

Development and collapse of karstic cavities in folded marbles: Geomorphological and geophysical evidences in Nerja Cave (southern Spain)

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ABSTRACT

Karstic evolution leads to the growth and collapse of cavities by the interaction between geological structures and the hydrogeological framework. Nerja Cave developed within marbles belonging to the Alpujarride complex of the Internal Zones in the Betic Cordillera of Spain. The residual gravity anomaly map of the karstified areas –surrounding the known Nerja Cave– may indicate a likely elongated parallel cave system, N-S oriented, unknown up to present, and formed by both small shallow and large deep caves below a nearby hill located north-westwards to the known cave. At the east hillside, a moderate gravity anomaly minimum and geomorphological evidence (vertical walls and sunken terrains) suggest the presence of an old collapsed cave. At the west hillside, a marked gravity minimum is associated with a strongly folded marble layer without evidence of collapse. An electrical resistivity tomography (ERT) profile across the hill –in the E-W direction– supports an interpretation of several voids, two of the bigger ones located on either side of the hill. The combination of geomorphological, ERT and gravity forward modelling indicate the location of unknown caves, one of them partially collapsed. These caves, located at a higher topographic level than the known Nerja Cave, may represent an early stage of cave development, and suggest the preferred dissolution of some layers in the folded marbles. This field example provides new insights on the interaction of structure in the karstic evolution that determines the cavity stability.

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1. Introduction

Karstic structural features depend on several factors including fracture abundance, opening and orientation, topography, precipitation and temperature, which in turn determine the groundwater hydrodynamics. The structures may remain gravitationally unstable, causing subsidence with gradual settling or sudden changes like sinking or collapses (Waltham et al., 2005). The development of a karstic cave can cause large rock blocks to collapse into the cave, modifying its shape, although the roof remains stable (Martínez-Moreno et al., 2016a). Surface features are related to the high degree of cave development; the fact that it remains gravitationally unstable can cause roof collapses. These processes creates changes in the topography and/or cave

openings to the outside, generally surrounded by vertical walls at the perimeter.

The most effective cave detection procedure relies on a combination of geomorphological and geophysical methods (Martínez-Moreno et al., 2014). Geomorphology indicates likely boundaries of partially collapsed caves and possible openings through recognition of the subsidence area, including the magnitude of sinking when vertical walls remain after the collapse (Galve et al., 2009). Geophysical methods are used to verify the surface evidences and to constrain the features in-depth (Martínez-Moreno et al., 2013). The methods that typically offer most accurate results –even in partial collapses– are electrical and gravity methods, owing to the high physical property contrast between the unaltered host rock versus cavity voids and/or collapse deposits.

The detection and determination of unexplored voids in karst systems are very important in two senses: tourism and hazard. Caves can be a significant economic factor for the surrounding population and voids should be detected before the construction of anthropic structures to avoid future collapses of those structures (Martínez-Moreno et al., 2016b).

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The present research focuses on the Nerja Cave area (Fig. 1), located in the Betic Cordillera at the southern margin of the Iberian Peninsula. It is an outstanding touristic cave, receiving almost half a million visitors per year (Carrasco et al., 2016). On the hill located north of the known cave, surface evidence as vertical walls suggests the presence of an old collapsed cave on the eastern side of the hill. The present study aims: (a) to characterize the extension of such 'new' cavities north of the known cave by means of geomorphological and geophysical methods and (b) to describe the origin of the unexplored caves through the structural, geomorphological and hydrogeological evolution of the area.

2. Geological and geomorphological framework

The study area encompasses the Nerja Cave and surroundings, in southern Spain (Fig. 1a). The cavity is located NE of the town of Nerja and N of Maro village. This sector is less than 3 km away from the Mediterranean Sea, in the southeaster part of the Sierra de Almirajara mountainous massif, made up almost completely of carbonate materials (Triassic marbles, Fig. 1b). The carbonate outcrops reach their maximum altitude (slightly more than 1800 m a.s.l.) at a distance of about 10 km from the coast (Fig. 1c). This implies high slope gradients that favour surface runoff and associated erosion.

The marbles where Nerja Cave developed belong to the Alpujarride complex of the Internal Zones of the Betic Cordillera (Fig. 1d). They are medium-coarse-grained recrystallized dolomitic marbles from Middle Triassic –400-500 m thick—affected by open folds and low penetrative cleavage, with 10°-20° S average dip regional bedding. The base of this unit is formed by Paleozoic schists and Permian-Triassic phyllites (Fig. 1c) with foliations dipping 60°-70° S, at least 1 km thick.

It is worth noting that locally the marbles can show complete disaggregation leading to dolomitic sandy formations, as happens in a few sites inside the cave and in outcrops located in its immediate vicinity (Andreo et al., 1993). Interbedded with the tabular marbles sequence are calc-schist intercalations of a metric scale. They are generally less resistant to the erosion than the marbles, and they allow soil generation and growth of vegetation over them to a certain degree. For these reasons, they are easily identifiable in the landscape.

Above the Alpujarride units, Neogene-Quaternary sediments lie in stratigraphic unconformity. The base of this sequence is formed by 50–60 m thick detritic layers of sands, microconglomerates and breccias of Pliocene- Pleistocene age, overlain by 30 m thick travertines from the Pleistocene. The intense calcareous cementation of the breccia formation is noteworthy; it makes it highly resistant to erosion and thus appears in the slope profiles as nearly vertical cliffs in response to the flu-

