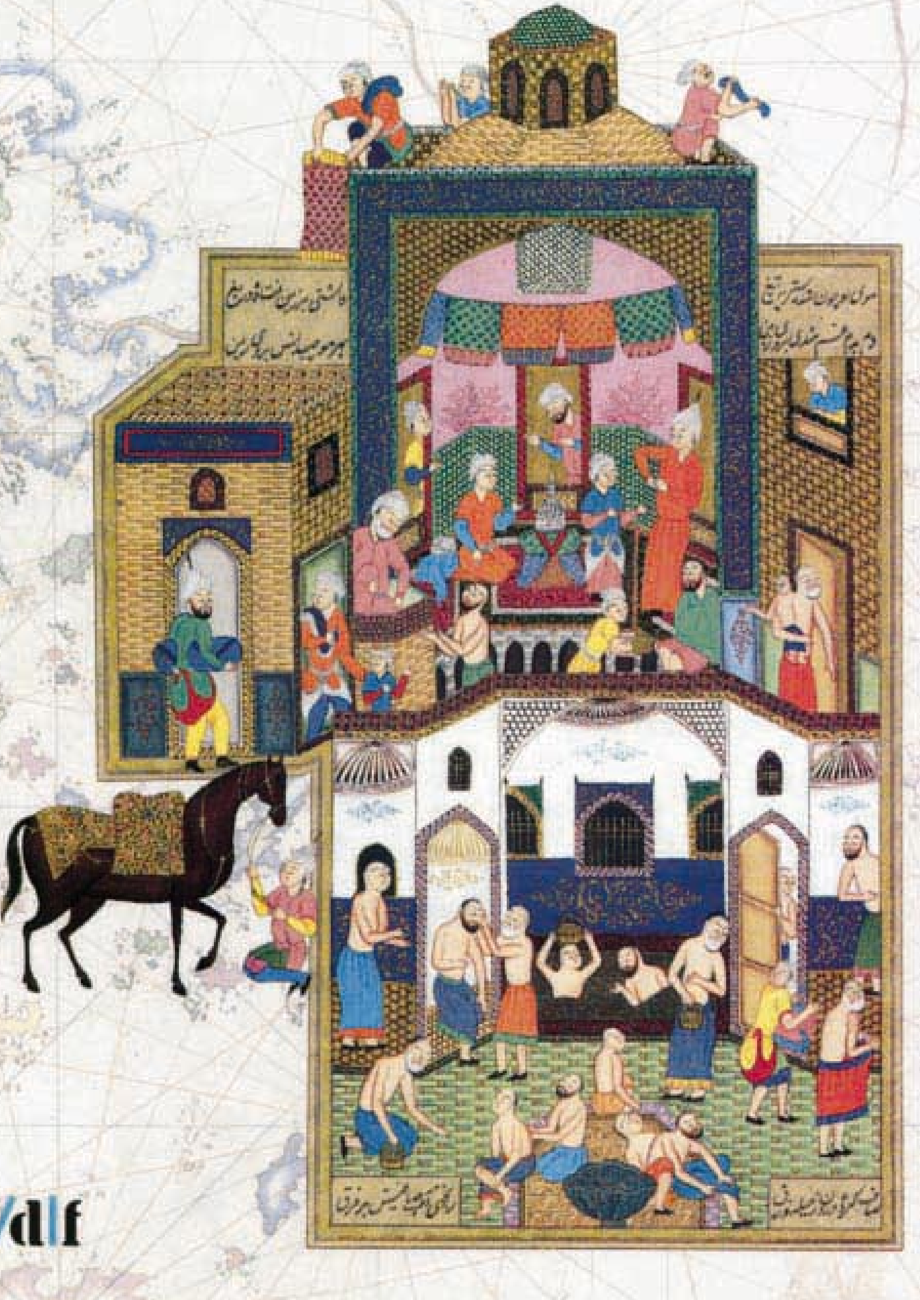
Active Tectonics of Northwestern Anatolia – The MARMARA Poly-Project

A Multidisciplinary Approach
by Space-Geodesy,
Geology, Hydrogeology,
Geothermics and Seismology



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Conrad Schindler, Martin Pfister (eds.)

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ISBN 3- 7281-2425-7

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Preface

Conrad Schindler

In 1988, a new kind of scientific concept was created at the ETH Zürich, a so-called "Poly-Project". The idea was to study complex scientific subjects using an interdisciplinary approach also involving foreign universities. Thus, the idea for the "MARMARA Poly-Project" began with a draft project submitted in July 1988, followed by a final draft in October 1989 and the official start in January 1990. The project included three periods of two years, ending in December 1995. However, saved research money allowed us to continue work until Spring 1997. During this additional time the last two doctoral theses were completed, a synthesis was made and the final publication was prepared.

Northwestern Anatolia, including the Marmara sea region, proved to be, for Earth sciences, the ideal opportunity for an efficient collaboration of representatives from different disciplines. In this part of Turkey, active crustal movements take place, combined with very high seismicity and numerous outflows of thermal waters and gas outputs. Previous work in Turkey by N. Pavoni and C. Schindler and existing contacts with Turkish scientists were very favourable for the initiation of scientific investigations in Turkey. Work and progress would never have been possible without the logistic and scientific support of Turkish universities, research centres and state owned organisations, our main partner being the Technical University of İstanbul (İTÜ). The first enthusiastic promoter of the MARMARA project on behalf of the İTÜ was the outstanding engineering geologist Kemal Erguvanli. Unfortunately he died soon after the work had begun.

The main *aim of the MARMARA Poly-Project* was to study tectonic activities and their relationship to the circulation of normal and geothermal waters, the distribution of zones with elevated seismicity and the spatial heat flow pattern. All of the scientists involved worked, in different disciplines such as Geology, Hydrogeology, Geodesy, Geothermics and Seismology and were dependent on each other. For this reason, information was exchanged periodically in conferences held in Zürich and seminars in İstanbul completed by shared field trips in Turkey. The contacts between Turkish and Swiss scientists were also intensified through the exchange of students and advisers for PhD theses. Parallel to the increasing knowledge concerning the investigated objects, co-operation between the research groups became very close and peaked during the period when this final report had to be drafted and written. Additional scientists from Switzerland and Turkey who helped to complete or add to the previous work of the MARMARA project with their contributions were contacted during this period.

Evolution of the project

Not all participants in Switzerland and Turkey began their work at the same time. The first group, *Geology and Hydrogeology*, already started work in Turkey in 1986, four years before the MARMARA project was launched. Through this, a reliable basis was created for the groups which followed. Up to the end of the project, a total of five Swiss and one Turkish student worked on separate areas of special geological and geothermal interest, including detailed mapping at the scale of 1:25,000. These studies were able to be completed by previous work done for petroleum research in the years 1956 – 1959 by two of the authors (Pavoni and Schindler), however, no additional studies were made, as thermal springs do not exist in these areas.

In order to confirm crustal movements along fault lines as suggested by the geologists, some 50 GPS-stations were installed all over NW Turkey by the *Geodesy* group according to the indications of the geologists. The first measurements were made in 1990, steadily improving in quality during the campaigns of 1992, 1994 and 1996. Besides the groups from the ETH and the İTÜ, the General Command of Mapping (GCM) participated in this project. The GPS stations were concentrated in tree large areas, each covering the North Anatolian Fault Zone system and reaching the more stable areas to the south and to the north. 10 of our GPS stations were measured again in 1996, this in the context of an international project covering large parts of the Eastern Mediterranean.

In 1991, the *Geothermics* group made borehole measurements over the entire research area, including the Ergene basin in Thrace. The purpose was to establish a heat flow map covering a large area of NW Turkey and to find correlations with the results of the other disciplines. Based on data provided by the Geology and Hydrogeology group, numerical models of selected thermal water systems were developed.

The *Seismology* group started their work in 1992. The main subject of the scientists from the ETH, the İTÜ, the Observatory of Kandilli and Tübitak was the investigation of the region of Bursa. Twelve new seismic stations were installed there in 1992. Attention was also paid to the seismicity and its relationships with neotectonics for the other areas where the MARMARA project was underway. However, the database used there was completely furnished from the Turkish stations.

All field studies of the MARMARA project were finished by the end of 1995 (except Seismology). An extensive synthesis of the results of each group started at that time. Concurrently, Turkish scientists worked on Theme 3 which synthesises the actual state of the knowledge in Earth sciences in Western Turkey outside of the MARMARA project.

Organisation

Even though the project was guided and co-ordinated by C. Schindler, the various groups and especially their leaders, were responsible for their own work. The organisation at the ETH had a counterpart at the İTÜ, directed by E. Yüzer, with one or more representatives of each group. Apart from these direct partners, co-operation was also established with other scientists in Turkey, as well as in other countries. The names of all the persons involved appear in the respective themes.

For the co-ordination of the groups, for the work on a general synthesis and for the preparation of the final report a full time postdoctoral fellow was at the disposal of the MARMARA project co-operating closely with C. Schindler. This key job was carried out by Th. Imbach (1992-1994) and for the final stage by M. Pfister (1995-1997), both former PhD students of the project.

Remarks on the final report

The present publication contains, in a condensed form, contributions from many authors. They alone are responsible for the content of their papers. Included are summaries from the ETH dissertations carried out in the framework of the MARMARA project. They were printed in full in German or English, but are available only in limited numbers, copies, as well as the complete database, are available for consultation at ETH-Hönggerberg.

Current knowledge concerning stratigraphy, tectonics, geothermics and the structure of the lithosphere in NW Turkey lies at a much lower level than in Central Europe, for example, where Earth science research began more than 100 years ago. In addition, good outcrops and long sequences of stratigraphic profiles are missing over large areas and fossiliferous series are sparse. As neotectonics often obliquely cut older structures and disturb them intensively, the reconstruction of pre-tertiary development becomes very difficult. Therefore, it is not surprising that large differences exist not only in the interpretation of age and tectonic history of the series older than Upper Cretaceous, but also for many other questions. Controversies can be observed between older and more recent publications and also among current interpretations. Therefore, some controversial interpretations can be recognised if different papers of the final report are compared. As many problems can not be currently solved in a definitive way, different opinions were expressed in the hope that the future will bring clear answers. The external conditions in the working field of the MARMARA project may be difficult. On the other hand, they are fascinating and a challenge to everyone concerned.

This final report starts with an introduction (Theme 1) to the investigated Marmara sea region and to the main aims and problems of the Poly-Project. It is followed by a general view of Eastern Mediterranean plate tectonics in Theme 2. Turkish colleagues give a condensed overview of the actual knowledge in the different research disciplines for the area of Western Turkey (Theme 3). Different papers from the extensive Geology and Hydrogeology groups are collected in Theme 4. These studies were carried out in locally restricted areas. Condensed regional evaluations of the results according to single disciplines follow in Theme 5. These contributions are representative of the Turkish-Swiss collaboration under the guidance of the different group leaders. The articles of Theme 4 and 5 show interdisciplinary aspects already and results as they were written after intensive mutual contacts. In the last part of the final report (Theme 6), an attempt is made by a few persons included in the MARMARA Poly-Project to pursue the interdisciplinary approach even farther and to obtain results from the large field existing between the specialists – a very difficult and uncommon task. The proposed results may open the way for many further discussions.

Acknowledgements

The MARMARA Poly-Project was financed and supported by the Swiss Federal Institute of Technology (ETH Zürich). I would like to thank Vicepresident R. Hütter and the research commission of the school for their broadmindedness and confidence. The very effective and straightforward assistance was of great help during all stages of the project. Similar generous support came from the İstanbul Technical University: on one hand the project was sponsored by the research fund (İTÜ araştırma fonu), and on the other hand the entire infrastructure of the İTÜ, the always ready guesthouse and various invitations helped the project to survive.

Thanks go to all colleagues at the ETH and the İTÜ involved within the MARMARA Poly-Project. I remember intensive and agreable collaboration, fruitful and intense discussions and shared adventures, not only with my PhD students, but also with all the other research group members or leaders, in Turkey as well as in Switzerland.

Special thanks go my colleague E. Yüzer of the İTÜ: he organised numerous seminars, diverse social events, excursions and prepared the necessary political contacts within the diverse investigation areas. I also remember fondly our former colleague K. Erguvanli who was our project partner and pathfinder during the first years. M. Vardar, O. Dumlu (İTÜ) and O. Eroskay (İstanbul University) contributed valuable assistance, help and scientific knowledge to the project, and prepared an atmosphere of friendship. Thanks to you all of you!

St. Mueller supported with all his forces, his experience and wisdom our project until his premature death in February 1997. We remember him for ever with great respect and appreciation.

Numerous persons and institutions supported the project:
in Switzerland: E. Klingelé, R. Gysin, S. Tschudi, P. Smith, M. Spühler, M. Gurtner, P. Signer, M. Grünenfelder, L. Martinenghi, J. McKenzie (ETH Zürich); Institutions: EAWAG (Dübendorf), WSL (Birmenstorf), Institutes of Geophysics, Geology and Geodesy at ETH Zürich.
in Germany: H. Woith (GfZ Potsdam); Institutions: gsf (Neuherberg, Munich).
in Turkey: E. Saker and H. Tezel (DSİ Bursa), O. Öztuncer (Yeni Kaplıca Bursa), G. Dikmen (Köy Hizmetleri Balıkesir), İ. Kınık (GCM); Institutions: DSİ (State department for water resources), MTA (State department for mining purposes), GCM (General Command of Mapping in Ankara), Kandilli Observatory, Tübitak Organisation, Köy Hizmetleri (State department for rural purposes).

My wife Ursula often took part in our excursions, establishing personal contacts and pointing our attention to the fascinating living Turkey around us after endless scientific discussions.

Finally, I would like to thank the Turkish people for their hospitality and generosity. The warm welcome and help will never be forgotten; we experienced an eventful and beautiful time.

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THEME 1

Introduction

The MARMARA Poly-Project: an introduction

MARTIN PFISTER AND CONRAD SCHINDLER

The Marmara region in Northwestern Anatolia represents an area of major earthquake occurrence caused by recent tectonic activity of the Earth's crust and accompanied by numerous thermal springs and geothermal fields. The possibility to observe an ongoing deformation of the Earth's crust with such an intensity is unique and, therefore, extremely promising.

As a consequence of the collision of the Arabian with the Eurasian plate, other plates – including the Turkish plate – are moving away from the Caucasus. Because of this structural lithospheric setting, the sinistral East Anatolian and the dextral North Anatolian strike-slip faults have been neotectonically active. The North Anatolian Fault Zone (NAFZ) is the dominant feature in the research area and forms a tectonic connection between the East Anatolian convergent zone and the Hellenic trench, where the motion is compensated by the consumption of oceanic crust (Şengör 1979).

The strong seismic activity of the research area is triggered mainly by the westward moving Turkish plate (McKenzie 1972) combined with the southward extension of the Aegean and westernmost Anatolian realm. More to the east, the NAFZ is characterised by quite a narrow strike-slip zone with occasional pull-apart basins, but in the project realm it progressively splits up to the west. The pure strike-slip regime changes into a stress regime with additional N-S extension.

The NAFZ is characterised by elongated valleys, rift morphology, isolated hills, pull-apart basins, tectonic breccias, crushed tectonic lenses, fault scarps, landslides, diverted river courses, as well as high seismicity and hot springs. South of the NAFZ, Horst-Graben like structures developed in the research area due to the extensional forces of the Aegean system.

The Geology exhibits a complex interplay of various, partly metamorphic or magmatic, rocks recalling changing tectonic regimes as far as back to Variscan orogenies. To understand the present conditions, the past has to be analysed. This is a difficult, but fascinating, task. Besides, new space geodetic developments have had a great impact on geodynamic theories since they have measured the rates of moving lithosphere over long distances (hundreds of kilometers) even though the displacements are relatively small (<150mm/a).

Interrelations between surface ruptures, groundwater and earthquakes in history

Looking back into history, earthquakes and surface ruptures of the Earth's crust have always fascinated philosophers and natural scientists. In ancient Greece, the philosopher Democrites from Milet (south of current day İzmir on the western coast of Turkey) explained in the Pleiade the cause for earthquakes by water transport or 'wind' in the underground (Democrites, 2000 BP). Nowadays, we cannot imagine any air turbulence in the Earth's underground, but the influence of fluid circulation on the release of earthquakes has developed as a key problem of modern geoscience.

In the 19th century AD, important observations about fluids in the Earth's crust were presented in literature. Among these, observations were also made in Northwestern Anatolia: the large earthquakes on April 4th, 1850, and on April 11th, 1855, in the environs of the beautiful city of Bursa, a former sultan's capital, caused enormous destruction and visible displacements of the Earth's crust. The occurrence of new hot springs in Çekirge and Kükürtlü, two thermal spa districts in Bursa dating back to Byzantine times, were documented (Palmerston 1851, Sandison 1855, see also Imbach this volume). These new springs subsequently partly disappeared, the old ones remained and some of them slightly changed their outflow characteristics, but the main portion could still be used for thermal spa purposes. Kluge (1858) described the important earthquakes of the years 1855 and 1856 in his article "Die Reaktion des Erdinnern gegen die Erdoberfläche in den Jahren 1855 und 1856". He too recognised significant changes in the thermal spring behaviour in Bursa caused by these large earthquakes. But without the knowledge of plate tectonics at that time, he postulated an active zone of elevated seismicity parallel to the equator going around the world in the northern hemisphere.

