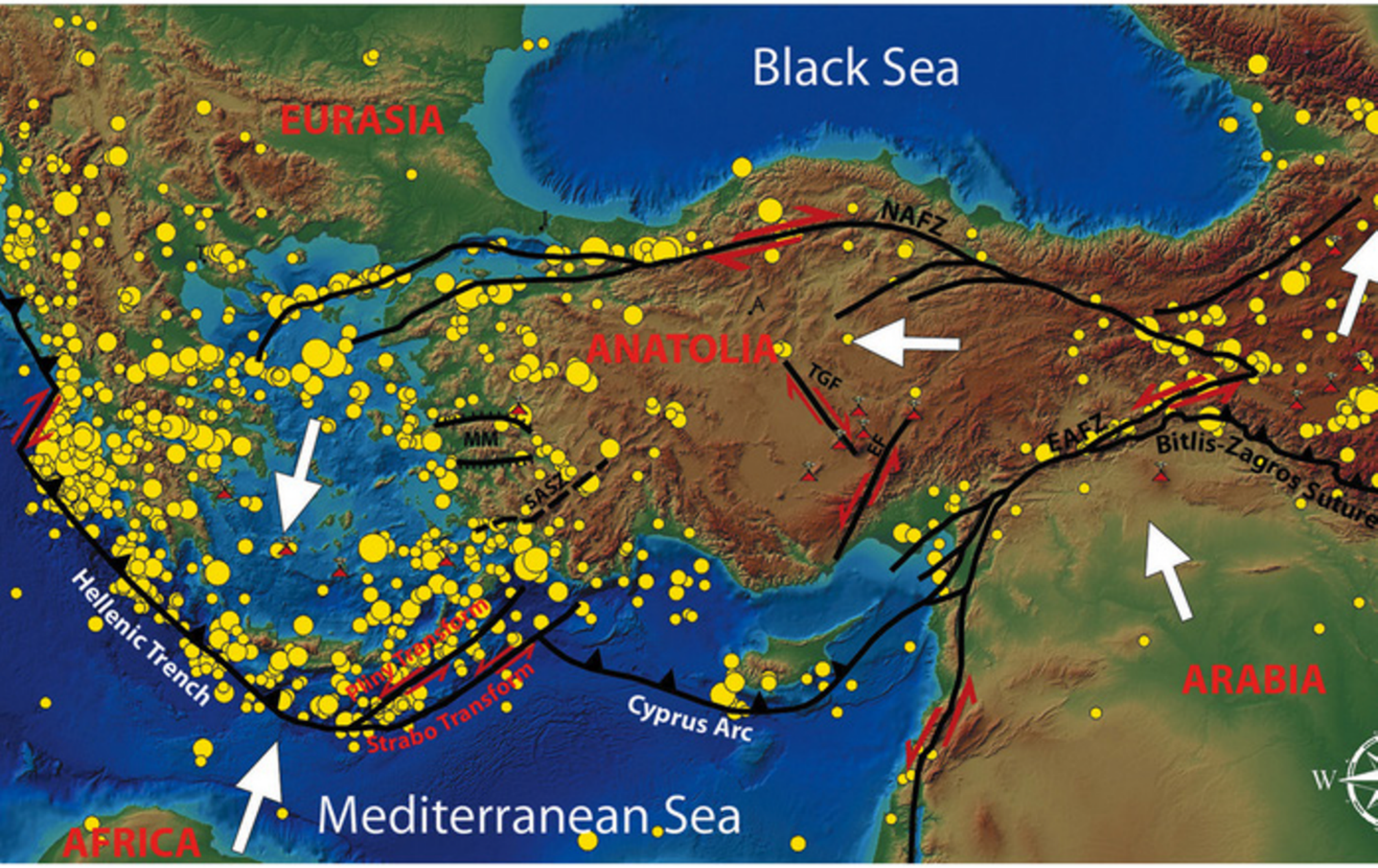
Active Global Seismology

Neotectonics and Earthquake Potential of the Eastern Mediterranean Region



İbrahim Çemen and Yücel Yılmaz

Editors

AGU American Geophysical Union

WILEY

Geophysical Monograph Series

Geophysical Monograph Series

Geophysical Monograph 225

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Published under the aegis of the AGU Publications Committee

Brooks Hanson, Director of Publications
Robert van der Hilst, Chair, Publications Committee

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data is available.

ISBN: 978-1-118-94498-1

Cover image: The image presents the water-level response in an aquifer due to periodic excitation of four groundwater wells at different amplitudes and frequencies.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

CONTENTS

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PREFACE

Within the last two decades or so, earth scientists realized that the ultimate goal of global seismology is to invent a method to forecast earthquakes similar to meteorologists forecasting the weather. Presently, almost all earthquake scientists believe that this goal is still out of reach. However, they are trying to develop algorithms and computer models, using new satellite data and other resources, to predict when an earthquake will occur. Many earthquake scientists hope that earthquake forecast will be possible within the 21st century. Until then, we need to investigate earthquake potential of the regions where large historical earthquakes have occurred and future ones are expected. These investigations involve interdisciplinary research.

The eastern Mediterranean is one of the most seismically active continental regions of the world. It includes three of the most active strike-slip faults: the North Anatolian, East Anatolian, and Dead Sea fault zones. Many devastating historical earthquakes have occurred along these fault zones and along other active tectonic features in the region, such as the Hellenic and Cyprus subduction zones, extensional faults in the Aegean region, and the Zagros suture zone. Considering that the eastern Mediterranean has experienced many devastating earthquakes throughout history, including numerous ones of $Mw > 7.0$ during the 20th century, it is safe to assume that the region can expect many large earthquakes during the 21st century and beyond. Consequently, there is an urgent societal need to understand the neotectonics and earthquake potential of the region.

This AGU-Wiley book is an outgrowth of a research symposium titled “Neotectonics and Earthquake Potential of the Eastern Mediterranean Region” at the 2013 AGU fall meeting. The symposium, organized by the editors of this book, was well attended by researchers from all over the world and provided a formal discussion on several important issues related to neotectonics and earthquake potential of the region. The book contains 10 chapters organized under three thematic groups: (1) morphotectonic characteristics of neotectonics in Anatolia and its surroundings, (2) neotectonics of the Aegean-western Anatolian region, and (3) seismotectonics in the eastern Mediterranean region. We hope this book will provide basic knowledge for the development of new earthquake research projects in the region and elsewhere in the world.

We thank all of our contributors and reviewers for their excellent and timely work that helped realize this book. We are in debt to Rituparna Bose and Mary Grace Hammond for their efforts on behalf of this volume, which would not have been realized without their constant push on our editorial duties. Most important, we thank our families for not only their support during the long hours of editing this book but also for supporting us constantly through the years while we were conducting research to contribute to the science of geology.

