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PS Facies Distribution in Collapsed Carbonate Karsts: A Mechanical Approach*

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Abstract

Paleokarst are economically viable hydrocarbon reservoir and aquifer. For instance, the Kirkuk Field (Northern Iraq) had produced up to 9.1 BBO until 1980 and the Idd Shargi North Dome Field in Qatar is producing 3,500 BOPD on sub-vertical crestal wells (Trice, 2005). In China, the estimated reserve of the Jingbian field is evaluated at 25 BBO (Li et al, 2008), whereas in North America, the Devonian carbonate reservoirs in Alberta show very large potential with heavy oil production due to the dissolution of the evaporitic Hondo Formation (Huebscher, 1996), in the Grosmont carbonate section. Characterization of such geobodies, performed for reservoir simulation, must carry the typical sediment architecture and facies properties, most often observed within collapsed paleocaves. Although collapsed chambers may be compared with modern analogs (Loucks, 2001), only a few paleocave outcrops are available with very few of them providing insight about the 3-dimensional architecture. We propose to use numerical simulations of cave collapse to study the architecture and reservoir properties of paleokarsts carbonates to improve the accuracy of the static reservoir model in such reservoir setting.

The object of this study is to perform a mechanical analysis of collapsed sediment patterns within carbonate paleocaves, using a continuum/discrete forward modeling approach (Zienkiewicz and Taylor, 2000; Klerck, 2000; Vyazmensky et al, 2007). These patterns are associated, through the distribution of the fracture network, to observed facies within collapsed paleokarst: chaotic and clast breccias, disturbed and undisturbed strata facies (sediment-fill facies are related to flow of sediments within the caves). The strength of this numerical approach is that it allows us to examine and quantify porosity redistribution from an open void to the complex juxtaposition of different types of breccia and the enhanced fracture network associated with the collapse of the initial cave. First, results have been produced on a synthetic model showing typical carbonates stacking patterns. The generated fracture network shows concordant features with that observed in natural collapsed paleocaves. Then, this analysis is conducted on an outcropping collapsed paleocave situated in the Mallorca Island, Western Mediterranean. Bed markers are digitized and restored to a presumed pre-collapsed state. Following the collapse simulation, comparisons with the observed facies distributions are presented.

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Research Questions

How do karst collapse characteristics impact reservoir quality?
What is the relationship between fracture distribution (related to collapse) and breccia classification?
How does the stratigraphy impact breccia distribution during the collapse?

Objectives

The final goal of this research project is to provide training images of fracture networks for a multiple point statistics algorithm, which aims at describing paleokarst reservoirs. As a first step towards this approach, we focused on providing realistic fracture networks which result of karst collapse using a geomechanical framework.

Collapse of paleokarsts

Fig. 1 - Karst collapse on the Pecos river, Texas, USA.

Triggering process for karst collapse

According to Davies (1951), breakdown in caves is mostly the result of an upset in the equilibrium of the forces applied to the cavern roof, during the progressive removal of dissolution waters and increasing burial of the system. The relief of the stresses as fractures and subsequent structural instability is then dependant on the rock strength of the roof, that could have been damaged during the dissolution process (White and White, 1969).