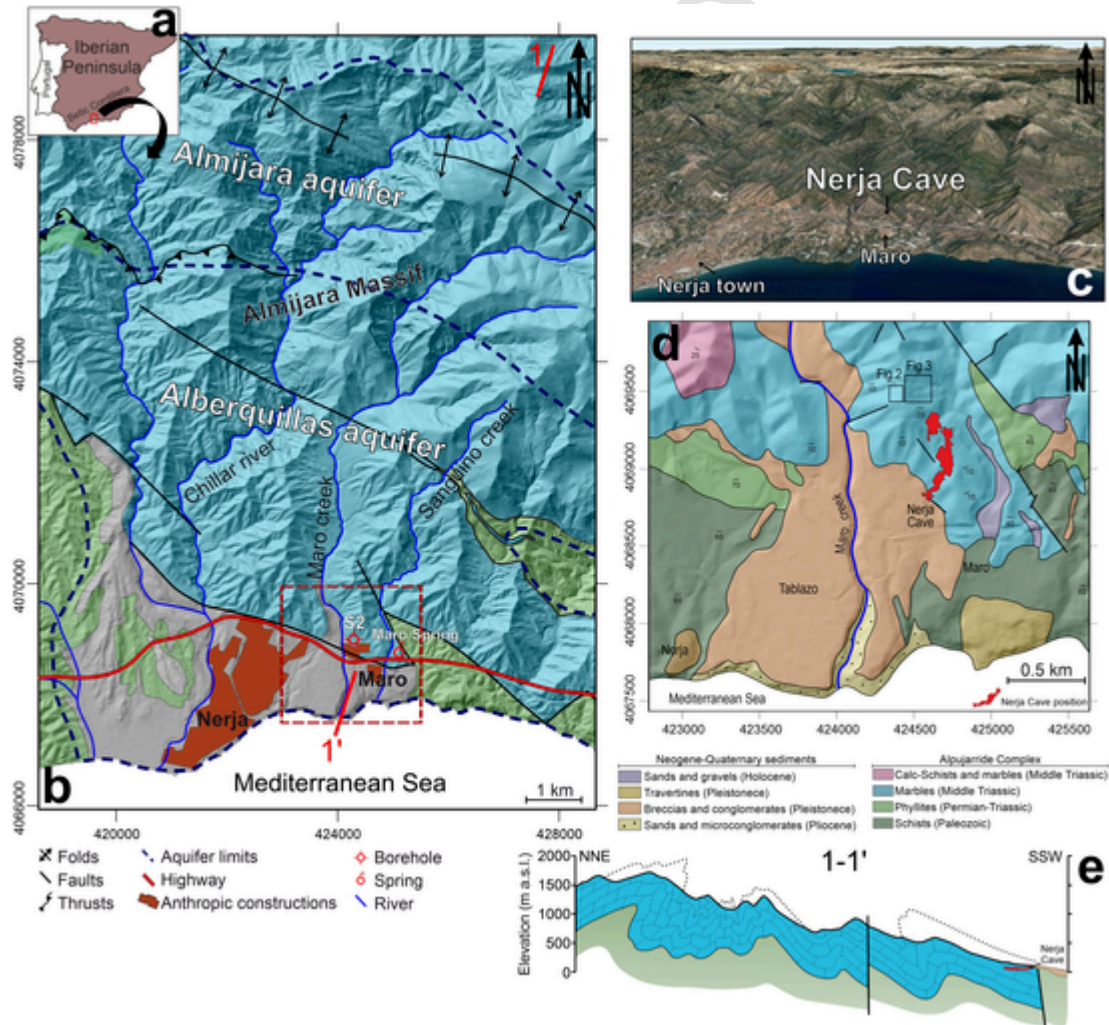


Fig. 1. Geological map of the study area. (a) Geographical location. (b) General geological and hydrogeological map. Red lines correspond to the boundaries of the cross section shown in part e. (c) Air view of the Sierra Almirajara badlands (Source: Google Earth). (d) Detailed geological map of the study area. Location of Figs. 2 and 3 are indicated by black squares. (e) Interpreted geological cross-section (position indicated in Fig. 1b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vial incision. At the top, there are detrital sediments (silts, sands and gravels) from the Holocene.

Close to the Nerja Cave, the structure of the marbles is complex due to thrusting, and regional and local folds with reverse limbs. Large sets of faults from Pliocene-Pleistocene age striking roughly NW-SE have horizontal/oblique displacements, in addition to NE-SW fractures. The development of the first sets of faults led to overall uplifting of its northern limb or mountainous sector with respect to its southern limb –coastal sector– from the late Miocene to the present, with frequent associated seismicity (Carrasco et al., 1998).

Around the Nerja Cave, there is a well-developed NNW-SSE joint set in addition to other sets with NNE-SSW and E-W orientations. The two first joint sets are more karstified because their orientation parallels the main topographical slope, favouring the percolation of meteoric water. These two sets, striking roughly N-S, seem to condition the general trend of the Nerja Cave development (Sanz de Galdeano, 1993).

The main fault system separates two sectors from a geomorphological point of view (Guerra-Merchán et al., 2004). The NE sector, with outcrops of Triassic marbles, presents highly rugged relief with slopes often exceeding 40°–50°. In the SW sector, Paleozoic schists and Plio-Quaternary deposits crop out, producing an undulating relief of 10°–30°.

While exokarstic forms (karren, dolines, sinkholes) are scarce, there is an intense karstification at depth. It is likely that exokarstic forms once existed but disappeared by the effects of the surface erosion associated with the intense fluvial incision since the late Miocene (Lhènaff, 1986; Benavente and Almécija, 1993). At the highest topographical areas of Sierra Almirajara, the karstic voids are mainly shallow with small vertical development (< 50 m), whereas in its lower parts the caves tend to be longer, with horizontal development (Arrese González, 2009). Durán et al. (2002) describe the latter as typical forms of horizontal groundwater flow and/or aquifer discharge, affected by a complex geological history. Around Nerja Cave several cavities have been recognized, some having direct access from the surface, others identified by geophysical surveys (Vadillo et al., 2012; Benavente et al., 2017). Benavente et al. (2017) detected by gravity measurements the existence near Maro spring of three cavities in the vadose zone located 150–135 m a.s.l., and another in the saturated zone, at about 110–120 m a.s.l. Some of these were later corroborated through the drilling of boreholes, crossing significant voids as well as cavities full of speleothems. Jordá Pardo (2004) also describes a small old cavity with a few forms of very eroded lithogeochemical reconstruction (flowstones, stalactites...) cut by erosion produced by the incision of Sanguino creek (to the E of Nerja Cave), which currently is practically inactive. In contrast, a relatively deep borehole (380 m) near Nerja Cave (S2 in the Research Site, Fig. 1b) was drilled along the marble formation without encountering significant karstic features (Arrese González, 2009). Aranburu Artano et al., 2018, Aranburu Artano et al., 2019 describe and study another speleothems that crop out near Nerja Cave but at a higher altitude. The speleothems fill fissures (flowstone type), are up to 0.33 m thick, and are of Pleistocene age, according to the two dates obtained (340 ka and 400 ka).

2.1. Hydrogeological setting and Nerja Cave development

The Triassic marbles are made permeable by fissuring, fracturing and karstification. Two partially connected aquifers (Fig. 1b) have been identified in the Sierra Almirajara carbonate massif. The one nearest the sea is known as the Las Alberquillas aquifer (Fig. 1b). Recharge is mainly produced by rainfall infiltration through interconnected permeable and surface karst features, like fractures or fissures. The discharge takes place mainly through springs at altitudes from 2 m to 770 m a.s.l., with average flows in the 1–100 L/s range. The aquifer

also discharges by pumping and, to a lesser degree, by groundwater flow to the sea (Andreo et al., 2018).

The Nerja Cave covers an area of 35,000 m² and has a practically horizontal development, lying between 127 and 195 m a.s.l. It has three natural entrances located at 158, 161, and 162 m a.s.l. (S.E.M., 1985): two sub-circular sinkholes with diameters of 1 and 6 m, respectively, and another with a semi-circular form measuring about 12 m², which is used for the access and exit of visitors. Nowadays, the cave is located at the unsaturated zone of the aquifer, 10 m above the piezometric level. Previously, when the piezometric level was higher, the cave was partially flooded, as evidenced by remnants of phreatic speleothems in the non-visitable halls of the cavity (Durán, 1996).

The thickness of the marbles throughout the cave varies from 4 m to 50 m in the tourist galleries, and it exceeds 80 m in the non-visitable area, according to the outside topography. The roof generally corresponds to gently dipping stratification surfaces. The cave floor itself has an irregular morphology, and is covered by rock debris. Both, the floor and the roof are profusely covered by speleothem deposits. Some large speleothems have fallen and broken, and above them new generations of deposits have grown. This allowed approximate dating of the seismic event that produced their fall, some 800,000 years BP (Durán, 1996).

The springs draining the aquifers in the Sierra Almirajara massif typically appear in the immediate vicinity of the main creeks of the area. Their discharge regime is quite regular, indicating low functional karstification. Thus, diffuse flow conditions seem to prevail in the aquifers. This is in contrast with the karstic behaviour of the Maro spring, located near the Nerja Cave at an altitude of approximately 120 m a.s.l. (Fig. 1b), which is supposed to be linked with unexplored cavities at present. The spring has peak flows of more than 1500 L/s after intense precipitation events, in contrast to the common flow values of some ten L/s during summer periods.

