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# Intra-messinian gypsum palaeokarst in the Northern Apennines and its palaeogeographic implications

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**ABSTRACT**

**A short intra-Messinian continental period has been recognised in some North Italian gypsum areas, mostly under the form of palaeokarst deposits. This emersion appears to have occurred only locally, and is explained as caused by the intra-Messinian tectonic phase and a major sea level lowering. Evidences of this palaeokarst are mostly small, although at some places the palaeontological content of its fillings is of great importance. The discovery near Zola Predosa (Bologna) of a new intra-Messinian extensive karst system and of its infilling sheds new light on the importance of this karst episode.**

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## Introduction

The Messinian salinity crisis (MSC) is one of the world's most studied catastrophic geological events (Clauzon *et al*., 1996; Krijgsman *et al*., 1999). The geological succession of the MSC is generally subdivided in: (i) the Lower Evaporites (5.96–5.60 Ma), characterised by shallow water evaporites, and (ii) the erosional surface and its products (5.60–5.55 Ma) followed by the resedimented Upper Evaporites (5.55–5.33 Ma), composed of non-marine deposits known as Lago Mare (Clauzon *et al*., 1996; Roveri and Manzi, 2006). The Lower Evaporites, mainly consisting in an alternation of gypsum beds and marls, and the resedimented Upper Evaporites are well represented in the Emilia-Romagna region (N-Italy), and crop out in several more or less small fragments along the northern border of the Apennines (Fig. 1). Notwithstanding the limited extension of these gypsum outcrops, the Emilia-Romagna Region hosts some of the most developed epigenetic gypsum caves in the world (Klimchouk *et al*., 1996). The great majority of surface and underground karst forms are related to the present-day karst episode, that most probably started some ten thousands of years ago. Excavations in the filling of a fossil shaft intersected by a gypsum quarry immediately South of Bologna (area 3 in Fig. 1) revealed a Pleistocene mammal fauna of the Last Glacial (*c*. 20 000 years BP) (Pasini, 1968, 1970). This karst episode extended back at least to the penultimate glacial period (Pasini, 2012).

During excavations in a gypsum quarry near Brisighella (area 5 in Fig. 1) some karstified fissures containing sediments with late Messinian terrestrial mammals evidenced, for the first time in the region, an intra-Messinian continental period (Costa *et al*., 1986). This short emersion has also been documented in other North Italian areas (e.g. Moncucco Quarry, Piedmont) (Fioraso and Boano, 2002; Fioraso *et al*., 2004) and elsewhere (e.g. Sorbas, SE Spain, Martin and Braga, 1996), and caves presently forming by rising fluids (hypogenic caves) appear to be propitiated upon these intra-Messinian karst voids (Vigna *et al*., 2010). This continental phase is believed to have developed in response to an intra-Messinian tectonic phase (Fioraso *et al*., 2004; Lugli *et al*., 2010), and a dramatic sea level drop (Clauzon *et al*., 1996). This lowering of sea level triggered the entrenchment of many karst systems around the Mediterranean (e.g. Audra *et al*., 2004; Mocochain *et al*., 2009, 2011). The intra-Messinian tectonic event, well-documented for example in the Vena del Gesso basin, is connected to the evolution of the Apenninic orogenic wedge and the migration of the compressive front and associated foredeep basin toward the North (Roveri *et al*., 2003).

The discovery of a new and extensive intra-Messinian palaeokarst near Zola Predosa (Bologna) sheds new light onto this continental erosion period and its relationships with tectonic events.

## Geological background

At Zola Predosa (area 4 in Fig. 1) Messinian gypsum beds crop out over a length of 1.5 km, reaching their maximum thickness of 300 m in the central part of the outcrop. The evaporites are composed of mostly thick selenite layers, interbedded with more or less thin marly sediments. They cover Miocene fine-grained sediments ranging in age from Langhian to Lower Messinian. The whole evaporite sequence is overlain by Upper Messinian and Pliocene clays and marls. The general strike of the gypsum beds is ENE–WSW; the dip is more or less regular to the NNW, with angles ranging between 40$^{o}$ and 47$^{o}$ (Martelli *et al*., 2008).

