



Uncovering the traces of unknown earthquakes at Segesta (NW Sicily, Italy): insights from multidisciplinary investigations

Carla Bottari¹ · Pierfrancesco Burrato² · Patrizia Capizzi³ ·
Raffaele Martorana³ · Mauro Lo Brutto⁴ · Antonino Maltese⁴ ·
Gino Dardanelli⁴ · Alessandro Canzoneri³ · Alessandra Carollo³ ·
Luigi Ferranti^{5,2}

Received: 8 November 2024 / Accepted: 13 August 2025
© The Author(s) 2025

Abstract

The transformation of Segesta, from the Hellenistic period (sixth century BCE) to the early Middle Ages (fifth–sixth century CE), has been extensively studied by archaeologists and historians. While social and political changes were the main drivers of urban evolution, practices such as abandonment, spoliation, and building transformations increased buildings' structural vulnerability, making them more prone to seismic damage. Although historical sources from the Roman period do not mention any earthquakes affecting Segesta, recent archaeological investigations have revealed collapsed layers in the Agora and Mango Sanctuary, and structural deformations in the Theater and Doric Temple. Furthermore, architectural analysis indicates the use of anti-seismic construction techniques in at least two structures on the site. Through multidisciplinary archaeoseismological investigations, this study aims to: (i) provide evidence of past earthquakes based on recent excavations literature review, and on-site observations; (ii) explain, through local site-effects, the selective collapse observed in the Agora and Mango Sanctuary, as well as the deformations at the Theater and Doric Temple; and (iii) analyze the seismotectonic framework of the potential seismic sources. To achieve these objectives, the study combines architectural damage surveys, stratigraphic analysis, drone-based photogrammetry, and non-invasive geophysical prospection (HVSr and MASW). This integrated approach enables a quantitative reconstruction of the local seismic response and deformation patterns across the site, while supporting a replicable framework for investigating ancient seismicity in similarly complex archaeological landscapes. These findings highlight a previously unrecognized gap in the seismic history of this low tectonic strain rate region, pointing to the occurrence of significant past earthquakes that are absent from historical records and current seismic catalogs—which, for this area, list only the 1968 Belice Valley sequence. Therefore, this study contributes essential input data for refining the seismic hazard and enhances our understanding of the historical seismicity and regional seismic risk.

Extended author information available on the last page of the article

Keywords Archaeoseismology · Historical seismicity · Local site effects · Cultural heritage preservation · Seismic hazard assessment · Segesta · North-Western Sicily

1 Introduction

The study of archaeological remains is invaluable in understanding past natural disasters, particularly those poorly documented by historical sources. Archaeoseismology, which analyzes seismic effects on ancient structures, has advanced our knowledge through interdisciplinary approaches that integrate archaeological, geological and geophysical data (Bottari et al. 2024). This study focuses on Segesta, an ancient city in north-western Sicily, with the aim of uncovering previously unrecorded seismic activity through archaeological and geophysical investigations (Fig. 1a, b). The main objectives are to clarify the evidence emerging from recent excavations, assess local site effects, and contextualize the observed damage within the seismotectonic framework of the responsible seismic sources. A quantitative approach is adopted to document and analyze deformation evidence (Hinzen et al. 2011).

Ancient archaeological sites are critical for understanding past natural catastrophes, particularly in regions with millennial recurrence intervals and limited historical records. Such knowledge is essential for the development of robust seismic hazard assessments. Archaeoseismology specifically focuses on the "seismic effects on ancient structures, detected through archaeological reports and excavation data". The relevance of this discipline has long been recognized, with early studies documenting earthquake-related damage in ancient sites (Lanciani 1918). Even qualitative historical descriptions of seismic damage can be integrated into modern seismotectonic analysis, complementing geological, archaeological, and geophysical datasets.

Analyzing damage in ancient buildings caused by historical earthquakes requires a precise reconstruction of their damage history—including causes, sequence, and dating—which can be achieved through integrated archaeological and historical approaches (Karcz and Kafri 1978; Stiros 1996; Galadini et al. 2006). Key archaeological indicators for this practice include the sudden structural collapses, restoration or reconstruction activities, and periods of abandonment. Chronological constraints are typically derived from datable materials found in archaeological stratigraphy.

This contribution investigates the possible seismic origin of the structural damage observed in the archeological site of Segesta (north-western Sicily, Italy). Archaeological excavations have revealed evidence of directional collapses, widespread destruction in buildings of the site (e.g. in the Agora, Doric Temple and Mango Sanctuary), and temporary abandonment of large parts of the site—possibly triggered by earthquakes or landslides. There are also signs of later reconstruction efforts. Evidence of ancient earthquakes at Segesta relates to multiple archaeoseismological perspectives: enriching the understanding of Roman-period seismicity, identifying local amplification phenomena that intensified ground shaking, and providing a historical framework for conservation strategies.

To investigate damage patterns and possible earthquake effects across the site, a multi-disciplinary field campaign was conducted in two stages: the first, in autumn 2022, focused on the acquisition of geophysical (HVSr and MASW) and architectural data; the second, in summer 2023, aimed to refine and expand the dataset through additional HVSr measurements and drone-based topographic surveys. The methodology combined architectural

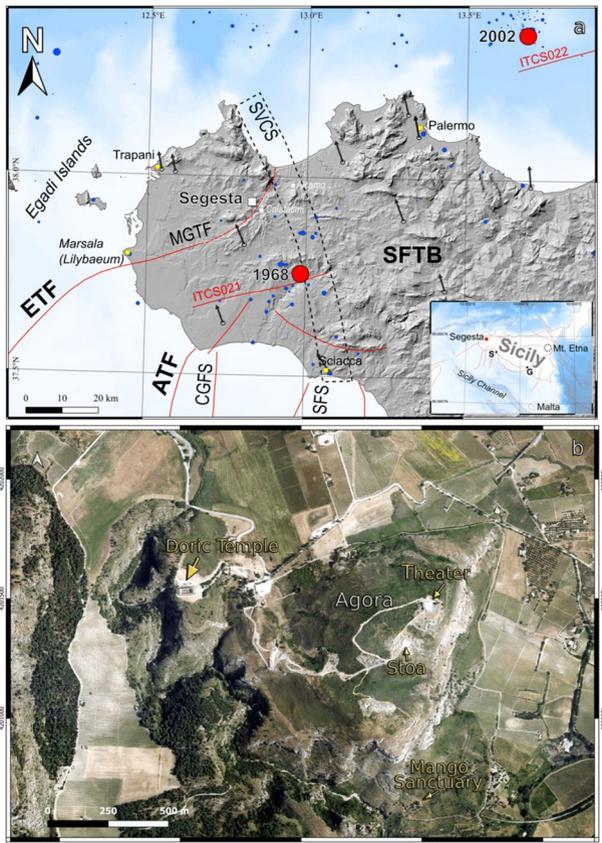


Fig. 1 a Seismotectonic map of western Sicily, showing the main tectonic structures of the region, including fault traces, instrumental seismicity ($M > 3.5$) from the INGV CPTI15 database (Rovida et al. 2020, 2022), and GPS data from Devoti et al. (2017). Fault traces have been modified from the INGV DISS database (DISS Working Group 2025). The epicenters of the 1968 Belice Valley earthquake (M_w 6.4, CPTI15, Rovida et al. 2020, 2022) and the 2002 Southern Tyrrhenian earthquake (M_w 5.9) are highlighted with large red circles. Key fault systems include the Adventure Thrust Front (ATF), Capo Granitola Fault System (CGFS), Egadi Thrust Front (ETF), Montagna Grande Thrust Fault (MGTF), Sciaccia Fault System (SFS), and the Sicilian Fold and Thrust Belt (SFTB). The proposed San Vito Lo Capo—Sciaccia Shear Zone (SVCS) is marked with a dashed line, indicating a possible structural boundary that requires further investigation. The inset map provides the regional tectonic framework of Sicily, showing the location of Segesta, Sciacca (S), and Gela (G) in relation to the Sicily Channel Rift Zone and Mt. Etna. The site under investigation is shown in Fig. 1b and is represented with a white box. Topographic and bathymetric data are sourced from Copernicus EU-DEM (25 m resolution) and the EMODnet Bathymetry Consortium (2022). b Orthophoto of the archaeological site of Segesta, showing the location of four key structures: the Doric Temple, the Theater, the Stoa, and the Mango Sanctuary

damage mapping, stratigraphic observations, 3D photogrammetric models, and geophysical prospection to characterize the local seismic response in three key areas: the Doric Temple, the Theater and Agora in the Northern Acropolis, and the Mango Sanctuary (Fig. 1b). Particular attention was given to the collapses observed in the Agora, especially in the Stoa, to evaluate whether local amplification phenomena played a role. This integrated approach enabled us to correlate deformation evidence with subsurface conditions and to frame the

observed damage within the broader seismotectonic context. Our findings form the foundation for discussing potential threats to the cultural heritage of the Segesta site and reconstructing the territory's history, providing valuable insights into the interplay between past natural events and human activities.

Despite the widespread application of archaeoseismology across the Mediterranean (Stiros 2001; Meghraoui et al. 2003; Marco 2008; Hinzen et al. 2021), Segesta had never previously been investigated within this framework. To date, no integrated archaeoseismological and geophysical study has been conducted at the site, leaving a gap in the understanding of seismic phenomena in western Sicily's archaeological record. This absence of prior multidisciplinary analyses highlights the broader need for integrated approaches in archaeologically rich but historically undocumented regions.

In addition to stratigraphic and architectural data, systematic field surveys—including detailed field geological and structural investigations—were conducted between autumn 2022 and summer 2023 to document damage throughout the site and to support the interpretation of structural instabilities. This study not only enhances our understanding of Segesta's seismic history, but also provides a replicable methodology that can be applied to other archaeological sites located in complex tectonic or geomorphological settings across the Mediterranean region.

2 Geologic, geomorphologic and seismotectonic framework of the Segesta archaeological site

The archaeological site of Segesta is situated within the northern (internal) sector of the Sicilian Fold and Thrust Belt (SFTB), a segment of the Maghrebian–Apennines orogenic belt (Fig. 1a). This southward-verging thrust system defines the collisional boundary between the African and European tectonic plates in the central-western Mediterranean region, which is influenced by the paleogeographic evolution of the Tethys Ocean and the North African continental margin (Faccenna et al. 2001; Catalano et al. 2002).

In western Sicily (see Fig. 1a), the outermost extension of the Pliocene–Quaternary Sicilian Fold and Thrust Belt (SFTB) follows a northeast–southwest orientation in the Sicily Channel, where it is referred to as the Adventure Thrust Front (ATF in Fig. 1a). Farther inland, the thrust front bends northward around the Saccense carbonate platform and transitions offshore into the Gela Nappe (Catalano et al. 2000; Ferranti et al. 2008). While the outer front in southern Sicily exhibits evidence of recent and ongoing deformation based on structural, geodetic, and geomorphological data (Monaco et al. 1996; Ferranti et al. 2021), paleo-earthquake records from Selinunte and its surroundings indicate episodic deformation and the seismic potential of these structures (Guidoboni et al. 2002; Bottari et al. 2009; Barreca et al. 2014, 2020; Palano et al. 2021). More recent investigations by Sulli et al. (2021) suggest that compressional deformation has migrated northward, toward inland and offshore areas of northern Sicily and the southern Tyrrhenian Sea, during the Middle–Late Pleistocene. This shift may reflect a change in regional tectonic polarity, with implications for the activity of inner thrust fronts such as the Montagna Grande Thrust Front (MGTF). The offshore foreland region in southern Sicily is intersected by the ~ NNE–SSW trending left-transpressional fault systems of Capo Granitola and Sciacca (CGFS and SFS, respectively, in Fig. 1a), which were characterized by large displacements during the Pliocene–

Early Pleistocene, with reduced activity afterwards (Fedorik et al. 2018; Civile et al. 2018; Ferranti et al. 2019).

However, there is ongoing debate regarding the dominant seismogenic sources in western Sicily. Some studies attribute seismicity to active ramps along the SFTB thrust front (Monaco et al. 1996; DISS Working Group 2025), while others emphasize the role of the San Vito Lo Capo-Sciacca Fault System (SVCS), a long-lived lithospheric strike-slip fault zone with transpressional kinematics (Di Stefano et al. 2015) that would represent the northward continuation of the Sciacca fault system beneath the SFTB (Fig. 1a).

Western Sicily, including the region around Segesta, is considered as a low strain-rate area (Parrino et al. 2022). GNSS measurements indicate weak compressional activity (Devoti et al. 2017), consistent with the low seismicity recorded in historical and instrumental times (ISIDe Working Group 2007; Rovida et al. 2022), and results in a low to moderate seismic hazard according to the current Italian and European models (Stucchi et al. 2004; Danciu et al. 2024).

The 1968 Belice sequence, which includes the closest known seismic events to Segesta, has been assigned different magnitude values in the literature. The official CPTI15 catalog (Rovida et al. 2020, 2022) reports a maximum moment magnitude of M_w 6.4, whereas a more recent re-evaluation based on macroseismic data suggests a lower maximum magnitude of M_w 5.8 (Azzaro et al. 2020). This sequence, located approximately 20 km south of Segesta, caused widespread destruction in south-western Sicily and highlights the nearest known seismogenic area. However, the seismotectonic potential north of the Belice Valley, particularly in the Segesta region, remains poorly understood. This underscores the need for further investigation into internal thrust fronts, such as the Montagna Grande Thrust Front (MGTF) (Fig. 1a), which recent studies indicate may still be active (Barreca et al. 2024) and could have been responsible for the seismic activity registered at Segesta.

Existing geological maps (e.g., Bommarito et al. 1991; Mauz and Renda 1996; Catalano et al. 2011), and our field survey show that the Segesta site was built on rocks of a Mesozoic-Paleogene pelagic platform succession pertaining to the Trapanese Unit (Catalano et al. 2000; 2002) (Fig. 2). This succession, comprising nodular limestones, marls, and chalky deposits, outcrops in Monte Barbaro high. The Northern Acropolis is underlain by stratified breccia limestones, representing slope deposits of the Scaglia succession. The pelagic platform succession was folded and faulted during the Miocene-Quaternary deformation events that built the SFTB. We identified and mapped a new fault, the NE-SW striking left-lateral Segesta Fault (SF) that bounds the steep eastern flank of the Monte Barbaro high. The SF juxtaposes the Trapanese succession with younger Miocene deposits that outcrop in the east and cuts Quaternary breccias, suggesting activity into recent times. The Mango Sanctuary, located on an alluvial terrace dissected by a tributary of the Gaggera River east of the SF, provides further evidence of landscape evolution influenced by both tectonics and fluvial processes.