The bottom of Nerja Cave lies roughly ten metres higher than the Maro spring, that is, at present the cave is perched over the groundwater level characterizing the karst system drained through the spring. A nearby well about 150 m deep (built to supply water for the Nerja Cave facilities) has very low productivity; it nearly dries out after pumping because of the large drawdown produced. This suggests that the current karstification of the aquifer below the level of the Maro spring system is comparatively low. The Maro spring system can therefore also be considered as perched with respect to the regional groundwater level of the Las Alberquillas aquifer, near to the sea level. This circumstance is also found inside the study area, when comparing the results of the shallow boreholes (< 30 m) and the deepest one (S2, 380 m; Fig. 1b). In fact, one of the boreholes (S6) shows the anomaly of a perched water level in its two final metres. Finally, a few kilometres to the east of Nerja Cave there are highly productive pumping wells near the coast, owing to the karstification of the Las Alberquillas aquifer there.

3. Geophysical methods

Microgravity and Electrical Resistivity Tomography (ERT) were applied in the Nerja Cave karst system. Microgravity prospecting was performed in a map distribution covering an area of 92 ha, and the ERT was applied along a profile at the north of the study area crossing the hill in W-E direction.

3.1. Microgravity prospecting

The gravity method determines lateral density contrasts at depth through the measurement of local gravity variations. Gravity measurements were acquired with a Lacoste-Romberg model G gravimeter. Accurate altitude data were measured with a differential GPS with a precision under 1 cm. The measurements were taken at 2009 stations with variable spacing: a general spacing of 25 × 25 m, and a more precise

one of 10×25 m in the E-W direction at the centre of the study area. The measurement cycles were shorter than 3 h to ensure the quality of the data set. The data were processed using Oasis Montaj (from Geosoft). After tidal and instrumental corrections, the Bouguer anomaly was determined using a standard density of 2.67 g/cm^3 and 1.03 g/cm^3 for the seawater.

Terrain correction removes the effect of the topography on the gravity measurements, by means of a combination of the methods described by Nagy (1966) and Kane (1962). The correction is calculated based on three zones. In the near zone, the algorithm sums the effects of four sloping triangular sections (surface gravity station and elevation at each diagonal corner). In the intermediate zone, the terrain effect is calculated for each point using the flat-topped square prism approach of Nagy (1966). In the far zone, it is based on the annular ring segment approximation to a square prism, as described by Kane (1962). All calculations were made in view of the Digital Terrain Model (DTM) of the Spanish National Geographic Institute (IGN), with 5 m horizontal resolution and bathymetry from GEBCO (Kapoor, 1981).

The regional and residual anomalies were separated using first order polynomial regression on the Bouguer anomaly (Martínez-Moreno et al., 2015). Furthermore, we calculated a forward model along perpendicular profiles by means of GRAVMAG v.1.7, from the British Geological Survey (Pedley et al., 1993), with 2.5D approximation according to the geological and geophysical information. The 2.5D modelling allowed us to assign lateral extensions to the modelled structures.

3.2. Direct current resistivity

The electrical resistivity tomography (ERT) method determines the resistivity distribution underground. There is a high resistivity contrast between cavities and host-rock, which enhances the detection of caves by means of this method. The profile was measured using Terrameter SAS 4000 (ABEM, Inc.). The equipment injects an electrical current by a pair of steel electrodes and measures the potential differences in another pair of electrodes. The resolution of the equipment is about $\pm 1 \mu\text{V}$.

The profile was acquired with a 4-channel multiple gradient electrode array that uses an 'alpha' type electrode arrangement where the potential electrodes are between the current ones (Loke, 2019). This array was developed for a multi-channel resistivity meter system (Dahlin and Zhou, 2006). The profile is 400 m long –350 m in the horizontal real distance– with 80 m of topographical variation. The electrode spacing was 5 m on the surface, with a total of 81 electrodes used.

Data inversion was performed using the Res2Dinv v.3.59 program (Geotomo Inc.) by means of standard least-square inversion methods (deGroot-Hedlin and Constable, 1990; Sasaki, 1992; Loke et al., 2003) and finite elements. In addition, calculation of the depth of investigation (DOI index) indicates the depth to which the inversion results are reliable. For this purpose, two data inversions were carried out using two different initial models with a resistivity 100 times higher for the second reference model with respect to the first (Loke, 2019). As a cut-off value, we used the more restrictive 0.1, according to Marescotti et al. (2003).

4. Structures and geomorphology of marbles north of Nerja Cave

4.1. Anisotropic folded marbles

Most outcrops in the Sierra Almijara massif are affected by important folding (Fig. 1b,e). In the study area, however, only small folds locally affect the roughly southward dipping structure of the marbles in the Nerja Cave. Although lithology is homogeneous at the massif scale –with the local exception of the dolomitic sandy sectors– the presence of both calc-schist layers or more competent/less karstified marble lev-

els evidences the internal structure of the carbonate formation. A more competent marble layer is folded northwest of the Nerja Cave (Fig. 2). It corresponds to a 5 m thick layer that describes a syncline and an anticline with northward vergence, whose limbs dip 40° – 45° . It is not possible to follow its continuity due to the absence of markers and the late brittle deformation.

4.2. Geomorphological evidence of a cave collapse

Close to the northern end of the Nerja Cave on the E side of the hill, there is a sunken area (Fig. 3a) delimited to the W by vertical walls with a height of 10–15 m decreasing toward the E (Fig. 3b,c). The area occupies an extension of $10,000 \text{ m}^2$ and it is 50 m away from the northern end of the known cave. Topographically, at the lower part of this zone, the sunken area connects to a small cavity called 'Pintada Cave', located at ~ 235 m a.s.l. that horizontally and vertically develops only a few meters. However, there is an artificial well of 80 m deep and 2 m wide with no connection with the known cave.

5. Gravity and ERT results

5.1. Gravity anomalies

The residual gravity map shows connected minima surrounded by maxima (Fig. 4). The area is divided into 4 main anomalies. The minimum anomaly 1 is associated with the known Nerja Cave halls, mainly oriented in N-S and NNW-SSE directions, with values of -0.5 mGal at the shallowest parts of the cave, and -0.1 to -0.2 mGal for the deeper ones to the N. Close to this anomaly, three additional ones are probably related to other unknown cavities. Anomaly 2 is found at the lower part of the hill, reaching values of -0.5 mGal at its centre. It has an almost circular shape and is located under anthropic constructions. To the NNE of this minimum, anomaly number 3 is separated –from S to N– into two parallel conduits with NNE-SSW direction, elongated about 400 m. This anomaly registers gravity values around -0.1 mGal . The strongest anomalies are located to the N, near the highest topographical areas of the hill. The anomalies are displaced from the peaks, so they are not caused by topographic effects. To the W, the minimum has a circular shape of about 100 m diameter, with values lower than -1 mGal . East of this area, the anomaly shows a more elliptical shape, 150 m long and oriented in a E-W direction, with residual gravity values of -0.6 mGal . Along the eastern boundary of the study area, there are other small anomalies with values from -0.1 to 0 mGal , signature features of a karstic system with fractures and small isolated caves.