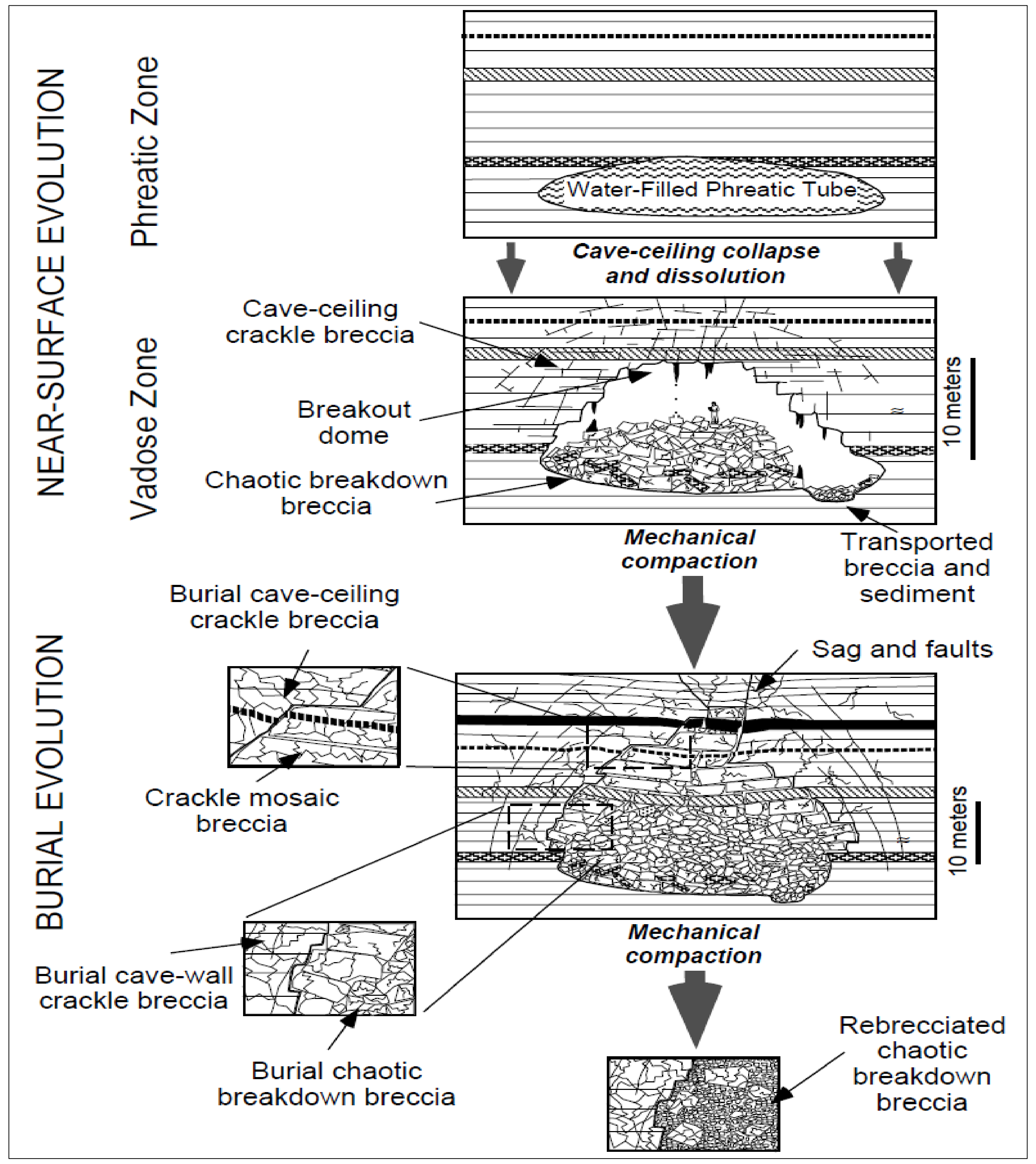


Fig. 2 – Diagram depicting the collapse of a cave during the passage from the phreatic zone to the vadose zone and further brecciation in the deep subsurface (Loucks, 1999).

Mechanical modeling of karst collapse

To improve the accuracy of the static reservoir model, we propose using numerical simulations of cave collapse to study the architecture and reservoir properties of paleokarsts carbonates. The object of this study is to perform a mechanical analysis of collapsed sediment patterns within carbonate paleocaves, using a continuum/discrete modeling approach (Klerck, 2000; Zienkiewicz et al., 2005; Vyazmensky et al., 2007).

These patterns are associated, through distribution of the fracture networks, to observed facies within collapsed paleokarst: chaotic, mosaic, and clast breccias, disturbed, highly disturbed, and undisturbed strata facies (sediment-fill facies are related to flow patterns within the paleokarst system). These simulations are performed using a transient analysis in the software ELFEN, developed by the company Rockfield Software Ltd.

Explicit analysis

Compute the final stationary state of the transient problem

A collapse of caves has long been studied in block caving (Vyazmensky *et al*, 2005) and in general, excavation studies (Alejono *et al*, 2007). It is proposed the same approach as Vyazmensky *et al* (2005) to use a finite/discrete element method.

Explicit algorithm in time (central difference), modeling of highly non-linear phenomenon, simplified numerical implementation of non-linear problems, fast computation but possibly numerically instable.

$$\mathbf{M'}\,\ddot{\mathbf{U}} + \mathbf{C}\,\mathbf{U} + \mathbf{F}^{int}(\mathbf{U}) - \mathbf{F}^{ext}(\mathbf{U}) = \mathbf{0}$$

$\mathbf{M'}$: Lumped mass matrix
$\mathbf{U}$: displacement vector
C: damping matrix
$\mathbf{F}^{int}$ and $\mathbf{F}^{ext}$: internal and external forces

Material properties and fracturing

Elfen has a single surface rate independent non-associated elasto-plastic model, called Soft Rock 3 model (Crook *et al*, 2006). The SR3 empirical model used in the following cave collapse simulation expresses the elastic constants as a function of effective mean stress, deviatoric stress and porosity. Reference values for the model used is depicted in Table 1.

Compacted brittle limestone	
Young's modulus E_{ref} (MPa)	1700
Poisson ratio ν_{min}	0.27
Density ϱ (kg/m$^{-3)}$	2190
Failure criterion	Freudenthal

Table 1 – Material properties of the limestone used in the simulation.

Freudenthal's fracture criterion (Freudenthal, 1950): initiation and propagation of a crack is dominated by a critical value of the total plastic work.

