1

Neotectonics and Earthquake Potential of the Eastern Mediterranean Region: Introduction

İbrahim Çemen[1] and Yücel Yılmaz[2]

1.1. INTRODUCTION

Neotectonics is a subdiscipline of tectonics and involves the study of recent motions and deformation of the Earth's crust. These recent motions, particularly those produced by earthquakes, can provide insights on the physics of earthquake recurrence, the growth of mountains, orogenic movements, and the seismic hazard. This volume focuses on neotectonics of the eastern Mediterranean region (Figure 1.1), which has experienced many major devastating earthquakes throughout its recorded history. A major devastating earthquake in the region occurred at 3:02 a.m. on 17 August 1999 in Izmit, Turkey (Mw = 7.4), lasted for 37 sec, killed around 17,000, injured 44,000 people, and left approximately half a million people homeless. Economic loss due to this earthquake is estimated at around \$20 billion. Since the Izmit earthquake, several North American, European, and Turkish research groups have been studying the neotectonics and earthquake potential of the eastern Mediterranean region by using different geological and geophysical methods, including GPS studies, geodesy, and passive source seismology. Some results from these studies were presented in major North American and European geological meetings and published in major earth science journals. However, the first comprehensive collection of research case studies of this region was convened by the editors of this book at the 2013 AGU fall meeting in San Francisco, California, USA, which included 8 oral and 12 poster presentations. This book is a collection of the research that was presented at the meeting.

The eastern Mediterranean region is one of the most dynamically complex and seismically active neotectonic settings on Earth (Figure 1.1). It includes the following major geographic divisions: the Aegean Sea region, the Anatolian Peninsula, and the northern part of the Arabian Peninsula. Each of these geographic domains corresponds to a distinctly different and composite tectonic entity.

The Anatolian Peninsula is part of the Alpine-Himalayan orogenic belt. Along its northern and southern edges lie approximately E-W trending mountain ranges known as the Pontides (the northern range) and the Taurides (the southern range). In Anatolia, the orogeny started in the north, migrated progressively to the south, and ended up in the Bitlis-Zagros orogenic belt. Following the latest phase of the collision along the Bitlis-Zagros suture, the Arabian Plate continued moving northward and generated a north-directed contraction (Figure 1.1). Consequently, the East Anatolian crust and lithosphere have been thickened, and the region was elevated to form the East Anatolian-Iranian high plateau. This shortening gave way to the formation of the North Anatolian and East Anatolian fault zones (Figure 1.1). The initiation of the two fault zones is generally considered as the beginning of neotectonics in Anatolia and surrounding regions.

Neotectonics of the eastern Mediterranean region is dominated by the African Plate subduction along the Hellenic and Cyprus trenches, collision between the Anatolian and Eurasian plates, and westward extrusion

[1]*Department of Geological Sciences, The University of Alabama, Tuscaloosa, Alabama, USA*
[2]*Department of Geological Engineering, İstanbul Technical University, İstanbul, Turkey*

Active Global Seismology: Neotectonics and Earthquake Potential of the Eastern Mediterranean Region, Geophysical Monograph 225, First Edition. İbrahim Çemen and Yücel Yılmaz

