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Geo-archaeology, archaeometry, and history of a seismic-endangered historical site in central Apennines (Italy)

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Abstract

Ancient human settlements accumulate essential historical, archaeological, and geological information. An example is the St. Angel Cave, which preserves a Romanesque church and a complex of lustral tubs in the Eastern Maiella Massif (Central Apennines of Italy). Historical chronicles and archaeological data show that the church dates to the 10th–11th century. The archaeometry applied to the ceramic, coin, and wooden artefacts resulting from the excavation established a chronology of the periods of use and abandonment of the St. Angel Cave. The layering of architectural elements, changes in style, and alterations of the church structure account for two collapses. The first could be related to the poorly known 1209 earthquake. In addition, we describe the damage and changes to the structure and the use of space caused probably by the 1706 and 1933 earthquakes.

Keywords Geo-archaeology, Water-worship, Historical earthquake, Lead-glazed pottery, Abruzzo region, Italy

Introduction

A multidisciplinary approach involving geologists, archaeologists, cultural heritage conservators, and art historians allows a comprehensive investigation of the St. Angel Cave site (Palombaro, Abruzzo Region, Italy). The study of this archaeological site combines the interpretation of ancient pagan and Christian worship, variations of ecclesial properties, and seismic damages, adding new items to archaeoseismic cases history in Italy [1–8]. This study is based on a comprehensive archaeometry analysis of the archaeological findings and the philological study of relevant chronicles. In many cases, chthonic worship linked to the interpretation of natural events reflects geological phenomena. For example, in the Abruzzo region, a series of shrines dedicated to the Italic Hercules and Demeter are associated with active faults [9]. Furthermore, during the Medieval Age, the Chthonic cults syncretise with the cult of Christian saints, St. Agatha (Demeter) and St. Michael (Hercules). This process is documented in St. Angel Cave. In addition, Medieval written sources suggest significant variation in ecclesial territorial authority domains following major seismic events.

The Italian peninsula is among Europe's regions with the highest seismicity and has one of the most complete catalogues of historical earthquakes worldwide [10, 11].

In memory of Danilo Cavaliere (1988–2017), who loved St. Angel Cave so much to die for it.

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Despite this, many ancient earthquakes are not confidently or sufficiently known, and the effects produced are poorly understood. These uncertainties make multidisciplinary studies critical to improving our knowledge of medieval earthquakes [12–16]. St. Angel Cave holds a small Romanesque church and conspicuous evidence of earlier pagan cults. However, it had minor importance as a religious centre and had never been investigated in depth before this study.

Geological setting

St. Angel Cave is located a few kilometres west of the village of Palombaro, 840 m a.s.l. (Lat. 42°7′35.48″ N; Long. 14°11′55.59″ E), on the eastern slope of the Maiella Massif (Fig. 1).

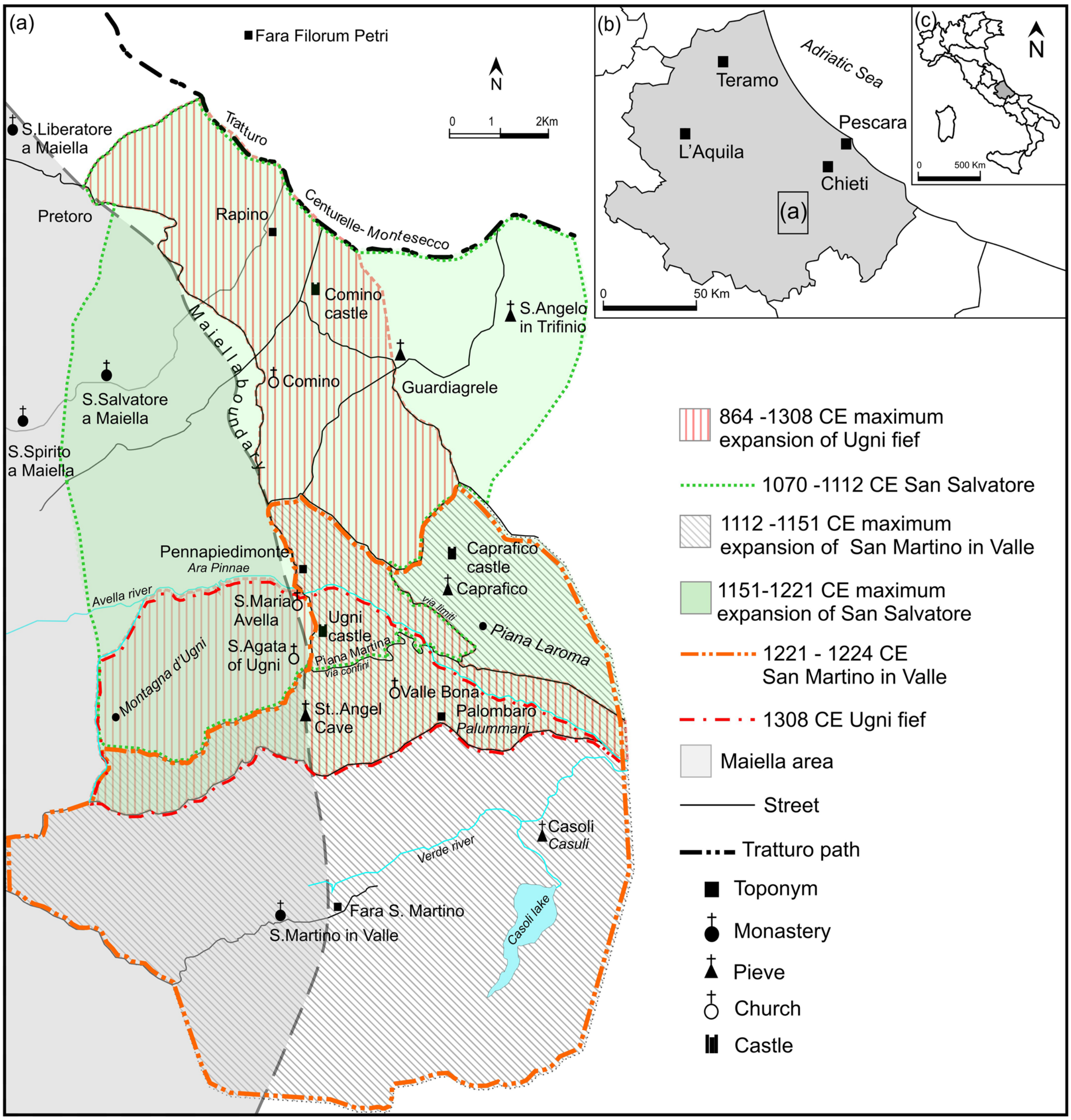

Fig. 1 Location of St. Angel Cave, general geography, main historical monastery domain areas in the late medieval age and fief of Ugni extension; inset (**a**) study area; inset (**b**) Abruzzo Region; inset (**c**) position of Abruzzi Region in Italy. Map modified after [34, 35].

St. Angel Cave is a karst structure that measures ~ 40 × 20 m and is 15 m high. It developed due to the dissolution of Upper Cretaceous carbonate rocks that form most of the Maiella Massif. The cave lies within an east-verging anticline and is crosscut by an E-W-striking strike-slip fault [17, 18]. The age of folding likely dates to the Late Pliocene (Piacenzian 3.5–2.5 My.) [19]. A tectonic discontinuity horizontally intersects the cave with a dip of about 20° towards SW. The hanging wall comprises massive bioclastic grainstones with highly porous medium-coarse grains (Orfento Formation, Upper Maastrichtian—Upper Campanian, 73–67 Ma). The footwall comprises white-beige mudstone-packstone and breccias, dipping 47° towards E-SE. It belongs to the Scaglia Bianca Formation (Cenomanian—Campanian, 100.5–91 Ma). The Orfento's Formation is much more permeable than the Scaglia. It thus hosts underground water that flows into and pours out in the cave's northern section.

