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7 Conclusions and perspectives

7.1 Conclusions

This thesis presents the results of a study that aims at setting up and testing a best-practise interdisciplinary archaeoseismological workflow. The specific test area for this workflow is the Eşen Basin in SW Turkey and more particularly the archaeological site of Pınara. The workflow incorporates information from geological, archaeological, historical and recent timescales. This allows assessing the seismic hazard in the Eşen Basin through increasing the understanding of its geological evolution, its tectonic significance within the Fethiye-Burdur Fault Zone, and the record of historical and recent seismicity in this region. This study is the first archaeoseismological investigation that incorporates structural geology, geomorphology, seismotectonics, construction engineering, archaeology and quantitative measurement techniques.

The tectonosedimentary evolution of the Eşen Basin, as presented here, is mainly based on collected sedimentological-, stratigraphic-, and structural field data. A lithofacies analysis of the basin fill indicates a typical tripartite composition with alluvial-fan, fluvial and lacustrine facies associations of Miocene to Recent age. The macrofossil findings (i.e. cf. *Pliocervus* and *Gazella* sp.) collected from the oldest basin margin alluvial fans provide a Late Miocene age, which constrains the age of basin initiation. Based on a fault-kinematic analysis three major tectonic phases between Late Miocene and Pleistocene could be distinguished.

The Late Miocene opening phase of the basin is characterized by activity of NE-SW trending normal faults, such as the Kabağağaç and Saklıkent faults. The second tectonic phase is assigned to the Early Pleistocene and fault-plane solutions indicate an E-W extensional tectonic regime. The third phase is represented by activity of the E-W-trending Ören and Kınık faults in the north and south of the basin respectively.

Continued activity of the basin-margin faults is evidenced by tilted Pleistocene terraces that dip 5° to 15° towards the basin margin. One of these coarse-grained terraces is strongly affected by the E-W trending Kınık fault and provides U/Th ages of ~ 26.5 kyr. This result constrains the maximum age of faulting as Late Pleistocene. The present-day morphology also expresses the role of the Kınık fault in delineating the boundary between a mountainous area in the northern-part and low-land swamp area in the southern part of the Eşen Basin. The fault-plane solutions of the Late Pleistocene faults suggest NNE-SSW extensional tectonics at that time.

Recent seismic and tectonic data from the Eşen Basin and its surroundings have been combined and studied in order to formulate the seismotectonic setting of the basin. This information can be used, for instance, as a reference frame for archaeoseismological investigations. The parameters of more than 6000 earthquakes, published between 1900 and 2010 in several catalogues, have been combined in a uniform catalogue with moment magnitude (M_w) to present the degree of seismicity in the study area. A Gutenberg-Richter model with magnitude range from $3.7 < M_w < 6$ has been applied to determine the distribution of earthquakes with respect to the magnitude. The provided a -value of 6.37 and b -value of 1.20 describe the seismic activity and tectonic parameter, respectively, which are in agreement with the values from previous studies and indicate the geological and tectonic complexity of this area.

The earthquake activities in the central part of the Fethiye-Burdur Fault Zone (i.e. Eşen Basin, Çameli Basin) are located at relatively shallow depths (< 50 km) and have focal mechanism solutions that indicate extension. These earthquakes are most probably related to the active oblique normal faults within the Fethiye-Burdur Fault Zone. The depths of the earthquakes' hypocentres are systematically increasing from the centre towards the east, west and south.

The focal mechanism solutions of the earthquakes from the southern (particularly offshore) regions indicate intermediate reverse faulting which is related to plate convergence at the Hellenic Subduction Zone. Focal mechanism solutions to the east of the study area also indicate reverse faulting, which is related to the back-thrust systems that delineate the Isparta Angle. Stress inversion analysis using the focal mechanism solution parameters of 36 earthquakes from between 1957 and 2009 suggest an E-W trending extensional tectonic regime with σ_1 sub vertical and σ_2 and σ_3 sub horizontal. These first inversion results of the Eşen Basin area support the working hypothesis that the N-S-trending basin margin faults have a high reactivation potential. This present-day seismotectonic information forms a reliable foundation for extrapolating the seismic hazard to the historical period and validates in the Eşen Basin and its surroundings. Furthermore, it validates archaeoseismological investigations in the Eşen Basin and surrounding ancient cities, which may constitute highly valuable records of past earthquake activity.

