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Seismic Activity Along the Periadriatic and Sava Faults in the Past Two Millennia—An Archaeoseismological Assessment

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Abstract: Most of the Periadriatic Fault System has been active during the Oligocene and Miocene times. Its western part seems to be almost inactive ever since, while the eastern segments show limited seismic activity. We conducted a systematic archaeoseismological survey along the Periadriatic-Sava fault system, assessing buildings and archaeological sites for earthquake damage. Eleven sites, four Roman and seven Medieval, bear evidence of destructive earthquakes which occurred during the past 2000 years. These are (from east to west): Roman Siscia (Sisak) near the Sava fault in Croatia, Roman Celeia (Celje) at the Savinja/Sava faults in Slovenia, Magdalensberg (Roman) just north of the Karavanka fault, Medieval Villach, the Dobratsch landslide and Medieval Arnoldstein at the junction of Mölltal and Gailtal faults, Medieval Millstatt, Sachsenburg. and Roman Teurnia on the Mölltal Fault, Medieval Lienz (all in Austria) and San Candido on the Pustertal fault, as well as Medieval Merano and Tirol (in Italy) adjacent to the North Giudicarie fault zone. Damaged upright walls of Medieval buildings and deformed floors of Roman settlements testify to local intensity up to IX. Ongoing studies of archaeological stratigraphy and construction history allow the dating of one or more seismic events at each site, ranging from the 1st century AD to the 17th century. It is remarkable that the sites, 20 to 70 km apart, along a <400 km long segment of the Periadriatic Fault system, carry evidence for so many high-intensity destructive events, suggesting that the region is tectonically active.

Keywords: earthquake; Eastern Alps; Southern Alps; paleoseismology

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1. Introduction

The fault system separating the Central and Eastern Alps from the Southern Alps is collectively called the Periadriatic fault system [1]. It is an Oligocene–Miocene dextral strike-slip system, parts of which (esp. the Giudicarie Fault) subsequently suffered some less spectacular left-lateral deformation [1]. An eastern continuation towards the Pannonian Basin is probably towards the Balaton Fault [2] or to the Croatian Sava Fault [3,4]. Northward motion and concurrent counterclockwise rotation of the Adriatic microplate determines the stress field of the Alpine region. S_{max} trajectories meet the Periadriatic Fault at a high angle [5,6], permitting but not demanding recent activity. The seismically most active, easternmost part—east of Villach—in Slovenia displays ca. 1–2 mm/year dextral displacement [7], while the rest towards the west seems to be inactive. Historical and instrumental seismicity [8,9] do not show any significant activity that is out of the background [10–13]. However, major past displacements along the Periadriatic Fault [14–16] and the clear visibility of the fault trace at various sites in the relief raised interest in tracking its Quaternary activity. Prince et al. [17] found evidence for Late Pleistocene faulting by electron spin resonance (ESR) and optically stimulated luminescence (OSL) dating of fault gouge. Lacustrine sedimentology yielded data for major seismic shocks during both the Late Pleistocene and historical times [18–22]. Observing fractures

with growing displacements within caves in the Slovenian Karavanka Mts showed ongoing, slow tectonic deformation [23].

We applied the methods of archaeoseismology [24–28] to find evidence for past earthquakes recorded by the built environment.

The Mediterranean is the home where archaeoseismology was born and where most of the studies have been published up to now (See Appendix A for those Italian studies, mainly from the Appennines, which supply details on the methodology applied). Those related to the southern Alps are from Trento [29], from Egna between Trento and Bolzano [30,31], from Verona [32], and from Como [33]. Archaeoseismological studies just started in Slovenia [34] and in Croatia [35]. A book chapter on Magdalensberg represents studies in the southern part of Austria [36].

We systematically surveyed Roman settlements, inhabited mostly in the first to fourth centuries AD, to identify and parametrize unknown earthquakes along the Periadriatic Fault system [37]. Here, we present the results of archaeoseismological studies on eleven sites, four Roman and seven Medieval, which display evidence for destructive earthquakes during the past 2000 years (Figure 1).

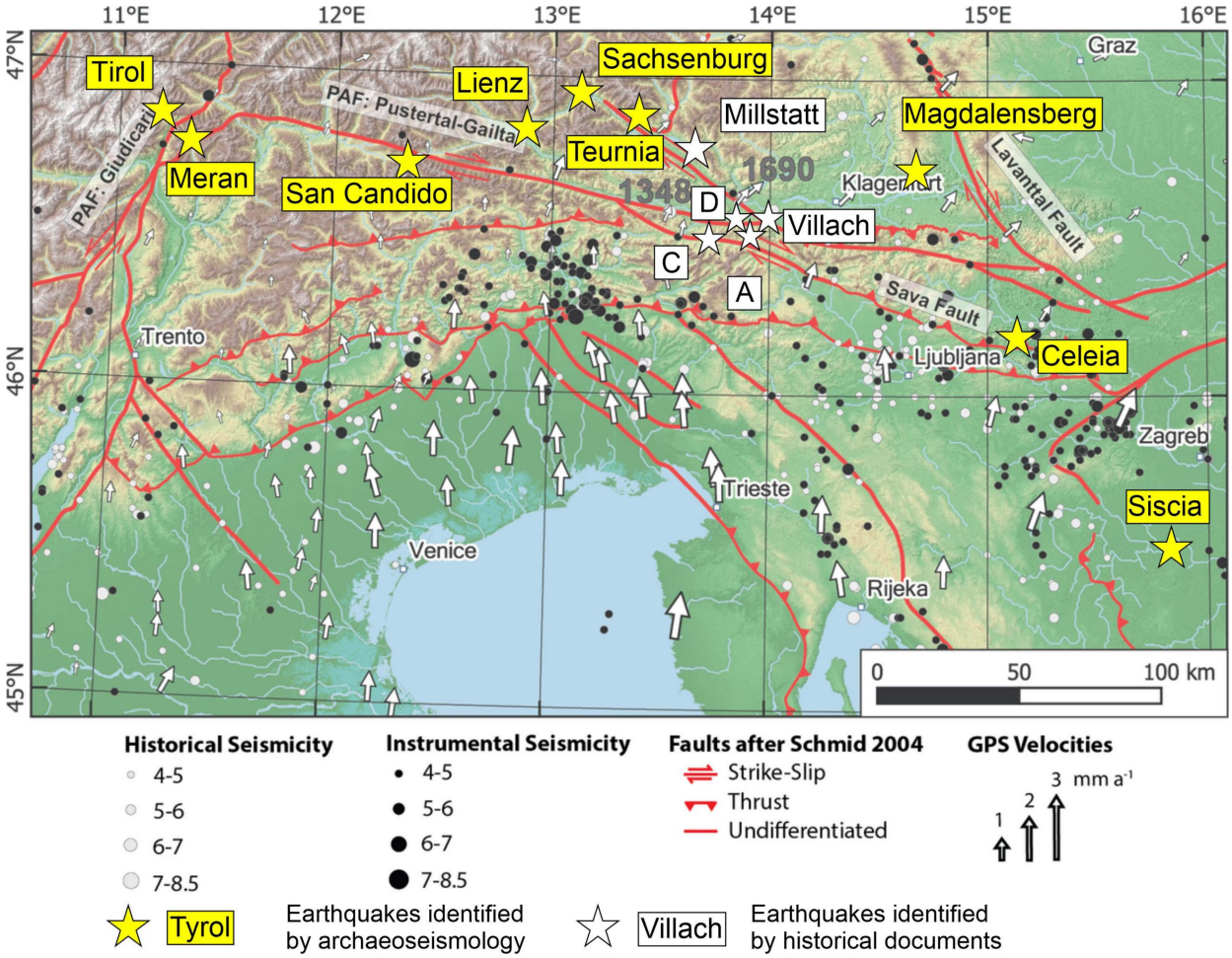


Figure 1. Sites studied for archaeoseismological evidence for earthquakes of the past two millennia along the Periadriatic Line fault system. Base map after [17], modified. A—Arnoldstein, C—Camporosso, D—Dobratsch. Main faults are based on the Active Faults of Eurasia Database—AFEAD. Earthquakes in 1000–1899: SHARE European Earthquake Catalog. Earthquakes in 1900–2006: SHARE European Earthquake Catalog.

2. Methods

We investigated the possibility that there were damaging earthquakes near the Periadriatic Fault system in historical times by archaeoseismology: studying standing buildings

and archaeological sites for potential seismic damage. Seismic damage was assessed based on standard methods of describing deformed upright walls and floors [24,26,28,38,39]. Intensity according to the Earthquake Archaeological Effects scale (EAE13) was assessed via the comparative table of [40,41]. It assigns a minimum intensity value to each seismic damage, comparing these with the European Macroseismic Scale (EMS-98). We kept in mind that the EMS-98 is preferably not applied to individual buildings, and it is not advised to use it to assess damage observed on structures of monumental architecture, which behave somewhat differently than common buildings of habitation [42]. Most of the sites we studied consist of only one building, often heavily restored (e.g., San Candido), or a very few, closely connected structures, sometimes built on extreme sites (e.g., Tirol castle). However, the surviving deformation is a clear indicator of a much larger case of destruction, which can offer at least a rough possibility of assigning an intensity value to the event. Since only single buildings or sites were available for intensity assignment, we were unable to create maps of intensity data points (IDP) for the eventual calculation of local intensity I_0, magnitude and surface rupture. A systematic, well-funded study of archaeoseismicity in the Alps will be able to achieve these.

Remnants of Roman architecture are eminently suitable for preserving evidence of past earthquakes [43]. In the absence of upright walls, collapse features, and floor-level deformation additionally give evidence within the Pannonian Basin: Carnuntum in Austria [44], Brigetio in Hungary [45], Siscia (modern Sisak) in Croatia [35], Magdalensberg in Austria [36], and Celeia (modern Celje, Slovenia) [34], to name a few. Medieval buildings, mostly churches, rarely fortresses, are also capable of recording past earthquakes (e.g., [46–48]). Earthquake-induced damage includes toppled walls, dropped keystones, and in-plane and out-of-plane displacement of masonry ashlars in short: ancient seismoscopes [49], which essentially record various seismic parameters: date, damage location, intensity, strong motion direction (e.g., [50–54]).

3. Results

A short description is provided for each building or archaeological site, concentrating on successive construction, destruction, demolition, and reconstruction events. Our observations are discussed separately from published data. The reader should note that repeated reconstructions of millennial buildings mostly hide or repair any damage resulting from external forces, including earthquakes. Occasionally, there is a remainder preserved, a relic of a former deformation, which is left intact, possibly for reasons of economy. A concise description of deformations attributable to earthquakes is provided. Dates taken from the history of the site are used to bracket the time of the seismic event.

3.1. Siscia

Evidence. Excavations of the Roman city of Siscia (modern Sisak, Croatia) yielded metre-sized fragments of the city wall collapsed in the adjacent ditch (Figure 2). In situ portions of the wall display twisting and shearing. The construction level is underlain by sandy clay. We suggest that a major earthquake damaged the city wall of Siscia, enhanced by site effects on the alluvial plain of the Kupa River [35].

Date. Rebuilding in the late antique period suggests that the wall collapsed between the beginning of the 3rd and the middle of the 4th century. This earthquake between ~200 AD and ~350 AD is missing from historical catalogues [35].

Causative fault. The Petrinja (Croatia) earthquake sequence (mainshock 29 December 2020, Mw 6.4) was caused by displacement along the NW-SE trending Petrinja fault, 6 km SW from Petrinja town and 11 km from Siscia. Additionally, notable activity was recorded along minor faults up to 25 km away from the main fault (Figure 3) [55]. Surface ruptures were mapped by Baize et al. [56]. Focal mechanism solutions, InSAR analysis, and re-measuring geodetic benchmarks suggest right-lateral motion [56,57]. We suggest that the damage observed in the Siscia archaeological site could have been triggered by an earthquake along the Petrinja Fault or adjacent minor faults. The European Database of Seismogenic Faults

records the main fault as transpressional [58]. The recent European Fault Source Model 2020 [59] kept the same geometry, but the fault is classified as right-lateral. Herak and Herak [55] have shown that it is pure strike-slip. This fault system extends along the contact of the Internal Dinarides with the Pannonian Basin. It is considered part of the Croatian Sava Fault [4].