There are three main fault systems in the area: transcurrent N–S and NW–SE faults (anti-apennine faults) and extensional E–W faults (apennine faults). As for the Vena del Gesso area (area 5 in Fig. 1), the most important tectonic phases are believed to be two: intra-Messinian (minor tilting phase, 5.60–5.33 Ma) and Middle to Late Pliocene-Quaternary (transversal faults and major second tilting) (Marabini and Vai, 1985; Clauzon *et al*., 2005; Bache *et al*., 2012).

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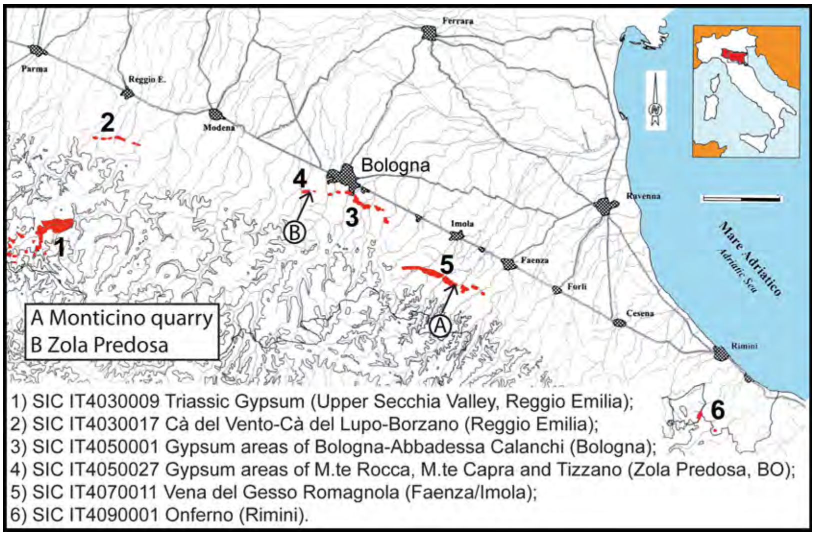


**Fig. 1** Triassic and Messinian gypsum outcrops (in red) in Emilia Romagna Region (N-Italy).

## The Zola Predosa palaeokarst

Several fragments of an extensive karst system – named 'Grotta di Monte Rocca', and now completely filled with sediments – have been cut by a quarry tunnel at Zola Predosa, some km West of Bologna (Emilia-Romagna, Italy) (area 4 in Fig. 1). The massive selenite gypsum was quarried along one of the main Messinian gypsum cycles, and the tunnel follows the bedding planes in a ENE–WSW direction (Fig. 2). Some of the palaeokarstic conduits have a typical vadose morphology, in the form of meandering canyons (Fig. 3A–C), but most are phreatic tubes (Fig. 4A,B). All are completely filled prevalently with finely layered sediments. The most interesting fragment of the fossil cave is found at the western end of the quarry tunnel, where a phreatic 4 × 5 m wide tube has been sectioned almost perpendicularly in two parts, and is well-exposed on both tunnel walls (Figs 2D, E and 4A, B). This stretch of the 'Grotta di Monte Rocca' has been named 'Galleria dei Quattro', and is the only one so far studied in detail. It develops in an E–W direction, almost parallel to the strike of the gypsum beds.

The total development of the visible karst conduits of the Grotta di Monte Rocca is around 80 metres, but many parts have been destroyed by the quarry, and the real development of the cave must have been several hundreds of metres. This palaeocave developed inside one of the thickest gypsum strata.

