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1 Introduction

1.1 Archaeoseismology

Until the 20th century, earthquake threats were only assumed for large active faults, for instance at plate boundaries, which were known to produce devastating earthquakes. In the beginning of the 20th century, due to the development of instrumental measurement techniques for seismicity, the earthquake risk could be determined for other less obvious areas as well. Present-day “instrumental” seismic quiescence may be falsely interpreted as an absence of earthquake threat, since periods of fault activity can be separated by more than hundreds of years, or even longer. A proper seismic hazard assessment should include a full range of observational time scales and not only be based on geological, historical or instrumental seismicity information (Ambraseys 2006). Archaeoseismology is one of the key disciplines that bridges the information gap between geological and recent time scales and therefore provides valuable information for a reliable seismic hazard assessment.

Archaeoseismology is defined as the study that aims to find significant criteria for recognizing past earthquakes in archaeological sites (Ambraseys 2005, 2006, Caputo & Pavlides 2008, Caputo & Helly 2008). Archaeoseismology is also defined as the detailed study of the pre-instrumental period of recognizing earthquakes that affected human settlements and their surroundings and which are acknowledged in ancient records (Buck & Stewart 2000). Instrumental seismicity provides detailed information only for the last century and historical catalogues cover just a few percent of the devastating earthquakes over the last centuries. Usually, historic records describe an undefined or small region and show strong deficiencies (Sintubin & Stewart 2008). Thus, archaeoseismology is the tool that provides necessary information on past earthquakes that occurred between the recent instrumental and the historical periods on the one hand and the period that is covered by the fields of palaeoseismology and neotectonics, i.e., geological studies, on the other hand (Ambraseys 2006, Galadini *et al.* 2006, Sintubin & Stewart 2008); see also Figure 1.

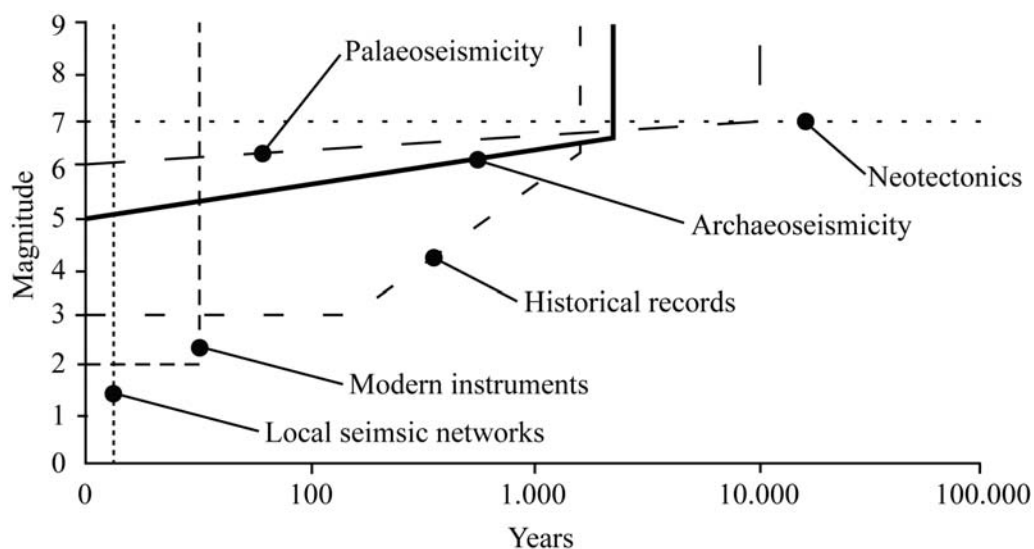


Figure 1 The magnitude and chronological separation and distribution of the different disciplines applied to the study of earthquakes in the past (modified after Levret 2002b).

In bridging this gap of seismic information between the instrumental and the geological period, the interdisciplinary field of archaeoseismology is crucial for reliable seismic hazard assessments.

Although the foundation of archaeoseismology has already been established in the 19th century (Galadini *et al.* 2006), only during the last two decades this discipline was fully developed through the integration of geosciences and archaeology. Several studies discuss the chronological separations as well as the overlap of these disciplines in earthquake research (e.g. Gürpinar 1989, Levret 2002a,b, Galadini *et al.* 2006, Caputo & Helly 2008). A key factor is that the integration of disciplines has boosted the importance and potential of archaeoseismology as an indicator of earthquakes in antiquity and history (< 1900) and as an assessor of seismic hazards (Nikonov 1988, Stiros & Jones 1996, Korjenkov & Mazor 1999, Galadini *et al.* 2006, Caputo & Helly 2008). As is proven by many studies, it is essential to know the frequency and intensity of past seismic activities in order to be able to interpret and to estimate potential seismic hazards in a region.