İbrahim Çemen
Yücel Yılmaz

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

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

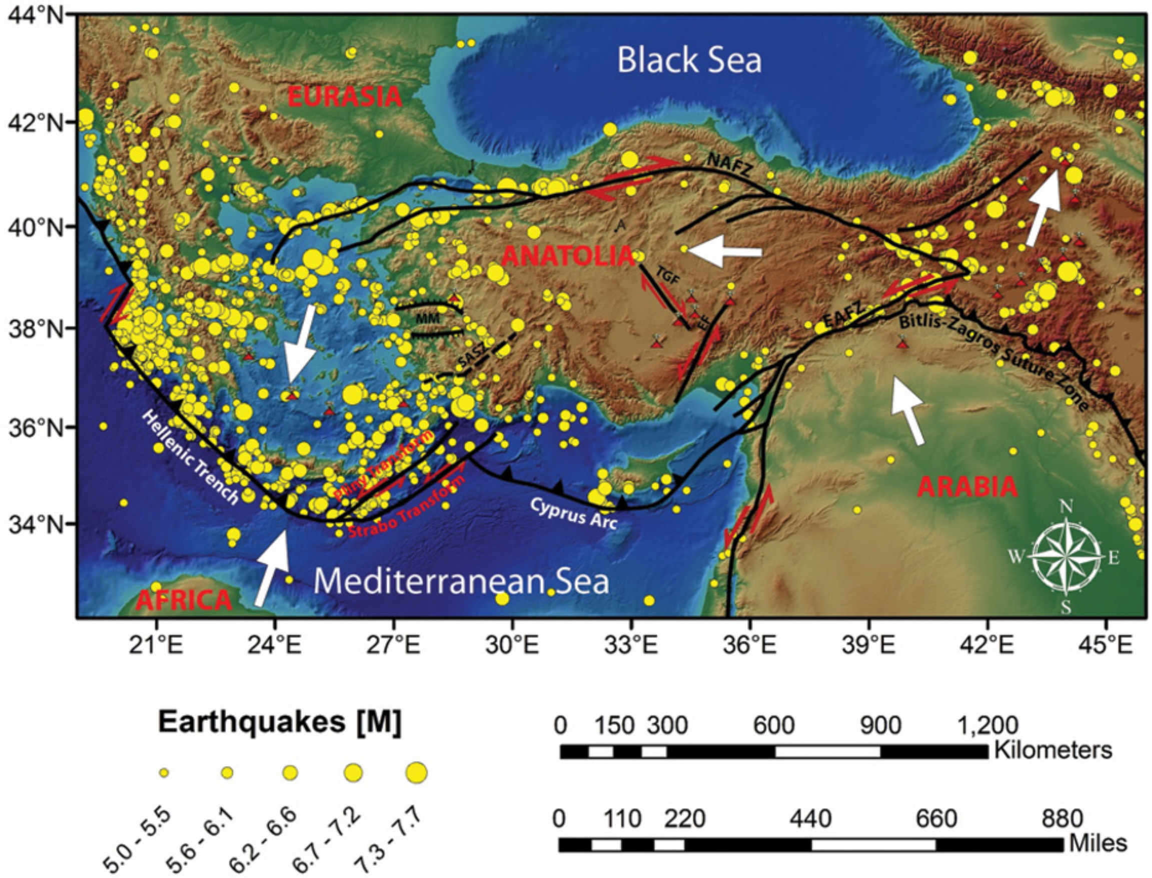

Figure 1.1 Digital elevation map of the eastern Mediterranean region showing major neotectonics structural features, volcanic centers (red triangles), and epicenters of the earthquakes (M > 5.0) since 1950. A = Ankara; EAFZ = East Anatolian fault zone; EF = Ecemis fault; I = Istanbul; MM = Menderes Massif;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

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Part I
Morphotectonic Characteristics of Neotectonics in Anatolia and Its Surroundings

2

Morphotectonic Development of Anatolia and the Surrounding Regions

Yücel Yılmaz

ABSTRACT

In Anatolia, the late–post orogenic deformation is still continuing severely today. The north-south compression initially deformed eastern Turkey. East and central Anatolia began to rise together. Slab break off of the northerly subducting plate and lithospheric delamination played a significant role in this. Compression then formed the North and East Anatolian transform faults. They defined the Anatolian Plate, which began escaping to the west. Major morphotectonic features, the peripheral mountains, the Pontides and the Taurides, and the western Anatolian horsts and grabens, have formed from this time onward. The transform faults played roles in the transfer of the stress. Compared to the east, the west of Anatolia has followed a different path of morphotectonic development. The region was a highland during the Early Miocene period, while eastern Anatolia was under shallow sea. The environments began to change in opposite ways from Late Miocene onward. Southerly retreat of the subducting eastern Mediterranean oceanic slab has generated north-south extension on the upper plate. As a result, the present morphology began to develop. The east-west trending horst and graben structures that dominate the landscape today began to form during later periods of the extension in the Quaternary.

2.1. INTRODUCTION

Anatolia is being deformed presently under an ongoing severe post-late orogenic tectonic regime. The two lines of evidence manifest this: (1) frequent earthquakes that occur in a vast terrain from the east to the west, and (2) a 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. Some local and regional morphological studies were also conducted on different parts of Anatolia. However, a morphological treatment of the whole of Anatolia has not yet been attempted to evaluate interactions of different morphotectonic regions and major tectonic elements. This is a first attempt in this direction to establish a platform for future studies.

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Anatolia is located in the middle of the Alpine-Himalayan mountain ranges. The orogeny started north of the Anatolian orogenic belt (the Pontides) and migrated progressively to the south and ended up in the Bitlis-Zagros orogenic belt (Fig. 2.1). The late-post orogenic deformation is still continuing severely as expressed by GPS data, which display clearly that Anatolia is moving in an anticlockwise sense from the east to the west (Fig. 2.2). The Arabian Plate is moving in a north-northwest direction. Rate of motion of the Anatolian Plate increases to the west from 15–20 mm/yr to 30–35 mm/yr [*Reilinger et al.*, 2006, 1997, 2006, 2010; *Kahle et al.*, 2000; *Taymaz et al.*, 2007; and references therein]. This motion is controlled by the two major parameters: (1) the Arabian Plate steadily advancing northward and bulldozing eastern Anatolia, and (2) the Hellenic trench, along which the eastern Mediterranean Oceanic Lithosphere is being consumed

