Insights into Late Quaternary Rock Shelter Sedimentation at Santuario Della Madonna Cave (Northern Calabria, Italy)

Gaetano Robustelli * and Federica Lucà

Abstract: Shelter caves serve as crucial repositories that provide valuable insights into Late Pleistocene-Holocene depositional mechanisms and environmental changes. In this study, we conducted a stratigraphic analysis of the easternmost cave-fill succession within the Santuario della Madonna cave, located along the Tyrrhenian coasts of southern Italy. By examining the cave-fill deposits and their relationship with archaeological successions from previous excavation campaigns, we aimed to enhance our understanding of sedimentary evolution, specifically, the interplay between local and global environmental factors. A comprehensive sedimentological analysis was conducted, enabling the identification of three distinct sedimentary facies within the clastic succession that overlays the calcareous cave roof. Our findings reveal a noticeable shift in cave sedimentation processes, characterized by a gap in detritus accumulation followed by the deposition of flowstones. Furthermore, the presence of oversized boulders within the succession was attributed to failures from the cliffs that overhang the cave opening. We interpret these boulders as possible evidence of cave collapses induced by earthquakes, similarly to rockfall phenomena observed in the archaeological test pits within the shelter, which show a strong correlation with paleoseismic events.

Keywords: shelter cave; clastic sedimentation; Calabria; Late Quaternary; earthquake-induced rockfall

1. Introduction

A number of caves of northern Calabria (southern Italy) are well known primarily for their prehistoric records (Figure 1). Cave and/or rock shelter deposits have, in fact, provided evidence of human occupation from the Upper Paleolithic to the Middle Ages [1–9]. Historically, considerable attention has been given to understanding the relationships between natural environments and human communities in these settings [3,7], whereas stratigraphic analysis of the cave-fill successions, crucial for understanding their evolution in terms of local vs. global environmental changes, has been somewhat neglected. Nevertheless, in recent decades geoarchaeological investigations of sedimentary records have been conducted in northern Calabria by integrating geological and archaeological data, revealing new insights into the relationships between natural environments and human communities since the Upper Paleolithic [4–6,8].

Along the Tyrrhenian rocky coasts of Calabria, many karstic caves along the steeply westward-dipping scarp, corresponding to MIS 5.1 paleo sea-cliff, are notable and exhibit evidence of marine re-shaping ([10] and references therein). The Santuario della Madonna cave at Praia a Mare (Figure 1) is considered one of the most important archaeological records of the Mediterranean Neolithic to Bronze Age cultures [2,3]. The cave has been the subject of several excavation campaigns since the 1950s, which continued until 1970. Since 2002, additional campaigns in the cave have focused on the upper and the middle layers of the stratigraphic sequence [1], corresponding to about 5.5 m of anthropogenic deposits ranging from Neolithic to Middle Bronze Age cultures [3], down to the Mesolithic occupation [9]. Through physical, chemical, mineralogical and micromorphological analyses, [5]
investigated the patterns of human occupation within the cave during this period, as well as the evolution of the natural landscape and climatic changes.

Figure 1. (a) Location and (b) geological map (modified after [11]) of the study area (PC: Pollino–Castrovillari fault system). (c) Overview of the openings of the most important caves at the foot of Mount Vingiolo. Santuario della Madonna cave is characterized by three openings (1, 2, 3, photo V. Tinè). (d) Plan view of Santuario della Madonna cave (modified after [2]). Opening 1 is the main entrance. Outcrops of studied clastic succession are located along the side walls of the eastern cave opening (e).