Based on observations of rocks exposed at the surface which show fractures as well as ductile deformations, new conclusive questions were established. If we can assume fluid circulation within the crust, how deep do these fluids circulate and how deep do the fractures reach? And further, is the whole crust fractured or where does a so-called ductile zone begin? Is fracturing the only generating process for earthquakes? During the year 1912, Frank D. Adams wrote an article entitled 'An experimental contribution to the question of the depth of the zone of flow in the Earth's crust'. According to him, 'this subject has an interest and importance, not only as bearing many problems in geology, but also on one question at least of direct importance in mining, namely, that of the depth to which mineral bearing fissures may extend in the Earth's crust'. This depth range was thought to be a gradual zone, where the brittle behaviour changes into a ductile one. The model of a brittle, fractured upper crust with a change in rheology at greater depths to a zone of flow (ductile regime) was also proposed by the geologist Albert Heim, 30 years previously, from observations in the Swiss Alps. Finally, the main conclusions of Adams were the possible presence of fluids up to depths of 11 miles below the surface and the importance of water in the crust for the release of earthquakes.

Methods used in the MARMARA Poly-Project

This collection of historical quotations outlines the complex interplay between active tectonics, groundwater circulation, seismicity and the thermal state of the Earth's crust. Modern reflections speak about interrelations of physical, structural and chemical factors which control faulting of the crust. Main controlling factors are probably geological conditions, geophysical parameters or geochemical composition (structural orientation, rock fabric, grain size, strain localisation, age and total displacement of fault zones, temperature, stress, strain rate, crack size, fault roughness, porosity, fluid pressure, permeability, mineral assemblage, pore-fluid chemistry).

Data concerning these factors had to be collected in NW Turkey, this forcing various research disciplines to carry out detailed observations. The geoscience endeavour was therefore to combine the results of individual disciplines into an overall picture, a multidisciplinary synthesis. In the following, we shall try to explain some of the key research aspects of the different single disciplines, as well as give a short outlook on the multidisciplinary approach.

Geology The geological study serves as a basis for all other disciplines: a thorough comprehension of local and regional tectonic/geological evolution is essential. Special attention should be paid to fault phenomena of the neotectonic stress regime, including the deformation behaviour of different rock types. However, tectonic events and structures older than Miocene were also studied in detail, as they might have had an influence on the circulation patterns of normal or thermal groundwater, on the orientation of neotectonic disturbances and the modern stress field. From these tectonic studies, a better understanding of the actual crustal motion pattern was obtained, which will be compared with the geodetic and seismic observations.

Hydrogeology The hydrogeological study tries to explain the existence of thermal and mineral waters within the local normal groundwater circulation system. Every step of groundwater evolution between infiltration and exfiltration area needs to be reconstructed. All of the different processes of water evolution, such as rock-water-gas interaction, gas exchange, heating and mixing, must be the subject of thorough investigation. The interpretation of thermal and mineral waters as a product of groundwater evolution requires a detailed study of the local normal groundwater system.

Geodesy Applying GPS (Global Positioning System) technology, large geodetical networks over distances of hundreds of kilometres can be constructed and measured in short time. Second and third measurements of the same network after several years allow the interpretation of coordinate differences by geodynamic explanations. The motion of upper crust blocks due to plate tectonics is characterised by the calculated velocity field and strain rate pattern.

Geothermics Terrestrial heat flow as a main boundary condition of geodynamic processes is calculated using the following two observable quantities. First, a geothermal gradient is determined by geophysical logging of existing drillholes; second, thermal conductivity of the main lithologies is measured on rock samples in the laboratory. Interpolation of the irregularly distributed point determinations leads to the regional surface heat flow field. Furthermore, numerical modelling of coupled thermohydraulic processes is able to describe groundwater flow and the special conditions for the presence of thermal springs. Geothermal methods, therefore, provide a powerful tool for investigating deep-reaching groundwater circulation systems on the one hand, and to interpret the spatial pattern of seismicity in terms of crustal rheology on the other.

Seismology Distinct seismoactive structural features have to be defined to establish the relationship between local tectonics and seismicity, based on the precise distribution of microearthquakes and the types of observed focal mechanisms. This allows scientists to gain insight into the present strain and stress state of the crust.

Gravimetry The Earth's gravity field and its anomalies indicate mass lows and highs. Significant anomalies can be interpreted as thinning or thickening processes of the crust or lithosphere. These findings will be major indications for a possible extensional neotectonic process.

The picture of the present neotectonic activity and its influence on different observable quantities such as seismicity, groundwater circulation and terrestrial heat flow should be presented. This has to be performed through a combination of all research results and working hypotheses of the above-mentioned single disciplines.

The first step of the *multidisciplinary synthesis* should integrate the different geological research results of the local areas (stratigraphy, structural geology) into an overall valid model of the geological evolution of the Marmara region. This evolution ends with the definition of the present neotectonic activity and its surface appearance (e.g. faults). Furthermore, so-called "Key observable quantities" of other disciplines, e.g. present day terrestrial heat flow density or 3D seismicity distribution, have to be defined and investigated.

The second step is mainly concerned with the interpretation of these key observable quantities. This involves the definition of physical and chemical models and processes. Finally, a combination of these models can lead to answers for some of the following questions:

What is the influence of older tectonic and geologic structures on the modern neotectonic activity?

Are the present faults completely newly developed or do they follow mainly old structures?

The occurrence of thermal springs is bound to which kind of faults and what are the conditions to bring about thermal water outflow at surface?

How deep do these waters circulate and is the historically supposed triggering effect on the release of earthquakes quantifiable with modern measuring methods?

Do we recognise any different levels of the Earth's crust or the lithosphere?

Which processes may be involved with the release of earthquakes and where do we observe them?

What is the interpretation of repeated GPS measurements at the Earth's surface in the context of plate tectonic motions?

General map of NW Turkey (Figure 1)

The region covered by this map has a size of approximately 100,000km^2. A first look at the map shows the dominating features of the Marmara sea and the city of İstanbul, the historical Byzantine capital Constantinople. The important Black sea – İstanbul – Marmara sea – Aegean sea – Mediterranean sea trade route crosses the investigation area of the project from northeast to the southwest. Modern İstanbul and the Bosporus symbolises the bridge between Europe and Asia. The second largest city is Bursa with over 1 million citizens. Small towns with a history dating back to ancient times are Bergama (Pergamon: Hellenistic and Roman province capital, 3rd to 1st century BC) and also İznik (Nicea: city of the first Christian council, 7th century AD). The Dardanelles, connecting the Marmara and the Aegean seas, are well known today under the ancient Greek expression Hellespont, where nearby probably the most famous ancient city Troia was discovered on the Biga peninsula.

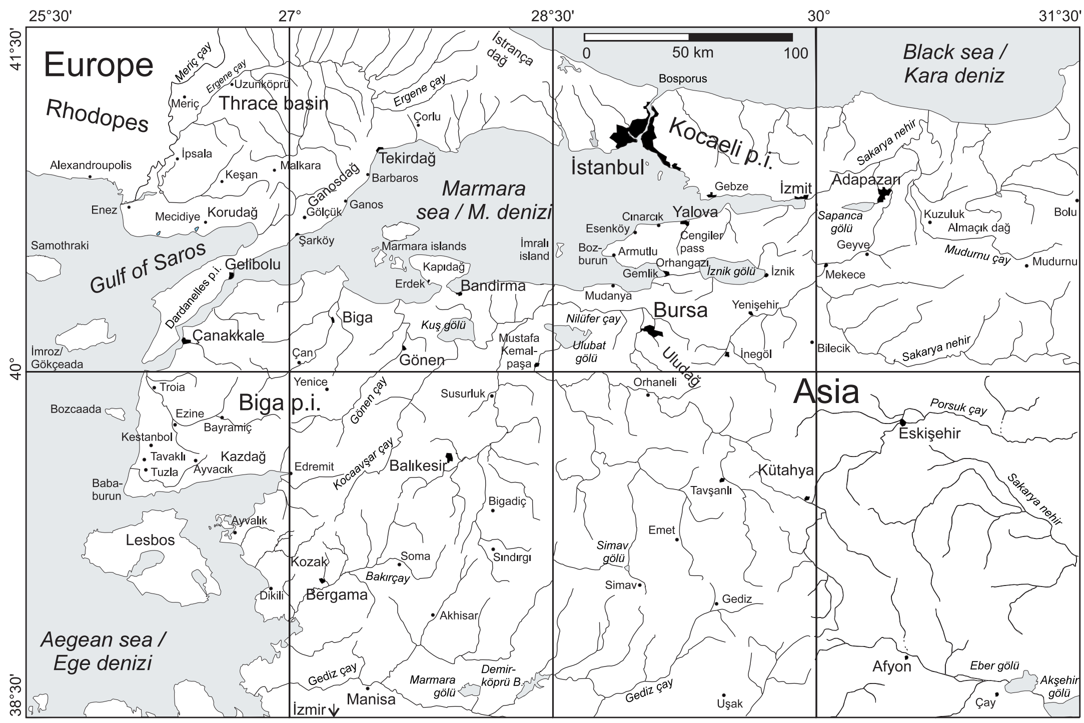

Figure 1: *Geographical map of the Marmara sea region*

Numerous rivers and some large freshwater lakes are characteristic for the region. The abundance of water serves for irrigation of large agricultural plains. Very significant are the river systems of the Ergene çay in the Thrace basin area, of the Sakarya nehir, as well as the Gönen çay. Famous agricultural areas are the plains of Bursa, the plains between the Kuş and Ulubat lakes, the plains in the vicinity of Biga and Bergama, as well as the plains of İzmit-Adapazarı. Most of the area, however, is hilly, relief being moderate, without sharp cut ridges. Prominent are two large massives, Kazdağ at 1710m (ancient Ida) and Uludağ at 2543m (ancient Bythinian Olymp). Some of the most commonly used Turkish words with a geographical meaning are given below in Table 1.

English	Turkish
Marmara sea	Marmara deniz
Black sea	Kara deniz
Aegean sea	Ege deniz
Mediterranean sea	Akdeniz
plain	ova
island	ada
mountain	dağ
city	şehir, kent
village	köy
spring	kaynak
thermal spa, hot spring	kaplıca, ılıca
hot water	sıcak su
river	nehir
brook, creek	çay, dere
lake	göl

Table 1: Most commonly used Turkish words with a geographical meaning

Topography and bathymetry of NW Turkey (Figure 2)

Due to moderate erosion and deep-reaching weathering processes, the topography generally is quite smooth and rises from west to east, reaching 2000m a.s.l. in some points. The bathymetry is dominated by basins over 2000m deep in the Marmara sea, the Black sea (only partly visible) and the gulf of Saros.

Topography and especially bathymetry reveals first impressions of a possible influence of the neotectonic activity of the NAFZ. The deep basins in the Marmara sea and the gulf of Saros show sharp borders and trace the continuation of the NAFZ to the west and into the Aegean sea. This picture demonstrates that the clear strike-slip regime of the NAFZ has changed into a combination of strike-slip and extension. The Gelibolu peninsula and its prolongation to the northeast interrupts the connection between the two deep troughs as a topographical local high. At this point, a local zone with a compressional stress regime can be supposed. The northern zone of the NAFZ shows the most significant influence on topography.

Valleys and rivers in the eastern part of the research area show an enhanced east-west directed appearance. The Sakarya river (compare Figure 1) and its valley structure especially indicate a right lateral displacement of the southern part versus the northern part along the NAFZ. Furthermore, in the region south of the E-W oriented plain connecting the Kuş and Ulubat lakes, the landscape is dominated by NE-SW oriented valleys and ridges. From Edremit to the southeast, large plains or depressions oriented W-E to WSW-ENE become frequent, which likely can be brought into correlation with the actual Aegean extensional stress regime, indicating a NNE-SSW instead of a N-S directed extension in this area.

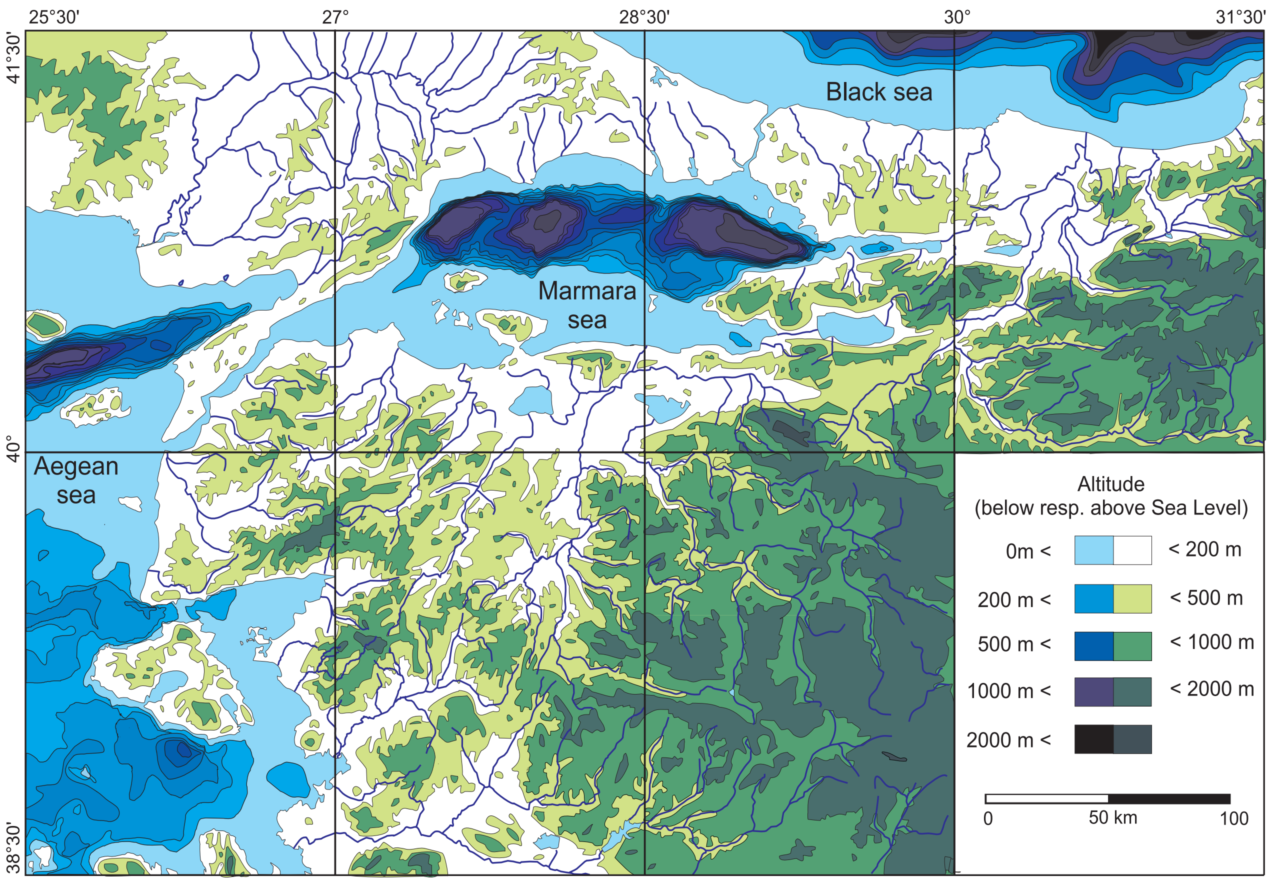

Figure 2: Topographic and bathymetric map

Investigation areas of the research disciplines (Figure 3)

A total of 9 geological working areas were differentiated and these areas are distributed over the entire Marmara sea region: Kuzuluk in the east directly located on the NAFZ, Bursa, Yalova-Armutlu-Gemlik, Yenice-Gönen, Tuzla-Kestanbol, Bergama-Kozak, Şarköy, Tekirdağ and Uzunköprü. Except Şarköy, Tekirdağ and Uzunköprü north of Marmara sea, all these regions show significant thermal spring occurrence and were investigated by the Hydrogeology group, too.

Five GPS networks were set up, directly related to the geological research areas. The measurement points were selected in collaboration with the geologists on relevant rock underground. All five networks together were combined into a unifying large geodetic network to determine the overall displacement field.

Geothermal research was mainly driven by the search for reliable drillholes which could be used for heat flow determination. These drillholes, distributed over the whole Marmara sea region, are necessary for a regional interpretation. Furthermore, thermal spring modelling studies were concentrated in the region of Bursa and Yalova-Armutlu-Gemlik, where a MARMARA project seismological network was installed. A large and frequent thermal spring occurrence, high seismicity and distinctive distribution of active faults were favourable here. On the other hand, the well developed infrastructure of the area aided our field activities immensely.

Not indicated on Figure 3 but covering the whole Marmara sea region on land are Turkish measurements of Bouger gravity anomalies. Unfortunately, offshore data are very rare for all disciplines involved in our project but would contribute precious significant knowledge. The only relevant offshore data at present are recent seismic investigations of the sediments in the Marmara sea (Wong et al. 1995, Ergün and Özel 1995) and some geothermal measurements in oil wells.