Close to the western end of the quarry's tunnel some karst morphologies free of sediments are exposed on the northern wall; their filling was removed by the quarry works and recent infiltration waters. In particular there is a passage with a well-developed post-antigravitative ceiling channel with flat roof (Fig. 2, point G; Fig. 5B) (Pasini, 2012). This kind of ceiling channels formed after the end of the antigravitative erosion process (Pasini, 2009; Farrant and Smart, 2011); they are always characterized by a flat sub-horizontal roof – sometimes a few metres wide – owing to their formation (their roof is bevelled by the water table: Pasini, 2012). This speleoform developed during a sedimentation stage of the cave, and its flat roof is now inclined 42° toward the NNW (Fig. 2, point G; Fig. 5B). The gypsum beds measured nearby show an inclination of around 40° in the same direction. All this can be explained only by admitting that the post-antigravitative ceiling channel obviously formed after the end of the deposition of the Primary Lower Gypsum beds, dated at 5.61 Ma BP (Lugli *et al.*, 2010), and before the onset of the intra-Messinian tectonic phase, dated at about 5.55 Ma BP (Krijgsman *et al.*, 1999). After the formation of the ceiling channel the sub-horizontal gypsum layers and the whole fossil 'Grotta di Monte Rocca' – including obviously its

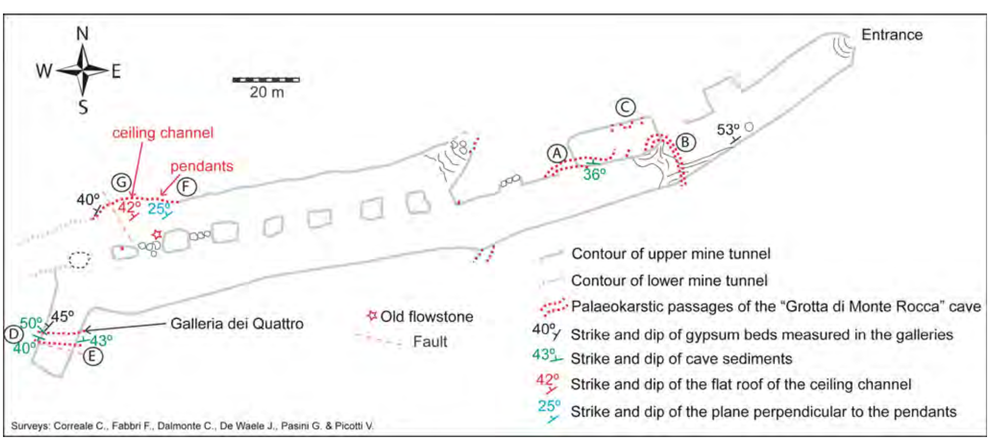


**Fig. 2** Part of the Zola Predosa underground gypsum quarry and the intercepted palaeokarst speleoforms, all belonging to the 'Grotta di Monte Rocca' palaeocave.

 