The study area falls inside two different seismogenic zones: the Morrone Porrara Fault System (hereinafter MPFS) [20, 21] and the Abruzzo Citeriore Basal Thrust (ACBT) in [21] (Additional file 2: Fig. S1) the first belonging to the extensional domain of the central Apennines and the latter to the compressional seismogenic province of Italy [22–26]. Local seismic events are reported in CPTI15 [10, 11] and CFTI5Med [27]. However, the Italian catalogue can be considered complete only for the destructive earthquakes of the last 500 years [28]. The location of the epicentre and hypocenter is problematic for historical earthquake sequences. Nevertheless, a rough localisation can be deduced from studying the mesoseismic zones [29] included in the macroseismic zone of some significant medieval seismic events with multiple shakes that affected the central-southern Apennines. There are records of damage to buildings and victims in the study area for the earthquakes of 1349 and 1456.

Table 1 reports available information about the historical earthquakes in the area under examination.

The Sulmona area includes the active MPFS, which extends for approximately 45 km and is considered responsible for Pleistocene earthquakes [30, 31] and for an earthquake (M_w 6.5) which occurred in the II century that also produced a landslide that damaged the *Ercole Curino* temple built on the fault itself [9] and for which there is evidence of surface rupture (Table 1) [2, 32]. No later ruptures are known on this fault system. The second area corresponds to the compressional seismogenic structure of the ACBT [21], extending towards the Adriatic coast. ACBT might be considered responsible for destructive historical earthquakes such as the 1706 Maiella earthquake (M_w 6.8, X-XI MCS), the 1881 Orsogna (M_w 5.6, VIII MCS), and the 1933 Pacentro (M_w 6.0, IX MCS) (Table 1) [10, 11, 21, 33].

Table 1 Preliminary information about damaging historical earthquakes $M_w > 5$ and I > VII MCS in the Maiella area.

Main event date	Seismic sequence area	Local maximum macroseismic intensity[a] (M.C.S.)	Estimated M_w	Hypothesised Seismogenic structure in literature	Main references
II century CE	Maiella	IX-X (San Valentino in Abruzzo Citeriore Lat 42.233–Long 13.987)	6.5	MPFS	[11, 36]
1209	Dioceses of Valva and Teathe	IX (Popoli (CPTI15) Lat 42.167–Long 13.075)	6.0	Deep ACBT?	[11]
09-09-1349	Central Southern Apennines	IX (Sulmona Lat. 42.022–Long 13.970)	6.0	(Aquae Iuliae + Gran Sasso) + Sulmona?	[10, 11, 15]
5-12-1456	Central Southern Apennines	X (Tocco da Casauria Lat. 42.18–Long. 13.91)	5.9	Sannio region Bojano Plain Tocco da Casauria	[16]
03-11-1706	Maiella	X-XI (Pacentro Lat. 42.076–Long-14.080)	6.8	Deep ACBT	[10, 21]
10-06-1841	Maiella	VII (Pacentro Lat. 42.076–Long-14.080)	5.0	Deep ACBT?	[10, 11]
10-09-1881	Chieti area	VIII (Orsogna Lat. 42.232–Long. 14.284)	5.6	Shallow ACBT	[10, 21]
12-02-1882	Chieti area	VII (Crecchio Lat. 42.291–Long. 14.347)	5.3	Shallow ACBT	[10, 21]
26-09-1933	Maiella	IX (Pacentro Lat. 42.076–Long-14.080)	6.0	Deep ACBT	[33]

[a] The local maximum macroseismic intensity refers to the study area

Summary of the site history from literature

Very little information about St. Angel Cave has been known so far. The comparative study of chronologically arranged chronicles (chronotaxis S1 in Additional file 1) aims to define domain boundaries, events, and territorial and power shifts within the study territory. In this case, the fiefdom of Ugni encompasses the study area. Historians have focused on the significant upheavals, including earthquakes, that occurred in the fourteenth and fifteenth centuries, such as the 1349 earthquake that damaged the study area [37]. Indirect information about earthquakes can change territorial authority in the political and social background. For example, Gaeta's agreement between Giorgio Castriota Skanderbeg and Ferdinando II d'Aragona allowed for a strong wave of immigration by the Arbërëschë communities to repopulate the devastated areas by the earthquake of 1456 [38].

The toponyms cited in the chronicles are shown in Fig. 1 and concern the ancient Ugni's fief area. Historically the most influential territorial authority having a very long existence is the Ugni's fief. Inside this area are three main ecclesial domains that have changed the most during these years: S. Liberatore a Maiella, S. Salvatore a Maiella and S. Martino in Valle. In addition, more considerable ecclesial non-local powers such as S. Clemente a Casauria and Monte Cassino influenced the study area territory. In the medieval period, the hierarchy of ecclesiastical dominions was divided into monastery, parish and church. Pieve was a little ecclesiastical district concerning the monastery, church, on the other hand, was circumscript to the building and possession of a monastic domain.

Lombard castellum de Ugni is mentioned in the *Memoratorium of the Cassinese* Abbot *Bertario* at the end of the ninth century (see Chronicle 1 in Additional file 1). The first mention of a church of St. Angel near Castro *Laroma* dates to 1064 (see Chronicle 2 in Additional file 1) [39]. The church of St. Angel, located inside a cave, seems to be recognised in a papal document issued in favour of the monastery of *S. Salvatore* of the Maiella by Pope Alexander II (see Chronicle 7 in Additional file 1) [40] confirms the frequent occurrences in the documentation of *S. Salvatore a Maiella* monastery's dedication to St. Angel. Over the years, the definition *ad gruttam* (in the cave) disappears from the papal documentation (see Chronicle 3–4 in Additional file 1), which continues to keep the toponymic indications such as *Ara Pinnae/de Castro Laroma* and mentions a St. Angel church. The church is recorded in 1199 in the legal documentation of Innocent III to Matteo, abbot of *S. Salvatore* a *Maiella (s*ee Chronicle 9 in Additional file 1). St. Angel Cave belonged to the territory of *Laroma*, as mentioned in the *Libellus* of *S. Salvatore a Maiella* in 1064 (see Chronicle 2 in Additional file 1) and again in 1112, in the legal document issued to *S. Martino in Valle* (see Chronicle 5 in Additional file 1). In 1151, the legal documentation issued by Eugene III to *S. Salvatore a Maiella* said, "*Ecclesia S. Angeli et S. Petri de Castro Laroma*." This denomination includes papal legal documentation for 1155, 1175, and 1199 (see Chronicles 6–9 in Additional file 1). The thirteenth century marked a period of strong contention over the assets of San Salvatore between feudal laypeople and other ecclesiastical domains [41]. On the 8th of March 1218, the abbots of S. Clemente, Pope Honorius III, delegated *S. Liberator*e *a Maiella*, and *S. Eufemia* to eradicate the simony practised in the monastery of *S. Salvatore a Maiella* [42] (see Chronicle 10–11 in Additional file 1). The denomination changes again in 1221, in the legal documentation of Honorius III (see Chronicle 11 in Additional file 1), in which the ecclesia St. Angel is placed at *Laroma in Castro Palumbani*. In the 14th century documentation taken from the '*Rationes decimarum'* for 1324-25, an *Ecclesia S. Angeli* is mentioned in *'Ungio' (Ugni Castle* toponym) (see Chronicle 7 in Additional file 1). In the inventory of the assets of *S. Salvatore, a Maiella* of 1365, however, an *ecclesia S. Angeli apud Laroma* is mentioned (see Chronicle 16 in Additional file 1). In the book of tithes, in 1324–1325, a church of St. Angel is listed near the fief of Ugni and in the territory of *Guardiagrele* (see Chronicle 14 in Additional file 1).