In this framework, this study aims to provide new geological data on the Late Pleistocene sequence in the eastern sector of the Santuario della Madonna cave by analyzing a previously unstudied succession. The primary objective was to achieve a precise reconstruction of the Late Quaternary cave sedimentary evolution, looking for environmental changes affecting shelter deposits and to complement the findings put forth by earlier researchers. The cave represents an important archive documenting the transition between the Pleistocene and Holocene, when alternations of cold and warm phases occurred. Moreover, its distinctive morphological features are noteworthy, including three openings tightly connected to subaerial environments. These unique characteristics could have influenced the cave infilling. Prior research has extensively investigated deposits in the main cave room and the western opening. Nevertheless, no previous studies have addressed the succession in the shelter’s eastern sector, which forms a collapse sinkhole with the Fumarulo cave below. The relationship of studied deposits with the archeological successions from past excavation campaigns is analyzed, and evidence of rockfalls connected to cave wall/ceiling collapse within the archaeological layers is investigated. Because the studied cave is located in a highly seismically active area, the possible influence of earthquakes on shelter sedimentation has been investigated.
2. Study Area

The study area is located along the Tyrrhenian coast of northern Calabria (Figure 1a), where Meso-Cenozoic carbonates of the Lungro–Verbicaro and the Pollino–Ciagola Units [11] are tectonically overlain by ophiolites and deep-sea sedimentary deposits (Calabride Complex, Figure 1b). Late Miocene to Quaternary wedge-top basins border the Pollino ridge, where a NW-striking normal fault system runs along the regional boundary, continuing towards the Ionian offshore of Calabria.

At the foot of Mount Vingiolo, along the rocky cliff behind the Praia a Mare coastal plain (Figure 1c), the Santuario della Madonna cave is one of a number of karst caves carved in fractured Mesozoic carbonatic rocks, hanging Late to Early Pleistocene marine terraces and deposits [10]. The studied cave is a large, single room over 2000 m² in area and 15 m in height (Figure 1d) located between 40 and 70 m a.s.l. Although the floor of the main cave room has been somewhat modified by the construction of the sanctuary buildings, it exhibits a low westward slope and is characterized by a wavy surface with small hemispherical cavities (related to active dripping) filled with carbonate soft concentrations [5].

The cave is characterized by three openings. The westernmost opening (opening n. 2 in Figure 1d) exhibits evidence of marine re-shaping during the late Middle Pleistocene [10], as supported by sea-level indicators such as lithodomus holes and sea-cliff base deposits found at elevations ranging from 50 to 58 m a.s.l. On the other hand, the easternmost cave opening (39°53′46.55″ N, 15°47′07.18″ E) shows evidence of slope deposits [5] which rest on the roof of the “great chimney” or Fumarulo cave [12,13]. Opening 3 overlaps the Fumarulo cave, forming a collapse sinkhole.

In the 1950s, early exploratory excavations were conducted in this area, revealing significant archaeological and prehistoric findings [1] and reference therein, [14]. After the early exploratory excavations of the 1950s, the Santuario della Madonna cave was excavated in the 1960s, revealing impressive archaeological successions dating from the Late Paleolithic (around 12 ky BP) to the Bronze Age (3rd millennium BC) [1,2]. Since 2002, the Soprintendenza al Museo Nazionale Preistorico Etnograico “L. Pigorini” has carried out further excavations. The original trench (Cardini test pit in Figure 1d) was enlarged on the northeast side (Pigorini test pit in Figure 1d), involving the upper and the middle layers of the stratigraphic sequence described by [1]. The new systematic excavation has provided a refined record of human occupation lasting a record of 10 ky. Below the cave floor, five main horizons have been identified in the new stratigraphic sequence [3,9,15] resting on a 6 m thick clayey deposit. Each archaeological unit contains several archaeological layers (palaeosurfaces) formed during periods of intensive human activity within the cave, ranging from the Mesolithic Age (8th–7th millennia BC) to the advanced phases of the Middle Bronze Age (2nd millennium BC). In particular, [9] argued that the lowermost lithic assemblage of the Mesolithic sequence can be referred to the undifferentiated Epipaleolithic facies.