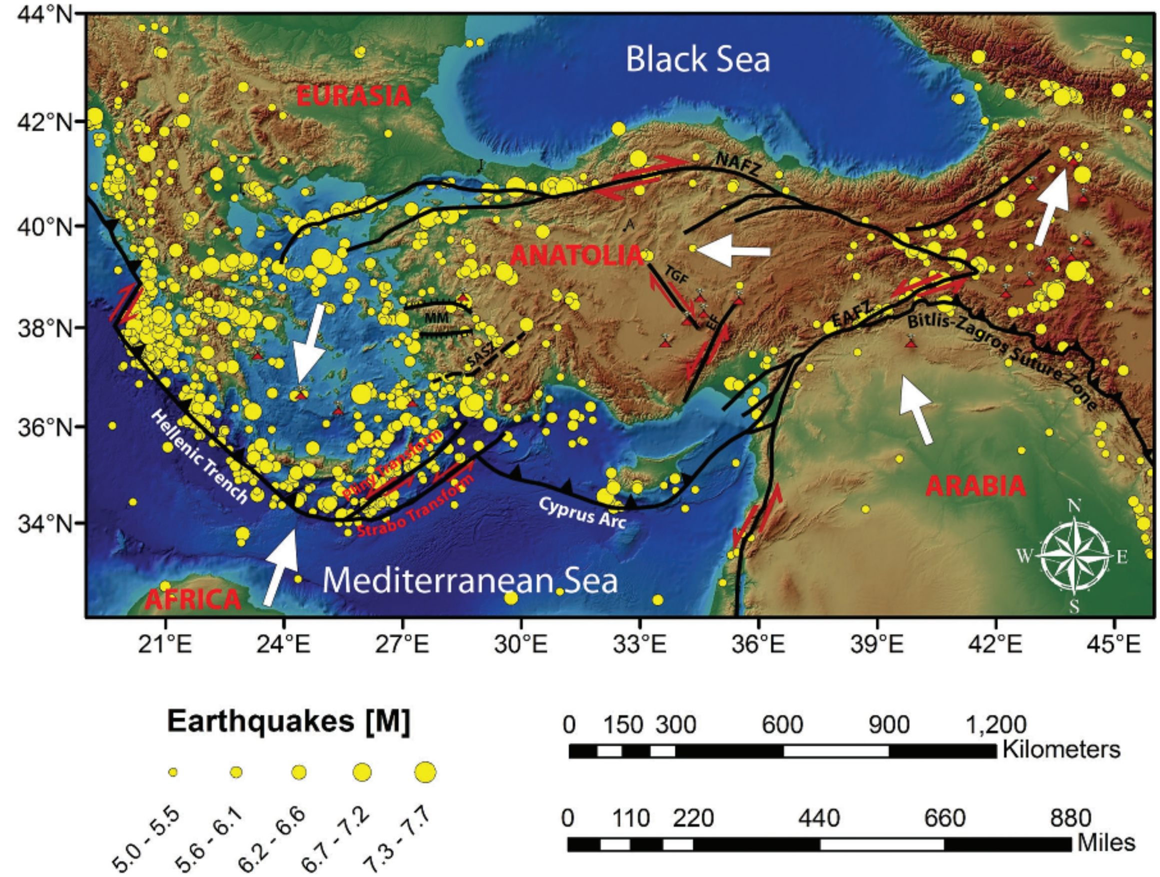

Figure 1.1 Digital elevation map of the eastern Mediterranean region showing major neotectonics structural features, volcanic centers (red triangles), and epicenters of the earthquakes (M > 5.0) since 1950. A = Ankara; EAFZ = East Anatolian fault zone; EF = Ecemis fault; I = Istanbul; MM = Menderes Massif; NAFZ = North Anatolian fault zone; T = Thessaloniki; TGF = Tuz Golu fault.

of the Anatolian Plate along the north and east Anatolian fault zones [*Sengor and Yilmaz,* 1981; *Sengor et al.*, 1985; *Robertson and Dixon*, 1984; *Çemen et al.,* 1999, 2006; *Aksu et al.*, 2005]. The convergent zones are characterized by deep earthquakes along the Hellenic and western segment of the Cyprus arcs [*Di Luccio and Pasyanos,* 2007], volcanism [*Pe-Piper and Piper*, 2006; 2007; *Altunkaynak and Dilek*, 2006; *Prelević et al.*, 2012; *Jolivet et al.*, 2013], large-scale continental extension [*Faccenna et al.*, 2003; *Çemen*, 2010; and *Ersoy et al.*, 2014], uplift [*Schildgen et al.*, 2012; 2014], trench retreat, slab tear, and slab detachment [*Faccenna et al.*, 2006; *Biryol et al.*, 2011; *Hall et al.*, 2014]. The extension and uplift are related to the southwest retreating Hellenic trench and westward movement of the Anatolian Plate [*Çemen et al.*, 2006 and 2014; *Reilinger et al.*, 2010; *Cosentino et al.*, 2012; *Schildgen et al.*, 2014].

This book contains nine chapters covering a wide range of contributions to the neotectonics and earthquake potential of the eastern Mediterranean region. The chapters cover an extensive and overlapping tectonic mosaic of new data that contribute significantly to our understanding of the crustal and lithospheric behavior manifested by tectonic, seismotectonic, and morphotectonic elements in the region.

The chapters are organized under the following thematic groups.

1.1.1. Part I: Morphotectonic Characteristics of Neotectonics in Anatolia and Its Surroundings

Two chapters are in this section of the book.

1.1.1.1. Chapter 1. Morphotectonic Development of Anatolia and the Surrounding Regions by Yücel Yılmaz

This chapter may be regarded as a tectonic backbone of the book in the sense that it covers tectonic framework of Anatolia and its surroundings. Several local and regional morphological studies were conducted on different parts of Anatolia. However, this chapter is the first attempt to encompass morphological treatment of the whole Anatolian peninsula to evaluate interactions of morphotectonically different regions and major tectonic elements, and along this direction it provides a platform for similar future studies.