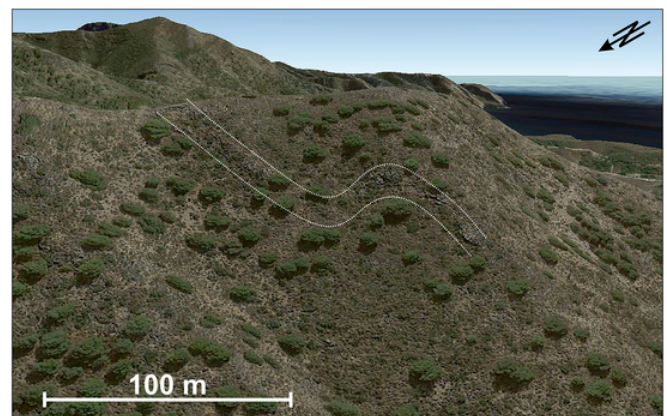


Fig. 2. Folded layer within the marbles where the Nerja Cave is developed (aerial photo source: Google Earth 10/28/2017).

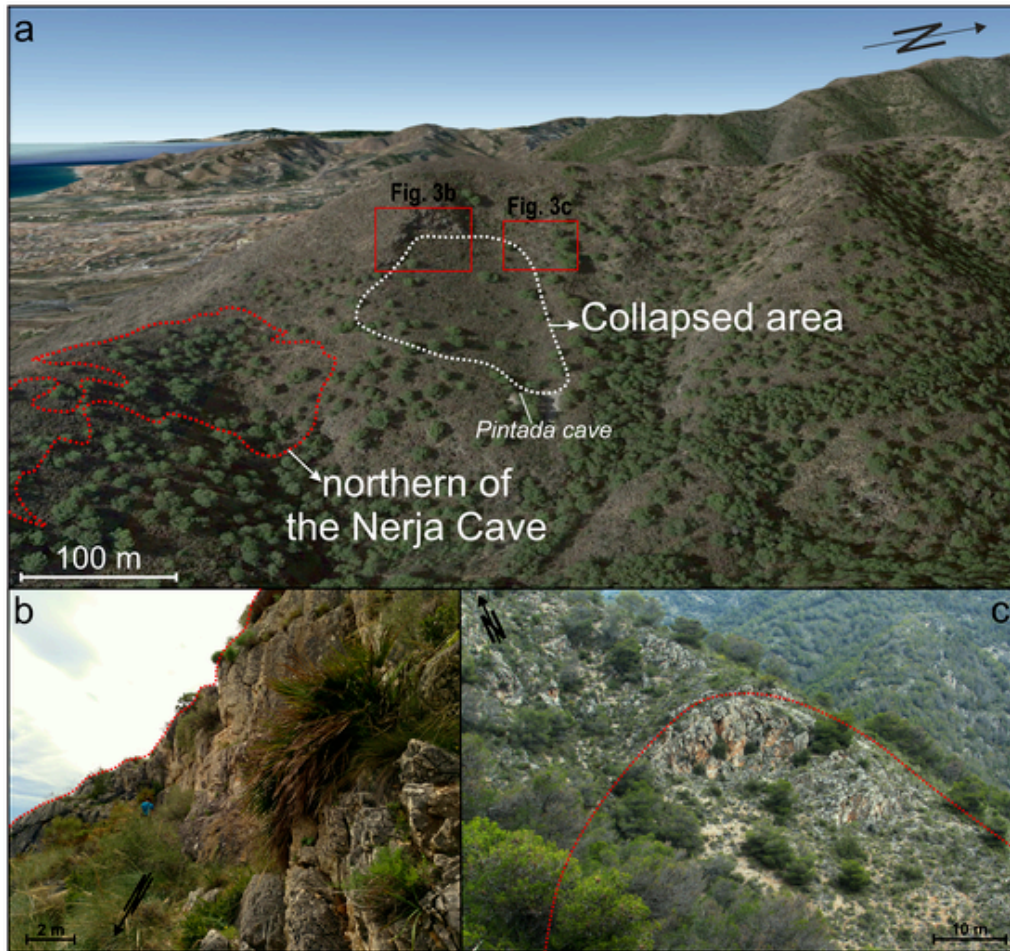


Fig. 3. Sunken area at the E hillside. (a) Delimitation of the sunken area north of the Nerja Cave. The location of this area is indicated in Fig. 1d. (b) and (c) Photos of the vertical walls in the western border of the collapsed area (locations indicated in Fig. 3a). Aerial photo source: Google Earth 10/28/2017.

5.2. Gravity and ERT pseudo-sections

In order to determine the sources of the strongest anomalies located to the N, an electrical resistivity profile together with a gravity forward model were calculated and analysed (Fig. 5). This profile crosses the residual gravity minimum number 4 (Fig. 4) in a W-E direction. The gravity forward model is based on the ERT results (Martínez-Moreno et al., 2013), so that the ERT profile constrains the morphology of the caves in the gravity model. The fit of the profile between the observed versus calculated gravity anomaly has an RMS error of 0.26% and a 0.34 standard deviation of data.

The model highlights four main cavities, two of them with larger dimensions. Cavity 1 causes the strongest residual gravity anomaly of -1.3 mGal and the most resistive values, higher than 500 k Ω m (k Ω m). The modelled cave has a development parallel to the slope of the hill, dipping 30° - 35° to the W. It extends 200 m in the E-W direction, with a vertical thickness of 15 - 20 m high, and 100 m width perpendicular to the profile alignment. Cavity 2 corresponds to a gravity minimum of about -0.6 mGal, lower than the modelled Cave 1, but it reaches the same values of resistivity. It develops 200 m in length sub-horizontal and almost parallel to the surface. Its height varies between 10 and 15 m to the W and 5 - 10 m to the E. The cave extends 80 m orthogonal to the profile orientation. The sunken area is modelled above Cavity 2. According to the electrical results, the sedimentary infill of the sunken area reaches 30 m, decreasing to the E. Finally, two small voids are in-

dicated in the model. Cavity 3 lies outside of ERT measurements and it generates an anomaly of -0.4 mGal. It is located at 390 m from the beginning of the profile, and its dimensions are: 30 m long in the profile direction, 40 m wide and 30 m high. Cavity 4 is located above Cave 1, at the top of the hill, with small dimensions of $5 \times 5 \times 5$ m. This void is only detected in the ERT model.

6. Discussion

6.1. Karst evolution, hydrogeology and cave development

The karstogenic evolution in the area is complex (Lhènaff, 1986). The oldest karstification phase of the dolomitic marbles of Almjara unit is probably Miocene, as indicated by Rodríguez Vidal and Cáceres Puro (1993). Durán (1996) and Durán et al. (2002) consider that the karstification phase creating the first important voids of Nerja Cave was during the Pliocene. At that time climatic conditions favoured the generation of both the *endo*- and the *exokarst*, and the associated residual red soils.