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

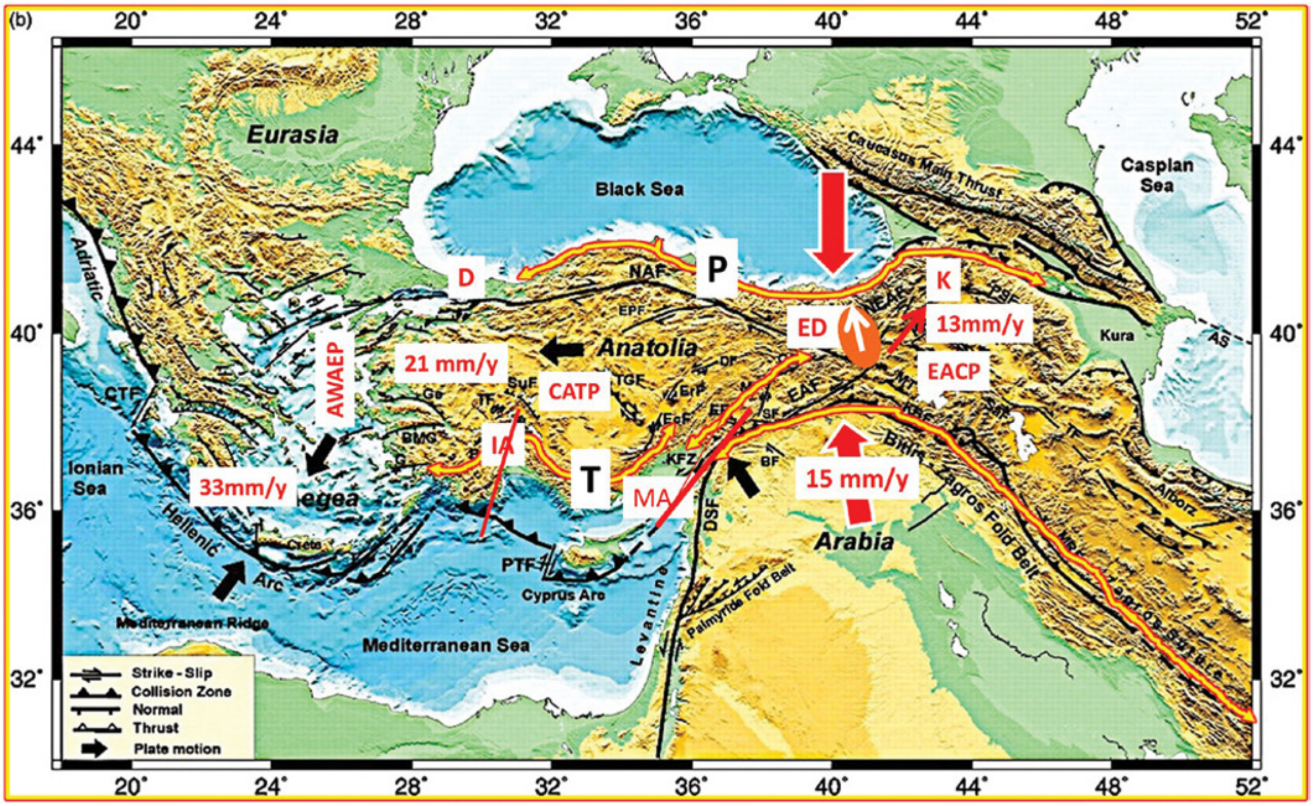


Figure 2.1 Morphotectonic map of Anatolia [modified from *Yolsal-Çevikbilen et al.*, 2012]. Global topography data taken after USGS. Bathymetry data are derived from GEBCO/97–BODC, provided by *GEBCO* [1997] and *Smith and Sandwell* [1997a, b]. Summary sketch map of the faulting and bathymetry in the eastern Mediterranean region, compiled from our observations and those of *Le Pichon and Angelier* [1981], *Taymaz* [1990], *Taymaz et al*. [1990, 1991a, b], *Şaroğlu et al*. [1992], *Papazachos et al*. [1998], *McClusky et al*. [2000], and *Tan and Taymaz* [2006]. Big black arrows show relative motions of plates with respect to Eurasia [*McClusky et al*., 2003]. Bathymetry data are derived from GEBCO/97–BODC, provided by *GEBCO* [1997] and *Smith and Sandwell* [1997a, b]. Shaded relief map derived from the GTOPO-30 global topography data taken after USGS. The yellow lines with red glow are peripheral mountains: P = Pontide mountain range; T = Tauride mountain range; IA = Isparta angle; MA = Misis-Andırın wrench fault zone; ED = Erzincan depression; EACP = Eastern Anatolian compressional province; CATP = Central Anatolian transitional province; AWAEP = Aegean-western Anatolian extensional province. The red ellipse and white arrow indicates orthogonal shortening area within the East Anatolian compressional province. The black and red arrows indicate directions of motions. NAF = North Anatolian fault; EAF = East Anatolian fault; DSF = Dead Sea fault; NEAF = northeast Anatolian fault; EPF = Ezinepazarı fault; PTF = Paphos transform fault; CTF = Cephalonia transform fault; PSF = Pampak-Sevan fault; AS = Apsheron sill; GF = Garni fault; OF = Ovacık fault; MT = Muş thrust zone; TuF = Tutak fault; TF = Tabriz fault; KBF = Kavakbaşı fault; MRF = Main Recent fault; KF = Kağızman fault; IF = Iğdır fault; BF = Bozova fault; SaF = Salmas fault; SuF = Sürgü fault; G = Gökova graben; BMG = Büyük Menderes graben; Ge = Gediz graben; Si = Simav graben; BuF = Burdur fault; BGF = Beyşehir Gölü fault; TF = Tatarlı fault; SuF = Sultandağ fault; TGF = Tuz Gölü fault; EcF = Ecemiş fault; ErF = Erciyes fault; DF = Deliler fault; MF = Malatya fault; KFZ = Karataş-Osmaniye fault zone (part of MA); K = Kaçkar Mountain; D = Düzce.

by subducting northward under the Aegean-Anatolian Plate (Fig. 2.2).

The continuing northward advance of the Arabian Plate and the resulting compression has been accommodated in eastern Anatolia by shortening deformation. As a consequence, the East Anatolian crust has been thickened and the region was elevated to form the East Anatolian-Iranian high plateau to the end of Miocene (Fig. 2.1). Further shortening generated two transform faults, namely the North Anatolian transform fault (NATF) and the East Anatolian transform fault (EATF).