3 Segesta: historical background

Segesta, located in northwestern Sicily within the Calatafimi territory (province of Trapani), is an important archaeological site with a complex, multilayered occupation history. According to tradition, it was founded by the Elymians, an indigenous population of Sicily (Nenci

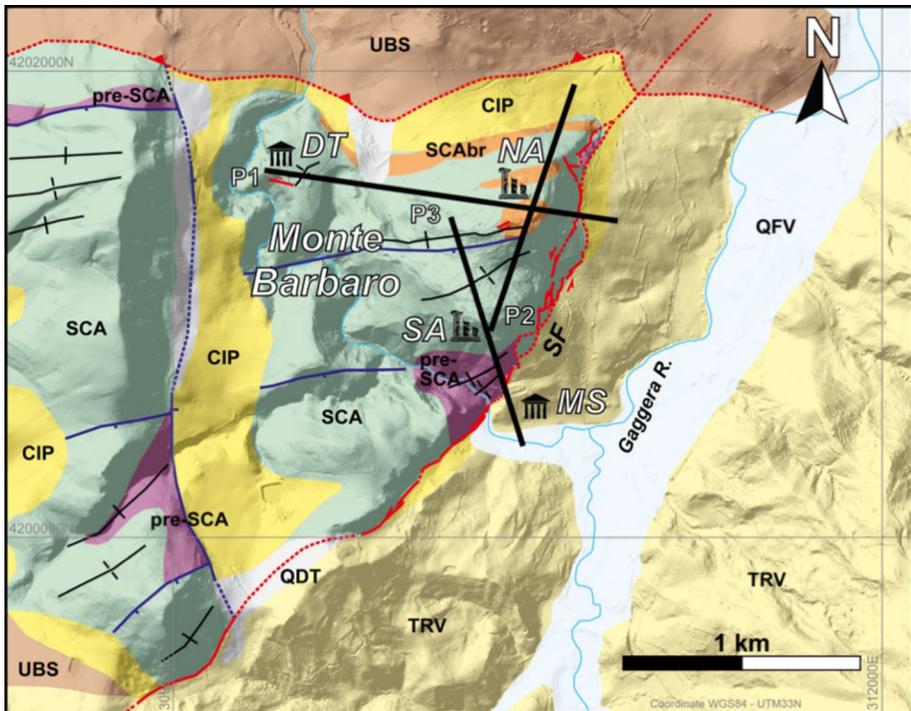


Fig. 2 Geological map of the Segesta site, showing the position of ancient buildings analyzed in this study, redrawn from Bonmarito et al. (1991) after original fieldwork. Thick solid lines, numbered from P1 to P3, indicate the geological and geophysical profiles used to assess the local site effects and shown in Fig. 6. Acronyms for the outcropping geological formations: QDT, Quaternary slope deposits; QFV, Quaternary alluvial deposits; TRV, Terravecchia Fm., foredeep deposits (Tortonian lower Messinian); CIP, S. Cipirrello Fm., marine marls (upper Langhian-Tortonian); UBS, Numidic Flysch (upper Oligocene-lower Miocene); SCA, Scaglia Fm. (upper Cretaceous-lower Oligocene); SCAbr, stratified breccia within the Scaglia Fm. (upper Cretaceous-lower Oligocene); pre-SCA, basal limestones (Jurassic-Cretaceous). The Segesta Fault zone (SF) is marked by red lines (dotted where hypothesized) along with red arrows indicating its left-lateral kinematics, while hinge zones of short-wavelength folds are shown as thin black lines with crosses. Inherited normal faults in the Scaglia Fm. with ticks on the down-thrown side are shown in blue. To the north, the E-W trending overthrust of the Numidic Flysch on younger formations is shown with red dashed line and triangles on the hanging-wall side. Archaeological sites and structures: DT – Doric Temple; MS – Mango Sanctuary; NA – Northern Acropolis; SA – Southern Acropolis

et al. 1988). Strategically positioned at 429 m a.s.l. on Monte Barbaro, Segesta evolved over centuries, incorporating terraced settlements, defensive structures, and monumental architecture (Abate and Cannistraci 2012, 2013; Erdas 2010; Faccella and Olivito 2013; Giglio 2021). Monte Barbaro comprises three hills that host Segesta's major architectural landmarks (Fig. 1b): the Northern Acropolis, which houses the Agora and the Greek Theatre; the Southern Acropolis, slightly lower and connected by an ancient road, which accommodated various buildings; and the Northwestern Hill, where the Doric Temple stands prominently. The Mango Sanctuary is situated at the base of the eastern slope of the Southern Hill.

The archaeological research has identified five distinct phases of occupation at Segesta (Dipasquale 2014):

- Phase A (sixth century BCE): Archaic period, marking the earliest settlement.
- Phase B (5th–fourth centuries BCE): Classical period, characterized by the construction of the Doric Temple and the Mango Sanctuary, along with major public buildings.
- Phase C (3rd–second centuries BCE): Greek period, a phase of urban expansion, including enhancements to the Agora and the Theater.
- Phase D (second century BCE–third century CE): Roman period, featuring the reconstruction of the Agora into a Roman forum, followed by partial abandonment.
- Phase E (5th–sixth century CE): Early Medieval period, marked by new buildings reusing earlier materials (Infarinato 2004; Erdas 2010).

This sequence of occupation and abandonment suggests that Segesta underwent cycles of destruction and rebuilding, influenced by warfare, environmental degradation, and possibly seismic activity, a hypothesis explored in this study through archaeoseismological evidence (Mertens 1984; Miles 2019).

3.1 Architectural description of key structures and evidence of possible seismic damages

3.1.1 The Agora and Stoa

Constructed in the second century BCE, the Agora reflects architectural models typical of Hellenistic Asia Minor and is situated atop a modest hill at approximately 400 m a.s.l. (Fig. 1b). Enclosed by porticoes with double colonnades, its rectangular square is further distinguished by monumental *xedrae* on the northern and southern sides (Ampolo and Parra 2012; Cannistraci and Olivito 2018).

Excavations led by the Scuola Normale Superiore di Pisa since 1990 have focused on the Agora and its adjacent structures, providing insights into its architectural features, construction techniques, and socio-political role within the settlement (Ampolo and Parra 2012).

The Stoa dominates the northern section of the Agora, measuring approximately 82 m in length and 11 m in height (Olivito and Taccola 2014). It consists of two wings, each with two levels, and an additional subterranean level in the eastern wing. The Stoa's architecture blends Doric and Ionic elements (Ampolo and Parra 2018). The lower level showcases a Doric colonnade reaching a height of 6.6 m, while the upper level displays an Ionic colonnade standing at 4.3 m. Remnants of octagonal columns, still partially visible on-site, delineate the two floors (Ampolo and Parra 2012).

The Stoa was built along three sides of the Agora, enclosing it with colonnades two aisles deep. The external aisle measured approximately 5.8 m in depth, while the internal aisle was about 5.5 m deep. Unlike many other Stoas, the northern section lacked rooms along its back wall, instead featuring stone arches reinforcing areas where the rock had been cut prior to construction (Olivito and Taccola 2014).

Excavations have revealed evidence of structural deformation and oriented collapse, consistent with seismic-induced failure (Parra 2006). Further field surveys have identified rotated column drums and cracks in the paved road, primarily concentrated in the central section of the Stoa (Fig. 3). Virtual simulations and photogrammetric reconstructions suggest that the collapse most likely occurred in the early third century CE, potentially due to seismic activity (Olivito and Taccola 2014).

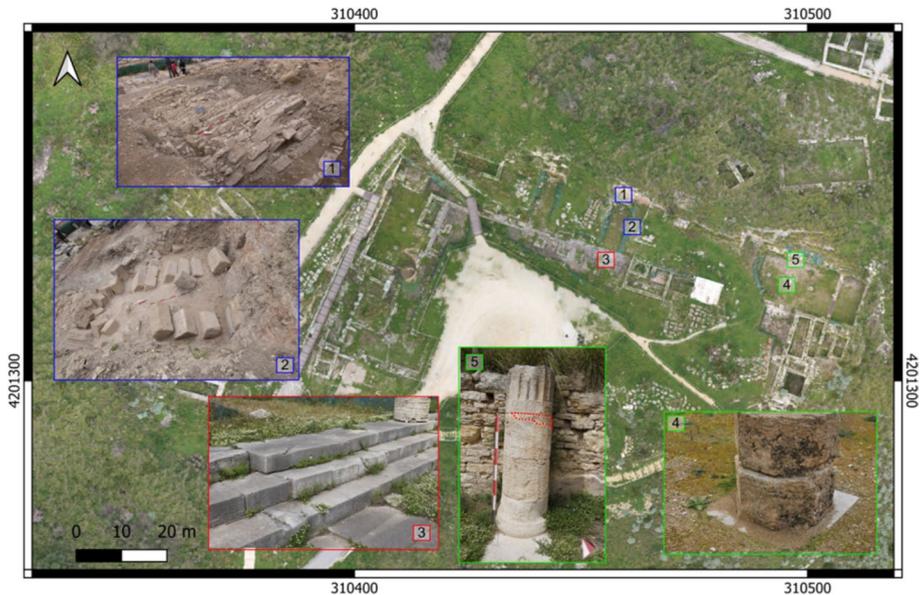


Fig. 3 Orthophoto of the Stoa at Segesta, highlighting key deformation and collapse areas in the central and eastern portions of the structure. The numbered locations (1–5) correspond to zoomed-in images illustrating different types of structural damage: (1) Lateral view (S, 208°) of an oriented collapse observed at the retaining wall of the northern Stoa, indicating a southward failure direction (photo by MC Parra); (2) Lateral view (SE, 117°) of an arch positioned below the collapsed retaining wall, highlighting out-of-plane failure, with the collapse direction oriented towards the southeast (photo by MC Parra); (3) Lateral view (E, 85°) of step misalignment in the eastern wing, indicating seismic displacement and offset (displacement direction marked with black arrows); (4) Lateral view (E, 105°) of a rotated basal drum, suggesting seismic-induced column rotation (rotation direction marked with a curved black arrow); (5) Lateral view (NE, 66°) of a fractured column base, attributed to seismic oscillations, showing signs of lateral shifting (restored portion marked with a dashed red line)

3.1.2 The Greek Theater

The Theater, a remarkably well-preserved structure on Segesta's Northern Acropolis, was constructed between the third and second centuries BCE (D'Andria 1997; Figs. 1b, 4). It is located behind the Stoa and oriented to the northeast. Unlike most ancient theaters, which were typically built into natural slopes for structural support, the *cavea* (seating area) at Segesta was constructed on artificial fill, requiring advanced engineering techniques to stabilize construction over the steep northern slope of Monte Barbaro. Preliminary stratigraphic surveys suggest that the bedrock lies at a considerable depth beneath the structure, posing significant technical challenges for its construction (D'Andria 1995 and references therein).

The *cavea* is supported by self-sustaining chambers, with seating rows placed above blind corridors formed by two lateral walls and covered by radially arranged slabs (D'Andria 1997; De Bernardi 1997). This design helped to mitigate earth pressure exerted by the fill material on the retaining wall (*analemma*) that encased the structure. Field surveys have revealed multiple deformations in the *analemma* wall, particularly along the western side, where cracks, misalignments, and vertical distortions are evident (Fig. 4). The wall, com-

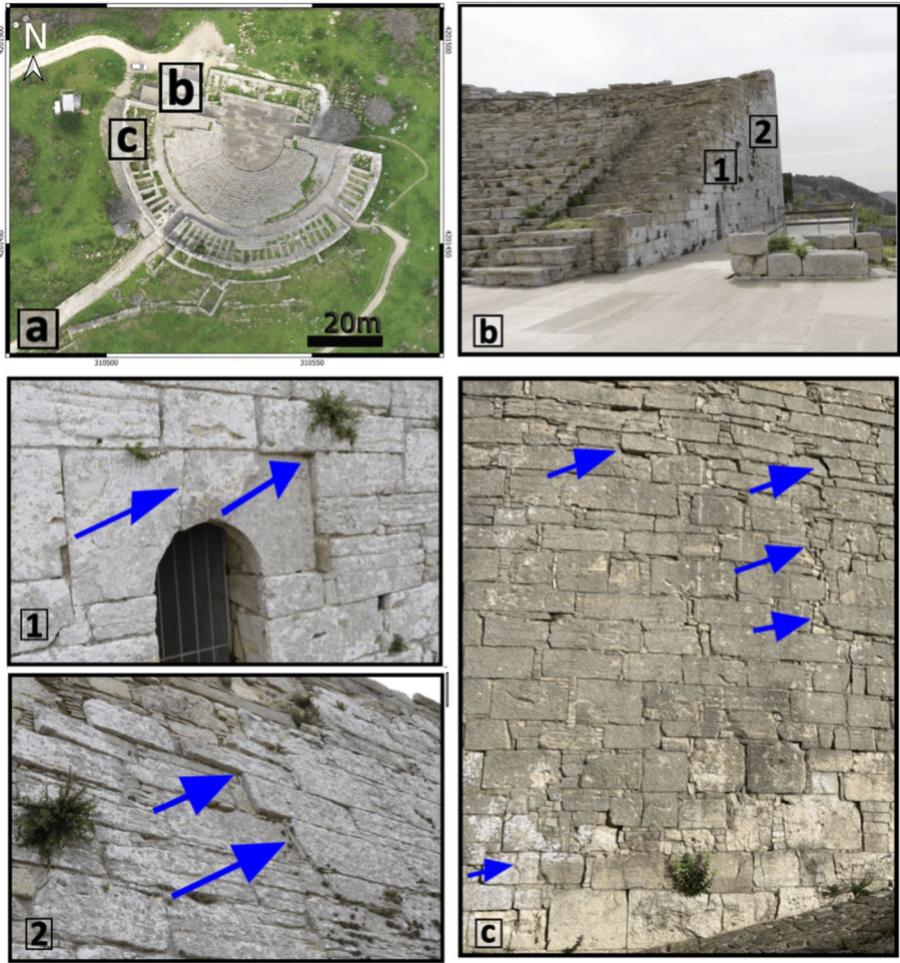


Fig. 4 Deformation of the *analemma* wall of the Greek Theater, showing cracks, offsets, and structural misalignments; Top: **a** Orthophoto of the Greek Theater, with locations **b** and **c** indicating the positions of the detailed images below. Bottom: **b** Overview of the wall, with zones (1) and (2) marking key areas of deformation; (1) Close-up of the doorframe at the base of the wall, showing horizontal displacement and sagging of the arch (displacement direction: WNW-ESE); (2) Mid-section of the wall, displaying rotational misalignments and cracks, predominantly oriented along a WNW-ESE axis, suggesting progressive structural stress over time. **c** Rear view of the *analemma* wall, illustrating both vertical (N-S) and horizontal (E-W) cracks, as well as block offsets. These deformations are consistent with known seismic damage patterns in ancient masonry structures

posed of rectangular limestone blocks, exhibits visible cracks and shifts, especially in its middle and lower sections.