Further, a pedostratigraphic study was carried out in the Santuario della Madonna cave focusing on the Holocene succession characterized by thinly laminated loamy-sand bedsets of the Late Neolithic to Middle Bronze age overlying a soil with finer texture, illuvial clay coatings and hydromorphic features [5]. Particularly, [5] claimed that the buried soil developed under humid and seasonally contrasted conditions during the Middle Neolithic climatic optimum; conversely, the overlying “zebra” layers are consistent with short-term climate changes during the Late Neolithic to Bronze Age, with increasing aridity and seasonality and rapid oscillations in the moisture regime and geomorphic processes.

3. Methods

To enhance the understanding of the sedimentary succession at the Santuario della Madonna cave, a comprehensive fieldwork campaign was conducted. A new clastic succession, consisting of two exposed outcroppings, was investigated in proximity to the eastern shelter opening (Figure 1e) characterized by the presence of a cave roof hanging on the Fumarulo cave (Figure 1c). A detailed sedimentological analysis was carried out, based on...
macroscopic criteria. Lithological features, grain size, clast shape and roundness, fabric and sedimentary structures were used to discriminate depositional environments, identifying different sedimentary facies. The employed descriptive sedimentological terminology was adopted from previous studies [16,17]. In the fabric description, the notation ‘a’ is used for the long axes of the clast, accompanied by the index (l) or (p) to denote whether the axes’ orientation is transverse or parallel to the flow direction, respectively. Imbrication is denoted as (i).

Moreover, in order to analyze sedimentary cave evolution, our efforts were directed toward verifying the lateral relationship between the study succession and geoarcheological sequences outcropping in the main cave room [1–3], interpreting the results by uniform methods of stratigraphical and geomorphological analysis. Particular attention has been addressed to coarse-grained deposits within the Holocene archaeological succession.

Factors controlling Late Quaternary shelter sedimentary assemblage are discussed in light of the main available data on paleoclimate and/or paleoseismolology, the cave being located in a seismically active area.

4. Results

Close to the eastern opening of the Santuario della Madonna cave (Figure 1e), a 7 m thick clastic succession, dipping 25° toward the main cave room, outcrops along the shelter side walls. The succession does not show any macroscopic evidence of human presence that might have altered the original clastic deposits. Based on the main sedimentary features, three facies (Table 1) have been distinguished and attributed to different depositional processes: rockfall deposits (RF), debris-flow deposits (DF) and waterflow deposits (WF).

Table 1. Main features of the sedimentary facies recognized in the eastern section of Santuario della Madonna cave.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Diagnostic Feature</th>
<th>Depositional Process</th>
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<tbody>
<tr>
<td>RF</td>
<td>Subangular clast-supported, immature coarse pebble to cobble gravel with openwork texture, illuviated with fine-grained matrix. Isolated, outsized limestone boulders occur.</td>
<td>Rockfalls from the ceiling and walls of the cave.</td>
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<tr>
<td>DF</td>
<td>Massive to crudely stratified gravels, rich in a poorly sorted matrix. DF1: Pebble- to fine cobble-sized gravels, locally inverse graded; DF2: Matrix-rich granule to fine pebble clast layers.</td>
<td>Debris flows with low to moderate viscosity; DF1: failures of the weathered bedrock from the cliffs overhanging the cave opening; DF2: mobilization of the upper part of slope-deposit accumulations.</td>
</tr>
<tr>
<td>WF</td>
<td>Moderately sorted, sandy to fine pebble- and granule-sized clastic layers, locally carbonate-encrusted. Calcite flowstones locally occur.</td>
<td>Shallow, unconfined or poorly confined waterflow.</td>
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4.1. Rockfall Deposits (RF)

Rockfall (RF) deposits are primarily characterized by scattered or randomly clustered cobbles and boulders (Figure 2a,b), composed of limestones and dolostones from the rock-shelter ceiling and walls. Locally, lenses of clast-supported, immature coarse pebble to cobble gravel occur with an openwork texture (Figure 2b). Beds are illuviated with fine-grained debris and soil sediments, covering the overhanging marine terrace [5]. RF deposits are sometimes arranged in wedges or tongues that penetrate and accommodate the surrounding facies (Figure 3a), pinching out individually, without any evidence of erosion. Basal bedding contacts are quite sharp and slightly irregular, breaking down into DF deposits (Figure 3a).