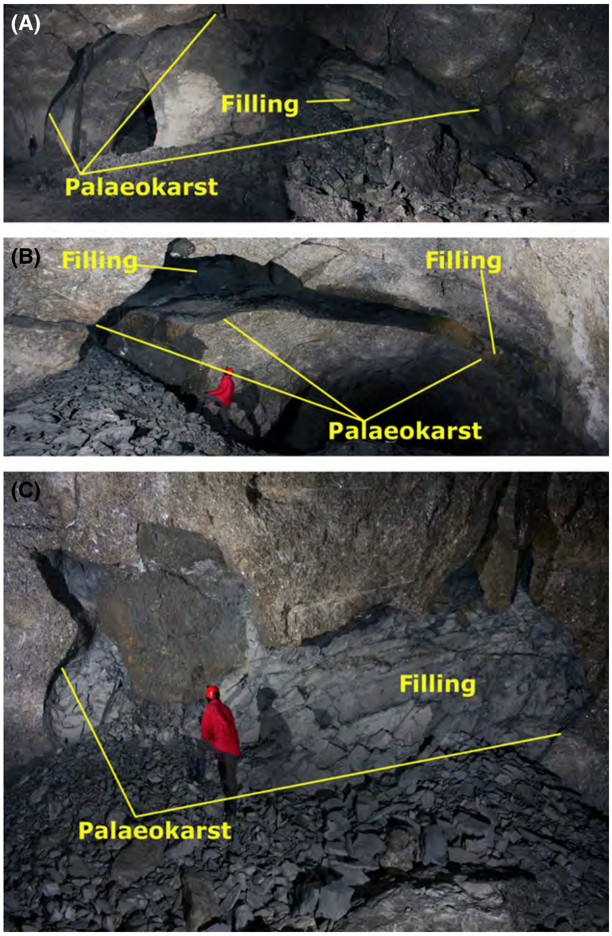


**Fig. 3** Palaeokarst conduits cut by the underground gypsum quarry: (A) Twenty metre long vadose passage along the N wall of the quarry's tunnel (A in Fig. 2). (B) Canyon-like passage crossing the roof of the quarry's tunnel (B in Fig. 2). (C) Meandering passage cut on the N side of a gypsum pillar (C in Fig. 2); probably it is the prosecution of passages A and B. Person for scale.

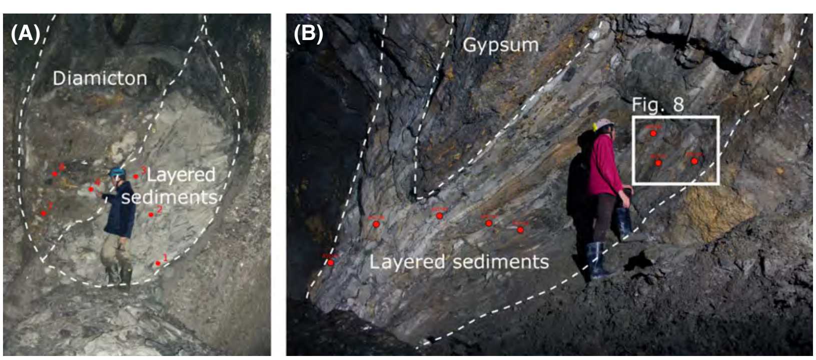


**Fig. 4** Palaeokarstic phreatic conduit, called 'Galleria dei Quattro', intercepted in the final part of the quarry's tunnel (D, E in Fig. 2). A. Portion of the conduit exposed on the western wall (D in Fig. 2); on the left the diamicton layer, about 1.7 m thick, is visible; (B) Filling of the larger portion of the same conduit displayed along the eastern wall (E in Fig. 2). Red dots show sampling sites for micropaleontological analyses. Person for scale.

post-antigravitative ceiling channel with a flat subhorizontal roof – were tilted by the intra-Messinian and by the Plio-Quaternary tectonic phases, acquiring an inclination of about 40° toward NW.

So the concordance of the inclination of the gypsum beds (about 40–45° toward NW) with the inclination of the 'Galleria dei Quattro' filling (about 43° toward NNW; Fig. 2E) and with the one of the roof of the post-antigravitative ceiling channel (42° toward NW; Fig. 2G) clearly demonstrates that the 'Grotta di Monte Rocca' underwent a conspicuous tilting after its formation. Close to the western end of the quarry's tunnel, near to the ceiling channel, there are also pendants (group of similarly proportioned projections, with vertical axes, in the bedrock ceiling of a cave), separated by decimetre wide anastomoses (Fig. 5A). The axes of these pendants, about 30 cm long, today form angles of about 25° with the vertical line; consequently the plane perpendicular to the pendants axes is inclined nearly 25° (toward NW): this means that these pendants underwent a rotation of about 25°, which is 15°–18° less than the one which involved the gypsum layers, the filling of the 'Grotta di Monte Rocca' and the post-antigravitative ceiling channel. This discrepancy can be explained by admitting that these pendants are younger than the ceiling channel, and that they formed when the 'Grotta di Monte Rocca' was already inclined by the tectonic movements of 15°–18° (Fig. 6). This means that in the 'Grotta di Monte Rocca' at least two phases of antigravitative erosion, separated by a long time interval, took place.

All the data concerning the strikes and dips of the gypsum layers, of the 'Grotta di Monte Rocca' filling and of the ceiling channel's roof are rather consistent, but one, still unexplained: in the western stretch of the 'Galleria dei Quattro' the marly filling, clearly stratified, dips 40°–50° toward SW (Figs 2D and 4A).