Collapse of a synthetic cave systems using a explicit dynamic approach

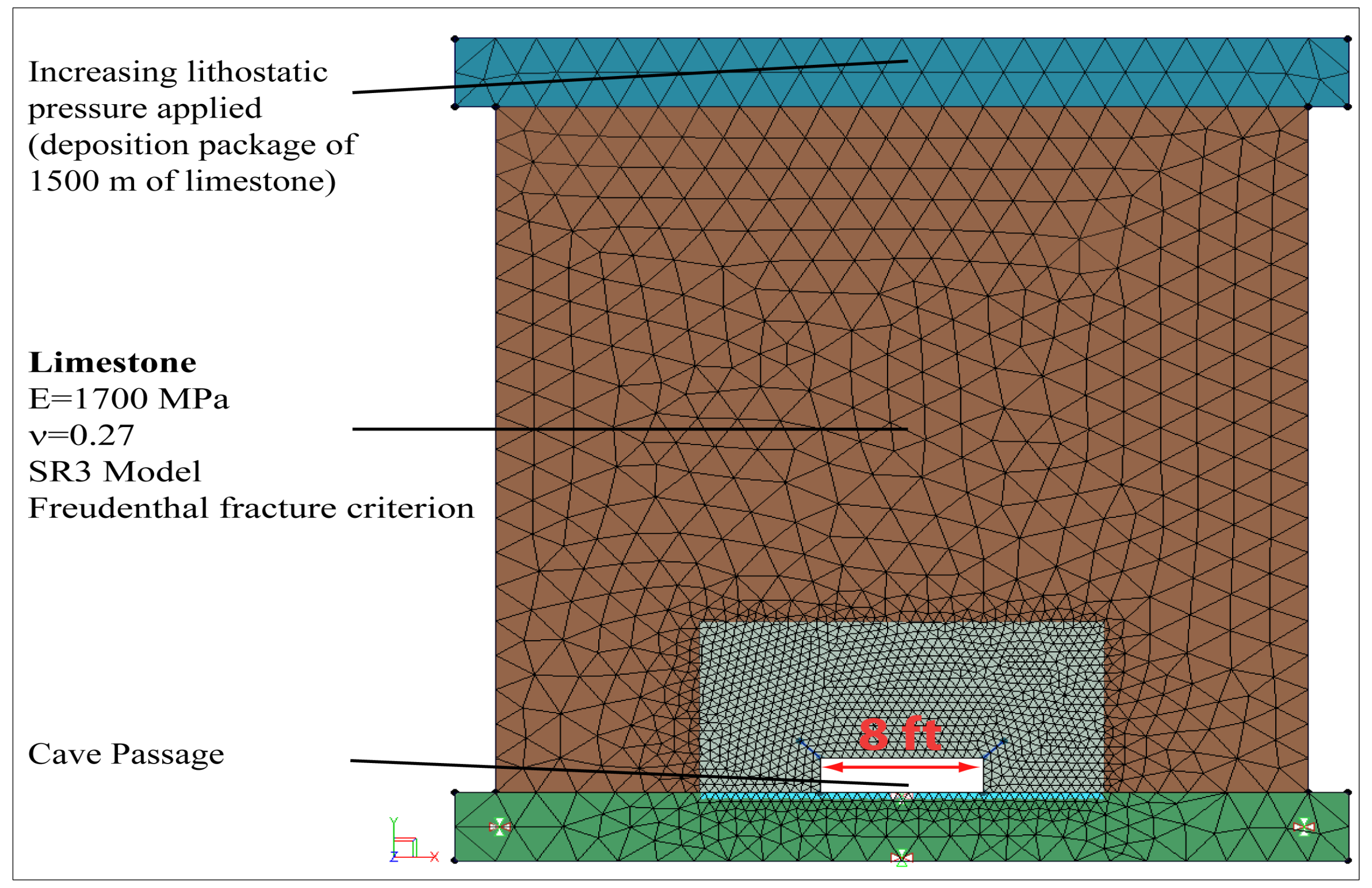
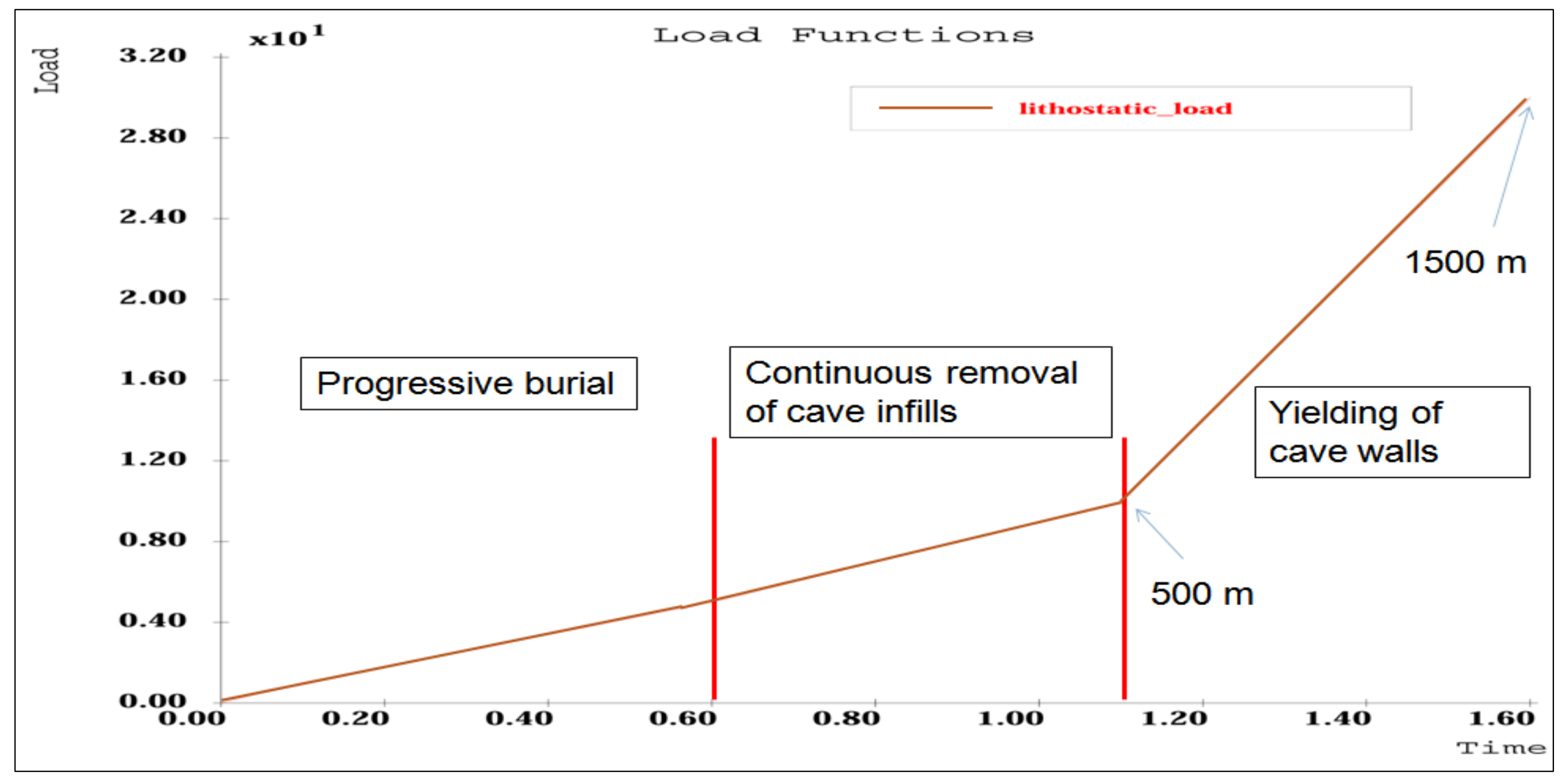


Fig. 3 – Design of the synthetic case, with the initial mesh used in the simulation. Width of the model: 100 ft.
Two initial fractures are introduced at the hinges of the cave, with a 45° angle dip. Both the top and bottom blocks are chosen as ductile elastic materials.

Fig. 4 – Kinematics of burial and collapse episodes. Initial water pressure inside the cave is set to 1 psi and progressively dropped to 0 while increasing lithostatic pressure is applied on top block.