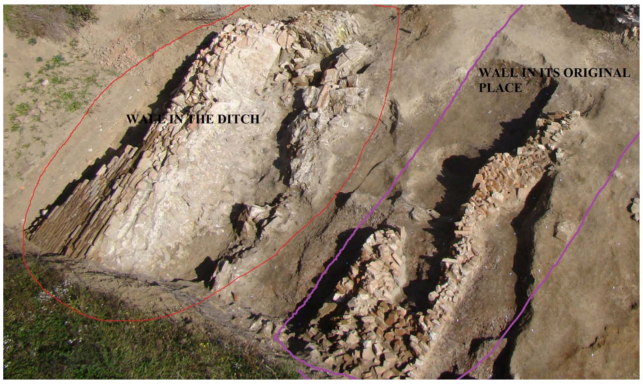


Figure 2. A collapsed segment of the city wall of Roman Siscia. The wall on the left overturned (bottom-up), now lying in the moat. It has been sheared off from its foundation on the right. Deformed rows of bricks mark the shear zone. Site of St. Quirinus church, Sisak, Croatia (after [35], modified).

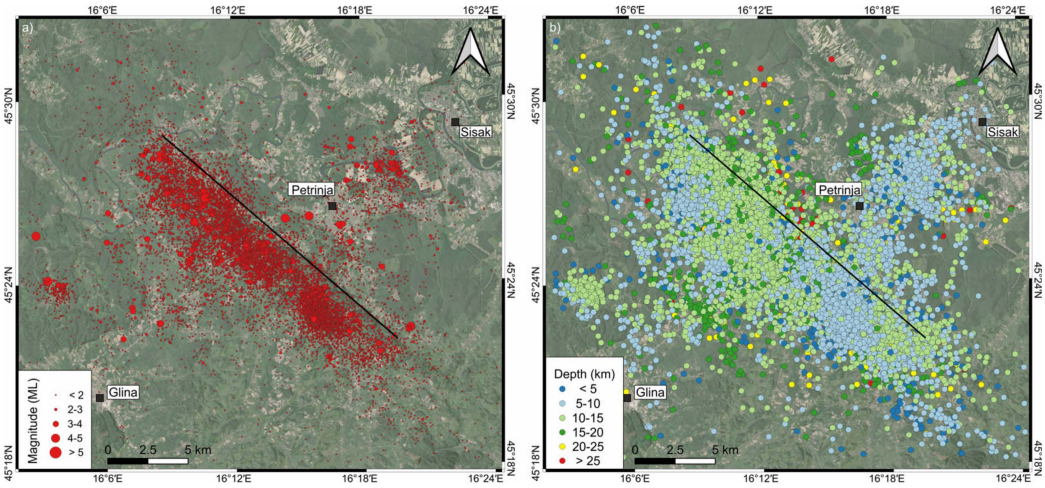


Figure 3. Epicentres of the most reliably located aftershocks near the trace of the Petrinja fault (black line). (**a**): Best-located aftershocks are concentrated on the SW side of the Petrinja fault. (**b**): Depth distribution of the aftershocks (after [55], modified).

3.2. Celeia

Evidence. The Mesto pod mestom museum in Celje exhibits a paved road belonging to the Roman town of Celeia. It suffered severe deformation, displaying a bulge and trench, pop-up structures, and tilted pavement slabs (Figures 4 and 5). Subsequently, the city wall was built over the deformed road in Late Roman times. Folded pavements indicate earthquake-induced liquefaction (for details, see [34]).

Date. The city wall, overlying the deformed road, was built shortly before 350 AD. The severe earthquake that hit the town occurred somewhat before that date [34].

Causative fault. Several known active faults surround the Celje Basin (Figure 6): from south to north, there are the Sava, the Celje, the Šoštanj and the Labot Faults. Each of them is a dextral strike-slip fault. Additionally, there are various potentially active thrust faults. The town of Celje is straddling the Celje Fault. Other faults are less than 20 km away. Additionally, the northern border of the Karawanken Mountain to the NW is being overthrust the clastic-filled Klagenfurt Basin [60]. The Sava Folds in the east are 20 km away. Either of these could be the causative fault for the earthquake that damaged Celeia [34].

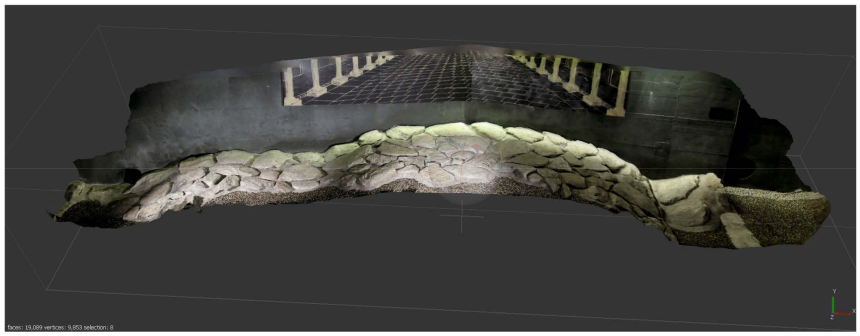


Figure 4. Roman road as built (above, graphical reconstruction) and deformed by a seismic-induced liquefaction event (below). A 3D reconstruction by Agisoft Metashape. Exhibited in situ in the underground museum Mesto pod mestom in Celje (after [34], modified).

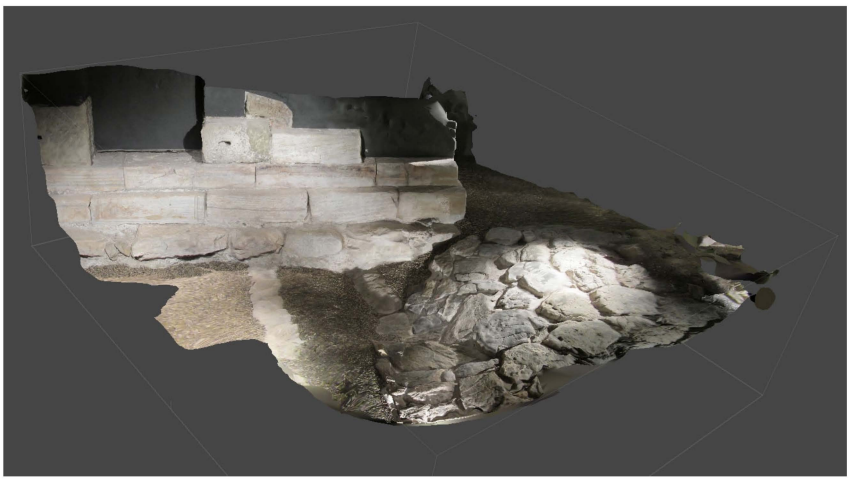


Figure 5. Tilted slabs of the pavement on the Roman road of Celeia, deformed by differential settlement caused by seismic-induced liquefaction. The deformed surface is unconformably overlain by horizontal ashlars of a new city wall tower built shortly after the earthquake (after [34]).

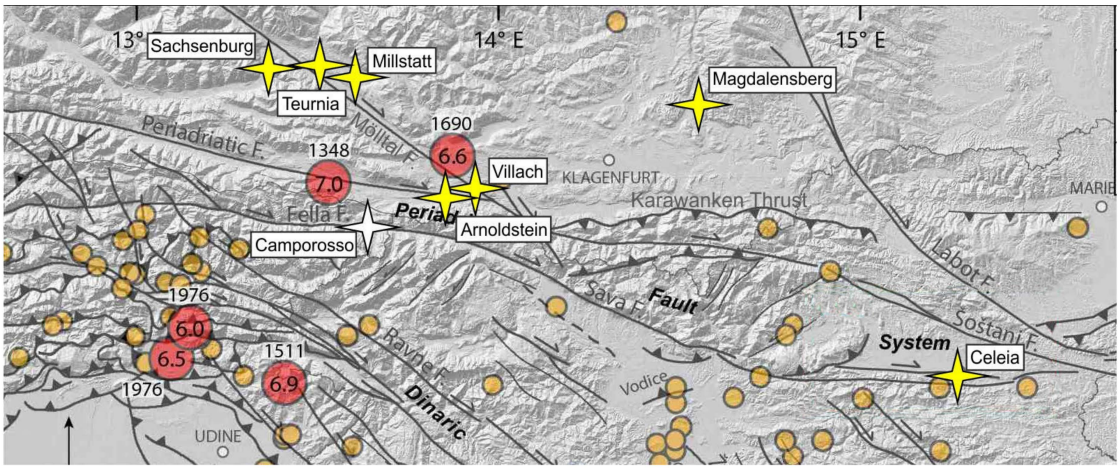


Figure 6. Faults and archaeoseismological sites (yellow stars) in the Periadriatic Fault system. Celeia could be affected by the Sava, Šoštanj or the Labot faults. Magdalensberg is near the Karawanken Thrust fault and the strike-slip Šoštanj Fault. Villach is at the junction of the Gailtal segment of the Periadriatic Fault and the Mölltal Fault. Arnoldstein is straddling the Gailtal Fault. Millstatt, Teurnia, and Sachsenburg are in dangerous proximity to the Mölltal Fault. The white star marks the epicentre of the 1348 Villach earthquake at the Camporosso Pass along the Fella-Sava Fault. Earthquakes shown (orange dots) are Mw $\geq$ 5.0 (after [7], modified).

3.3. Magdalensberg

Evidence. The ruined Celtic and Roman town on the hilltop of Magdalensberg, ca. 15 km north of Klagenfurt, existed from the first century BC until the first century AD. During its mere 90 years of existence, it was a prosperous settlement, having several iron manufacturing workshops, baths, and a large temple on the top. Excavated buildings—standing on solid rock—display a variety of damage probably caused by earthquakes: dropped and fractured voussoirs (arch segments), displaced columns in the heating system (hypocaust), and large fragments of collapsed walls [36] (Figure 1). The most spectacular construction anomaly is the set of 23, irregularly positioned buttresses (Figure 7), which provided support to three walls or colonnades of the hilltop temple, which had severe structural problems. Roman temples never used buttresses to support the walls under normal conditions. As the damaged residential buildings display typical earthquake damage, we suggest that an earthquake also damaged the temple.



Figure 7. Foundations of a Celtic or Roman temple, supported by many buttresses of different sizes, arranged irregularly. Magdalensberg, near Klagenfurt. ADB #7983. Temples of the period were never built with buttresses—severe structural problems, presumably caused by an earthquake, made their construction necessary.

Date. Dolenz [36] mentioned an earthquake in AD 9, based on sources north of the Alps. As there are further restored and unrestored parts of the settlement, which also bear features of seismic damage, additional studies might attribute other date(s).

Causative fault. Magdalensberg is ca. 20 km north of the Karavanken thrust, which deformed Pleistocene terraces in the Klagenfurt Basin [60]. The nearby active Šoštanj, Sava, and Labot Faults could be potential sources of shaking [7].

3.4. Villach

Villach is the name most frequently mentioned in contemporary reports of the 1348 AD earthquake, the most significant historical seismic event north of the Mediterranean [61,62]. Considering the abundance of records, it is all the more surprising that very little evidence of destruction was preserved. The probable cause is thorough restoration and reconstruction after the catastrophe.

Evidence. St. James church, the parish church of the town, was first mentioned in 1136. Archaeological excavations yielded a Romanesque church below the current one, dating back to ca. 1000. It had two towers adjacent to the choir [63]. On 25 January 1348, the Romanesque church was destroyed by a severe earthquake. The economic consequences of the shaking caused the rebuilding of the whole church delayed by more than a century. The choir was rebuilt between 1360 and 1370 in Gothic style. The three-nave longhouse was constructed between 1450 and 1460. Instead of the two eastern towers, a single western tower was built. It is Gothic despite carrying a Romanesque-style ledge on top of the ground

floor [64]. After the large fire of 1524, the longhouse was vaulted. The 1690 earthquake caused the collapse of the choir and the upper part of the western tower [65].

Archaeologists attribute fractures and other damage in the Villach fortress to the 1201 earthquake [66]. They bring up the deformation observed in the abbey of nearby Millstatt as a supporting argument. There is no historical record of this event in Villach.

