

ARTICLE INFO

Article history:

Received 4 July 2014

Received in revised form 18 November 2014

Accepted 1 December 2014

Available online 16 December 2014

Keywords:

Coastal caves

Mixing corrosion

Sea-level highstands

Fico Cave

Island karst

Uplifted flankmargin caves in telogenetic limestones in the Gulf of Orosei (Central-East Sardinia—Italy) and their palaeogeographic significance

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ABSTRACT

This work reports the results of geomorphological observations carried out in the coastal Fico Cave and surrounding areas (Baunei, Central East Sardinia) in the Gulf of Orosei. A tidal notch, generally believed to be of Eemian (MIS 5e) age, is barely visible at 8.5 above present sea level (asl), some metres below the main entrance of the cave. Old cave passages, now partially opened by cliff retreat and parallel to the coastline, are clearly visible at around 14 m asl and correspond to the main level of Fico Cave. Two more notches are located higher, at 22 and 50 m asl. Fico Cave itself is composed of at least 6 clearly distinguished more or less horizontal levels (–10 m below present sea level (bsl), and +14, +22, +40, +50, and +63 m asl), independent of the stratal dip, arguing for a sea-level, and hence, fresh-water lens control. Cave passages develop along main fractures more or less parallel to the coastline and never extend landward for more than 150 m, mostly ending blindly, or diminishing in their dimensions progressively landward. Most passages only contain clay deposits, lacking fluvial or marine sediments or typical fluvial erosion morphologies (i.e. scallops). It is suggested from this body of evidence that Fico Cave was formed in the coastal mixing zone along major discontinuities during several Quaternary interglacial periods, when sea level was high and relatively stable for enough time to develop large dissolutional voids. The geomorphological observations indicate the main +14 m asl level of the cave to have formed during MIS 9, and was heavily reworked during MIS 5, while the higher levels are relative to older interglacial highstands that occurred between 1 Ma and 325 ka. The small active branch developed below present sea level has formed during MIS 7 (225 ka). These observations shed new light on the position of the MIS 5e highstand markers in this area of the coast, much higher than previously thought.

1. Introduction

It is well-known that in coastal limestone outcrops several types of dissolution caves can develop and evolve. The most important and studied type of caves are the flank margin caves (Myrroie and Carew, 1990, 2000; Myrroie, 2012, 2013). Flank margin caves are formed by mixing dissolution, and can be distinguished from other cave types by the following criteria (Myrroie et al., 2008):

- presence of phreatic dissolution morphologies at the wall rock and chamber scale;
- absence of high-velocity, turbulent-flow wall sculpturing (scallops) and stream sediment deposits;
- lack of integration of adjacent caves into a continuous flow path.

Flank margin caves have mostly been described in eogenetic limestones, young carbonates that are diagenetically immature, where the primary porosity makes the intrusion of the salt water and its mixing with seeping fresh water rather easy. Other flank margin caves occur in brecciated limestone facies, such as in the case of the Island of Cres (Croatia) (Otoničar et al., 2010). Flank margin caves, however, have also been reported in telogenetic limestones, i.e. diagenetically mature carbonate rocks (Choquette and Pray, 1970; Vacher and Myrroie, 2002). The few observed and studied caves in telogenetic limestones are located in New Zealand (Myrroie et al., 2008) and in Sicily (D'Angeli et al., 2013; Ruggieri and DeWaele, 2014). Mature carbonate rocks have little or no matrix permeability, so the mixing of fresh and saltywater can penetrate deep into the rock only by way of faults, joints and bedding planes.

The process involved in the genesis of these karst voids is related to the increasing of dissolution aggressiveness of the water due to the mixing of solutions that are saturated at different initial conditions with respect to CaCO₃ (Dreybrodt, 1988, 2000), as the case of vadose and phreatic fresh water (Bögli, 1980), and/or saline and fresh waters (Plummer, 1975). As in carbonate islands, coastal areas show a freshwater lens, where the top is a site of mixing of vadose and phreatic fresh waters, while the bottom of the lens is a site of marine and fresh water mixing. The maximum dissolution occurs in the distal margin of the lens, under the flank of the enclosing landmass, and caves form in this location (Myrroie and Carew, 1990; Neuendorf et al., 2005). This mixing creates aggressive dissolution effects on the carbonate rocks. Further dissolution potential is created by organic materials that produce CO₂ and promote the dissolution of carbonate rocks.

The cave described in thiswork is entirely formed in telogenetic carbonate rocks of Jurassic age that form high coastal cliffs. The combination of low tectonic activity and glacioeustasy control the altitude of sea level with respect to the coastal carbonate outcrops. The duration of stable sea-level position, i.e. during interglacial periods, controls the time stability of the fresh-water lens, and hence dissolution. Quaternary glacioeustatic rising and falling of sea level and the consequent oscillation of the fresh-water lens would allow too little time for macroscopic dissolution and development of flank margin caves (Myrroie and Myrroie, 2007).

Fico Cave is located along the coast and shows several cave levels. The cave was examined for evidence of mixing dissolution and also for evidence that would indicate turbulent-flow conduit origin. These geomorphological observations have the aim of reconstructing the speleogenetic phases that have created the cave, and revealing information regarding the uplift rates of the coastline and sea-level changes.