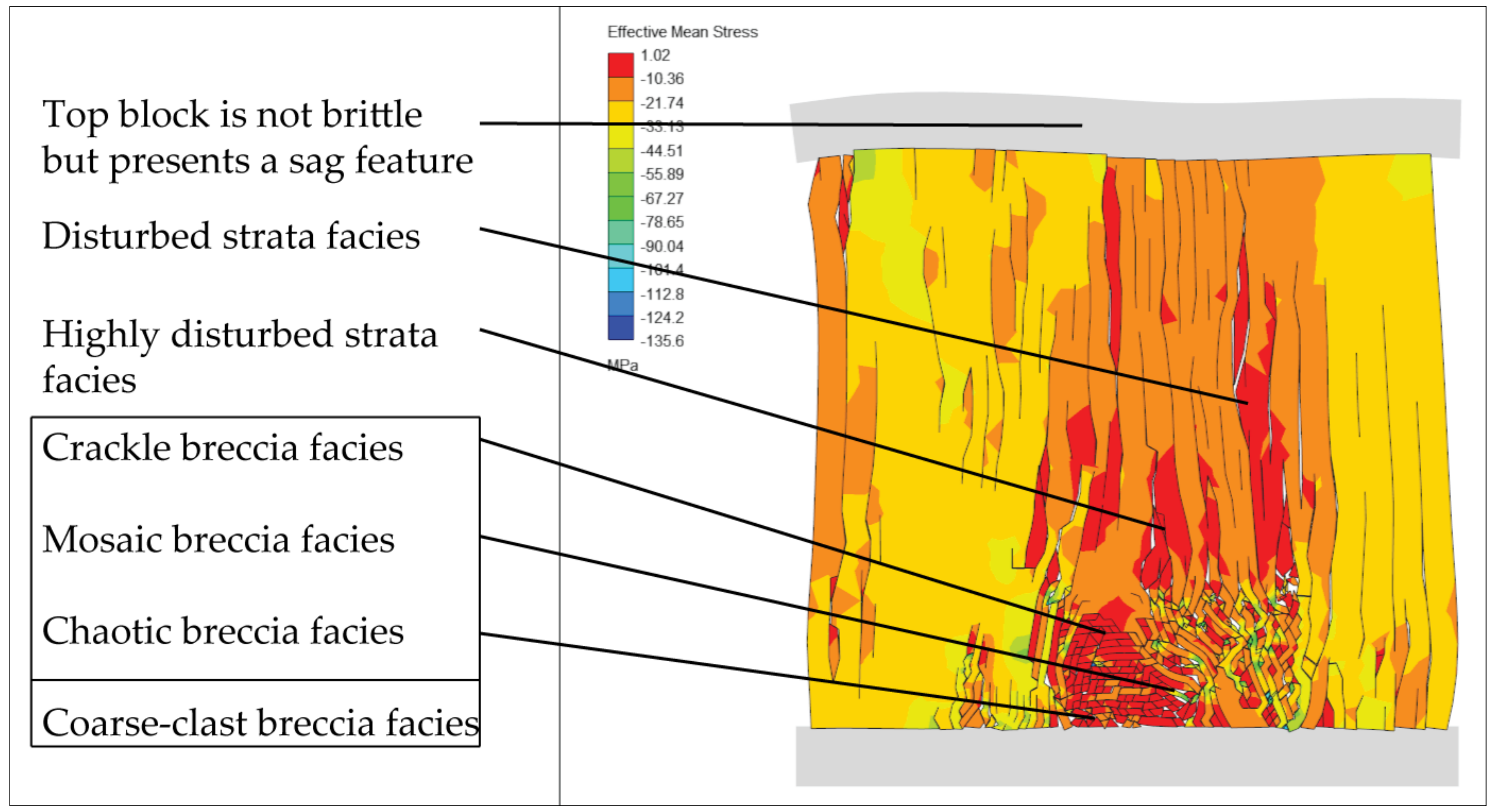


Fig. 5 – Result of the compression of the synthetic cave system after the equivalent of a deposition of 1500 m of limestone as a lithostatic pressure applied onto the top block. Color refers to effective mean stress, which is the elastic component of stresses during porosity loss in a compaction. The higher value (close to) indicates a probable permanent loss of volume (inelastic). We identified five categories of facies by simple observation and comparison of the fracture networks. We interpreted the vertical (mode I) fractures to be due by tensile stresses applied vertically to the rocks in compression, no structural fixities being imposed on the lateral sides of the model.