The chapter's major points are summarized as follows: Anatolia is being deformed presently under an ongoing severe post-late orogenic tectonic regime, which is expressed by the GPS data; frequent earthquakes that occur in a vast terrain from the east to the west; and rugged, irregular, and tectonically controlled morphology. In order to understand the tectonics of Anatolia, structural analyses of the tectonically different regions and the earthquakes are studied extensively using a variety of methods and techniques. but the morphotectonic features that are also equally important are commonly ignored. Therefore, this chapter is complementary to most of the structurally and tectonically oriented regional and local treatments.

Anatolia and the surrounding regions contain a number of morphotectonic subdivisions including the East Anatolian-Iranian high plateau. The other subdivision are the peripheral mountain ranges (the Pontides and Taurides), the central Anatolian plateau, and the western Anatolian extensional region. They have all essentially formed during the Neotectonics period. Therefore, a critical period in the geologic-tectonic and particularly morphotectonic history of the region corresponds to a change from the Paleotectonic to Neotectonic periods. This chapter first addresses the timing and cause of the transition between these periods for each tectonic subdivision of the region, and then discusses at length morphotectonic character and characteristic features of each of the morphotectonic subdivisions, starting from the northwestern edge of the Arabian Peninsula around the Bitlis-Zagros suture mountains because this belt is the latest product of the Anatolian Orogen that formed as a result of the collision between the Arabian and Anatolian plates. The northward advance of the Arabian Plate continuing after the collision generated a north-directed severe contraction to push Anatolia northward. The N-S contraction initially deformed eastern Turkey. East and central Anatolia began to rise together. In this, slab break off of the northerly subducting plate and lithospheric delamination played a significant role. The contraction then formed the North and East Anatolian transform faults. These faults border the Anatolian Plate, which began escaping to the west. Major morphotectonic features, the peripheral mountains (the Pontides and Taurides) and the western Anatolian extensional region, have evolved together with the transform faults, which played an important role in transfer of the stress in the region.

Compared to the east, the western of Anatolia has followed a different path of morphotectonic development. The region was a high land during the Early Miocene period while eastern Anatolia was under a shallow sea. The environments began to reverse from Late Miocene onward. Southerly retreat of the subducting eastern Mediterranean oceanic slab has generated N-S extension in western Anatolia, Turkey. As a result, the present morphology began to develop. The E-W trending horst and graben structures that dominate the landscape today began to form during later periods of extension in the Quaternary.

1.1.1.2. Chapter 2. Diversion of River Courses Across Major Strike-Slip Faults and Keirogens by A. M. C. Şengör

The second chapter describes a pioneering morphotectonic study. It explores some theoretical possibilities of river bends along strike-slip fault zones using the example of the North Anatolian fault that forms a family of faults, which constitute the North Anatolian keirogen [*Şengör et al.* 2005]. The author, documenting preliminary results of his research, draws our attention to the following points. Studies along the North Anatolian fault and other major active strike-slip faults and keirogens in the world have revealed complications in river offsets that cannot simply be explained by preexisting slope conditions and capture events. These seem to result from the presence of numerous lesser strike-slip faults parallel with the main displacement zone of a large strike-slip fault, and from the structure and topographic evolution of synthetic and antithetic pull-apart basins. Some cuspate pull-apart-basin-bounding normal faults may give the mistaken impression of a river bending into a strike-slip fault because of numerous parallel faults. Other complications result from the presence of structures that predate the formation of a through-going, main strike-slip fault.

All strike-slip faults consist of surfaces of slip anastomosing along the strike of a fault zone, when a fault zone is narrow as a line. However, when its width exceeds a few kilometers, the motion of individual lozenges or phacoids surrounded by the anastomosing branches visibly influence the topography creating whaleback ridges, that in places may function as shutter ridges at the mouths of valleys consequent to the drainage of the main fault valley, sag ponds, and pull-apart basins that can be of various sizes and aspect ratios, and push-up ridges that may be simple folds or thrust blocks. Whatever basins form along a strike-slip fault zone, their floors may assume various slopes, both in direction and amount, depending on the geometry of the down-dropping fault(s).

1.1.2. Part II: Neotectonics of the Aegean-Western Anatolian Region

This section contains four chapters.

1.1.2.1. Chapter 4. Effect of Slab-Tear on Crustal Structures in Southwestern Anatolia: Insight from Gravity Data Modeling by R. Mahatsente, S. Alemdar, and İ. Çemen

This chapter examines the effects of the asthenospheric window on major crustal structures in western Turkey and the upper mantle using gravity data modeling. The authors use a combination of terrestrial and satellite gravity data. Their gravity model is also constrained by the results of recent receiver function and seismic tomography studies [e.g., *Biryol,* 2011].