2. Study area

2.1. Geological setting

Fico Cave is located in the Gulf of Orosei (Central East Sardinia), one of the most important coastal karst areas of Italy, developing for more than 37 km with high coastal cliffs (up to 300m) facing the Tyrrhenian sea (De Waele, 2004). This coastal setting is characterised by the outcropping of a Mesozoic sequence of dolostones and limestones deposited by the transgression of Alpine Tethys over the Palaeozoic Variscan basement composed of granites and phyllites (Dieni and Massari, 1985) (Fig. 1).

In the study area marine conditions persisted probably for almost 100Ma, leading to the deposition of a Tithonian, distally-steepened carbonate ramp in a prograding complex (Jadoul et al., 2010) that reaches a thickness of around 800 m (Dieni and Massari, 1985) of diagenetically mature clinostratified calcarenites (Mt. Bardia Formation). This carbonate sequence forms a monocline ridge dipping gently eastwards to the centre of the Gulf, showing two transcurrent arcuate fault systems directed NE–SW and NW–SE (Codula Sisine Fault), with right-lateral movement and a subordinate normal component (Pasci, 1997). The general structure of this coastal karst area, confined by underlying less permeable basement rocks, obliges infiltrating water from the western part of the massif to flow diffusely towards the sea with outflows located along the coast (DeWaele et al., 2009a).

According to some authors, except for recent deep-seated gravitational slope deformations, since Middle Pliocene until Early Pleistocene a nearly continuous moderate uplift occurred, followed by a Late Pleistocene–Holocene quiescent period (Ambrosetti et al., 1987). The eastward lowering of the Jurassic carbonates is thus compensated by this geodynamic style, and the sediments outcrop continuously up to a bathymetric depth of almost 100 m on the continental shelf (Orrù and Ulzega, 1987).

These Mesozoic rocks are locally covered with alluvial conglomerates and quartz sands, related to an intense erosion–deposition cycle caused by an uplifting phase of Middle Pliocene age (Massari and Dieni, 1973). In the same period Plio-Pleistocene basalts with K–Ar ages of 2.5million years (Beccaluva et al., 1977) were emplaced. Several karst conduits in Bue Marino and Su Molente cave (Codula Ilune) and the Golgo shaft are filled with Pleistocene basalts (Mahler, 1979; Sanna and De Waele, 2010), demonstrating speleogenesis to be older than the Quaternary (DeWaele, 2004).

Early Pleistocene alluvial sands and conglomerates are found upon these effusive rocks (Dieni and Massari, 1966). Stratified slope deposits (éboulis ordonnées) (Ozer et al., 1980) and aeolian sands visible in karst pockets and coastal cave entrances were deposited during Pleistocene periglacial periods and have partially covered the foot of the carbonate cliffs.

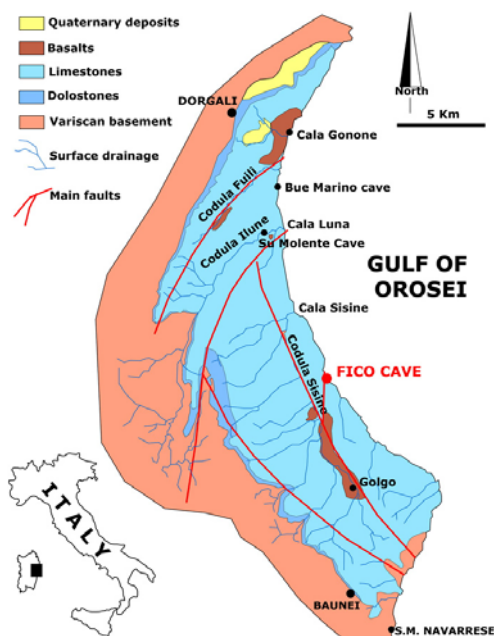


Fig. 1. Geological sketch map of the Gulf of Orosei (modified from Sanna and De Waele, 2010).

2.2. Karst landforms

The Gulf of Orosei is a carbonate coastal karst in a continental setting with typical fluviokarst landscape characterised by many dry valleys that become active only in response to heavy rainfall. Average annual precipitation ranges from around 1300 mm a⁻¹ in the inland areas (around 900 m asl) to less than 700 mm a⁻¹ in the coastal areas close to sea level (Cossu et al., 2007). The moderate recharge from the landmass is comprised between altitudes of 900 and 200 m asl, where allogenic ephemeral streams and minor amounts of authigenic recharge feed the aquifer through several discrete sinks (De Waele et al., 2010) and diffuse infiltration.

Canyons (e.g. Codula Ilune and Codula Sisine) are the major surface features, which end in the sea interrupting the continuous limestone cliffs with beaches. This hydrographic network is most probably a relict of the ancient drainage pattern related to the lowstands of the Mediterranean Sea, i.e. during the Last Glacial Maximum around 22 ka ago (Sanna and DeWaele, 2012) and continues also on the continental shelf for several kilometres up to a depth of at least –120 m bsl (Orrù and Ulzega, 1987).

The landscape is enriched by typical micro- and macro-karst landforms. Karst micromorphologies are locally well developed on the pure microcrystalline limestones, with solution flutes (rillenkarren) and solution pans (kamenitze) (Fig. 2). Among the karst macroforms, well developed dolines occur on the dolostones close to the contact with the Palaeozoic granites, and flat limestone areas, such as the San Pietro plateau, are the main physiographic inland landforms.

