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Uplifted flank margin 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 (Mylroie and Carew, 1990, 2000; Mylroie, 2012, 2013). Flank margin caves are formed by mixing dissolution, and can be distinguished from other cave types by the following criteria (Mylroie 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 Mylroie, 2002). The few observed and studied caves in telogenetic limestones are located in New Zealand (Mylroie et al., 2008) and in Sicily (D'Angeli et al., 2013; Ruggieri and De Waele, 2014). Mature carbonate rocks have little or no matrix permeability, so the mixing of fresh and salty water 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 $CaCO_3$ (Dreybrodt, 1988, 2000), as the case of vadose and phreatic fresh water (Bögli, 1980), and/or saline and fresh waters

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(Plummer, 1975). As in carbonate islands, coastal areas show a fresh-water 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 (Mylroie 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 CO_2 and promote the dissolution of carbonate rocks.

The cave described in this work 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 (Mylroie and Mylroie, 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 300 m) 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 100 Ma, 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 (De Waele 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 2.5 million 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;

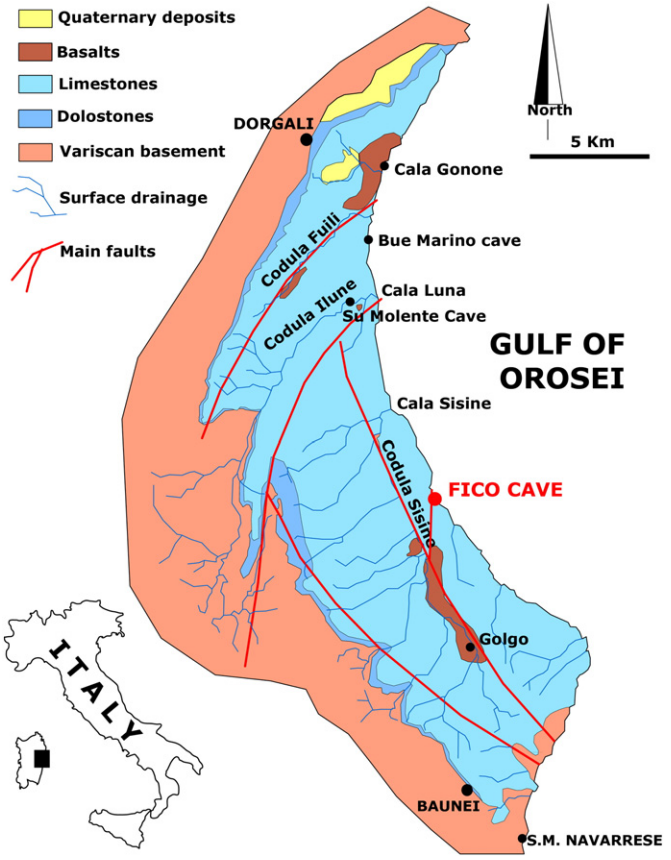

Fig. 1. Geological sketch map of the Gulf of Orosei (modified from Sanna and De Waele, 2010).

Sanna and De Waele, 2010), demonstrating speleogenesis to be older than the Quaternary (De Waele, 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.

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 De Waele, 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