During the Pleistocene the climate shifted toward less humid conditions, approaching the Mediterranean trend which, with more or less aridity, continues nowadays. Important calcareous precipitation is evidenced by the intense cementation of the breccias, resulting from a dismantling of the *exokarst* previously generated as a consequence of important surface erosion triggered by the very active tectonic uplift of the carbonate massif. Calcite precipitation also occurred –as travertines associated with Maro spring– in the karst voids previously generated, and so several phases of speleothems are identified in Nerja Cave dur-

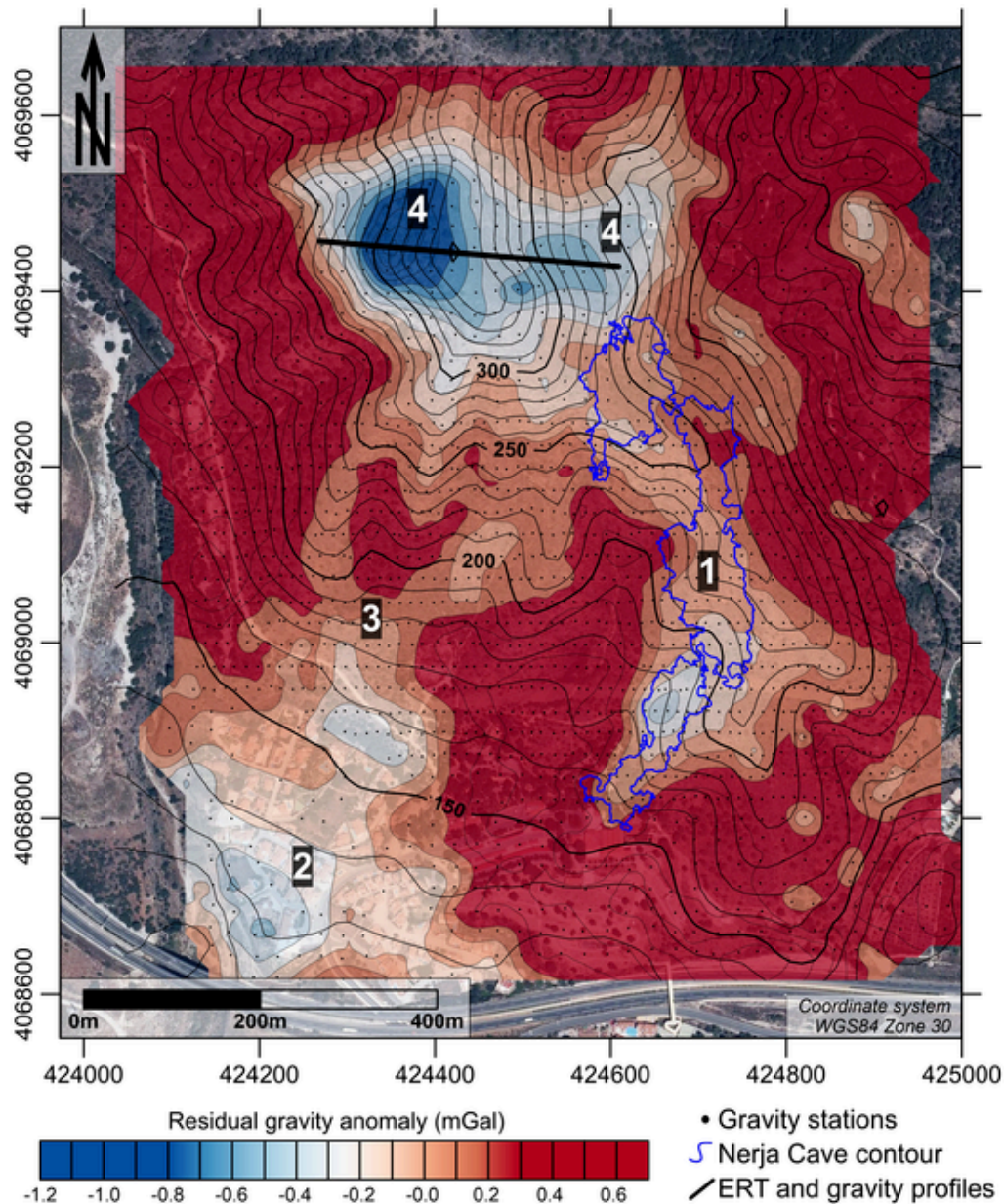


Fig. 4. Residual gravity anomaly over topographic map of Nerja Cave and surroundings. The Nerja Cave location is indicated with a blue line. The main gravity anomalies are indicated with white numbers. The position of the ERT and gravity forward model profiles is marked with a thick black line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ing the Pleistocene, separated by erosive or non-chemical sedimentation periods (Durán, 1996). Speleothems were also affected by seismically-induced collapses, related to the uplifting of the Sierra Almijara massif.

Vadillo et al. (2012) show the altitudinal range of the cavities. The speleothem fill intersected during borehole drilling coincides with that of the Nerja Cave, but also with that exposed in the cliffs developed in the Pleistocene breccia, visible along Maro creek. This suggests common phases of karstification that affected both the Triassic dolomitic marbles and the Pleistocene calcareous breccias. Finally, the Holocene includes periods of chemical precipitation in the endokarst, coinciding with a climatic optimum (Durán et al., 2002).

The karstification processes have created different karstic networks, accessible or not from the surface, nowadays located at different altitudes. The known caves *Autovía* (120 m a.s.l.) *Nerja* (158 m a.s.l.) and *Pintada* (235 m a.s.l.) are some examples of caverns in marbles with di-

rect access from the surface. The differences in altitude are a consequence of the progressive elevation of the Sierra Almijara since the late Miocene (Sanz de Galdeano and Alfaro, 2004). This regional uplifting also produced the incision of the area's creeks and the perched location of the Nerja Cave above the water table.

The hydrogeological circumstances found in the surroundings of the Nerja Cave suggest a general situation of vertical heterogeneous distribution of karstic levels, and proof of this can be found from less than zero to more than 700 m metres of altitude in the mountainous massif of Sierra Almijara Triassic marbles. A conceptual model of the karstification in the carbonate massif given these circumstances (Fig. 6) indicates an undetermined number of more-or-less connected sub-horizontal cavities distributed along the massif, although vertically separated by relatively thick zones with very low karstification. These low-karstified zones may be a consequence of the existence of calc-schist intercalations in the carbonate sequence, which can favour the genesis of