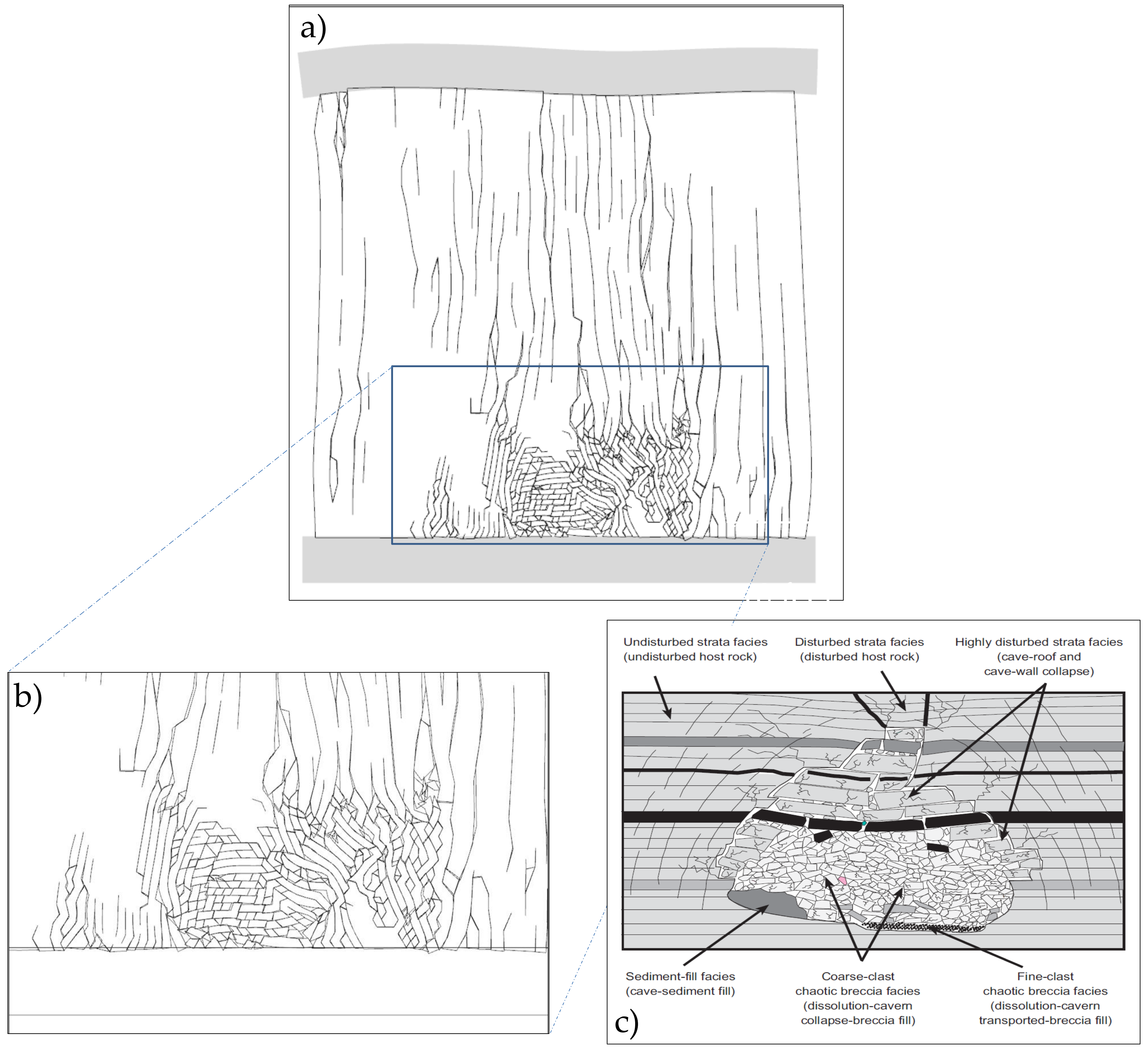


Fig. 6 – a) Fracture distribution after approximately an equivalent of 1,500 m of limestone has been deposited. Modeling performed using ELFEN (Rockfield); b) zoom on the cave zone; c) Cave facies in a paleocave system (Loucks, 2007), for comparison.

Localization and classification of coarse-clasted breccia zones, however, could be well captured using this numerical approach. The generated fracture network shows concordant features with what are observed in natural collapsed paleocaves. Proper characterization of facies in overlying strata still needs to be pursued.

Application to a paleocave system in the Upper Miocene Reef Complex of Mallorca

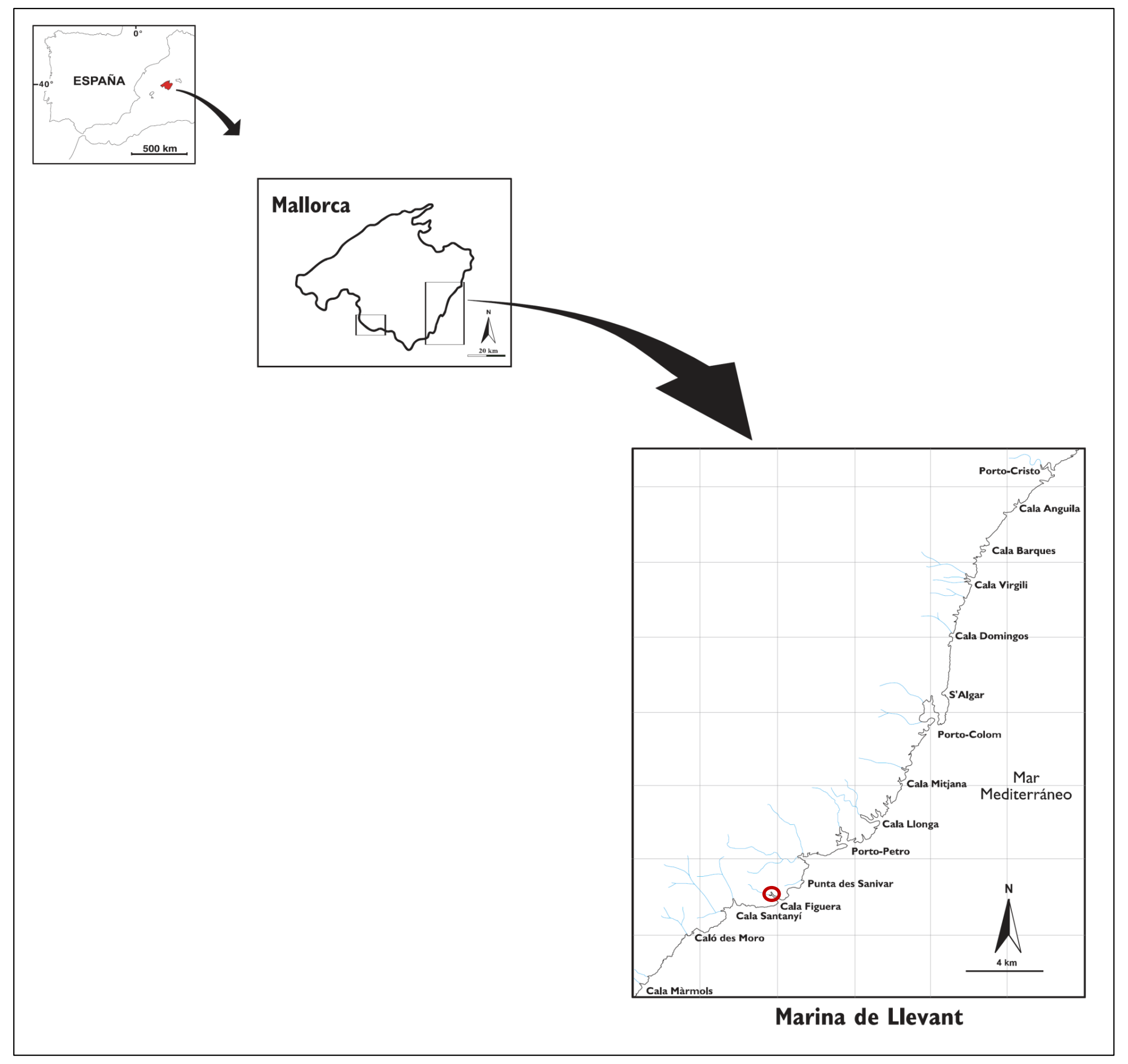


Fig. 7 – Location map of the Cala Figuera paleokarst coalesced systems. Modified from Robledo (2005)

Carbonate depositions in the Upper Miocene of the Balearic archipelago expose two reefal complexes on the eastern coast of Mallorca, which were affected by epigenic caving dissolution processes (Robledo *et al*, 2004).