Coastal area morphology is the result of a combination of littoral and karst processes. Many erosion sea caves, formed by the wave action on joints and structurally weaker areas, are located along the coast, and accelerated corrosion phenomena become prevalent where mixing between fresh and salt water occurs (De Waele, 2004).

Several tidal notches, indicating present and past mean sea levels, are well developed along the entire carbonate coast of the Gulf, and are clearly visible in particular in caves elongated perpendicularly to the coastline. Such tidal notches are well described from depths of –10 m below present sea level (bsl) to heights of +14.5 m asl (Carobene, 1978; Carobene and Pasini, 1982; Antonioli et al., 1999; De Waele et al., 2009b). During the Eemian (Marine Isotope Stage MIS 5e, 125 ka ago) sea level in the Gulf of Orosei would have reached 6 m asl and the associated tidal notch is nearly completely visible along the 37 km-long shoreline, testifying a relative tectonic stability of the outcrop, exception given for a slight N–S tilting related to little tectonic activity and very small post-glacial rebound (Mariani et al., 2009). The level of this tidal notch goes from +11.5 m to +7.7 m asl, decreasing from north to south with a major flexure at the Cala Luna hinge (Carobene, 1978). The preservation of this Eemian notch over such

long distances implies that denudation and scarp retreat must have been minimal during the last 125 ka (Waterstrat et al., 2010). The -10 m bsl tidal notch, corresponding also to a well recognisable base level since most of the underwater springs are located at this water depth, formed during a period of sea level stability probably occurred during MIS 7 (245–190 ka B.P.) (Dutton et al., 2009). The aeolian sand deposits outcropping on the continental shelf up to a depth of -120 m bsl are attributed to a period comprised between MIS 5a and MIS 2, probably characterised by climatic pulses with frequent arid intervals (Antonoli and Ferranti, 1992; Sanna et al., 2010). To the south of Cala Sisine, Orrù and Ulzega (1987) have recognised four tidal notches at 0 m, +4 m, +6 m asl and -7 m bsl respectively. They have also described three marine abrasion platforms at +5 m asl and -7 m and -15 m bsl. A sea-level lowstand is also documented at a depth of -45 to -50 m bsl, correlated by Orrù and Ulzega to the pre-Versilian transgression (approximately 10 ka ago). The present marine notch is a horizontal U-shaped undercutting, 2 m deep with a vertex located near present mean sea level. At Fico Cave, in addition to this precise sea-level indicator, two different higher lying horizontal reentrants have been identified at +22 and +50 m asl (Fig. 2).

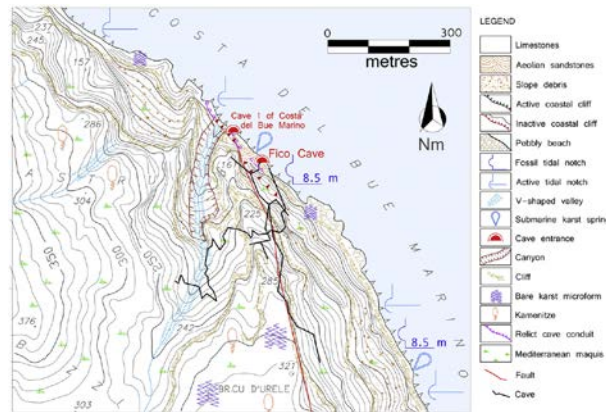


fig. 2. Geomorphological sketch map of the area around Fico Cave. Topographic map (Carta Tecnica Regionale) in scale 1:10,000 of the Autonomous Region of Sardinia has been used as base.

2.3. Fico Cave

Fico Cave is located about 20 km north of Santa Maria Navarrese village (Fig. 1) and it was the ultimate refuge of the monk seal (*Monachus monachus*), the last individuals being reported in the seventies (De Waele et al., 2009b). Known by local people for centuries, the cave explorations started in the 1960s (Donini and Monaco, 1968; Donini, 2007) and later was surveyed for around 1,980 m, with an elevation around 70 m, by the Höhlenforschungsgruppe Kirchheim (Germany) and the Società Speleologica Baunese caving clubs (Fig. 3). Recently German cave divers have led to the discovery of several underwater passages, bringing the total development to more than 3 km and the explorations stopped in front of a dry ascending passage (Thorsten Waelde, 2014 personal communication).

Fico Cave has three entrances, of which the main one opens on a steep cliff accessible by boat and also on foot following a difficult pathway (Fig. 4). The main entrance is located at an elevation of +14 m asl, while the other two are present at 0 m and -7 m bsl, respectively. The cave shows a complex network of air-filled and underwater cave passages organised in six almost sub-horizontal levels of galleries. Most of the inactive branches are developed in the relatively porous coarse-grained bioclastic limestone of the Mt. Bardia Formation. A N–S directed fault that puts these limestones in contact with a much more massive limestone of the same formation appears to inhibit the development of the lower passages landward, while the +50 and +63 m asl branches also extend west of this fault (Table 1).