The two transform faults together define an independent tectonic entity known as the Anatolian Plate, which has been protruding away from the thickened and shortened

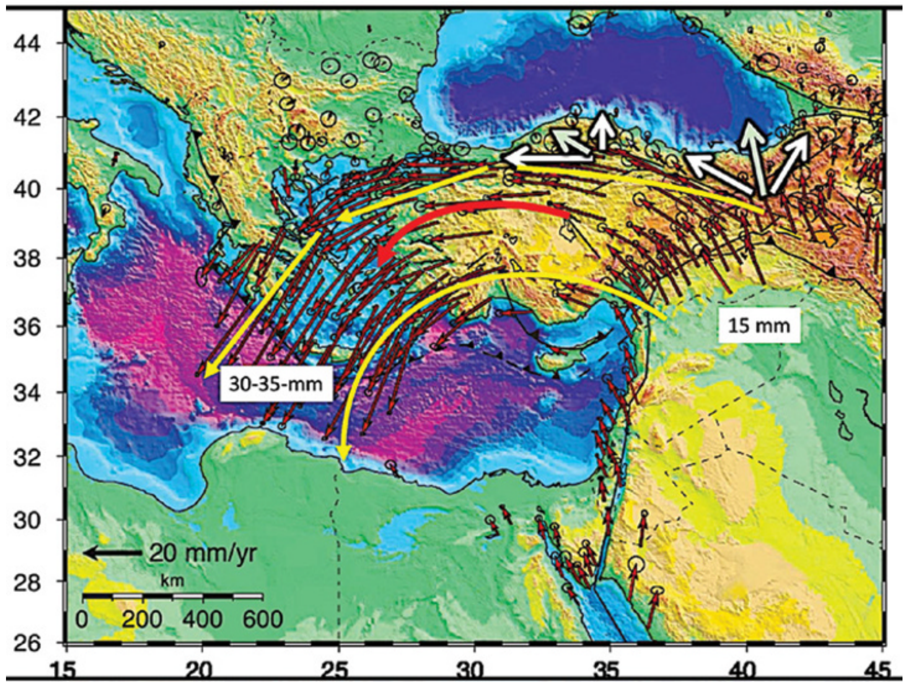


Figure 2.2 GPS observations of relative motion of Anatolia with respect to the Africa-Arabia-Eurasia plates [modified from *McClusky et al.*, 2000; *Reilinger et al.*, 2006]. The red arrow displays counterclockwise sense of motion of Anatolia. The yellow arrows display different circular motions of the northern (Pontides) and the southern (Taurides) peripheral mountain ranges of Anatolia. The white arrows are the major components of the stress field that effects the Pontides, and the light green arrows are the resultant.

eastern Anatolian region to the west possibly from late Pliocene-Pleistocene onward (Figs. 2.1 and 2.2). In the Aegean region, such westward escape of the Anatolian Plate accelerated a north-south extensional regime (Fig. 2.1). Combination of forces, the pull from the subduction zone and push from the convergent zone, is collectively causing the Turkish Plate to rotate southwestward (Fig. 2.2).

The Anatolian orogenic belt is the product of the Tethyan oceanic realm. Initially the PaleoTethyan Ocean during the Late Paleozoic–Early Mesozoic period, and then the NeoTethyan Ocean from Early Mesozoic to the Tertiary Period are responsible from the development of this complex orogenic belt (see *Şengör* [1979b]; *Şengör et al.* [1980, 1982]; *Şengör and Yılmaz* [1981]; *Şengör et al.* [1985] for the PaleoTethyan and NeoTethyan evolution of the eastern Mediterranean regions). During the NeoTethyan period, some continental slivers rifted off of the northern edge of the Arabian Plate and new branches of the NeoTethyan oceans, marginal basins, related arcs, and back arc basins were developed, and then they were all destroyed during the demise of the oceanic environments. This began during the Late Mesozoic, and continued to the end of Tertiary. The collision of the NeoTethyan tectonic entities began in the north, and migrated to the south from Late Cretaceous–Early Eocene to Miocene [*Ketin*, 1966; *Şengör and Yılmaz*, 1981; *Yılmaz*, 1993; *Yılmaz et al.*, 1997]. Eventually, the continental slivers welded together to form the present amalgamated tectonic entities, the Anatolian orogenic belt.

There is a critical period in the geologic-tectonic and particularly morphotectonic history of Turkey that corresponds to a change from the PaleoTectonic to the NeoTectonic eras. Although the term *NeoTectonic* is widely used in geological literature, its application appears to be rather vague. Some use it as a time frame for referring to events that happened during or after Miocene or Neogene. Some others use it irrespective of any time-space reference. Since we also use this division extensively in our narrative, we find it useful to state at the beginning of the chapter that we use it in the same sense as was first defined by *Şengör* [1979a], and we will briefly explain the concept again in the following.

During the late stage of the development of the Bitlis-Zagros orogenic belt, the suture mountain [*Yılmaz*, 1993] began elevating between the converging jaws of the Arabian Plate and the northerly located amalgamated tectonic entities during the Middle Miocene time [*Yılmaz*, 1993], and then the whole of eastern Anatolia and possibly central Anatolia began to rise as a coherent block, approximately to the end of the Late Miocene time. This rapid elevation may be the consequence of the break off of the subducting plate under East Anatolia (*Piromallo* *and Morelli*, [2003]; see Chapter 3 for a discussion on this and related topics). As northward advance of the Arabian Plate continued after the collision, the compressive forces were initially accommodated along the orogenic belt, and then it began to deform the regions farther north more affectively. As a result of this, the east of Turkey (the region of eastern Anatolia and the Pontides) began to be severely deformed (the Neogene successions were tightly folded and faulted). The two transform faults, namely the northern Anatolian transform fault (NATF) and the East Anatolian transform fault (EATF) were formed during this period, when the shortening of the East Anatolian crust reached an excessive stage that could no longer be accommodated within the volume of eastern Turkey alone. From this time onward, the land bounded by the two transform faults defined an independent tectonic entity known as the Anatolian Plate, which began to move away from the point of convergence to the west. This event began possibly during the late Pliocene-Pleistocene time (see Chapter 3 for a discussion on the topic). This is the time of initiation of the NeoTectonic era. From this time onward, the morphotectonic nature of the eastern Mediterranean region and particularly Anatolia began to change drastically. Three distinctly different tectonic zones were developed as a result of this event [*Şengör*, 1979a], (1) eastern Anatolian compressional province, (2) western Anatolian extensional province, and (3) the transitional zone of central Anatolia (the Ova region of *Şengör* [1979a]) that began to behave as a bridge between East and West Anatolia (Fig. 2.1).