The gravity model in this chapter suggests that depth to the top of the asthenospheric material (i.e., the crust of the Earth), ranges from 24 to 29 km below the Menderes Massif. The location of this thinned crust coincides with high heat flow of magmatic centers in the Menderes Massif complex. The asthenospheric material, as deduced from its density value and dimensions, is most probably deep in origin (asthenospheric and lithospheric mantle origin) and may be related to the low-velocity asthenospheric material in the upper mantle imaged by seismic tomography. The absence of no deep earthquakes in the asthenospheric window area is also a line of evidence for the presence of the low-velocity zone. This indicates that the subducting African slab has experienced major slab-tear beneath southwestern Anatolia, and the gap in the slab may be a channel through which asthenospheric material is rising up to the uppermost mantle [e.g., *Chang et al.*, 2010; *Biryol et al.*, 2011; *Salaün et al.*, 2012].

The crustal thinning in the Menderes Massif area is partly attributed to the hot asthenospheric material in the upper mantle and extensional tectonics related to the southwest retreating Hellenic trench and westward movement of the Anatolian Plate. The authors suggest that hot asthenospheric material in the upper mantle may have induced thermal erosion in the overlying crystalline basement and the lower crust. They use the slow average shear wave velocity [e.g., *Delph et al.*, 2015] of the crust in southwestern Anatolia as a line of evidence to indicate a thermally altered crust. Moreover, the presence of volcanic centers and high geothermal gradients in the Menderes Massif complex indicate the existence of asthenospheric flow beneath southwestern Anatolia.

The gravity model in this chapter suggests that crust thickens from southwestern Anatolia toward the Hellenides in western Greece and central Anatolia in Turkey, respectively. The regions outside the asthenospheric window show, by far, the largest crustal thickness (30–42 km). This basically leads to the conclusion that the observed crustal thinning in southwestern Anatolia may be partly attributed to thermal erosion induced by an upwelling hot asthenosphere and extensional tectonics related to the southwest retreating Hellenic trench and westward movement of the Anatolian Plate.

1.1.2.2. Chapter 5. Geodynamical Models for Lithospheric Delamination in an Orogenic Setting by O. Gögüs, R. Pysklywec, and C. Faccenna

In this chapter, the authors use a synthesis of geological, geophysical, and petrological data to infer that a portion of the mantle part of the lithosphere may have been removed from beneath the crust in several orogenic regions. To quantify the response to delamination, they applied numerical and laboratory-based analogue experiments. Numerical model predictions show that the lithospheric delamination is associated with broad surface uplift due to the thermal and isostatic effect driven by mantle upwelling. They claim that mantle lithosphere delamination can occur with slow plate convergence, where the slab peels off/rolls back similar to a retreating ocean slab subduction.

The results suggest that continental delamination may be a natural progression from prior ocean plate subduction and illustrate also that the removal of mantle lithosphere does not necessarily require a significant density heterogeneity to initiate. Their experiments reveal that when the plate convergence is higher, the mantle lithosphere is less prone to delaminate from the crust. With higher plate convergence, the consumed mantle lithosphere can drape forward instead. The proplate crust separates from the mantle lithosphere only at the collision zone and is overthrusted/accreted on top of the retroplate. The numerical results may satisfy geological and geophysical observations for the East Anatolia plateau uplift that occurred since the last 13 Myrs. The delaminating slab may produce subsidence over the crust in response to the migration of the mantle lithosphere. The surface uplift may increase with higher plate convergence. Laboratory based experiments show that slower plate convergence with retreating ocean lithosphere subduction can develop into delamination whereas for the experiments with higher plate convergence, the crust above the consumed mantle lithosphere becomes accreted on the retro-plate similar to flake tectonics.

1.1.2.3. Chapter 6. Major Problems of Western Anatolian Geology by Y. Yılmaz

The western Anatolian and Aegean regions have long been known to represent a broad zone of N-S extension stretching from Bulgaria in the north to the Hellenic arc in the south [*McKenzie*, 1972, 1978; *Jackson and McKenzie*, 1978; *McKenzie and Yılmaz*, 1991; *Taymaz,* 1996]. Under the close tectonic control of the extension, the western

Anatolian region is characterized by a number of approximately E-W trending, subparallel, normal fault zones, which border a swarm of grabens and the intervening horst blocks. As a consequence of this, there is an intense seismic activity.