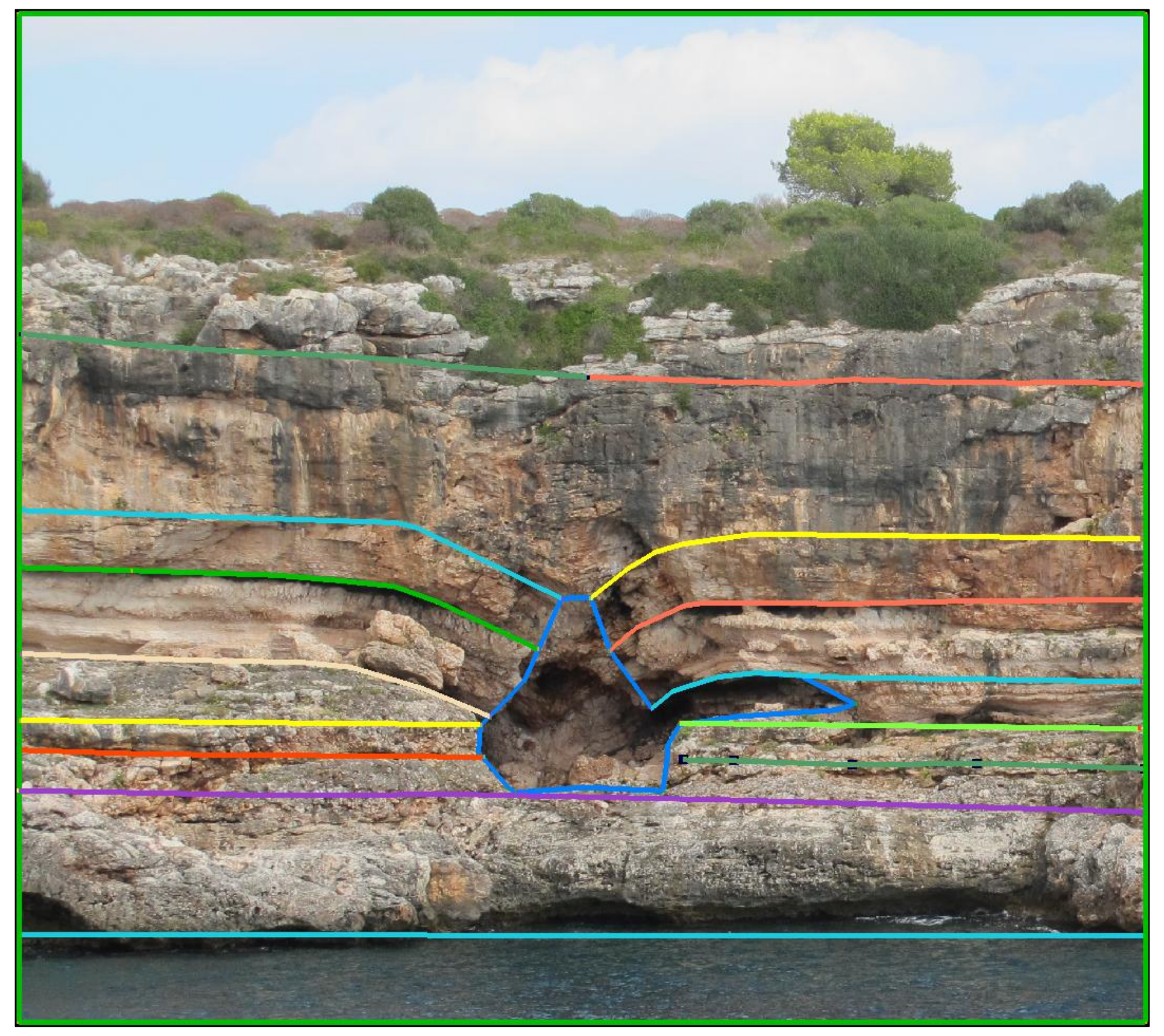


Fig. 8 – Photo of the Cala Figuera outcrop, interpreted as a collapsed paleocave system, located in on the Santanyi limestones unit in the Upper Miocene Reef Complex of Mallorca, Spain (Robledo, 2005).

The interpretations made for this work have been added by the author.