Although long-term structural stress or differential settlement may account for some of the observed deformations, external triggers—particularly seismic activity—cannot be ruled out. To clarify the spatial distribution of these features, a detailed map (Fig. 4) illustrates the locations of cracks, misalignments, and rotated blocks, annotated with lettered

labels for each anomaly. Additionally, orthophotos provide a complementary visual context for interpreting these structural pathologies.

3.1.3 The Mango Sanctuary

The Mango Sanctuary is located on a terrace at approximately 200–225 m a.s.l., on the southeastern edge of the Segesta site (Fig. 1b). It lies between the steep eastern limestone slope of Monte Barbaro and the eastern termination of a deep gorge carved by a left tributary of the Gaggera River (Figs. 1b, 2 and 5). Archaeological excavations have revealed a monumental wall (*temenos*) enclosing the architectural remains of a large peripteral Doric temple dated to ca. 470–460 BCE (de Cesare 2023). The sanctuary was laid out within a rectangular enclosure of approximately 47.8×86 m, supported by retaining walls to stabilize the uneven terrain.

Modeled after Selinunte's Temple E, the temple was founded on travertine-like calcarenite blocks, each measuring approximately 39 cm in height. Parts of the northern cella foundation are still extant, whereas the peristyle foundations were lost due to later spoliation (de Cesare et al. 2022). Historical and archaeological evidence indicates that the temple remained in use for only two or three decades before its abandonment. Although the precise cause of this abandonment remains unclear, several natural events—including flooding, landslides, and earthquakes—have been proposed as possible triggers (Mertens 1984; Miles 2019).

Archaeological excavations carried out by Tusa in the 1950s and 1960s, which were not conducted systematically, did not yield conclusive data; more recent publications likewise

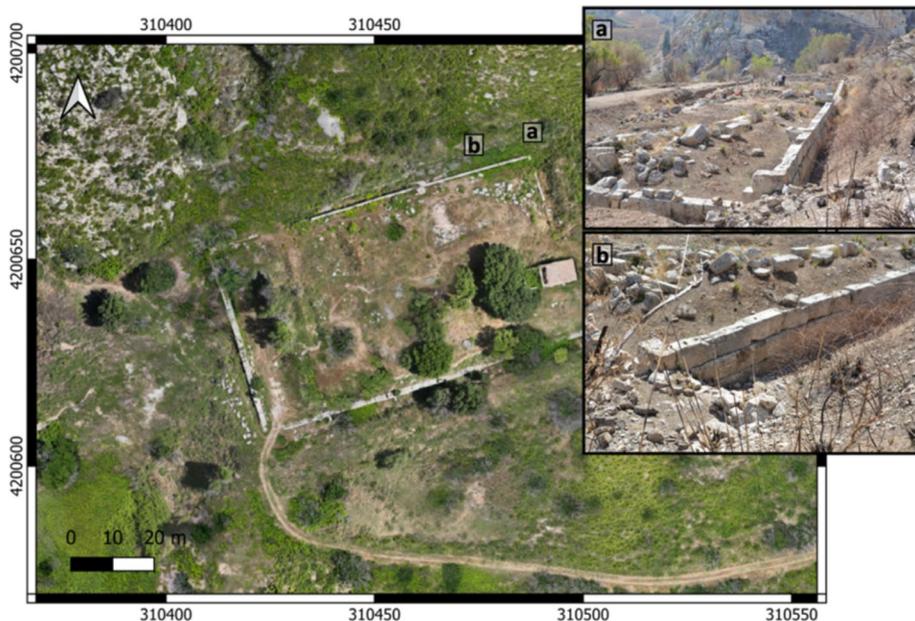


Fig. 5 Orthophoto of the Mango Sanctuary with letters marking the locations of detailed images. **a** Northern view of the Sanctuary, showing the architectural layout. **b** Close-up of the foundation walls, highlighting construction techniques and preservation state

offer no definitive clues regarding the site's abandonment and subsequent reuse. However, a later excavation conducted roughly 70 years after Tusa's work, despite facing substantial stratigraphic disturbance, succeeded in identifying the foundation layer. Within this context, collapsed and overturned architectural blocks and capitals were discovered, attesting to a sudden and violent disruption in the sanctuary area. Excavations also identified a compact layer of limestone fragments beneath the foundations, possibly intended as a stabilization platform (de Cesare et al. 2022).

During subsequent periods—especially under Roman influence—the site underwent systematic spoliation, with architectural blocks and column drums being repurposed for other uses, such as millstones. In assessing the natural phenomena that may have led to the sanctuary's sudden abandonment, both landslides and earthquakes were initially examined. A geomorphological survey of Monte Barbaro's eastern slope ultimately excluded the presence of landslides, based on the absence of detachment niches or related deposits. This absence shifts attention toward seismic activity as the most likely cause.

3.1.4 The Doric Temple

The Doric Temple of Segesta, located on the lowest hill of Monte Barbaro at approximately 310 m a.s.l., was built between 430 and 420 BCE and ranks among the best-preserved Greek temples in western Sicily. Uniquely, it lacks a *cella* (inner chamber), suggesting incomplete construction. While the Carthaginian invasion is often cited as the cause (Giglio 2021), political or economic factors may also have played a role (Mertens 1984; Tusa 1984).

The temple is peripteral, with a rectangular layout measuring approximately 21.6×56.3 m, featuring six columns on the short sides and fourteen on the long ones. Each column stands about 9.3 m high and is characterized by 20 flutes. The structure rests on a three-step *crepidoma*, and the *stylobate* shows a slight curvature—an architectural refinement to correct optical distortion. The columns, made of local limestone—likely travertine from the Alcamo area—were originally coated in stucco for both aesthetic and protective purposes (Catalano and Maniaci 1992).

Structural observations reveal that most columns remain in their original positions, except for two: the second column from the south on the eastern side (E2vS) and the upper drums of the third column from the south on the western side (W3vS), both of which show rotational misalignments. These features, interpreted as seismic in origin, were already noted as damaged and underwent restoration in the late twentieth century (Amico and Manzo 1977; Mertens 1984). Consolidation efforts between 1979 and 1985 especially targeted the corner columns, which show measurable tilts likely resulting from cumulative stress and seismic shaking (Lo Jacono 1985).

Mertens (1984) recorded the following displacements (Fig. 6):

- The SE corner: 3.7 cm east and 2.6 cm south;
- The NE corner: 1.0 cm east and 8.0 cm north;
- The NW corner: 1.0 cm west and 3.1 cm north;
- The SW corner: 1.4 cm west and 2.2 cm south.

Further evidence of past seismic effects, now no longer visible due to restoration, includes:

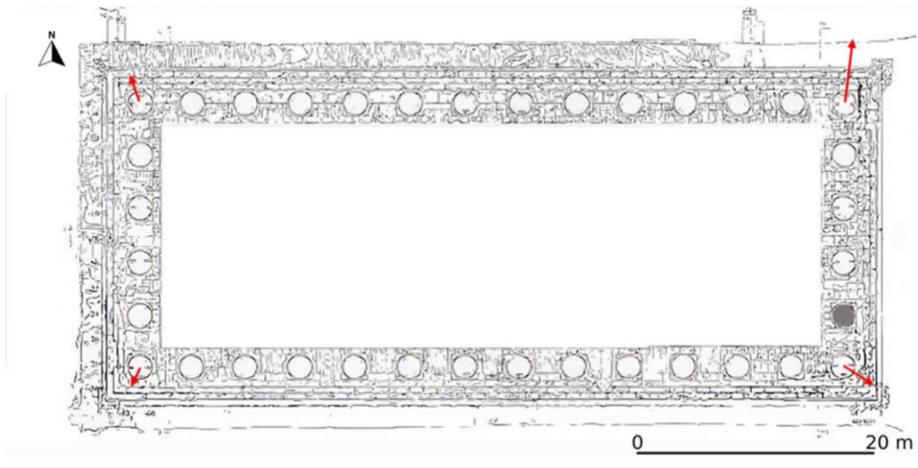


Fig. 6 Plan of the Doric Temple showing the direction of column tilting (red arrows). The SE corner column shifted 3.7 cm east and 2.6 cm south, the NE column moved 1.0 cm east and 8.0 cm north, the NW column was displaced 1.0 cm west and 3.1 cm north, and the SW column shifted 1.4 cm west and 2.2 cm south. The column restored after the 1781 thunderstorm is shown in grey (modified after Mertens 1984)

- Fractures along the edges of column drums, interpreted as indicators of rotational movement caused by ground shaking.
- Localized block displacements, partially covered by travertine encrustations, suggesting multiple displacement phases over time.
- Reinforcement interventions using stainless steel bars and resin injections to stabilize fractured elements and prevent further structural failure (Lo Jacono 1985).

Today, the inclination of the corner columns remains the most visible sign of structural deformation, as much of the previous damage has been masked or repaired.

4 Methodology: a multidisciplinary approach to seismic and environmental assessment

The archaeological site of Segesta was investigated using a multidisciplinary methodology aimed at disentangling the complex interplay between seismic activity, geomorphological evolution, and structural degradation. Rather than relying on a single line of inquiry, the study integrates structural archaeology, high-resolution remote sensing, and non-invasive geophysical techniques to build a comprehensive understanding of the site's seismic vulnerability.

A central objective was to identify and interpret structural damage patterns potentially attributable to past earthquakes, while rigorously evaluating alternative degradation processes such as long-term weathering, differential settlements, or environmental erosion. This analysis was grounded in detailed on-site documentation of structural anomalies, which were systematically correlated with high-resolution drone imagery and digital surface models (DSMs) to ensure spatial accuracy and contextual integration.

To evaluate the potential role of local geological conditions in amplifying seismic ground motion, two established passive seismic techniques were employed: the Horizontal-to-Vertical Spectral Ratio (HVSr) and the Multichannel Analysis of Surface Waves (MASW). These methods are widely used in seismic microzonation (e.g., Mucciarelli and Gallipoli 2001; SESAME 2004) and have increasingly been adopted in archaeological geophysics to characterize subsurface stratigraphy and assess site effects in heritage contexts. Notable examples include the Selinunte Archaeological Park (Schwellenbach et al. 2020), the Palermo Plain (Canzoneri et al. 2025) and Altavilla Milicia area (Martorana et al. 2017).

These studies demonstrate the suitability of HVSr and MASW for investigating the dynamic response of archaeological sites situated on heterogeneous or stratified ground, particularly in cases where excavation is restricted or inadvisable. By combining damage pattern analysis, detailed topographic data, and subsurface velocity profiles, our integrated approach provides a robust framework for assessing seismic response at Segesta. Beyond local implications, this methodological framework contributes to broader risk reduction strategies for archaeologically and culturally significant sites exposed to seismic hazards, especially in tectonically active regions such as southern Italy and the broader Mediterranean basin.

4.1 Structural and archaeoseismic analysis

A systematic archaeoseismic analysis was undertaken to investigate potential earthquake-induced damage at Segesta, following established methodologies (Stiros 1996; Galadini et al. 2006; Hinzen et al. 2011). The approach integrated structural damage assessment, high-resolution orthophoto analysis, and seismotectonic contextualization, with the aim of distinguishing seismic effects from alternative causes such as long term degradation, foundation instability, or environmental erosion.

The methodology followed five key steps:

1. Field-based documentation of structural damage

Detailed field surveys were conducted across the Stoa, Greek Theater, Doric Temple, and Mango Sanctuary. All visible anomalies—fractures, rotated column drums, displaced blocks, step offsets, and localized collapses—were recorded through photography, notes, and spatial referencing. Table 1 summarizes the main damage types observed, along with their preliminary interpretations.

2. Integration of high-resolution orthophotos (see paragraph 4.2.1)

Drone-based photogrammetry and georeferenced orthophotos were used to digitally map the architectural remains and associated damage features. This allowed for the precise documentation of deformation patterns and their correlation with local topographic and structural conditions.

3. Geophysical survey and subsurface characterization (see also paragraph 4.2.2)

Table 1 Summarizes the structural damage observed in various buildings at Segesta (Stoa, Doric Temple, Greek Theater, Mango Sanctuary), listing the types of damage, their descriptions, and possible causes

Damage type	Description	Possible cause	Seismic probability (Qualitative)	Seismic probability (Quantitative)	Supporting factors
Oriented collapse	Structures collapsed in a single preferred direction, consistent with ground motion effects	Earthquake-induced shaking vs. progressive decay	High	0.8–1.0	Collapse patterns in the Stoa and retaining walls indicate a directional failure mechanism consistent with seismic shaking
Rotated column drums	Partial or complete rotation of column drums, indicative of seismic-induced torsional forces	Seismic oscillation vs. soil compaction	High	0.7–1.0	Observed in the Stoa and Doric Temple colonnades; rotation aligned with expected ground motion directions
Offset between blocks	Horizontal or vertical displacement of large architectural blocks	Seismic shaking vs. ground settlement	High	0.8–1.0	Block misalignments in the Stoa and Greek Theater match earthquake-induced displacement patterns
Broken corners on blocks	Corner fractures at masonry blocks, typically due to impact forces	Seismic movement vs. mechanical degradation	Moderate	0.5–0.7	Fractured column bases in the Stoa, mainly at structural junctions and load-bearing points, suggest stress concentrations from seismic loads
Step offsets	Steps within architectural features exhibit horizontal misalignment	Seismic uplift vs. soil compaction	Moderate	0.4–0.6	Step misalignments at the entrance of the Stoa align with seismic displacement patterns in similar archaeological sites
Analemma wall deformation	Outward bulging and misalignment of retaining walls	Seismic load vs. ground settling	Moderate to High	0.6–0.8	The Greek Theater's <i>analemma</i> wall, located along the outer seating structure, exhibits cracks and misalignment that match seismic amplification effects

Table 1 (continued)

Damage type	Description	Possible cause	Seismic probability (Qualitative)	Seismic probability (Quantitative)	Supporting factors
Displaced arch blocks	Large arch blocks shifted out of alignment	Seismic oscillations vs. soil compaction	High	0.7–1.0	Deformed arch at the theater's retaining wall, with displacement consistent with seismic shaking
Cracks in masonry	Structural cracks in walls and columns	Seismic stress vs. thermal expansion	High	0.8–1.0	Cracks in the Greek Theater and Stoa, mostly at load-bearing walls and stress points, are aligned with seismic ground motion directions
Confused collapse not related to stratigraphy	used for two or decades and shortly after abandoned	Seismic stress vs. landslide	High	0.8–1.0	Mango Sanctuary's abrupt abandonment suggests a seismic event as the primary cause

It also includes both qualitative and quantitative estimates of seismic probability, along with key supporting factors that help distinguish earthquake-induced failures from alternative explanations, such as soil compaction or material decay

Geophysical methods, including Horizontal-to-Vertical Spectral Ratio (HVSr) (Nakamura 1989) and Multichannel Analysis of Surface Waves (MASW) (Park et al. 1999), were employed to assess the dynamic response of subsurface layers and their potential role in amplifying ground motion.