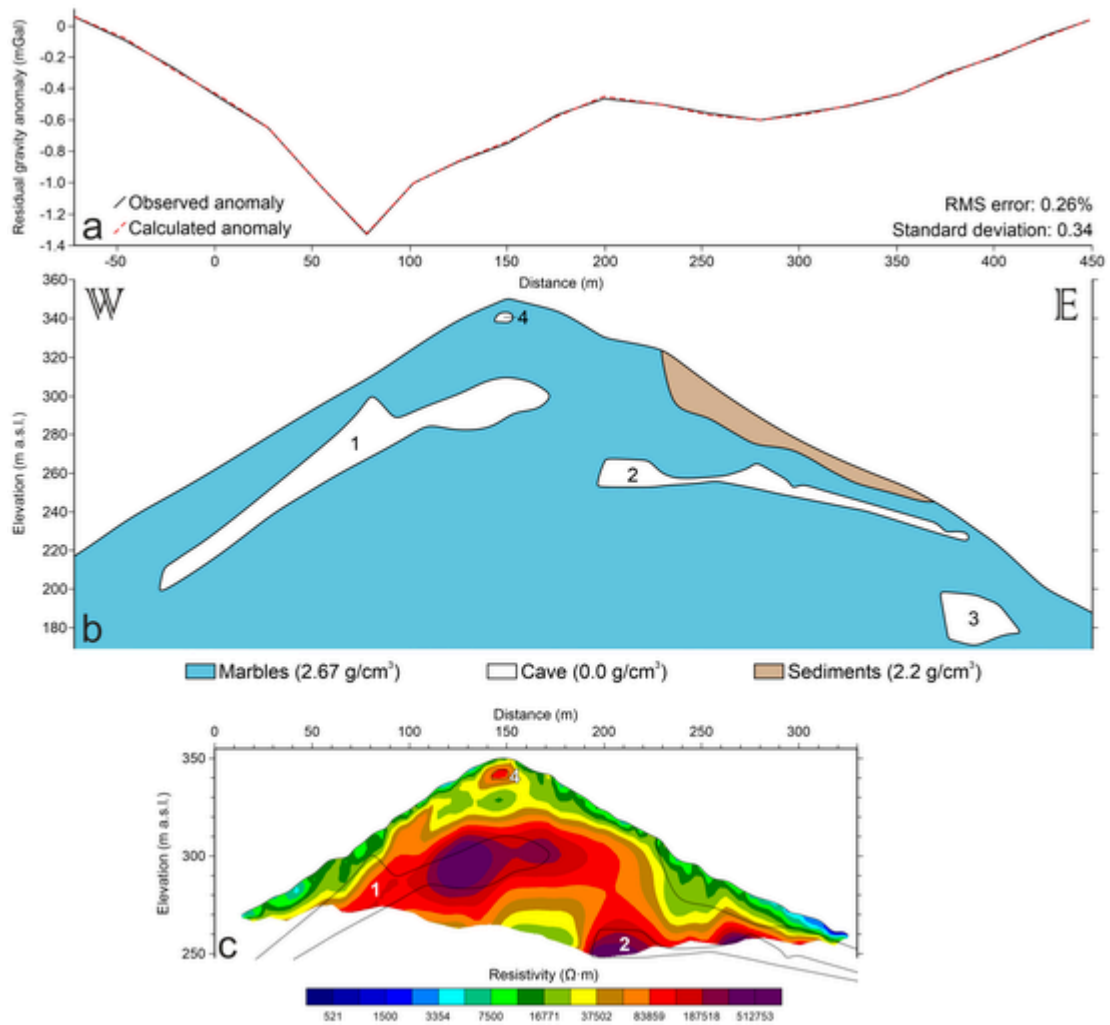


Fig. 5. Geophysical profiles and models over the strongest minima of residual gravity anomaly (see location in Fig. 4). (a) Gravity profile and (b) forward gravity model based on (c) ERT profile. Modelled caves marked with dashed black lines.

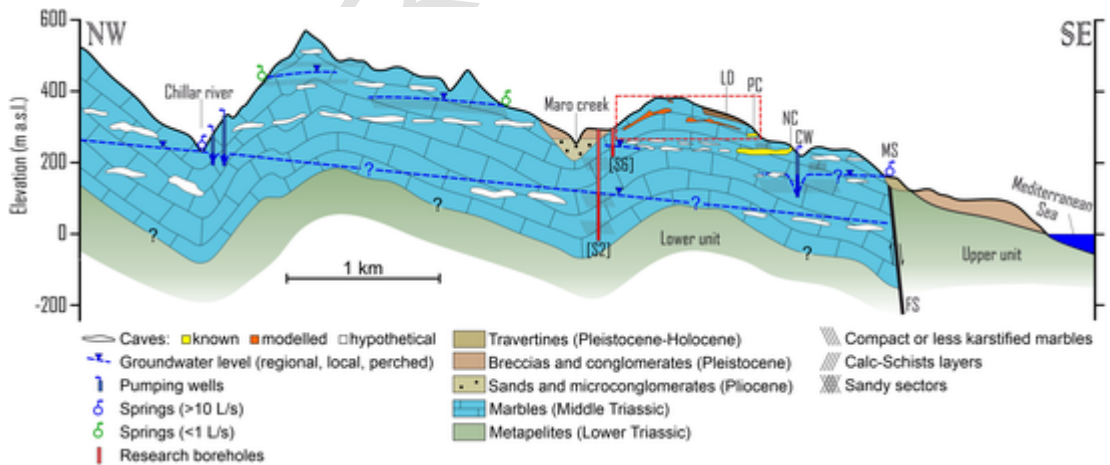


Fig. 6. Interpreted cross-section sketch showing the main hydrogeological and geomorphological features of the study area. The dashed red rectangle indicates the area of the ERT and gravity profiles referred to in Fig. 5. MS: Maro spring; NC: Nerja Cave; PC: Pintada Cave; LD: Landslide debris; CW: Nerja Cave well; FS: fault system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

small springs located at relatively high altitudes, as sketched in Fig. 6. Nevertheless, more frequently they derive from the above-described karstogenic evolution of the area with the uplifting of Sierra Almijara. On a more local scale, heterogeneity may arise from the occurrence of

loose sandy material generated by the complete disaggregation of the dolomitic marbles. This circumstance, however, has been identified inside the Nerja Cave and in its immediate vicinity.

The model sketched in Fig. 6 can explain the general trend of a series of local, perched water tables found over the regional one, as well as the commented evolution from phreatic to vadose conditions in the Nerja Cave itself. More locally, it can also explain the occurrence of gravitational instability processes leading to mass rock collapse. These collapses can develop along the relatively steep slopes generated by the intense fluvial incision, induced by a lack of lateral mechanical support, but also in relatively flat sectors, as the aforementioned sinkholes at the entrance of Nerja Cave. They could have been generated by collapse because of the loss of mechanical support following the drawdown of the water table, and this may have affected parts of the roof of some halls in Nerja Cave.

Within the Nerja Cave karst system, gravity results reveal the likely presence of unexplored cavities. At the highest topographical zones of the hill, located north of the study area, the negative gravity anomaly is divided into two parts due to the gravity variation of 0.6 mGal. This setting highlights the presence of two close main cavities with different features. Additional evidence suggesting rock collapses based on the results of this study will be commented in the following section.

6.2. Geomorphological and geophysical evidences of the cavity collapse at the eastern hillside

To the E of the hill, there is geomorphological evidence of a sunken area, namely vertical walls 10–15 m high (Fig. 3) with a semicircular shape at the top. The gravity anomaly map superimposed on the aerial photo highlights such limits with minima values. In addition, the lower part indicates the entry of the *Pintada* Cave (Figs. 3 and 7).

As this cave developed it remained gravitationally unstable, provoking its partial collapse. This gave rise to a cave with a lower dimension than its analogue to the W, and probably filled with large rock blocks (Fig. 5). As a consequence, sedimentary infill of 30 m is accumulated over the cave. The collapse is greater at the highest topographical areas and disappears toward the lowest ones. The minimum of the gravity anomaly is stronger above the collapse limits, which implies the existence of non-collapsed small caves.

Below the collapsed area, the ERT profile reveals the presence of another sub-horizontal cave, probably developed in a later stage of the karstic evolution. According to the thickness of the sedimentary infill, the initial height of the collapsed cave (at present 5 m; Fig. 5) would be 35 m at its centre part. Due to the collapse, there is no evidence of its outside connection but it could be located at *Pintada* Cave.