The eastern Mediterranean as a tectonic domain covers a vast region, which includes the following major geographic divisions. The eastern Mediterranean region (sensu stricto), northwestern part of the Arabian Peninsula, the Anatolian Peninsula, the Aegean Sea region. Each one of these geographic domains represents a distinctly different tectonic entity. The Arabian Plate represented initially a passive continental margin and remained as the passive continental margin till the present orogenic belt began to form during the Late Tertiary period (see *Yılmaz* [1993] for a detailed account of the development of the southeast Anatolian orogenic belt). The Anatolian Peninsula represents an orogenic belt from the northern edge to the southern edge. Along the edges lie approximately east-west trending mountain ranges known as the Pontides and the Taurides in the north and south, respectively. They are peripheral mountain belts, which rise steeply like a wall from the surrounding seas, and separate the interior of Anatolia from the Black Sea and the Mediterranean Sea. During the initial stage, the uplift of eastern and central Turkey and the peripheral zones accompanied the elevation. Later the border zones were elevated to higher levels and formed the present peripheral mountains.

The Aegean region is an extensional tectonic province. Development of this tectonic entity is closely connected with the surrounding tectonic units, demise of the eastern Mediterranean Ocean, and the western escape of the Anatolian Plate (Fig. 2.1). The Black Sea is delimited in the south by the Pontides. Thus, development of the southern part of the Black Sea has been under the strict tectonic control of the Pontide Range.

Each of these tectonic provinces may be divided into some subdivisions. Within the eastern Mediterranean Sea region (Fig. 2.3), there are remnant oceanic basins (e.g., the Herodotus and Levantine basins), young rifted marine basins (most of those are located in the south of the Tauride Range such as the Rhodes, Antalya, Cilicia-Adana, and İskenderun basins), the trenches (e.g., the Hellenic, Pliny, Strabo, and Pytheus-Cyprus trenches), seamounts (e.g., the Anaximander and Eratosthenes seamounts), and some ridges (e.g., the Mediterranean, Latacia, and Larnaca ridges). In the following paragraphs, outlines of the major tectonic, morphotectonic, and seismotectonic characteristics of the main tectonic provinces are summarized.

2.2. SOUTHEAST ANATOLIA (NORTHWESTERN PART OF THE ARABIAN PLATFORM)

The northern periphery of the Arabian Plate curves around the southeast Anatolian orogenic belt, which delimits the Arabian platform in the north (Fig. 2.1). Approaching the mountain ranges, the Arabian platform turns to a foreland fold and thrust belt (Figs. 2.1, 2.4, 2.5, and 2.6). From the interior toward the orogenic belt, folding and tightening are gradual. Within the 30–100 km zone from the mountain range on the western part of the Arabian platform another gradual change is noticed. The folds and the closely associated faults began to display an en echelon pattern (Fig. 2.5). This is due to the replacement of the orthogonal shortening in the central part (apex of the curve) by an escape tectonic regime as expressed by the development of the oblique faults having strike-slip and reverse-slip components. The southerly overturned folds are truncated by the left-stepping oblique faults [*Yılmaz et al.*, 1985; *Yılmaz and Yıldırım*, 1996; *Yiğitbaş and Yılmaz*, 1997] (c in Fig. 2.5). The seismic data and the analyses of the frequently generated earthquakes also support motions along the oblique slip faults (Fig. 2.7 a, b).

The northern edge of the Arabian platform in the southeast Anatolian region was a site of marine environment, which survived with three major interruptions from the Cambrian to the end of Middle Miocene (Fig. 2.4). Starting from the Late Miocene, a continental environment replaced the marine environment [*Tuna*, 1973; *Yılmaz et al.*, 1988; *Yılmaz*, 1993; *Yılmaz and Duran*, 1997; *Siyako et al.*, 2013].

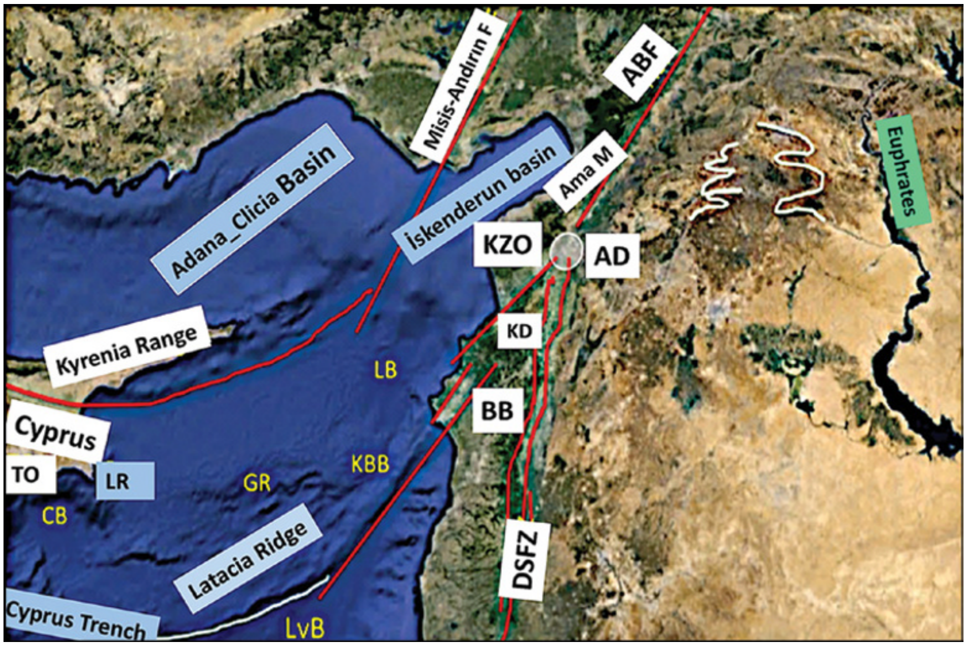


Figure 2.3 Major tectonic units of the eastern Mediterranean region and their extension to the neighboring land areas. LvB = Levantine basin; TO = Troodos ophiolite; CB = Cyprus basin; LR = Larnaca ridge; GR = Gelendzik rise; KBB = Kiti Baer Bassit unit; LB = Larnaca basin; BB = Baer Bassit; DSFZ = Dead Sea fault zone; KD = Keldağ horst; KZO = Kızıldağ ophiolite; AD = Amik depression; Ama M = Amanos Mountains; ABF = western boundary fault of the Karasu depression (the fault that separates the Amanos Mountain from the Karasu depression). The sinusoidal lines refer to the general pattern of the river network on the Arabian platform.