These techniques have been widely applied in seismic microzonation and archaeoseismological studies (e.g. Martorana et al. 2017; Schwellenbach et al. 2020; Hinzen et al 2021; Bottari et al. 2024), particularly for evaluating local site effects and identifying stratigraphic amplifications near heritage structures.

4. Evaluation of archaeoseismic indicators and probability assessment

Structural anomalies were evaluated against established archaeoseismic indicators (Galadini et al. 2006). While direct instrumental measurements (e.g., tiltmeter data) were not available, specific failure mechanisms—such as out-of-plane collapses, rotational displacement of column drums, and block offsets—were compared with recognized seismic damage typologies. Each damage class was then assessed using a qualitative-to-quantitative probability scale, based on:

- Structural and architectural context (e.g., support systems, construction technique)
- Collapse pattern (e.g., directional vs. random)
- Regional seismic history (e.g., nearby faults or known events)

5. Correlation with the seismotectonic framework

The final step involved comparing documented deformation patterns with the known seismotectonic setting of northwestern Sicily through geological and structural field surveys. Although Segesta lies in an area of historically moderate seismicity, site-specific geological conditions—such as those associated with the Monte Barbaro fault system—could significantly amplify ground motion. This step aimed to determine whether seismic loading represented a plausible causal mechanism, without necessarily attributing the damage to a specific historical earthquake.

4.2 Remote sensing and geophysical analysis

To achieve a comprehensive understanding of the seismic vulnerability and geomorphological evolution of the Segesta site, this study employed an integrated approach combining drone-based photogrammetry and geophysical surveys. The synergy between high-resolution aerial imagery and subsurface geophysical data enabled a detailed assessment of structural deformation, topographic variations, and local seismic amplification effects.

4.2.1 Aerial photogrammetry and surface modeling

High-resolution drone-based photogrammetry was conducted to capture the topographic and morphological characteristics of Monte Barbaro, with a particular focus on the Northern Acropolis and the Mango Sanctuary. This methodology has become standard practice in archaeology, cultural heritage preservation, geomorphology, and geophysics (Lo Brutto et al. 2014; Ebolese et al. 2019; Adamopoulos and Rinaudo 2020; Jiménez-Jiménez et al. 2021; Li et al. 2021; Petropoulos et al. 2021; Pepe et al. 2022), offering non-invasive, high-resolution mapping capabilities crucial for understanding site degradation.

For the Northern Acropolis, a DJI Air 2S drone was deployed at 70 m altitude, achieving a Ground Sample Distance (GSD) of ~ 2 cm. The survey covered an area of ~ 500 m, following a NE-SW flight pattern with 70% overlap, capturing nearly 500 high-resolution images. The Mango Sanctuary survey, conducted under more complex topographic conditions, utilized a DJI Mavic 3 M drone with a Network Real-Time Kinematic (NRTK) module, allowing real-time positioning corrections. This survey was performed at 100 m altitude, capturing 600 images with a GSD of ~ 3 cm.

To ensure georeferencing accuracy, Ground Control Points (GCPs) were distributed across both areas and measured using a Stonex S850 GNSS receiver operating in NRTK mode, receiving real-time corrections from the Topcon Topnet Live GNSS network (Dardanelli et al. 2020). The acquired imagery was processed using Agisoft Metashape (v. 2.1.0, Agisoft LLC), yielding a final georeferencing accuracy of < 10 cm, sufficient for detailed morphometric and structural analysis.

The Digital Surface Models (DSMs) and 3D photorealistic reconstructions provided critical data for assessing surface deformations, potential subsidence zones, and erosion patterns, forming a baseline dataset for geophysical investigations.

4.2.2 Geophysical surveys and seismic response analysis

Geophysical surveys are essential tools in archaeoseismology, offering non-invasive methods to investigate subsurface conditions, detect stratigraphic discontinuities, and assess local

amplification phenomena or fault-related deformation (Schwellenbach et al 2020; Hinzen et al. 2021; Bottari et al. 2024). These techniques are particularly valuable in archaeological contexts, where excavation is limited or not permitted, and where a robust understanding of seismic site effects is necessary to interpret structural damage patterns (Martorana et al. 2023).

To characterize local seismic response and its potential contribution to structural instability, two complementary methods were applied: the Horizontal-to-Vertical Spectral Ratio (HVSr) and the Multichannel Analysis of Surface Waves (MASW). HVSr, first introduced by Nakamura (1989), estimates the resonance frequencies of soft sediment layers, by analyzing the spectral ratio of horizontal to vertical ground motion components. MASW (Park et al. 1999) on the other hand, provides 1D shear-wave velocity (V_s) profiles by inverting the dispersion of surface Rayleigh waves. Both techniques are widely used in seismic microzonation studies (Mucciarelli and Gallipoli 2001; Lunedei and Malischewsky 2015) and have proven particularly effective in heritage settings with soft sediments and limited accessibility.

MASW data were acquired using a 24-channel system with vertical 4.5 Hz geophones spaced at 2 m intervals and an 8 kg sledgehammer as a seismic source. Each profile extended 46–48 m, with a 5 m source offset. A total of ten profiles were acquired across the site: three at the Doric Temple, three at the Mango Sanctuary, and four at the Agora (Fig. 7). Dispersion curves were extracted in the frequency–wavenumber domain and inverted using a genetic algorithm (Park et al. 1999), with initial models informed by stratigraphic logs and field observations. The maximum depth of investigation reached ~ 30 m, with highest resolution in the upper 10–15 m. The configuration was optimized to ensure high-resolution imaging of shallow stratigraphy and sufficient penetration to the seismic bedrock.

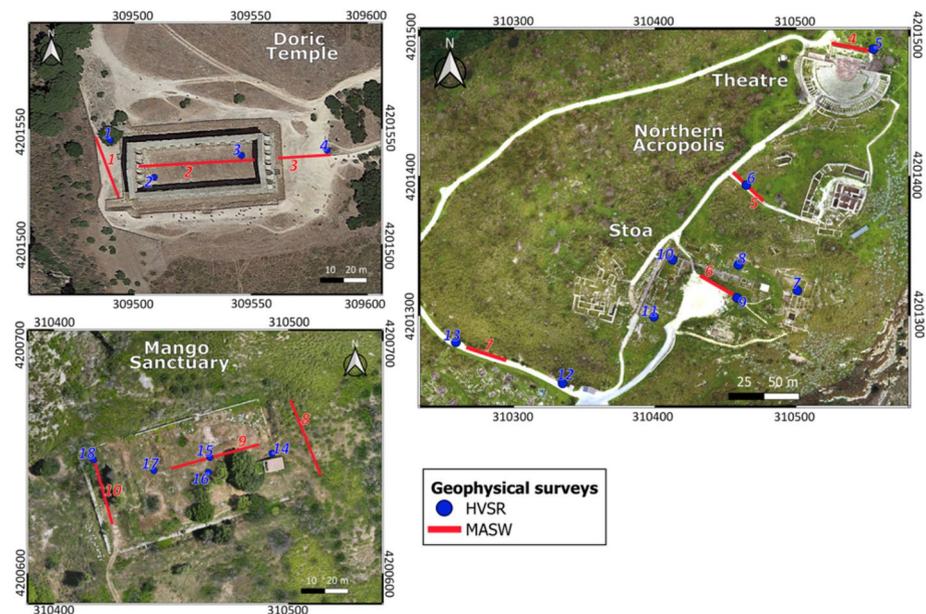


Fig. 7 Orthophoto of the Segesta Archaeological Park showing the locations of the geophysical surveys. HVSr measurement points are marked with blue dots, and MASW survey lines are shown in red

HVSR measurements were conducted with 3-component broadband seismometers (100 Hz sampling), acquiring ambient noise at 18 locations (four at the Doric Temple, five at the Mango Sanctuary, and nine at the Agora). Data were processed following SESAME (2004) recommendations: ambient noise recordings were divided into overlapping 10- or 40-s windows, depending on the stationarity of the signal; a 10% triangular smoothing function was applied to reduce spectral fluctuations; and transient signals were removed to ensure the clarity and stability of the resonance peaks.

The choice of processing parameters was guided by theoretical considerations and field conditions. Window lengths were selected to balance frequency resolution and statistical robustness. The investigated frequency range (0.5–15 Hz) was chosen based on expected impedance contrasts within the top 30 m, as derived from MASW results and prior stratigraphy. The smoothing function was applied to highlight fundamental peaks without excessive loss of spectral detail, following SESAME guidelines.

HVSR and MASW results were jointly interpreted to derive seismostratigraphic models and estimate the depth to seismic bedrock. HVSR inversion was constrained using MASW-derived V_s profiles, enhancing model stability and reducing non-uniqueness in the interpretation. This integrated approach has been demonstrated to improve the reliability of seismic response characterization, particularly in stratified or heterogeneous settings (Martorana et al. 2017; Vantassel et al. 2018).

To further quantify site effects, we performed 2D numerical modeling of local seismic response using the LSR2D software (Stacec 2013). The subsurface was discretized into quadrangular finite elements and modeled using an equivalent linear viscoelastic framework in the time domain. The Newmark method (Newmark 1959) was applied to iteratively update soil properties with strain-dependent moduli. Seismic input was defined through hazard disaggregation, and synthetic accelerograms were extracted, normalized, and scaled before being applied at the bedrock interface.

This workflow included:

1. Seismic input definition and disaggregation;
2. Selection and normalization of accelerograms;
3. Integration of MASW and HVSR-derived stratigraphy;
4. Execution of 2D simulations;
5. Visualization of amplification patterns.

The integration of field-derived geophysical data with dynamic modeling enabled a spatially explicit assessment of local seismic amplification and identified zones of heightened vulnerability within the archaeological site. These findings enhance the interpretation of observed damage patterns and support broader strategies for seismic risk mitigation in heritage contexts. The results are presented and discussed in the following section.

5 Possible causes of structural collapse and deformation

The structural damage observed at Segesta results from a combination of natural degradation, geological conditions, and seismic phenomena. While long-term weathering and environmental exposure have certainly contributed to material deterioration, the specific nature

of several failure patterns— such as rotated column drums, displaced blocks, and abrupt collapses—suggests a strong seismic component (see Table 1). Warfare or human-induced destruction can be excluded as primary causes, given the absence of associated archaeological or historical evidence.

The damage patterns identified at Segesta closely align with those documented in other archaeoseismological case studies across the Mediterranean. Notably, the systematic directional collapse of temples at Selinunte (Guidoboni et al. 2002; Bottari et al. 2009) and the extensive deformation observed at Hierapolis (Hancock and Altunel 1997) provide comparable examples where local site effects significantly influenced the extent and distribution of destruction. The seismic probability values assigned to each damage type in Table 1 reflect this comparative framework, reinforcing the interpretation of a seismic origin for much of the structural damage at Segesta.

5.1 Natural deterioration and environmental factors

Long-term weathering and climatic variability have significantly contributed to the degradation of Segesta's monuments. The porous and heterogeneous nature of the local lithotypes (limestone and travertine) has made the architecture particularly vulnerable to thermal expansion, moisture infiltration, and chemical weathering, progressively undermining stone cohesion. Cycles of wetting and drying have intensified microfracturing and surface erosion, especially on exposed elements such as column drums and architraves (e.g., noted by Mertens at the Doric Temple).

In addition, biological colonization—including lichens, mosses, and microbes—has accelerated surface disintegration and the loss of material integrity.

5.2 Geological instability and foundation weakness

Segesta's geological setting has played a key role in structural deformations across different sectors of the site. The Doric Temple, located on the northwestern ridge of Monte Barbaro, rests on the Scaglia Formation (Upper Cretaceous–Lower Oligocene), composed mainly of compact limestones and marls (Bonmarito et al. 1991). This solid lithological context makes large-scale subsidence unlikely, suggesting that the tilted corner columns and displaced foundation blocks are more plausibly due to seismic ground motion or tectonic uplift affecting the Monte Barbaro block.

By contrast, the Greek Theater and the Stoa—both on the Northern Acropolis—are founded on stratified breccia limestones, slope deposits of the same Scaglia succession. These steeply inclined and potentially unstable settings, often involving artificial fills, increase the susceptibility to structural failure. In the Theater, deformations of the analemma wall—such as cracking, misalignment, and outward bulging—point to progressive collapse possibly aggravated by seismic forces or differential ground settling.

Similarly, the Stoa shows rotated column drums and shifted blocks, indicative of significant structural stress related to underlying geological conditions.

The Mango Sanctuary, constructed on a man-made terrace, shows signs of differential subsidence, especially where retaining structures face lateral pressure from unstable slopes (De Cesare 2023). Our field and morphological analyses have not detected landslide deposits or detachment niches, excluding large-scale gravitational phenomena. However, local-

ized ground instability appears more pronounced here than at the Doric Temple, which benefits from a more competent bedrock foundation.

5.3 Seismic activity and evidence of earthquake damage

Multiple failure patterns across Segesta are consistent with known indicators of earthquake damage (Stiros 1996; Galadini et al. 2006; Hinzen et al. 2011), including:

- Offset and rotation in column drums (Doric Temple and Stoa), consistent with torsional seismic forces rather than static gravitational stress. Such features have been widely documented in archaeoseismology (e.g., Theseion in Athens: Stiros 1996; Bottari 2005), and experimental studies confirm that gravitational sliding alone cannot explain these displacements (Stiros 2020).
- Misaligned and displaced masonry blocks in the Greek Theater and Agora, particularly in retaining structures, show bulging and collapse patterns comparable to seismic damage recorded at the Parthenon (Korres 1996; Stiros 2020).
- Offset steps and disrupted alignments reflect dynamic loading and possible coseismic deformation. Similar phenomena have been observed in the necropolis of Abakainon, where seismic shocks caused the displacement of funerary stelae (Bottari et al. 2013).
- Stratigraphic evidence from excavations reveals abrupt collapses, not attributable to long-term decay. These discontinuities corroborate a sudden, high-energy trigger, consistent with earthquake impact. The convergence of architectural, stratigraphic, and structural indicators supports the hypothesis that seismic events played a central role in the site's damage history (Mertens 1984; Miles 2019).

6 Results and discussion

6.1 Processing and results of geophysical data

Given the seismic-related damage patterns observed in the archaeological structures, a detailed geophysical investigation was undertaken to quantify the potential influence of local site effects. The processing and interpretation of MASW seismic data were carried out using winMASW software (Eliosoft 2018), which enables the analysis of Rayleigh wave dispersion to derive vertical shear-wave velocity (V_s) profiles. Figure 8 illustrates an example of the field velocity spectrum obtained from MASW survey #10 at the Mango site. In this figure, the dispersion curve of the fundamental Rayleigh mode (pink) is compared with the best-fit inverse model (blue) and the average of the models derived through genetic algorithm-based inversion (green dashed line).