The air-filled passages develop parallel to the coastline, reaching a maximum altitude of +66 m asl. These cave environments are locally characterised by important speleothem formations, including fragile helictites. The underwater tunnels stay close to sea level, and reach -27 m bsl. Submerged branches are organised in two large passages, both decorated with speleothems and black crusts: a north–south directed sump (in the Ramo del Lago), as well as the main gallery, is parallel to the coastline, while a westward developing (perpendicular to the coast) meander (Ramo del Mare), drains a very low base freshwater flow (some L s⁻¹) from the inland recharge area to the Tyrrhenian Sea. Fresh-water flow is present only along this last submerged branch, containing sediments deriving from the weathering of granite and carbonate rocks inland. During most of the year at the transition between fresh- and sea-water a sharp boundary (halocline) can be observed at a depth of -9 m bsl, then it disappears (probably dropping below floor level) and re-appears further inland at -16 m bsl. After this point the underwater cave conduits are filled only by fresh water. Despite the presence of a halocline, the water-filled conduits do not show noticeable flow except during flood (Thorsten Waelde, 2014: personal communication).

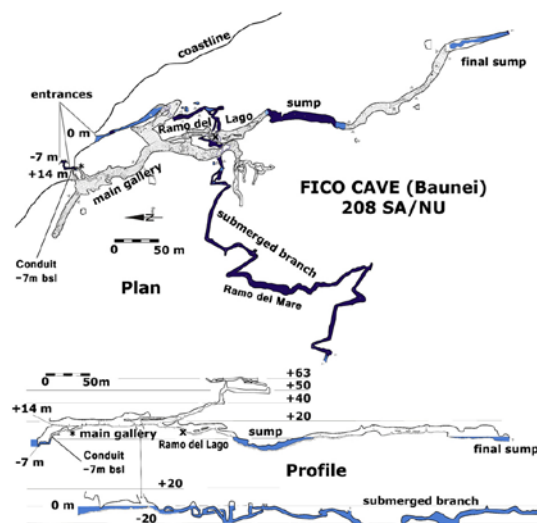


Fig. 3. Map and profile of the Fico Cave (modified from Höhlenforschungsgruppe Kirchheim—Germany). Dark coloured areas in plan are sumps.

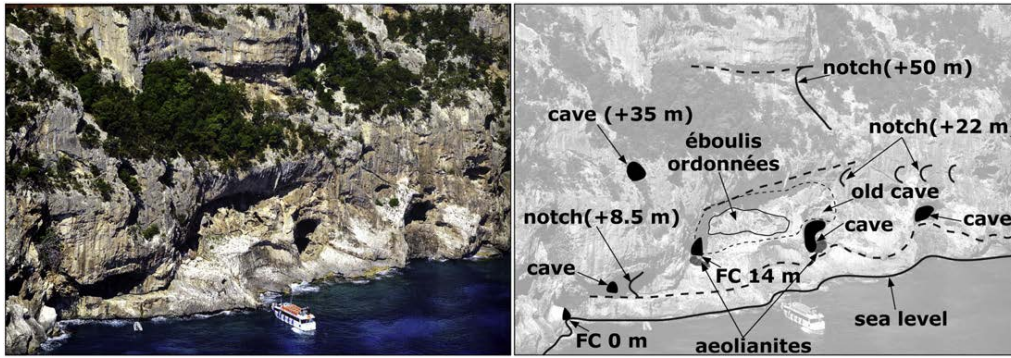


Fig. 4. Coastal area around Fico Cave (left) and schematic explanation (right): FC= Fico Cave entrances. Photo provided by Massimiliano Maddanu.

Table 1 Sea-level indicators in the Gulf of Orsei.

Altitude (m asl)	Features	References (no citation = this work)
66.00	Maximum cave altitude	
63.00	Cave level	
50.00	Cave level	
	Horizontal reentrant	
40.00	Cave level	
35.00	Cave entrance	
22.00	Cave notch with flat ceiling	
	Cave level	
	Horizontal reentrant	
	Aeolian sediment	
14.50	Tidal notch	Carobene (1978), Carobene and Pasini (1982), Antonoli et al. (1999), De Waele et al. (2009a,b)
14.00	Cave level	
	Cave entrance	
12.00	Marine overgrowth	Carobene (1978)
11.50	Tidal notch	
10.00	Cave entrance	
8.50	Tidal notch	Carobene and Pasini (1982), Antonoli et al. (1999)
8.00	Beach sediments	
7.70	Tidal notch	Carobene (1978)
6.00	MIS 5e tidal notch	Antonoli et al. (2006), Tuccimei et al. (2012), Carbone et al. (2014), Orrù and Uzzega (1987)
	Tidal notch	Orrù and Uzzega (1987)
5.00	Marine abrasion platform	Orrù and Uzzega (1987)
4.00	MIS 5e tidal notch	Antonoli et al. (2006), Tuccimei et al. (2012), Carbone et al. (2014), Orrù and Uzzega (1987)
	Tidal notch	Orrù and Uzzega (1987)
2.00	Beach sediments	
0.00	Tidal notch	Orrù and Uzzega (1987)
	Cave entrance	
-7.00	Tidal notch	Orrù and Uzzega (1987)
	Marine abrasion platform	Orrù and Uzzega (1987)
	Cave entrance	
-9.00	Halocline	
	Cave level	
-10.00	Tidal notch	Carobene (1978), Carobene and Pasini (1982), Antonoli et al. (1999), De Waele et al. (2009a,b)
	Underwater spring	
-15.00	Marine abrasion platform	Orrù and Uzzega (1987)
-16.00	Inland halocline	
-27.00	Minimum cave altitude	
-45.00	Sea-level lowstand	Orrù and Uzzega (1987)
-50.00	Sea-level lowstand	Orrù and Uzzega (1987)
-120.00	Maximum sea-level lowstand	Orrù and Uzzega (1987)

3. Cave morphology and deposits

Surficial geomorphological observations carried out along the Gulf of Orsei in the surroundings of Fico Cave have shown that it is hosted in a highly fractured stripe zone with cracks, joints and fractures (Fig. 5) related to a subordinate normal component of Codula Sisine fault. This subordinate fault, which can be tracked for a hundred metres from the inland escarpment to the underwater platform, opens on a carbonate cliff that instead developed along a NNW-trending fault plane.