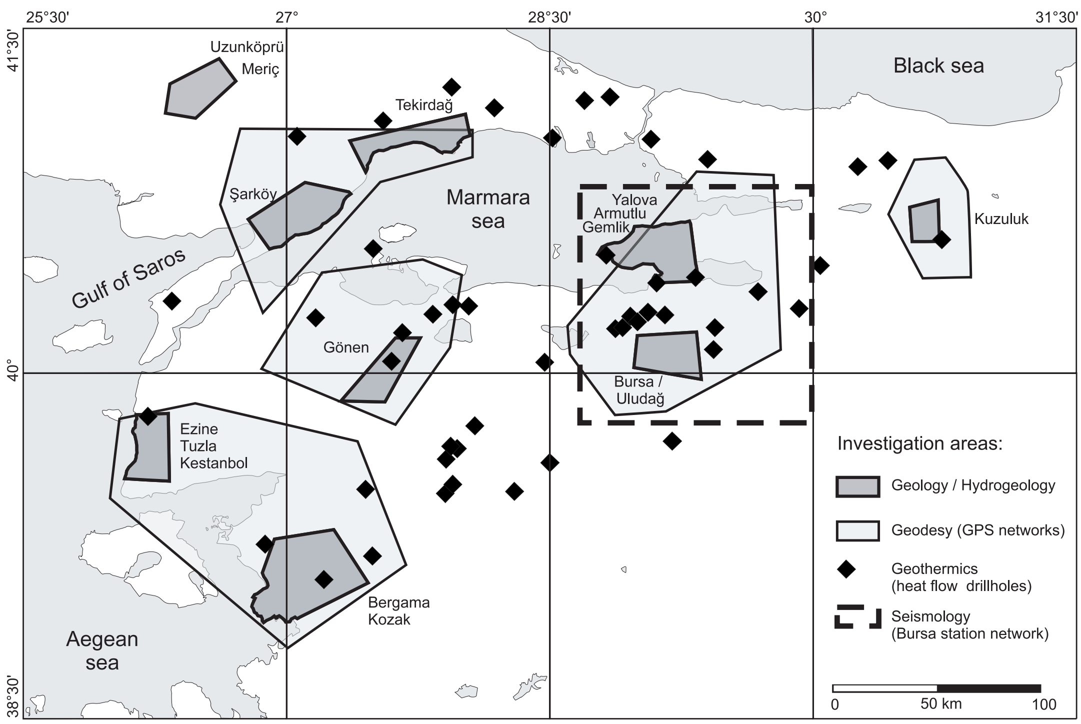

Figure 3: *Map of investigation areas of the MARMARA Poly-Project.*

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THEME 2

Plate tectonics

Plate tectonic situation in the Anatolian-Aegean region

STEPHAN MUELLER, HANS-GERT KAHLE AND AYKUT BARKA

Abstract

The Eastern Mediterranean region marks the tectonically most active part of the broad transition zone between the African/Arabian and Eurasian plates. Its present activity is clearly marked by a most conspicuous earthquake belt surrounding the Aegean Sea. While this belt follows the subduction zone along the Hellenic arc in the Ionian and Aegean Seas it forms a triangle in the central and southern part of western Anatolia. The various regional features associated with the seismotectonic framework indicated by the seismicity are discussed from the Near East (Anatolia) through the Aegean Sea to the Ionian Sea. The crustal and upper mantle structure is described by using p- and s-wave tomography sections. The dynamic processes are elucidated by examining heat flow data, helium distribution in crustal fluids and recent space geodetic results. The current rates of crustal deformation provide a detailed pattern of vectors constraining the westward motion of NW Anatolia to 22mm/a, relative to Eurasia.

Introduction

The tectonic activity in the Eastern Mediterranean is caused by the very complex lithospheric regime which evolved since the break-up of the Tethys belt and which can still be surmised from the present bathymetry and topography of this region. In a simplified scheme the formation of the present-day tectonic framework can be understood as a consequence of the counter-clockwise rotation of the African plate since the last 92m.y. which has led to a lithospheric shortening rate increasing from west to east. For the last 10 to 9m.y. the Eurasian / African plate contact is to a large extent under SE-NW directed compression (Dewey et al. 1989). This paper is intended to give an overview of the current knowledge of the plate-tectonic setting of this region. It also describes the apparent relationship between the deep structure of the lithosphere-asthenosphere system, deduced from seismological data, with the kinematic field derived from space geodetic observations and with the present stress pattern, as well as with heat flow estimates and helium isotope distribution.

Seismicity and seismotectonics

The earthquake activity observed around the Aegean Sea comprising large parts of Greece and Western Anatolia has been the most conspicuous geodynamic phenomenon in the Eastern Mediterranean region (Fig. 2) during this century (Ambraseys and Finkel 1991). At a first glance the clearest seismicity feature is associated with the Hellenic arc forming an almost perfect "semicircle” from the Ionian islands in the west to the central part of western Anatolia in the east, with endpoints at about 38°N / 20°E and 38°N / 32°E. A closer inspection reveals, however, that southwest of the Peloponnesus and particularly south of the island of Crete the Hellenic arc is transected by clusters of earthquakes which are oriented perpendicular to the arc (cf. also Fig. 1). Noticeable is also the clear offset of the seismicity of about 220km to the NNW between the islands of Karpathos and Rhodes which is probably due to an irregularity in the crust and upper mantle.

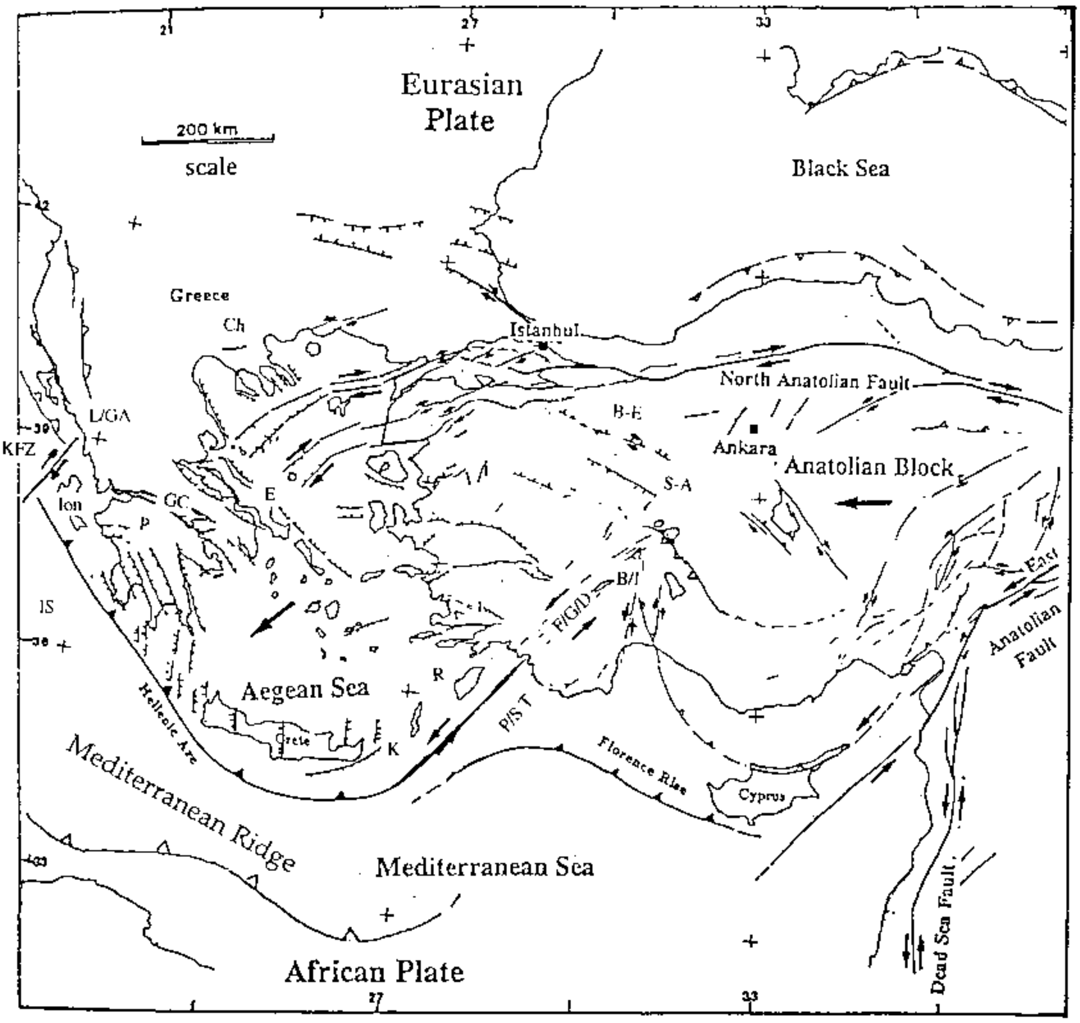

Figure 1: *Tectonic sketch map of the Aegean-Anatolian region, after Barka (1992). B-E: Bursa – Eskişehir fault, S-A: Simav – Afyon fault, F/G/D: Fethiye / Gökova – Burdur / Dinar zone, B/I: Burdur / İsparta, K: Karpathos, Ion: Ionian islands, P: Peloponnesus, R: Rhodes, KFZ: Kephalonia fault zone, P/S T: Pliny / Strabo trench, IS: Ionian Sea, L/GA: Levkada / Gulf of Arta, GC: Gulf of Corinth, E: Evia, Ch: Chalkidike.*

North of the Hellenic arc, proceeding from west to east, the right-lateral Kephalonia Fault Zone (KFZ) dominates the activity in the Ionian Sea (Anderson and Jackson 1987). The maximum strain values (180 nanostrain/a) were found in the area of Levkada / Gulf of Arta, and the strain energy reaches a maximum of 0.004J/m^3 (Müller 1995). The central part of Greece is characterised by two parallel west-east trending seismicity belts: a southern one along the Gulf of Corinth and a northern one from the Gulf of Arta to the Gulf of Evia. Three clear SW-NE striking earthquake lineaments can be traced across the northern Aegean Sea (Fig. 2). They can be considered as southwestward prolongation of the seismicity of the North Anatolian Fault Zone (NAFZ). The northernmost belt extends from Cape Kanastraion at the tip of

Kassandra peninsula (Chalkidike peninsula) into the Gulf of Saros with the three most recent larger earthquakes, namely 1975 (Magnitude M = 6.7), 1982 (M = 7.1) and 1983 (M = 6.9). Between central Evia and the Dardanelles a second belt can be located with the strongest recent earthquake 1968 (M = 7.2). Similarly, a third zone is identifiable between southern Evia across Lesbos island towards the Gulf of Edremit; two large earthquakes happened there in 1981 (M = 7.2 and 6.5).

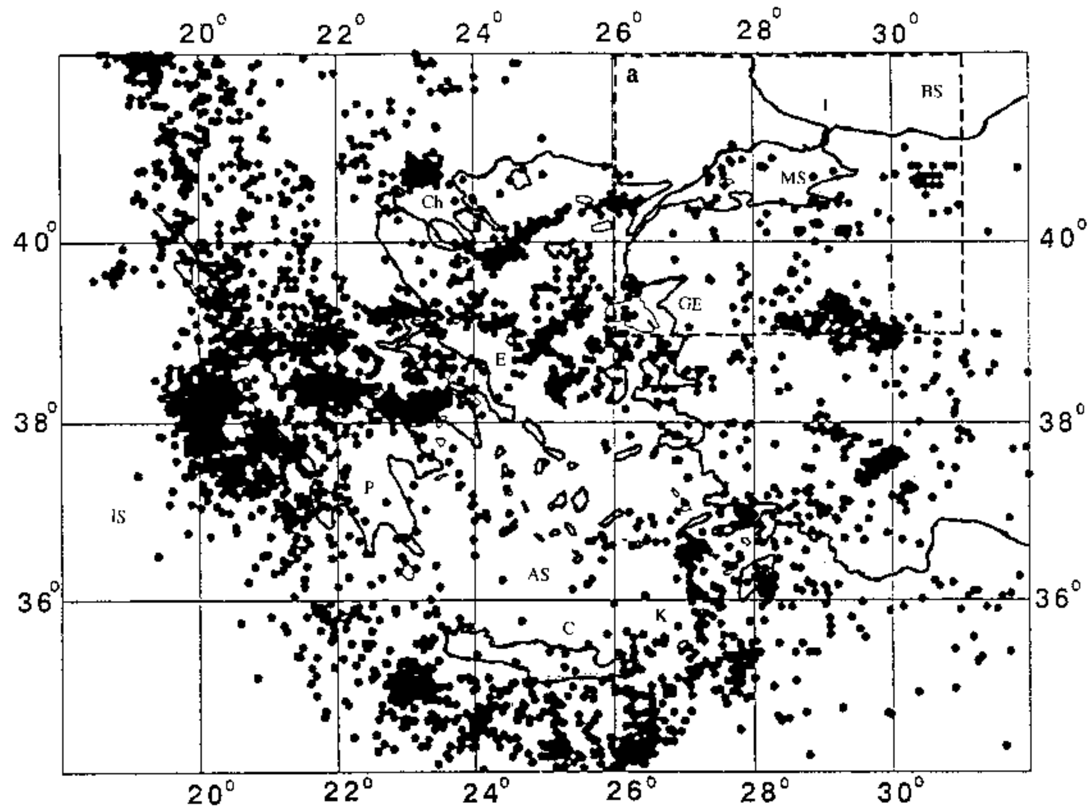

Figure 2: Seismic activity in the Aegean Sea and neighbouring regions reported by the USGS in the period 1963 to 1987, probably complete down to magnitudes 4.5. Inset (a) shows the seismic activity in the Marmara Sea region, after Ambraseys and Finkel (1991). IS: Ionian Sea, AS: Aegean Sea, MS: Marmara Sea, BS: Black Sea, C: Crete, R: Rhodes, Ch: Chalkidike, K: Karpathos, P: Peloponnesus, E: Evia, GE: Gulf of Edremit, I: İstanbul.

The seismicity in westernmost Anatolia for M > 4.5 is considerably lower than that in the northern part of the Aegean. At this point it should be mentioned that the moderate seismic activity in the Marmara Sea region is being dealt with in the context of neotectonics (Barka this volume) which is enlarged especially in the region around the city of Bursa (Sellami et al. this volume).

South of Bursa (at about 39°N) a striking seismicity feature is located. It has the shape of a NW-SE oriented extended active cluster from the small town of Sindirgi (NE of Akhisar) as far as Cay (SE of Afyon) (Fig. 2) which is obviously related to the Simav-Afyon fault zone and not to the Bursa-Eskişehir fault which has not been significantly affected by major earthquakes in the recent past. At its western end this zone is cut by a SW-NE directed seismically moderate lineament which goes past the Mudanya (NW of Bursa) region, the Gulf of Gemlik and terminates at Yalova. Further south segments of the seismic activity associated with the broad Fethiye – Burdur zone (F/G/D in Fig. 1) of parallel faults can be identified. They are most likely affected by the offset of seismicity between the islands of Rhodes and Karpathos as has been mentioned earlier. Also clearly visible in Fig. 2 is the SE-NW oriented short active segment between the Burdur / İsparta and the Dinar regions. Details have recently been published by Eyidoğan and Barka (1996). In summary it can be stated that the recent and present seismicity in the Aegean-Anatolian region is much more complex than it appears from descriptions in the current literature.

Kinematic fault plane solutions (FPS) of earthquakes provide insight into the processes and causes associated with the seismicity pattern described in the previous section and the tectonic framework outlined in the first section. They are illustrated by lower hemisphere projections of the seismic rays traced back from distant observation stations to the sphere which encompasses the earthquake focus. In Fig. 3b the principal stresses $\sigma_1 > \sigma_2 > \sigma_3$ are indicated (from left to right) as thrust motion (reverse faulting), lateral strike-slip motion (non-unique, could either be right or left lateral), and rifting (normal faulting). “Pure” deformations as described in the previous examples are usually rare. Mixed mechanisms are the more likely case. For the region under consideration (Fig. 3a) there are quite a number of fault plane studies available (see e.g. Kiratzi and Papazachos 1995). The distribution of focal mechanisms of the stronger shallow earthquakes shows thrust faulting along the Dalmatian coast of Croatia and Montenegro. The main shock and the largest aftershock of the 1979 Montenegro sequence exhibit almost pure thrust mechanisms with nodal planes striking parallel to the coast. This belt of thrust faulting continues south along the coastal region of western Albania and also along the westernmost part of the mainland of Greece. It can be assumed that the above-mentioned zone of thrust faulting is due to the collision of two continental lithospheric plates, i.e. the Adriatic with the Eurasian plate. There is no evidence of subduction along this part of the plate boundary.

Thrusting continues southward along the coastal regions of Northwestern Greece up to the island of Kephalonia. The rather frequent earthquake activity there revealed dextral strike-slip movement on SW-NE striking nodal planes. This belt of dextral strike-slip faulting is generally considered as the western termination of the Hellenic subduction zone. Along the convex side of the Hellenic arc the distribution of focal mechanisms (with depths less than 40km) indicates the existence of low-angle thrust faulting with the shallow dipping plane ascribed to the active fault plane in the subduction process (McKenzie 1978). The trend of the compressional (P) axis is perpendicular to the Hellenic arc in its western and southern part, keeping the same pattern to become parallel to the arc in the Pliny and Strabo trenches (with left-lateral strike-slip motion) at the eastern end of the arc.

The focal mechanisms of intermediate-depth events, i.e. with foci between 40 and 100km depth, all in the southern Aegean, north and south of Crete, are characterised by thrust faulting with a significant strike-slip component – not shown in Fig. 3a (Papazachos et al. 1991). It seems that the shallow seismicity along the external part of the Hellenic arc is coupled to the deeper-reaching intermediate activity. In this depth range all the big earthquakes (with magnitudes up to M = 8) occur. At a depth of around 100km the slope of the dipping Benioff zone increases from 23° to 38° (Papazachos 1990). As can be seen in Fig. 3a normal faulting is dominating most of the Greek mainland as well as the western part of Turkey. The study of recent seismic sequences has illustrated that the normal faults with predominantly west-east striking nodal planes are in most cases listric faults limited to relatively shallow depths (10 to 15km).

Central Greece and in particular the region north of the Gulf of Corinth is governed by extensional focal mechanisms which interrupt the right-lateral strike slip regime between the Kephalonia fault in the west and a corresponding segment across the northern Aegean in the northeast. A joint interpretation of the neotectonic features (Fig. 1) and the seismotectonic pattern (Fig. 3) suggests that this wide extensional zone in central Greece is actually representing a large-scale transtensional "pull-apart" structure as has been proposed some time ago by Reuther et al. (1993). Along the northernmost branch of seismicity in the northern Aegean (Fig. 2) a change from dextral strike-slip to normal faulting is observed when the Gulf of Saros is approached. This explains the differential rifting and thus the opening of the gulf.