Date. Abundant historical records supply an identical earthquake date: 25 January 1348, at 4 pm [61,67,68].

Causative fault. Various suggestions were published, attributing the Villach earthquake alternatingly to the Periadriatic Fault s. str. [69] or to the Friuli region, inspired by the 1976 earthquake there [62]. Recently, Caracciolo et al. [68] reviewed all available original historical records, concluding that the causative fault was the Fella-Sava Fault, with the epicentre at Camporosso Pass, ca. 25 km SW of Villach. This site is ca. 10 km to the south of the Gailtal Fault (Figure 6).

3.5. Arnoldstein

Evidence. The destruction of the Benedictine monastery in Arnoldstein by the earthquake of 1348 was depicted on a mural in the Lady Chapel in Karlstein castle near Prague (now Karlštejn in Czechia) (Figure 8). The painter, Nikolaus Wurmser of Strasbourg, created it as a part of an Apocalypse cycle on the order of Emperor Charles IV. It is one of the oldest depictions of an earthquake [70]. The monastery was first mentioned in charters in 1106, and the existence of St. George church was recorded in 1316 [71] (pp. 20–22). It is widely accepted that the painter has seen Arnoldstein in ruins: some of the details, e.g., corner expulsion on at least two buildings, support the authenticity of the image.



Figure 8. The destruction of the Benedictine monastery in Arnoldstein by the earthquake of 1348 as depicted on a mural in Karlstein castle near Prague (now Karlštejn in Czechia).

Date. Abundant historical records supply an identical date for the earthquake: 25 January 1348, at 4 pm [61,67,68].

Causative fault. Fella-Sava Fault, epicentre at Camporosso Pass [68] (Figure 6).

3.6. Dobratsch

Evidence. The Dobratsch Range is 1300 m higher than the valley of the Gail River to the south. The steep slopes of fractured limestone and dolomite were frequently subjected to landslides in post-glacial times [72]. Six of these are attributed to the 1348 earthquake [72]. The Rote Wand landslide was the most extensive (Figure 9): the mass movement transported and deposited 100 million m^3 of debris on the fluvial plain, damming the river Gail, which yielded additional destruction [73].



Figure 9. Runout field of the catastrophic 1348 landslide south of the steep Dobratsch hill. The landslide scar (left) exposes the Triassic dolomite of Dobratsch mountain near Villach. The rough surface is the mass movement deposit on the plains of the Gail River, which is seen on the right (forested). Photo: https://www.mergili.at/worldimages/picture.php?/14988 by Martin Mergili. Accessed on 1 December 2024.

Date. 25 January 1348, at 4 pm [61,67,68].
Causative fault. Fella-Sava Fault, epicentre at Camporosso Pass [68] (Figure 6).

3.7. Millstatt Am See

Evidence. All three known major earthquakes in Austria—the 1201, the 1345, and the 1690 ones—left behind recognisable traces on the monastery church (Stiftskirche) in Millstatt am See [74]. The deformations caused as well as the repairs and restorations which followed were described by [74].

The Benedictine monastery was founded in 1070/1080. The early history of the church is mostly unknown. However, minor remarks in chronicles and charters provide ample evidence for environmental catastrophes, like fires. The monastery church (today, St. Salvator and All Saints parish church) was built in early Romanesque style between 1122 and 1200. The westwork with the towers and the ornamental portal was built during the rule of Abbot Heinrich I (1166–1177). Today, the frontal part of the porch is dangerously tilted outwards, and the columns of the main gate are displaced (Figures 10 and 11). The opening of the porch between the towers was walled up in late Romanesque—early Gothic style (Figure 10) [74,75]. The Romanesque basilica was rebuilt and vaulted in Gothic style between 1511 and 1519 [76].

The church, the surrounding buildings, and the oldest buildings of the town display deformed walls, which are supported by a large number of buttresses (Figure 12) [77].

Date. A strong earthquake in 1201 destroyed various buildings in Upper Carinthia, including the Romanesque west portal of the monastery church. The damaged porch reconstruction occurred within the late Romanesque to early Gothic period—before the 1348 Villach earthquake—which fits the 1201 date perfectly. We note that Hammerl [78,79] considered this earthquake as fake, an artefact of historical error and misinterpretation. If her comments are correct, then another unknown earthquake within the 13th century is responsible for the destruction. However, Alexandre and Alexandre-Lamotte [80] found the evidence for a major seismic event convincing. This subject requires further in-depth studies. Both the 1348 and the 1690 earthquakes affected the town [62]; efforts to separate their effects and a detailed archaeoseismological analysis are in progress.

Causative fault. The closest available fault is the Mölltal fault is less than 1 km away (Figure 6).



Figure 10. Abbey church, Early Romanesque west facade. Note the walled-up porch, filled by a circular window and the Late Romanesque gate. Millstatt. ADB #8493.



Figure 11. Former Dominican monastery, Millstatt. The Early Romanesque porch of the western façade, deformed and tilted outwards, was walled up in 1290 AD to restore structural integrity. ADB photo #8442.



Figure 12. Surplus buttresses support the walls of the monastery in Millstatt. ADB photo #8421.

3.8. Teurnia

Evidence. Teurnia (later Tiburnia, next to St. Peter-in-Holz village) was a Roman town that became the capital of the province Noricum Mediterraneum in late Roman times. Excavated ruins are in the village of St. Peter-in-Holz in western Carinthia. The Roman town was built before AD 50, having a forum, a basilica (market), a temple, public baths, and residential houses arranged on two terraces. A great fire completely destroyed these buildings in the early third century, leaving behind a landscape of catastrophe, with abundant collapsed walls. After the fire, inhabitants left the terraces; the houses were never rebuilt. Material from the deserted houses was used to build walls surrounding the hilltop [81].

Earthquakes often cause fire and destroy whole settlements. The best-known example is the 1 September 1923 Tokyo earthquake (the Great Kanto earthquake) with a magnitude of 7.9. Most of the residential houses of the city were made of wood: these mostly resisted shaking, but the ensuing fire (shaking occurred at noon, when everyone was cooking lunch) burned down Tokyo, with deaths exceeding 140,000. We suggest that Teurnia was heavily damaged by a destructive earthquake, which—additionally—caused a fire. While fire annihilates roofs and furniture only, the causative earthquake destroyed walls; this led to the abandonment of the terraced quarter of the town [81].

Date. We suggest that the fire, which ruined the stone edifices of the city, was caused by an earthquake in the early 3rd century.

Causative fault. The closest branch of the Periadriatic Fault system is the Mölltal Fault (Figure 1).

3.9. Sachsenburg

Evidence and dating. St. Margaret church outside the ring wall. First mention in charter: 1425. Parish from 1449. Construction was completed in 1510, marked by a building inscription above the west gate. Late Gothic, three aisles. Massive buttress at the SW corner and along the aisle (Figures 13 and 14) [71,75]. The 1690 AD earthquake might be responsible for the structural damage, which needed reinforcement by buttresses.



Figure 13. A tall, massive buttress supports the SW corner. Sachsenburg, St. Margaret parish church. ADB photo #8636.



Figure 14. Three low, massive buttresses support the northern wall. Sachsenburg, St. Margaret parish church. ADB photo #8652.

Causative fault. The closest branch of the Periadriatic Fault system is the Mölltal Fault, 2–3 km away (Figure 6).

3.10. Lienz

Evidence. The late Gothic St. Michael church was built by local merchants at the cattle market, probably replacing an earlier Gothic church and restored in the first half of the 16th century. An inscription above the pointed arch western gate is from 1510. The empore was completed in 1531, and the choir vault was renovated in ~1667. We noted that the longhouse has two-tiered buttresses, common for Gothic churches, but the Gothic choir has not. As the renovation of its vault was finished in 1667, possibly this work extended to the walls supporting the vault [82].

The keystone of the western gate arch shows a conspicuous drop (Figure 15). Dropped keystones are clear indicators of earthquake shaking (e.g., Autre-Eglise, Belgium, caused by the 1828 earthquake [83] (Figures 8.6C and D); Baelo Claudia, Spain [84] (Figure 5.7B); Goshavank, Armenia [85] (Figure 5); police station at Halssa, Israel, damaged in the 1995 Aqaba earthquake [86] (Figure 14a).



Figure 15. Dropped keystone above the western gate of St. Michael church, Lienz, Austria. A (re)construction date is visible: 1510. ADB #9564.

The formation of this damage was modelled by [87]. Although these authors say that keystone drops can occur only in cases when the walls or floors above the arch have collapsed already, our experience shows that walls up to 10 m high or more are able to withstand this shaking. In this case, the wall suffered severe fracturing from the top to the ground (e.g., the northern gate of St. Michael church, Cluj-Napoca, Transylvania) [88].

Date. The earthquake responsible for the keystone drop occurred after 1510 (the date in the arch), probably after 1537 (completion of the emporium) and possibly before the renovation of the choir vault in 1667. The 1690 AD earthquake might also be responsible for the damage.

Causative fault. The Pustertal and Mölltal faults are nearby, crossing each other within the town's limits.

3.11. San Candido/Innichen

Evidence. The monastery church in San Candido (German: Innichen) is a three-nave, Romanesque church, built to host the Benedictine order. Construction started around 1143 AD. Originally, it had a flat, wooden ceiling, but it was annihilated by a fire in 1200. Reconstruction was completed in 1284: a Romanesque vault was added. The tower was built in 1320–1326 [89] (p. 22).

The building seems to be intact. However, we noted that the eastern wall of the northern transept contains a frieze block, which shows clockwise rotation, a typical feature of seismic shaking (Figure 16). Similar, rotated blocks were widely documented in

buildings that suffered seismic damage (e.g., in Llorca, Spain, in 2011 [90] (Figure 59b); in Tartous, Syria: [91] (Figure 6.55); in Macchu Picchu, Peru: [92] (Figure 3); in Manjal, Gujarat, India [93] (Figure 5c); in Ateret, Israel: [94] (Figure 1h)).



Figure 16. Rotated masonry block in the eastern wall of the northern transept (Dominican monastery church, San Candido/Innichen, Italy). The rotated Romanesque block was not repaired, but preserved before the new vault was built above in 1284 AD. ADB #9887.

Date. The block, rotated by a supposed seismic event, was uniquely preserved in its deformed position during the reconstruction, which added the Romanesque vault to the transept in 1284 or before. Known destruction of the church by fire occurred in 1200: this or a later date (but before 1284) can be assigned to the earthquake. Earthquakes are known to cause fire: fallen burning candles can be the culprit. Of course, an unknown seismic event of any other date within the 13th century might be responsible for the deformation.

Causative fault. The building stands next to the Pustertal Fault.

3.12. Tirol Castle

Tirol castle (German Tirol, Italian Tirolo, English Tyrol) [95]. The castle was the seat of the aristocratic family (Burggraf), which ruled Tyrol for centuries. The buildings and defensive walls stand on lithified fluvioglacial sediments; the cliffs below the walls are rock solid (Figure 17) [96] (p. 552). The earliest construction periods are not dated. A second phase is dated to 1138 AD by dendrochronology. As this contains walls built previously, those are probably the results of a late 11th-century construction period. For us, the most important parts of the building are two majestic portals of the castle chapel: based on artistic and iconographic arguments, these were built shortly before 1138.



Figure 17. Tyrol Castle (Italy) standing on rugged rock cliffs made of lithified fluvioglacial sediments. The main building consists of the southern palace (on the left) and the eastern palace (on the right). The rounded corner between these hides the chapel. Note the large apron buttress on the far left of the southern palace: it supports the western wall of the palace, with the deformed Romanesque gate within. ADB #20230723_131040.

Evidence. The palace:

- south wing decorative gate: fractured and misplaced tympanum;
- chapel gate: damaged: deformed arch (Figures 18 and 19);
- chapel wall common with the palace's south wing: demolished and rebuilt;
- east wing west wall, lower floor: tilted outwards, supported by external apron buttress (Figure 20);
- east wing west wall, lower floor: axial fractures in column of twin window (Figure 21).



Figure 18. Chapel gate, built in 1129/41, damaged before 1300 (Dating from [97] (p. 173). Tirol Castle, Italy. ADB #20230723_142115.

