are normally organized in sub-horizontal levels, and are characterized by the lack of high flow velocity markers (scallops) and alluvial sediments. Instead, they show rounded cave passage morphologies, often with horizontal wall notches, a characteristic swiss-cheese or sponge morphology, and passages that narrow going away from the coastline (due to the decreasing of sea water influence and mixing-corrosion effect). This paper describes some flank margin cave systems found in Apulia, Sicily, and Sardinia. In particular, five cave systems are illustrated: Sant'Angelo caves (Apulia), Pellegrino and Rumena caves (Sicily), and Giuanniccu Mene cave and Fico cave (Sardinia), explaining their relationship with past sea levels and local uplift rate.

Keywords: salt-fresh water mixing, coastal karst, cave geomorphology, coastal uplift, speleogenesis

1. Introduction

Despite the fact that Italy has a very long coastline, being bathed on its northwestern, western, southern and eastern borders by the Ligurian, Tyrrhenian, Ionian, and Adriatic seas respectively, carbonate rocks crop out only locally along its rocky shoreline. Most of these coastal karst areas are composed of Mesozoic rocks, limestones and dolostones of Triassic, Jurassic and Cretaceous age, but also Miocene or Cambrian limestones occur locally. All these lithologies are mostly well diagenised, so-called telogenetic limestones (Chocquette and Pray 1970), with a poor primary porosity and its permeability mainly caused by structural elements (bedding planes and fractures).

Coastal caves in these carbonate rocks are mainly derived by marine abrasion and erosion processes, and sometimes are related to freshwater outflows from the continental catchment areas. Extensive underwater cave systems are especially known from Sardinia (Gulf of Orosei, De Waele 2004). These caves are characterized by clear morphological indicators of fast running waters, such as scallops and fluvial sediments, and only in their most proximal areas to the sea they can have clues of mixing dissolution. The main morphologies are largely dominated by fluvial karst erosion, with only a minor imprint of dissolutional features.

Smaller caves, often with isolated chambers, or a spongework pattern, are known from Apulia (Onorato *et al.* 2003; Belmonte *et al.* 2009), from Syracuse (Guido *et al.* 2013), and from Capo Palinuro in Campania (Antonioli *et al.* 2004). Many of these caves were formed when sea level was lower than today, but their speleogenetic history has never been studied.

Whereas coastal mixing processes have been described since a long time (e.g. Cigna *et al.* 1963; Plummer 1975; Back *et al.* 1986; Smart *et al.* 1988), the model for cave development in a typical coastal mixing zone was published only in 1990 (Mylroie and Carew 1990). These coastal mixing caves (flank margin caves) are characterized by the lack of fluvial sediments and scallops, rounded and smoothed cave wall morphologies, dissolutional notches, locally swiss-cheese morphologies (spongework), and typical plan form with interconnected passages and rooms at intersections more or less parallel to the coastline and passages tapering out going inland, away from the mixing zone. This model was first developed in young eogenetic limestone settings, such as those of the Bahamas

Figure 1. Location of the studied caves: 1. Rumena and Fantasma Caves, San Vito Lo Capo area; 2. Pellegrino Cave, Plemmirio, Syracuse; 3. Fico Cave, Gulf of Orosei; 4. Giuanniccu Mene Cave, Quirra area; 5. Sant'Angelo Cave, Ostuni.