The seismic noise data were processed using GRILLA software (Micromed s.p.a.). The H/V ratio has been calculated for all the segmented time windows, followed by the computation of an average HVSR curve after the removal of transient noise windows. An example of HVSR #14 data processing is presented in Fig. 9. The inversion of the HVSR curves, constrained by MASW derived models, yielded shear wave velocity models employed to estimate the depth of seismic bedrock and to construct three seismostratigraphic sections (Fig. 10) required for the LSR analysis.

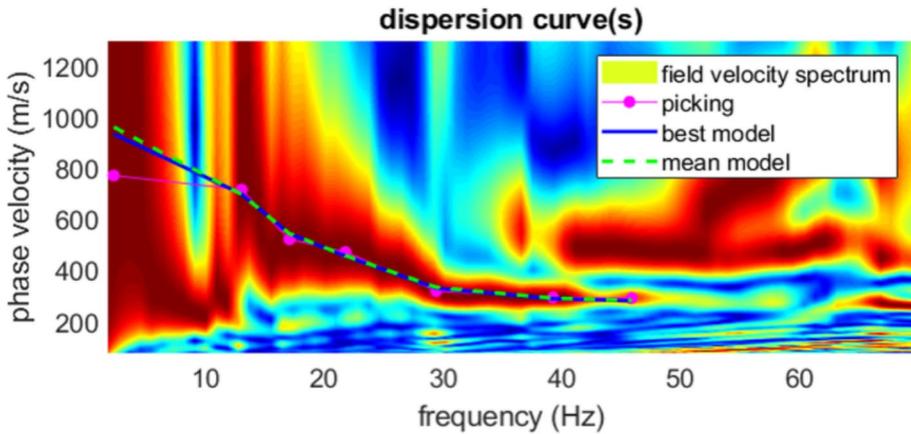


Fig. 8 Field velocity spectrum in the frequency/phase-velocity domain of MASW #10 conducted at the Mango site. The dispersion curve of the fundamental mode of Rayleigh waves (pink) is compared with the best-fit inverse model (blue) and the average of the models derived through inversion using genetic algorithms (green dashed)

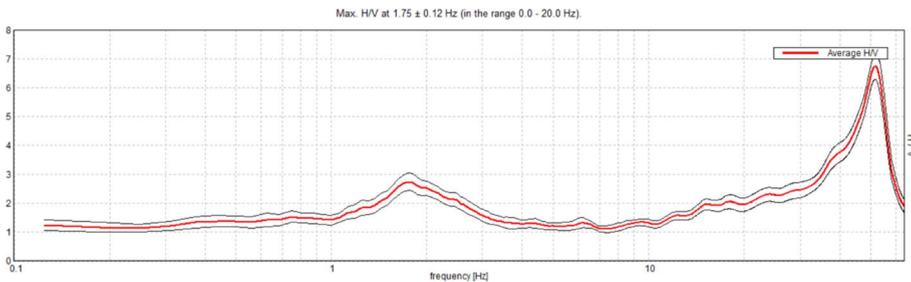


Fig. 9 Example of HVSR #14 processing. The H/V ratio was calculated for all time windows of the recorded seismic noise, and the average HVSR curve was obtained after removing windows affected by transient noise

The interpretation of the HVSR results plays a crucial role in distinguishing between topographic and stratigraphic amplification effects. A key diagnostic feature of topographic amplification is the presence of significant azimuthal variations in the H/V spectral ratio, which are typically observed along ridges, slopes, or isolated topographic highs due to directional resonance effects (Martorana et al. 2018). In the present study, no such azimuthal variations were identified in the analyzed HVSR curves, suggesting that the observed amplification phenomena are not primarily driven by topographic effects.

Instead, all valid spectral peaks, identified according to the SESAME project criteria, have been interpreted as indicative of stratigraphic amplification. This interpretation is further supported by the consistency of the identified resonance frequencies with the impedance contrasts inferred from the MASW-constrained HVSR inversion. The seismostratigraphic sections derived from the integrated analysis indicate the presence of significant velocity contrasts between the upper layers and the underlying seismic bedrock, reinforcing the

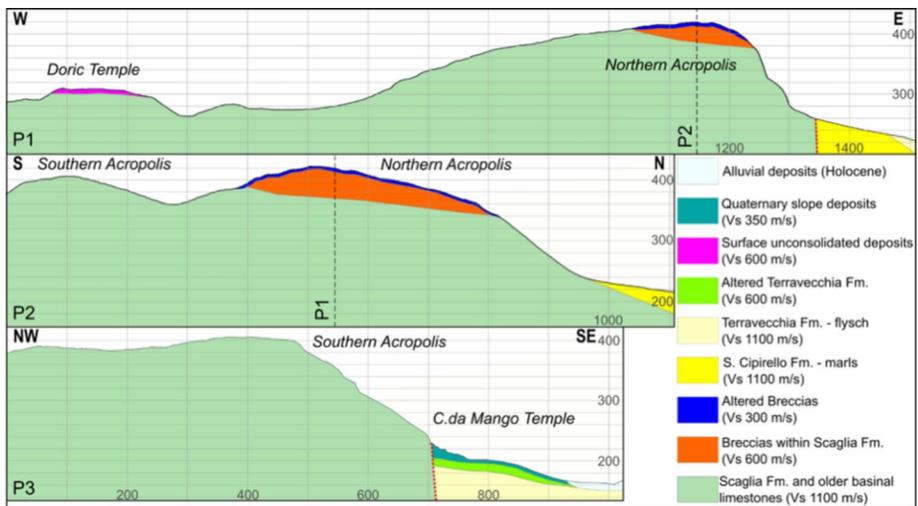


Fig. 10 Seismo-stratigraphic sections showing the geology, modified using the results of the HVSR and MASW analysis, and the location of the analyzed buildings (see profile traces in Fig. 2)

hypothesis that local site effects are predominantly governed by stratigraphic rather than topographic conditions.

The inverse model obtained by the MASW-constrained HVSR inversion at the Doric Temple site revealed a three-layered subsurface structure: a 3.5 m thick alteration deposit with $V_s = 570$ m/s; an underlying 3.5 m thick layer with $V_s = 650$ m/s, a seismic bedrock with $V_s = 1100$ m/s. The two near surface layers have been merged into a single layer of 600 m/s in the seismostratigraphic section needed for the local seismic response estimation.

Analogously, the inverse model obtained in the Agorà site is a four-layered model characterized by a superficial 3.5 m thick alteration deposit with $V_s = 300$ m/s. This can be due to the superficial alteration of the calcareous breach outcropping at the top of the hill that seismically is represented by a 2.5 m thick layer with $V_s = 550$ m/s followed by a 650 m/s layer 10 m thick. Finally, the seismic bedrock is characterized by 1100 m/s.

Also, for this site the near surface layers have been merged into a single layer of 600 m/s for the local seismic response estimation.

In the Mango Sanctuary site, the inverse model shows a 4 m superficial cover of $V_s = 300$ m/s. Under this the shear-wave velocity increases, reaching 600 m/s to a depth of 20 m. These values could be attributed to the coarse and sandy deposits dated to the upper Miocene. At the bottom, a 1100 m/s bedrock characterizes the lower section of the model.

6.2 Seismic amplification and structural vulnerability

The integration of remote sensing and geophysical methods has provided a multiscale, data-driven assessment of the seismic vulnerability of Segesta's archaeological structures. Drone-based photogrammetry enabled the precise documentation of structural deformations, while geophysical surveys characterized subsurface conditions, offering critical insights into site-specific seismic hazards.

The seismic action in the site is defined by a set of seven-time histories of recorded ground acceleration. The extraction of input accelerograms (Table 2) was performed using the REXELWEB tool. The average spectral ordinates of the seven selected signals approximate the site's target spectrum with a tolerance of -10% (deficiency) and + 30% (excess). The site's target spectrum is interpolated from the elastic spectrum defined by INGV based on 16,582 nodes across the national territory.

To construct the target spectrum, the Engineering Strong-Motion database (ESM) (Luzi et al. 2016; available at: <https://esm.mi.ingv.it>) was filtered based on specific parameters to ensure an accurate representation of the seismic action at the site under examination. In particular, a NTC site category of type A was considered, along with a topographic class T1, corresponding to a flat or slightly sloped terrain. The design was carried out assuming a nominal design life of 50 years, classifying the structure under use class 2, which includes standard buildings. Additionally, the limit state probability was set at 10%, in accordance with regulatory standards.

Further filtering criteria were applied to ensure the spectral compatibility of the selected time histories. Only records from stations with subsoil type A were considered, thereby excluding significant local amplification effects. Moreover, only signals corresponding to a single horizontal component were selected, with a magnitude range between 5.5 and 7, and an epicentral distance between 0 and 30 km, ensuring the representation of seismic events relevant to the site.

For spectral compatibility verification, a period range between 0.1 and 1.1 s was adopted, with a tolerance of -10% and + 30% relative to the target spectrum. Finally, to maintain the accuracy of the seismic action representation, a scaling factor of 1 was applied, avoiding artificial alterations of the transmitted seismic energy (Table 2).

Figure 11 shows the overlap of the input accelerograms' spectra with the site's target spectrum.

The results of the LSR2D analysis reveal varying levels of seismic amplification across the surveyed structures. Figure 12 presents average spectral data for four key locations: the Doric Temple, Theater, Stoa, and Mango Sanctuary, compared against the NTC2018 regulatory spectrum for type A soil. The Doric Temple (green curve) exhibits low amplification, with spectral values closely aligning with NTC2018 standards. In contrast, the Stoa (red curve) demonstrates significantly higher amplification, particularly within the 0.3–0.6 s range, with values exceeding 1.7 g, suggesting that site-specific geological conditions may have contributed to its structural instability. Moderate amplification is also observed at the

Table 2 Input accelerograms available at <https://esm.mi.ingv.it>

Accelerogram	Earthquake name	Date	Mw	Fault mechanism	Epicentral distance (km)	EC8 site class
Acc (1)	Bingol	01/05/2003	6.3	Strike slip	14	A
Acc (2)	Lazio Abruzzo	07/05/1984	5.9	Normal	22	A
Acc (3)	Kranidia	25/10/1984	5.5	?	23	A
Acc (4)	Friuli	06/05/1976	6.5	Thrust	23	A
Acc (5)	Lazio Abruzzo	07/05/1984	5.9	Normal	22	A
Acc (6)	Izmit (aftershock)	13/09/1999	5.8	Oblique	15	A
Acc (7)	South Iceland (aftershock)	21/06/2000	6.4	Strike slip	28	A

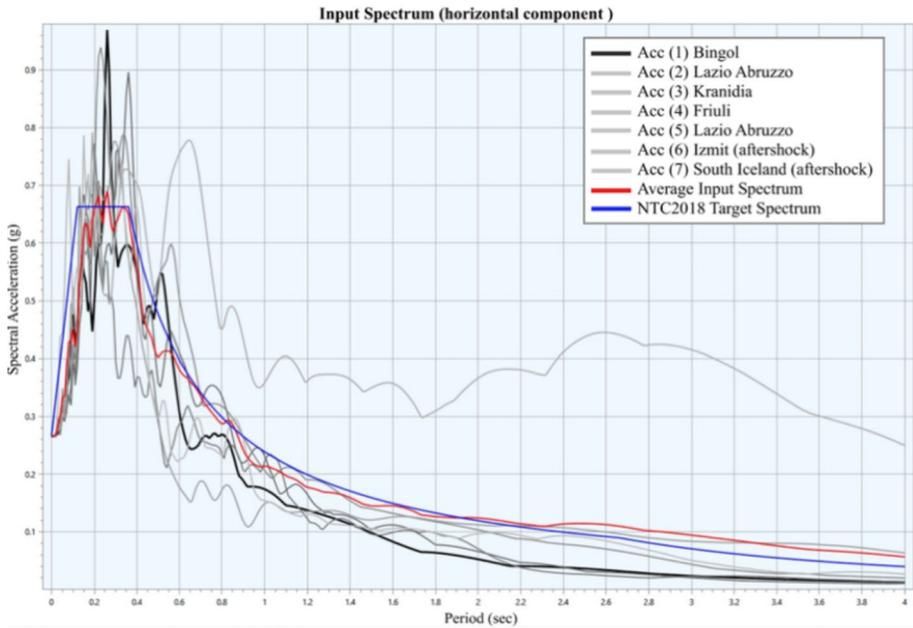


Fig. 11 Overlay of the target spectrum with the spectra of the input accelerograms

Mango Sanctuary (blue curve) and the Theater (yellow curve), though less pronounced than at the Stoa.

These findings indicate that local geological conditions and topography have influenced seismic wave propagation, likely exacerbating structural vulnerability and contributing to partial collapses. This is particularly relevant at the Stoa, where amplified seismic response may have played a decisive role in its destruction. The correlation between high spectral acceleration (S_a) values and structural damage underscores the importance of geomorphological and site-specific seismic studies in heritage conservation.

6.3 Evidence of earthquake-induced structural deformations

The archaeological and structural evidence suggests that seismic activity may have been a contributing factor in the collapse of several structures at Segesta, particularly during Phase D of the site's occupation. However, alternative explanations such as material degradation, structural instability, or environmental erosion cannot be ruled out. The following key observations support the hypothesis that seismic activity played a role in structural failures:

Oriented Collapse – The sequential and directional failure of structures is consistent with earthquake-induced collapse patterns rather than intentional destruction or gradual material degradation (Stiros 1996; Hancock and Altunel 1997; Jones and Stiros 2000; Galadini et al. 2006; Bottari et al. 2009; Hinzen 2009).

Stratigraphic Differentiation and Large Blocks – The stratigraphic differences between collapsed materials and in situ layers argue against gradual degradation. The presence of large, contiguous blocks suggests sudden structural failure (Bottari et al. 2013), which could be associated with a seismic event.