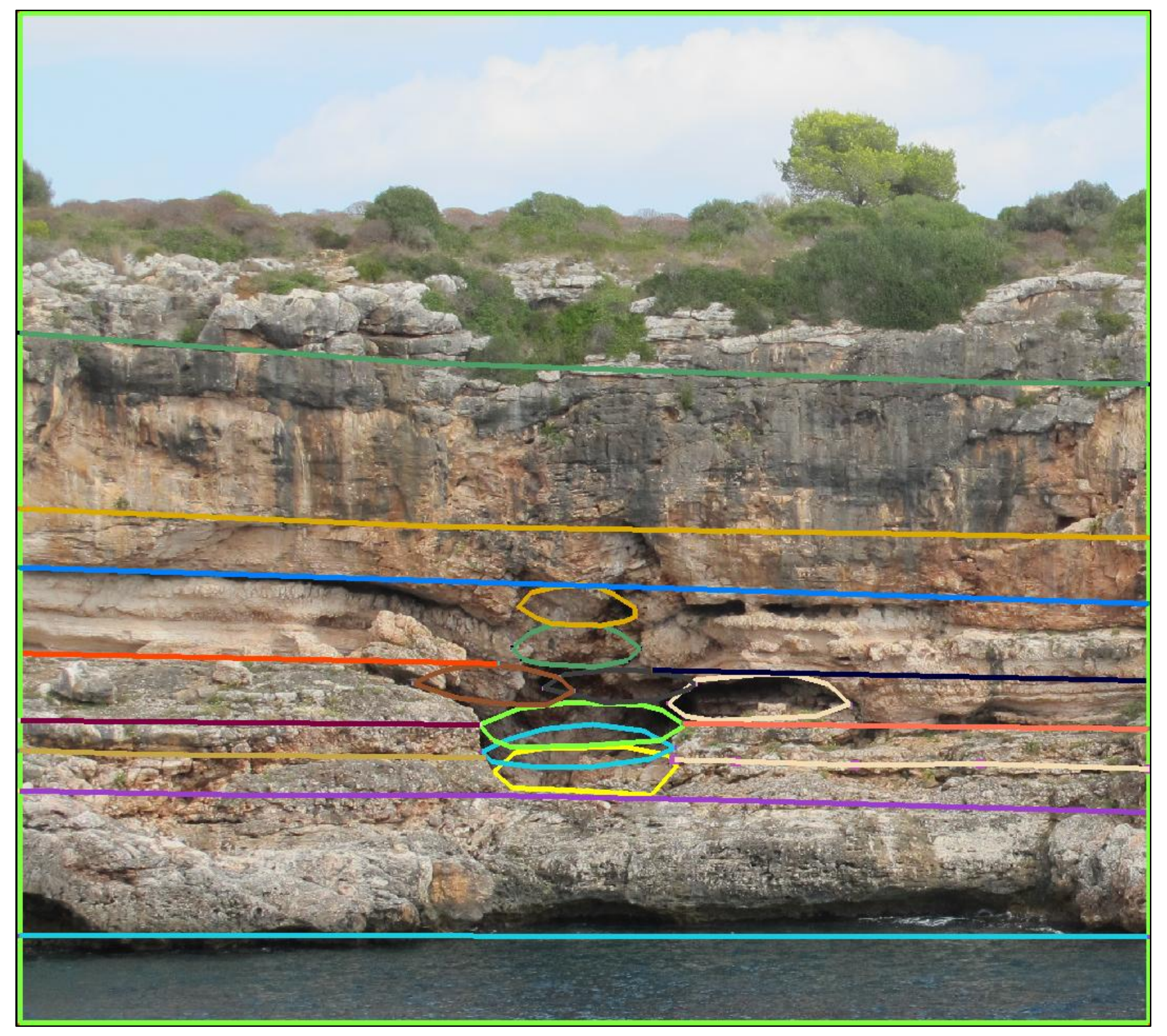


Fig. 9 – An interpretation of the initial stage of the paleocave system. As Robledo (2005) points out, this collapsed paleocave is composed of several collapsed caves.

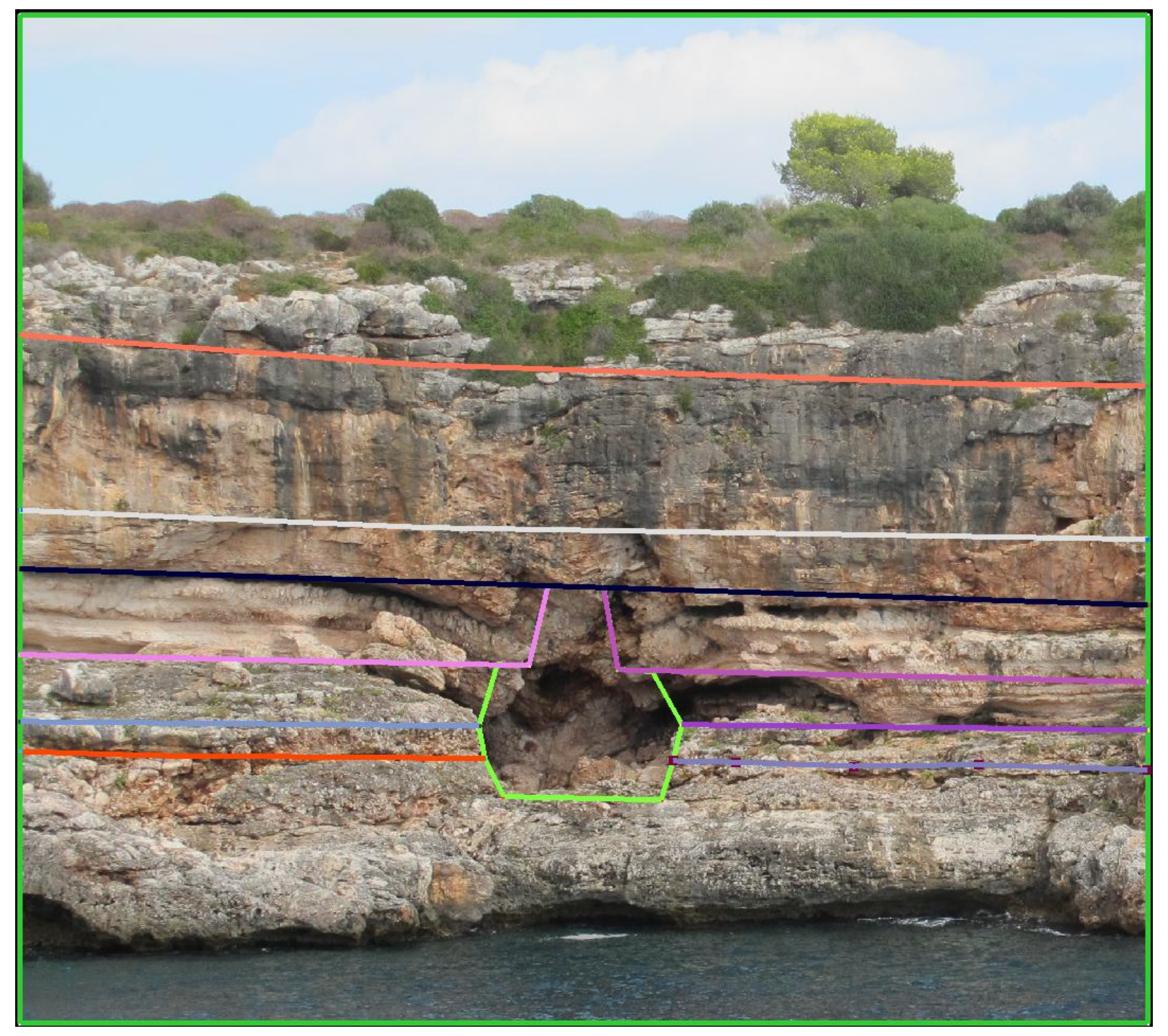


Fig. 10 – A simplified interpretation of the initial stage of the paleocave system for the purpose of the ELFEN computation. Only one cave that covers the main part of the system has been kept.