The main entrance of the cave (+14 m asl) with a rounded crosssection 6 m in diameter, looks out at the foot of a 50 m-high hanging wall that slopes down to the sea along a relict ledge (Fig. 4). Also the underwater openings (0 m and -7 m bsl) stand on a footwall parallel to the same lineation and the -7 mbsl entrance opens in correspondence of a marine abrasion platform. In this point the coastal cliff is shaped as a wide rock cirque carved on rather pure fossiliferous coarse-grained bioclastic limestones (Mt. Bardia Formation), dipping approximately 40° toward the south-east, with low- to medium matrix porosity.

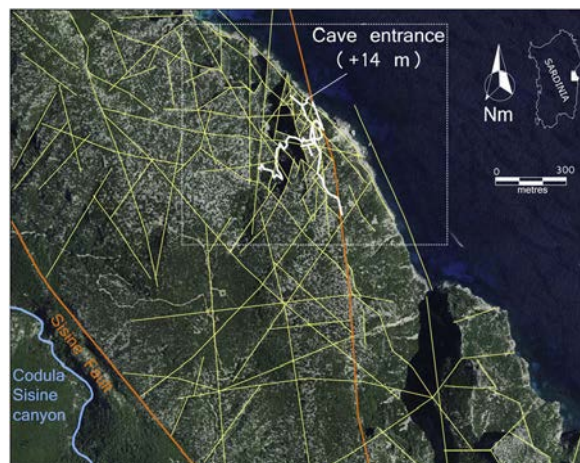


Fig. 5. Structural aerial sketchmap of the coastal area around Fico Cave (speleological map shown in white). Inset shows location of geomorphological map of Fig. 2 (based on aerial survey dated 2008 available online at www.sardegnaoportale.it/webgis/fotoaeree).

An ancient tidal notch has been preserved on the coastline on the southern side of the cave entrance at +8.5 m (Fig. 4). Few metres above the main cave entrance, a sub-horizontal reentrant, likely the remains of a cave passage cut by cliff retreat, has been identified (Fig. 4).

The upper part of this reentrant forms a notch-like feature located at +22 m asl. The remains of this cave passage can be followed on the northern side of the surrounding cliff for several metres, passing through a 91 m-long tunnel (Cave number 1 of Costa del Bue Marino, see Fig. 2 and Fig. 7D) that opens 200 m north of Fico Cave with three entrances at +10 m asl. This small cave develops parallel to the coastline with phreatic dissolutional morphologies, well-crystallised calcite speleothems, no evidence of stream sculpturing and ending in a blind wall. Around 25 m south of the main entrance another cave opens on the cliff at +35 m asl (Fig. 4). Finally, another notch is visible 15 m higher, at +50 m asl (Fig. 4). Remains of aeolian sands and breccialike slope deposits are stuck on the steep cliff wall or fill pockets and small phreatic tubes at different altitudes (Fig. 4).

Detailed cave geomorphological studies have recognised six more or less horizontal cave levels: +14, +22, +40, +50, and +63 m asl, and the active submerged branch (Ramo del Mare) at -10 m bsl. The dry levels are characterised by large passages running parallel to the coastline, while the submerged branch is an active conduit running perpendicular away from the coast in a west-southwest direction. The development of most cave passages is clearly influenced by tectonic structures directed NNW-SSE and NE-SW. All branches follow a joint/ fault while the limestone strata dip does not influence the altitudinal distribution of cave levels. This unmistakably argues for a sea-level or fresh-water lens control on these horizontal cave levels.

The main branch at +14 m asl and the four other air-filled levels present walls with curvilinear mixing dissolution surfaces (corrosion notches) (Fig. 6A-D), sometimes with a flat ceiling (Fig. 6B), and with wall and ceiling cusps (Fig. 6C). In the gallery at +40 m asl the presence of canopy flowstone and of a horizontal line under which submerged speleothems similar to poolfingers are visible testify that there was a pensile lake. Also in the gallery +50 m asl a horizontal mud-stained line is well visible (Fig. 7A). Most galleries and the halls are roundish (Fig. 7A, B) and tend to diminish in size going landward, away from the coastline (Figs. 6C, 7C), and ending in blind walls. The underwater branch (Ramo del Mare) is organised in undulating rounded passages, with blind dissolution pockets on ceilings and walls (Fig. 7G, H).

Tidal notches and Lithophaga borings are absent in the cave. Signs of phreatic flow (e.g. scallops) have not been observed, except in a small portion of the cave in a phreatic lift tube near the "Ramo del Lago" close to the sump (0 m, X in Fig. 3). The scallops in the aerial part indicate an upward flow away from the lowest point, suggesting water to have flown uphill from the below lying active submerged branch. fluvial sediments have been detected within Fico Cave except for white well-rounded, 5 cm in diameter, carbonate clasts and soft granitic sandy deposits in the underwater passages of Ramo del Mare (Fig. 7F). Some residual clays (authigenic deposits) and wind-blown fine silts have been found in the air-filled passages.