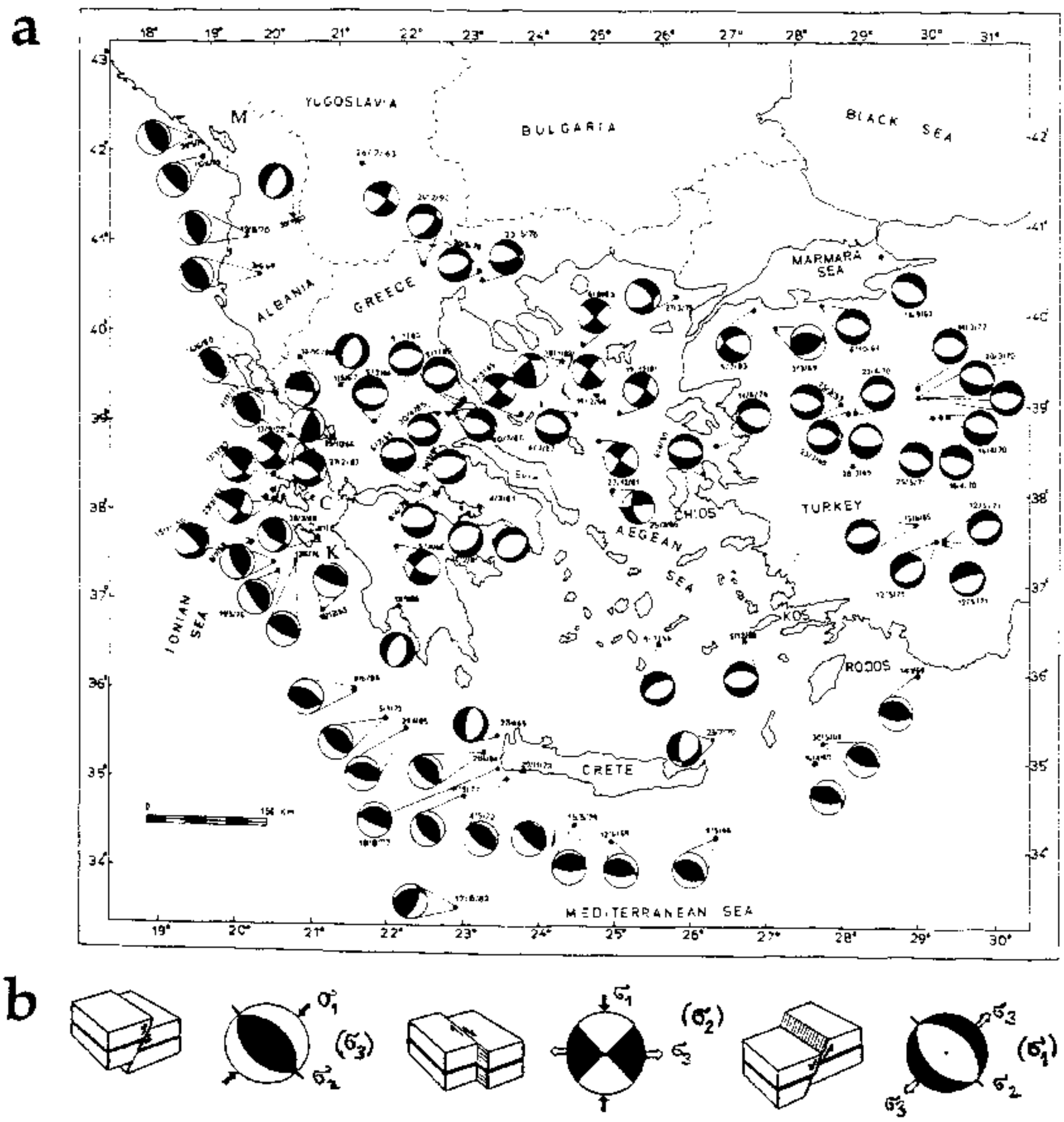

Figure 3: The distribution of the focal mechanisms. (a) The Aegean area and the surrounding lands, after Kiratzi and Papazachos (1995). (b) Fault plane solutions and respective fault models. M: Montenegro, C: island of Cephalonia, K: Karpathos.

As has been mentioned before the most conspicuous seismicity feature in Western Anatolia is obviously associated with the Simav-Afyon fault zone (Fig. 2). It is characterised by normal faulting and a sporadic right-lateral strike-slip component with predominantly NNE oriented nodal planes (Fig. 3a). The same focal mechanism pattern was listed in a catalogue by Udias et al. (1989) and has been refined on a much more detailed scale by Zanchi and Angelier (1993). A somewhat different situation is encountered in the broad Fethiye – Burdur tectonic zone (Eyidoğan and Barka 1996) where the normal faulting is more distributed with a strongly pronounced left-lateral strike-slip component (cf. Fig. 1). Based on this evidence it can be surmised that the central and southern part of Western Anatolia forms a triangle which is pulled out to the west and at the same time possibly rotated counter-clockwise as indicated by the shape of the gulf inlets along the west coast of Anatolia.

Crustal and upper mantle structure

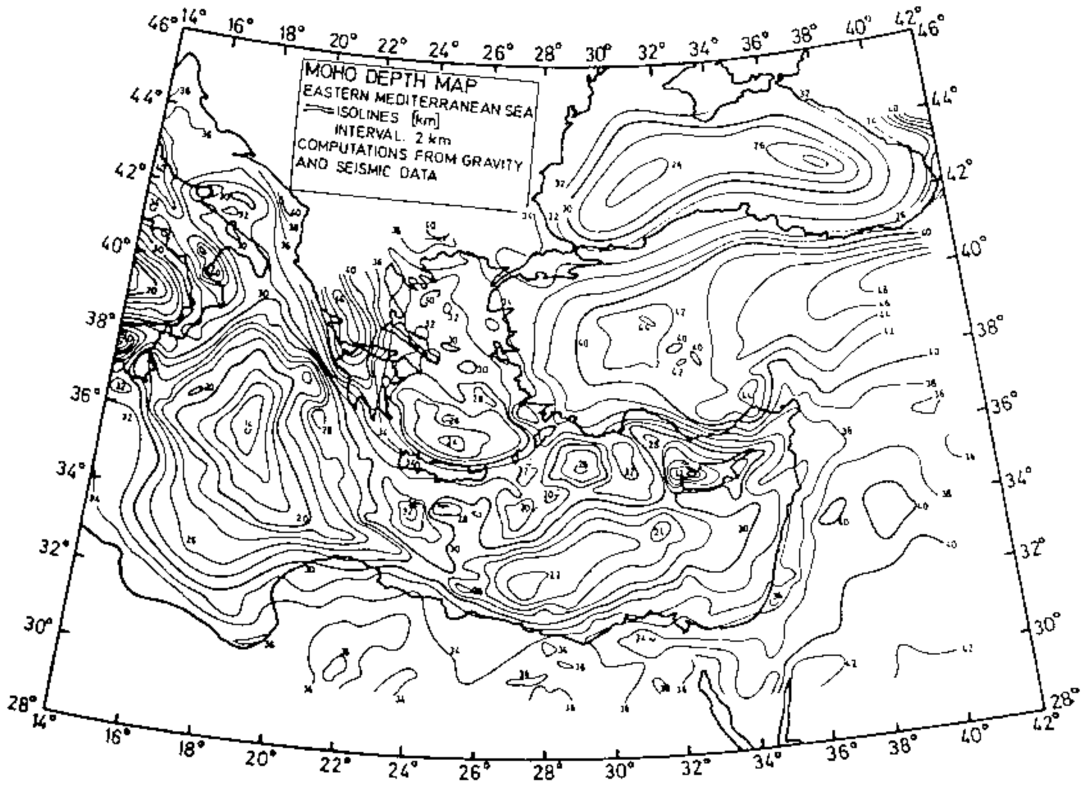

Figure 4: *Contour map of depth (in kilometers) to the crust-mantle boundary, i.e. the Moho discontinuity, in the Eastern Mediterranean and adjacent regions (after Makris und Stobbe 1984). The Moho depth map has been deduced from seismically constrained gravity data.*

From the presently available data the Aegean region is underlain by a thinned continental crust, having a mean thickness of 28-32km and a minimum thickness of 24km north of Crete. Beneath the Peloponnesus and Western Anatolia the continental crust reaches a maximum thickness of about 40km (Fig. 4), (cf. Makris 1978, Makris and Stobbe 1984).

The upper mantle of the European-Mediterranean region has been the subject of many recent tomographic studies with the aim to determine the velocity-depth distribution of seismic p- and s-waves in an attempt to obtain quantified images of the lithosphere-asthenosphere system. Our knowledge about the variations in the physical state and chemical composition of the upper mantle is still rather limited. The availability of accurate velocity data for both p-waves and the geophysically more significant s-waves would provide answers to the question whether the observed velocity information are primarily caused by regional stress conditions, temperature variations (cf. Yan et al. 1989) or differences in composition. Most likely it is an interaction of all these factors, particularly in complex regimes, such as the Anatolian-Aegean region.

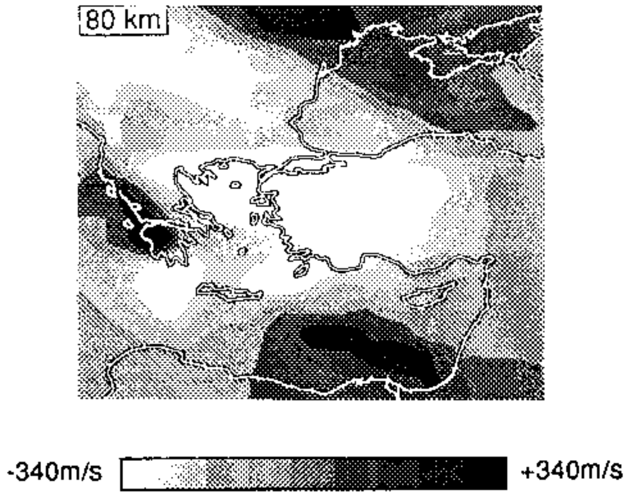

Figure 5: *Horizontal s-wave tomographic cut (at 80 km depth), after Zielhuis (1992).*

The most comprehensive study so far of the three-dimensional (3-D) s-wave velocity field below Europe based on delay-time and waveform inversions has been carried out by Zielhuis (1992). Assuming the reference values of Yan et al. (1989) for the s-wave velocity and temperature at 150km depth (4.5km/s and 1300°C, respectively) which are representative for the eastern European craton, the low s-wave velocities in the depth range from 80 to 140km beneath the Pannonian basin, the northern Aegean and the Anatolian region (Fig. 5) can only be explained by partial melting in the asthenosphere. It should be noted here that the p-wave velocity model of Spakman et al. (1993) with variations of 2% correlates reasonable well with respect to the sign of the s-wave anomalies, but the amplitudes of the s-wave velocity variations are significantly larger (7.5%).

A vertical section to a depth of 700km extending from central Greece to the Crimea (Fig. 6, after Zielhuis 1992) illustrates the subducting lithospheric slab in the Hellenic collision zone and the adjoining low-velocity asthenosphere reaching to a depth of 140km between the northern Aegean Sea, Thrace and the Black Sea coast (Fig. 6). That part of the tomographic model is the one with the highest resolution, because there the coverage by s-wave paths has the highest density.

For the central Mediterranean region also an estimate of the present p-wave velocity structure exists derived from delay-time tomography (Spakman et al. 1988 and 1993). These tomographic results describe the three-dimensional (3-D) mantle structure from the surface down to a depth of 800km and provide a qualitative handle on the possible causes of the complicated velocity field. In Fig. 7a the recent seismic activity between the Tyrrhenian sea and Western Anatolia is depicted illustrating once more the same basic seismicity features as shown in Fig. 2.

The vertical cross-section of Fig. 7b clearly shows the earthquakes associated with the Tyrrhenian (Calabric) and Hellenic subduction zones which are superimposed on the p-wave tomographic velocity structure (De Jonge et al. 1994).

A surprising new tomographic feature is the deep-reaching mantle plume in the Ionian Sea which separates the two subduction slabs and is capped by a high-velocity lid in the upper part of the mantle (above 200km depth). The seismic activity in the central Aegean and Western Anatolia is restricted to the lithosphere, but at the eastern end of the mantle profile in Turkey a clearly defined subduction zone seems to exist which dips westward reaching to a depth of about 200km.

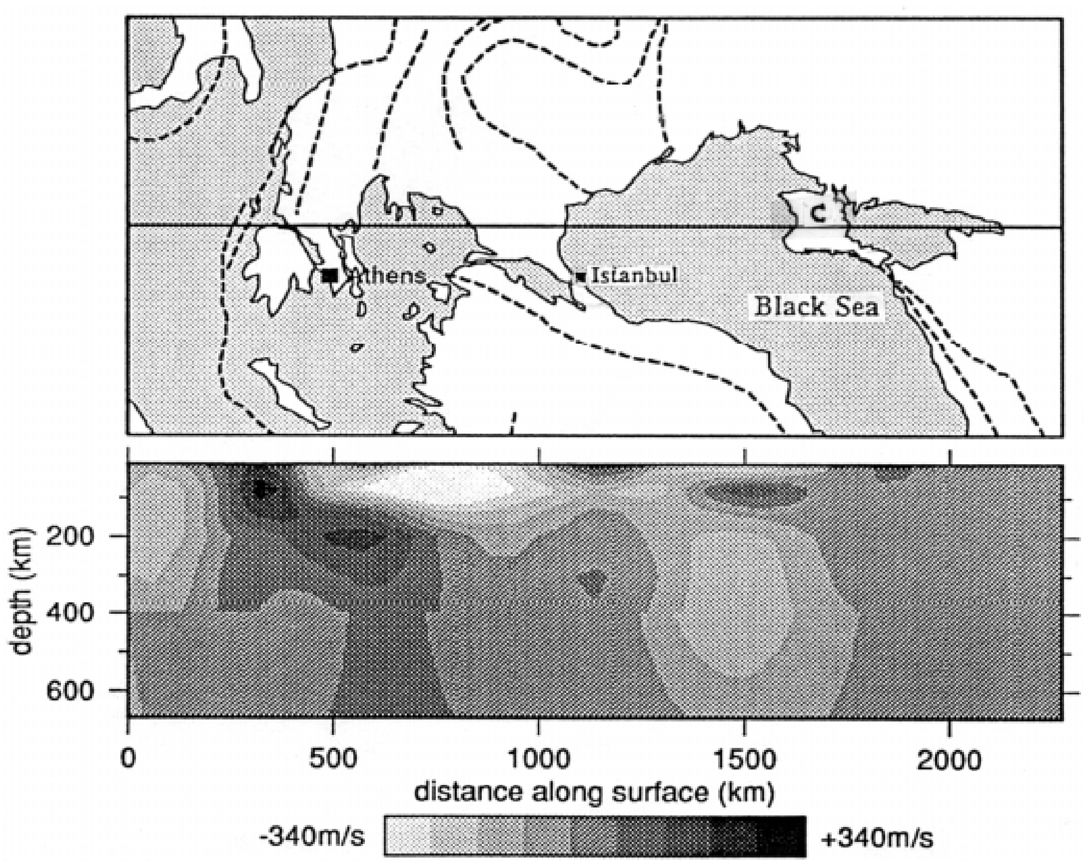

Figure 6: *Vertical cross section by s-wave tomography (down to 700km depth), after Zielhuis (1992). C: Crimea.*

The heat flow map presented in Fig. 8 (Tezcan and Turgay 1991) is based on 204 not evenly distributed temperature soundings in oil, gas and coal wells (Thrace and SE-Turkey) and especially in Western and central Anatolia in deep geothermal wells. Since there are no in-situ thermal conductivity measurements available a typical standard value of $2.1 Wm^{-1}K^{-1}$ has been used in all the heat flow calculations. In Fig. 8 it can be seen that the general level of heat flow in Western Anatolia may be much higher (100 to $120 mWm^{-2}$) than that in the Eastern Mediterranean Sea and the Black Sea with values of 20 to $30 mWm^{-2}$. Also the heat flow in the north Aegean trough, the Biga peninsula and the “horst and graben” structures (metamorphic core complexes, misleadingly called “massifs”) in the central part of Western Anatolia points to elevated heat flow values if compared with the remainder of the Turkish territory.

If an attempt is made to relate the pattern of heat flow to the observed seismicity (cf. Fig. 2) a strikingly similar picture becomes visible which exhibits the same structural “triangular” configuration. It also coincides with the region of increasing crustal thickness (from W to E) and lower average crustal velocities as well as a decreased sub-Moho (p_n) velocity, indicating that the high heat flow is not only caused by a crustal contribution, but that it must also contain a sizeable mantle component.

Additional evidence of a strong crust-mantle interaction in Western Anatolia is provided by the results of measurements aimed at a determination of the $^3He/^4He$-isotope ratio in crustal fluids (Gülec 1988). Samples from natural springs and one drilling hole were collected and analysed. The majority of samples are from groundwater discharges associated with the faults bounding the well-mapped graben structures in Western Anatolia. In Figure 3 of the

Poly-Project synthesis (Theme 6 this volume) sampling locations in NW Anatolia are shown with the measured He-isotope ratios. It is customary to express the He-isotope composition relative to that of a standard atmosphere, i.e. $(^3He/^4He)_{sample} / (^3He/^4He)_{atm} = R / R_a$.