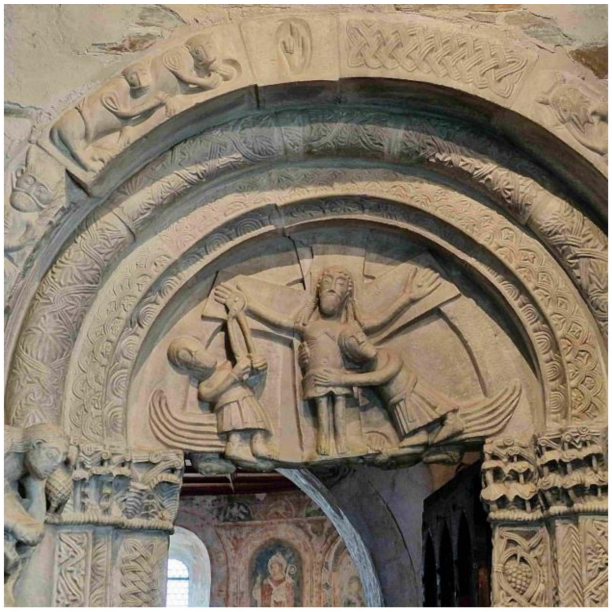


Figure 19. Tympanon above the chapel gate, broken, tilted, misplaced. Tirol Castle, Italy. ADB #20230723_143459.

Date. The seismic event damaging the castle occurred between 1221 and 1301. This dating is supported by the terminus post quem 1138 AD construction date of the damaged southern wing and the date of the intact chapel frescoes not later than 1331. These

were proposed—and certainly funded—by Volkmar von Burgstall; he was captain of the castle until 1331 [98]. The eastern palace was built in the 1220s. Exact dating for timber components is provided by dendrochronology [99]: the lower floor of the east wing was built in 1221, and the second floor—with apparent marks of demolition and restoration in 1301 [100] (p. 60).



Figure 20. The early Baroque apron buttress supporting the sunken and deformed NW corner of the Romanesque eastern palace, built ca. 1641 [100] (pp. 61, 63). The staircase covering the buttress was built in 1894. Tirol Castle, Italy. ADB #20230723_155339.



Figure 21. Marble column separating two fields of a Romanesque window in the western wall of the eastern palace. Note the axial fracture, repaired by iron wiring. The top of the column was outward misplaced relative to the capital above. Tirol Castle, Italy. #20230723_150703.

Causative fault. There was an M4.8 earthquake at Merano on 17 July 2001 along the ENE–WSW trending Passiria deformation zone, which crosses the town of Merano. It is part of the North Giudicarie fault system. The latter is continued northeastwards by the Merano-Mules Fault, which ultimately merges into the Pusteria Fault [101]. Any of the faults in close proximity can be held responsible for damage in Tirol Castle (Figure 22).

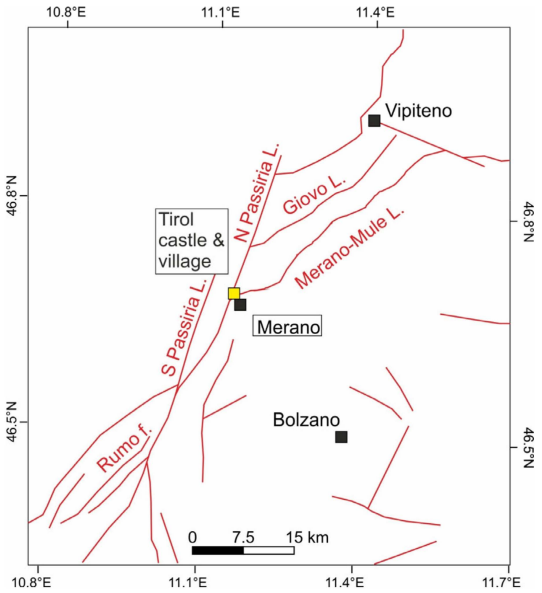


Figure 22. The Passiria deformation zone, responsible for the 17 July 2001 Merano earthquake, within the Northern Giudicarie fault system (after [101], modified). The earthquake(s) responsible for Tirol castle and village church and for Merano church damage could have been caused by any of these faults.

3.13. Tirol Village

The John the Baptist church in the village of Tirol has an early Gothic choir and longhouse. However, the tower is Romanesque: it displays windows with semi-circular arches. Choir and longhouse windows carry pointed Gothic arches. This arrangement suggests that there was a Romanesque church, demolished and replaced by a Gothic structure. Construction of the latter was in progress by 1370 [102] (p. 18).

Evidence. The twin window above the clock on the west side of the tower is conspicuously asymmetric; the middle column is tilted. The typically Romanesque, cubic capital is slightly shifted to the north (left on the picture) (Figures 23 and 24). Gothic arches and windows of the choir and longhouse are intact. These deformations are similar to those documented in the Great Mosque of Kairouan, Tunisia [103] (Figure 5c) and in the Byzantine church in Rusafa, Syria [104] (Figure 7c).



Figure 23. John the Baptist church, Tirol village, Italy. View from the northwest. The deformed Romanesque windows are on the top of the quadratic part of the tower. ADB photo #20230723_125038.



Figure 24. Strongly asymmetric Romanesque window, the middle column slightly tilted to the left, and the cubic capital shifted left of the arches above. The western window above the clock of John the Baptist church in Tirol village. ADB photo #20230723_130240.

Dating. The Romanesque church was built in the 11th or early 12th century, based on stylistic marks on the tower [102] (p. 11). Construction of the Gothic choir was in progress already in 1370. As the Romanesque tower shows minor but clear evidence of deformation, the date of any earthquake can be bracketed between ca. 1130 and 1370.

Causative fault. Same as for Tirol castle: any of the faults of the northern Giudicarie fault zone.

3.14. Merano/Meran

Evidence. Whether a 13th-century earthquake damaged the St. Nicholas church in Merano is up for discussion. Potential evidence includes mainly the tilted foundations of northern nave columns. The columns standing on these are perfectly vertical. Construction of the Gothic choir was started in ca. 1300 AD, gradually replacing the pre-existing Romanesque church. The longhouse was completed in 1358 [105].

Date. An earthquake bracketed between 1221 and 1301, based on the construction history of Tyrol Castle, probably damaged the pre-existing Romanesque church; construction of a new, Gothic church became necessary, starting in 1300.

Causative fault. Same as for Tirol castle: northern Giudicarie fault zone.

4. Discussion

4.1. Earthquake or Not?

We opted for seismic origin of damage based on extensive field experience and on the abundant literature database we are familiar with. The most important publications are these [25–33,38,41] On hard subsoil, buildings tend to suffer both in-plane and out-of-plane deformation from horizontal shaking (Figures 2, 11, 12, 14, 15, 19, 20 and 22). On soft subsoil liquefaction of the soil causes excessive differential subsidence (Figures 4 and 5). In the absence of upright walls conspicuous repairs indicate that the walls these buttresses supported suffered tilting from lateral loads (Figure 7). In general, evidence for lateral loading caused by horizontal shaking is a strong argument for seismic origin.

4.2. Distribution of Seismicity in Space and Time

Supposed epicentres of known major historical earthquakes are marked in Figures 1 and 25. We added several new cases of seismic destruction (unknown before), showing that archaeological and historical data on seismicity complement each other (Figures 1 and 25).

Historical data are more accessible from the 16th century onwards, while Antiquity provides mostly archaeological information. A combination of both sources gives the best results in assessing earthquake hazards.

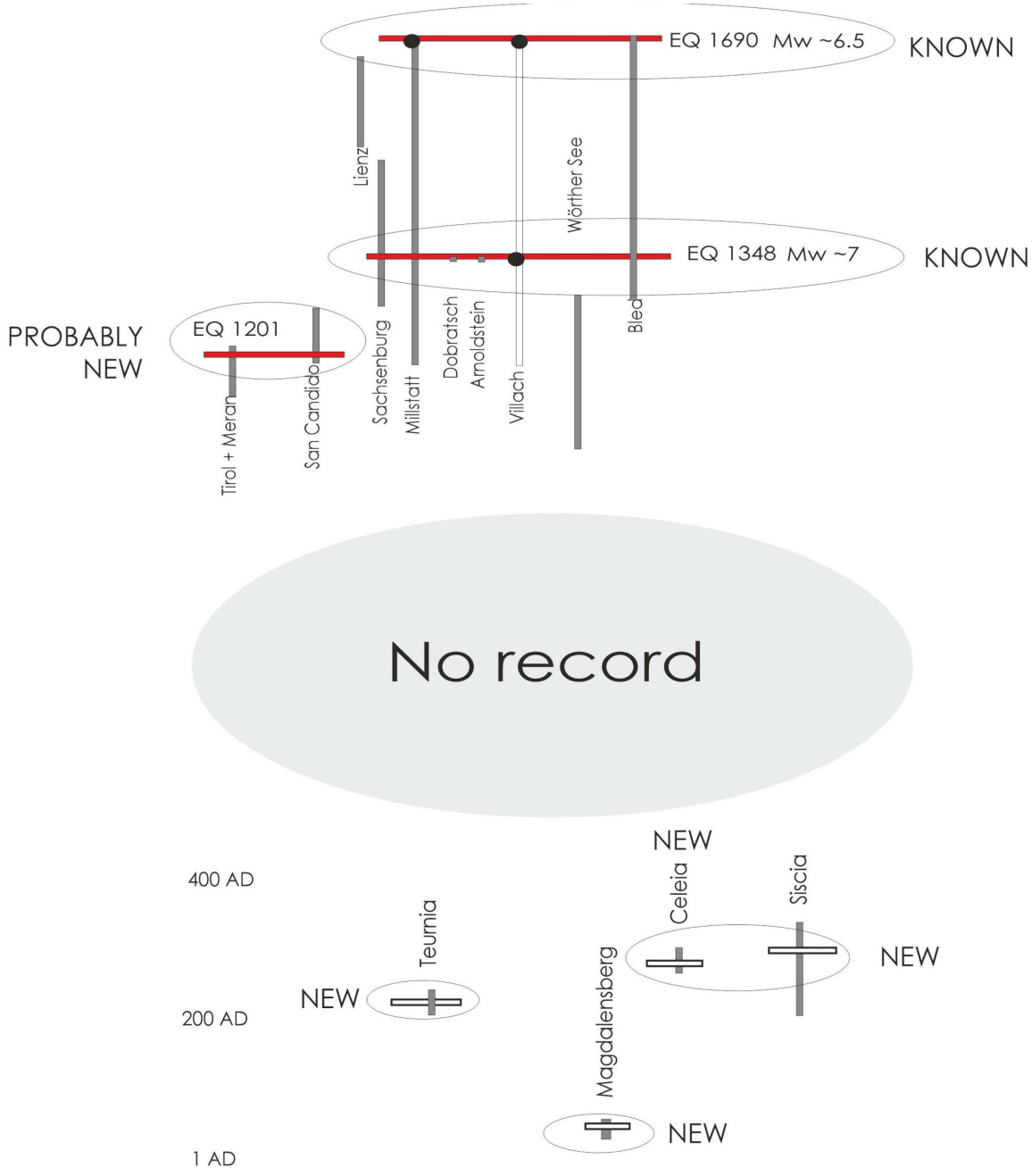


Figure 25. Distribution of destructive earthquakes along the Periadriatic Fault system during the past 2000 years. Horizontal lines in the plot: approximate length of the fault segments involved. Vertical bars: uncertainty of the date of an earthquake. Encircled events were probably caused by the same fault. For individual earthquakes, see Table 1.

The plot in Figure 25 clearly shows that the eleven earthquake-hit sites are about 20 to 70 km from each other along the Periadratic Fault system. The same earthquake could destroy more than one site, as exemplified by the grandiose 1348 earthquake (Millstatt, Villach, Arnoldstein, and Dobratsch landslide). We were unable to identify any directivity among successive earthquakes, similar to the features found along the North Anatolian Fault [106]. Instead, earthquakes occur seemingly randomly. This random distribution is

spread along the studied 430 km long segment, both along the Periadriatic sensu stricto and along adjacent faults.

Vrabec et al. [107] provided a GPS-based estimate for fault displacement along the PAL: 1.2 mm/year. The largest known earthquake (1348: Villach) was M 6.8 [108]. This magnitude allows ca. 1 m displacement along a strike-slip fault [109], which can be repeated every millennium. Earthquakes having lower magnitudes can be repeated more frequently.