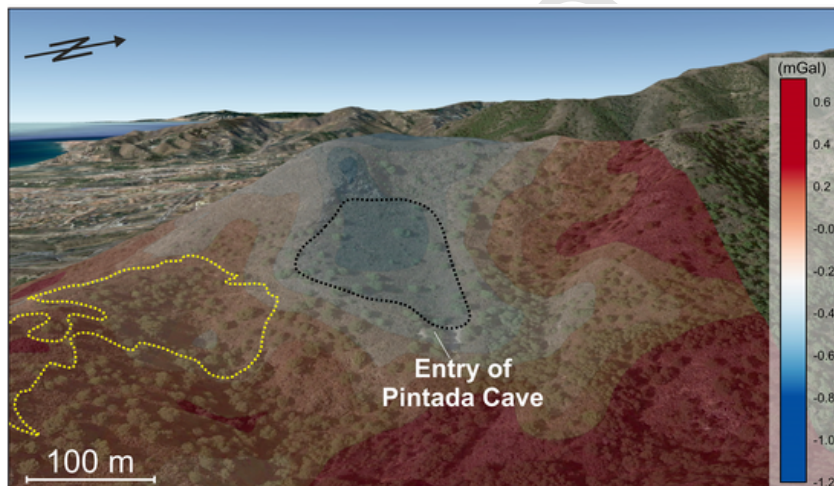


Fig. 7. The boundaries of the collapsed area (dashed black line) defined by geomorphological evidence and residual gravity anomaly results. Dashed yellow line indicates the position of Nerja Cave. Aerial photo source: Google Earth 10/28/2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

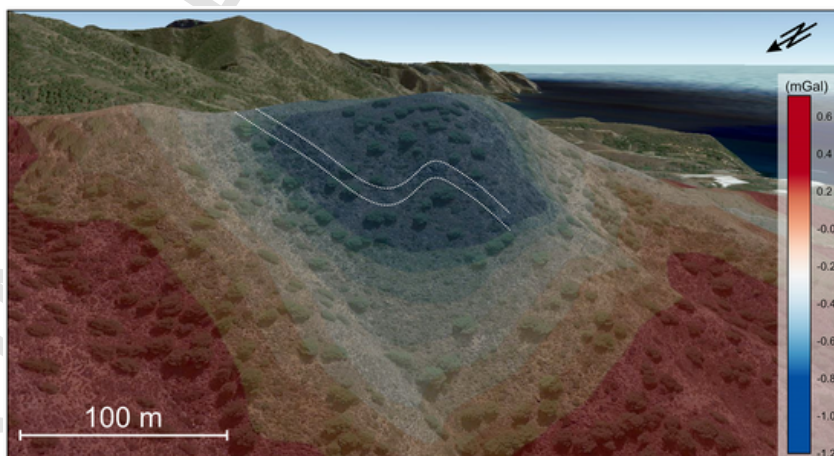


Fig. 8. Folded layer inside the marbles at the top of the hill integrated with residual gravity anomaly results. Aerial photo source: Google Earth 10/28/2017.

6.3. Anisotropic layers and caves position

The two caves located in the northern part of the study area (moderated cavities 1 and 2, Fig. 5) had comparable development. Yet the cavity 2 collapsed whereas the cavity 1 remains unaltered, probably owing to the strong marble folded layer located at the top of the western hillside (Figs. 2 and 8).

The strong folded layer culminating the hill acts as a barrier against collapses, protecting the cave and its development. The location of the folded layer matches the position of the strongest minima of the gravity residual anomaly (Fig. 8). Under this layer, the great cavity will be located close to the surface.

6.4. Undiscovered cavities in the karst system of Nerja Cave

Nerja Cave has an almost N-S development of about 600 m in length highlighted in the residual gravity anomaly map. Gravity results (Fig. 4) suggest the existence of a parallel cave W of the known cavity. Analysing from south to north, the unknown cave extends from area 2 in Fig. 4, as far as cavities located to the north in area 4. In the middle, the anomaly indicates the division of the cave into two conduits that join northwards. This area encompasses a large cave or a succession of disconnected caves close together.

7. Conclusions

Nerja Cave developed on a southward dipping folded marble layer with main known cavities elongated along an N-S open arch morphology, having a horizontal extension of approximately 600 m. Negative residual gravity anomalies highlight the presence of unexplored caves parallel to and even larger than the known Nerja Cave, with prominent minima at the hill located to the North. An E-W ERT profile contributes to revealing the deep structure of the twin minima located on both hillsides. Geomorphological evidence at the E hillside, including subsidence and vertical walls, would point to the presence of a collapsed cave above a sub-horizontal deeper cavity. The W side offers no evidence of collapse, and a folded strong marble layer is observed at the top. The two separate twin caves at either side of the hill have undergone different evolutions. High dissolution on the E side triggered a collapse of the cave when it remained gravitationally unstable, and sedimentary infill is located above it. At the W side, the strong folded layer protects the cave below against collapse. The Nerja Cave system is progressively deeper southwards, parallel to the marble layer, suggesting a southward and deeper progression of the karstification. The Nerja Cave system provides a remarkable example for karstic cavity geometry research combining geomorphological and geophysical methods to integrate the known caves; it moreover reveals the presence of unknown cavities and serves to advance in our knowledge about the collapse of shallow cavities.