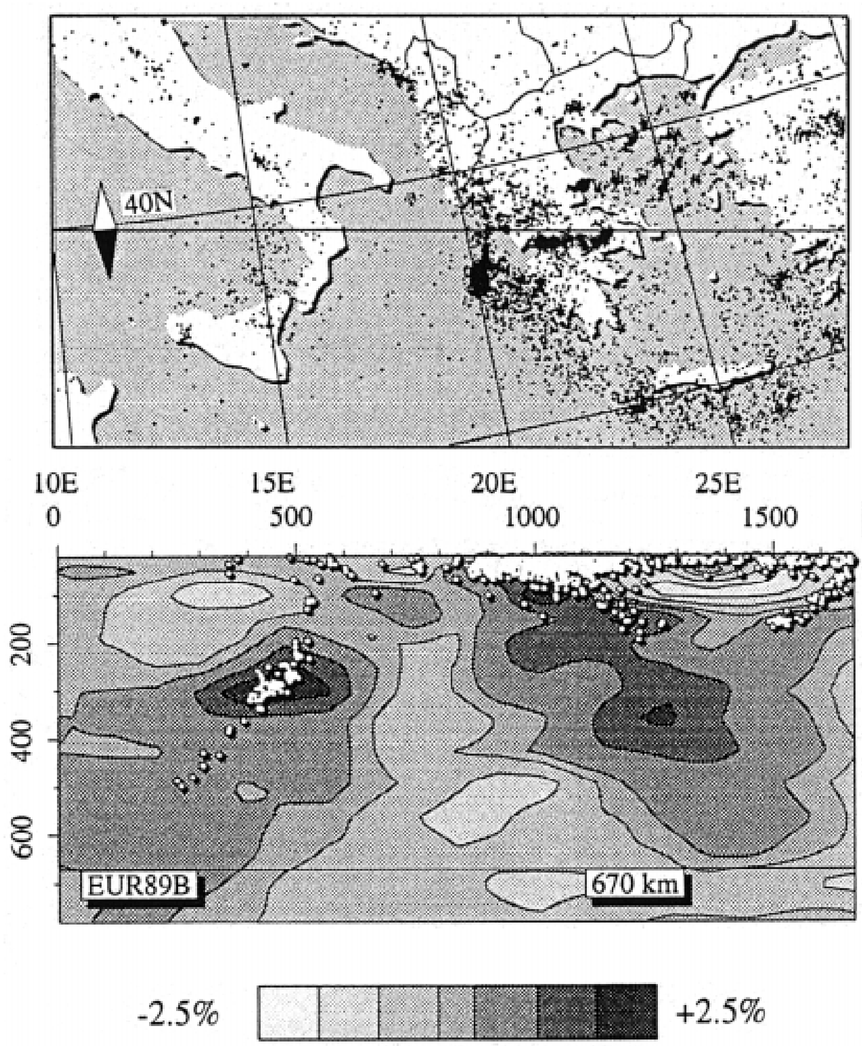

Figure 7: *Vertical section by p-wave tomography crossing both the Tyrrhenian (left) and Hellenic (right) subduction zones (down to 700km depth), after De Jonge et al. (1994).*

Detailed geophysical surveys carried out in some continental rift systems, such as the Rhinegraben, the east African, Rio Grande, Baikal, and Oslo rifts (cf. Olsen 1995), have revealed the presence of anomalous zones of low seismic velocities in combination with high electrical conductivity within the crust and uppermost mantle. These anomalies have been interpreted as magma accumulations assuming that these partial melts also play an efficient role in transporting mantle-helium e.g. into the Western Anatolian crust, where extension is prevailing since about Upper Miocene time, i.e. in the last 20m.y. Since mantle helium is widely distributed in the western part of Turkey extensive melt additions to the lithosphere are apparently taking place. The fault structures have presumably aided the escape of mantle helium through crustal channel ways to the surface. There is no obvious evidence for a related distribution between mantle helium and surface volcanism which suggests that helium is degassing from plutons emplaced deeper in the crust and upper mantle.

Dynamic processes

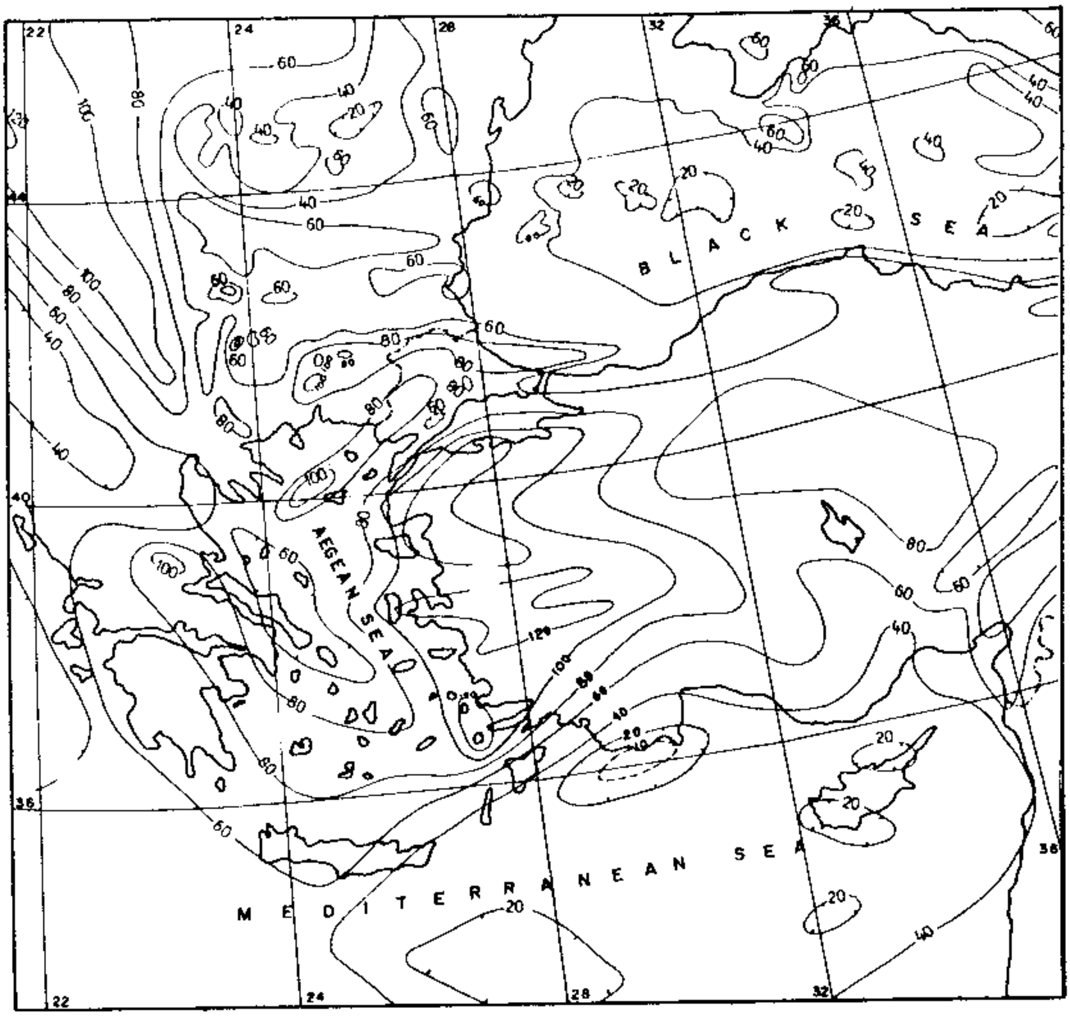

Figure 8: *Heat flow in Western and Central Anatolia and the surrounding areas [mW/m2], compiled from Tezcan und Turgay (1991) and heat flow map of Europe (Cermak and Rybach (eds.) 1979).*

The rates of crustal motion were initially measured by Satellite Laser Ranging (SLR) using permanent and mobile tracking equipment (Smith et al. 1994, Noomen et al. 1995, Robbins et al. 1996). The SLR data have been used by Oral et al. (1995) and LePichon et al. (1995) to model the velocity field of the Anatolian region as a counter-clockwise rigid rotation about a pole located in northern Egypt. The SLR solutions give a good pattern of the large-scale deformation in the Eastern Mediterranean. The northward motion solution for Diyarbakır reflects the movement of the Arabian plate (19mm/a N and 8mm/a W). The westward motion of the Anatolian block is seen in the solutions for the motion of Yozgat and Melengiclik. Three stations (Rhodes, Roumeli and Chrisokellaria, Greece) located on the leading edge of the overriding Aegean plate show SW oriented motion with rates of nearly 40mm/a, relative to a Europe-fixed reference system. The solutions for the sites in the Italian part of the network suggest that the motion there is similar to the Europe-fixed sites.

Since 1988 Global Positioning System (GPS) networks have been used to measure the motion between Italy and Turkey to assess the fine structure of the kinematic field. From west to east these networks are: the Calabrian arc (Zerbini et al. 1994, Kaniuth et al.1995), the West Hellenic arc (Kahle et al. 1993), Central Greece (Denys et al. 1995), the Aegean Sea (Kastens et al. 1997), the Anatolian plate (Oral 1994), and the Marmara Sea (Straub and Kahle 1995, Straub 1996). A first combination of the motion vectors of the four networks was presented by Reilinger et al. (1995).

The kinematic field of Western Greece, relative to Matera, Apulia (S. Italy), is characterised by a negligible motion north of the Kephalonia fault zone (KFZ), and a homogeneous southwest oriented motion of SW Greece reaching rates of 40mm/a. The stations in the southern part of the Aegean Sea, south of a line from Evia to Chios are moving essentially together at about 40-45mm/a to the SW relative to the Eurasian plate.

The Marmara Sea (MS) network covers the northwestern part of the boundary between Eurasia and Anatolia. The continuation of the single North Anatolian Fault Zone (NAFZ) is divided into several so-called strands when traversing the region from east to west (Barka and Kadinsky-Cade 1988). In the analysis discussed later we will introduce a different division of the Marmara Sea region, instead of strands separating it into two different zones (compare Theme 5 and 6 of this volume). The results of the MS network are summarised in Straub and Kahle (1995) (compare also Straub and Kahle this volume). The average westward motion of the Anatolian plate in the Marmara Sea region is 22mm/a relative to the Eurasian plate. West of 27.5°E the motion turns to ENE-WSW. Most of the deformation occurs along the northern zone which passes through the northern Marmara Sea. A detailed description of the data analysis, the crustal motion derived, and models constructed, are given in Straub(1996).

The results of the network on the Anatolian plate are summarised and discussed by Reilinger et al. (1997). The velocities for the sites located south of the Bitlis suture zone in Eastern Anatolia indicate NNW to NW oriented motion relative to Eurasia (18mm/a). Stations located north of the Bitlis suture zone in eastern and central Turkey show velocities similar to those to the south of it. The stations bridging the Caucasus mountains in Armenia, Georgia, and Russia indicate shortening across the Caucasus (10mm/a). Sites north of the NAFZ and north of the Greater Caucasus show insignificant motion in the Europe-fixed reference frame.

Sites west of the Karliova triple junction have a tendency to a more westerly directed motion which becomes progressively more pronounced to the W-WSW with stations indicating SW oriented rates in southwestern Turkey (Reilinger et al. 1997).

The principal axes of the strain rate tensor and the principal values of compressional and extensional strain rates calculated from the GPS deformation field (Kahle et al. 1996) yield insights into the major features: In the western part of Turkey as well as in central and southern Greece, N-S oriented extensional strain rates dominate, accompanied by normal faulting earthquake mechanisms (cf. Fig. 3a). They are most likely due to trans-tensional type of active processes in the Aegean graben system.

New GPS campaigns were recently commenced in the Eastern Mediterranean area including the Balkan region and northern Africa. In addition, a permanent network has been installed, which is designed to monitor the ongoing deformation across the KFZ and the West Hellenic arc (Peter et al. 1997). The new data will help to connect the networks and fill significant gaps in the knowledge of the crustal deformation pattern in the Eastern Mediterranean.

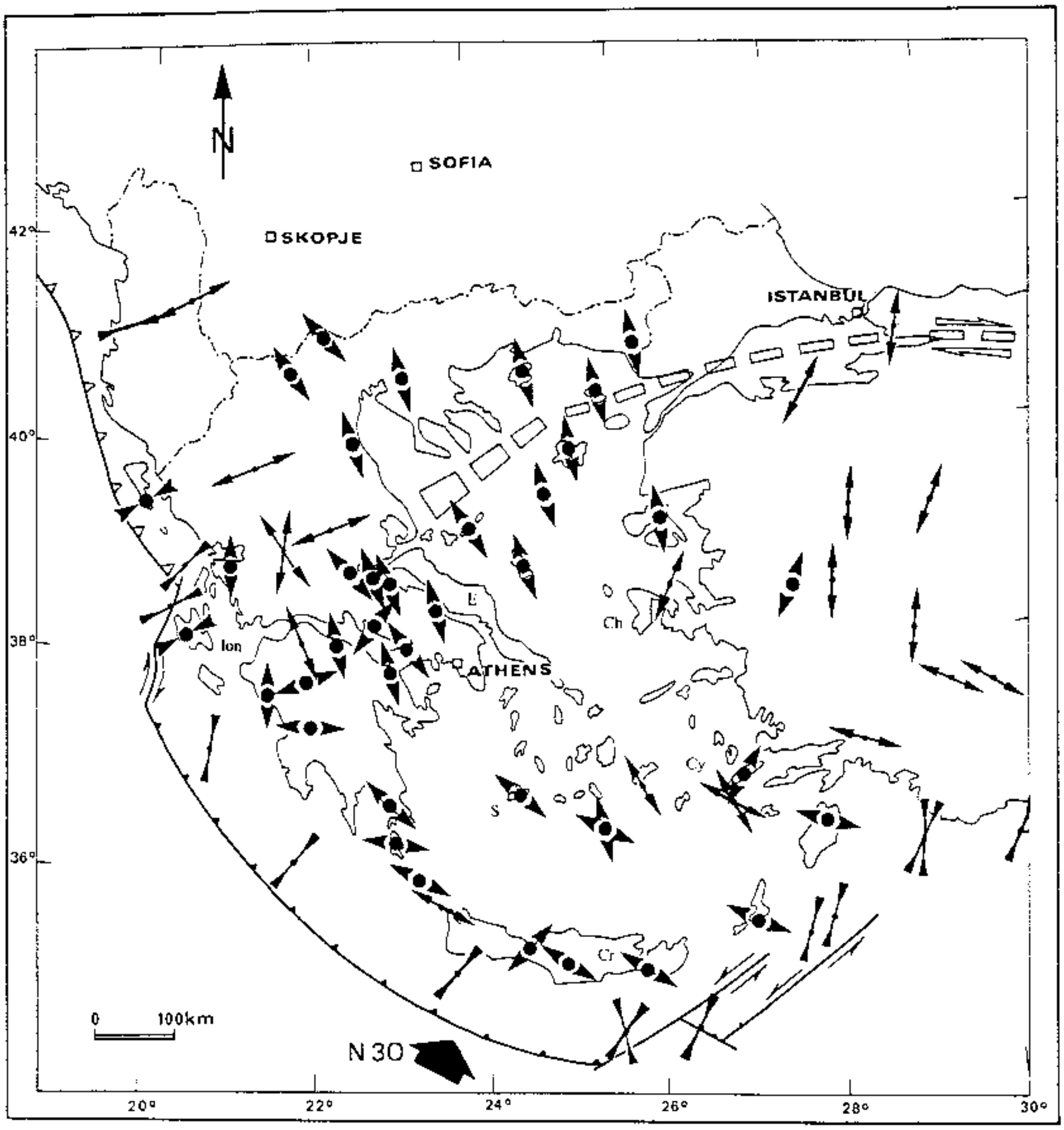

Figure 9: *Seismic stress pattern from FPS and structural analysis of faults, after Mercier et al. (1987). E: Evia, Ch: Chios, S: Santorin, Cr: Crete, Ion: Ionian islands, Cy: Cyclades.*

Conclusions

In this paper we have made an attempt to present a summary of the dominant structural and dynamic features that characterise the broad contact zone between the African / Arabian and European plates in the Eastern Mediterranean. The discussion is based on geodetic, geological and geophysical data available on the Anatolian/Aegean region. Our main conclusions are set forth below:

1) A detailed analysis of the focal mechanisms of earthquakes, and of structural field work, has produced evidence that the state of stress in the Aegean region has changed several times in the last 9m.y. (Mercier et al. 1987). The Hellenic arc exhibits geophysical and geological characteristics ascribed to those of island arcs. From the Hellenic trench towards

the northeast a subduction zone dips as deep as 180 to 200km. Its curvature is outlined by the calc-alkaline volcanic arc of the Cyclades and the southern Aegean sedimentary arc. The southern part of the Aegean Sea represents a back-arc basin, termed the Southern Aegean Trough, between Santorin (Thira) and Crete.

2) The Hellenic arc is located between the Arabia-Africa / Eurasia collision in the east and the Africa-Adria / Eurasia collision in the west. It is there, in the region of the Ionian islands, that the transition from the Hellenic arc to the Adriatic collision zone takes place (cf. Fig. 1). Northeast of the volcanic arc of the Cyclades, the back-arc basin transforms laterally into a zone of different intracontinental deformation which influences the tectonics in the central Aegean Sea and the adjoining western region of Anatolia. The northern Aegean Sea is dominated by the western continuation of the NAFZ.

3) Along the edge of the Hellenic arc which borders the deep-sea trench, the present-day tectonic regime is compressional whereas in the southern Aegean Sea region it is extensional. Since the Lower Pliocene, two compressional events have affected the Aegean domain. It would therefore appear that the neotectonics is characterised by an alternation of long-lived extensional periods – as at the present time – and short-lived compressional events (Mercier et al. 1987). In the last few decades numerous data have been collected revealing the principal directions of extension and compression during these four tectonic phases. It seems likely that compressional tectonics dominated briefly during the Lower to Middle Pleistocene (about 1m.y. ago). Following this short interval up until the present day, the internal Aegean domain has again been under extension (Fig. 9), whereas compressional structures have formed along the Hellenic arc. The focal mechanisms of the Aegean earthquakes agree with both these tectonic manifestations.

4) The upper mantle structure deduced from p- and s-wave tomography is dominated by the subduction of the African lithosphere along the Calabrian and Hellenic arcs. The corresponding two subducting slabs are separated by a deep-reaching mantle plume in the Ionian Sea.