The author defines the aim and approach adopted in the chapter as follows: despite a pile of new data that has been collected during the last two decades, some major problems of western Anatolian geology still remain controversial. Among these cause and timing of generation of the Menderes Massif and the magmatic associations, the N-S trending grabens, and time of inception and continuity of the E-W grabens are at the forefront. A number of different views have been proposed on each one of these subjects. Models proposed by different authors were commonly incompatible with one another. As a consequence of the nature of the problem, to establish a cross connection between the different events and to evaluate them in time-space and regional geological perspective is critical.

In this chapter, main geological entities of western Anatolia are reviewed under separate headings, the ongoing controversies around them are discussed first, and then some solutions are proposed.

1.1.2.4. Chapter 7. The Çataldağ Plutonic Complex in Western Anatolia: Roles of Different Granites on the Crustal Build-up in Connection with the Core Complex Development by O. Kamacı, A. Unal, S. Altunkaynak, M. Z. Billor, S. Georgiev, P. Marchev

This chapter provides a detailed geological map of the Çataldağ area of western Anatolia, Turkey, accompanied by structural and geochemical data set to review origin of granites generated during the Neotectonics extensional setting. The metamorphic core complex in the Çataldağ area was exhumed in Early Miocene as a dome structure in the footwall of a low-angle detachment surface. A number of micro- and mesoscale shear sense indicators display evidence that the rocks underwent ductile deformation in the earlier stage of the exhumation, which was superimposed later by a semibrittle and brittle deformation. They indicate a top-to-north and top-to-NE sense of movement. The exhumation process was partly contemporaneous with the development of the major core complexes of the region (e.g., the Menderes and Kazdağ massifs) as a result of combined effects of thermal weakening and rollback of the Aegean subducted slab during the Oligocene–Early Miocene. Closely associated with the development of the core complex, this study documents in detail, geology, structure, and age of the Çataldağ Plutonic Complex (CPC) as the main rock association within the footwall of the Çataldağ Detachment surface. CPC consists of two contrasting granitic bodies; an older granite-gneiss-migmatite complex (GGMC) and a younger I-type granodioritic body: Çataldağ granodiorite (CG). The former is a heterogeneous body consisting of migmatite, gneiss, and two-mica granite, and represents a deep-seated pluton. By contrast, the latter represents a discordant, shallow level intrusive body. New U-Pb zircon (LA-ICPMS) and monazite ages of GGMC yield magmatic ages of 33.8 and 30.1 Ma (Latest Eocene-Early Oligocene). The 40Ar/39Ar muscovite, biotite, and K-feldspar from the GGMC yield the deformation age span 21.38 ± 0.05 Ma and 20.81 ± 0.04 Ma, which is also the age of the emplacement (20.84 ± 0.13 Ma and 21.6 ± 0.04 Ma) of ÇG. The age data when evaluated together with the contact relationships, internal petrological, and primary structural textural features indicate collectively that the two plutons were formed at different times, and were emplaced at different levels in the crust.

1.1.3. Part III: Seismotectonic in the Eastern Mediterranean Region

This section includes three chapters dealing with the recent earthquakes in the eastern Mediterranean region.

1.1.3.1. Chapter 8. Fault Structures in Marmara Sea (Turkey) and Their Connection to Earthquake Generation Processes by M. Aktar

This chapter investigates seismotectonics of the North Anatolian fault around the Marmara basin based on data previously derived from bathymetry and seismic reflection profiles. The investigation concentrates on the high-resolution seismological data collected in recent years to verify if earthquake occurrences are conformal with the structural elements. The chapter contains a short compilation of the structural elements in the Marmara basin and evaluates the high-resolution seismological data. The author also analyzed sensitivity limits of the seismological data in detail and determined error bounds. In the major part of the chapter, the seismicity and inferred fault structures are analyzed in detail for the western high, central, and Kumburgaz basins in the Marmara basin.

The chapter concludes that a single rectilinear fault plane is likely to stand as the single source for the majority of earthquakes occurring along the central axis of the Marmara Sea. A single fault plane hypothesis is seen to be largely supported by the seismological observations. The western Marmara high is modeled as a pressure ridge. The central Marmara basin is confirmed to reflect a negative flower structure. No clear evidence is found for a major step over or pull-apart structure. The chapter concludes also that resolution of seismological data is insufficient to study small-scale secondary fractures such as Riedel structures along the single rectilinear fault.