The church, referred to in different toponyms, seems to be inserted near *Laroma* when mentioned in the documents concerning *S. Salvatore a Maiella* or near *Casuli or Palummani* (Casoli and Palombaro) when it is said to be among the possessions of *S. Martino in Valle*.

During the 13th–14th century, St. Angel Cave is reported as a *Pieve*. In the Medieval Age, *Pieve* was a minor ecclesiastical district. *S. Salvatore a Maiella* declined between the fifteenth and seventeenth centuries, as described in the '*Acta Visitationis,'* written in the sixteenth and seventeenth centuries. The monastery was suppressed in 1808.

Some authors have hypothesised that the Church of St. Angel was previously dedicated to St. Agatha [43, 44]. In 1070, among the church's dependent on *S. Maria de La Vella* a monastery sited along the Avello river, in the appurtenances of *Pennapiedimonte (Ara Pinnae*) and dependence of the monastery of *S. Salvatore a Maiella* di *Rapino* Ecclesia *Sancte Agathe'* was mentioned. Moreover, there is a church called *St. Agatha d'Ugni,* in the *Castle of Ugni*, now *Piana Martina*, far away from St. Angel. The idea that the St. Angel church is St. Agatha is denied by the *San Salvatore* Inventory of 1365, which names '*St.*

Agatha apud Ungium' when the *'Rationes Decimarum'* mentioned a St. Angel *d'Ugni* [45, 46]. Therefore, we are confident that St. Angel and St. Agatha are different churches.

Data and methods

OPTECH optical microscopy was used to study archaeological samples in thin sections. Phenom XL SEM–EDX electron microscope was used to obtain glaze, minerals, ceramic analyses, and BSE images. Powder XRD analyses were carried out using the diffractometer Bruker D2 PHASER. The acquisition parameters used in the XRD data were Cu-K (1.540598 Å) radiation generated at 30 kV and 15 mA in an exploratory interval between 3 and 70 2θ, 0.1 steps, and a scan rate of 0.15/s. Once the diffractogram was obtained, background subtraction and indexing of peak with semi-quantitative analysis were performed. Mineral identification was performed using Match 3 software. ^{14}C dating was performed at the Beta Analytic laboratories in Miami, USA, calibrated with the High-Probability Density Range (HPD). The calibrated age intervals are calculated at 68% and 95% probability. The conventional radiocarbon age is 110 ± 30 years BP, and the IntCal20 calibration curve is the conventional radiocarbon age vs calendar date.

Archaeology

Excavation stratigraphy

In the St. Angel Cave environment, the sedimentation rate is low. It corresponds to about 1 mm/y, mainly due to the cave's walls and ceiling disaggregation by cryoclastism and erosion. The rest of the deposit consists of debris from collapsed structures, and then the floor was evened out to be flush (Figs. 2, 3 UUSS 166 A-B, 145 A-B).

Fragments of daily use pottery dating back to the 19th–20th century were recovered from the superficial debris layer (Fig. 3, US 137). It is followed by light brown crumbly debris accumulation and sheep droppings (Fig. 3, US 139). A series of small circular hearths have been found in the layer, including charcoal US 139 (UUSS -141, -142, -143, -144). In addition, large tree holes dug into the deposit below preserve the remains of wooden poles partially burned and humified (Fig. 3, UUSS -169, -171, -201). The next layer (Fig. 3, UUSS 145 A-B) comprises irregularly shaped ashlars belonging to the missing northern church wall (Fig. 3, USM 125; Fig. 2, W2). The wall foundation is still recognisable in situ, consisting of the same irregular ashlars used in drystone masonry. After removing the layer of the collapsed wall, a hearth (Fig. 3, US -162) with ovine bone fragments and levelled surface appeared (Fig. 3, US 164). In this layer, a 16th century coin was found. The levelled surface layer (Fig. 3, US 166 B) overlaps the chaotic ashlars of the collapsed wall of the ancient building (US 166; USM 139; Fig. 2, W1C). A thick lead-glazed pottery fragment was discovered within the rubble of US 166 A (Fig. 3). Below this stratigraphy, the bedrock Scaglia Bianca Formation occurs.

The St. Angel Church

The church of St. Angel in Palombaro was initially built on the flat top of a rocky spur (Fig. 2, US 140), constituting the foundation plane found on the Scaglia Bianca Formation. It had a small dimension with the east and north side walls measuring about 6.5×5 m. In contrast, the west side of the church is an irregular cave wall (Fig. 4a). Five stairs on the northern side allowed entry into the church (Fig. 2, UUSS -126, -127, -128, -129). A rectangular grave near the western inside corner of the church measures 2×0.6 m (Fig. 2, US -134; Fig. 4b). It shows a burial excavation with a pillow, the housing for the closing slab.

The church masonry (Fig. 3, USM 132, W1) is characterised by limestone ashlars, which constitute the internal and external walls (Fig. 4b). A mixture of mortar and rock blocks is used between the two walls to fasten them together. This construction technique is visible in the lower part of the church, where the ashlars of the external wall are missing. Four arches in succession decorate the upper part of the frontal *façade* (Fig. 4c). A graffito is scratched on the rock next to the tomb. It is an empowered cross deriving from a Latin and a Greek cross, superimposed with a decussate cross (Fig. 2, US -135; Fig. 4d). Part of the church masonry was thoughtfully remodelled in 13th century style (Fig. 2, USM 139, W1C; Fig. 4e) [37]. Notably, the upper part of the apse and the rest of the walls are made with local stones, incongruent with the decorative style of the rest of the church (Fig. 2, USM 125, W2). With a flared profile, the single lancet window in the centre of the apse has a framework with a spiral motif (Fig. 4e). The upper part of the apse has four arches that present a heterogeneous decoration and ideally follow those present in the previous structure. It seems possible to recognise the remains of vegetable racemes and intertwined wicker ribbons resembling the decoration at the church of *S. Salvatore* and *S. Liberatore a Maiella* [37, 47]. This stage of rebuilding is associated with the enlargement of the church. The walls were rebuilt and enlarged, incorporating the stairs outside the earlier cell. The church attained the final dimensions of 7.5×10 m, adding about 12 m^2 to the earlier floor surface (Fig. 2, P2; Fig. 4f). Only a few portions of the northern walls, pavement base, and part of the eastern wall are preserved. A visitor left the date 1808 engraved just below the lancet window. Local testimonies report that until the 1930s, there was a wooden altar and two niches