5) In addition to the well-known seismicity belt following the subducting slabs, a dominant cluster of earthquakes exists in southern and western Anatolia. It has a triangular shape and it is surmised that this part of Anatolia is being pulled out to the southwest and at the same time being rotated counter-clockwise, as indicated by the shape of the gulf inlets along the west coast of Anatolia. It should also be noted that there is a clear offset of the seismicity of about 220km to the NNW, between the islands of Karpathos and Rhodes, which is probably due to an irregularity in the crust and upper mantle related to the triangular feature.

6) The level of heat flow in western Anatolia is much higher (100 to 120mWm^{-2}) than that in the Eastern Mediterranean Sea and the Black Sea, with values of 20 to 30mWm^{-2}. In addition, the heat flow in the North Aegean Trough, the Biga Peninsula and the “horst and graben” structures in the central part of western Anatolia clearly shows considerably elevated heat flow values when compared with the remainder of the Turkish territory. The heat flow pattern is similar to the observed seismicity which exhibits the structural “triangular” configuration.

7) Recent GPS results obtained in extensive GPS campaigns (Reilinger et al. 1997, Straub and Kahle 1996) constrain the crustal motion of western Anatolia to rates of about 22mm/a, relative to a Europe fixed reference system. The Aegean region is characterised by rates reaching SW oriented velocities of about 40mm/a at the leading edge of the Hellenic arc. The driving mechanism of this spatial acceleration is as yet unkown.

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Theme 3

General Overview

Geology of Western Anatolia

Yücel Yilmaz

Introduction

The sequence of Western Anatolia may be divided into two parts: the lower association and the upper association. The lower association is a tectonic mosaic consisting of the different tectonic entities. From north to the south these are: the Sakarya continent, the İzmir-Ankara ophiolitic suture, the Menderes massif and the Taurides (Figure 1).

The Sakarya continent is a narrow continental fragment that is delimited along the northern and the southern boundaries by the ophiolitic suture zones. The İzmir-Ankara ophiolitic suture zone is the remnant of the Tethyan ocean that was totally consumed between the Sakarya continent and the Taurides. The Menderes massif is a metamorphic complex that represents the northern margin of Gondwanaland.

The rocks which will be described as the upper association or the cover make up the succession which was formed following the final amalgamation of the tectonic entities mentioned above, and are post Oligocene rocks which consist essentially of continental deposits and associated widespread volcanic rocks. The lower association and the upper association will be briefly outlined in the following pages.

The lower association

The tectonic units of the lower association of Western Anatolia will be described below, starting from the northern areas.

The Sakarya continent

The Sakarya continent between the Intra-Pontide suture and the İzmir-Ankara suture extends from the Biga peninsula to the Ankara region and even further east (Figure 1). It consists of metamorphic and non-metamorphic Palaeozoic rocks at the base and Mesozoic and Cenozoic rocks as the cover.

Across the Biga peninsula and Bilecik region, there are widespread outcrops of a Pre-liassic basement complex. A large proportion of this basement is formed of Permian and Triassic tectonostratigraphic units which have previously been grouped together and referred to as the "Karakaya complex" (Bingöl et al. 1973).

The distribution of the Preliassic basement and the major tectonic elements of Northwestern Anatolia are shown in Figure 2. From the map, it is seen that these rocks outcrop mainly within the cores of antiformal culminations, which have subsequently been stripped of their Postliassic cover successions.

In the Sakarya continent, there are two distinctly different basement associations which are separated from one another by normal faults or thrusts. They will be referred to here as the Uludağ group and the Yenişehir metamorphic complex. The Uludağ group has a high-grade metamorphic basement and a Permo-Triassic cover succession. The Yenişehir metamorphic complex consists of metalavas and associated low-grade metasediments, and a slab of a metamorphosed ophiolite, which was wedged tectonically into the metamorphic rocks.

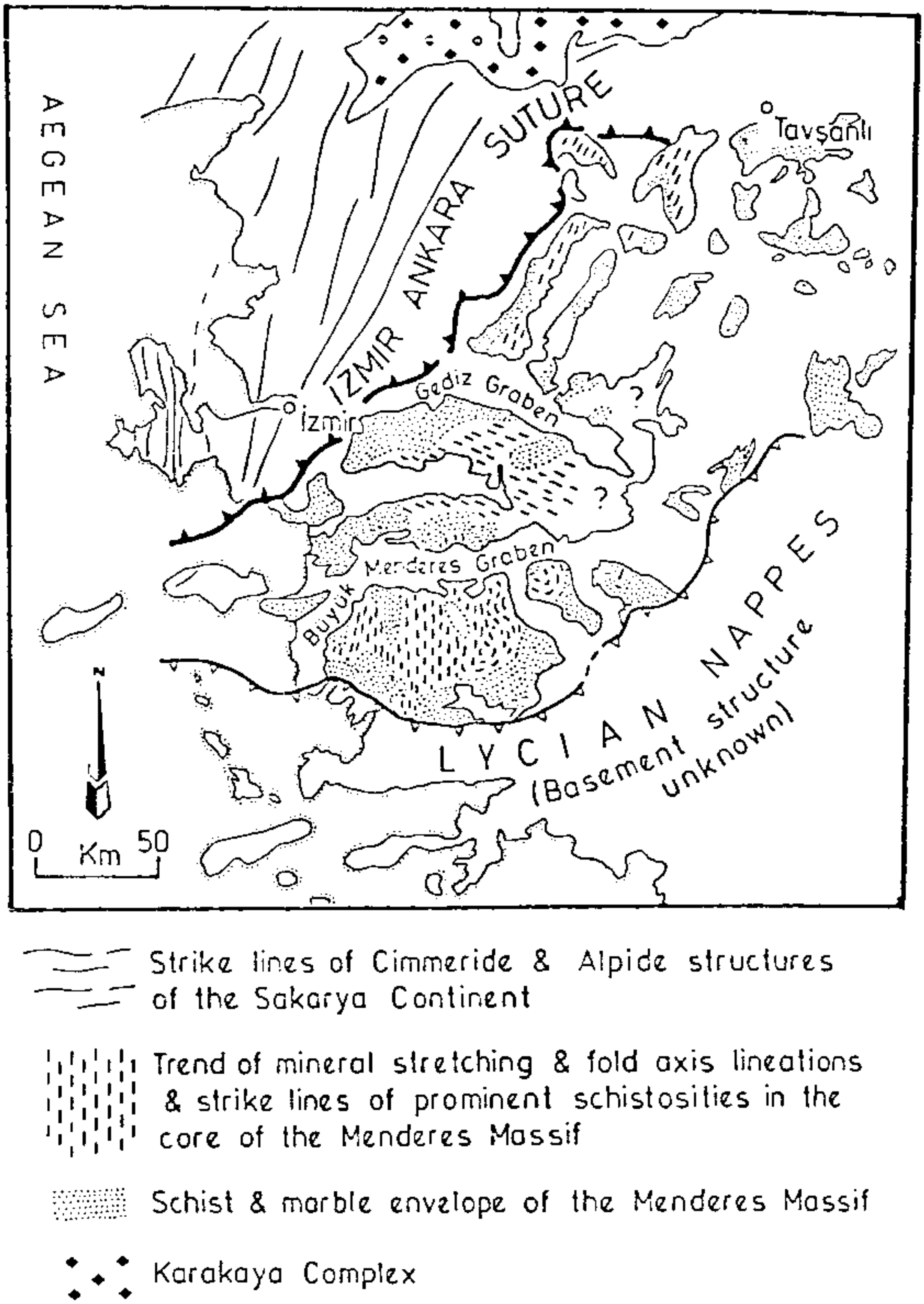

Figure 1: Tectonic map of Western Anatolia.

The Uludağ group outcrops predominantly around the towns of Bursa and Bilecik. The Yenişehir metamorphic complex outcrops mostly around the towns of Yenişehir, Boğaz, Ezine and along the Göksu river valley. In the following paragraphs the basement units will be described, beginning with the Uludağ group.

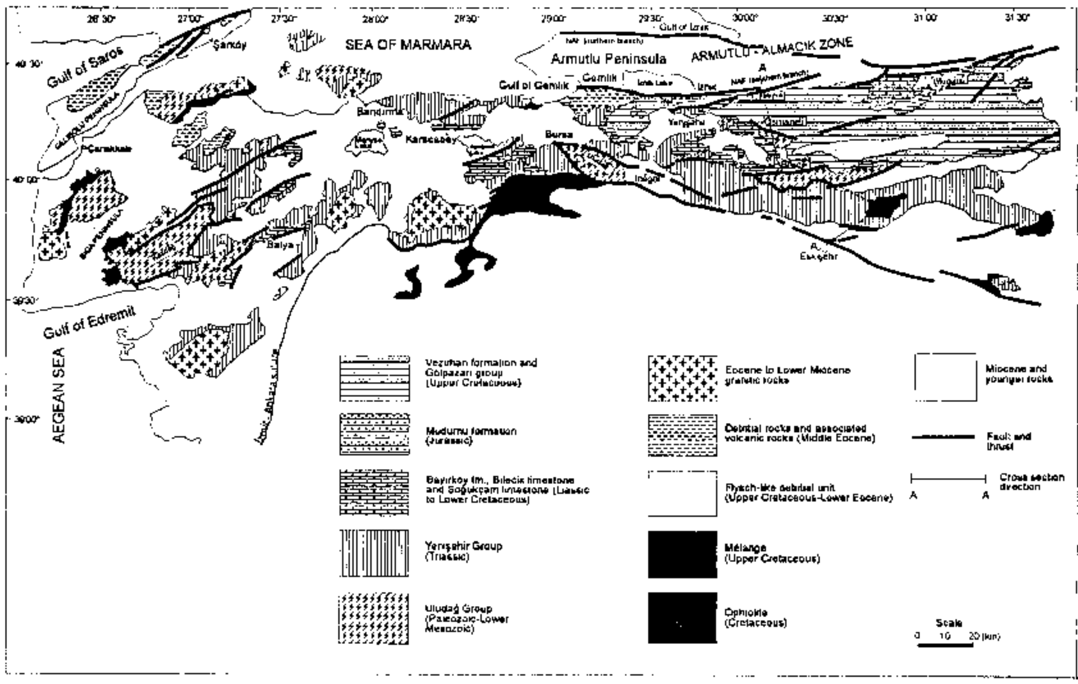

Figure 2: *Geological map of the Sakarya continent of Western Anatolia.*

The Uludağ group

The Uludağ group is best exposed in the Uludağ and the Bilecik areas. It consists of amphibolite facies, metamorphic gneisses, schists and migmatites and overlying green schists and phyllites (Ketin 1947, Yılmaz 1977). These metamorphic rocks are metapelitic in origin and represent the Paleozoic and older continental fragment. The metamorphic association is intruded by a post tectonic granitic pluton (Yılmaz 1977) that has been dated at about 272±3m.y. old (Çoğulu 1967), corresponding to Carboniferous-Early Permian. These metamorphic associations are overlain by a sedimentary cover succession.

The lowermost lithologies of the sedimentary succession are arkosic conglomerates and sandstones with a disconformable relationship with the Pre-Carboniferous metamorphic complex. These sandstones and conglomerates pass laterally and vertically into a richly fossilifereous neritic limestone of Permo-Carboniferous age (Altınlı 1973, Saner 1977). The limestone gives way to a flysch-like succession of the same age.

However authochthonous, the Permo-Carboniferous sedimentary successions are very rare in Northwestern Anatolia. Most of the Permo-Carboniferous rocks are more commonly observed as blocks and debris hosted with the overlying Triassic rocks. This suggests that Carboniferous and Permian successions were largely removed by erosion prior to and during the deposition of the Triassic. As a result of this, initial products of the Permo-Triassic transgression rest upon the Pre-Carboniferous metamorphic complex rather than the Carboniferous sedimentary rocks. However, in spite of erosion, there are a few scattered remnants of the in-situ Permo-Carboniferous succession beneath the Triassic. The Göksu gorge, the Karasu valley, the area to the north of the town of Osmaneli and north and east of the town of Ezine are the areas where this can be recognised. A generalised stratigraphic section of the Triassic successions is shown in Figure 3, where two major groups may be distinguished in the sequence: a lower basal detritial unit and a partly overlapping upper unit which is a lava-sediment alternation. Between these successions, rapid lateral and vertical transitions are observed.

The cover rocks display two different types of contact with the underlying metamorphic rocks: either a normal stratigraphic contact or a tectonic contact along which the cover sedimentary rocks were displaced as a decollement.

The lower unit is a basal arkosic sandstone and conglomerate. These white or pink basal rocks pass vertically into alternations of dark gray siltstone and marl (Figure 3), which display severe deformation. There are moderately thin (<50m), neritic limestone lenses also occurring within this lower unit. Petrographically, this unit contains arkose, lithic arenite and orthoquartzite. These lithologies are derivatives from a granitic and quartzo-feldspathic metamorphic source.

The age of this basal unit has been established as Upper Permien-Lower Triassic, according to the fossil assemblage (Kaya 1991)

The basal clastic rocks pass laterally and vertically to the lava sediment association. This commonly begins as an internally chaotic sediment and volcanic assemblage which becomes less chaotic upwards. The volcanic rocks comprise partly spilitised basaltic lavas and pyroclastic rocks such as tuffs and agglomerates. Amongst the sedimentary lithologies, in decreasing order of abundance, there are graywackes, quartz-rich sandstones, micaceous siltstones and different varieties of limestones.These sediments gradually give way to deep-sea sedimentary and volcanic rocks, including pelagic red mudstone, radiolarian and ribbon cherts, and tholeiitic basalts, which are thought to be Middle-Upper Triassic in age (Kaya 1991, Okay et al. 1990).

The lower detritial rocks of the Triassic succession are regarded as representing a transgressive sequence beginning with continental and/or shallow marine sediments, progressively succeeded by relatively deepening marine sedimentary units. The upper part of these sequences are represented by pelagic rocks, including radiolarian chert, shale, mudstone, micritic pink limestone and intercalated, locally pillowed basaltic lavas. However, within the upper pelagic succession, there are also abundant blocks and fragments derived from the Carboniferous and Permian limestones and an ophiolite. Therefore, due partly to the rapid influx of foreign material and frequently developed olistostromes, the lower, as well as the upper parts of the Triassic successions are internally chaotic. The middle part is well-ordered. This suggests that an active tectonic environment governed the development of the Triassic units at the beginning, and the final stages. The lower basaltic lavas display alkaline affinity and compare favourably with rift-type basaltic rocks (Genç 1993, Yılmaz 1977). The upper basalts are either mildly alkaline or tholeiitic.

The data outlined above indicate that the Triassic sequence of the Uludağ group is bounded by two angular unconformities developed during the pre-late Permian and the Early Liassic. The sequence may result from deposition in a short-lived basin that existed during the Triassic. The lower part of the sequence is interpreted as having formed in a continental environment which evolved subsequently into a deep marine basin, as evidenced by the upper part of the succession containing the pelagic sedimentary rocks and associated tholeiitic basalts. The large quantities of olistostromes, blocks and fragments of the top of the succession is interpreted as indicating the tectonic phase which led to the closure of the basin and compressional deformation of the basin fill.

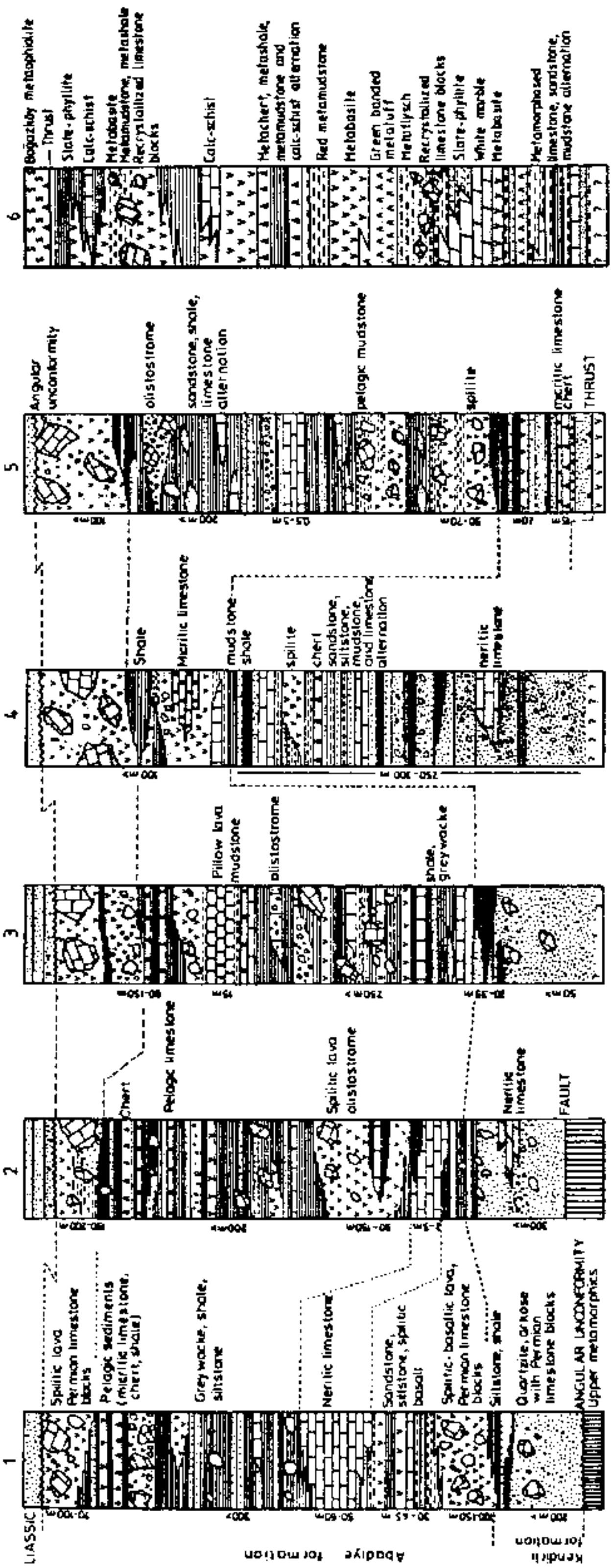

Figure 3: Triassic stratigraphic sections of Northwestern Anatolia.