Although the overall fabric is rather disordered and shows weak downslope alignment, the clast fabric of rockfall deposits is variable. Further isolated boulders (Figure 2a,c)
and scattered outsized debris show an a(t) “rolling” fabric [16] or adjust their resting positions with secondary sliding and re-orientation, thus showing an aligned fabric a(p) or random orientation.

Figure 2. Sedimentary facies recognized in the studied clastic succession. (a) A tongue-shaped rockfall (RF) deposit with openwork texture blankets a calcareous boulder (RF Bld). (b) Concave up lenses of RF show a slightly irregular basal bedding contact. (c) Alternating of debris flows (DF, cyan dashed line) in unsorted fine-grained matrix and RF deposits. The coarse-grained subfacies DF1 is characterized by a disorderly clast fabric and crude inverse grading. Matrix-rich, granule to fine pebble clasts with aligned a(p) fabric (red arrow) characterize DF2. Waterflow (WF) deposits consist in carbonate-encrusted sandy to granule beds (d), and dm thick flowstone layers (e), with RF intercalated.
4.2. Debris-Flow Deposits (DF)

Debris-flow deposits consist of beds ranging from granule to cobble-sized clast and matrix-rich layers. The gravel clasts are exclusively calcareous in composition and sub-angular in shape. They are embedded within a poorly sorted matrix, consisting of a mixture of brownish and reddish sand and silt (Figure 2c). The gravel beds, with thicknesses varying between 10 and 45 cm, do not show any evidence of erosive processes such as high-relief bedding contacts. They are lenticular in shape or extend up to a few meters in sections parallel to the downslope direction. DF tongue-shaped beds may show locally a(l) fabric, with the largest clasts possibly having rolled down in the distal part. The sediment texture has prompted the subdivision of debris-flow deposits into two distinct subfacies: DF1 and...
DF2. DF1 consists of pebble- to fine cobble-sized gravels with a predominantly disordered clast fabric. A number of beds with an $a(p)$ and $a(p)a(i)$ orientation and crude inverse grading occur locally (Figure 2c). Subfacies DF2, on the other hand, is composed of matrix-rich granule to fine pebble clasts (Figure 2c). Based on their distinctive characteristics, the above deposits are ascribed to debris-flow facies characterized by low to moderate viscosity [18]. The thicker and coarser beds (DF1) are thought to have originated from failures of the weathered bedrock from the cliffs overhanging the cave opening, whereas the thinner beds (DF2) result from the mobilization of the upper part of slope-deposit accumulations.

4.3. Waterflow Deposits (WF)

Moderately sorted, sandy to fine pebble- and granule-sized clastic layers, arranged in sheet-like units a few cm thick, are interpreted as deposits resulting from waterflows (sensu [17]). Some isolated sets occur as small scour-and-fill features nearby or between some cobbles and boulders. A number of intervening clastic layers are carbonate-encrusted (Figure 2d) as a result of case-hardening processes.

Further, pale brownish and/or whitish flowstone layers (Figure 2e) are identified in the lowermost part of the succession (Figure 3b), but calcite flowstones also seal the whole sedimentary succession (Figure 3a).

The flow of water is believed to take place as a shallow, unconfined or poorly confined sheet-flow. This process leads to fine fraction winnowing from the upper slope, which, in turn, causes fine sediment to infill the openwork RF from previous depositional events.

4.4. Facies Assemblage

The clastic succession consists of alternating lenticular beds of pebbly to boulder gravel, whose texture varies from matrix-rich to clast-supported, occasionally openwork (Figure 3a). Based on the facies assemblages, four intervals (In) can be recognized (Figure 3c).