In a small conduit in the hall close to the main entrance (star * in Fig. 3) some sands of aeolian and marine origin occur at altitudes up to +8 m asl, partly forming the floor of the hall. These sediments were introduced through an ascending conduit (similar in size, altitude range and morphology to the Ramo del Mare branch) connected to the sea at -7 m bsl (Fig. 3) and intercepted by the main passage. These aeolian and marine sands contain an association of organisms among which are: foraminifera typical of marginal environments, such as *Astigerinata mamilla* (Williamson, 1858), *Cancris auricolus* (Fichtel & Moll, 1798), *Criboelphidium poeyanum* (d'Orbigny, 1839), *Elphidium crispum* (Linnaeus, 1758), *Rosalina bradyi* (Cushman, 1915), *Rosalina* sp., *Globigerina* sp. and *Globigerinoides quadrilobatus* (d'Orbigny, 1846), the bivalves *Lima lima*, *Spondilus* sp., and the gastropods *Bolma rugosa*, *Balani* sp. and *Patella ferruginea*. The presence of *P. ferruginea* and the height reached by these deposits are compatible with an Eemian age (MIS 5e).

A rich association of speleothems has made this cave famous (Donini and Monaco, 1968): in the highest levels (+63 and +50 m asl) the walls are covered with helictites (Fig. 6F), while in the main branch (+14 m asl) normal speleothems such as stalactites, draperies, stalagmites, columns, flowstones, canopy flowstones, popcorn and rimstone dams are widespread. Also some rare poolfingers in a dry pool and conulites and a disk in the small branch called "Ramo del Lago" occur. In this last branch, a broken stalagmite at +12 m asl shows marine overgrowths, testifying submersion during its formation (X in Fig. 3, close to the scallops mentioned before, Fig. 6E). Also underwater passages are decorated with vadose speleothems, such as very large rimstone dams (Fig. 7H), columns, stalagmites and draperies.

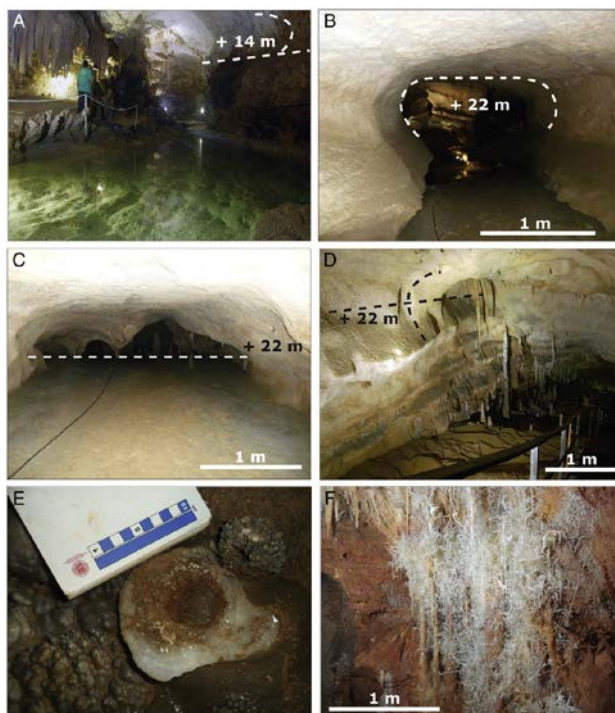


Fig. 6. Morphological features of Fico Cave: A. Main gallery with the +14 m notch visible where speleothems do not cover the walls (Photo of Massimiliano Maddanu); B. The small horizontal passage with notch at +22 m asl and flat ceiling; C. dissolution cusps on the ceiling at the end of the +22 m passage; D. Main gallery with notch at +22 m asl clearly visible close to the ceiling (Photo of Massimiliano Maddanu); E. Broken stalagmite at +12 m asl in the Ramo del Lago, with evidence of submersion and deposition of reddish clays, and new white speleothem formation. F. Helictites in the +40 m branch (photo of Società Speleologica Baunese).

4. Discussion

Fico Cave with its sub-horizontal levels, its morphological features and abrupt endings can be classified as formed by dissolutional processes related to laminar flow. Its position close to the coast and the lack of hypogene caves in the entire coastal area allow us to assess its formation to be related to

mixing between fresh water (from inland or meteoric water) and salt-water (from the sea) during long-lasting sea-level highstands. The morphologies typical of flank margin caves were preserved in this cavity because the marine cliff is subjected to slow erosion as testified by the preservation of several levels of tidal notches.

Denudation rates in Mediterranean coastal limestone areas in the north of Italy are around 0.1 m ka^{-1} , rising up to 0.31 m ka^{-1} in the intertidal zone (Furlani et al., 2009; Furlani and Cucchi, 2013). For the eastern coast of Sardinia, where rainfall is much lower, evaporation is much higher and wave action is less strong than in the northern Adriatic, this denudation value might be an order of magnitude lower. Based on our geomorphological observations, and the lack of Aeolian sands in the entrance area, the cave opening at +14 m asl appears to have been intercepted by coastline retreat relatively in recent times (probably less than 20 ka). The slope deposits found near this entrance probably covered the entire area and were able to protect the internal cave environments from the high-energy waves and from the infilling by coastal sediments.