The Yenişehir metamorphic complex

In this rock association, two different rock groups are differentiated. These are regional metamorphic rocks and an ophiolitic slice. The former is a polyphase metamorphic assemblage, in which metabasic rocks dominate. The latter is represented by a thin (<200m) slice of an ordered ophiolite. Within the variety of metamorphic rocks, basic lavas, pyroclastic rocks, such as meta-tuffs and meta-sedimentary rocks including mudstone, chert and limestone, dominate. Also, in this association there are abundant blocks and fragments of marbles and recrystallised limestones of various sizes.

The age of this group may be estimated from available stratigraphical data; there are fossiliféreous Upper Permian recrystallised limestone blocks within these rocks, which, in turn, are overlain by Liassic basal sandstones. This evidence clearly places the age of this group of rocks in the Triassic. The Triassic age estimation is further supported by two lines of evidence: (1) The rock units of the Yenişehir metamorphic complex correlate closely with the non-metamorphic cover association of the Uludağ group which is Middle – Upper Triassic in age, (2) Triassic fossils were obtained from similar rocks (Okay et al. 1990).

The ophiolite, which is tectonically mixed with the Triassic units, is seen as a tectonic wedge in the Yenişehir area and in the Bandırma-Erdek region. The ophiolite in these areas is seen as a thin (>500m thick) slice and is represented by an ordered ophiolite, represented by ultramafic rocks (particulary in the Kazdağ) and layered gabbros (the Erdek area), gabbroes (the Erdek and Yenişehir areas) and spilitised lavas. The have undergone greenshist facies metamorphism, possibly together with the enclosing metasedimentary rocks (Genç and Yılmaz 1994, Genç 1993).

In addition to the ordered ophiolite, there are also some ophiolitic melange associations. They outcrop in the south of the Bayramiç graben and to the south of the Armutlu peninsula, between İznik and Geyve (Figure 2). The melange displays greenschist facies metamorphism and consists mainly of spilitised basic volcanic rocks, radiolarian red cherts, marbles, metagraywackes and pyroclastic rocks.

Within the phyllitic hosts, there are number of ophiolitic blocks. They crop out mainly in the Gemlik, Geyve and Körfez areas.

In the Biga peninsula, there are few granitic stocks which cut the Yenişehir metamorphic complex. These are possibly Late Triassic in age, because they intruded into the Triassic rocks following their regional metamorphism and are overlain unconformably by the Liassic basal detritials. They outcrop south of Biga and south of Körfez. These data lead to the conclusion that, prior to the Latest Triassic deformation and the metamorphism of the Yenişehir metamorphic complex, these two assemblages were assembled together to form the amalgamated tectonostratigraphic unit.

When the Permo-Triassic rocks that cover the Uludağ metamorphic assemblage in normal stratigraphic contact are compared to the Yenişehir metamorphic complex, a close similarity between the two is apparent. However, the former is non-metamorphic and the latter is metamorphosed. Both assemblages show similar depositional histories and the facies, in both their upper and lower parts, were governed by an active tectonic regime. This supports a genetic link between the two groups. Both of these assemblages are covered collectively by the Liassic (Hettangian-Pliensbachian) basal detritial succession (the Bayırköy formation). The post-metamorphic cover succession is illustrated in Figures 2, 4A, 4B and 5. The basal detritial rocks are overlain by a thick neritic limestone succession that is known as Bilecik limestone (Altınlı 1973). This begins at the base with oolithic or terrigeneous limestones of Bathonian-Oxfordian age (Granit and Tintant 1960, Altınlı 1973, Saner 1977, Yılmaz 1981, 1990a, b, Altıner and Koçyiğit 1992). Nowhere is the contact between the basal clastic rocks and the succeeding shallow marine limestone an angular unconformity, despite a stratigraphic break corresponding to the Dogger interval, which has been identified locally based on fossil findings (Granit and Tintant 1960, Altınlı 1973, Altıner and Koçyiğit 1992). The Jurassic limestones are laterally and vertically replaced by a cherty, thinly-bedded, white limestone of Early Cretaceous age (Soğukçam limestone). These limestones pass upward into a reddish pelagic limestone, radiolarite, mudstone unit of Cenomanian-Turonian age. After that, the uniform and continuous Cretaceous pelagic limestone succession is replaced by units showings wide lateral facies changes. In the southern areas, the limestone is followed initially by a carbonate flysch and then by a flysch. The northern areas consist of a coeval basal sandstone and/or limestone unit which overlies a variety of older rocks, including the basement metamorphic rocks (Figure 5). The basal clastic rocks, or carbonate rocks, pass upward into a flysch sequence, identical to the flysch extending from the continuous succession of the southern areas. Thus, the continuous and deeply-eroded successions both underlain by the same flysch blanket suggest that part of the region was elevated and eroded prior to the flysch deposition during the Coniacian-Santonian. The post-erosional flysch yields Campanian-Maastrichtian age.

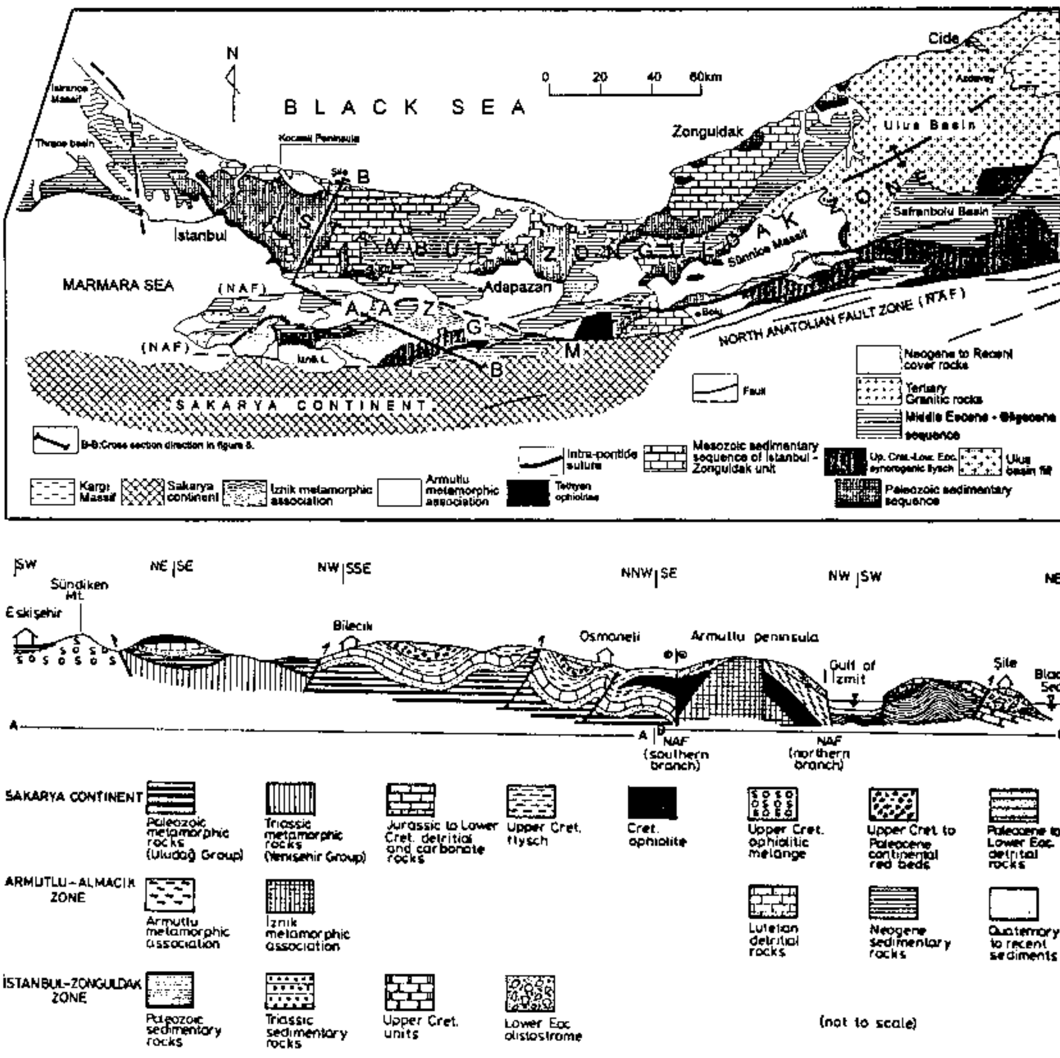

Figure 4: *Geological map (Fig. 4A) and accompanying geological cross section (Fig. 4B) of the western Pontide, NW Turkey (after Yılmaz et al. in press).*

There are abundant blocks, olistostromes and fragments of the older units, comprising debris flow deposits within the flysch. Among the older unit fragments, the upper Jurassic and lower Cretaceous limestones predominate. There are also blocks and fragments of an ophiolite, ophiolitic melange association and blue-schist metamorphic rocks, within the flysch succession.

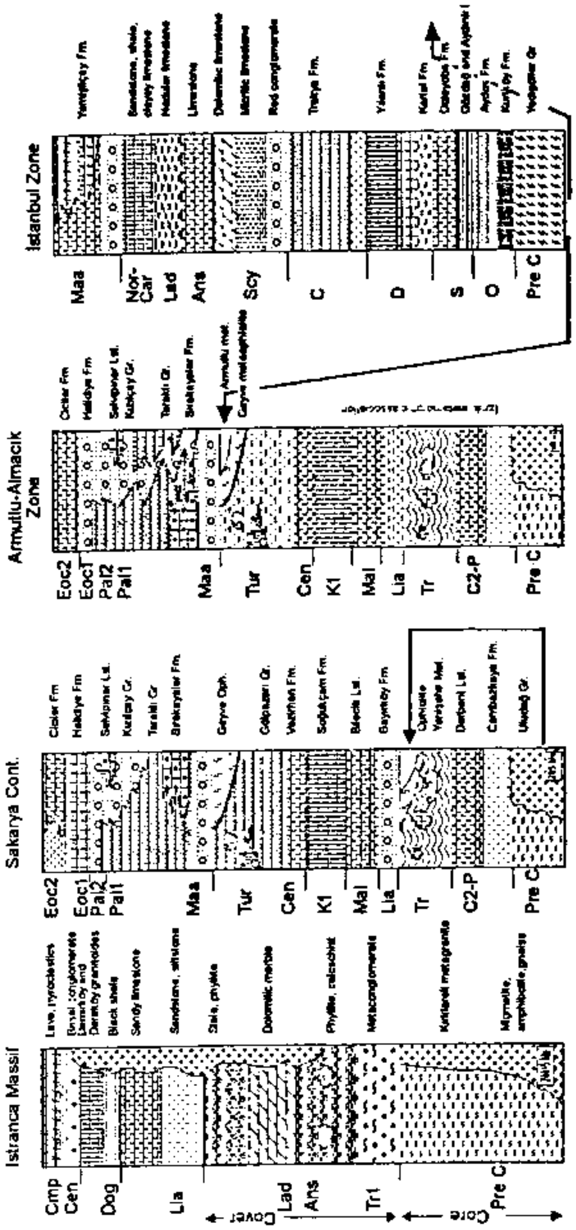

Figure 5: Generalised stratigraphic sections from the Sakarya continent and adjacent regions (after Yılmaz et al. in press).

Following the incorporation of the olistostromes and blocks, the depositional environment changed from deep sea to shallow sea (Yılmaz 1981, Yılmaz 1990a, b), as evidenced by the gradual replacement of the flysch with shallow marine sandstone and reefal limestone (Altınlı 1973, Yılmaz 1990a, b). This change occurred during the Maastrichtian (Yılmaz 1990a, b).

The regressive succession was then overlain by continental red beds that formed during the Maastrichtian-Palaeocene transition (Altınlı 1973, Bargu 1982, Yılmaz 1990a. b). Around the Geyve and Taraklı areas, an ophiolite slice rests on the flysch which, in turn, is overlain by the lower Maastrichtian shallow marine sediments. The sediment deposition continued until the end of the Early Eocene period along roughly E-W oriented depressions; i.e. the Osmaneli area (Fig. 2). The whole region was then gradually elevated and eroded prior to the deposition of the new region wide transgression in the Middle Eocene (Fig. 5). These shallow marine sedimentary rocks are accompanied by widespread intermediate volcanics that were formed in fault-bounded interconnected basins governed by a regional extensional system. The marine environment and volcanism survived to the Late Eocene. It then gradually gave way to the continental red beds in the Oligocene period due to the new compressional tectonics and consequent region wide deformation.

The İzmir-Ankara suture zone

The İzmir-Ankara suture divides the Sakarya continent from the Taurid system (Figures 1 and 2). It consists of a metamorphic and nonmetamorphic ophiolitic melange association and a peridotite nappe. Therefore, it is regarded as the remnant of an oceanic realm that was consumed between the two continents.

The İzmir-Ankara suture displays different geological features in different areas. From Orhaneli eastward to the Yunak area, it displays HP/LT metamorphism. The width of this belt (30-100km) decreases westwards and terminates to the west of Orhaneli. The contact between this belt and the Sakarya continent is presently a high angle, young fault which cuts and obscures the original contact, which is a low-dipping thrust, along which the basement metamorphic rocks of the Sakarya continent rest on the ophiolitic melange (Figure 4B). The thrust is well exposed around Orhaneli. To the west of Orhaneli, rare outcrops of an ophiolitic melange occur, but it is either non-metamorphic or a green schist facies metamorphic unit. Along this suture zone olistostromes of ophiolitic rocks embedded in a flysch matrix also occur. Outcrops of this unit extend from the İzmir region in the west to the Eskişehir and Konya areas to the east.

The matrix of the melange is a strongly tectonised volcano-sedimentary association. These rocks are spilitised basic lavas, shales and graywackes. Among the blocks, there are radiolarian cherts, pelagic limestones, manganifereous cherts, neritic limestone olistoliths, marble blocks and serpentinite lenses. The sedimentary rocks were tectonically intercalated with ophiolitic rocks. Some eclogites are reported from the İzmir-Ankara suture zone (Çoğulu 1967, Okay 1984).

The age of generation of the blue schists in the suture zone occurred over a period from 108 to 88m.y., according to the radiometric age-dating data (Harris et al. 1994). However, generation of the ophiolitic tectonic melange definitely lasted to the Late Cretaceous, because the melange also contains Upper Cretaceous pelagic sedimentary rocks, such as red pelagic limestones.

The Menderes massif

The Menderes massif is the major metamorphic culmination of Western Anatolia (Figure 1). It extends from the İzmir-Ankara suture in the north to the Kale -Tavas molasse basin in the south. It is roughly elliptical, with a NE-SW oriented long axis. The massif has a complex internal structure and lithological distribution. Despite this, there are high grade (the amphibolite facies) gneisses and schists, commonly regarded as the core of the massif (Şengör et al.

1984). The lower grade (the greenschist facies) schists, marbles and phyllites, and the lowest grade (the lower greenschist facies) recrystallised limestones and associated metasedimentary rocks surround the core rocks. The low grade rocks are considered to be representing the cover rocks that envelope the core.

There are a number of radiometric and paleontologic data obtained from the metamorphic rocks, and during the recent years a number of detailed studies were conducted on the massif. Despite these, age, generation and development of the massif are still widely debated. The radiometric ages obtained from the high grade gneisses show a wide scatter varying from 1.2b.y., 900m.y., 500m.y., 470m.y (Şengör et al. 1984, Satır and Friedrichsen 1986), up to 56, 37, 35, 25 and even to 10 to 5m.y. (Şengör et. al. 1984).

Erdoğan and Güngör (1992) demonstrated a relatively well ordered cover succession dominated by the carbonate rich rocks and listed fossil assemblages covering a wide range from Carboniferous to the Upper Cretaceous. These data alone indicate that the main metamorphic phase occurred between the latest Cretaceous and the Early Miocene interval, because the Late Oligocene continental red beds rests stratigraphically on the metamorphic rocks along the southern margin of the massif.

The tectonic history of the Menderes massif involves a major regional dynamothermal metamorphism, which reached amphibolite-facies at the so-called core rocks. This event is referred to as the main Menderes metamorphism, which resulted from burial under the nappe stack of the Lycian nappes during the compressional regime which affected the region from the Late Cretaceous to Miocene interval.

This Barrowian regional metamorphism has been dated to be 35±5m.y. (Şengör et al. 1984, Satır and Friedrichsen 1986) corresponding to Oligocene.

The regional metamorphism was followed by thermal doming during the Early Miocene and then the Menderes dome collapsed, creating a region wide extensional system all around the massif. This is thought to have triggered development of the first fault-bounded basins, prior to the E-W oriented Aegean grabens.

The Menderes massif is regarded as the northern margin of the Taurides (Şengör and Yılmaz 1981). This assumption is based on the close similarities of the Mesozoic successions that are recorded in the Taurus and the Menderes massif. The rock units common to the two tectonic entities cover the entire Mesozoic section, including the Upper Cretaceous.

The ophiolitic nappes which were emplaced on the platform successions during the Late Cretaceous ceased further development of the Tauride passive margin. From then on, the Menderes and the Taurus began having different geological evolutions. The former underwent regional metamorphism, while the latter remained as a sedimentary succession. This may be related to the progressive burial of the nappe-laden northern edge of the Taurus passive margin.