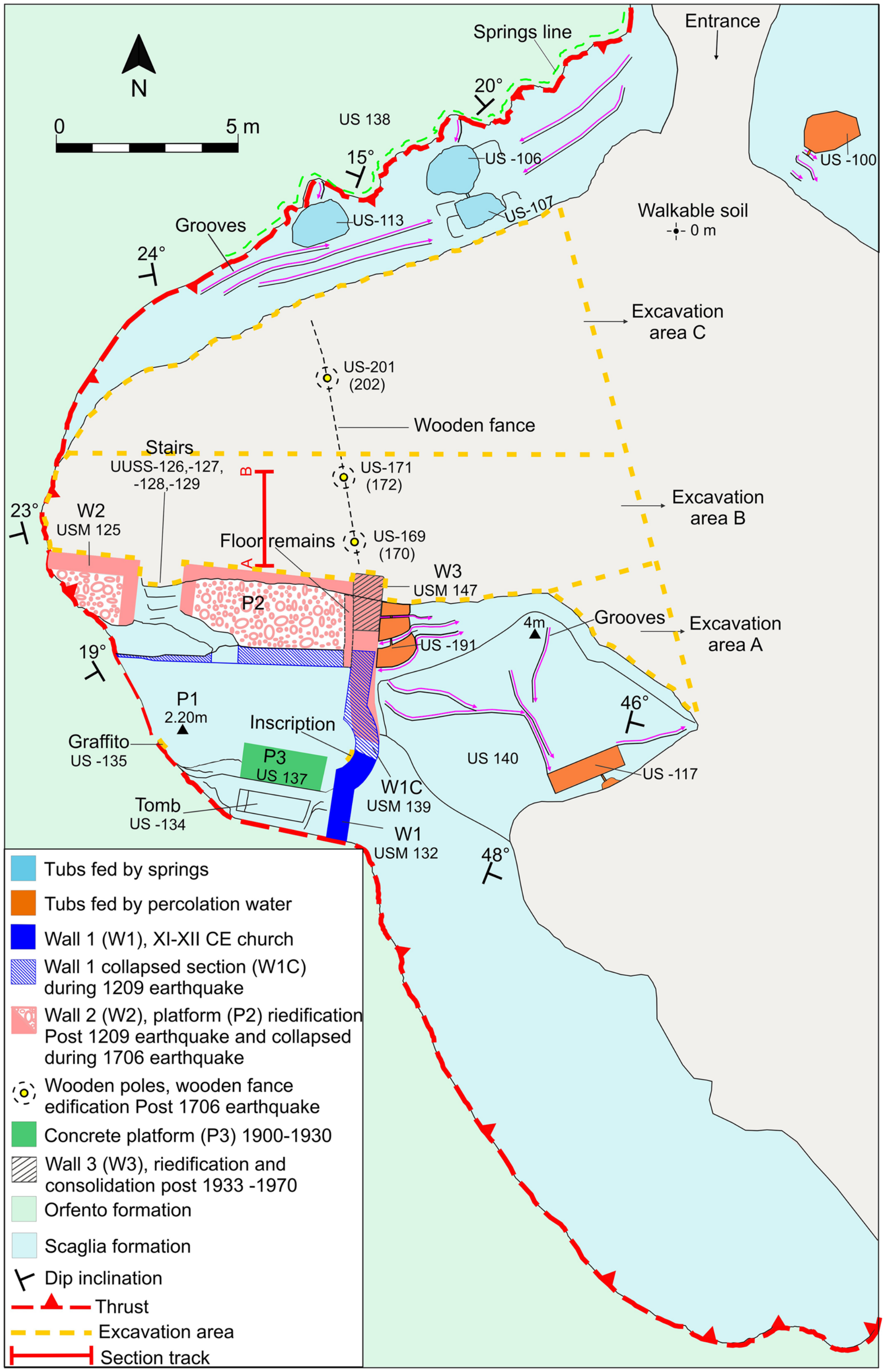

Fig. 2 Planimetry of St. Angel Cave shows the artefacts' location, the various phases of reconstruction of the church of St. Angel, and the main geological features.

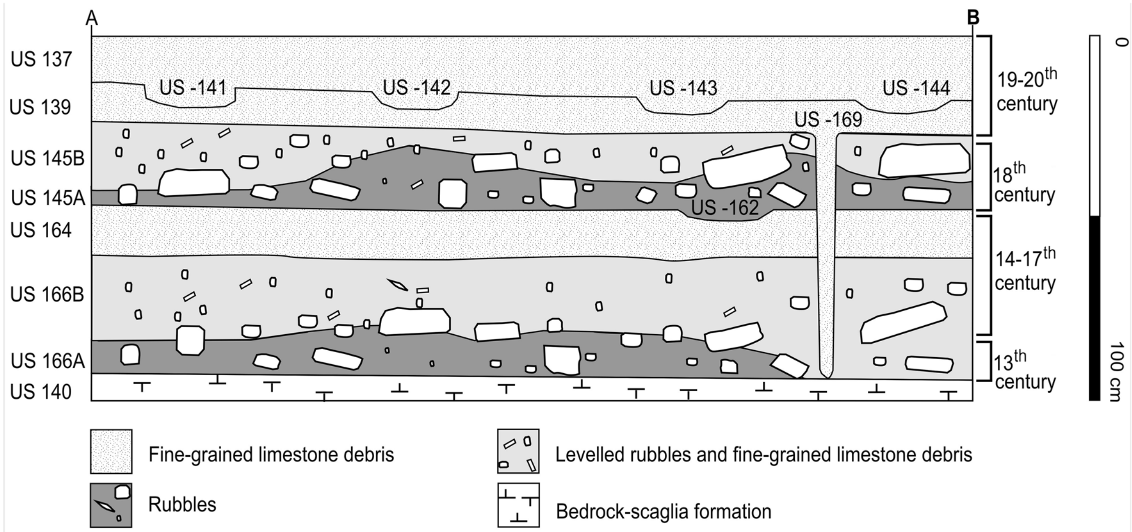

Fig. 3 Sketch section showing the deposit stratigraphy (red section track as in the figure 2).

with statues of saints [44, 48]. Just after that period, following the earthquake in 1933 (according to witness accounts), some consolidation interventions were recognisable (Fig. 2, US 137, P3; Fig. 4b) and were annexed a counterfort (Fig. 2, USM 147, W3; Fig. 4g). Concrete plaster date to the 1970s.

The tubs

Besides the church, another essential feature of the site is tubs excavated in the country rock (US 140), shown in Fig. 2**.** Inside the cave on the N side, close to the cave wall, various sub-rectangular tubs are connected by holes. The tub (US -113) is about 1 × 0.50 m and about 0.40 m deep. The tub (US -106) is approximately 1.50 × 0.50 m and about 0.50 m deep linked tub (US -107). It has a sub-circular shape with a diameter of about 0.70 m and a depth of about 0.50 m. These tubs have a complex structure and are well refined by chisel. Tubs have lateral shelves to accommodate some mobile coverage. The tubs were fed by spring water (Figs. 2, 4h). Two parallel horizontal steps follow the cave wall's curved gait a few meters on the left. They seem to drive the water from the tubs through handmade grooves (Figs. 2, 4g, h). The church wall crosscuts this tub earlier than the church (Fig. 2, US -191, Fig. 4g).

Other tubs in the cave are not directly fed by springs but collect percolating water. Near the area's modern access is an irregular tub 1.5 m × 0.6 m (Fig. 2, US -100). Finally, a tub of regular rectangular shape 2 × 0.8 m (Fig. 2, US -117) is excavated at the base of the rock spur in the middle of the cave. Many handmade grooves feed it on the slide of the spur that converges toward the tub.