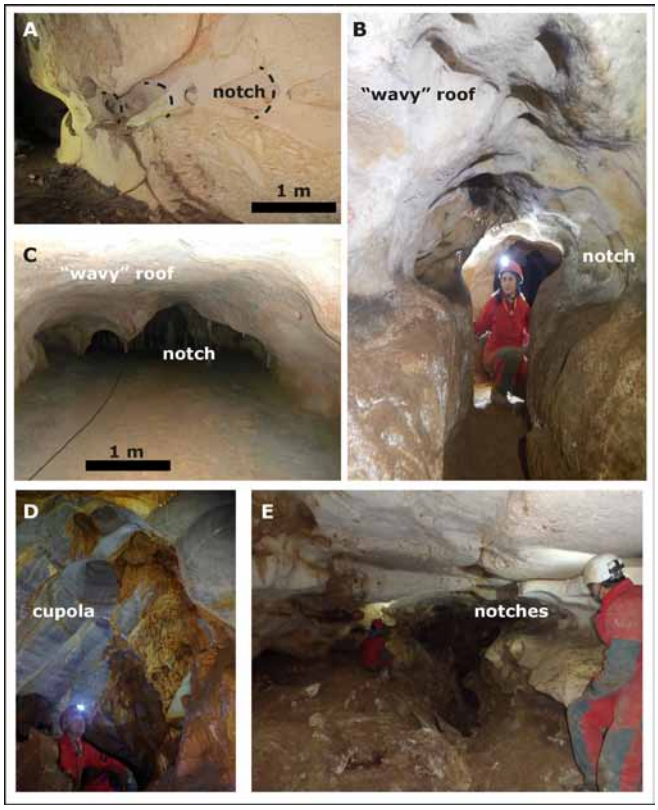

Figure 2. Typical salt-fresh water mixing dissolutional morphologies. A. The dissolutional notch at 70 m asl in Fantasma Cave (Sicily) (photo Rosario Ruggieri); B. Notch and smooth morphologies in the Pellegrino Cave (Syracuse, Sicily) (photo Marco Vattano); C. Wavy roof and notch in the 22 m asl level of Fico Cave, Sardinia (photo Ilenia M. D'Angeli); D. Cupola carved in the Devonian marbles of the Giuanniccu Mene Cave (Sardinia) (photo Laura Sanna); E. The rounded morphologies and notches in the lower Sant'Angelo cave passages, Ostuni (Apulia) (photo Mario Parise).

and other carbonate islands in the Caribbean and the Pacific, but also explained cave genesis in coastal areas with hard well-diagenised limestones (e.g. Mylroie *et al.* 2008).

In the past few years several flank margin caves have also been found in coastal areas at different altitudes above sea level in Italy (Ruggieri and De Waele 2014; D'Angeli *et al.* 2015). These caves have often an importance in sea level change studies, being precise markers of past highstands (Mylroie and Carew 1988; Florea *et al.* 2007). These uplifted flank margin caves are located in the San Vito Lo Capo peninsula (Ruggieri and De Waele 2014) and in the Plemmirio Marine Protected area south of Syracuse, both located in Sicily, in the Gulf of Orosei (Central-East Sardinia) (D'Angeli *et al.* 2015), in the area of Quirra (Southeast Sardinia), and in the area of Ostuni (Apulia) (Fig. 1). Plan views of the caves are given in Fig. 3.

2. San Vito Lo Capo (Sicily)

Several caves have clear morphologies of mixing-corrosion in the salt-freshwater boundary, not only close to the coasts, but also at a certain distance inland on ancient coastal limestone cliffs. Although some of these caves are hosted in the Pleistocene eogenetic carbonates of old marine terraces, most are mixing-corrosion caves in massive Triassic to Lower Cretaceous limestones. The best examples are Rumena, Scurati, and Fantasma caves, but other twenty cavities have been classified as flank margin caves in this area (Ruggieri, 2015). Their position at different altitudes (10-20 m, 60-75 m and 95-110 m asl) indicates variable sea level highstands during which these caves were carved. The exceptional discovery of fossil corals on the walls of Rumena cave at 95 m asl, and their dating using Sr isotopes (see Ruggieri, 2015) has allowed this highstand to be estimated at MIS29 or MIS31 (ca. 1 Ma), while the Fantasma cave and its mixing-corrosion notch (Fig. 2A), together with the Scurati caves at 70 m asl would be related to MIS19 (ca. 790-761 ka). These evidences suggest an average coastal uplift rate of around 0.9 mm/ka for this area of Sicily, and also demonstrate that not all sea level highstands are recorded in the geological record, being erased during successive highstands (Ruggieri and De Waele, 2014).