An archaeoseismologic logic tree assessment has been carried out to evaluate the probability that the ancient city of Pınara within the Eşen Basin has recorded palaeo-earthquakes during the historical period, i.e., the period not covered by geological field data. This evaluation also served to support the suggested seismic-hazard potential for Pınara and its surroundings. This quantitative approach suggests that the ancient city of Pınara, due to its tectonic setting, has a high potential of recording earthquakes and indeed is a suitable site for archaeoseismological studies. Furthermore, the residential era of about 1500 years, the wide spread settlement area and the variety of construction methods make the city highly suitable as archaeoseismological archive.

An inventory of damage structures (e.g. axial loading fractures, broken edges in the floor and masonry, shifted keystones, fallen columns and walls) on the archaeological relicts, suggests that most of the damage is seismic-related. Rebuild- and damaged structures show that at least two proven events with intensities between VIII – IX (MSK), one in the Lycian era until 43 AD and one after the Roman occupation in 43 AD, affected the city. Although the Eşen Basin and its surroundings are thought to represent a seismically quiet region, the recent historical earthquake activity strongly supports the notion that the Eşen Basin is exposed to a considerable earthquake hazard.

LIDAR surveying of the Roman theatre in Pınara was performed to assess possible faulting-induced tilting of this structure. Comparison of conventional compass readings and LIDAR measurements show that the latter is about 100 times more accurate. This high accuracy enables to assess very small details of deformation that the human eye cannot detect. Accordingly, the three-dimensional (3D) high-resolution LIDAR data were used to quantify the deformation of the Roman theatre.

The results reveal that the seating rows are tilted systematically to the NW with a mean dip angle of 0.81° . The mean dip direction (N314E) is perpendicular to the nearby NE trending basin margin fault. The location of the theatre and the geological features suggest that a fault-block rotation mechanism can be held responsible for the measured tilt. The basic geometrical relationship based on the 250 m distance and the dip angle of 0.81° of the theatre indicates a total fault offset of 4.0 m since the 2nd century AD, i.e., the age of the theatre. According to fault characteristics and damage intensity of VIII-IX (MSK scale) in Pınara this offset is inferred to be the result of two or more seismic events, an inference that is supported by historical records as well.

To further investigate the link between damage and earthquake activity, a well preserved and rotated sarcophagus in the ancient city of Pınara was selected to differentiate between seismic and anthropogenic deformation scenarios. A 3D laser scanning model of the sarcophagus with 11.5 million points shows a 6.37° clockwise rotation of the sarcophagus with respect to its foundation. It also shows a crater in the eastern side of the coffin, which was most probably caused by the detonation of an explosive charge during looting.

With a numerical rigid block model the feasibility of a detonation or earthquake ground motion as the reason for the rotation of the coffin has been studied. Various computer models for the seismogenic scenario represent different horizontal maximum accelerations of up to 10 m/s^2 and predict vertical-axis rotations smaller than 1° between the base-block and the coffin. The back-calculated amount of explosive, which can cause the crater in the sarcophagus, is around 60 g of TNT equivalent.

Numerical explosion simulations suggest that this amount of explosive is sufficient to cause a 6.37° rotation of the sarcophagus. From the numerical experiments it follows that an explosion is a much more likely cause for the rotation of the sarcophagus than an earthquake. The study thus proves that precaution is required in interpreting damaged archaeological structures.

In summary, the results presented in this thesis reveal that tectonic activity in the Eşen Basin took place continuously from the Late Miocene onward. Fault activity was controlled by three different stress regimes and the associated deformation controlled the deposition and morphological development at the geological time scale. During historical time, at least three strong seismic events occurred in the Eşen Basin and its surroundings that explain the seismically-related damage of the building structures in Pınara. The recent seismic intensity in the Fethiye-Burdur Fault Zone has led to several major earthquakes; however the Eşen Basin experienced only minor earthquakes. Stress inversion results from both fault kinematic data and earthquake focal mechanism solutions suggest that both past and active tectonic regimes of the Eşen Basin are characterized by an E-W extensional stress field. It further suggests that the basin margin faults were likely intermittently reactivated from the Late Miocene onward.