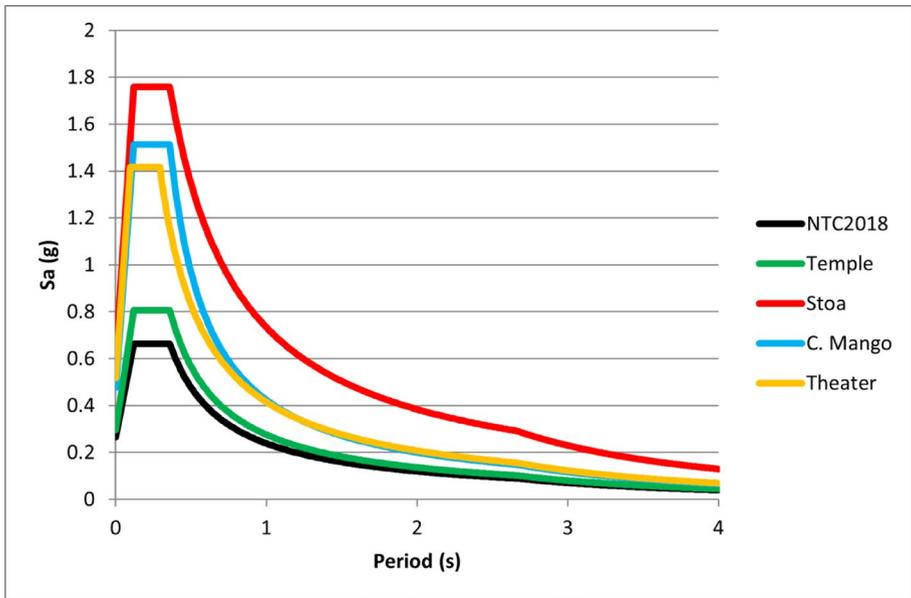


Fig. 12 The spectral graphs calculated at four distinct locations: the Doric Temple, the Theater, the Stoa, and the Mango Sanctuary. These spectra have been derived within the framework of parameterized seis-mostratigraphic sections (Newmark 1959) and are compared with the reference spectrum for soil type A, as defined by the Italian NTC2018 standards

Out-of-Plane Mechanisms – Observed out-of-plane displacements in the northern Stoa align with post-earthquake damage patterns documented at other seismically impacted sites (De Felice et al. 2022), although other destabilizing factors cannot be excluded.

Rotational Displacement of Column Drums – The misalignment of column drums, as seen at the Colonna Traiana in Rome and the Temple of Hephaistos in Athens, suggests dynamic forces consistent with seismic-induced acceleration (Boschi et al. 1995; Stiros 1996; Bottari 2005). While soil movement could also contribute to such displacements, numerical modeling indicates that ground accelerations exceeding 0.2–0.3 g are sufficient to induce this type of rotation, supporting the hypothesis of seismic involvement at Segesta (Hinzen 2009; Hinzen et al. 2011).

Offset in Steps and Blocks – Displacements in architectural steps and misalignment of adjoining blocks may be indicative of seismic shaking (Bottari et al. 2013), though differential settlement or structural instability cannot be dismissed.

Fractured Column Drum Corners – The presence of broken corners in column drums corresponds to oscillatory stress effects from seismic forces (Stiros 1996), yet mechanical degradation over time could also have contributed to this pattern.

Azimuthal Deformation Patterns – The observed structural deformations appear to align with known fault plane orientations, suggesting a correlation with seismic waves (Hinzen 2009), though further geophysical investigations are needed to confirm this hypothesis.

Seismic-Resistant Construction Techniques – The architectural layout of the Agora at Segesta, with open spaces and strategically designed rectangular forms, may indicate an awareness of seismic risk and a deliberate attempt by Greek and Roman engineers to

mitigate earthquake damage (Stiros 1995; Ferrigni 2005). However, these design choices could also reflect broader urban planning strategies rather than a direct response to seismic hazards.

While these indicators collectively support the hypothesis that seismic activity may have contributed to structural damage at Segesta, they do not provide conclusive proof of earthquake-induced collapse. Further investigations, including numerical modeling and detailed geotechnical analyses, are required to distinguish seismic effects from other potential causes of structural instability.

6.4 Chronological constraints on seismic events

Determining the exact timing of seismic events at Segesta remains challenging due to incomplete stratigraphic records, particularly at the Mango Sanctuary, where excavations in the 1950s–60s disrupted critical depositional contexts. However, a combination of ceramic analysis, numismatic evidence, and archaeological stratigraphy allows for the tentative dating of key seismic episodes affecting the Stoa:

- Mid-to-Late 5th Century BCE – The collapse of the Mango Sanctuary is tentatively attributed to this period, inferred primarily from occupation layers and the lack of subsequent architectural modifications (De Cesare et al. 2022; De Cesare 2023).
- Mid-3rd Century CE – A later seismic event is more precisely constrained by numismatic evidence, including coins from 236–238 CE found within the Stoa destruction layer, marking the final phase of occupation (Gandolfo 1995; Facella 2009; Ampolo and Parra 2012). Additional African tableware from the third century CE supports this timeframe, suggesting the collapse occurred after 238 CE and before 270 CE (Parra and Gagliardi 2006; Facella 2009; Ampolo and Parra 2012).

These chronological markers, reinforced by intact stratigraphy and archaeoseismological indicators, suggest that the most significant seismic impact at Segesta likely occurred in the mid-third century CE. However, this does not preclude the possibility of cumulative damage from earlier seismic events.

A review of archaeoseismological case studies indicates that the third century CE was a period of increased seismic activity across parts of the Mediterranean, with earthquake-induced damage documented at sites such as Hierapolis (Hancock and Altunel 1997) and the Colosseum in Rome (Galadini et al. 2018). However, no direct evidence exists for a major earthquake in Sicily during this time (Bottari et al. 2009). The structural damage observed at Segesta aligns with broader patterns of seismic activity affecting archaeological sites, though whether it resulted from a regional event or local fault activity remains uncertain.

6.5 Seismotectonic and archaeoseismological implications

Exploring the seismic and archaeological features of the Segesta site offers an intriguing insight into its historical context. Geophysical surveys utilizing MASW and HVSR methods have revealed significant spectral acceleration (S_a) values. Specifically, the Stoa exhibits a spectral acceleration of approximately 1.7 g, nearly double the 0.8 g recorded at the Doric Temple and considerably higher than the 1.4 g observed in the Mango Sanctuary. This ele-

vated S_a value, combined with factors such as the Stoa height, construction style, imposing columns, and strategic topographical placement, contributes to the site's high seismic vulnerability. The collapse of the Stoa at Segesta likely reflects a partial failure of the structure during a seismic event.

The potential seismogenic source responsible for the inferred seismic damage at Segesta is not defined yet. The known sources of earthquakes (DISS Working Group 2025) are located ca. 20 km to the south of Segesta, in the Belice area (ITCS021 Mazara-Belice; Fig. 1a), and ca 35 km to the north, in the Tyrrhenian offshore (ITCS022 Southern Tyrrhenian Sea), and are deemed to potentially generate M 6 and M 7 earthquakes, respectively. These sources are considered to be active within the present regional stress field induced by the $\sim 3\text{--}5$ mm/yr convergence between the North African and the European continental margins, where Sicily is trapped in between. As GNSS observations (Ferranti et al. 2008; D'Agostino et al. 2011; Devoti et al. 2017; Palano et al. 2020), borehole breakouts (Ragg et al. 1999), seismicity (Neri et al. 2005; Scarfi et al. 2024) and active stress data demonstrate (Mariucci and Montone 2025), this convergence is reflected in a NNW-SSE compressive axis that characterizes thrust and transpressional earthquakes like the 1968 Belice and the 2002 Palermo offshore events (Monaco et al. 1996; Azzaro et al. 2003; Guidoboni et al. 2003).

A useful observation for constraining the possible source comes from the macroseismic intensity induced near Segesta by the 1968 and 2002 seismic sequences. The 1968 sequence, characterized by three main shocks, has been assigned a magnitude of M_w max 6.4 in the CPTI15 catalog (Rovida et al. 2020; 2022), while a more recent re-evaluation based on macroseismic data suggests a lower magnitude of M_w 5.8 (Azzaro et al. 2020). During this sequence, the town of Calatafimi, located 4.5 km southeast of Segesta (Fig. 1a), experienced a maximum MCS intensity of VII, corresponding to an estimated PGA value of approximately 1.96 m/s^2 ($\sim 20\%$ of g ; see the INGV historic shakemap database, available at <https://shakemap.ingv.it/index.html>; Michelini et al. 2020). In contrast, the M_w max 5.9, 2002 sequence, which was located in the offshore area approximately 90 km northeast of Segesta, induced only an MCS intensity of IV–V in Calatafimi. However, this offshore seismogenic fault system extends further west, and a 2002-type earthquake occurring closer to Segesta (Fig. 1a) could potentially induce a higher macroseismic intensity at the site.

To complete the seismotectonic framework, Segesta sits close to the Montagna Grande Thrust Front (MGTF), which has been recently considered active in its south-western part, based on geophysical observations in the offshore of Marsala, and archaeoseismological observations in the historical site of *Lilybaeum* (Barreca et al. 2024). The thrust front merges to the NE with the Segesta fault (Fig. 1a) along the base of Monte Barbaro, where our field analysis has shown evidence of recent activity. In this view, the deformation of the archaeological structures in Segesta may also be ascribed to a moderate-sized earthquake sourced by the MGTF. In this scenario, even a smaller magnitude earthquake occurring closer to the site may induce macroseismic effects similar to those caused by larger events localized further away on a major seismogenic source (Belice or Southern Tyrrhenian sources), even if the spectral content of the seismic waves may be different.

Site response analyses indicate that local geological conditions, particularly the contrast between the Scaglia Formation and overlying deposits, likely amplified ground motions. Similar effects have been documented at Selinunte, where local soil conditions exacerbated earthquake damage (Schwellenbach et al. 2020).

The site-specific topographical features and suboptimal masonry quality likely exacerbated out-of-plane collapse mechanisms. While archaeological data play a vital role in identifying the occurrence of ancient earthquakes, estimating local seismic intensity, and determining the age, they do not provide detailed tectonic information on the origin of the seismic event, unless using quantitative methods, such as modeling of the expected shaking generated from a dataset of potential sources (e.g. Hinzen et al. 2011). The absence of historical earthquake records should not be interpreted as an absence of seismic events or of the presence of potential seismogenic sources, particularly given the sparseness or non-existent documentation from antiquity and the low tectonic rates.

6.6 Archaeoseismological significance and engineering adaptations

This study highlights the complex interplay between seismic activity and structural deformation in ancient architecture, using Segesta as a key case study to illustrate how seismic hazards influenced building design, structural failure, and eventual abandonment. The damage patterns documented at Segesta—including the fractured analemma wall of the Greek Theater, the collapse and overturning of architectural elements in the Stoa, and the misalignment of column drums in the Doric Temple—reflect not only the effects of seismic shaking, but also the limits of ancient engineering adaptations to local geological and topographic conditions.

At the same time, this research provides critical insights into the methodological integration of archaeological, stratigraphic, and geophysical data—particularly HVSR and MASW techniques—for identifying site-specific seismic vulnerabilities and interpreting damage scenarios. These results contribute both to the reconstruction of undocumented seismic events and to the development of interdisciplinary frameworks for seismic risk assessment and conservation in archaeologically and tectonically sensitive landscapes.

Furthermore, this research reinforces the importance of accounting for environmental interactions—such as the combined effects of seismic ground motion, stratigraphy, and slope geometry—when assessing the resilience of cultural heritage sites. In this context, the data presented here can inform future conservation strategies and risk assessments in archaeologically sensitive and seismically active regions.

7 Conclusions

This research provides a comprehensive assessment of structural deformation and seismic vulnerability at the Segesta archaeological site, integrating archaeological, geophysical, and remote sensing data. Our multidisciplinary approach reveals how local conditions—including site geometry, lithostratigraphy, and seismic response—critically shaped the stability of key monuments.

The observed damage patterns strongly support the occurrence of two previously undocumented local earthquakes, absent from historical records and national seismic catalogs. Features such as oriented collapses, rotated column drums, azimuthal fracture alignments, and displaced masonry blocks are consistent with established archaeoseismological indicators (Table 1). Alternative explanations—such as material decay, soil instability, or anthro-

pogenic interventions—fail to adequately account for the distribution and nature of the deformations.

Seismic amplification emerges as a key factor in damage variability. Site response analysis reveals substantial differences in spectral acceleration across Segesta, with the Stoa experiencing nearly double the amplification recorded at the Doric Temple, and similarly elevated levels at the Mango Sanctuary and Greek Theater. Although the Doric Temple appears less affected, structural features such as tilted columns and rotated drums—along with restoration evidence reported by Mertens (1984)—suggest that ground shaking likely occurred but was partially masked by the building's roofless state.

The identification of anti-seismic construction features in the Stoa, Theater, and Doric Temple points to an awareness of seismic risk among ancient builders. However, the extent of damage indicates that these measures were insufficient to withstand intense ground motion. The absence of landslide evidence and the limited stratigraphic documentation from mid-20th-century excavations suggest a cumulative damage scenario driven by multiple seismic events.

Based on stratigraphic and archaeological constraints, we propose two distinct seismic episodes: one affecting the Mango Sanctuary between ca. 450–430 BCE, and a later event between ca. 238–270 CE impacting the Northern Acropolis, including the Agora and Theater. These findings contribute new data to the seismic history of northwestern Sicily, a region long considered to exhibit low to moderate seismic hazard, with few historically documented events apart from the 1968 Belice earthquake and the destruction of Selinunte.

Beyond the specific case of Segesta, this research proposes a scalable and transferable methodological framework for archaeoseismological investigation in complex geo-archaeological contexts. By integrating stratigraphic, architectural, and geophysical data—particularly HVSR and MASW techniques—our approach enables the identification of site-specific seismic vulnerabilities and amplification effects that critically inform damage interpretation. This integrated framework not only enhances the detection and reconstruction of undocumented seismic events, but also provides a replicable model for assessing seismic risk in other heritage sites affected by similar geological and tectonic conditions. As such, it contributes to the broader theorization of archaeoseismological practices and supports the development of interdisciplinary strategies for cultural heritage conservation and disaster risk reduction.

While the presented evidence supports a seismic origin for many structural anomalies at Segesta, further numerical modeling and chronological refinement are required to quantify earthquake impact and disentangle overlapping natural and anthropogenic processes. Nonetheless, this study underscores the essential role of multidisciplinary archaeoseismology in reconstructing undocumented seismic events and enriching our understanding of past seismicity in regions lacking robust historical records.

Acknowledgements We would like to express our gratitude to Arch. Luigi Biondo and Arch. Antonella Ricotta, the Executive Director and Deputy Director of the Parco Archeologico of Segesta (Soprintendenza BB.CC.AA. di Trapani), for their support and for granting permission to conduct geophysical investigations. Special thanks go to Rossella Giglio and Cecilia Parra for their valuable and constructive discussions, as well as for providing critical historical and archaeological data. We also sincerely thank the reviewers for their insightful comments and suggestions, which have significantly improved the quality of this work.