1.1.3.2. Chapter 9. The North Aegean Active Fault Pattern and the 24 May 2014, Mw 6.9 Earthquake by S. Sboras, A. Chatzipetros, and S. Pavlides

This chapter provides an excellent overview of the Aegean geodynamics with a particular emphasis on the active fault geometry of northern Greece and especially the North Aegean Trough (NAT). Findings of this study may be summarized as follows. The North Anatolia fault extends westward from the Sea of Marmara and the Gulf of Saros into the Aegean Sea. The fault strike changes from WSW-ENE in the Gulf of Saros and Samothraki Island, to SW-NE south of Chalkidiki Peninsula and reaches to the coast of the Greek mainland (Thessaly), where it terminates. The fault displays almost pure strike-slip character within Turkish territory, while it shows oblique-slip to normal sense of movement in the North Aegean Sea (transtensional tectonics). The causative fault of the 24 May 2014 strong earthquake is a segment (45 km long and 12 km wide) of the NAT, part of the North Anatolian fault (NAF) system, located offshore between Samothraki and Lemnos islands. This interpretation is supported by the earthquake epicenter, the aftershock distribution, and the seafloor morphology. In this chapter, an ENE-WSW striking right lateral strike-slip, SSE-dipping fault plane has been modeled. The receiver faults have been modeled according to the Greek Database of Seismogenic Sources (GreDaSS) and include both Individual Seismogenic Sources (ISSs) and Composite Seismogenic Sources (CSSs). The static stress change after the 2014 mainshock on the nearby faults shows that only the immediately eastern segment of the "North NAT" CSS (CSS290), that is, the "Samothraki SE" (ISS-ISS291) bears stress rise. This can explain the eastern aftershock cluster that lies along its fault plane. Static stress rises on the Samothraki SE ISS and triggering effect could be expected. Although this source was reactivated during the 1975 earthquake, rapidly deforming crust in this region and the effects of other earthquakes since then, either strong or weak, left the triggering issue open to discussion. Moreover, it is not clear how the 2014 aftershock eastern cluster affects the stress state of the fault. The normal dip-slip "North Samothraki" ISS (ISS288) is situated in the stress drop area, as well as the entire Samothraki Island (for faults of similar geometry and kinematics). The last fault that is affected by the 2014 rupture is the "South NAT" CSS (CSS800), which is almost entirely situated in the stress drop area, while a small part of it (toward its northeastern tip) is lying in an insignificant stress rise area.

The 2014 earthquake fault plane rupture was not enough for the static stress change to reach more distant faults ("Saros Gulf": ISS290, "Athos": ISS282, "NAB segment A": ISS810 and "NAB segment B": ISS811). More importantly, the "Athos " ISS, which is located at the western cluster of the aftershock sequence, is too far away from any calculated stress change. Thus, static stress transfer cannot explain the nucleation of the western cluster.

The "Lemnos" CSS (CSS825) was intentionally left out of the calculations, due to the presence of several similar faults on the northern part of Lemnos Island. However, the effects of stress changes can be inferred from receiver faults with similar properties that have been part of the calculations, such as the "NAB segment B" ISS and the "South NAT" CSS. Thus, for this kind of receiver fault, the entire island demonstrates stress drop and, hence, a probable earthquake delay.

1.1.3.3. Chapter 10. Seismic Intensity Maps for the Eastern Part of North Anatolian Fault Zone Turkey Based on Recorded and Simulated Ground Motion Data by A. Askan, S. Karimzadeh, and M. Bilal

This chapter provides synthetic intensity maps for a selected set of earthquake scenarios for the sparsely monitored and relatively unstudied eastern part of the North Anatolian fault zone (NAFZ). The maps are produced to evaluate connections between intensity and peak ground motion values. The study focuses on the eastern segments of the NAFZ around the Erzincan region where there are only sparse seismic networks. The city of Erzincan in eastern Turkey is located in the area where three active faults intersect: the North Anatolian, Northeast Anatolian, and Ovacik faults. The city center is in a pull-apart basin underlain by soft sediments, which significantly amplify the ground motions. The seismicity in the region through ground motion simulations is used for potential earthquake scenarios of various magnitudes. The combination of the tectonic and geological settings of the region have led to destructive earthquakes such as the 27 December 1939 ($Ms = 8.0$) and the 13 March 1992 ($Mw = 6.6$) events resulting in extensive losses. In this chapter, first ground motion simulations for a set of hypothetical events as well as the 1992 Erzincan earthquake are performed. Second, local relationships between MMI (Modified Mercalli Intensity) and PGA (Peak Ground Acceleration) as well as PGV(Peak Ground Velocity) are utilized to obtain the corresponding MMI values.

The study presents the results in the form of synthetic intensity maps for the 1992 event and the earthquake scenarios. The maps are useful for the earthquake hazards reduction program in the region, especially within the area of the city of Erzincan where a devastating earthquake of $Ms = 8.0$ occurred in 1939.