Archaeometry

Early medieval age lead-glazed pottery

The oldest finding is a single fragment of thick lead-glazed pottery (Additional file 2: Fig. S3) in layer US 166 B**.** The ceramic body is clay-based (illite) and light grey. The groundmass is glassy micro vesiculated, and plastically arranged (Fig. 5a, b, c). Coarser components are scarce millimetric rounded clast of quartz-arenite. The inside of the ceramic body shows wheel-throwing traces and pink pastel colours. The pink colour extends inside the ceramic body for 0.4 mm and is not present below the glazed surface. The oxidation is due to contact with oxygen during the heating of the ceramic body. The thick lead glaze is homogeneous, coating the ceramic body's surface. It is light-brown olive-green, spotted with darker stains and strips (decoration) with an orange peel-like aspect. It shows brush streaks and minute vesiculation (Fig. 5a, b, c). The glaze is homogenous in composition, 0.1–0.2 mm thick, with PbO 71.9 to 68.9 wt%, SiO_2 19.5 to 17.9 wt%, Al_2O_3 5.79 and 5.32 wt%, K_2O 1.90 to 1.38 wt% and FeO 1.52 to 1.58 wt%. There are also traces of As, Ti, and Mg (Fig. 5d, e, f, g, h)**.** An increase of Si, Al, Ca, and K vs lead decrease suggests contamination with the ceramic clay during the glaze melting. According to the Pb/Si ratio, vitrification of the glaze would be > 725 °C [49]. According to chemical analysis, the BSE mapping images at Scanning Electron Microscope show the presence of silica throughout the ceramic mixture. At the same time, there is a significant amount of Pb in the glaze.

Comparing glaze chemistry and ceramic body mineralogy with those in the bibliography, their composition allows distinction in age and provenance (Additional

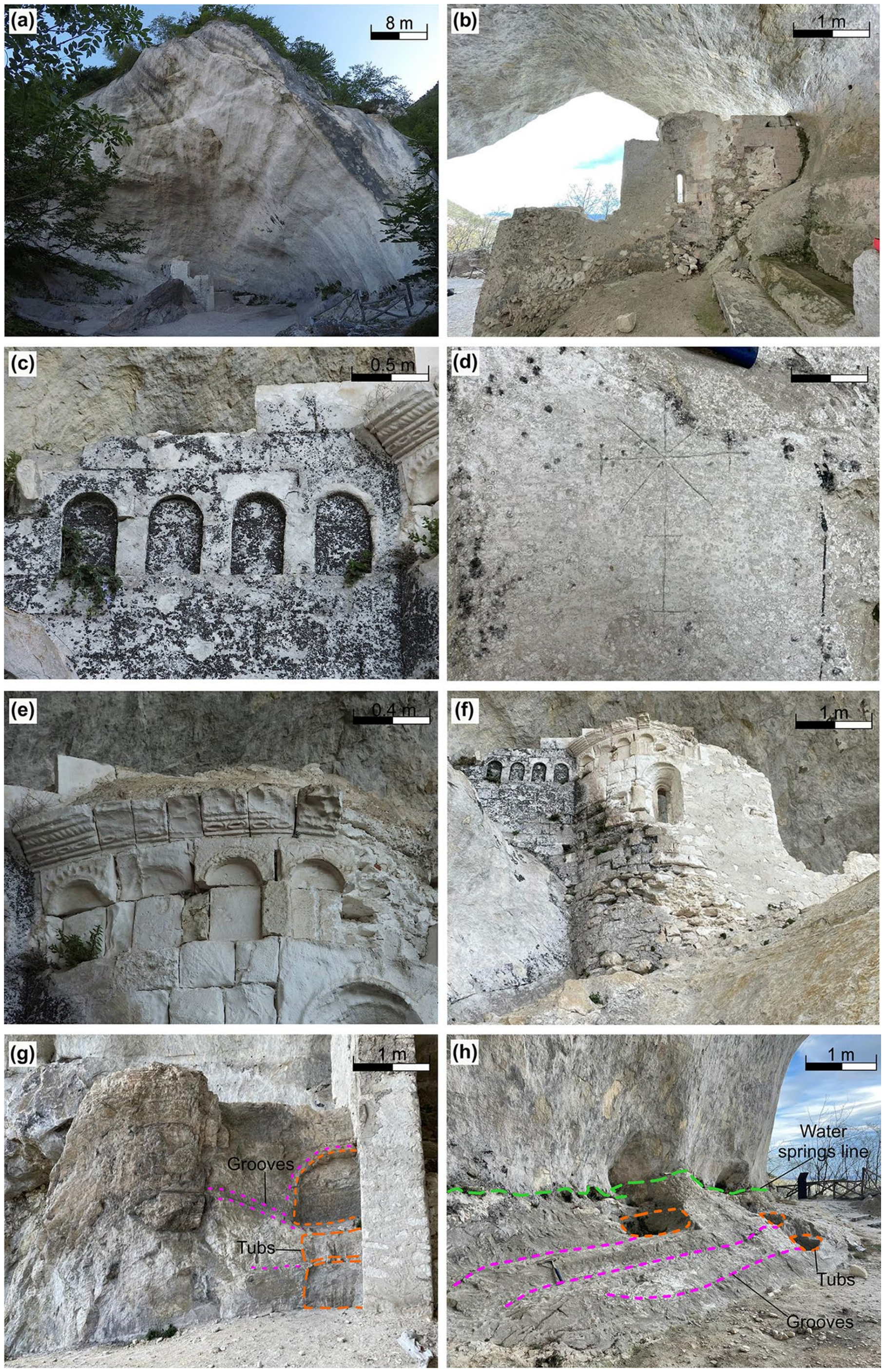

Fig. 4 **a** general view of St. Angel Cave showing an east-verging fold. The church remains in the bottom centre of the picture; **b** inside St. Angel church. Lombard tomb is visible at the bottom right corner; **c** decorative arches belonging to the 10th–11th century; **d** Christogram; **e** details of the decorative arches of the thirteenth century; **f** general view of the Eastern side of St. Angel church remains; **g** rock spur showing handmade groove to collect water percolation tubs (orange and pink dotted line) crosscut by the church wall on the right. North is shown in Figs. 2, 7. **h** details of the tectonic discontinuity (top of the hammer) dipping 20° toward NNE. The karstic holes corresponding to the water spring line (green dotted line) settled on the tectonic contact. Some water tubs are visible below the tectonic contact (orange dotted line) where grooves converge (pink dotted line).