CRedit authorship contribution statement

F.J. Martínez-Moreno: Conceptualization, Writing - original draft. **J. Galindo-Zaldívar:** Conceptualization, Writing - review & editing, Writing - original draft. **C. Liñán Baena:** Conceptualization, Writing - review & editing, Writing - original draft. **L. González-Castillo:** Conceptualization, Writing - review & editing, Writing - original draft. **J. Benavente Herrera:** Conceptualization, Writing - review & editing, Writing - original draft. **Y. del Rosal Padial:** Conceptualization, Writing - review & editing, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Andreo, B., Carrasco, F., Sanz de Galdeano, C., 1993. Estudio geológico del entorno de la Cueva de Nerja. In: Carrasco, F. (Ed.), *Geología de la Cueva de Nerja*. pp. 23–50.
- Andreo, B., Barberá, J., Mudarra, M., Marín, A., García-Orellana, J., Rodellas, V., Pérez, I., 2018. A multi-method approach for groundwater resource assessment in coastal carbonate (karst) aquifers: the case study of Sierra Almirajara (southern Spain). *Hydrogeol. J.* 26 (1), 41–56.
- Aranburu Artano, A., Arriolabengoa, M., Bodego, A., Álvarez Llano, I., Bilbao Lasa, P., Yusta, I., Liñán, C., 2018. Meteorización de mármoles dolomíticos y su relación con la arena dolomítica de la Cueva de Nerja (Málaga, España). *Geogaceta* 64.
- Aranburu Artano, A., Bodego Aldasoro, A., Jiménez de Cisneros, C., Álvarez, I., Liñán Baena, C., Arriolabengoa, M., Bilbao Lasa, P., Iriarte, E., González Ramón, A., Cheng, H., 2019. Calcretas, espeleotemas y depósitos aluviales: tres registros de una misma historia geológica (Nerja, Málaga). *Asociación Española para el Estudio del Cuaternario (AEQUA)*.
- Arrese González, B., 2009. *Geomorfología, evolución geológica y condiciones ambientales actuales de la Cueva de Nerja, Málaga* (PhD Thesis) Autonomous University of Madrid.
- Benavente, J., Almécija, C., 1993. Estudio geomorfológico del entorno de la Cueva de Nerja. *Geología de la Cueva de Nerja* 3, 119–158.
- Benavente, J., Vadillo, I., Liñán, C., Martínez-Moreno, F.J., Galindo-Zaldívar, J., Carrasco, F., 2017. Identification of Vadose Karst Voids and Ventilation patterns Coupling Hydrochemical and Geophysical Methods (Maro Spring, near Nerja, Southern Spain). In: Renard, P., Bertrand, C. (Eds.), *EuroKarst 2016, Neuchâtel: Advances in the Hydrogeology of Karst and Carbonate Reservoirs*. Springer International Publishing, Cham, pp. 327–334.
- Carrasco, F., Durán, J.J., Andreo, B., Liñán, C., Vadillo, I., 1998. Consideraciones sobre el karst de Nerja. *Karst en Andalucía* 173.
- Carrasco, F., Vadillo, I., Liñán, C., Andreo, B., Durán, J.J., 2016. Control of environmental parameters for management and conservation of Nerja Cave (Malaga, Spain). *Acta Carsologica* 31 (1).
- Dahlin, T., Zhou, B., 2006. Multiple-gradient array measurements for multichannel 2D resistivity imaging. *Near Surf. Geophys.* 4 (2), 113–123.
- deGroot-Hedlin, C., Constable, S., 1990. Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophysics* 55 (12), 1613–1624.
- Durán, J., 1996. Los sistemas kársticos de la provincia de Málaga y su evolución. (Contribución al conocimiento paleoclimático del Cuaternario en el Mediterráneo Occidental).
- Durán, J.J., López-Martínez, J.J., Andreo, B., Carrasco, F., Jiménez de Cisneros, C., Caballero, E., Juliá, R., 2002. Fases de karstificación y sedimentación endokárstica plioleptocenas en el mediterráneo occidental: evolución de la Cueva de Nerja (Málaga, sur de España). *Geogaceta* 31, 3–6.
- Galve, J., Gutiérrez, F., Lucha, P., Bonachea, J., Remondo, J., Cendrero, A., Gutiérrez, M., Gimeno, M., Pardo, G., Sánchez, J., 2009. Sinkholes in the salt-bearing evaporite karst of the Ebro River valley upstream of Zaragoza city (NE Spain): geomorphological mapping and analysis as a basis for risk management. *Geomorphology* 108 (3–4), 145–158.
- Guerra-Merchán, A., Serrano, F., Ramallo, D., 2004. Geomorphic and sedimentary Plio-Pleistocene evolution of the Nerja area (northern Alboran basin, Spain). *Geomorphology* 60 (1–2), 89–105.
- Jordá Pardo, J., 2004. Análisis geomorfológico y paleogeográfico de la Costa del Sol Oriental en los alrededores de Nerja (Málaga, S de España). *Zona Arqueológica S 4*, 52–71.
- Kane, M., 1962. A comprehensive system of terrain corrections using a digital computer. *Geophysics* 27 (4), 455–462.
- Kapoor, D., 1981. General bathymetric chart of the oceans (GEBCO). *Mar. Geod.* 5 (1), 73–80.

- Lhénaff, R., 1986. Répartition des massifs karstiques et conditions générales d'évolution dans les Cordillères Bétiques andalouses. *Karstologia Mém.* 1, 5–24.
- Loke, M.H., 2019. Tutorial: 2-D and 3-D Electrical Imaging Surveys. Geotomo Software, Malaysia.
- Loke, M.H., Acworth, I., Dahlin, T., 2003. A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys. *Explor. Geophys.* 34 (3), 182–187.
- Marescot, L., Loke, M.H., Chapellier, D., Delaloye, R., Lambiel, C., Reynard, E., 2003. Assessing reliability of 2D resistivity imaging in mountain permafrost studies using the depth of investigation index method. *Near Surf. Geophys.* 1 (2), 57–67.
- Martínez-Moreno, F.J., Pedrera, A., Ruano, P., Galindo-Zaldívar, J., Martos-Rosillo, S., González-Castillo, L., Sánchez-Úbeda, J.P., Marín-Lechado, C., 2013. Combined microgravity, electrical resistivity tomography and induced polarization to detect deeply buried caves: Algaídilla cave (Southern Spain). *Eng. Geol.* 162, 67–78.
- Martínez-Moreno, F.J., Galindo-Zaldívar, J., Pedrera, A., Teixido, T., Ruano, P., Peña, J.A., González-Castillo, L., Ruiz-Constán, A., López-Chicano, M., Martín-Rosales, W., 2014. Integrated geophysical methods for studying the karst system of Gruta de las Maravillas (Aracena, Southwest Spain). *J. Appl. Geophys.* 107, 149–162.
- Martínez-Moreno, F.J., Galindo-Zaldívar, J., Pedrera, A., Teixido, T., Peña, J.A., González-Castillo, L., 2015. Regional and residual anomaly separation in microgravity maps for cave detection: the case study of Gruta de las Maravillas (SW Spain). *J. Appl. Geophys.*, 114(0), 1–11.
- Martínez-Moreno, F.J., Pedrera, A., Galindo-Zaldívar, J., López-Chicano, M., Azor, A., Martín-Rosales, W., Ruano, P., Calaforra, J.M., Hódar-Pérez, A., 2016a. The Gruta de las Maravillas (Aracena, South-West Iberia): setting and origin of a cave in marbles from dissolution of pyrite. *Geomorphology* 253, 239–250.
- Martínez-Moreno, F.J., Galindo-Zaldívar, J., González-Castillo, L., Azañón, J.M., 2016b. Collapse susceptibility map in abandoned mining areas by microgravity survey: a case study in Candado hill (Málaga, southern Spain). *J. Appl. Geophys.* 130, 101–109.
- Nagy, D., 1966. The gravitational attraction of a right rectangular prism. *Geophysics* 31 (2), 362–371.
- Pedley, R.C., Busby, J.P., Dabek, Z.K., 1993. GRAVMAG User Manual - Interactive 2.5D gravity and magnetic modelling. British Geological Survey, Technical Report (WK/93/26/R).
- Rodríguez Vidal, J., Cáceres Puro, L., 1993. Rasgos generales del relieve en el sector suroriental de la sierra de Almirajara (Málaga). *Geogaceta* 14, 49–51.
- S.E.M., 1985. La Cueva de Nerja. Grupo de Exploraciones Subterráneas de la Sociedad Excursionista de Málaga.
- Sanz de Galdeano, C., 1993. La fracturación en el entorno de la Cueva de Nerja. *Geología de la Cueva de Nerja* 3, 96–114.
- Sanz de Galdeano, C., Alfaro, P., 2004. Tectonic significance of the present relief of the Betic Cordillera. *Geomorphology* 63 (3–4), 175–190.
- Sasaki, Y., 1992. Resolution of resistivity tomography inferred from numerical simulation. *Geophys. Prospect.* 40 (4), 453–463.
- Vadillo, I., Benavente, J., Neukum, C., Grützner, C., Carrasco, F., Azzam, R., Liñán, C., Reicherter, K., 2012. Surface geophysics and borehole inspection as an aid to characterizing karst voids and vadose ventilation patterns (Nerja research site, S. Spain). *J. Appl. Geophys.* 82, 153–162.
- Waltham, T., Waltham, A.C., Bell, F.G., Culshaw, M.G., 2005. Sinkholes and Subsidence: Karst and Cavernous Rocks in Engineering and Construction. Springer Science & Business Media.