3. Plemmirio Marine Protected area (Sicily)

Miocene carbonate rocks form coastal cliffs up to 50 meters high in the Maddalena peninsula, southeastern Sicily. These fossiliferous biocalcarenites and calcirudites of the Monti Climiti Formation (Serravallian-Burdigalian) create a horst structure bounded by NNW-SSE trending normal faults (Grasso and Lentini 1982). The area is characterized by a series of marine terraces located at altitudes centered at 10, 20, 40 and 48 m asl, and two submerged terraces at 10 and 32 m bsl (Di Grande and Raimondo 1982; Guido *et al.* 2013). One of the most extensive karst systems in the area is Pellegrino Cave, over 2 km long, characterized by a branching network of anastomotic passages with typical rounded wall sculpturing (Fig. 2B) more or less parallel to the ancient coastal cliff and the actual coastline. This cave is believed to have formed during MIS 5e (Marziano and Chilardi 2002).

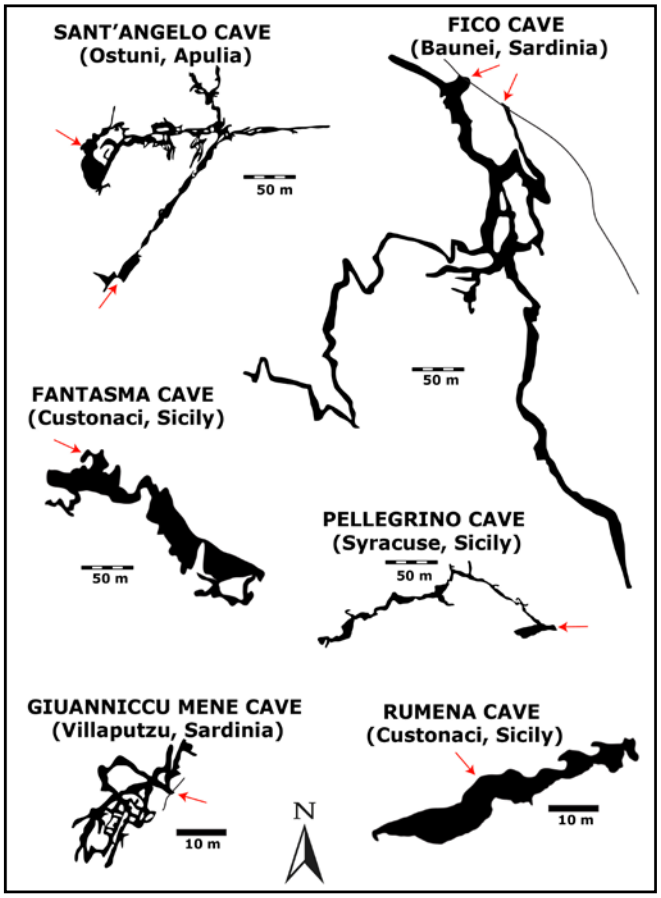

Figure 3. Plan views of the flank margin caves described in the text. Red arrows indicate cave entrances. Note scale for caves is the same for the four bigger ones (above) and the two smaller ones (below).

4. Gulf of Orosei (Sardinia)

This area is one of the most extensive and impressive limestone coasts of Italy, stretching North-South for 37 km from Cala Gonone to Santa Maria Navarrese with vertical carbonate cliffs reaching 700 meters in height (De Waele 2004). This coastal karst is renowned for its very long cave systems, but also extensive underwater cave systems (De Waele *et al.* 2009). Until recently these compact Jurassic limestones were believed to host only epigenic cave systems, shaped by dominant fluvial processes and, only in the areas closest to the coast, by some minor coastal mixing processes. A detailed observation of the morphologies in the Fico Cave, instead, has shown this cave to be mostly formed by salt-fresh water mixing-corrosion processes along major structural discontinuities. In fact, it mostly develops parallel to the coastline, along fractures, lacks the typical scallops and fluvial sediments (except for one smaller but active underwater branch), and has some typical morphologies of mixing dissolution (rounded walls and ceiling, dissolutional notches) (Fig. 2C). The altitude of the cave levels and notches above present sea level indicate the cave to have formed over the last 1 Ma during several sea level highstands, the main level, now at 14 m asl, started to be carved during MIS9 but it developed mainly in the Tyrrhenian age (MIS5e). The higher levels (22, 40, 50 and 63 m asl) in older interglacials, while the now active submerged level at -10 m below sea level probably formed during MIS7. This cave, the only flank margin type of cave preserved in this coastal stretch, sheds new light on the presumed stability of Sardinia's coastlines since Eemian (MIS5e) (D'Angeli *et al.* 2015).