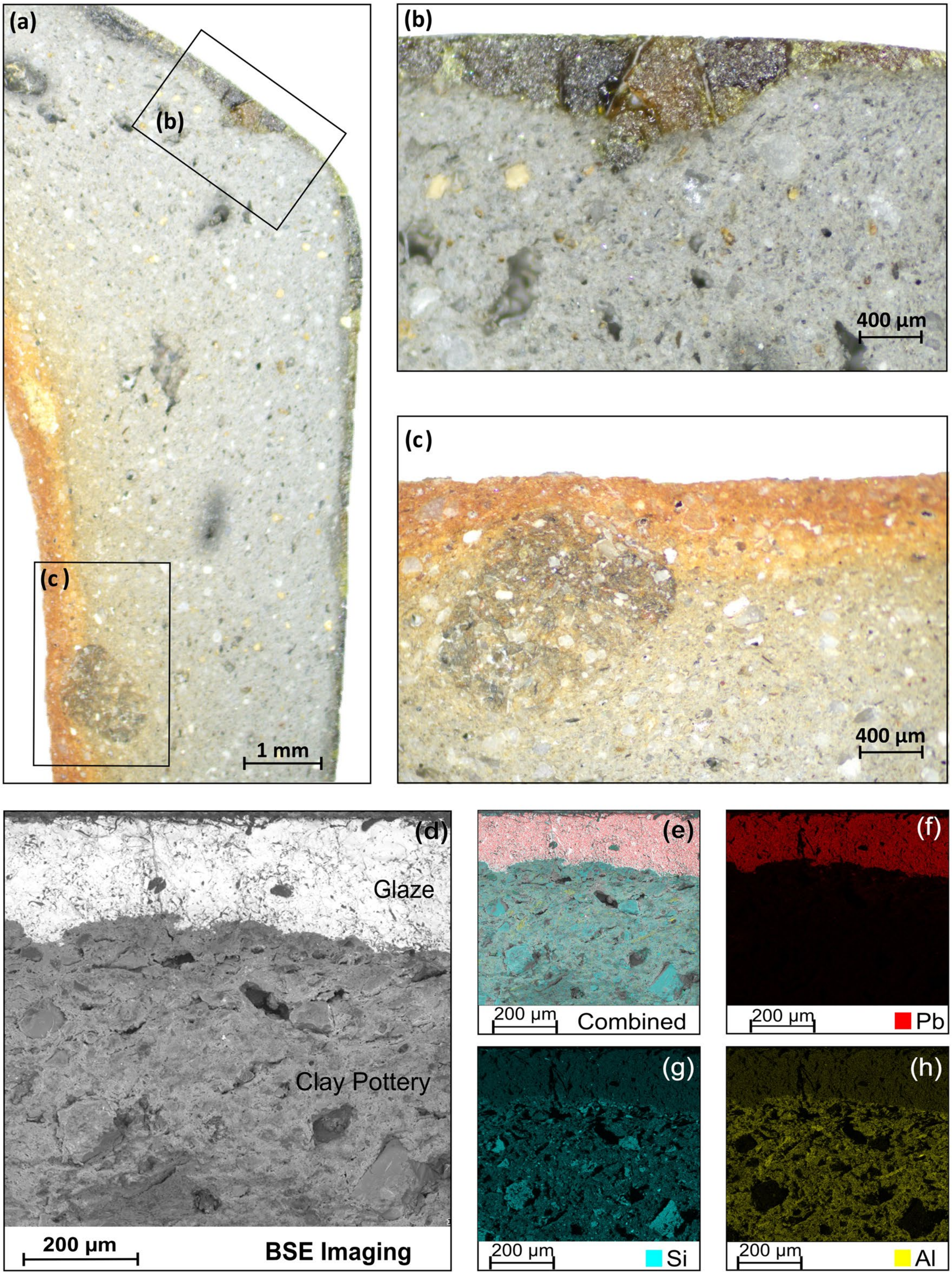

Fig. 5 Reflection light microscope polished section of 9th-century lead-glazed Pottery. **a** general view of the section showing the convex bottom of the pottery. The dark vugs are remains of charcoal; inset **b** detail of the external margin. Note the irregular thickness of the glaze due to the penetration into the ceramic mixture when it was still plastic; inset **c** detail of the inner margin of the pottery showing rounded quartzite clast, white feldspar cleavage fragments, and grey quartz fragments. The orange colour suggests oxidation dues to the contact with oxygen during the ceramic firing; **d** grayscale BSE. Image mapping (SEM-EDAX) shows the different chemical composition of the Pottery is marked by white lead glaze and grey vesicular clay pottery with Christal's of quartz and K-feldspar; **e** combined elements distribution in false colours of investigation area of the sample; Pb (**f**), Si (**g**), Al (**h**) distribution in the sample.

file 2: Table S3). The red line (Fig. 6) is the trend of the database samples from the richest glaze to the least in PbO, which is a generalisation for ceramic glazes. Thick Pb-glazed pottery is typical of the 9^{th}–11^{th} centuries [50].

In the pink area were the samples of glaze richer in PbO, which coincide with the early medieval period (high-lead glaze), where glazes are transparent [51]. From the Medieval Ages to the Renaissance in the Abruzzo region pottery production, there was a progressive decrease in the wt% of PbO in the glaze, up to a composition of approximately 50 wt% of SiO_2 and PbO, with traces of Al, Na, Mg, K, Ca, and Fe oxides (silicate-lead glazed pottery). In the fifteenth century, adding Sn to the glazes marked the passage to proto-majolica and majolica in the Abruzzo region [52]. The Modern Age differs from the ancient productions for the use below 40 wt% of PbO represented in the yellow area (silicate-alkaline glaze). That of St. Angel is typical of ancient productions of northern Italy (e.g., Nogara, VR) [53] and different from those of Orvieto in central Italy, which have a Pb less rich composition (Additional file 2: Table S3).

Olive tree wood

The remains of semi-carbonised olive poles were found in the holes shown in Figs. 2, 3 (UUSS -169, -171, -201), as already described in the archaeological paragraph. It was possible to recover the core of one pole to be dated through AMS analysis. Dating was performed on a small fragment of wood (weight ~ 100 mg) that did not present any macroscopic contamination after a cleaning treatment. The sample of wood was processed at first with combustion and graphitisation phases and secondary with a chemical procedure. Measurement results are shown in supplementary materials. Age is expressed in pMC and years BP and results from the weighted average of the two measured fractions. The calibrated age intervals are calculated at 68% and 95% probability [54]. The conventional radiocarbon age is 110 ± 30 years BP measured for the wooden fragment. After calibrating the conventional radiocarbon age measurement result, the wood origin was set to date back to 1754–1938 cal. AD with a probability of 95% (see Additional files 2 and 3; S4).

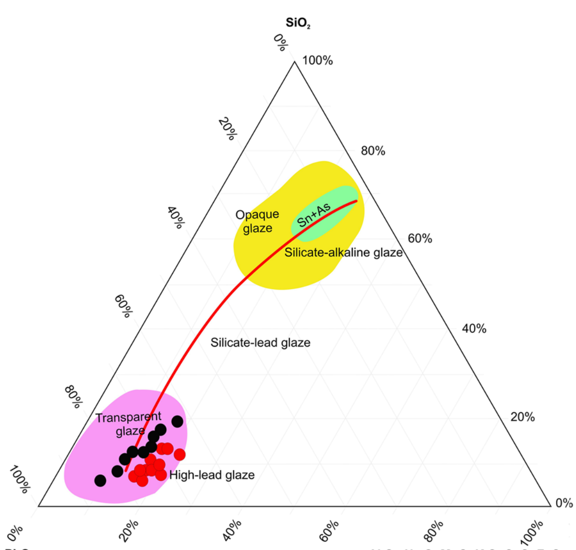

Fig. 6 Ternary plot diagram of SiO_2 vs PbO vs $Al_2O_3 + Na_2O + MgO + K_2O + CaO + FeO$ of the glaze composition from different localities compared with St. Angel Cave glazes. Pottery. St. Angel Cave's 9^{th} pottery (red circles); Nogara's 9^{th} pottery (black circles) [53].

Sixteenth century Coin

A coin of 0.62 gr with a diameter of 15 mm was found during the excavation in layer US 164. An optical microscope analysed it for further investigation. It comes from the Tuscan area, particularly from the city of Florence. The recto has a sign · FLOR ENTIA · with a Florentia lily. On the verso of the coin, there is · S · IOAN NES · B · the mint: shield with a central strip with three half-moons, "G;" there is also a figure of the saint. Therefore, it is possible to attribute the coin's value to the denomination of *Nominal Quattrino* coined in 1512 (Additional file 2: Fig. S5). Also, a chemical analysis of the coin is reported in supplementary materials.

Late nineteenth century glazed pottery

Abundant ceramic fragments refer to open and closed shapes in US 137 layer (Fig. 2). They are internally decorated open-shape and externally glazed decorated closed-shape dating to the end of the nineteenth century and the first decades of the twentieth century. Dishes and minor pitchers are painted green and brown with phytomorphic decorations on an ivory-coloured background. 19^{th}–20^{th} century decorated ceramic has a colourless transparent glaze. This pottery was probably produced by local production centres, such as Orsogna and Lanciano (Troiano D. *personal communication*).