Both glacioeustasy and limited tectonic movements have controlled the position of sea level with respect to the coastal carbonate outcrops. Considering the Middle Pliocene–Early Pleistocene moderate uplift and the relative Late Pleistocene–Holocene stability, the key factor in sea-fresh-water boundary position is the duration of the stable sea-level position, which in turn controls the stability in time of the fresh-water lens. Stable sea levels influence the position of the fresh-water lens and thus cause cave development in distinct levels, which can thus be used to identify past sea levels (Florea et al., 2007). Sea-level highstands characterised interglacial times, with sea levels similar or even higher than today occurred during MIS 5, 9, and 11 (Martinson et al., 1987; Shackleton, 1987; Vesica et al., 2000; Muhs et al., 2011, 2014), while MIS 7 appears to have produced three slightly lower highstands between 250 and 190 ka, probably around 18 m lower than today (Zazo, 1999; Dutton et al., 2009). Highstands older than MIS 11 do not appear to have been as high as today, except for MIS 21 and older (Bintanja et al., 2005).



Fig. 7. Morphological features of Fico Cave: A. Level at +50m asl showing a clear horizontal water level on its walls; B. Level at +63masl with typical rounded forms and a clay bottom, and C. with small passages ending blindly going landward; D. Large rounded entrance of the Cave number 1 of Costa del Bue Marino, and E. large calcite crystals; F. Initial part of the submerged branch (Ramo del Mare) with rippled granitic sand on the bottom; G. Rounded phreatic passage in the submerged branch (Ramo del Mare) and H. Drowned and partly eroded rimstone dams (underwater photos courtesy of Pro Tec Sardinia).

The main cave level at +14 m asl, being the best preserved and the biggest, has most probably formed during the multiple highstands of MIS 5 (130–80 ka BP). The presence of the stalagmite with marine overgrowths found at +12 m asl shows that this level was at least partially open to the sea already during MIS 5e. The main cave level is at least 6m higher than that of the tidal notch at +8.5 m asl, considered by all earlier authors to be 125 ka old (Carobene and Pasini, 1982; Antonioli et al., 1999). The presence of marine sands of MIS 5e in the submerged branch with the entrance at –7mbsl indicates that this level has been formed prior to MIS 5e, during a period with a lower sea level than today, probably during MIS 7. Also the submerged branch (Ramo del Mare), being developed at altitudes between –26 and 0 m bsl (mean –10 m bsl) most probably formed during MIS 7. Sea level worldwide during MIS 7 is believed to have reached –18 m bsl (Siddall et al., 2007), indicating this part of the coast to have been uplifted by around 8 m since. This would also explain the anomalous altitude of the MIS 5 passages, which are 8 m higher than the mean value of +4 to +6 m asl reported for MIS 5e by other authors in Sardinia (Antonioli et al., 2006; Tuccimei et al., 2012; Carboni et al., 2014). Uplift would thus have happened mostly in the last 125 ka, allowing calculation of an average uplift rate for the Fico Cave area around 0.067 m ka^{-1} , twice as much as that reported by earlier authors (0.03 m ka^{-1}) for the coastline of the Gulf of Orosei (Carobene and Pasini, 1982). The tidal notch at +8.5 m asl close to Fico Cave, previously considered to be MIS 5e in age, might be younger, probably MIS 5a.

Based on all data reported above, the speleogenetic history of Fico Cave might thus be outlined as follows (Fig. 8). The upper levels at +40, +50, and +63 m asl are most probably older than MIS 21 (N800 ka). During MIS 11 the relative sea level was similar to today, so that the 22 m asl level might have formed during this stage (ca. 400 ka ago), while the main level at +14masl started forming during MIS 9 (ca. 325 ka ago). MIS 7 sea-level highstands stayed around –18 m bsl (Dutton et al., 2009), so the active submerged level might have formed during this period (ca. 250–190 ka ago). During MIS 5 the sea level rose higher than today and enlarged the MIS 9 passages, explaining their exceptional dimensions and fresh appearance. During this period these upper passages locally reached the underlying MIS 7 passages, allowing the sea water to directly enter the cave in some parts (e.g. Ramo del Lago above the Ramo del Mare, X in Fig. 3). This explains the localised presence of a stalagmite with marine overgrowth at +12 m asl and the introduction of MIS 5 sediments in some of the lower conduits. Most tidal notches also formed during the multiple highstands of MIS 5.

The active submerged branch at around –10mbsl does not display sufficient diagnostic indicators to allow its classification as a flank margin cave, nor as a traditional stream conduit cave. In fact its passages, formed at the limit of the fresh water lens within the phreatic zone, underwent modifications within the vadose zone during a sea-level low stand (as submerged speleothems and erosional features confirm). A subsequent sea-level rise flooded these lower passages again leading to an overprinting with more recent dissolutional wall-rock features and corrosion of speleothems. However, the fact that it hosts an active water flow, and its westward development, penetrating deep into the coast far away from the potential mixing zone, allows it to be classified as an epigenetic stream conduit cave.

The air-filled cave also contains abundant vadose speleothems and its morphology reflects the overprinting of vadose and phreatic conditions resulting from glacioeustasy in the Quaternary. The presence of well-crystallised speleothems and helictites, especially in the higher levels, suggests that there are humid (non-evaporative) conditions in the cave. Speleothem growth is mainly controlled by CO₂ diffusion.