Figure 2 shows the temporal distribution of archaeological remains of different cultures in the Mediterranean area and surroundings. Archaeological sites in these regions cover a large time span of at least 6000 years. These sites have a high potential of recording ancient earthquakes and most of them have been discovered and are well described. Moreover, because many of these sites are located in the same region they can be considered as a seismic network, as they are likely to be affected by the same ancient earthquakes. Thus, archaeoseismic information from ancient settlements all around the Mediterranean can be compared and used for the determination of seismic events.

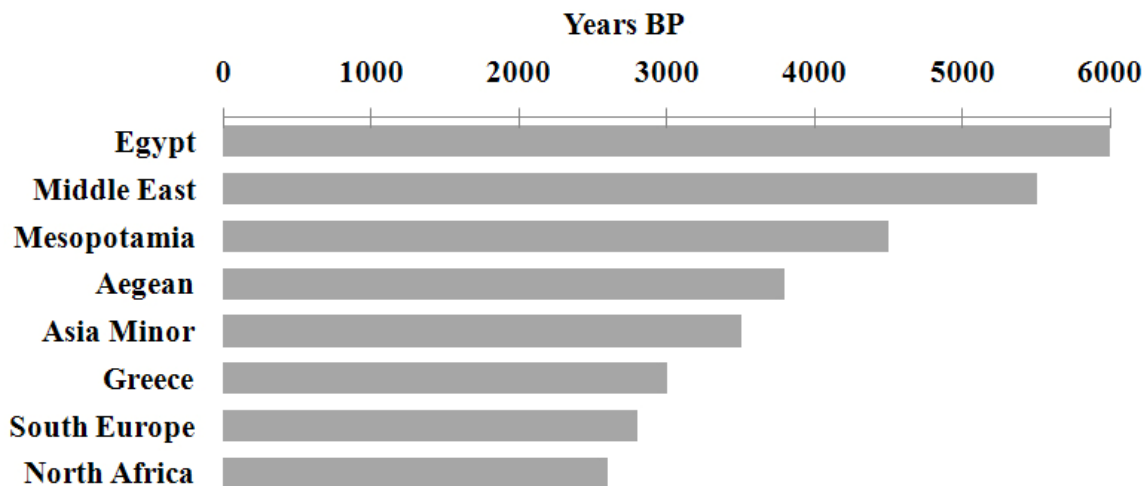


Figure 2 Time distribution of the potential of archaeological and historical sites in the Mediterranean region which are suitable for archaeoseismological investigations (modified after Caputo & Helly 2008).

Primarily, archaeoseismology provides information on the role of ancient earthquakes in the destruction and abandonment of ancient settlements. However, this knowledge can also be used to estimate possible future threats on archaeological sites. Therefore, an important additional objective of archaeoseismology is to study the potential effects of future earthquakes on archaeological remains which are relevant for the *in situ* preservation of archaeological heritage (Tendürüs *et al.* 2008).

Next to this, earthquake effects on ancient man-made structures provide important information on the seismic response of ancient structures and the dynamic behaviour of the geological subsurface (Hinzen 2005 and references therein). The different intensities and deformation patterns observed in the ancient constructions largely depend on the strength of earthquake shocks related to the subsurface conditions of the bedrock, as well as type and quality of the building structures. These latter aspects require knowledge on engineering issues as well and, therefore, the seismological data and observations should be integrated with civil engineering methods. This integration might also be interesting since it describes the influence seismic activities had on the evolution of ancient building styles and construction techniques in a certain region.

1.2 Interdisciplinary archaeoseismological studies

Initially, archaeologists investigated earthquake effects in ancient cities only when they were mentioned in historical records or in case the damage was very obvious. Earth scientists, however, tend to use the damaged structures on ancient sites only as an evidence of tectonic activity without referring them to the archaeological context.

During the last two decades or so, this qualitative approach evolved rapidly into a modern discipline with a broader vision. The necessity of a standardised and systematic archaeoseismological approach and a multi- to interdisciplinary cooperation between scientists from different disciplines was anticipated since the beginning of archaeoseismology (Guidoboni 2002, Galadini *et al.* 2006, Sintubin & Stewart 2008). Several approaches, methodologies and collaboration between different disciplines (e.g. geologists, archaeologists, seismologists, historians, engineers and architects) have been discussed in numerous scientific publications (Karcz & Kafri 1978, Rapp 1986, Nikonov 1988, Guidoboni 1996, Stiros 1996, Korjenkov & Mazor 1999, Guidoboni 2000, Nur & Cline 2000, Noller 2001, Hinzen 2005, Ambraseys 2006, Galadini *et al.* 2006, Caputo & Helly 2008, Sintubin & Stewart 2008, Hinzen *et al.* 2010a).