Discussions of the event chronology

Stage A (Italic-Roman age)

The territory of Palombaro has been frequented since the pre-Roman period. It shows traces of settlements dating back to the fifth century BCE [55]. A St. Angel Cave feature that could tentatively belong to this period is the series of tubs associated with the water-worship Chthonic cult. The tubs and associated structures inside the cave make up a complex system allowing water to be collected and flow in small channels and stairs. This type of arrangement makes us guess about water worship. Water used in rites differs entirely from water worship in which it is worshipped. Therefore, we meant water worship and not water used in worship. The water's sinuous flow mimics the snake movement, considered in the Abruzzi mythology to symbolise underground movements, particularly telluric phenomena such as earthquakes. The serpent is an attribute of chthonic deities. However, local legends say women might have wet their breasts to improve lactation [48]. St. Agatha is an Early-Mediaeval age cult and thus syncretises with the previous water worship linked to the Demetra cult. Thus, a water-worship turned into a rite using water.

Stage B (early Medieval age)

The Lombard expansion, between the late sixth and seventh centuries, is accompanied by the spread of the cult of the Archangel Michael. Regarding the church, the presence of a tomb is notable (Fig. 2, US -134). The tomb preserves a style that may resemble the late Roman Age (5^{th}–6^{th} century), although it was still used during the Lombard age (6^{th}–8^{th} century). Therefore, it seems reasonable that the tomb has some connection with the church construction. The tomb could belong to an important personage of the *Ugni's* fief or some local Saint related to the church. This process is confirmed elsewhere by the late construction of the Sant' Agathe and Sant' Onofrio churches that incorporate a funerary area and previous uses, remarkably like those at St. Angel [57]. Another artefact that gives us a clue to the date of the church is the Latin-Greek cross graffito (Fig. 2, US -135). This symbol is reminiscent of the coats of arms of the orders of chivalry and is also common in Lombard coinage. In addition, the X-shaped cross *(crux decussata*) was added, so it is the union of two symbols representing a Christogram. Another constraint of the church building is the fragment of thick lead-glazed pottery datable in the ninth century. The first mention of the church dates from 1064. Therefore, we deduced that the church's foundation dates from the ninth and eleventh centuries.

The production of thick glazed groundmass ceramics is typical of the 9^{th}–11^{th} century. Comparing the compositional data of the glaze and groundmass, it can be seen that there is a geological component of crystalline basement in the groundmass ceramics, which is not present in Abruzzo. In particular, the composition confirms an affinity with the Nogara ceramic body's minerals and the Adige Valley's geological environment [53]. Furthermore, that of St. Angel is typical of ancient productions of northern Italy (e.g., Nogara, VR) [53] and different from that in central Italy, which has a different mineralogical composition.

The first mention of the church dates from 1064. Therefore, we deduced that the church's foundation dates from the ninth and eleventh centuries.

Stage C (11^{th}–16^{th} century)

After examining the items that suggest some information about the church foundation, the following notable feature is a collapse of 3/4 of the church, mainly the northern wall, including part of the apse, and all the eastern wall (Fig. 3, US 166 A). The collapse resulted from a lateral wall failure towards the cave's western limit (Fig. 7a). Concerning the possible age of the collapse, we have just one coeval chronicle, which describes an earthquake of destructive intensity in the dioceses of Sulmona and Chieti. The chronicle referred to the 1209 earthquake, a typical example of a poorly known late middle-age earthquake [27, 57]. The primary source of information about this earthquake is the coeval' *Annales Casinenses*' (the year 1000–1212), which tells us that a '*Terre motus magni per loca in Valvis at Tetee province Samni munitions diruuntur, plura edificia et castella.*' The Chronicle reports that the earthquake destroyed many fortresses and castles in *Valva* (Sulmona) and *Theate* (Chieti) *dioceses* that correspond to a vast area where our site also falls. The authoritativeness of the source allows us to believe that the chronicle attests to a strong, destructive event. At the same time, the Monastery of *San Liberatore a Majella* was restored in the late 13^{th} century style and may have been restored after this earthquake.

Other earthquakes that affected the area were those of 1349 and 1456. However, the decorative style of reconstruction of the St. Angel church likely belongs to the 12^{th}–13^{th} century. Therefore, according to this hypothesis, it cannot be correlated to a 14^{th}-century or later earthquake. In addition, a kind of indirect evidence which supports a destructive event during the first two decades of 1200 is the chronicle of the 1224 sources (see Chronicle 12 in the Additional file 1). It is well known that the destruction of critical monastic buildings and centres of power can displace and produce a reorganisation of the territory or ecclesiastical appurtenances, as reported by the Chronicle of 1224. Therefore, the urgency of finding funds for extensive reconstruction and restoring control over the territory due to an extreme event would fit quite well with the occurrence of an earthquake. We are aware that there is no direct dating of this collapse, but considering the political and territorial variations deduced from the chronicles and the presence of stratigraphy testifying to a prolonged period of use after the collapse, makes us infer that the event is ancient and predates, for a long interval of time, the coinage found on top of it (Fig. 3).

Stage D (16^{th}–8^{th} century)

After the 1209 collapse, the church underwent considerable changes: the east and north walls were rebuilt with different techniques and styles (Fig. 7b). The church was frequented and generated income, so disputes arose