It is important to stress that in the gypsum outcrop near Zola Predosa there is also an active vadose cave system, the 'Grotta Michele Gortani', with a length of over 2 km (Bertolani


**Fig. 5** Palaeokarstic morphologies, visible where the filling was removed by the quarry works and recent infiltration waters. (A) Pendants, whose axes form angles of about 25° with the vertical line (F in Fig. 2). (B) Ceiling channel (G in Fig. 2) with flat roof dipping 42º towards the NNW and roughly parallel to the gypsum bedding measured nearby. Person for scale.

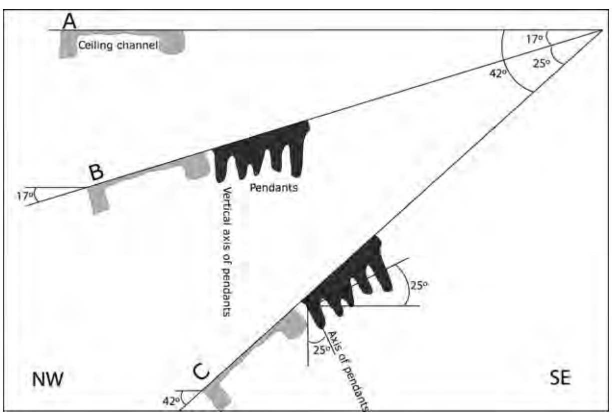


**Fig. 6** Evolution in time of the inclinations of the post-antigravitative ceiling channel's roof and of the pendants of the 'Grotta di Monte Rocca'. (A) Inclination of the gypsum layers and of the cave sediments (filling) when the post-antigravitative ceiling channel (with flat subhorizontal roof) formed. (B) Inclination of the gypsum layers, the cave sediments and the post-antigravitative ceiling channel's roof when the pendants formed. (C) Present inclination of the gypsum layers, the cave sediments and the post-antigravitative ceiling channel's roof.

and Rossi, 1972) (Fig. 7). This cave develops in an ENE–WSW direction, following the strike of the gypsum strata and paralleling both the quarry's tunnel and the palaeokarstic cave. At the moment there is no physical connection between this active cave and the fossil one, although they are separated by only a few metres (Fig. 7). The active cave has also no signs whatsoever of palaeokarstic conduits filled with more or less lithified sediments.

## Cave sediments

Cave sediments have been studied in detail only in the 'Galleria dei Quattro' (Fig. 2). They are composed mainly of an alternation of centimetre thick layers of gypsrudites, gypsarenites, siltstones and up to several decimetre thick shale beds (Fig. 8). The filling also contains blocks of selenitic gypsum. In the western stretch of the 'Galleria dei Quattro' also a diamicton layer, about 1.7 m thick, is present (Fig. 4A).

These sediments, light grey or brown in colour, are generally well lithified, and greatly differ from the euxinic dark grey shales interbedded between the gypsum strata. The sediment layers show often a lenticular stratification, caused by the shifting of the depositional centre in the ephemeral cave stream. Coarser lenses correspond to the channel deposits, while finer sediments were deposited in the bars or on the flanks of the water flow. The flow direction is difficult to establish, but was probably from East to West. Also the inclination of the filling's sedimentary beds is not easy to assess, being variable, since bedding is influenced by the conduit morphology. In the larger eastern stretch of the 'Galleria dei Quattro', however, the bedding near the centre of the filled conduit is clear (Fig. 4B), and the layers dip 43º towards NNW (with a strike of N260º).

Twelve samples were taken from the filling of the 'Galleria dei Quattro' for micropaleontological analyses (Fig. 4A,B). These have shown the sediments to contain reworked benthic and planktic fauna (foraminifera and nannoplancton), Langhian-Tortonian in age.

## Discussion

The karst conduits recently discovered near Zola Predosa – as told above – are now completely fossilised by sediments. The inclinations of the cave sediments and of the flat roof of the post-antigravitative ceiling channel are very similar to that of the gypsum beds, and suggest that the sediments and the ceiling channel formed before the late Messinian and the Plio-Quaternary tectonic phases. A reconstruction of the major events that brought to the formation of the cave system is shown in Fig. 9.