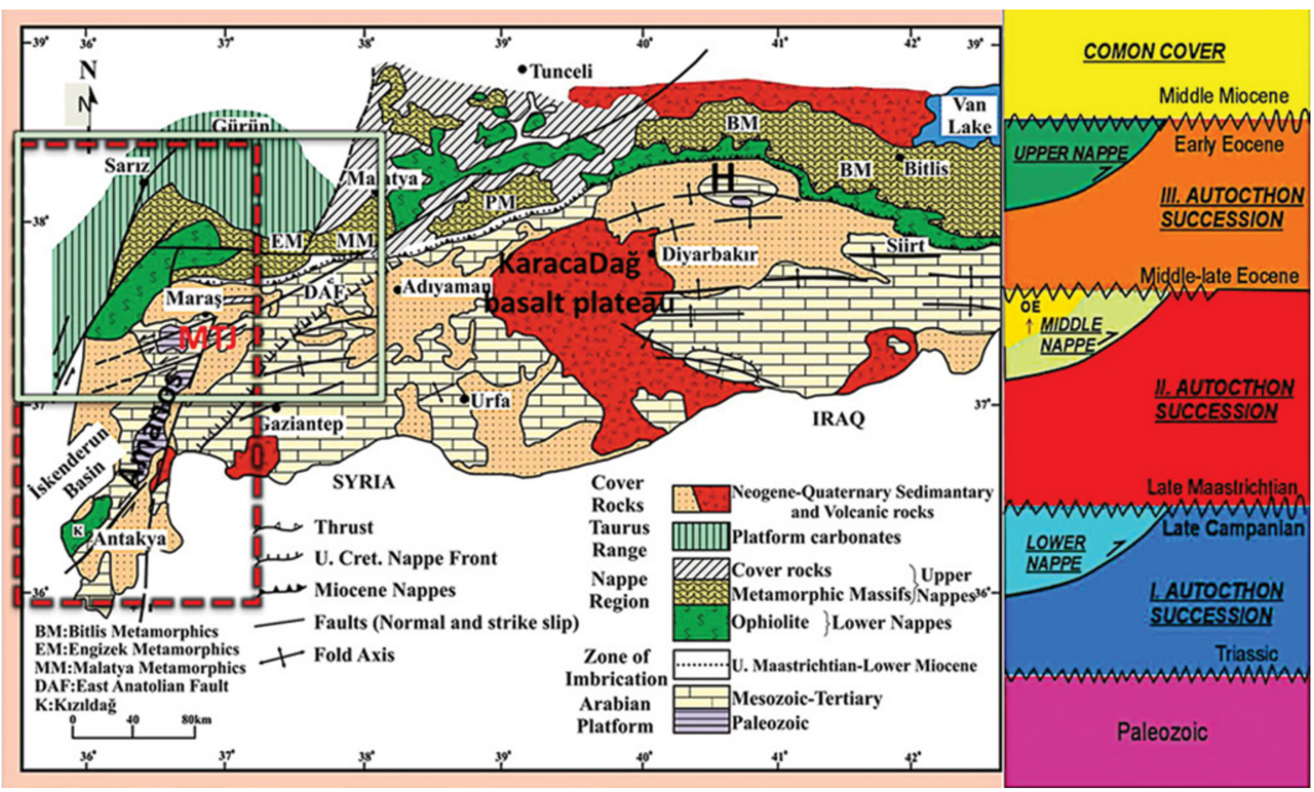


Figure 2.4 Geology map of southeastern Anatolia [modified from *Yılmaz*, 1993]. H = Hazro high-anticline; EM = Engizek metamorphic massif; DAF = East Anatolian transform fault; MTJ = Maraş triple junction; K = Kızıldağ ophiolite. The white and red rectangles refer to the locations of Figures 2.5 and 2.6, respectively.

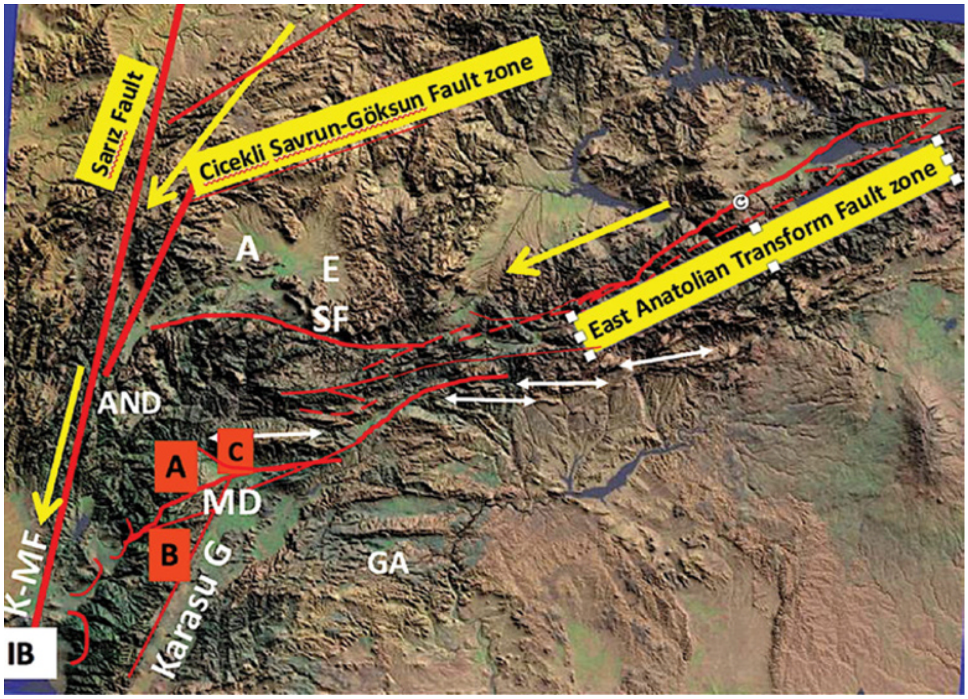


Figure 2.5 Morphotectonic map of the western part of the Bitlis-Zagros suture mountains; (a) and (b) in the red rectangles are two strike-slip fault zones (the Deliçay fault and the Türkoğlu-Haruniye fault that are detailed in Fig. 2.9) that cut the entire width of the Amanos Mountain (see also Fig. 2.8 for their locations); C = the northern boundary fault of the Maraş basin; MD = the Maraş triple junction (depression); K-MF = Kyrenia-Misis fault zone (MA in Fig. 2.1); SF = Sürgü fault; A, E, and GA are the locations of Afşin and Elbistan towns and the city of Gaziantep. Yellow arrows indicate relative motion of the fault-bounded blocks. The white arrows display some prominent foreland folds in the fold and thrust belt of the Arabian platform. The current stress state of the region is transpressional field with southwest trending sigma 1, associated strain is strike-slip with transpressional component.