Although the Eşen Basin at present is assumed to be in a zone of moderate seismic activity, this study suggests that clusters of devastating earthquakes occurred, separated by long intervals of seismic quiescence. Several active faults are surrounding the basin and have the potential to generate large earthquakes after the present seismic quiescence.

7.2 Perspectives

The data, methods, results and conclusions presented in this thesis provide both solutions and answers to several multifaceted questions. However, new questions were raised as well, which requires improvement through future studies and investigations. In the following a general outlook for further studies building on the main conclusions of this thesis is given:

- Geological information of the offshore region in the southern Eşen Basin should be incorporated by using geophysical surveying methods and should shed light on the extension of the basin margin faults and the relation with the offshore Rhodes Basin.
- Palaeoseismological study (e.g. trenching) of active fault zones can provide additional information that will broaden our knowledge on the number and intensity of past seismic events.
- Additional age data, particularly from younger basin fill deposits, will improve the resolution of their deformation history as well.
- High resolution GPS campaigns would provide important relative movement data which is valuable for the understanding of recent seismic and tectonic behaviour of a region with complex geological structures like SW Turkey.
- Archaeoseismological investigations in other ancient sites in the Eşen Basin are essential to get more information of historical seismicity and allow comparison of presumed seismic events from different sites. Additional archaeoseismological investigations will also improve the production of a historical earthquake intensity map for the region.

- More applications of the archaeoseismological logic tree are desirable, in order to standardize this evaluation methodology as well as to increase its significance and validity.
- Quantitative laser scanning and computer modelling methods should be applied as standard techniques for the analysis of damage and deformations of structures in ancient cities. Such quantitative data will help to improve our understanding of the systematic relation between the seismic source, ground motion and building response.
- This thesis shows how archaeoseismological studies can benefit from interdisciplinary collaboration and use of quantitative data and methods. This working approach could serve as a blue print for future studies that serve: 1) seismic hazard assessment either for populated areas or to address preservation of archaeological site, and 2) to perform geological studies that encompass the full time range of tectonic activity.

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Abstract

Throughout the last century, earthquake activities can be monitored by a network of instrumentation, allowing reliable determination of the timing and magnitude of the events. Before this era of “instrumental” seismicity, information can be incomplete because earthquakes are not always acknowledged in ancient records, even though they affected human settlements and their surroundings. Archaeoseismology is an evolving study that aims to bridge that gap by defining significant, and preferably independent, criteria for recognizing past earthquakes in archaeological ruins. Next to the understanding of the ancient history, archaeological evidence may form the basis for long-term seismic-hazard assessment in earthquake-prone regions where there is a long and lasting cultural heritage. Moreover, the cultural heritage sites themselves are at stake here as well, since the seismic hazard assessment can also predict how ancient structures and monuments respond to faulting and ground shaking.

Many types of earthquake-related damage (‘archaeoseismic indicators’) have been proposed and debated, but rarely have they been subjected to a critical and systematic analysis. This study is aimed at setting up and testing an interdisciplinary workflow that provides such a critical and systematic analysis and that eventually can serve to extend neotectonic studies over a larger time period. The Eşen Basin in SW Turkey was selected as study area because it is situated in a regionally active fault zone, the Fethiye-Burdur Fault Zone (FBFZ), which is regarded as a seismically active zone with strong and major earthquakes. An interdisciplinary study of the Pınara site in the Eşen Basin (SW Turkey) is presented, which is innovative as it builds on integration of several disciplines and techniques in both earth sciences and archaeology. Observations and analysis relate to geological, historic and recent times and include geological-, palaeoseismological-, and archaeological- data, geophysical data acquisition, a regional seismotectonic evaluation, and numerical engineering modelling.

A geological study of the Eşen basin, including tectonic stress inversion based on fault kinematic data, reveals that from Late Miocene until Pleistocene E-W extension with oblique components prevailed. However, the spatial and temporal relationships between the different tectonic processes that converge in this area and contribute to the local stress field are poorly understood. Next to this, a seismotectonic background study for the Eşen basin and surroundings is conducted, which compiles various tectonic and seismological data from published catalogues. For the study area, the instrumental seismic records show seismicity only with minor or light earthquakes. The assumed relative seismic quiescence is puzzling, especially since stress inversion calculations of 36 focal mechanism solutions of earthquakes in the region indicates that the E-W trending extensional tectonic regime is prevalent at present as well. For the intervening historic period, the geological context and the framework of recent seismicity in SW Turkey suggest intensity ranges and earthquake magnitudes that authorize archaeoseismic investigation.