ACKNOWLEDGMENT

We thank very much Ms. Rituparna Bose and Mary Grace Hoboken-Hammond for their endless support and encouragement during the preparation of this volume. We are indeed in debt to them. This volume would not be realized without their relentless pursuit for perfection and constant push on us, as editors, our contributors, and reviewers. A number of reviewers provided their reviews for the chapters in this volume. These reviews definitely helped us to elevate the scientific standards of the chapters included in the volume. We would like to take this opportunity to thank our colleagues who shared their geological knowledge freely with us over the years. We learned tremendously from these interactions. Last but not least, we would like to thank our families who supported us throughout the completion of this volume. We would also like to thank our families for supporting our constant desire to contribute to the science of geology, and, in many respects, paying the price of not seeing us enough due to our constant travels as geologists throughout the years.

REFERENCES

Aksu, A. E., J. Hall, and C. Yaltirak (2005), Miocene to recent tectonic evolution of the eastern Mediterranean: New pieces of the old Mediterranean puzzle, *Marine Geol.*, *221*, 1–13.

Altunkaynak, S. A., and Y. Dilek (2006), Timing and nature of postcollisional volcanism in western Anatolia and geodynamic implications, *Geological Society of America Special Paper.*

Biryol, C. B., S. L. Beck, G. Zandt, and A. A. Özacar (2011), Segmented African lithosphere beneath the Anatolian region inferred from teleseismic P-wave tomography, *Geophys. J. Int.*, *184*(3), 1037–1057.

Çemen, İ. (2010), Extensional tectonics in the basin and range, the Aegean, and western Anatolia: Introduction, 1–6, in Extensional Tectonics in the Basin and Range, the Aegean, and Western Anatolia, edited by I. Çemen, *Tectonophysics*, *488*.

Çemen, İ., C. Goncuoglu, and K. Dirik (1999), Structural evolution of the Tuzgolu basin in central Anatolia, Turkey, *J. Geol.*, *107*, 693–706; doi: 10.1086/314379.

Çemen, İ., C. Helvaci, and Y. Ersoy (2014), Cenozoic extensional tectonics in western and central Anatolia, Turkey: Introduction, *Tectonophysics*, *635*, 80–99, 10.1016/j.tecto.2014.09.004.

Çemen, İ., E. J. Catlos, O. Göğüs, and C. Özerdem (2006), Postcollisional extensional tectonics and exhumation of the Menderes massif in the western Anatolia extended terrane, Turkey, *Geological Society of America Special Papers*, *409*, 353–379.

Chang, S. J., S. van der Lee, M. P. Flanagan, H. Bedle, F. Marone, E. M. Matzel, and C. Schmid (2010), Joint inversion for three-dimensional S velocity mantle structure along the Tethyan margin, *J. Geophys. Res. Sol. Earth (1978–2012)*, *115*(B8).

Cosentino, D., T. F. Schildgen, P. Cipollari, C. Faranda, E. Gliozzi, N. Hudáčková, S. Lucifora, and M. R. Strecker (2012), Late Miocene surface uplift of the southern margin of the central Anatolian plateau, Central Taurides, Turkey, *Geol. Soc. Am. Bull.*, *124*, 133–145.

Delph, J. R., C. B. Biryol, S. L. Beck, G. Zandt, and K. M. Ward (2015), Shear wave velocity structure of the Anatolian plate: Anomalously slow crust in southwestern Turkey, *Geophys. J. Int.*, *202*(1), 261–276.

Di Luccio, F., and M. E. Pasyanos (2007), Crustal and upper-mantle structure in the eastern Mediterranean from the analysis of surface wave dispersion curves, *Geophys. J. Int.*, *169*(3), 1139–1152.

Ersoy, Y., I. Çemen, C. Helvaci, and Z. Billor (2014), Tectonostratigraphy of the Neogene basins in western Turkey: Implications for tectonic evolution of the Aegean extended region, *Tectonophysics* (2014), 10.1016/j.tecto.2014.09.002.

Faccenna, C., L. Jolivet, C. Piromallo, and A. Morelli (2003), Subduction and the depth of convection in the Mediterranean mantle, *J. Geophys. Res.*, *108* (B2), 2099, 10.1029/2001JB001690.

Faccenna, C., O. Bellier, J. Martinod, C. Piromallo, and V. Regard (2006), Slab detachment beneath eastern Anatolia: A possible cause for the formation of the north Anatolian fault, *Earth Planet. Sci. Lett.*, *242*, 85–97.

Hall, J., E. A. Aksu, I. Elitez, C. Yaltırak, and G. Çifçi (2014), The Fethiye-Burdur fault zone: A component of upper plate extension of the subduction transform edge propagator fault linking Hellenic and Cyprus arcs, eastern Mediterranean, *Tectonophysics*, *635*, p. 80–99.