Three major phases of deformation are differentiated in the northwestern part of the Arabian platform [*Yılmaz*, 1993; *Yılmaz et al.*, 1993]. These are associated with the nappe emplacements from the north (Fig. 2.4), where the NeoTethyan Ocean was located during the Mesozoic and Cenozoic periods [*Şengör and Yılmaz*, 1981]. During the first two phases, giant ophiolite nappes were obducted onto the Arabian platform (Fig. 2.4; *Yılmaz* [1985]; *Yılmaz et al.* [1993]). The last phase is connected with the development of the present orogenic belt (Fig. 2.4; *Yılmaz* [1993]; *Yılmaz et al.* [1993]). The first deformation phase began during the Turonian time and lasted until the end of Early Maastrichtian. Results of this deformation phase are clearly seen in the Amanos Mountains (Figs. 2.4). The second phase occurred in the Early-Middle Eocene time, and its imprints were observed more clearly in the central Amanos Mountains (*Yiğitbaş et al.* [1992], *Yılmaz et al.* [1993]). The effects of the last phase are observed in the thick sedimentary succession covering an age range from the Late Eocene-Oligocene, when the frontal parts of the southerly transported nappe package first hit the Arabian platform (Figs. 2.4, 2.5, 2.6, 2.7, and 2.8; *Yılmaz* [1993]; *Hüsing et al.* [2009], *Silja et al.* [2009]), and then it survived to the end of Middle Miocene. The deformation became severe particularly to the end of Middle Miocene, when the allochthonous units were thrust onto the Arabian platform (Fig. 2.4; *Yılmaz* [1993]). Despite the collision, the northerly advance of the Arabian Plate has continued to the present. The convergence rate is established to be about 15 mm/yr reaching to 21 mm/yr, according to GPS measurements (Fig. 2.2; *Reilinger et al.* [1997, 2006, 2010]; *Kahle et al.* [2000]; *McClusky et al.* [2000]) (for recent kinematic data from the northwest part of the region, the reader is referred to *Seyrek et al.* [2014]).

In light of the detailed geological studies [*Yılmaz*, 1984a; *Yılmaz et al.*, 1985; *Yılmaz*, 1990b, 1993; *Yılmaz et al.*, 1993a; *Parlak et al.*, 2004; *Rızaoğlu et al.*, 2009; and references therein], the evolution of the southeastern Anatolian orogen may simply be summarized as a progressive relative southward transport of the nappes toward the Arabian Plate during the Late Cretaceous to the Late Miocene period. This caused progressive accretion of different tectonic units into the nappes (Fig. 2.4). Within the nappe stack are the fragments of a small

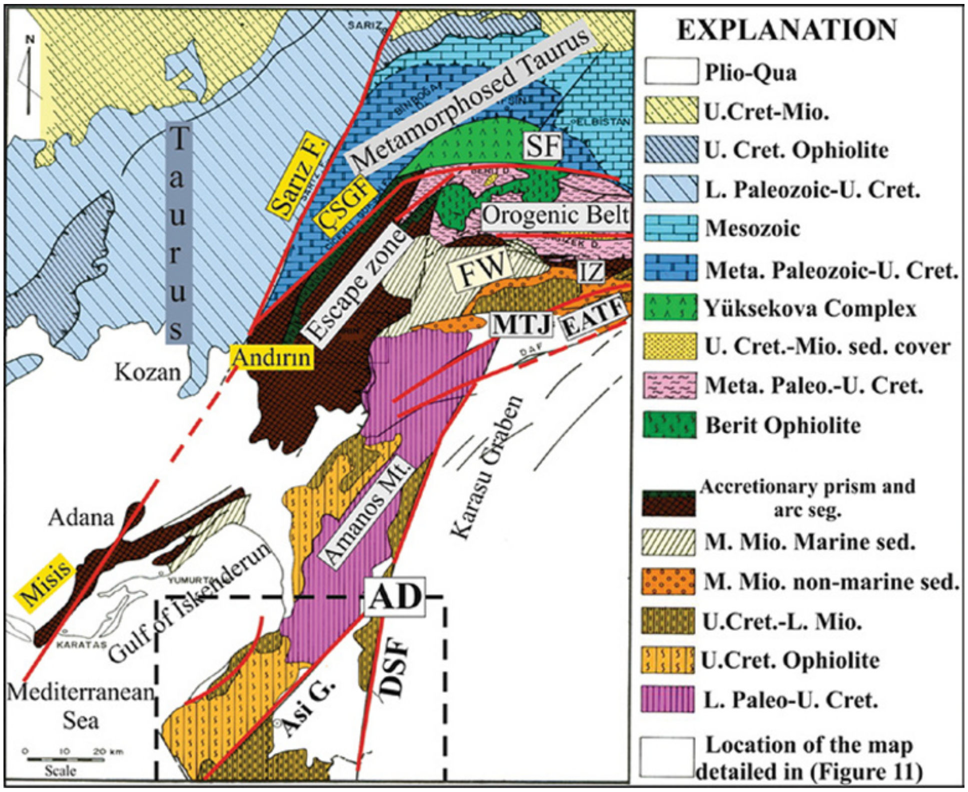


Figure 2.6 Geology map of western part of the Southeast Anatolian orogenic belt (Bitlis-Zagros suture mountains). EATF: East Anatolian transform fault; SF = Sürgü fault; CSGF = Çicekli-Savrun-Göksun fault; IZ = imbricated zone of the southeast Anatolian orogenic belt. Its western continuation is the escape zone that has escaped away from the collision. Asi G = Asi (River) graben; DSF = Dead Sea fault zone; MTJ = Maraş triple junction (note the pair of faults on both sides of the Maraş triple junction. The two faults in the west cut the entire width of the Amanos Mountains obliquely aligning along the extension of the major branches of the East Anatolian transform fault zone). The black rectangle indicates the location of Figure 2.11. The Sürgü fault is one of the old and yet still active major faults of the orogenic belt. It separates the nonmetamorphic Elbistan ophiolite (light green area) (an intact ophiolitic slice, above which an in situ, thick sequence was deposited from Late Cretaceous to the Eocene period, prior to the emplacement of the ophiolite on to the metamorphic massifs [*Yılmaz et al.*, 1985,1993a] and high-grade metamorphic ophiolite assemblage (the Berit ophiolite and the associated units (including the Eocene successions) (dark green area) [*Genç et al.*, 1993; *Yılmaz et al.*, 1993b]. Across the fault, a kilometers-thick column of rocks was exhumed during the Eocene time. Therefore, the Sürgü fault zone acted as a major normal fault (a detachment fault?). The fault reactivated under the transpressional tectonic regime as an oblique (strike-slip dominant) fault zone during the NeoTectonic era. Therefore, the fault has changed its character from a normal fault to an oblique fault (possibly as an inverted fault). The Çicekli-Savrun-Göksun (ÇSGF) and the Sarız faults are two major faults that were formed under transpressional tectonic regime. Between the two faults, a metamorphosed slice of the Taurides (consisting mainly of marble and recrystallized limestone succession) wedged tectonically into the southern region. The southward advance of the tectonic wedge along the Misis-Andırın fault zone into the Adana plain is manifested by the progressive southerly migration of the Plio-Quaternary coarse fluvial clastic wedges [*Yılmaz and Gürer*, 1996]. ÇSGF presently connects the Sürgü fault and the Misis-Andırın fault zone. The Sarız fault is also a major fault zone of the region. Across the fault the nonmetamorphic Taurus units are in direct contact with the high-grade metamorphic rocks of the Taurus Range. These two fault zones were formed during the PaleoTectonic era and have continued as major faults during the NeoTectonic era. They have played major roles in the development of the present morphology of the region. FW represents the flysch wedge that forms when the escape tectonic regime began.