Shortly after the deposition of the Primary Lower Gypsum (5.97–5.60 Ma BP; Fig. 9A) the evaporites experienced a relatively brief interval in which they were exposed to the atmospheric agents (Fig. 9B). This emersion was mainly caused by a dramatic sea level lowering accompanied with tectonic uplift (intra-Messinian tectonic phase). A torrent, transporting sediments from the upstream (southward) areas, penetrated into the gypsum rocks and caused the formation of an extensive cave system (Fig. 9C). Debris deriving from the Langhian-Tortonian deposits bordering the gypsum outcrop were carried into the cave and deposited inside the conduits (Fig. 9D). The dip of these cave sediments was very close to the one of

 

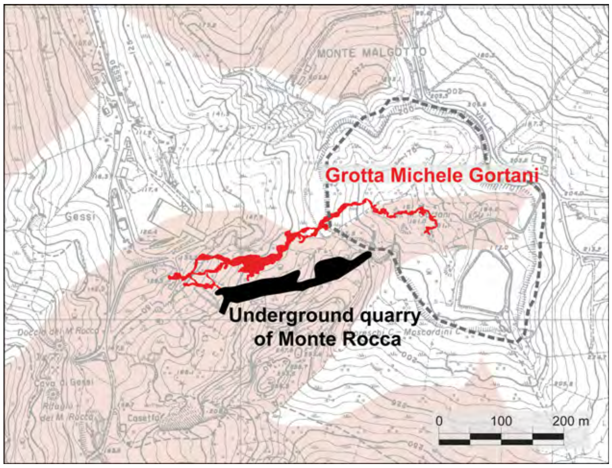


**Fig. 7** Location sketch of the 'Grotta Michele Gortani' (red) and the Monte Rocca underground quarry, that intercepted the 'Grotta di Monte Rocca' (see Fig. 2 for details). Shaded areas show the Messinian gypsum outcrops. The grey dashed line indicates the karst depression that recharges the cave.

**Fig. 8** Detail of the sediments filling the eastern part of the 'Galleria dei Quattro' conduit (see Figs 4B and 2, point E, for location). The lenticular stratification and the alterning gypsrudites, gypsarenites and finely bedded shales show them to be fluvial cave deposits. Here they have a strike of 260ºN with a dip of 43º towards the NNW. Paper tags, 5 cm by side, mark points where samples for micropaleontological analyses were collected.

the sub-horizontal gypsum beds. Progressive upward sedimentation caused the torrent to carve typical antigravitative and post-antigravitative morphologies (i.e. pendants and post-antigravitative ceiling channels; Fig. 9D). At the end of this speleogenetic phase, before being submerged, the cave system was completely filled with sediments inclined 15–18º to the NW (Fig. 9D).

Re-establishment of marine conditions in the Upper Messinian caused this karst episode to come to a complete end (Fig. 9E). Afterwards, the whole gypsum sequence was tilted in two subsequent tectonic phases (late Messinian and Middle Pliocene-Quaternary) to about 40º (Fig. 9F). Both gypsum beds, cave morphologies and cave sediments acquired the same inclination. Cave sediments, in the meanwhile, underwent diagenesis becoming consolidated shales, gypsrudites and gypsarenites.

After the last emersion of the Zola Predosa area, a Quaternary karstic cycle took place, which originated the 'Michele Gortani' cave (Fig. 9F).

## Conclusions

The discovery of a well-developed gypsum palaeokarstic cave and the detailed study of its sediments and post-antigravitative morphologies have allowed us to verify this cave to be related to the intra-Messinian continental period (Fig. 9). Compared to the size of the present-day gypsum cave systems, this cave might have formed in some ten thousands of years, during a wet and probably warm period. This intra-Messinian cave was excavated in almost horizontally bedded gypsum. Both gypsum layers, cave and filling have then been tilted to their present inclination of about 40–45º towards NNW, one third of which occurred between 5.50 and 5.33 Ma BP.