Particularly, studies in different countries and regions in the Mediterranean region have contributed significantly to the fast development of archaeoseismology as a multidisciplinary approach, e.g., Turkey (Hancock & Altunel 1997, Altunel 1998, Waelkens *et al.* 2000, Akyüz & Altunel 2001, Altunel *et al.* 2003, Similox-Tohon *et al.* 2002, 2004, 2005, 2006, Sintubin & Stewart 2008, Karabacak 2010), the Middle East (Nur & Cline 2000, Meghraoui *et al.* 2003, Haynes *et al.* 2006, Marco 2008, Karak-hanian *et al.* 2008, Wechsler *et al.* 2008), Italy (Galadini & Galli 2001, Guidoboni *et al.* 2002, 2003, Ceccaroni *et al.* 2009, Bottari *et al.* 2008), Spain (Silva *et al.* 2005, Grützner *et al.* 2010), and Greece (Koukouvelas *et al.* 2001, Monaco & Tortorici 2004, Caputo & Helly 2005, Caputo *et al.* 2006, 2011).

In this paragraph, several of the key studies that have introduced important methodologies are summarized.

Marco (2008) focuses on the evaluation of seismic-related deformation patterns from different sites within the Dead Sea Fault Zone. The study provides observational evidence from archaeological sites and focuses on how earthquake-related features can be recognized and distinguished from natural or anthropogenic causes. It is emphasized that the combination of geology, history and engineering is a key for a successful and reliable interpretation of earthquake related damage.

Grützner *et al.* (2010) apply and compare the archaeoseismological and palaeoseismological logic-tree methods in their study of the Baelo Claudia site in SW Spain. They indicate that the semi-quantitative archaeoseismological observations are more reliable than palaeoseismological data, but that both methods may give clues for different events. Individually, none of the methods provides significant results for archaeoseismological questions.

Bottari *et al.* (2009) did apply “classical” or qualitative archaeoseismological investigations at several sites in Sicily and they provide evidence for three seismic events between 400 BC and 600 AD. The events are based on archaeoseismic observations and are dated according to the archaeological remains (e.g. coins, pottery) which were found between different destruction levels. They suggest that historical earthquake records support these proven events as well. Thus, they provide evidence for destructive seismic activity in Sicily before 1000 AD.

Caputo *et al.* (2011) focus on multidisciplinary quantitative evaluation of damage structures on the walls of the Great Theatre of Larissa in Greece. They use finite element modelling to calculate the effects of different earthquake scenarios for reactivation of faults that surround the theatre. The combination of geophysical information and numerical engineering modelling shows that most of the surrounding faults have the potential of creating destructive earthquakes.

Since SW Turkey is covered by numerous ancient cities and settlements, it is one of the most important archaeoseismological research areas in the Mediterranean. The young and active tectonism and the complex geological structure of SW Turkey make it a very attractive research area, where archaeoseismological studies may help to solve long-standing geological questions.

Akyüz and Altunel (2001) discuss the damage patterns in the ruins of the ancient city Cibyra in SW Turkey. This city is situated on the Cibyra fault that is part of the complex Fethiye-Burdur Fault Zone (FBFZ). The study shows that geological observations, ancient records and damaged ruins relate to a high seismic potential of this region. The ca. 50 cm sinistral offset in the sitting rows of the stadium and fault traces within the neighbouring Pliocene deposits indicate an active NE-SW trending strike-slip motion which confirms the inferred character of the FBFZ. The damage is interpreted to be caused by a post-Roman earthquake, possibly in 417 AD.

Karabacak (2010) extends the scope of the archaeoseismological research for Cibyra and its surroundings by including geological and geomorphological field studies. These provide several lines of evidence for Holocene tectonic activity of the Cibyra fault zone. Furthermore, this study applies a laser scanning method to quantify the deformation of the stadium. The precise measurements indicate a ~ 20 cm vertical and a ~ 65 cm left-lateral displacement along the earlier mentioned rupture.

Altunel (1998) focused on earthquake evidence in the ruins of the ancient city of Priene, located in the western part of the Büyük Menderes valley (Western Turkey). Around 350 BC, Priene has been relocated and Altunel (1998) claims that the reason for this shift of the city probably was a devastating earthquake. He gives several additional examples from other regions and periods of cities that were relocated after earthquakes. Furthermore, he evaluates damage structures on remains in Priene and categorizes the damages as either ground-rupture related (e.g. collapsed walls, tilted wall blocks, fractured and displaced floor blocks) or shaking-related (e.g. rotated columns, collapsed, tilted and toppled walls).