oceanic basin, a back arc basin, and an island arc [*Yılmaz*, 1993; *Yılmaz et al.*, 1993; *Parlak et al.*, 2004]. The nappe stack has finally collided with and welded onto the Arabian plate, when the separating ocean floor was totally obliterated by the Late Eocene time [*Yılmaz*, 1993; *Yılmaz et al.*, 1993; *Hüsing et al.*, 2009]. In the following period, a remnant sea, which remained between the colliding continents, began retreating westward

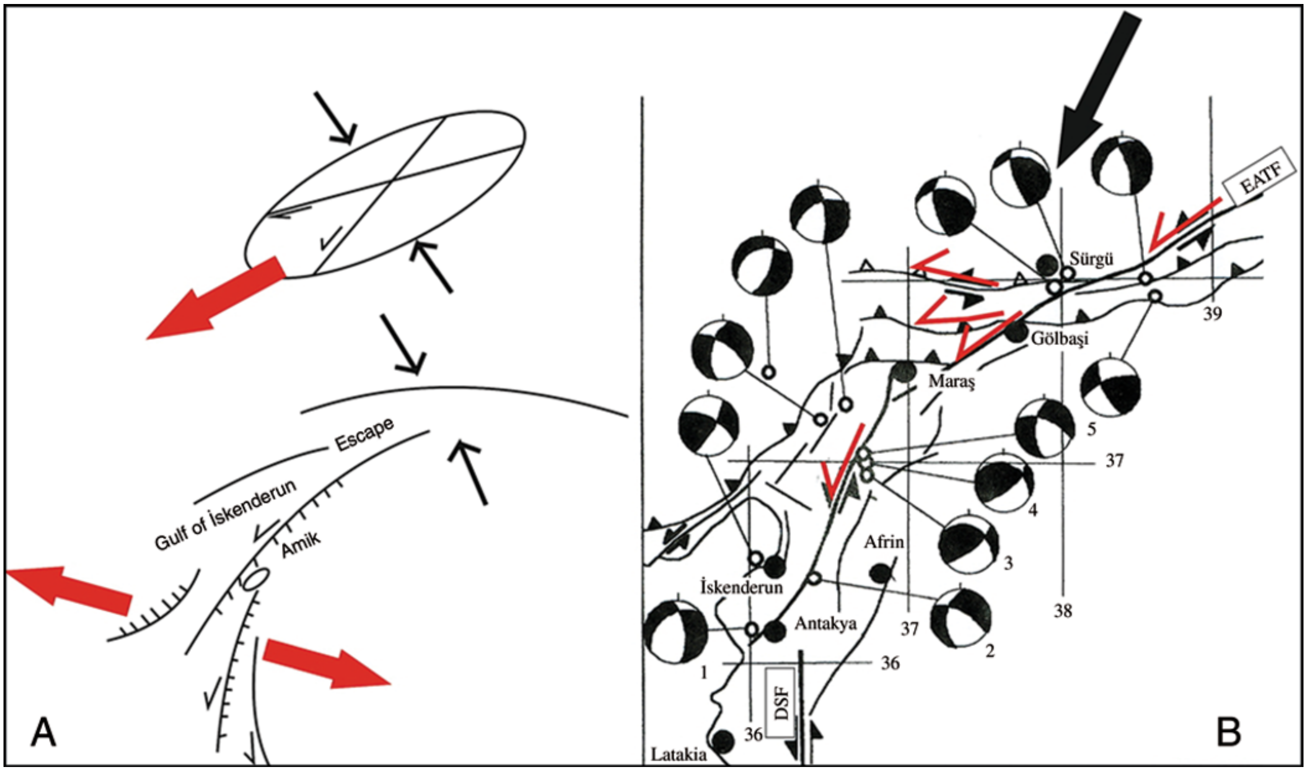
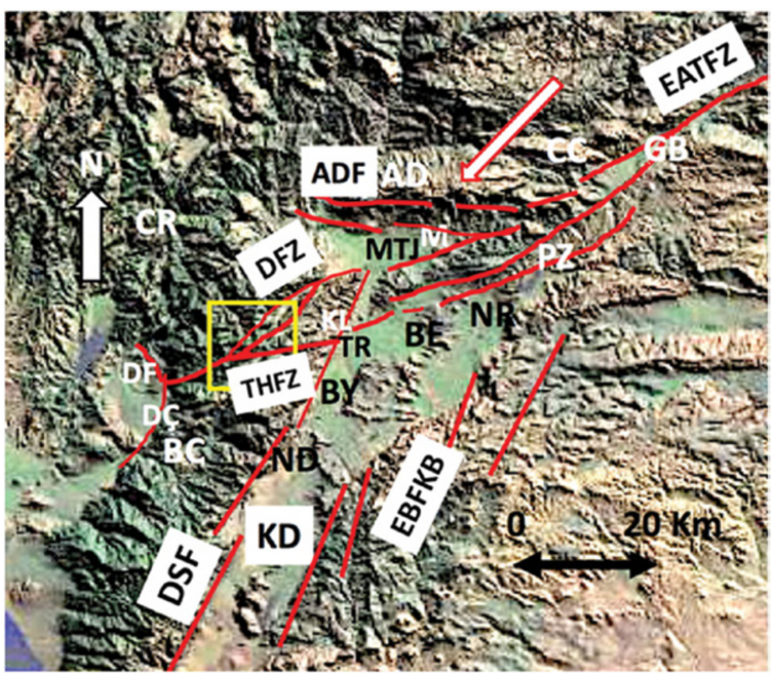


Figure 2.7 Maps showing (a) the regional stress distribution in northwestern part of the Arabian Plate and the Bitlis-Zagros orogenic belt; (b) major faults (see Fig. 2.6 for the names of the faults and seismicity of northwestern edge of the Arabian platform, and the earthquake fault plane solution data [modified from *Eyidoğan*, 1983]; EATF = East Anatolian transform fault; DSF = Dead Sea fault.



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