Table 1. Dates of earthquakes along the Periadriatic Fault system. Intensity assignment after [110,111]. For locations, see Figures 1 and 25.

Location	Country	Date/Interval of Earthquake	Intensity	Closest Fault(s)	Reference
Siscia (Sisak)	Croatia	200–350 AD	VIII	Croatian Sava Fault	[35]
Celeia (Celje)	Slovenia	<350 AD	VII	Savinja/Celje/Šoštanj/Labot fault	[34]
Magdalensberg	Austria	9 AD	VII	Karawanken/Sava/Šoštanj/Labot fault	[36]
Villach	Austria	1348		Fella-Sava Fault	[61]
		1690			[61]
Arnoldstein	Austria	1348		Fella-Sava Fault	[61]
Dobratsch	Austria	1348	IX	Fella-Sava Fault	[61]
Millstatt am See	Austria	1201	VII	Mölltal Fault	[74]
		1348		Fella-Sava Fault	[61]
		1690	VII		
Teurnia	Austria	200–250 AD		Mölltal Fault	[81]
Sachsenburg	Austria	1690	VII	Mölltal Fault	this study
Lienz	Austria	1690	VII	ZWD (Zwischenbergen-Wöllatratten-Drau) Fault	this study
San Candido/Innichen	Italy	<1284	IX	ZWD Fault Pustertal Fault	this study
Tirolo/Tirol—castle	Italy	1221–1301	VII	North Giudicarie Faults	this study
Tirolo/Tirol—village	Italy	1130–1370		North Giudicarie Faults	this study
Meran/Merano	Italy	1221–1301		North Giudicarie Faults	this study

The following features characterise the tectonic activity of the Periadriatic Fault system and surroundings (see Figures 1 and 6):

- Highest seismic activity at the tip of the Friuli wedge, therefore, relatively high activity with dextral displacement in the faults near Villach and east of it;
- PAL splays east of Friuli: Fella-Sava, Šoštanj faults, farther eastward into the Balaton and Croatian Sava Fault. Dextral displacements;
- Subtle seismicity to the west of the tip of the Friuli wedge;
- Sinistral kinematics along the North Giudicarie, inferred from the focal mechanism of the 17 July 2001 Meran event, would completely agree with a northward indentation of the Adria microplate [1].

We deliberately avoided finding epicentres for historical earthquakes. The ongoing preparation of the historical earthquake catalogue of Tirol (Christa Hammerl, pers. comm. 2020) will undoubtedly help the most in this respect. Extensive studies of lacustrine paleoseismology [19–22,112] and cave studies [23] also provide new data on known and unknown seismic events, which need to be correlated with archaeosesimological data.

4.3. Eastward Extension of the Periadriatic Fault System

The eastern portion of the Periadriatic Fault system splays into various subordinate faults towards the SE and E: the notable Idrija fault is one of these [113]. Further eastward, the Periadriatic Fault system is traditionally connected with the Balaton / Mid-Hungarian Fault system [114], based on Neogene palaeogeography and tectonics. However, active tectonics is less expressed in this ENE direction than in the SE, in the Croatian Sava Fault. Holocene activity could not be verified along the Balaton Fault [115]. However, the Croatian Sava Fault displays active seismicity both in instrumental [116] and in historical times [35]. Further studies are needed to reveal what roles the Medvednica transfer faults and the Drava Fault [117] play in the active tectonics of the region.

Together with the Mur–Mürz Fault, this pattern might be the Quaternary expression of the escaping tectonic wedge of the Alpine–Pannonian region, as understood by Ratschbacher et al. [118,119] The ongoing inversion within the Pannonian Basin [6] must be understood in this context.

5. Conclusions

The first results of a systematic archaeoseismological survey along the Periadriatic Fault and Sava Fault system assessed buildings and archaeological sites for earthquake damage. Eleven sites, four Roman and seven Medieval, display evidence of destructive earthquakes during the past two millennia. Six of these were previously unknown to science. Damaged upright walls of Medieval buildings and deformed floors of Roman settlements testify to local intensity up to IX. Construction history helped to range seismic events from the 1st century AD to the 17th century. Sites 20 to 70 km apart, along a more than four hundred km long segment of a partly 'inactive' fault zone, carry evidence for many high-intensity, destructive events. Last but not least, we at least doubled the number of destructive earthquakes known along the Periadriatic Fault system, proving that systematic studies of archaeoseismology are necessary for a more reliable assessment of seismic hazard.

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Appendix A

Archeoseismology was born in the Mediterranean (Crete: [120]), and widely spread where high seismicity and the territories of highly developed ancient cultures overlap: Greece, Palestine, Anatolia, and Italy. Italy is the place where the location of frequent earthquakes overlaps with the location of buildings constructed through many centuries [29], and where historical records of earthquakes are best studied and published [121] (Table A1).

The Austrian and Italian Alps are seismically much less active today than the Appennines of Italy, where much of the methods of archaeoseismology have been worked out. As we provide here the first attempt to describe ancient earthquakes along the Periadriatic Lineament, it is appropriate to refer to some of the highlights of Italian archaeoseismology as examples to be followed. We mention a few publications, starting from the Southern Alps, ranging as far as Sicily, which provided a major impetus to the studies of past earthquakes.

The first to mention is the work of Galadini, Hinzen and Stiros [24]: a classical paper with a concise, practical summary of the methods and practice of archaeoseismology. The authors—an Italian, a German and a Greek—put special emphasis on identifying the relationship of damaged edifices and their causative faults. Methods were developed step by step, and not without debates: first, the apparent collision of historical and data were worked out [29,122,123]; finished by a very careful study of seismicity at the southern part of Alpi Meridional in a wide European context [124]. Deformed and collapsed structures observed in archaeological sites affecting man-made constructions as well as historical buildings, monuments, pavements and defensive structures may have different causes: seismic ground motion, slope process, unstable soils, differential overburden, building decay or acts of war. All of these possibilities need a systematic identification and classifica-

tion of trigger mechanisms on archaeological damaged ruins, to prove if indeed the cause was seismic or not.

No surface rupture was known in the Southern Alps. Falcucci and co-workers [125] found the first one in the southeastern corner, next to the Dinarides, suspected from the 1511 AD earthquake. We note that their site would be a good place for archaeoseismology. Actually, it would be desirable that paleoseismological studies are simultaneously accompanied by archaeoseismological studies. Vice versa, archaeoseismological studies could outline a place where a successful search for surface ruptures can be conducted.

The study of Galadini and co-workers [126] on the Fucino Plain in the Central Appennines expresses all the complexities of understanding the seismic history of the Fucino Fault (archaeology, archaoseismology, paleoseismology, historical seismology, structural geology, etc.). A very careful association of damaged buildings with an epicentre on one or another causative fault in the Volturno Valley was discussed by Bottari and colleagues [47].

In the south, between the peninsula of Calabria and the island of Sicily is the Messina Strait, the site of the destructive 1908 earthquake. The first-century and fourth-century earthquakes were described there in the context of active tectonism [127]. Tindari, Selinunte, Bagnoli, Catania, and further Roman sites in Sicily, provided hard evidence of certain past and potential future destruction in regions where instrumental seismology does not record destructive earthquakes, and where the faults cannot be pinpointed [128]. Where an active fault is not known, various geophysical methods are applied [129]. Finally, there is an exemplary recent study on Lilybaeum (near Marsala, the western tip of Sicily), where both data and conclusions are on a very high level [130]. The paper describes tectonic deformation, the subsoil being folded, fractured and uplifted. The trend of folding and fracturing is consistent with the NNW–SSE-oriented tectonic maximum stress axis. The seismic rupture occurred along a previously unmapped deformation front. This reverse fault broke the surface at the end of the fourth century CE. This study redefines the seismic hazard of Western Sicily, a region where recurrence-time intervals for large earthquakes are still unknown [130]. One day, we hope that the Periadriatic Lineament will be known down to this depth.

Table A1. Distance between known active faults and damaged archaeological sites in Italy. These values allow estimation of the range of distance where causative faults of damaged sites can be looked for along the Periadriatic Lineament.

Site	Distance	Fault	Reference
Egna, Trento	0–18 km	Giudicarie system	[29,30]
Rome	>70 km	Fucino Fault System	[129]
Ostia, Roman port city	~12 km	the closest known fault	[130]
Fucino, Roman drainage tunnel	10 km	Fucino fault	[126]
Isernia	15 km	Aquae Iuliae fault	[47]
Crotone, Calabria	>30 km	Lakes Fault	[131]
Lilybaeum	>7 km	Mt. Grande trust ramp	[132]
Tindari	40 km	Messina Strait	[127]

A last remark: as a kind of fine-tuning of archaeoseismology, Sparice and co-workers [133] brought forward evidence that volcanic and tectonic earthquakes can be distinguished around the Vesuvius, regarding its 79 AD eruption.

References

1. Schmid, S.; Fügenschuh, B.; Kissling, E.; Schuster, R. Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geol. Helv.* **2004**, *97*, 93–117. [CrossRef]
2. Fodor, L.; Jelen, B.; Marton, M.; Skaberne, D.; Car, J.; Vrabec, M. Miocene-Pliocene tectonic evolution of the Slovenian Periadriatic fault: Implications for Alpine-Carpathian extrusion models. *Tectonics* **1998**, *17*, 690–709. [CrossRef]