The first one (In1), at the base of the succession, is characterized by 1 m thick flowstone deposits that blanket the calcareous bedrock (Figure 3b). Interval 2 (In2) is ~2.5 m in thickness and predominantly composed of massive to crudely stratified, locally amalgamated, high-matrix-content gravels (Table 1). Such deposits result from subaerial debris flows [18–20] with intercalated lenticular beds of immature, clast-supported openwork RF gravels. The overlying 3.5 m thick third interval (In3) shows the dominance of rockfalls, with a number of isolated, outsized limestone boulders. They occur scattered in inclined-bedded debris flow clastic deposits and alternate with rockfall concave-up, tongue-shaped lenses (Figures 2b and 3a). Intervening water flow deposits are subordinate (Figures 2d and 3a). The top of the succession (In4) is sealed over by dm thick calcite flowstones (Figure 3c).

5. Discussion

Based on the main field data, a detailed macroscopic sedimentological analysis was carried out and correlated with the sequences provided by the archeological test pits inside the cave. A characterization of the depositional settings of the Santuario della Madonna cave is proposed, with a focus on the major environmental changes in Late Quaternary rock shelter sedimentation. The studied succession exhibits a dip of 25° toward the main cave room, as determined through field measurements. Close to the wall separating opening n. 3 from the main cave room (Figure 1d), clastic deposits with a N–NW dip are observed in a discontinuous way. Furthermore, following the early exploratory excavations of the 1950s, [1,21] indicate the presence of breccias inclined towards the NW wall of the cave, at the base of clayey deposits. Although the colluvium/bedrock interface can be articulated, by projecting the N–NW measured dip of the colluvium within the main cave room (Figure 4), the top of the studied succession would descend to a depth of 14 m, approximatively 6 m below the upper Paleolithic levels (12.1 ± 0.15 ky) of the excavations carried out by [1,2].
Figure 4. Relationship between clastic deposits close to the eastern cave opening and sequences provided by the archaeological test pits (dashed line separating them) inside the shelter. NW dipping breccia outcrops in a discontinuous way close to the studied section, as well as at the base of clayey deposits according to the 1950s archaeological excavation. Dotted line marks the uncertain colluvium/bedrock interface. Bold letters refer to rockfall events recognized by [1–3]. Radiocarbon dates for the base of archaeological levels are also shown [1,9,15].

Based on the availability of numerous radiocarbon dates for the archaeological stratigraphic units (US) and their thickness [9,15], we calculated depositional rates ranging from 0.67 to 0.75 mm/y for different intervals, with an average of about 0.71 mm/y. Apart from the Early Neolithic, the narrow range and small standard deviation for the computed rates suggest the absence of significant breaks in deposition and erosional events since the Upper Paleolithic. If the average rate of deposition has remained steady over time, we can infer that the stratigraphic contact between the clayey deposits (Figure 4) and the easternmost cave-fill succession may be aged at 20 ky, approximately. Being older than 20 ky, the studied colluvium aligns with the lower clastic infilling of the Romito cave [4], located 12 km eastward of the study shelter (Figure 1b).