Seismic activity in historical times is proven through archaeoseismological research at the ancient city of Pınara that is located along the western basin margin fault of the Eşen Basin. This line of research includes a logic-tree approach to assess the suitability of the Pınara site as archaeoseismic data recorder, spatial surveying of the deformation patterns in the site using ground-based light detection and ranging system (LIDAR), and engineering modelling of laser-scanned damaged structures to determine the origin of deformation. All techniques provide information that enables an assessment of the probability that the Pınara site recorded earthquakes in historic times.

The quantitative logic-tree methodology proves the high earthquake-recording potential of Pınara and thus its suitability for conducting archaeoseismological studies. The archaeoseismological evidence supports that the city has been affected by at least three earthquakes with intensity VIII – IX (MSK) since about the 5th century B.C. Furthermore, the numerical experiments indicate that the slight tilt of the Roman theatre in Pınara is caused by the fault activity; however the rotation of the Arttumpara's sarcophagus is most likely caused by an anthropogenic effect and not by earthquakes. This approach indicates the necessity of a quantitative evaluation of damaged structures both to investigate details and to avoid exaggeration of the effects of earthquakes. This study reveals the pitfalls and indicates that the most of the structures at Pınara show damages and deformations that can only be caused by one or several of the historic earthquakes.

The evidence of continuous strong tectonic activity from Late Miocene until historical time and the intense recent regional seismicity proves that major seismic events can take place in and around the Eşen basin. Despite a long period of seismic quiescence, the identification of an “active” fault zone with the potential to generate large earthquakes necessitates re-evaluation of the seismic hazard potential currently assigned to the area.

Samenvatting

Sinds ongeveer 100 jaar kunnen aardbevingen gemeten worden door middel van een wereldwijd instrumenteel seismisch netwerk dat een betrouwbare bepaling van het tijdstip, de omvang en de locatie van deze geologische gebeurtenissen waarborgt. Vóór het tijdperk dat deze aardbevingen instrumenteel gemeten konden worden, is informatie hieromtrent zeer beperkt, daar aardbevingen zelden en bovendien onvolledig zijn beschreven in historische bronnen, ondanks het feit dat ze menselijke nederzettingen en hun omgeving beïnvloed kunnen en zullen hebben.

Archaeoseismologie is een discipline in ontwikkeling die zich tot doel heeft gesteld het ontbreken van directe en betrouwbare waarnemingen van historische aardbevingen aan te vullen door, waar mogelijk, onafhankelijke criteria te definiëren voor de herkenning, de datering en de kwalificatie van aardbevingen in archeologische en historische vindplaatsen. Aan de ene kant draagt dit onderzoek bij aan een beter begrip van aardbevingen en de daaraan gerelateerde gebeurtenissen in de oudheid, aan de andere kant kan het de basis vormen voor de voorspelling van seismische dreigingen in gebieden met cultureel erfgoed. Door het kunnen doen van betere seismische voorspellingen en door gebruik te maken van de kennis over hoe archeologische structuren en historische bouwwerken reageren op aardbevingen, kan het potentiële verwoestinggevaar van dit cultureel erfgoed geschat worden.

De verschillende soorten schade die kunnen optreden aan archeologische structuren en bouwwerken als gevolg van aardbevingen zijn talrijk en worden nog niet altijd goed begrepen. Hierdoor is de betrouwbaarheid van deze archaeoseismologische indicatoren onderwerp van diverse kritische beschouwingen in de literatuur. Het hier gepresenteerde onderzoek is gericht op het opzetten en testen van een interdisciplinair werkschema dat een degelijke, kritische en systematische analyse biedt van deze indicatoren. Met behulp van dit werkschema kunnen de onderzoeksresultaten van seismisch actieve gebieden beter geëxtrapoleerd worden naar het historisch verleden, maar ook dienen om voorspelling over toekomstige aardbevingen te doen.