Based on these new findings and on the previous knowledge on karst in the region, three karst episodes are recognizable at present in the Emilia-Romagna Messinian gypsum outcrops:

1 *the oldest karst episode* is roughly coeval to the intra-Messinian tectonic phase (5.60–5.33 Ma BP *c*.). This episode originated the 'Grotta di Monte Rocca', near Gessi di Zola Predosa (Bologna), in its early stages (5.60–5.55 Ma BP *c*.). The same episode originated also, at a later stage, the epigean karst morphologies and karstified fissures of Monticino Quarry (Brisighella), filled by the Formazione a Colombacci (terminal Messinian) and containing late Messinian vertebrate remains. The Pliocene transgression brought this karst episode to an end.
2 the beginning of *the second karst episode* is still unknown, but it probably dates back to the Penultimate Glacial Period; its end occurred about 127 000 yr BP. At the end of this episode a relief inversion took place (Pasini, 2012).
3 *the third and last karst episode*, not yet concluded, started about 127 000 years ago (Pasini, 2012), and gave origin to tens of caves. Many of these caves are still hydrologically active.

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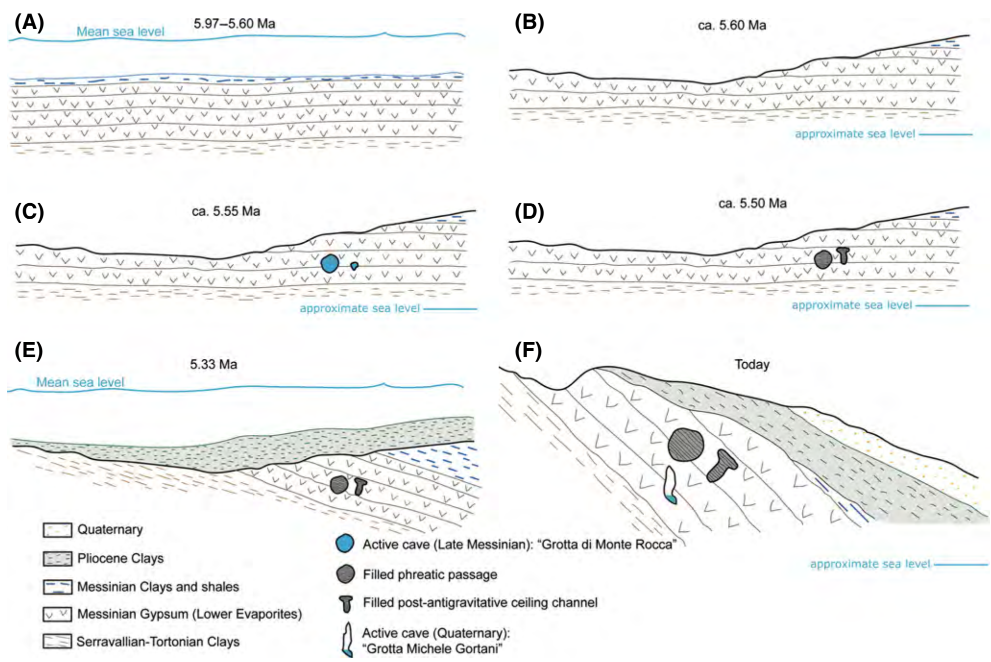


**Fig. 9** Scheme showing the formation of the 'Grotta di Monte Rocca' and 'Grotta Michele Gortani' cave systems: (A) Deposition of the Lower Evaporites. (B) Emersion of the gypsum rocks and surface erosion, caused by a dramatic sea level lowering and by uplift due to the intra-Messinian tectonic phase. (C) Formation of the older cave system ('Grotta di Monte Rocca'), with phreatic and vadose conduits. (D) Infilling of the older cave system, and formation of antigravitative and post-antigravitative morphologies. (E) New submersion of the area, and end of the first karst episode. (F) Last emersion, formation of the 'Grotta Michele Gortani' and present-day situation.

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