5. Giuanniccu Mene Cave (Quirra, Sardinia)

In the municipality of Villaputzu (Southeast Sardinia), some Middle-Upper Devonian marbles crop out in the isolated Quirra Castle hill at about 1 km from the coastline (Corradini *et al.* 1998; Cabboi *et al.* 2005). This karst relief is bordered to the west and to the south by the Quirra river which flows into the Tyrrhenian Sea crossing a lowland at 8 m asl. These marble outcrops host several small caves, the most important of which (Giuanniccu Mene Cave) reaches 135 meters of development (Bartolo *et al.* 1986). This cave opens at 8 m asl at the southern foot of the hill, on the left bank of the Quirra River, and is occasionally flooded during flash floods. Its labyrinth of small passages is characterized by smooth wall morphologies, a series of extremely well developed cupolas (Fig. 2D), lack of scallops and presence of only small quantities of stream pebbles. These features indicate that this cave was most probably carved by salt-fresh water mixing-corrosion during the Tyrrhenian (MIS5e) highstand, when this part of the floodplain was part of the coastline.

6. Ostuni (Apulia)

The Murge plateau in its southeastern part is dissected by an important fault that is morphologically expressed, striking NW-SE between the villages of Fasano and Ostuni. In this area the Upper Cretaceous Altamura limestones are overlain by the fossiliferous Ostuni limestones of Upper Campanian-Maastrichtian age and form a stepwise morphology of a set of terraces lowering to the Adriatic coast (Delle Rose and Parise 2003; Parise 2011). The Sant'Angelo cave system opens at the foot of one of these carbonate cliffs, probably a fault scarp modified by coastal erosion, at about 150 m asl. This 1.5 km long cave is characterized by a NW-SE striking main passage, developed along a fault-line, and a set of anastomosing wide and low passages with the typical mixing-corrosion morphologies (rounded walls, swiss-cheese morphologies) (Fig. 2E) and lacking scallops or stream sediments. Its elevation above sea level suggests its age to be Lower Pleistocene, and dating of this karst void might help in understanding local uplift rates and timing of these (and lower lying) marine erosion surfaces.

7. Conclusions

Although Italy has several coastal caves, most were described to have formed by marine erosion (wave action) along lithological or structural weaknesses, or by the carving of underground streams fed by the large coastal karst catchment areas and flowing out to the sea through cave passages. The effect of salt-fresh water mixing in the dissolution of these diagenized (telogenetic) carbonate rocks was believed to be important only in the parts of the caves nearest to the sea. The observation of clear signs of coastal mixing-corrosion, such as rounded wall morphologies, in-cave notches, anastomosing passages, and the lack of stream or marine sediments and scallops on the wall in some coastal caves has demonstrated them to be of the flank margin type. This kind of caves is now known from areas very close to the present coastline (e.g. Fico Cave), but also at slightly higher altitudes (e.g. Pellegrino Cave, Giuanniccu Mene Cave), or even rather far from the present coastline and at much higher altitudes (e.g. Sant'Angelo Cave, Rumena Cave, Fantasma Cave). These caves are good past sea level indicators, often better preserved than any other marker at the surface (e.g. tidal notches, marine abrasion platform,

raised beach sediments), and their age determination can help in getting new clues on Pleistocene sea level changes and/or coastal uplift along the western Mediterranean coast.

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