The studied deposits are characterized by debris-flow facies, alternating with rockfalls and minor waterflow sediments. Based on the facies assemblages, four intervals have been recognized. Following the basal flowstone layers (In1), interval 2 is dominated by multiple debris-flow deposits and, subordinately, openwork rockfall deposits; this is reversed upward, being that the In3 facies assemblage is composed predominantly of RF, alternating with DF deposits (Figure 3a,c). Several control factors interacting with each other may have influenced cave sedimentation. Although the paleoclimatic significance of clastic sedimentary facies is difficult to detect, colluvial depositional systems can bear important signatures of climatic changes [17]. Debris-flow facies, in isolation, cannot be considered as climatically diagnostic, but the repetitions of debris-flow facies with higher matrix content characterizing facies assemblage of In2 may suggest wet climatic conditions in that the debris flows probably occurred during a period of mild climate [17]. Glacial and Late Glacial climatic events are documented in the continental and marine record of southern Italy ([22] and references therein). According to them, between 25.5 and 18.5 ky BP, high temperatures, similar to those reconstructed for the Holocene, were recorded, even though the sole pollen data indicate the climate became cold and dry from 24 to 19 ky BP [23–25]. The study succession is supposed to be older than 20 ky as inferred from steady depositional rates. In light of the above, it can be assumed that the studied colluvium deposited during the long period of mild climate centered around 25 ky BP. Likewise, close to the sea, [26] argued that even during glacial periods, a persistent availability of moisture areas occurs, thus influencing mechanisms of detritus removal (e.g., [27]). Although, the
alternating of sheetflow sediments to debris flows of the so-called “wet” facies association of [17] are very limited, the presence of ~1 m thick flowstone at the base of the clastic succession (In1, Figure 3b) suggests deposition from poorly confined waterflow under humid conditions and reasonably persistent runoff. The In3 facies assemblage is instead dominated by openwork rockfall deposits alternating with DF, with very subordinate WF (Figure 3a,c). In the nearby Romito cave, [4] recognized major changes in water runoff intensity: after a mild and humid phase with high and persistent runoff about 24 ky BP, a progressive decrease in underground runoff occurred. Such a decrease culminated at about 20 ky BP with a phase of human presence and correlated with drier climatic conditions, recognized for inland areas of Southern Apennines ([4] and references therein). Rather than the drier trend recorded in the inland Romito cave [4], facies assemblage of In3 suggests the deposition in humid conditions characterized by a high seasonality close to the sea [22].

The abrupt formation of extensive flowstone deposits (Figure 3a) at the top of the studied colluvial deposits (In4) indicates a deactivation of the detritus accumulation, marking a change in cave sedimentation processes. Alterations in the hydrological regime of the shelter system can lead to such deactivation of the detritus. In fact, a shift from high-energy water flow to low-energy flow can reduce sediment transport and deposition within the cave, causing the detritus production to decrease. At the same time, low-energy flow conditions promote the precipitation of dissolved minerals, leading to the rapid formation of flowstone deposits on the cave floor and walls. The sharp change in facies assemblage recognized between In3 and In4 may be related to the peculiar setting of the shelter, given that the eastern opening overlaps the Fumarulo cave (Figure 1c). The decrease in coarse sediment supply within the clastic succession may result from the collapse of the cave ceiling which accounted for the shift of the N–NW sediment pathway direction, to a downward trajectory, causing the accumulation of a detrital cone in the Fumarulo cave recognized by [13]. Through a careful review of the late Paleolithic to the Middle Ages archaeological deposits within the Santuario della Madonna cave, a number of rockfalls have been recognized (Figures 4 and 5). Piles of rocks and boulders within the stratigraphic units resulted from cave wall and/or roof collapses. Such events occurred during the Holocene, characterized by a humid climate with high seasonality conditions, as derived from the pedostratigraphic succession within the shelter [5]. Since cave wall/roof collapses occurred in a relatively stable period, this suggests rockfall climate independence.

Although such collapses occur naturally as part of karstic dynamics, they can be triggered by earthquakes. Since the study area is near the seismogenic sources of the Pollino Range [28] and suffered a mean uplift rate of about 0.25 mm/y since the Last Interglacial MIS 5.5 [10], we compared the archeological test pits within the main cave room [1–3] with the paleoseismic data (Figures 4 and 5) in the surrounded Pollino [29,30]. Speleoseismological research carried out in the surrounding area [29,30] provided a timeframe for paleoearthquakes which have affected some cave sites of northern Calabria in the last ~42 ky. In particular, based on cave speleothem tilting and collapsed bedrock ceilings, [30] recognize six speleoseismic events which have actually influenced human activities and landscape evolution. In order to look for the possible role control of earthquakes on sediment successions within the study area, we cross-referenced rockfalls recorded in the archaeological succession (Figure 5) to speleoseismic data [29,30].
Figure 5. Comparison between earthquake-induced rockfalls [1–3] and speleoseismites [29,30] recorded in the study area surroundings. Reference are shown in square brackets. Letters and numbers in bold refer to events recognized by the authors; SMC: Santuario della Madonna cave. Main cold (cyan) and warm (yellow) climate periods mentioned in the text are also shown.