3. Vrabec, M.; Fodor, L. Late Cenozoic tectonics of Slovenia: Structural styles at the northeastern corner of the Adriatic microplate. In *The Adria Microplate: GPS Geodesy, Tectonics and Hazards*; Pinter, N., Ed.; Springer: Berlin, Germany, 2001; pp. 151–168. [CrossRef]
4. Vrabec, M. (University of Ljubljana, Slovenia). Personal communication, 2002.
5. Bada, G.; Grenerczy, G.; Tóth, L.; Horváth, F.; Stein, S.; Windhoffer, G.; Fodor, L.; Pinter, N.; Fejes, I. Motion of Adria and the ongoing inversion of the Pannonian Basin: Seismicity, GPS velocities, and stress transfer. In *Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues*; Stein, S., Mazzotti, S., Eds.; Geological Society of America Special Papers: Boulder, Colorado, USA, 2007; Volume 425, pp. 243–262. [CrossRef]
6. Bada, G.; Horváth, F.; Dövényi, P.; Szafián, P.; Windhoffer, G.; Cloetingh, S. Present-day stress field and tectonic inversion in the Pannonian basin. *Glob. Planet Change* **2007**, *58*, 165–180. [CrossRef]
7. Atanackov, J.; Jamšek Rupnik, P.; Jež, J.; Celarc, B.; Novak, M.; Milanic, B.; Markelj, A.; Bavec, M.; Kastelic, V. Database of active faults in Slovenia: Compiling a new active fault database at the junction between the Alps, the Dinarides and the Pannonian Basin tectonic domains. *Front. Earth Sci.* **2021**, *9*, 604388. [CrossRef]
8. Grünthal, G.; Wahlström, R. The European-Mediterranean Earthquake Catalogue (EMEC) for the last millennium. *J. Seismol.* **2012**, *16*, 535–570. [CrossRef]
9. Stucchi, M.; Rovida, A.; Gomez Capera, A.A.; Alexandre, P.; Camelbeeck, T.; Demircioglu, M.B.; Gasperini, P.; Kouskouna, V.; Musson, R.M.W.; Radulian, M.; et al. The SHARE European Earthquake Catalogue (SHEEC) 1000–1899. *J. Sei's* **2012**, *17*, 523–544. [CrossRef]
10. Serpelloni, E.; Vannucci, G.; Anderlini, L.; Bennett, R.A. Kinematics, seismotectonics and seismic potential of the eastern sector of the European Alps from GPS and seismic deformation data. *Tectonophys* **2016**, *688*, 157–181. [CrossRef]
11. Sarao, A.; Sugan, M.; Bressan, G.; Renner, G.; Restivo, A. A focal mechanism catalogue of earthquakes that occurred in the southeastern Alps and surrounding areas from 1928–2019. Earth Syst. *Sci. Data* **2021**, *13*, 2245–2258. [CrossRef]
12. Jozi Najafabadi, A.; Haberland, C.; Ryberg, T.; Verwater, V.F.; Le Breton, E.; Handy, M.R.; Weber, M.; AlpArray & AlpArray Swath-D Working Group. Relocation of earthquakes in the southern and eastern Alps (Austria, Italy) recorded by the dense, temporary SWATH-D network using a Markov chain Monte Carlo inversion. *Solid Earth* **2021**, *12*, 1087–1109. [CrossRef]
13. Bagagli, M.; Molinari, I.; Diehl, T.; Kissling, E.; Giardini, D.; AlpArray Working Group. The AlpArray Research Seismicity-Catalogue. *Geophys. J. Int.* **2022**, *231*, 921–943. [CrossRef]
14. Kázmér, M.; Kovács, S. Permian-Paleogene paleogeography along the eastern part of the Insubric-Periadriatic lineament system: Evidence for continental escape of the Bakony-Drauzug unit. *Acta Geol. Hung.* **1985**, *28*, 71–84. (In Budapest)
15. Tari, G. Alpine Tectonics of the Pannonian Basin. Ph.D. Thesis, Rice University, Houston, TX, USA, 1994.
16. Frisch, W.; Kuhlemann, J.; Dunkl, I.; Brügel, A. Palinspastic reconstruction and topographic evolution of the Eastern Alps during late Tertiary tectonic extrusion. *Tectonophys* **1998**, *297*, 1–15. [CrossRef]
17. Prince, E.; Tsukamoto, S.; Grützner, C.; Vrabec, M.; Ustaszewski, K. Not too old to rock: ESR and OSL dating reveal Quaternary activity of the Periadriatic Fault in the Alps. *Earth Planets Space* **2024**, *76*, 85. [CrossRef]
18. Rapuc, W.; Sabatier, P.; Andric, M.; Crouzet, C.; Arnaud, F.; Chapron, E.; Smuch, A.; Develle, A.-L.; Wilhelm, B.; Demory, F.; et al. 6600 years of earthquake record in the Julian Alps (Lake Bohinj, Slovenia). *Sedimentology* **2018**, *65*, 1777–1779. [CrossRef]
19. Daxer, C.; Sammartini, M.; Molenaar, A.; Piechl, T.; Strasser, M.; Moernaut, J. Morphology and spatio-temporal distribution of lacustrine mass-transport deposits in Wörthersee, Eastern Alps, Austria. In *Subaqueous Mass Movements and their Consequences: Advances in Process Understanding, Monitoring and Hazard Assessments*; Georgiopoulou, A., Amy, L.A., Benetti, S., Chaytor, J.D., Clare, M.A., Gamboa, D., Haughton, P.D.W., Moernaut, J., Mountjoy, J.J., Eds.; Geological Society, Special Publications: London, UK, 2020; Volume 500, pp. 235–254. [CrossRef]
20. Daxer, C.; Ortler, M.; Fabbri, S.C.; Hilbe, M.; Hajdas, I.; Dubois, N.; Piechl, T.; Hammerl, C.; Strasser, M.; Moernaut, J. High-resolution calibration of seismically-induced lacustrine deposits with historical earthquake data in the Eastern Alps (Carinthia, Austria). *Quat. Sci. Rev.* **2022**, *284*, 107497. [CrossRef]
21. Daxer, C.; Huang, J.-J.S.; Weginger, S.; Hilbe, M.; Strasser, M.; Moernaut, J. Validation of seismic hazard curves using a calibrated 14 ka lacustrine record in the Eastern Alps, Austria. *Sci. Rep.* **2022**, *12*, 19943. [CrossRef] [PubMed]
22. Daxer, C.; Wils, K.; Ramisch, A.; Strasser, M.; Moernaut, J. Contrasting sedimentary and long-lasting geochemical imprints of seismic shaking in a small, groundwater-fed lake basin (Klopeiner See, Eastern European Alps). *Sedimentologika* **2024**, *2*, 1–27. [CrossRef]
23. Baroň, I.; Plan, L.; Grasemann, B.; Melichar, R.; Mitrović-Woodell, I.; Rowberry, M.; Scholz, D. Three large prehistoric earthquakes in the Eastern Alps evidenced by cave rupture and speleothem damage. *Geomorph.* **2022**, *408*, 108242. [CrossRef]
24. Galadini, F.; Hinzen, K.-G.; Stiros, S. Archaeoseismology: Methodological issues and procedure. *J. Seismol.* **2006**, *10*, 395–414. [CrossRef]
25. Hinzen, K.-G. Archaeoseismology. In *Encyclopedia of Solid Earth Geophysics*; Gupta, H.K., Ed.; Springer Science: Dordrecht, The Netherlands, 2011; pp. 11–15.
26. Sintubin, M. Archaeoseismology: Past, present and future. *Quat. Int.* **2011**, *242*, 4–10. [CrossRef]
27. Sintubin, M. Archaeoseismology. In *Encyclopedia of Earthquake Engineering*; Beer, M., Patelli, E., Kouigioumtzoglou, I., Au, S.-K., Eds.; Springer: Berlin/Heidelberg, Germany, 2013; pp. 1–17.
28. Kázmér, M. Damage to ancient buildings from earthquakes. In *Encyclopedia of Earthquake Engineering*; Beer, M., Patelli, E., Kouigioumtzoglou, I., Au, S.-K., Eds.; Springer: Berlin/Heidelberg, Germany, 2015; pp. 500–506.

29. Galadini, F.; Galli, P. Archaeoseismology in Italy: Case studies and implications on long-term seismicity. *J. Earthq. Eng.* **2001**, *5*, 35–68. [CrossRef]
30. Galadini, F.; Galli, P. Palaeoseismology related to the displaced Roman archaeological remains at Egna (Adige Valley, northern Italy). *Tectonophysics* **1999**, *308*, 171–191. [CrossRef]
31. Galli, P.; Galadini, F. Surface faulting of archaeological relics. A review of case histories from the Dead Sea to the Alps. *Tectonophysics* **2001**, *335*, 291–312. [CrossRef]
32. Coden, F. "Terremotus maximus fuit": Il sisma del 1117 e l'architettura medioevale dell'area veronese. *Arta Veneta* **2010**, *67*, 6–25.
33. Livio, F.; Ferrario, M.F.; Martinelli, E.; Talamo, S.; Cercatillo, S.; Michetti, A.M. The footprint of a historical paleoearthquake: The sixth-century-CE event in the European western Southern Alps. *Nat. Haz. Earth Syst. Sci.* **2023**, *23*, 3407–3424. [CrossRef]
34. Kázmér, M.; Jamšek Rupnik, P.; Gaidzik, K. Seismic activity in the Celje Basin (Slovenia) in Roman times–archaeoseismological evidence from Celeia. *Quaternary* **2023**, *6*, 10. [CrossRef]
35. Kázmér, M.; Škrgulja, R. The 4th century Siscia (Croatia) earthquake–archaeoseismological evidence. In Proceedings of the 1st Croatian Conference on Earthquake Engineering, 1CroCEE, Zagreb, Croatia, 22–24 March 2021; pp. 257–266. [CrossRef]
36. Dolenz, H. Ein Erdbeben in der Stadt Alt-Virunum auf dem Magdalensberg? In *Antike Erdbeben im Alpinen und Zirkumalpinen Raum: Befunde und Probleme in Archäologischer, Historischer und Seismologischer Sicht*; Waldherr, G.H., Smolka, A., Eds.; Franz Steiner Verlag: Stuttgart, Germany, 2007; pp. 99–115.
37. Kázmér, M.; Gaidzik, K. Seismic activity along the Periadriatic and Sava Faults in the past two millennia—An archaeoseismological assessment. In Proceedings of the 15th Emile Argand Conference on Alpine Geological Studies, Alpshop 2022-35, Ljubljana, Slovenia, 12–14 September 2022; Abstracts. [CrossRef]
38. Stiros, S.C. Identification of earthquakes from archaeological data: Methodology, criteria, and limitations. In *Archaeoseismology*; Stiros, S.C., Jones, R.E., Eds.; British School at Athens, Fitch Laboratory Occasional Paper 7: British School at Athens, Athens, Greece, 1996; pp. 129–152.
39. Kázmér, M. Towards a protocol of archaeoseismological survey. In Proceedings of the Sixth International Colloquium on Historical Earthquakes & Paleoseismology Studies, Han-sur-Lesse, Belgium, 24–25 October 2018; Abstract Book; p. 28.
40. Rodríguez-Pascua, M.; Silva, P.G.; Perez-Lopez, R.; Giner-Robles, J.-L.; Martín-Gonzalez, F.; Perucha, M.A. Preliminary intensity correlation between macroseismic scales (ESI07 and EMS98) and Earthquake Archaeological Effects (EAEs). In *Seismic Hazard, Critical Facilities and Slow Active Faults. PATA Days, Proceedings of the 4th International INQUA Meeting on Paleoseismology, Active Tectonics and Archaeoseismology (PATA), 9–14 October 2013, Aachen, Germany*; Grützner, C., Rudersdorf, A., Perez-Lopez, R., Reicherter, K., Eds.; RWTH University: Aachen, Germany, 2013; pp. 221–224.
41. Rodríguez-Pascua, M.; Silva, P.G.; Giner-Robles, J.L.; Pérez-López, R.; Perucha, M.A.; Martín-González, F. Arqueosismología: Una nova herramienta para la sismología y la protección del patrimonio. *Rev. Otarq.* **2016**, *1*, 151–169. [CrossRef]
42. Grünthal, G. *European Macroseismic Scale 1998 (EMS-98) European Seismological Commission, Subcommission on Engineering Seismology, Working Group Macroseismic Scales. Conseil de l'Europe, 15*; Cahiers du Centre Européen de Géodynamique et de Séismologie: Luxembourg, 1998.
43. Ruggieri, N. Seismic vulnerability of the ancient Pompeii through the evaluation of the 62 AD earthquake effects. *Int. J. Architect. Herit.* **2017**, *11*, 490–500. [CrossRef]
44. Konecny, A., Humer, F., Decker, K., Eds.; Das Carnuntiner Erdbeben im Kontext. In Proceedings of the III Internationalen Kolloquiums, Carnuntum, Austria, 17–18 October 2013; Archäologischer Park Carnuntum: Carnuntum, Austria, 2019; 159p.
45. Dobosi, L.; Kázmér, M. Late Roman earthquake in Brigetio. In *Pannonia Underground, Proceedings of the International Conference Held at Szombathely, Hungary, 25–26 November 2021*; Biró, S., Ed.; Savaria Museum: Szombathely, Hungary, 2022; pp. 179–207.
46. Hinzen, K.-G.; Schreiber, S.; Fleischer, C.; Reamer, S.K.; Wiosna, I. Archeoseismic study of damage in Roman and Medieval structures in the center of Cologne, Germany. *J. Seismol.* **2013**, *17*, 399–424. [CrossRef]
47. Bottari, C.; Ferranti, L.; Di Maio, R.; Frisetti, A.; De Paola, C.; La Manna, M.; Piegari, E.; Marazzi, F. The 847 CE earthquake in central-southern Italy: New hints from archaeosismological and geophysical investigations in the Volturno River Valley area. *Tectonophysics* **2020**, *774*, 228301. [CrossRef]
48. Korzhenkov, A.M.; Gadzhiev, M.S.; Ovsyuchenko, A.N.; Larkov, A.S.; Rogozhin, E.A. Traces of seismic activity in architectural monuments in Derbent, Dagestan. *Geofiz. Process. Biosf.* **2020**, *19*, 5–29. [CrossRef]
49. Korjenkov, A.M.; Mazor, E. Archaeoseismological Damage Patterns at the Ancient Ruins at Rehovot-ba-Negev, Israel. In *Archäologischer Anzeiger*; Deutsches Archäologisches Institut: Berlin, Germany, 2014; pp. 75–92. [CrossRef]
50. Korjenkov, A.; Baipakov, K.; Chang, C.; Peshkov, Y.; Savelieva, T. Traces of ancient earthquakes in medieval cities along the Silk Road, northern Tien Shan and Dzhungaria. *Turk. J. Earth Sci.* **2003**, *12*, 241–261.
51. Hinzen, K.G.; Schwellenbach, I.; Schweppe, G.; Marco, S. Quantifying earthquake effects on ancient arches, example: The Kalat Nimrod Fortress, Dead Sea fault zone. *Seismol. Res. Lett.* **2016**, *87*, 751–764. [CrossRef]
52. Martín-González, F. Earthquake damage orientation to infer seismic parameters in archaeological sites and historical earthquakes. *Tectonophysics* **2018**, *724*, 137–145. [CrossRef]
53. Martín-González, F. Review and proposed method to study the damage orientation of earthquake effects in preinstrumental earthquakes. *Izv. Phys. Solid Earth* **2021**, *57*, 980–993. [CrossRef]
54. Kim, Y.S.; Naik, S.P.; Choi, J.H.; Jin, K.; Ho, G.R.; Kim, T.; Lee, J. Kinematic analysis and fault-dependence of building-wall fracture patterns during moderate earthquakes. *Geosci. J.* **2023**, *27*, 769–780. [CrossRef]