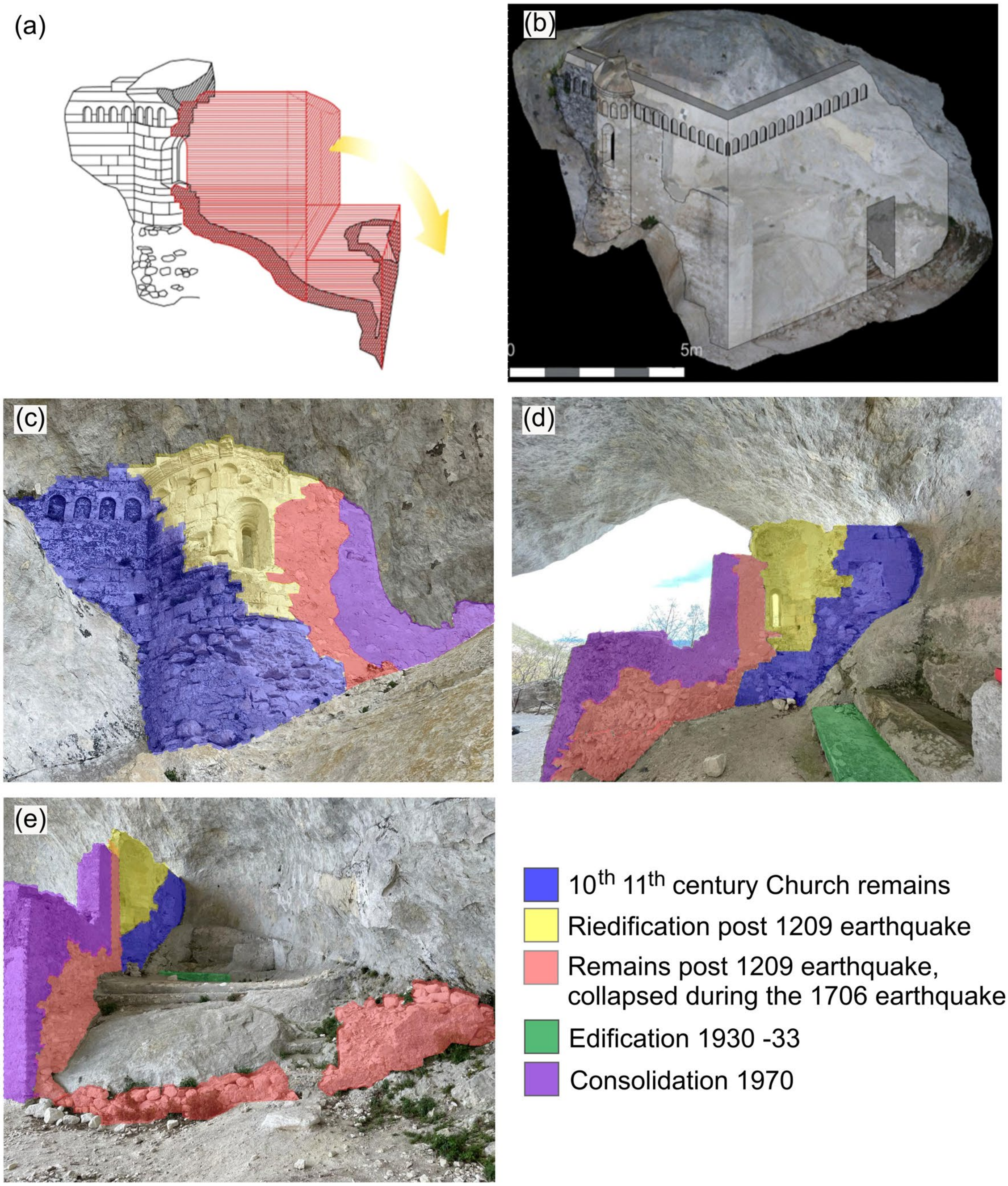

Fig. 7 Stratigraphy of church structure. **a** Collapse dynamic of the tenth-eleventh century church during the 1209 earthquake; **b** 3D reconstruction of the church after the 1209 earthquake and before the 1706 and 1933 earthquakes; **c**–**e** present-day East facade, internal side, and internal prospect, respectively.

between S. Liberatore a Maiella and San Salvatore. Tithes may have been paid to restore and maintain ownership of the church building. Only small hearths and levels of animal droppings are preserved from this period, attesting to the use of the area as a pastoral shelter (Fig. 3, US 164).

During this period, the only datable object was a coin minted in 1512. The *'Acta Visitationis,'* written in the sixteenth and seventeenth centuries, describes a state of severe neglect and decline of the S. Salvatore monastery and its landed property. The coin established a term ante quem the 1706 collapse, excluding thus the 1348 and 1456 earthquakes. After these earthquakes, there was only one destructive earthquake in the Maiella area, the 1706 earthquake, according to [57], which produced significant damage in the area. It is well documented in [10] with intensity IX-X near Palombaro. For this reason, it is the most likely hypothesis that this earthquake is the cause of the subsequent collapse of the church.

The 1706 event is constrained by the 16th century coin, followed by an archaeological layer showing a lengthy period of sporadic frequentation before the collapse. After the 1706 collapse, we could place the wooden fence construction, with the hosting holes excavated into the rubble. The holes extend the path of the east wall and the apse, delimiting an internal space of the church. However, the stratigraphic position of wooden poles and the ^{14}C data (1754–1938) suggest the pole was placed in the late 18th early twentieth century. The edification of the wooden structures may correspond to the abandonment phase resulting in the ecclesiastical property expropriation on the 22nd of June 1805, with the Napoleonic laws. These suppressed and confiscated ecclesiastical property, issued by *"establishments, guilds, congregations, communities and ecclesiastical associations of any nature and denomination."* However, an inscription in the inner part of the church bears the date 1808, when the church was still frequented by shepherds that used the cave as a refuge. Thus, the edification of a wooden fence was necessary for separating the church from the rest of the cave to allow pastoral use.

Stage E (19th century)

In 1900 there was a contemporary use of the site, both pastoral and religious. A rich archaeological documentation of local pottery sherds from fire and daily use dated to style and chemical composition in the early 1900s. The church has undergone some restoration and consolidation works. We have a reminiscence of the presence of votive statues and a wooden altar. In addition, there are oral testimonies related to female water-popular cults similar to those dedicated to St. Agatha. In the attempt to repair the remains of the church, a counterfort and some rough concrete reinforcements were employed following the 1933 earthquake (M_w 5.9, intensity VII-VIII in Palombaro) [27, 33], whose damage is apparent by cracks healed with concrete (Fig. 7c, d, e). After the 1933 earthquake, the church lost the altar and two statues of saints. Finally, the church was roughly consolidated in the 1970s [44, 48].

Conclusions

St. Angel Cave formed within an Upper Pliocene anticline in the Pleistocene, when fluvial erosion and karst phenomena modelled the site. The difference in permeability at the contact between Orfento Formation and the Scaglia Bianca Formation generated a line of springs. Water from local springs flowed into a complex system of tubs and carved grooves that conducted the water along specific paths. This structure suggests that the tubs had a religious rather than practical use. The tubs do not seem related to the church and precede it. Previous authors had assigned the time of the foundation of the church of St. Angel to the 12th–13th century. However, based on the archaeometry evidence in this study, the date can be shifted between the 9th–11th century. Based on the chronicles, we exclude a commitment to St. Agatha, a different church in the *Ugni Castle*. The St. Angel church, referred to in different toponyms, seems to be inserted near *Laroma* when mentioned in the documents concerning *S. Salvatore a Majella* or near *Casulii* or *Palummani* (Palombaro) when it is said among the possessions of S. Martino in Valle. The cross-study of chronicles and archaeological data indicates that the church was dedicated to St. Michael Arcangel. In the cave, a cult of water is linked to a chthonic deity like Hercules. However, the memory of a female lustral rite has been preserved in the popular oral tradition and predates the church.

The archaeometry data applied to the ceramic, coin, and wooden artefacts resulting from the archaeological excavation allowed the setting events of use and abandonment of the St. Angel Cave. Our results provide new data which could improve the knowledge of seismic hazards on the eastern side of the Maiella. The precise layering of architectural elements, changes in style, and conformation of the church indicate at least two phases of collapse. More notable and essential are the possible effects of the little-known 1209 earthquake. In addition, the damage and changes in use caused by the 1706 and 1933 earthquakes are also apparent. Chronological constraints come from the direct or indirect dating of archaeological materials and layers. The first collapse must have occurred between the eleventh and thirteenth centuries, making the 1209 earthquake the only reliable candidate. The extended period of use of the cave, which corresponds to various occupation events, dated precisely by a 16th century coin, predates the second collapse. In turn, the post-quem term of the 1706 collapse is given by the radiocarbon age of olive poles driven inside holes drilled in the earthquake rubble, thus clearly postdating these. Finally, damage from the 1933 earthquake is still clearly visible in the form of fractures healed with modern concrete and the erection of a coeval buttress.

Abbreviations

MPFS	Morrone-Porrara fault system
MCS	Mercalli Cancani Sieberg Intensity scale
ACBT	Abruzzo Citeriore Basal Thrust
UUSS	Stratigraphical units
USM	Masonry stratigraphic unit

US	Stratigraphical unit
HPD	Probability Density Range
XRD	X-ray Diffraction
SEM–EDX	Scanning Electron Microscopy–Energy-dispersive X-ray spectroscopy

Supplementary Information

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Additional file 1. Chronicles concerning the study area.

Additional file 2. Geological, archaeological and archaeometrical information, tables and samples figures.

Additional file 3. Radiocarbon dating certificate.

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Author contributions

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Availability of data and materials

The investigated materials are available, stored, and preserved in the archaeotheque of the C.A.A.M.-Centro di Ateneo di Archeometria e Microanalisi and DATA-U. D'A analytical high-tech Laboratory. Data of own property are available for sharing in the text or supplementary materials (Additional files 1, 2, and 3).

Declarations

Competing interests

The authors declare they do not have any competing interests.

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