Voor het opzetten en testen van het beoogde interdisciplinaire werkschema, is de Pinara site in het Eşen Bekken in ZW Turkije gekozen als studiegebied. Dit bekken ligt in een seismisch actieve zone met sterke en grote aardbevingen, de Fethiye-Burdur Fault Zone (FBFZ). De interdisciplinaire studie van deze site is vernieuwend daar deze is gebaseerd op de integratie van verschillende disciplines en technieken van de aardwetenschappen, de archeologie en de bouwkunde. De waarnemingen en de analyses hebben betrekking op geologische, archeologische, historische en recente tijden en omvatten onder andere geologische, palaeoseismologische, en archeologische datasets, maar betreffen ook het verzamelen van geofysische data, een regionaal seismotectonische evaluatie en een numerieke modelleringstechniek.

Door gebruik te maken van breuk-kinematische metingen uit het veld kunnen door middel van numerieke inversie technieken uitspraken gedaan worden over de tektonische spanning die de breuken in het geologische verleden heeft doen bewegen. Een dergelijke analyse is toegepast in een geologische studie van het Eşen Bekken, waaruit blijkt dat van het Laat Mioceen tot Pleistoceen afschuivingsbreuken actief waren als gevolg van een E-W gerichte rektektoniek. Dit spanningsveld wordt naar alle waarschijnlijkheid veroorzaakt door de interactie van verschillende grootschalige plaattektonische processen die samenkomen in ZW Turkije.

Voor de inventarisatie van recentere seismische activiteit in ZW Turkije (en het Eşen Bekken in het bijzonder) is een seismotectonische achtergrondstudie uitgevoerd waarin verschillende tektonische en seismologische gegevens uit gepubliceerde catalogi zijn geëvalueerd. Uit de instrumentale seismische gegevens blijkt dat in het studiegebied slechts kleine of lichte aardbevingen plaatsvonden wat doet vermoeden dat het gebied momenteel in een relatief seismische rust verkeert.

Deze vermeende rust valt niet goed te begrijpen, vooral omdat stress-inversieberekeningen aan 36 aardbevingen in ZW Turkije aangeven, dat de E-W rektektoniek ook vandaag de dag het gebied domineert. Zowel het geologische onderzoek en de seismotektonische analyse suggereren dat het gebied sinds miljoenen jaren gekenmerkt wordt door tektonische activiteit. De tot nu toe ontbrekende informatie om de huidige rust te begrijpen toont de noodzaak van archeoseismologisch onderzoek aan om de gebeurtenissen in de oudheid en subrecente tijd te kunnen interpreteren.

Seismische activiteit in de oudheid wordt aangetoond door archeoseismologisch onderzoek in de Lycisch-Romeinse stad Pinara, gelegen op de rand van de westelijke randbreuk van het Eşen Bekken. Het hiervoor genoemde werkschema begint met een *logic-tree* analyse die de geschiktheid van de Pinara site als archeoseismologische “data recorder” onderstreept. De archeoseismologische waarnemingen tonen aan dat de stad is getroffen door minstens drie aardbevingen met een intensiteit tussen VIII - IX (MSK schaal, gebaseerd op de effecten ter plaatse), sinds ongeveer de 5e eeuw voor Christus, waarbij er zware tot zeer zware schade is opgetreden.

De deformatie aan het Romeinse theater in Pinara is in beeld gebracht door middel van een ground laser detection and ranging systeem (LIDAR). Dergelijke meetgegevens zijn ook als input gebruikt voor een numerieke bouwtechnische modellering van de sarcofaag van Arttumpara, ten einde diverse scenarios voor de oorsprong van de verplaatsing te testen. Deze numerieke experimenten wijzen uit dat de rotatie van de sarcofaag waarschijnlijk veroorzaakt is door antropogene invloeden en niet door aardbevingen. Dit is echter een uitzondering; de meeste schades en vervormingen zullen veroorzaakt zijn door één of meerdere aardbevingen in de oudheid. De in dit proefschrift gepresenteerde aanpak onderstreept de noodzaak van een kwantitatieve evaluatie van de beschadigde structuren om de effecten van aardbevingen goed in te kunnen schatten en om overschatting van deze effecten te voorkomen.

Ondanks een lange periode van relatieve seismische rust, vormen de bevindingen in dit proefschrift reden genoeg het seismische risico voor het gebied opnieuw te evalueren, daar de continue tektonische en/of seismische activiteit van het Laat Mioceen tot aan de historische tijd en de intense recente regionale seismische activiteit hebben aangetoond dat grote seismische gebeurtenissen kunnen plaatsvinden in en rond het Eşen Bekken.