55. Herak, M.; Herak, D. Properties of the Petrinja (Croatia) earthquake sequence of 2020–2021–Results of seismological research for the first six months of activity. *Tectonophysics* **2023**, *858*, 229885. [CrossRef]
56. Baize, S.; Amoroso, S.; Belić, N.; Benedetti, L.; Boncio, P.; Budić, M.; Cinti, F.R.; Henriquet, M.; Jamšek Rupnik, P.; Kordić, B.; et al. Environmental effects and seismogenic source characterization of the December 2020 earthquake sequence near Petrinja, Croatia. *Geophys. J. Int.* **2022**, *230*, 1394–1418. [CrossRef]
57. Markušić, S.; Stanko, D.; Penava, D.; Ivančić, I.; Bjelotomić Oršulić, O.; Korbar, T.; Sarhosis, V. Destructive M6.2 Petrinja earthquake (Croatia) in 2020–Preliminary multidisciplinary researC. *Remote Sens.* **2021**, *13*, 1095. [CrossRef]
58. Basili, R.; Kastelic, V.; Demircioglu, M.B.; Garcia Moreno, D.; Nemser, E.S.; Petricca, P.; Sboras, S.P.; Besana-Ostman, G.M.; Cabral, J.; Camelbeeck, T.; et al. The European Database of Seismogenic Faults (EDSF) Compiled in the Framework of the Project SHARE. 2013. Available online: https://gfzpublic.gfz-potsdam.de/pubman/faces/ViewItemFullPage.jsp?itemId=item_667894_4 (accessed on 1 December 2024).
59. Basili, R.; Danciu, L.; Beauval, C.; Sesetyan, K.; Vilanova, S.; Adamia, S.; Arroucau, P.; Atanackov, J.; Baize, S.; Canora, C.; et al. *European Fault-Source Model 2020 (EFSM20): Online Data on Fault Geometry and Activity Parameters*; Istituto Nazionale di Geofisica e Vulcanologia (INGV): Rome, Italy, 2022. [CrossRef]
60. Nemes, F.; Neubauer, F.; Cloetingh, S.; Genser, J. The Klagenfurt Basin in the Eastern Alps an intra-orogenic decoupled flexural basin? *Tectonophysics* **1997**, *282*, 189–203. [CrossRef]
61. Hammerl, C. The earthquake of January 25th, 1348, discussion of sources. In *Historical Investigation of European Earthquakes*; Materials of the CEC Project "Review of Historical Seismicity in Europe"; CNR: Milano, Italy, 1994; Volume 2.
62. Hammerl, C. Das Erdbeben von 25. Jänner 1348. Rekonstruktion eines Naturereignisses. *Neues Aus Alt-Villach* **1994**, *31*, 55–94.
63. Vetterling, C. "Der Turm. . . ein ausgezeichnetes und schönes Werk". Beue Erkenntnisse zum Auusehen der Stadtpfarrkirche St. Jakob vor 1348. *Neues Aus Alt-Villach* **2014**, *51*, 37–46.
64. Schwark, A. Studien zur Baugeschichte der Stadtpfarrkirche St. Jakob in Villach. PhD. Thesis, Universität Wien, Wien, Austria, 2012; 145p.
65. Schlager, S.; Tropper, P.G. *Stadthauptpfarrkirche St. Jakob in VillaC. Christliche Kunststätten Österreichs, Nr. 560*; Verlag St. Peter: Salzburg, Austria, 2014; 42p.
66. Vetterling, C.; Karpf, K. Archäologie und Bauforschung in der Villacher Burg. *Neues Aus Alt-Villach* **2003**, *40*, 7–24.
67. Hammerl, C. Historical earthquake research in Austria. *Geosci. Lett.* **2017**, *4*, 7. [CrossRef]
68. Caracciolo, C.H.; Slejko, D.; Camassi, R.; Castelli, V. The Eastern Alps earthquake of 25 January 1348: New insights from old sources. *Bull. Geophys. Oceanogr.* **2020**, *63*, 335–364. [CrossRef]
69. Drimmel, J. Rezente Seismizität des Ostalpenraumes. In *Der Geologische Aufbau Österreichs*; Oberhauser, R., Ed.; Springer: Wien, Austria, 1980; pp. 505–528.
70. Kozák, J.; Cermák, V. *The Illustrated History of Natural Disasters*; Springer: Dordrecht, The Netherlands, 2010; 203p.
71. Dehio, A. *Die Kunstdenkmäler Österreisch. Kärntern. Dritte, Erweiterte un Verbesserte Auflage von Gabriele Russwurm-Biro*; Anton Schroll: Wien, Austria, 2001.
72. Brandt, A. Bergstürze and der Villacher Alpe (Dobratsch/Kärnten/Österreich). Ph.D. Thesis, University of Hamburg, Hamburg, Germany, 1981.
73. Lenhardt, W. Earthquake-triggered landslides in Austria–Dobratsch revisited. *Jahrb. Geol. Bundesanst.* **2007**, *147*, 193–199.
74. Huber, A. Erdbebenschäden and der Millstätter Stiftskirche–Folgerungen für deren Baugeschichte. *Carinth. I* **2002**, *192*, 343–361.
75. Ginhart, K.; Bacher, E.; Friesen, I.; Hajós, G.; Helke, W.; Herzig, E.; Huber, H.R.; Migacs, M.; Oberhaidacher, J.; Reichmann-Endres, E.; et al. *Kärnten. Die Kunstdenkmäler Österreichs*; Anton Schroll: Wien, Austria, 2001; pp. 703–705.
76. Nikolasch, F. *Millstatt, Hauptpfarrkirche St. Salvator und Allerheiligen, Stiftsmuseum, Kalvarienbergkapelle*; Kunstverlag Peda: Passau, Germany, 2010; 44p.
77. Weinzierl-Fischer, E. Geschichte des Benediktineklosters Millstatt in Kärnten. In *Archiv für Vaterländische Geschichte und Topographie 33*; Verlag des Geschichtvereins Kärntens: Klagenfurt, Austria, 1951; 144p.
78. Hammerl, C. Das Erdbeben vom 4. Mai 1201. *Mitt. Inst. Österr. Geschichtsforsch.* **1995**, *103*, 350–368. [CrossRef]
79. Hammerl, C. Historische Erdbeben in Kärnten mit besonderer Berücksichtigung des Bebens vom 4. Mai 1201. In *Arbeitstagung der Geologischen Bundesanstalt*; Gmünd, Geologische Bundesanstalt: Wien, Austria, 2005; pp. 125–128.
80. Alexandre, A.; Alexandre-Lamotte, D. Les tremblements de Terre en Europe au Moyen Age et al Renaissance. In *Étude Critique Des Sources et Catalogue des Tremblements de Terre en Europe de 284 a 1550*; Observatoire Royale de Belgique: Bruxelles, Belgium, 2024; 215p. [CrossRef]
81. Gugl, C. Archäologische Forschungen in Teurnia. In *Die Ausgrabungen in der Wohnterrassen 1970–1978. Die Latenezeitlichen Funde from Holzer Berg*; Sonderschriften; Österreichisches Archäologisches Institut: Wien, Austria, 2000; Volume 33, 287p.
82. Ammann, G.; Egg, E.; Felmayer, J.; Franckenstein, J.; Helke, W.; Huber, H.R.; Öttl, H.; Pizzinini, M. *Tirol. Die Kunstdenkmäler Österreichs*; Anton Schroll: Wien, Austria, 1980; pp. 485–504.
83. Camelbeeck, T.; Alexandre, P.; Sabbe, A.; Knuts, E.; Garcia-Moreno, D.; Lecocq, T. The impact of the earthquake activity in Western Europe from the historical and architectural heritage records. In *Intraplate Earthquakes*; Talwani, P., Ed.; Cambridge University Press: Cambridge, UK, 2014; pp. 198–230.
84. Grützner, C. The Baelo Claudia Earthquake Problem. Ph.D. Thesis, RWTH University of Aachen, Aachen, Germany, 2011; 168p.