Funding Open access funding provided by Istituto Nazionale di Geofisica e Vulcanologia within the CRUI-CARE Agreement. This work was supported by the ARES project “Archaeoseismological investigation in

western Sicily: new insights from geochemistry and tectonic data” of the Istituto Nazionale di Geofisica e Vulcanologia. (PI: C. Bottari), Grant No. 9999805.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abate A, Cannistraci OS (2012) Reimpieghi architettonici nell’agorà di Segesta. Il caso della Stoà Nord. In: Ampolo C (ed) *La città e le città della Sicilia antica*. Ottave Giornate Internazionali di Studi sull’area Elima e la Sicilia occidentale nel contesto mediterraneo. Roma
- Abate A, Cannistraci OS (2013) Agora. Analisi architettonica dell’ingresso monumentale all’ambiente I della Stoà Nord. *ASNP* 5(2):29–48
- Adamopoulos E, Rinaudo F (2020) UAS-based archaeological remote sensing: review, meta-analysis and state-of-the art. *Drones* 4(3):46. <https://doi.org/10.3390/drones4030046>
- Amico e Manzo (1977) Il trattamento delle lacune nel Tempio di Segesta, Soprintendenza per i Beni Culturali ed Ambientali di Trapani.
- Ampolo C, Parra MC (2012) L’Agora di Segesta: uno sguardo d’assieme tra iscrizioni e monumenti. In: Ampolo C (ed) *Atti delle Ottave Giornate Internazionali di Studi sull’area Elima e la Sicilia Occidentale*. Roma, pp 271–285
- Ampolo C, Parra MC (2018) Lavori pubblici e urbanistica tra storia epigrafia e archeologia: l’agorà ellenistico-romana di Segesta. In: Belvedere O, Bergemann J (eds) *Roman Sicily: cities and territories between monumentalization and economy crisis and development*. Palermo University Press
- Azzaro R, Barbano MS, Tertulliani A, Pirrotta C (2020) A reappraisal of the 1968 Valle del Belice seismic sequence (Western Sicily): a case study of intensity assessment with cumulated damage effects. *Ann Geophys*. <https://doi.org/10.4401/ag-8308>
- Azzaro R, Camassi R, D’Amico S, Mostaccio A, Scarfi L (2003) Il terremoto di Palermo del 6 settembre 2002: effetti macrosismici. *Quaderni di Geofisica* 31, Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://istituto.ingv.it/attivita-di-ricerca/prodotti-per-la-ricerca/le-collane-editoriali-ingv/quaderni-di-geofisica.html>
- Barreca G, Bruno V, Cocorullo C, Cultrera F, Ferranti L, Guglielmino F, Guzzetta L, Mattia M, Monaco C, Pepe F (2014) Geodetic and geological evidence of active tectonics in south-western Sicily (Italy). *J Geodyn* 82:138–149. <https://doi.org/10.1016/j.jog.2014.03.004>
- Barreca G, Bruno V, Dardanelli G, Guglielmino F, Lo Brutto M, Mattia M, Pipitone C, Rossi M (2020) An integrated geodetic and InSAR technique for the monitoring and detection of active faulting in south-western Sicily. *Ann Geophys*. <https://doi.org/10.4401/ag-8327>
- Barreca G, Pepe F, Sulli A, Morreale G, Gambino S, Gasparo Morticelli M, Grassi S, Monaco C, Imposa S (2024) Deformed archaeological remains at Lilybaeum in Western Sicily (southern Italy): possible ground signatures of a missed large earthquake. *Nat Hazards*. <https://doi.org/10.1007/s11069-024-06921-6>
- Bonmarito S, D’Angelo U, Vernuccio S (1991) Carta geologica della Tavoletta Segesta (F° 257 I NE) – Scala 1:25.000. Università di Palermo, Dipartimento di Geologia e Geodesia
- Boschi E, Caserta A, Conti C, Di Bona M, Funicello R, Malagnini L, Marra F, Martines G, Rovelli A, Salvi S (1995) Resonance of subsurface sediments: an unforeseen complication for designers of Roman columns. *Bull Seismol Soc Am* 85(1):320–324. <https://doi.org/10.1785/BSSA0850010320>
- Bottari C (2005) Ancient constructions as markers of tectonic deformation and of strong seismic motions. *Pure Appl Geophys* 162:761–765. <https://doi.org/10.1007/s00024-004-2639-6>
- Bottari C, Stiros SC, Teramo A (2009) Archaeological evidence for destructive earthquakes in Sicily between 400 B.C. and A.D. 600. *Geoarchaeology* 24(2):147–175. <https://doi.org/10.1002/gea.20260>
- Bottari C, Barbano MS, Pirrotta C, Azzaro R, Gueli A, Ristuccia G (2013) Archaeological evidence for a possible first century AD earthquake in the site of Abakainon (NE Sicily). *Quat Int* 316:190–199. <https://doi.org/10.1016/j.quaint.2013.10.004>

- Bottari C, Capizzi P, Sortino F (2024) Unraveling the seismic source in archaeoseismology: a combined approach on local site effects and geochemical data integration. *Heritage* 7(1):427–447. <https://doi.org/10.3390/heritage7010021>
- Cannistraci OS, Olivito R (2018) A Gymnasion at Segesta? A review of the archaeological and epigraphic evidence. In: Mania C, Trümper M (eds) *Proceedings of the international conference*, Berlin, pp 15–42
- Canzoneri A, Martorana R, Agate M, Gasparo Morticelli M, Capizzi P, Carollo A, Sulli A (2025) Reconstruction of a 3D bedrock model in an urban area using well stratigraphy and geophysical data: a case study of the city of Palermo. *Geosciences* 15(5):174. <https://doi.org/10.3390/geosciences15050174>
- Catalano R, Maniaci G (1992) Il santuario arcaico di Segesta. Un esempio di applicazione di metodi geologici all'archeologia. *Giornate Internazionali di Studi sull'Area Elima*. Gibellina, Pisa, pp 627–641
- Catalano R, Franchino A, Merlini S, Sulli A (2000) Central western Sicily structural setting interpreted from seismic reflection profiles. *Mem Soc Geol It* 55:71–85
- Catalano R, Merlini S, Sulli A (2002) The structure of western Sicily, central Mediterranean. *Petroleum Geosci* 8:7–18
- Catalano R, Agate M, Basilone L, Di Maggio C, Mancuso M, Sulli A (2011) Note illustrative della Carta Geologica d'Italia alla Scala 1:50.000. Foglio 593 – Castellammare del Golfo. Regione Siciliana – ISPRA. https://www.isprambiente.gov.it/Media/carg/note_illustrative/593_CastellammareDelGolfo.pdf
- Civile D, Lodolo E, Accaino F, Geletti R, Schiattarella M, Giustiniani M, Fedorik J, Zecchin M, Zampa L (2018) Capo Granitola-Sciacca Fault Zone (Sicilian Channel Central Mediterranean): structure vs magmatism. *Mar Pet Geol*. <https://doi.org/10.1016/j.marpetgeo.2018.05.016>
- D'Andria F (1995) Ricerche archeologiche sul teatro di Segesta. In: Guzzo PG (ed) *Studi e ricerche sul Teatro di Segesta*. Scuola Normale Superiore di Pisa, Pisa, pp 429–450
- D'Andria F (1997) Ricerche archeologiche sul teatro di Segesta. In: *Studi e ricerche sul Teatro di Segesta*. *Ann Sc Norm Super Pisa, Classe di Lettere e Filosofia*, vol 25, pp 1164–1168
- D'Agostino N, D'Anastasio E, Gervasi A, Guerra I, Nedimović MR, Seeber L, Steckler M (2011) Forearc extension and slow rollback of the Calabrian Arc from GPS measurements. *Geophys Res Lett* 38:L17304. <https://doi.org/10.1029/2011GL048270>
- Danciu L, Giardini D, Weatherill G, Basili R, Nandan S, Rovida A, Beauval C, Bard PY, Pagani M, Reyes CG, Sesetyan K, Vilanova S, Cotton F, Wiemer S (2024) The 2020 European seismic hazard model: overview and results. *Nat Hazards Earth Syst Sci* 24:3049–3073. <https://doi.org/10.5194/nhess-24-3049-2024>
- Dardanelli G, Lo Brutto M, Pipitone C (2020) GNSS CORS network of the University of Palermo: design and first analysis of data. *Geogr Tech* 15(1):43–69. https://doi.org/10.21163/GT_2020.151.05
- De Bernardi Ferrero D (1997) Il teatro di Segesta: architettura e funzione. In: Guzzo PG (ed) *Teatri Greci e Romani in sicilia*. L'Erma di Bretschneider, Roma, pp 145–168
- De Cesare M (2023) Segesta, santuario di contrada mango. Palermo University Press, Palermo
- De Felice G, Fuggeri R, Gobbi F (2022) Overturning of the façade in single-nave churches under seismic loading. *Bull Earthq Eng* 20:941–962. <https://doi.org/10.1007/s10518-021-01243-5>
- De Cesare M, Giuliano D, Montali G (2022) Segesta, santuario di contrada mango. Il cantiere del tempio: dalla progettazione alla costruzione. In: *Atti del Convegno di Studi Reggio Calabria*, Museo Archeologico Nazionale. Scienze e Lettere, Roma, 2024
- Devoti R, D'Agostino N, Serpelloni E, Pietrantonio G, Riguzzi F, Avallone A, Cavaliere A, Cheloni D, Cecere G, D'Ambrosio C, Franco L, Selvaggi G, Metois M, Esposito A, Sepe V, Galvani A, Anzidei M (2017) A combined velocity field of the Mediterranean region. *Ann Geophys*. <https://doi.org/10.4401/ag-7059>
- Di Stefano P, Favara R, Luzio D, Renda P, Cacciatore MS, Calò M, Napoli G, Parisi L, Todaro S, Zarcone G (2015) A regional-scale discontinuity in western Sicily revealed by a multidisciplinary approach: a new piece for understanding the geodynamic puzzle of the southern Mediterranean. *Tectonics* 34:2067–2085. <https://doi.org/10.1002/2014TC003759>
- Dipasquale C (2014) Segesta: l'ambiente A sulla terrazza inferiore sud-occidentale. Un contributo allo studio di Segesta Arcaico-Classica. PhD thesis, Università di Pisa
- DISS Working Group (2025) Database of individual seismogenic sources (DISS), version 3.3.1: a compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas. Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/diss3.3.1>
- Ebolese D, Lo Brutto M, Dardanelli G (2019) UAV survey for the archaeological map of Lilybaeum (Marsala, Italy). *ISPRS Ann Photogramm Remote Sens Spatial Inf Sci* 42(2/W11):495–502
- Eliosoft (2018) winMASW Academy—Software for surface wave analysis. Eliosoft, Italy. Available at: <https://www.winmasw.com>
- EMODnet Bathymetry Consortium (2022) EMODnet Digital Bathymetry (DTM 2022). <https://doi.org/10.12770/ff3aff8a-cff1-44a3-a2c8-1910bf109f85>
- Erdas D (2010) Segesta. Settore Nord dell'Agora (2007–08). *ASNPN* 2(2):41–49
- Faccella A, Olivito R (2013) Segesta. Agora. Area della Stoa Nord (SAS; 2012). *ASNPN* 5(5/2):10–14.

- Faccenna C, Becker TW, Lucente FP, Jolivet L, Rossetti F (2001) History of subduction and back-arc extension in the Central Mediterranean. *Geophys J Int* 145(3):809–820. <https://doi.org/10.1046/j.0956-540x.2001.01435.x>
- Facella A (2009) Segesta tardoantica: topografia, cronologia e tipologia dell'insediamento. In: Ampolo C (ed) *Atti delle VI Giornate Internazionali di Studi sull'area Elima e la Sicilia occidentale nel contesto mediterraneo*. Pisa, pp 589–607
- Fedorik J, Toscani G, Lodolo E, Civile D, Bonini L, Seno S (2018) Structural analysis and Miocene-to-present tectonic evolution of a lithospheric-scale transcurrent lineament: the Sciacca Fault (Sicilian channel, central Mediterranean Sea). *Tectonophysics* 722:342–355. <https://doi.org/10.1016/j.tecto.2017.11.014>
- Ferranti L, Oldow JS, D'Argenio B, Catalano R, Lewis D, Marsella E, Avellone G, Maschio L, Pappone G, Pepe F, Sulli A (2008) Active deformation in southern Italy, Sicily and southern Sardinia from GPS velocities of the Peri-Tyrrhenian Geodetic Array (PTGA). *Ital J Geosci* 127(3):299–316
- Ferranti L, Pepe F, Barreca G, Meccariello M, Monaco C (2019) Multi-temporal tectonic evolution of Capo Granitola and Sciacca foreland transcurrent faults (Sicily Channel). *Tectonophysics* 765:187–204. <https://doi.org/10.1016/j.tecto.2019.05.002>
- Ferranti L, Burrato P, Sechi D, Andreucci S, Pepe F, Pascucci V (2021) Late quaternary coastal uplift of southwestern Sicily, central Mediterranean Sea. *Quat Sci Rev* 255:106812. <https://doi.org/10.1016/j.quascirev.2021.106812>
- Ferrigni F (2005) The local seismic culture. In: Ferrigni F, Helly B, Mauro A, Mendes Victor L, Pierrotti P, Rideaud A, Teves Costa P (eds) *Ancient buildings and earthquakes: the local seismic culture approach: principles, methods, potentialities*. Centro Culturale Europeo di Ravello, Council of Europe, Strasbourg, p 360
- Galadini F, Hinzen KG, Stiros SC (2006) Archaeoseismology: methodological issues and procedure. *J Seismol* 10:395–414. <https://doi.org/10.1007/s10950-006-9027-x>
- Galadini F, Ricci G, Falcucci E (2018) Panzieri C (2018) archaeoseismological evidence of past earthquakes in Rome (fifth to ninth century AD) used to quantify dating uncertainties and coseismic damage. *Nat Hazards* 94:319–348. <https://doi.org/10.1007/s11069-018-3390-0>
- Gandolfo L (1995) Segesta. Parco Archeologico e relazioni preliminari delle campagne di scavo 1990–1993. *Ann Sc Norm Super Pisa Cl Lett Filos* 25(4):1204–1260
- Giglio R (2021) Il Parco Archeologico di segesta. L'Erma di Bretschneider, Roma
- Guidoboni E, Muggia A, Marconi C, Boschi E (2002) A case study in archaeoseismology: the collapses of the Selinunte temples (Southwestern Sicily): two earthquakes identified. *Bull Seismol Soc Am* 92(8):2961–2982. <https://doi.org/10.1785/0120010286>
- Guidoboni E, Mariotti D, Giammarinaro MS, Rovelli A (2003) Identification of amplified damage zones in Palermo, Sicily (Italy) during the earthquakes of the last three centuries. *Bull Seismol Soc Am* 93(4):1649–1669. <https://doi.org/10.1785/0120020145>
- Hancock PL, Altunel E (1997) Faulted archaeological relics at Hierapolis (Pamukkale), Turkey. *J Geodyn* 24(1–4):1–4. [https://doi.org/10.1016/S0264-3707\(97\)00003-3](https://doi.org/10.1016/S0264-3707(97)00003-3)
- Hinzen KG (2009) *Bull Seismol Soc Am* 99(5):2855–2875. <https://doi.org/10.13127/ISIDE>
- Hinzen KG, Fleischer C, Reamer SK, Schreiber S, Schütte S, Yerli B (2011) Quantitative methods in archaeoseismology. *Quat Int* 242(1):31–41. <https://doi.org/10.1016/j.quaint.2010.11.006>
- Hinzen KG, Meghraoui M, Bahrouni N, Houla Y, Reamer SK (2021) Archaeoseismological study of the Cherchira aqueduct bridge, Kairouan, Tunisia. *Med Geosci Rev* 3:403–430
- Infarinato A (2004) Segesta settore occidentale dell'Agora (SAS 4 Ovest; 2005–2006). *Not Sc ASNP* 9(2):447–455
- ISIDE Working Group (2007) Italian seismological instrumental and parametric database (ISIDe). Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/ISIDE>
- Jiménez-Jiménez SI, Ojeda-Bustamante W, de Jesús M-P, Enciso J (2021) Digital terrain models generated with low-cost UAV photogrammetry: methodology and accuracy. *ISPRS Int J Geo Inf* 10(5):285. <https://doi.org/10.3390/ijgi10050285>
- Jones R, Stiros S (2000) The advent of archaeoseismology in the Mediterranean. In: McGuire et al (eds) *The archaeology of geological catastrophes*, vol 171. Geological Society Special Publication, London, pp 25–31
- Karcz I, Kafri U (1978) Evaluation of supposed archaeoseismic damage in Israel. *J Archaeol Sci* 5(3):237–253. [https://doi.org/10.1016/0305-4403\(78\)90042-0](https://doi.org/10.1016/0305-4403(78)90042-0)
- Korres M (1996) Seismic damage to the monuments of the Athenian Acropolis. In: Jones R, Stiros SC (eds) *Archaeoseismology*. British School at Athens, Athens, pp 69–74
- Lanciani R (1918) Segni di terremoti negli edifici di Roma antica. *Bull Comm Arch Rom* 45:1–30