Jackson, J., and D. McKenzie (1988), The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East, *Geophys. J.*, *93*, 45–73.

Jolivet, L., C. Faccenna, B. Huet, L. Labrousse, L. Le Pourhiet, O. Lacombe, E. Lecomte, E. Burov, Y. Denèle, J. P. Brun, M. Philippon, A. Paul, G. Salaün, H. Karabulut, C. Piromallo, P. Monié, F. Gueydan, A. I. Okay, R. Oberhänsli, A. Pourteau, R. Augier, L. Gadenne, O. Driussi (2013), Aegean tectonics: Strain localisation, slab tearing and trench retreat, *Tectonophysics*, *597*, 1–33.

McKenzie, D. (1972), Active tectonic of the Mediterranean region, *Geophys. J. R. Astrol. Soc.*, *30*, 109–185; doi: 10.1111/j.1365-246X.1972.tb02351.x.

McKenzie, D. P.(1978), Some remarks on the development of the sedimentary basins, *Earth Planet. Sci. Lett.*, *40*, 25–32.

Mc Kenzie, D., and Y. Yılmaz (1991), Deformation and volcanism in western Turkey and the Aegean, *Bull. Tech. Univ. Istanbul, Spec. Issue on Tectonics*, *44*, 345–373.

Pe-Piper, G., and D. J. Piper (2006), Unique features of the Cenozoic igneous rocks of Greece, *Geological Society of America Special Papers*, *409*, 259–282.

Pe-Piper, G., and, D. J. Piper (2007), Neogene backarc volcanism of the Aegean: new insights into the relationship between magmatism and tectonics, *Geological Society of America Special Papers*, *418*, 17–31.

Prelević, D., C. Akal, S. F. Foley, R. L. Romer, A. Stracke, and P. Van Den Bogaard (2012), Ultrapotassic mafic rocks as geochemical proxies for post-collisional dynamics of orogenic lithospheric mantle: The case of southwestern Anatolia, Turkey, *J. Petrol.*, *53*(5), 1019–1055.

Reilinger, R., S. McClusky, D. Paradissis, S. Ergintav, and P. Vernant (2010), Geodetic constraints on the tectonic evolution of the Aegean region and strain accumulation along the Hellenic subduction zone, *Tectonophysics*, *488*(1), 22–30.

Robertson, A. H. F., and J. E. Dixon. (1984), Aspects of the geological evolution of the Eastern Mediterranean, 1–74, in The geological evolution of the eastern Mediterranean, edited by J. E. Dixon and A. H. F. Robertson, Spec. Publ. Geol. Soc., 17, London, Blackwell Scientific.

Salaün, G., H. A. Pedersen, A. Paul, V. Farra, H. Karabulut, D. Hatzfeld, and C. Pequegnat (2012), High-resolution surface wave tomography beneath the Aegean-Anatolia region: Constraints on upper-mantle structure, *Geophys. J. Int.*, *190*(1), 406–420.

Schildgen, T. F., C. Yıldırım, D. Cosentino, and M. R. Strecker (2014), Linking slab break-off, *Hellenic trench retreat, and uplift of the central and eastern Anatolian plateaus, Earth-Science Rev.*, *128*, 147–168.

Schildgen, T. F., D. Cosentino, A. Caruso, R. Buchwaldt, C. Yıldırım, S. A. Bowring, B. Rojay, H. Echtler, and M. R. Strecker (2012), Surface expression of eastern Mediterranean slab dynamics: Neogene topographic and structural evolution of the southwest margin of the central Anatolian plateau, Turkey, *Tectonics*, *31*(2).

Şengör, A. M. C., and Y. Yilmaz (1981), Tethyan evolution of Turkey: A plate tectonic approach, *Tectonophysics*, *75*(3), 181–241.

Şengör, A. M. C., N. Görür, and F. Saroglu (1985), Strike-slip deformation, basin formation and sedimentation: Strike-slip faulting and related basin formation in zones of tectonic escape, Turkey as a case study, Society of Economic Paleontologists and Mineralogists, Special Publication, *37*, 227–264.

Şengör, A. M. C., O. Tuysuz, C. Imren, M. Sakınc, H. Eyidogan, N. Gorur, X. Le Pichon, and C. Rangin (2005), The north Anatolian fault: A new look, *Ann. Rev. Earth Planet. Sci.*, *33*, 37–112; doi: 10.1146/annurev.earth.32.101802.120415

Taymaz, T. (1996), Wave travel-time residuals from earthquakes and lateral inhomogeneity in the upper mantle beneath the Aegean and the Aegean trench near Crete, *Geophys. J. Int.*, *127*, 545–558.