Except for the rockfall F, within age uncertainty, subsequent rockfall E recorded in the Paleolithic level (Figure 4) overlaps with speleoseismites V [30] and II [29] while rockfall D could be correlated to speleoseismite I [29] (Figure 5). Two younger collapses (B, C in Figure 4) characterize the Middle Neolithic and Eneolithic [1–3] and correlate well with the speleoseismite event I (Figure 5). Moreover, a correlation of rockfall C with event “VI” of [30] was observed. We did not find any evidence of correlation of rockfall A with speleoseismic data (Figure 5), but the latter might be correlated with the younger seismicity of the Castrovillari fault system [31].

In the studied clastic succession in Santuario della Madonna cave, In3 facies assemblage, commonly characterized by isolated boulders and scattered outsized debris (Figure 3a), suggests that the occurrence of large ceiling blocks and cave wall collapses. Although karstic collapse cannot be ruled out, we hypothesize that the above rockfalls may be earthquake-induced. In light of the above, In3 facies might be correlated with the event “IV” (Figure 5), recognized from speleoseismite data, notwithstanding the uncertainty in age [30]. In this framework, it is therefore hypothesized that the change in shelter sedimentation processes in the Santuario della Madonna cave was caused by a collapse of the Fumarulo ceiling (Figure 1d) below the studied clastic succession which interrupted...
sediment transport toward the large room. From then on, the Santuario della Madonna cave infilling is characterized by fine-grained sedimentation.

Reliable age dating would significantly contribute to the ability to better constrain cave evolution stages, unravelling the complex role of local and global controls on cave sedimentation.

6. Conclusions

The sedimentological investigation carried out in the Santuario della Madonna cave in southern Italy has yielded significant findings regarding the sedimentary facies associated with a slope-waste deposit. The studied succession is located close to one of the three shelter openings that interface with subaerial environments and lies on the shelter roof overlapping the Fumarulo cave. Slope deposits exhibit an in-cave dipping of 25° and underlie the Late Pleistocene–Holocene archaeological succession. The facies consist of coarse-grained and highly immature layers, with sediment gravity processes being the predominant depositional mechanisms. The colluvial deposits identified in the cave include debris-flow facies alternating with rockfalls from the cave roof and walls, along with minor waterflow sediments. Facies assemblages suggest a change in shelter sedimentation processes over time. Before the deposition of the topmost flowstone, the increase in spall production and large boulders is attributed to cave ceiling collapse. Similar rockfalls occurred during the relatively stable Holocene period as documented in the archaeological succession inside the Santuario della Madonna cave, thus suggesting cave walls and/or roof collapses’ independence from climate change. Since Holocene rockfalls show a good correlation with paleoseismic events, we hypothesize the boulders observed in the clastic succession are cave collapses induced by earthquakes, although we cannot exclude other causes. This study highlights the significance of coarse-grained, slope-waste cave-fill deposits to account for environmental changes affecting rock shelter sedimentation. However, it emphasizes the need for careful consideration in distinguishing between the influences of climatic changes and local factors in shaping the geomorphic evolution of cave environments. It is important to note that these control factors can interact with each other and exhibit complex feedback mechanisms, resulting in intricate patterns of cave sedimentation over time. Additionally, the relative importance of these factors can vary depending on the specific cave system and its regional context.

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