This approach was also applied in a study of Hierapolis (Hancock & Altunel 1997), another ancient city in the western Büyük Menderes valley. The Priene study provides an extensive overview of reconstructions and restorations of the major buildings, which, based on ancient records, can be related to seismic events. Although it is concluded that Priene in its history was affected by several earthquakes, dating of these events is the most challenging task.

Altunel *et al.* (2003) combined geological data and archaeological data to support past seismic activity at Cnidus (SW Turkey), during at least two events in the 2nd - 3rd centuries BC and in 459 AD. They have evaluated geological field observations, archaeoseismological observations, archaeological excavation records and ancient reports from Cnidus. Two archaeological structures, the Round Temple of Aphrodite Euploia and the Sanctuary of Demeter, lie directly on the trace of the Cnidus fault and show vertical offsets which indicate the recent activity of the fault. Fallen columns are used as indicators for seismic shaking and it is suggested that columns fall in the opposite direction of the seismic wave propagation.

Several archaeological, geological and archaeoseismological studies have been carried out in Sagalassos. These studies serve as a good example of the evolution of the interdisciplinary archaeoseismological approach. The first archaeological survey and excavations in the city began in the mid 80's. Waelkens *et al.* (2000) did present the first evaluation of archaeological and geological evidence for major earthquakes in Sagalassos. They suggested that at least four earthquakes affected the city and the last one was responsible for the abandonment of the city in the middle of the seventh century AD. Similox-Tohon *et al.* (2002) studied geomorphological and drainage patterns from satellite images of Sagalassos and its surroundings, which showed a series of NE-SW trending fault-related lineaments. Sintubin *et al.* (2003) have evaluated seismic related damage patterns on the ruins in Sagalassos and they suggest several seismic events based on deformation intensity, multiple repaired structures, and archaeological findings. Although their results support that the city was hit by at least four earthquakes, they could not identify seismogenic fault(s) in the vicinity of the city. Therefore, Similox-Tohon *et al.* (2004) used a 2D resistivity imaging method to proof the presence of the faults underneath Sagalassos that were previously identified from satellite and geomorphological data. With this geophysical method they provide several subsurface resistivity profiles perpendicular to the Sagalassos fault zone. The data show that the ancient city of Sagalassos is located on the hanging wall of a fault which explains the previous findings and which was later substantiated by a trenching study (Similox-Tohon *et al.* 2005). Similox-Tohon *et al.* (2006) have provided a summary of the multidisciplinary approach that aimed at the identification of the seismogenic fault in Sagalassos and point out the importance of archaeoseismology and its integration in neotectonic studies.

In addition to this, Sintubin and Stewart (2008) have developed and applied a new methodological approach to Sagalassos to test its suitability for archaeoseismological studies. This study provides a new semi-quantitative logic tree methodology for the evaluation of archaeoseismic potential of an ancient site.

The case study in Sagalassos indicates that Sagalassos has a high potential of recording past earthquakes and, therefore, is a suitable site for archaeoseismological research. Moreover, the logic tree method addresses several of the key weaknesses and strengths in tying earthquake hypotheses to a site and challenges these with a standardised multidisciplinary procedure to enable more meaningful seismic hazard assessments in future studies.

To date, most archaeoseismological studies are restricted in the sense that they include only few disciplines and usually do not incorporate quantitative methods. Although most studies present a clear wish for a better multidisciplinary (or better interdisciplinary) concept, its application is still quite limited and usually consists of partial collaborations between geology, archaeology, seismology and engineering only. The integration of other disciplines with the use of quantitative methods in particular within archaeoseismology needs further improvement. Modern archaeoseismology should consist of a wider range of scientific interests and combine different aspects for a more dependable seismic hazard assessment. Especially, the role of engineering modelling should be increased just as a proper assessment of the seismotectonic background of the region under investigation. This thesis focuses on testing and applying an interdisciplinary archaeoseismological approach that contains these missing elements. Test case is the ancient city of Pınara in the Eşen Basin in SW Turkey.