Dense, well-crystallised calcite speleothems are excellent indicators of a sealed cave environment (Taboroši et al., 2006). The main +14 m asl cave level has probably been opened by cliff retreat in relatively recent times, although local connections with the underlying MIS 7 cave branches were open already during MIS 5.

The presence of old, nowuplifted flankmargin caves in the area may be related to the negative water budget environment that retards the dissolutional denudation of the carbonate ridge enabling these caves to survive over long periods of time.

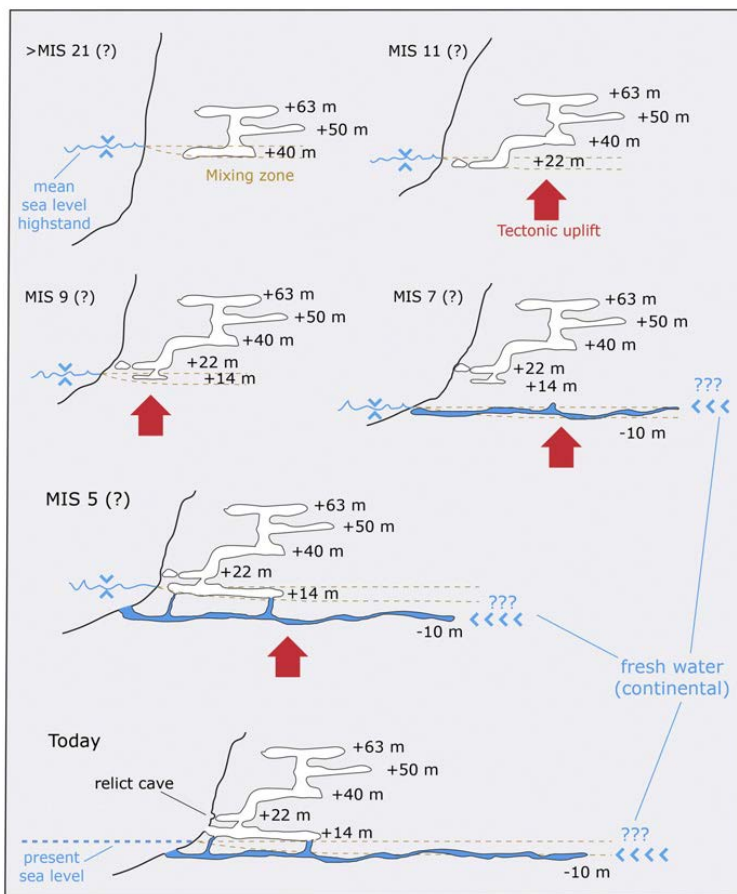


Fig. 8. Schematic representation of the evolution of the Fico Cave (psl=present sea level). Not in scale.

5. Conclusions

The detailed study of Fico Cave has revealed a good example of an old flank margin cave and how this speleogenetic model also works in dense, massive telogenetic rocks. Glacioeustasy, and to a minor extent tectonic movements, have controlled the position of sea level with respect to coastal carbonate outcrops in the Gulf of Orosei. These ancient sea levels are preserved in the cave levels and can be used as proxies for past sea-level stillstands.

On the basis of these observations, Fico Cave shows six different horizontal cave levels, five air-filled levels at +14, +22, +40, +50 and +63 m asl, and a submerged branch at around -10 m bsl that can be correlated to sea-level highstands since at least MIS 22 (around 1 million years ago). Our observations support the main cave level at +14 m asl to have formed during MIS 9, with further widening during MIS 5. In the sector of Fico Cave traces of the MIS 5e sea-level highstand are located higher than in other regions, suggesting tectonics to have acted also during the last 125 ka, with an uplift rate of 0.067 m ka⁻¹.

While in the upper parts of the cave, passage level adjustment is closely related to crustal movements, in the lower part the sea-level variations have a predominant role on cave passage development. The submerged branches are evolved as conduit caves when the platform was exposed to meteoric inputs by glacioeustasy.

Despite the fact that caves developed in the distal margin of the fresh-water lens may be the result of extremely fast dissolutional processes (a couple of thousands of years) (Fratesi, 2013), some Sardinian flank margin caves have probably persisted for over a million years. The presence of a visible halocline indicates that the mixing corrosion process is still active in the area.

The notch preservation proves the Gulf of Orosei to be a relatively stable coastline with very low denudation rates and cliff retreat at least since MIS 5a, and more flank margin caves might have formed and be preserved along the coast. Despite the overprinting of more recent standard karst processes, future investigation could allow recognition of other flank margin caves along Sardinian telogenetic carbonate coasts and along the whole Mediterranean coast, finding new evidences of sea-level highstands.

Acknowledgements

Access to the Fico Cave and field work were made possible by the cavers of the Società Speleologica Baunese. The detailed information on the submerged branches has been made available thanks to Thorsten (Toddy) Waelde of ProTec Sardinia. The palaeontological content of the sediments was analysed by Stefano Claudio Vaiani and Daniele Scarponi of Bologna University. Thanks to photographers of Società Speleologica Baunese, ProTec Sardinia and to Massimiliano Maddanu. The analysis of the historical pictures of the first explorers of the Gruppo Speleologico Bolognese/Unione Speleologica Bolognese has been extremely appreciated. Comments and suggestions by the two reviewers allowed us to improve our manuscript substantially. L.S. benefitted from a grant supported by the European Social Funding through the Regione Autonoma della Sardegna ("Master & Back" Programme code PR-MAB-A2009-381).

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