85. Helly, B.; Rideaud, A.; Salard, J.-F. Réhabilitation des bâtis anciens pour l'accueil du public: Entre humilité conservatrice et ingénierie audacieuse. In *Archéosismicité Vulnérabilité. Patrimoine Bâti et Société. Actes des VIe et VIIe Rencontres du Groupe APS*; Levret, A., Ed.; Groupe APS: Perpignan, France, 2008; pp. 273–286.
86. Korjenkov, A.M.; Mazor, E. The features of the earthquake damage pattern of ancient city ruins in the Negev Desert, Israel. *Geotectonics* **2013**, *47*, 52–65. [CrossRef]
87. Kamai, R.; Hatzor, Y.H. Numerical analysis of block stone displacements in ancient masonry structures: A new method to estimate historic ground motions. *Int. J. Numer. Anal. Methods Geomech.* **2008**, *32*, 1321–1340. [CrossRef]
88. Kázmér, M. Evidence for earthquake damage on St. Michael church in Cluj-Napoca, Romania. In Proceedings of the 6th National Conference on Earthquake Engineering and 2nd National Conference on Earthquake Engineering and Seismology, Bucharest, Romania, 14–17 June 2017; Pavel, F., Radulian, M., Arion, C., Popa, M., Aldea, A., Eds.; pp. 95–99.
89. Kühebacher, E. *Paesaggio Culturale e Artistico del Territorio di San Candido*, 3rd ed.; Associazone Turistico San Candido: San Candido, Italy, 2003; 144p.
90. Goula, X.; Irizarry, J.; Figueras, S.; Macau, A.; Barbat, A.H.; Carreno, L.M.; Lantada, N.; Valcarcel, J. *El Terratrémol de Llorca de l'11 de maig de 2011*; Institut Geológic de Catalunya: Barcelona, Spain, 2011; 91p.
91. Kázmér, M. Archaeoseismology. In *Atlas of Structural Geology*; Mukherjee, S., Ed.; Elsevier: Amsterdam, The Netherlands, 2015; pp. 153–155, figs. 6.52–6.55.
92. Rodríguez-Pascua, M.A.; Benavente Escobar, C.; Rosell Guevara, L.; Grützner, C.; Audin, L.; Walker, R.; García, B.; Aguirre, E. Did earthquakes strike Machu Picchu? *J. Seismol.* **2020**, *24*, 883–895. [CrossRef]
93. Satuluri, S.; Gadhavi, M.S.; Malik, J.N.; Vikrama, B. Quantifying seismic induced damage at ancient site Manjal located in Kachchh Mainland region of Gujarat, India. *J. Archaeol. Sci. Rep.* **2020**, *33*, 102486. [CrossRef]
94. Schweppe, G.; Hinzen, K.-G.; Marco, S. Archaeoseismological investigation of the deformation of the ruin of the crusader fortress Ateret, Israel with 3DEC. In *Applied Numerical Modeling in Geomechanics*; Billaux, H., Nelson, S., Eds.; Itasca International: Minneapolis, MN, USA, 2020; 6p, Paper 09-03.
95. Erhard, B. Le fasi do construzione di Castel Tirolo. In *Il sogno do un Principe: Mainardi II–la Nascita del Tirolo. Mostra Storica del Tirolo 1995*; Erhard, B., Brandstätter, G., Eds.; Castel Tirolo, Stift Stams. Museo Provinciale di Castel Tirolo: Tirolo, Italy; Tiroler Landesmuseum Ferdinandeum: Innsbruck, Austria, 1995; pp. 64–73.
96. Mirwald, P.W. Geologische und materialkundliche Untersuchungen auf Schloss Tirol. In *Tirol. Bd. 1. Baugeschichte. Die Burg Tirol von ihren Anfängen bis zum 21. Jahrhundert*; Hauser, W., Mittermair, M., Eds.; Schloss Südtiroler Landesmuseum: Schloss Tirol, Italy, 2017; pp. 550–557.
97. Mittermair, M.; Hauser, W. Die Baugeschichte von Schloss Tirol im Mittelalter. In *Schloss Tirol. Bd. 1. Baugeschichte. Die Burg Tirol von ihren Anfängen bis zum 21. Jahrhundert*; Hauser, W., Mittermair, M., Eds.; Südtiroler Landesmuseum: Schloss Tirol, Italy, 2017; pp. 136–285.
98. Andergassen, L. Le pitture murali della cappella di Castel Tirolo. In *Il Sogno do un Principe: Mainardi II–la Nascita del Tirolo. Mostra Storica del Tirolo 1995*; Erhard, B., Brandstätter, G., Tirolo, C., Stams, S., Eds.; Museo Provinciale di Castel Tirolo: Tirolo, Italy; Tiroler Landesmuseum Ferdinandeum: Innsbruck, Austria, 1995; pp. 97–112.
99. Nicolussi, K. Dendrocronologia: Un nuovo strumento di indagine storica. In *Il Sogno do un Principe: Mainardi II–la Nascita del Tirolo. Mostra Storica del Tirolo 1995*; Tirolo, C., Stams, S., Erhard, B., Brandstätter, G., Eds.; Museo Provinciale di Castel Tirolo: Tirolo, Italy; Tiroler Landesmuseum Ferdinandeum: Innsbruck, Austria, 1995; pp. 74–78.
100. Mittermair, M. (Ed.) *Schloss Tirol. Bd. 2. RaumbuC. Die Bauhistorischen und Archäologschen Befunde*; Südtiroler Landesmuseum: Schloss Tirol, Italy, 2017; 511p.
101. Caporali, A.; Braitenberg, C.; Massironi, M. Geodetic and hydrological aspects of the Merano earthquake of 17 July 2001. *J. Geodyn.* **2005**, *39*, 317–336. [CrossRef]
102. Gögele, M. *Die Kirche Hl. Johannes der Täufer. Dorf Tirol*; Pfarre Tirol: Tirolo, Italy, 2006; 64p.
103. Bahrouni, N.; Meghraoui, M.; Hinzen, K.; Arfaoui, M.; Mahfoud, F. The damaging earthquake of 9 October 859 in Kairouan (Tunisia): Evidence from historical and archeoseismological investigations. *Seismol. Res. Lett.* **2020**, *98*, 1890–1900. [CrossRef]
104. Trifonov, V.G.; Kozhurin, A.I. Study of active faults: Theoretical and applied implications. *Geotectonics* **2010**, *44*, 510–528. [CrossRef]
105. Andergassen, L. *Stadtpfarrkirche St. Nikolaus Meran. Schnell Kunstführer Nr. 719*, 8th ed.; Schnell und Steiner: Regensburg, Germany, 2019; 32p.
106. Sengör, A.M.C.; Zabci, C. The North Anatolian Fault and the North Anatolian Shear Zone. In *Landscapes and Landforms of Turkey*; Kuzucuoglu, C., Ciner, A., Kazanci, N., Eds.; Springer: Cham, Switzerland, 2019; pp. 481–494. [CrossRef]
107. Vrabec, M.; Pavlovčič, P.; Prešeren, P.; Stopar, B. GPS study (1996–2002) of active deformation along the Periadriatic fault system in northeastern Slovenia: Tectonic model. *Geol. Carp.* **2006**, *57*, 57–65. Available online: https://www.sav.sk/journals/uploads/05230801GeolCarp_Vol57_No1_57_65.pdf (accessed on 1 December 2024).
108. Carulli, G.B.; Slejko, D. The 1976 Friuli (NE Italy) earthquake. *G. Geol. Appl.* **2005**, *1*, 147–156. [CrossRef]
109. Wells, D.L.; Coppersmith, K. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bull. Seismol. Soc. Am.* **1994**, *84*, 974–1002. [CrossRef]

110. Rodriguez-Pascua, M.A.; Silva, P.G.; Giner-Robles, J.L.; Perucha, M.A.; Roquero, E.; Bardají, T.; Elez, J.; Perez-Lopez, R. Earthquake archaeological effects (EAEs) for identification of seismic damage and intensity assessments in the cultural heritage. In *Handbook of Cultural Heritage Analysis*; D'Amico, S., Venuti, V., Eds.; Springer Nature: Cham, Switzerland, 2022; pp. 1779–1789.
111. Michetti, A.M.; Esposito, E.; Guerrieri, L.; Porfido, S.; Serva, L.; Tatevossian, R.; Vittori, E.; Audemard, F.; Azuma, T.; Clague, J.; et al. Environmental Seismic Intensity Scale 2007—ESI 2007. *Mem. Descr. Carta Geol. D'italia* **2007**, *74*, 7–54.
112. Oswald, P.; Strasser, M.; Hammerl, C.; Moernaut, J. Seismic control of large prehistoric rockslides in the Eastern Alps. *Nat. Comm.* **2021**, *12*, 1059. [CrossRef]
113. Grützner, C.; Achenbrenner, S.; Jamšek Rupnik, P.; Reicherter, K.; Saifelislam, N.; Vicic, B.; Vrabec, M.; Welte, J.; Ustaszewski, K. Holocene surface-rupturing earthquakes on the Dinaric Fault System, western Slovenia. *Solid Earth* **2021**, *12*, 2211–2234. [CrossRef]
114. Schmid, S.; Fügenschuh, B.; Kounov, A.; Matenco, L.; Nievergelt, P.; Oberhänsli, R.; Pleuger, J.; Schefer, S.; Schuster, R.; Tomljenovic, B.; et al. Tectonic units of the Alpine collision zone between Eastern Alps and western Turkey. *Gondwana Res.* **2020**, *78*, 308–374. [CrossRef]
115. Visnovitz, F.; Jakab, B.; Czecze, B.; Hámori, Z.; Székely, B.; Fodor, L.; Horváth, F. High resolution architecture of neotectonic fault zones and post-8-Ma deformations in western Hungary: Observations and neotectonic characteristics of the fault zone at the Eastern Lake Balaton. Global Planet. *Change* **2021**, *203*, 103540. [CrossRef]
116. Ivančić, I.; Herak, D.; Herak, M.; Allegretti, I.; Fiket, T.; Kuk, K.; Markušić, S.; Prevolnik, S.; Sović, I.; Dasović, I.; et al. Seismicity of Croatia in the period 2006–2015. *Geofizika* **2018**, *35*, 69–98. [CrossRef]
117. Tomlienović, B.; Csontos, L. Neogene-Quaternary structures in the border zone between Alps, Dinarides and Pannonian Basin (Hrvatsko zagorje and Karlovac Basins, Croatia). *Int. J. Earth Sci. (Geol. Rundsch.)* **2001**, *90*, 560–578. [CrossRef]
118. Ratschbacher, L.; Merle, O.; Davy, P.; Cobbold, P. Lateral extrusion in the Eastern Alps; Part 1: Boundary conditions and experiments scaled for gravity. *Tectonics* **1991**, *10*, 245–256. [CrossRef]
119. Ratschbacher, L.; Frisch, W.; Linzer, H.G.; Merle, O. Lateral extrusion in the Eastern Alps, part 2: Structural analysis. *Tectonics* **1991**, *10*, 257–271. [CrossRef]
120. Jusseret, S. Archaeoseismological research on Minoan Crete: Past and present. In *Minoan Earthquakes–Breaking the Myth Through Interdisciplinarity*; Jusseret, S., Sintubin, M., Eds.; Leuven University Press: Leuven, Belgium, 2017; pp. 223–247.
121. Guidoboni, E.; Ferrari, G.; Mariotti, D.; Comastri, A.; Tarabusi, G.; Sgattoni, G.; Valensise, G. *CFTI5Med, Catalogo dei Forti Terremoti in Italia (461 a.C.-1997) e Nell'area Mediterranea (760 a.C.-1500)*; Istituto Nazionale di Geofisica e Vulcanologia (INGV): Roma, Italy, 2018. Available online: http://storing.ingv.it/cfti/cfti5/ (accessed on 1 December 2024).
122. Guidoboni, E. Comments on "Archaeoseismology in Italy: Case studies and implications on long-term seismicity" (J. Earthq. Eng. 5(1) [2001], pp. 35–68). *J. Earthq. Eng.* **2003**, *7*, 329–335. [CrossRef]
123. Galadini, F.; Galli, P. Response from the authors of "Archaeoseismology in Italy: Case studies and implications on long-term seismicity". [J. Earth Engrg. 5(1) [2001], pp. 35–68]. *J. Earthq. Eng.* **2003**, *7*, 339–346. [CrossRef]
124. Guidoboni, E.; Comastri, E.; Boschi, E. The "exceptional" earthquake of 3 January 1117 in the Verona area (northern Italy): A critical time review and detection of two lost earthquakes (lower Germany and Tuscany). *J. Geophys. Res.* **2005**, *110*, B12309. [CrossRef]
125. Falcucci, E.; Poli, M.E.; Galadini, F.; Scardia, G.; Paiero, G.; Zanferrari, A. First evidence of active transpressive surface faulting at the front of the eastern Southern Alps, northeastern Italy: Insight on the 1511 earthquake seismotectonics. *Solid Earth* **2018**, *9*, 911–922. [CrossRef]
126. Galadini, F.; Ceccaroni, E.; Dominus, G.D.; Falcucci, E.; Gori, S.; Maceroni, E.; Bonasera, M.; Di Giulio, G.; Moro, M.; Saroli, M.; et al. Combining earth sciences with archaeology to investigate natural risks related to the cultural heritage of the Marsica region (central Apennines, Italy). *Mediterr. Geosci. Rev.* **2022**, *4*, 287–318. [CrossRef]
127. Barbano, M.S.; Castelli, V.; Pantosti, D.; Pirrotta, C. Integration of historical, archaeoseismic and paleoseismological data for the reconstruction of the early seismic history in Messina Strait (south Italy): The 1st and 4th centuries AD earthquakes. *Ann. Geophys.* **2014**, *57*, S0192. [CrossRef]
128. Bottari, C. Archaeoseismology in Sicily: Past earthquakes and and effects on ancient society. In *Earthquakes and Their Impact on Society*; D'Amico, S., Ed.; Springer: Cham, Switzerland, 2016; pp. 491–504. [CrossRef]
129. Galli, P.A.C.; Molin, D. Beyond the damage threshold: The historic earthquakes of Rome. *Bull. Earthq. Eng.* **2014**, *12*, 1277–1306. [CrossRef]
130. Marra, F.; Milana, G.; Pecchioli, L.; Roselli, P.; Cangi, G.; Famiani, D.; Mercuri, A.; Carlucci, G. Historical faulting as the possible cause of earthquake damages in the ancient Roman port city of Ostia. *J. Seismol.* **2020**, *24*, 833–851. [CrossRef]
131. Galli, P.; Ruga, A.; Scionti, V.; Spadea, R. Archaeoseismic evidence for a Late Roman earthquake in the Crotone area (Ionian Calabria, Southern Italy): Seismotectonic implications. *J. Seismol.* **2006**, *10*, 443–458. [CrossRef]
132. Barreca, G.; Pepe, F.; Sulli, A.; Morreale, G.; Gambino, S.; Grassi, S.; Monaco, C.; Imposa, S. Deformed archeological remains at Lilybaeum in Western Sicily (southern Italy) as possible ground signatures of missed large earthquake in the area. *Nat. Hazards* **2024**. [CrossRef]
133. Sparice, D.; Amoretti, V.; Galadini, F.; Di Vito, M.A.; Terracciano, A.; Scarpati, G.; Zuchtriegel, G. A novel view of the destruction of Pompeii during the 79 CE eruption of Vesuvius (Italy): Syn-eruptive earthquakes as an additional cause of building collapse and deaths. *Front. Earth Sci.* **2024**, *12*, 1386960. [CrossRef]

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