1.3 Objectives

The aim of the current study is (1) to set up and test an interdisciplinary quantitative archaeoseismological approach and (2) application of this approach to assess the seismic hazard in the Eşen Basin (SW Turkey), which was used as a test case. This approach is based on geological, archaeological, seismicity and engineering studies of the Eşen Basin and surroundings and includes observations that relate to geological, (pre-)historical and recent timescales. As such, the thesis provides details of the evolution of the Eşen Basin from the geological past up until recent time and places its tectonic characteristics within the context of the larger Fethiye-Burdur Fault Zone (FBFZ). In addition, this study aims to stress the importance of using quantitative methods in archaeoseismology and to provide quantitative solutions for archaeoseismological investigations. By providing detailed quantitative archaeoseismological data that pertain to the various disciplines consulted, the seismic information gap between the geological past and the modern era of instrumental seismicity should be bridged. By extrapolating the results to the future, this study enables to assess the potential seismic hazard for the Eşen Basin and its surroundings.

The objectives of this study are summarized in the following research topics:

- ❖ To study the tectonic and sedimentological evolution of the Eşen Basin with field studies and to examine the structural geology to understand the complex tectonic structure of the FBFZ.
- ❖ To study seismicity in the Eşen Basin with archaeoseismological methods in the ancient Lycian city of Pınara in the western Eşen Basin.
- ❖ To improve the significance of archaeoseismological studies with quantitative methods.
- ❖ To analyse the earthquake reoccurrence, recent tectonic regime and stress field characteristics of the Eşen Basin and its surroundings.
- ❖ To assess the seismic hazard in the Eşen Basin based on interdisciplinary archaeoseismological studies in the basin and the ancient city of Pınara.

1.4 Organisation of the thesis

The thesis is structured in seven chapters. This first chapter provides an overview of the thesis including the research questions, main objectives of the thesis and the structure of the thesis. Furthermore, it summarizes the general aspects of archaeoseismological research as well as a number of relevant archaeoseismological case studies.

Chapter 2 addresses the tectonosedimentary evolution of the Eşen Basin and focuses on structural evidence for tectonic activity on a geological time scale. The tectonic phases are linked to the detailed sedimentological information and stratigraphic stages recognized in the Eşen Basin.

Chapter 3 is based on Yerli *et al.* (2010) “Seismotectonic Background for Archaeoseismological Studies in the Eşen Basin, SW Turkey”. The chapter presents the seismotectonic framework, particularly for archaeoseismic studies in the Eşen Basin and its surroundings based on seismotectonic data and historic and instrumental seismicity. It includes a Gutenberg-Richter model, a model of the depth variation of the hypocentres and a stress inversion.

In Chapter 4 the archaeoseismological evidence of historical earthquake activity in the ancient city of Pınara is described in order to close the gap between the tectonic activity in the Miocene - Early Quaternary and the seemingly seismic quiescence during the instrumental seismic period. This chapter is based on Yerli *et al.* (2011) “Testing a logic tree approach for archaeoseismology to the Ancient City of Pınara (SW Turkey)”. The logic tree methodology is applied to Pınara to assess the potential of earthquake recordings and its suitability for archaeoseismological research. Different damage patterns and structures are classified with qualitative and semi-quantitative methods and the seismic risk for this area is evaluated.

Chapter 5 is based on Yerli *et al.* (submitted) “Assessment of seismically induced damage using LIDAR: the ancient city of Pınara (SW Turkey) as a case study”. The chapter focuses on the application of laser scanning techniques in archaeoseismological investigations. In this study the ground-based light detection and ranging system (LIDAR) has been used for the first time as detection and evaluation method of damaged structures on archaeological sites. Deformations of the structures are quantified and the Roman theatre in Pınara has been studied as a test case, aiming at to determine seismic-related damage and to elucidate on its possible cause(s).

Chapter 6 “The Lycian Sarcophagus of Arttumpara, Pınara (SW-Turkey) - Testing Seismogenic and Anthropogenic Damage Scenarios” by K-G. Hinzen, S Schreiber and B Yerli (2010) is an additional study on the quantitative investigation of damages, based on laser scanning and 3D discrete element modelling. The study was carried out to distinguish seismic-related damage from other natural or anthropogenic-related damages and to find the best fitting scenario for the possible causes. The study addresses the origin of the rotation of the upper two ceilings of Arttumpara’s sarcophagus in Pınara. A series of rigid block model experiments are carried out, applying both seismic and anthropogenic scenarios and results are discussed. The paper was added to this thesis, because the archaeological, geological, and historical background information of the Pınara site, which forms an essential and substantial (~ 60%) part of this study, was performed by the author of this thesis.

Chapter 7 summarizes the results and interpretations of the different chapters of the thesis and gives an outlook to future research and development of the interdisciplinary archaeoseismological approach. Chapter 7 is followed by the references of all Chapters and a summary of this PhD research in English as well as in Dutch.