A simulation of the collapse of this simplified system has been performed on a ductile version of the limestone used in the synthetic case.

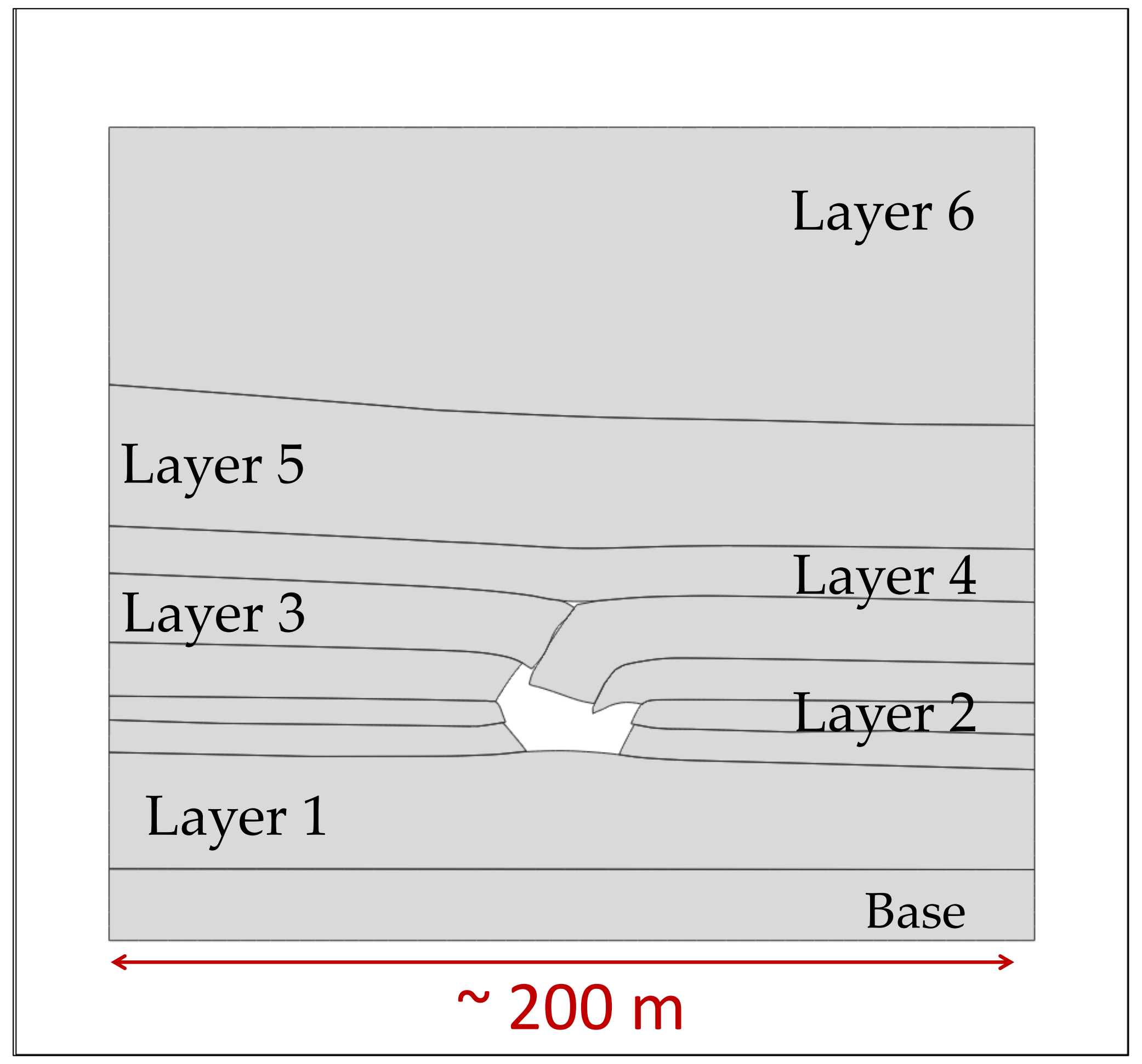


Fig. 11 – Ductile collapse of the simplified interpretation of the Cala Figuera paleokarst system.
The deformation of the layer 3 is realistic compared to the observed system, Fig. 8.
However, the cave is not filled, calling for a combination of ductile/brittle deformation type (ductile for Layer 3 and brittle for Layers 2, 4 and 5).
See video projector section for details on the brittle simulation.

Conclusions

The distribution of the types of breccia obtained with a forward simulation is similar to what is observed in paleo-caves. This approach can validate heuristic quantification of the brecciated zone (Loucks, 1999). From then, it is also possible to study the impact of different key parameters of an initial cave system on the distribution of fractures and extent of the breccia.

This quantitative approach allows to characterize fracture networks from the collapse of carbonates rocks in paleocave settings. This was applied to a real case example, in the Mallorcan Reef complex on a simplified interpretation of a 2D outcrop, for which we emphasized the importance of combination of brittle and ductile deformation

Future works

The importance of coalesced paleocave systems on the distribution and extent of the fracture networks must be tackled with, as underlined by Loucks (2007). Also, a systemic and stochastic generation of fracture networks using this approach must be performed, in order to produce different end-members of collapsed paleokarst reservoir patterns.

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Video projection

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