- Li X, Xiong B, Yuan Z, He K, Liu X, Liu Z, Shen Z (2021) Evaluating the potentiality of using control-free images from a mini unmanned aerial vehicle (UAV) and structure-from-motion (SfM) photogrammetry to measure paleoseismic offsets. *Int J Remote Sens* 42(7):2417–2439. <https://doi.org/10.1080/01431161.2020.1862434>
- Lo Brutto M, Garraffa A, Meli P (2014) Uav platforms for cultural heritage survey: first results. *ISPRS Ann Photogramm Remote Sens Spatial Inf Sci II-5*:227–234. <https://doi.org/10.5194/isprsnals-II-5-227-2014>
- Lo Jacono (1985) Miglioramento degli standard di fruizione e intervento di restauro del tempio di Segesta. Soprintendenza per i Beni Culturali ed Ambientali di Trapani, Trapani. Unpublished report
- Lunedei E, Malischewsky P (2015) A review and some new issues on the theory of the H/V technique for ambient vibrations. In: *Perspectives on European earthquake engineering and seismology*, pp 371–394. https://doi.org/10.1007/978-3-319-16964-4_15
- Luzi L, Puglia R, Russo E, ORFEUS WG5 (2016) Engineering strong motion database, version 1.0. Istituto Nazionale di Geofisica e Vulcanologia, Observatories and Research Facilities for European Seismology. <https://doi.org/10.13127/ESM>
- Marco S (2008) Recognition of earthquake-related damage in archaeological sites: examples from the Dead Sea fault zone. *Tectonophysics* 453:148–156. <https://doi.org/10.1016/j.tecto.2007.04.011>
- Mariucci MT, Montone P (2025) IPSI 1.7, Database of Italian Present-day Stress Indicators, Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/IPSI.1.7>
- Martorana R, Capizzi P, Avellone G, Siragusa R, D’Alessandro A, Luzio D (2017) Assessment of a geological model by surface wave analyses. *J Geophys Eng* 14(1):159–172. <https://doi.org/10.1088/1742-2140/14/1/159>
- Martorana R, Agate M, Capizzi P, Cavera F, D’Alessandro A (2018) Seismo-stratigraphic model of “La Bandita” area (Palermo Plain, Sicily) through HVSR inversion constrained by stratigraphic data. *Ital J Geosci* 137(1):73–86. <https://doi.org/10.3301/IJG.2017.18>
- Martorana R, Capizzi P, Pisciotto A, Scudero S, Bottari C (2023) An overview of geophysical techniques and their potential suitability for archaeological studies. *Heritage* 6(3):2886–2927. <https://doi.org/10.3390/heritage6030154>
- Mauz B, Renda P (1996) Tectonic features at the NW-coast of Sicily (Gulf of Castellammare): implications for the Plio-Pleistocene structural evolution of the southern Tyrrhenian continental margin. *Stud Geol Camerti* 1995:343–350
- Meghraoui M, Gomez F, Sbeinati R, Van der Woerd J, Mouty M, Darkal AN, Radwan Y, Layyous I, Al Najjar H, Darawcheh R, Hijazi F, Al-Ghazzi R, Barazangi M (2003) Evidence for 830 years of seismic quiescence from palaeoseismology, archaeoseismology and historical seismicity along the Dead Sea fault in Syria. *Earth Planet Sci Lett* 210(1–2):35–52
- Mertens D (1984) Der Tempel von Segesta und die dorische Tempelbaukunst des griechischen Westens in klassischer Zeit. Mainz am Rhein
- Michelini A, Faenza L, Lanzano G, Lauciani V, Jozinović D, Puglia R, Luzi L (2020) The new ShakeMap in Italy: progress and advances in the last 10 yr. *Seismol Res Lett* 91(1):317–333. <https://doi.org/10.1785/0220190130>
- Miles MM (2019) Large temples as cultural banners. In: Blakely S, Collins BJ (eds) *Religious convergence in the ancient Mediterranean*. Lockwood Press, Atlanta, pp 59–75
- Monaco C, Mazzoli S, Tortorici L (1996) Active thrust tectonics in western Sicily (Southern Italy): the 1968 Belice earthquake sequence. *Terra Nova* 8(4):372–381. <https://doi.org/10.1111/j.1365-3121.1996.tb00570.x>
- Mucciarelli M, Gallipoli MR (2001) A critical review of 10 years of microtremor HVSR technique. *Boll Geofis Teor Appl* 42(3–4):255–266
- Nakamura Y (1989) A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Q R Railw Tech Res Inst RTRI* 30(1):25–33
- Nenci G, Tusa S, Tusa V (eds) (1988) *Gli Elimi e l’area elima fino all’inizio della prima guerra punica*. Atti del Seminario di studi: Palermo, Contessa Entellina, 25–28 maggio 1988. Società Siciliana per la Storia Patria, Palermo, pp 393
- Neri G, Barberi G, Oliva G, Orecchio B (2005) Spatial variations of seismogenic stress orientations in Sicily, south Italy. *Phys Earth Planet Inter* 148:175–191. <https://doi.org/10.1016/j.pepi.2004.08.009>
- Newmark NM (1959) A method of computation for structural dynamics. *J Eng Mech Div* 85(3):67–94. <https://doi.org/10.1061/jmcea3.0000098>
- Olivito R, Taccola E (2014) 3D modelling in the agora of Segesta: techniques and data interpretation. *Archeol Calcol* 25:175–188
- Palano M, Ursino A, Spampinato S et al (2020) Crustal deformation, active tectonics and seismic potential in the Sicily Channel (Central Mediterranean), along the Nubia-Eurasia plate boundary. *Sci Rep* 10:21238. <https://doi.org/10.1038/s41598-020-78063-1>

- Palano M, Ursino A, Spampinato S, Sparacino F, Polonia A, Gasperini L (2021) Crustal deformation, active tectonics, and seismic potential in the Sicily Channel (Central Mediterranean) along the Nubia-Eurasia plate boundary. *Sci Rep* 10:21238. <https://doi.org/10.1038/s41598-020-78063-1>
- Park CB, Miller RD, Xia J (1999) Multichannel analysis of surface waves. *Geophysics* 64(3):800–808. <https://doi.org/10.1190/1.1444590>
- Parra MC (2006) Note di architettura ellenistica a Segesta intorno all'agorà. In: Osanna M, Torelli M (eds) *Sicilia ellenistica consuetudo Italica: alle origini dell'architettura ellenistica d'Occidente*. Ateneo, Roma, pp 107–122
- Parra MC, Gagliardi V (2006) Ceramiche africane dal Foro di Segesta: dati preliminari. In: Akerraz A, Ruggeri P, Siraj A (eds) *L'Africa romana. Mobilità delle persone e dei popoli, dinamiche migratorie, emigrazioni ed immigrazioni nelle province occidentali dell'Impero romano*. Atti del XVI Convegno di studio, Rabat, 15–19 December 2004, pp 1615–1628
- Parrino N, Pepe F, Burrato P, Dardanelli G, Corradino M, Pipitone C, Gasparo Morticelli M, Sulli A, Di Maggio C (2022) Elusive active faults in a low strain rate region (Sicily, Italy): hints from a multidisciplinary land-to-sea approach. *Tectonophysics*. <https://doi.org/10.1016/j.tecto.2022.229520>
- Pepe M, Alfio VS, Costantino D (2022) UAV platforms and the SfM-MVS approach in the 3D surveys and modelling: a review in the cultural heritage field. *Appl Sci* 12:12886. <https://doi.org/10.3390/app122412886>
- Petropoulos GP, Maltese A, Carlson TN, Provenzano G, Pavlides A, Ciruolo G, Hristopoulos D, Capodici F, Chalkias C, Dardanelli G, Manfreda S (2021) Exploring the use of unmanned aerial vehicles (UAVs) with the simplified 'triangle' technique for soil water content and evaporative fraction retrievals in a Mediterranean setting. *Int J Remote Sens* 42(5):1623–1642. <https://doi.org/10.1080/01431161.2020.1841319>
- Ragg S, Grasso M, Muller B (1999) Patterns of tectonic stress in Sicily from borehole breakout observations and finite element modeling. *Tectonics* 18:669–685
- Rovida A, Locati M, Camassi R, Lolli B, Gasperini P (2020) The Italian earthquake catalogue CPTI15. *Bull Earthquake Eng* 18(7):2953–2984. <https://doi.org/10.1007/s10518-020-00818-y>
- Rovida A, Locati M, Camassi R, Lolli B, Gasperini P, Antonucci A (2022) Catalogo Parametrico dei Terremoti Italiani (CPTI15), versione 4.0. Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/cpti/cpti15.4>
- Scarfi L, Barberi G, Barreca G, Musumeci C, Tusa G (2024) Insights into Western Sicily's seismotectonics from recent seismicity and 1968 Belice mainshock ground motion simulations. *Nat Hazards*. <https://doi.org/10.1007/s11069-024-07009-x>
- Schwellenbach I, Hinzen KG, Petersen GM, Bottari C (2020) Combined use of refraction seismic, MASW, and ambient noise array measurements to determine the near-surface velocity structure in the Selinunte Archaeological Park, SW Sicily. *J Seismol* 24:753–776. <https://doi.org/10.1007/s10950-020-09909-4>
- SESAME Project (2004) Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: measurements, processing, and interpretation. European Research Project, WP12—Deliverable D23.12. Available at: https://sesame.geopsy.org/Delivrables/Del-D23-HV_User_Guidelines.pdf.
- Stacec (2013) LSR 2D, software. Available at: http://www.stacec.com/lsr-2d_pp92.aspx
- Stiros SC (1995) Archaeological evidence of antiseismic constructions in antiquity. *Ann Geophys* 38:735–736. <https://doi.org/10.4401/ag-4056>
- Stiros SC (1996) Identification of earthquakes from archaeological data: methodology, criteria and limitations. In: Jones R, Stiros SC (eds) *Archaeoseismology*. British School at Athens, Athens, pp 129–152
- Stiros SC (2001) The AD 365 Crete earthquake and possible seismic clustering during the 4–6th centuries AD in the Eastern Mediterranean: a review of historical and archeological data. *J Struct Geol* 23:545–562
- Stiros SC (2020) Monumental articulated ancient Greek and Roman columns and temples and earthquakes: archaeological, historical, and engineering approaches. *J Seismol* 24:853–881. <https://doi.org/10.1007/s10950-019-09902-6>
- Stucchi M, Meletti C, Montaldo V, Akinci A, Faccioli E, Gasperini P, Malagnini L, Valensise G (2004) Pericolosità sismica di riferimento per il territorio nazionale (MPS04). Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/sh/mps04/ag>
- Sulli A, Gasparo Morticelli M, Agate M, Zizzo E (2021) Active north vergent thrusting in the northern Sicily continental margin in the frame of the Quaternary evolution of the Sicilian collisional system. *Tectonophysics* 802:228717. <https://doi.org/10.1016/j.tecto.2021.228717>
- Tusa V (1984) Il peristilio dorico di Segesta attraverso i secoli. Riproduzioni, descrizioni di studiosi e di viaggiatori. In: Mertens, D. (ed.), *Der Tempel von Segesta und die dorische Tempelbaukunst des griechischen Westens in klassischer Zeit*. Sonder-schriften des Deutschen Archäologischen Instituts, Römische Abteilung, Bd. 6. Mainz: von Zabern, pp. 132–151

Vantassel JP, Cox BR, Meles GA, Wood CM (2018) Mapping depth to bedrock, shear stiffness, and fundamental site period at CentrePort, Wellington using surface wave methods: implications for local seismic site amplification. *Bull Seismol Soc Am* 108(3B):1709–1721. <https://doi.org/10.1785/0120170287>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Carla Bottari¹  · Pierfrancesco Burrato²  · Patrizia Capizzi³  ·
Raffaele Martorana³  · Mauro Lo Brutto⁴  · Antonino Maltese⁴  ·
Gino Dardanelli⁴  · Alessandro Canzoneri³  · Alessandra Carollo³  ·
Luigi Ferranti^{5,2} 

✉ Carla Bottari
carla.bottari@ingv.it

Pierfrancesco Burrato
pierfrancesco.burrato@ingv.it

Patrizia Capizzi
patrizia.capizzi@unipa.it

Raffaele Martorana
raffaele.martorana@unipa.it

Mauro Lo Brutto
mauro.lobruzzo@unipa.it

Antonino Maltese
antonino.maltese@unipa.it

Gino Dardanelli
gino.dardanelli@unipa.it

Alessandro Canzoneri
alessandro.canzoneri@unipa.it

Alessandra Carollo
alessandra.carollo02@unipa.it

Luigi Ferranti
luigi.ferranti@unina.it

¹ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, Osservatorio Etneo, 95125 Catania, Italy

² Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Roma 1, 00143 Rome, Italy

³ Dipartimento di Scienze della Terra e del Mare, Università degli Studi di Palermo, 90123 Palermo, Italy

⁴ Dipartimento di Ingegneria, Università di Palermo, 90128 Palermo, Italy

⁵ Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università Federico II di Napoli, 89138 Naples, Italy