The upper association

The rocks that rest on the different tectonic entities of Western Anatolia (the Sakarya continent, the İzmir-Ankara suture, the Menderes massif and the Taurus), as the first common cover unit began to form during the Late Oligocene-Early Miocene period. This suggests that final development of the present tectonic configuration of Western Anatolia coincides with the Oligocene period. This conclusion is further supported by the radioactive ages obtained from the Menderes massif; the main Menderes metamorphism occurred approximately 35m.y. ago. According to this evidence, the high grade rocks of the massif were not yet unroofed and were still buried under a 15-20km rock pile during the Late Eocene – Early Oligocene period (Şengör et al. 1984, Akkök 1979).

This suggests that the massif was elevated and unroofed at a later period, possibly during the Late Oligocene – Early Miocene interval.

The removal of the envelope rocks of the Menderes massif may have been due to exhumation of the lower crustal rocks, accompanied by subordinate degrees of erosion, because the amount of sedimentary infill in the present Neogene basins around the Menderes massif cannot account for the obliteration of a 15-18km thick rock column. This rules out erosion as the single mechanism which is responsible for the complete removal of the envelope rocks.

Starting from the final tectonic amalgamation, Western Anatolia began to be covered by a region wide common cover of sediments and associated volcanic rocks. The sediments were formed mostly in the continental basins.

Figure 6 shows the generalised stratigraphic sections of the cover successions of Western Anatolia. In the following paragraphs, the cover successions will be summarised starting from the sedimentary assemblages.

According to the sedimentary successions recorded in the different areas of the region, two consecutive, major stages of the basin development may be distinguished. This is seen clearly in the Edremit-Ayvacık area (Fig. 6A), the Bergama-Korucu-Soma area (Fig. 6) and the Uşak area. The first stage corresponds to Late Oligocene(?) – Early Miocene and is represented dominantly by lacustrine limestone and associated fine-grained detritial depositions such as limestones, marls, and siltstones. These sediments were deposited mostly in a low energy environment. The following succession begins mainly with coarse detritial rocks and passes up into sandstones and conglomerates alternating with porous, lacustrine limestones. This new environment of deposition was tectonically more active and represented by the rocks of a higher energy environment.

In some areas, such as the Bayramiç graben and the southern part of the Bergama graben, these major phases of basin development were followed by yet a third phase, which corresponds to the Pliocene period.

The first phase of sedimentation occurred in continental basins, mostly in interconnected lake basins (Benda 1971). These rocks are not confined to the present graben system and apparently are independent from the grabens, as they outcrop more extensively, covering the horsts as well as the graben areas.

These lake basins appear to have covered very large areas in Western Anatolia. They extended from the Çanakkale area in the north down to the Muğla area in the south. There is a debate on the age of development and the tectonic regime during which the lake basins were formed. Seyitoğlu and Scott (1991a, b) suggested that these rocks were developed within the grabens that were formed due to a N-S extensional regime. Some other workers have suggested that the Early Miocene lake basins were developed over a region wide peneplain surface during the late phase of the compressional system (Şengör and Yılmaz 1981). Accordingly, this phase occurred prior to the formation of the present graben system.

The second phase began following a new tectonic phase, as evidenced by the following data:

1) A commonly angular unconformity is observed between the succession of the first phase of deposition and the rocks of the second phase.
2) The second phase begins with rapidly accumulated coarse clastic rocks, suggesting that the previous low energy environment ended and a new environment began with the development of irregular structural and morphological features.
3) The new phase of sedimentation is confined to narrow basins that correspond roughly to the graben systems.

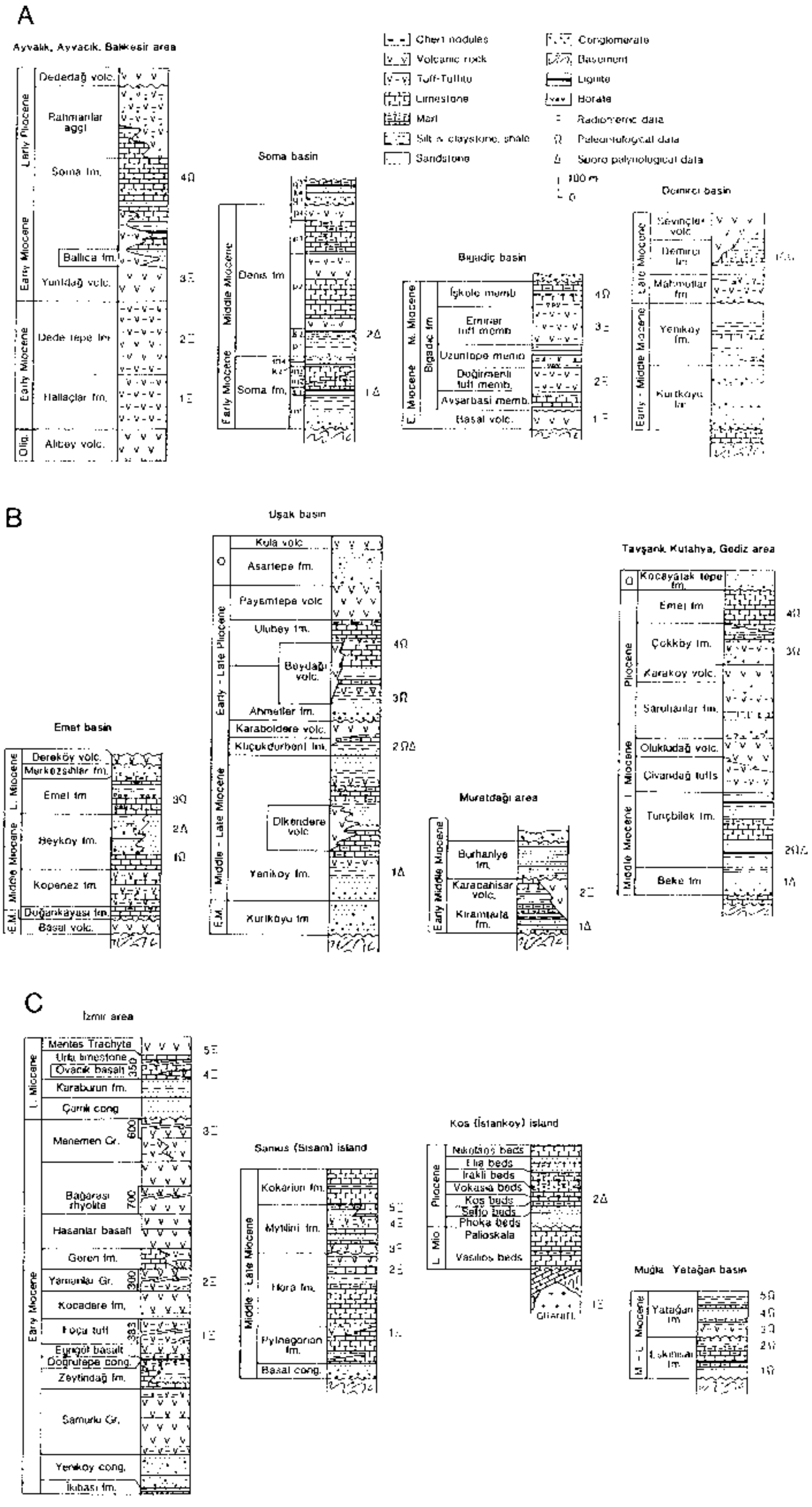

Figure 6: *Generalised stratigraphic sections from the Miocene successions of Western Anatolia (after Seyitoğlu and Scott 1991a, b).*

The sediment deposition in this phase began approximately during the Late Miocene, and restricted to fault-bounded basins.

The latest (the third) phase may be regarded as the reactivation of the horst graben system. During this phase, the graben and horst morphology became more distinct and, consequently, new continental deposition began in front of the newly elevated horst blocks. The scree deposits and debris flow deposits were commonly formed in this phase, and rate of the sediment infill increased.

In some graben areas, such as the Bayramiç graben, a much narrower and deeper graben began to form within the previously formed broad graben area. The major phase of uplift of the Kazdağ horst corresponds to this phase, which began in the Pliocene and continued during the Quaternary.

The magmatic rocks

The Neogene geological evolution of Western Anatolia involves a widespread magmatism producing intrusive, as well as extrusive rocks. The spatial and temporal relations of the magmatic rocks of Western Anatolia are shown in Figures 7 and Table 1. It is seen from Table 1 that the magmatism started at the Oligocene, intensified during the Early Miocene and waned in the Late Miocene-Pliocene. The only exception to this occurred in the Kula area, where volcanic activity continued until prehistorical times.

In the region, three different groups of rocks may readily be distinguished: a granitoid plutonic association, an intermediate volcanic association and a basaltic association. The plutonic rocks are dated from 35 to 20m.y. The intermediate volcanic rocks were partly formed contemporaneously with the plutonic rocks and are dated from 30 to 15m.y. These two groups also show close spatial association. There appears to be a brief nonvolcanic interval between 15m.y and 10m.y. The magmatic activity was rejuvenated approximately 10m.y. ago for a further 6m.y., continued until 4m.y. ago and then disappeared completely. During the latest phase, the basaltic lavas which were nearly absent previously, were formed as the dominant lavas.

The granitic plutonic associations are composed mainly of granodiorites and monzonites with subordinate amounts of adamellites, leucogranites and syenites (i.e. the Kestanbol pluton) (Karacık 1995).

The plutonic assemblage is commonly accompanied by hypabissal rocks, as exemplified by the granodiorite porphyry sheet intrusions in the Kozak granite (Altunkaynak and Yılmaz 1995). Some plutons display gradational contact with the surrounding volcanic rocks, as is the case in the Kestanbol pluton. This indicates that the granitic magmas were emplaced in shallow levels in the crust. This observation is further supported by the data that some plutonic bodies are surrounded by rhyolitic lava domes, ignimbrite flows and felsic pumiceous fall deposits. They all appear to be associated with one another in space and time, and connected collectively with shallow level intrusion in a caldera collapse environment.

The intermediate volcanic rocks display a large variety of composition including basaltic andesite, andesite, trachyandesite, latite and dacite. These rocks vary in the field from a dark-coloured, basalt-like lavas to light-coloured, felsic varieties. The pyroclastic rocks dominate this association. They display almost all of the pyroclastic rock varieties that were formed as the products of pyroclastic fall deposits, flow deposits and surge deposits. Lahar breccias and volcanogenic mud flow deposits are also common.

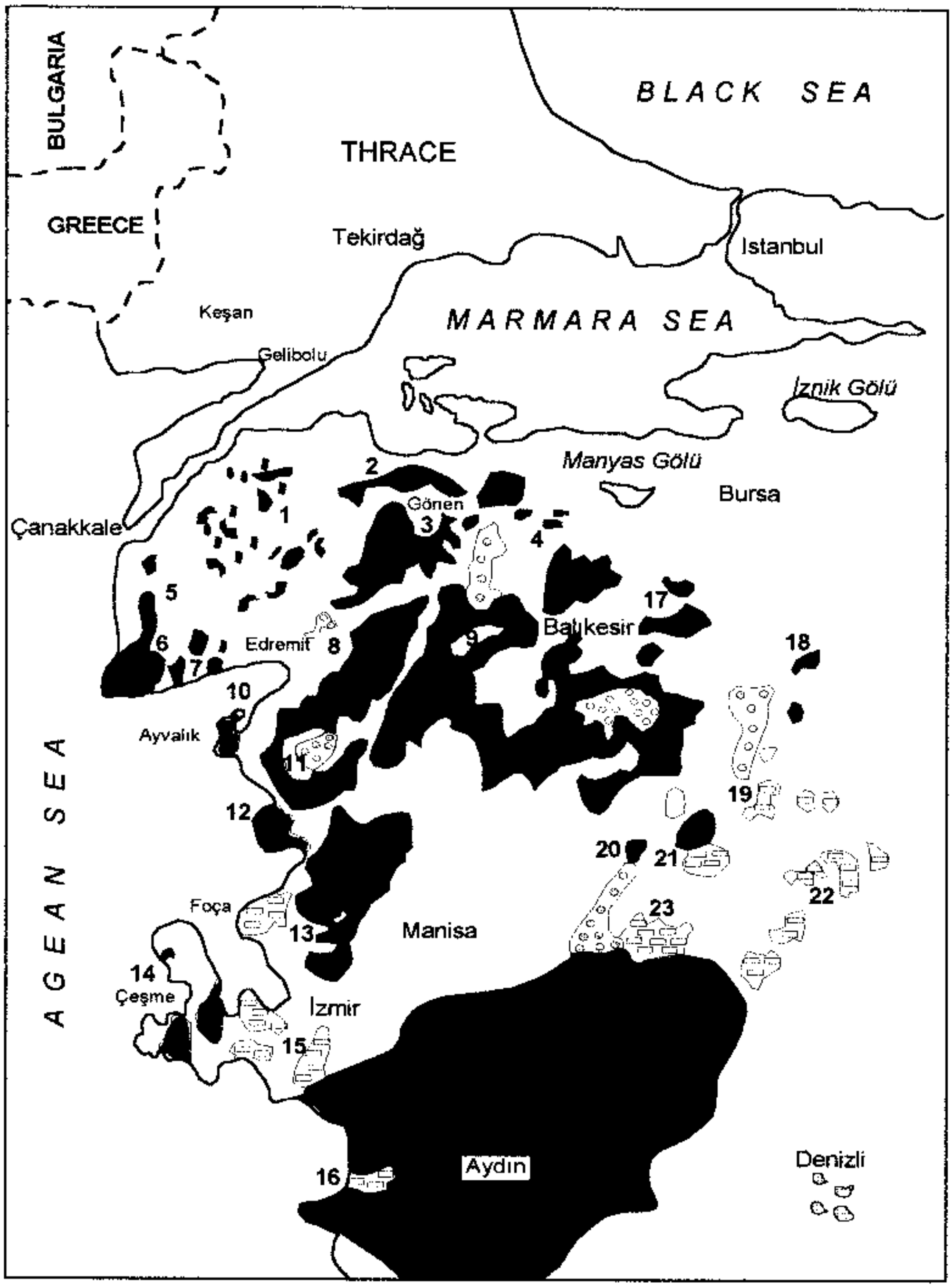

Figure 7: *Distribution of young volcanic and plutonic rocks in Western Anatolia. Numbers indicate the locations shown in Table 1.*

The volcanic layers are often intercalated with lacustrine sedimentary rocks, suggesting that the lavas or the pyroclastic rocks have, in places, been deposited in the lakes. As a consequence of this, welding of the pumiceous pyroclastic flows are only very rarely observed.

In Western Anatolia, two geochemically distinct phases of magmatic activities are distinguished. These are calc-alkaline and alkaline varieties. The early phase that produced the granitic plutons and associated intermediate volcanic rocks are commonly calc-alkaline in composition. Alkaline rock varieties during this period are rare. The late phase that produced basaltic lavas are generally alkaline or transitional. The basic extrusive rocks are nearly absent in the early phase. This does not mean that the basaltic magma in this period was totally missing, because the intermediate lavas of this phase include basaltic xenoliths, suggesting that the basic magmas were formed but were greatly modified before reaching the surface.

The calc-alkaline association has high volatile content, enriched in LIL elements and the isotope composition. All of this geochemical evidence suggest a hybrid origin, mantled derived magmas contaminated and/or mixed with crustal materials (Yılmaz 1989). The granitic sequence of rocks has much higher isotope ratios but still occupies an intermediate position between the mantle field and the continental values (Yılmaz 1989, 1990a, b).

The alkaline association is predominantly represented by the locally developed basalts and subordinate mugaerites, trachytes and hawaiites. On the petrological basis, two different sequences of alkaline rocks may be distinguished: a) a transitional sequence and b) a distinctly alkaline sequence. The former is the group that shows many similar features to the calk-alkaline volcanic group and is intricately intermixed with it. In this assemblage, the andesitic sequence intersperse with or grade into the dark, but silica enriched, mildly alkaline basaltic lavas. The latter, which is represented by basalts, are distinctly alkaline. This group show geochemical features of a typically mantle-derived magma composition (Yılmaz 1990a, b).

Referenz to the locations cited in fig. 7	Time/Stratigraphy	Lithology	Geochemical Affinity	Radiometric Age (m.y.)
Çanakkala- Bayramiç-Ezine 1,5	Late Pliocene	Basalt	A	3.85
	Late Miocene (?)	Basalt	A	8.4-9.7-11
	Early Miocene	Andesite-dacite-rhyodacite	CA	31.1
Biga 2	Late Pliocene	Basalt	A	
	Late Miocene (?)	Basalt		
	Early Miocene	Andesite-dacite-rhyodacite-rhyolite	CA	
Gönen 3	Late Pliocene	Basalt	A	
	Early Pliocene (?)	Andesite		
	Early Miocene	Andesite-tuff-agglomerate	CA	
Susurluk 4	Late Pliocene	Basalt	A	
	Early Pliocene (?)	Andesite		
	Early Miocene	Andesite-tuff-agglomerate	CA	
Gülpınar 6	Middle Miocene	Andesite-dacite- rhyolite	CA	18.5
	Early Miocene			19.5
Ayvacik 7	Late Miocene	Basalt	A	7 - 9.9
	Middle Miocene	Rhyolite-ignimbrite	CA	20.3 - 20.8
	Early Miocene	Andesite- dacite-rhyolite	CA	21.9 -23.6
Edremit-Burhaniye-Korucu 8	Early Pliocene	Tuff-agglomerate	CA	19.5 - 19.9
	Early Miocene	Dacite-rhyolite	CA	20.3 - 20.8
	Late Oligocene Early Miocene	Andesite-trachyandesite-dacite-tuff	CA	21.9 - 23.6
Balikesir-Bigadıç 9	Late Miocene (?)	Basalt	A	13.0
	Middle Miocene-Early Miocene	Rhyolite		
	Late Oligocene-Early Miocene	Andesite-Latite-dacite	CA	17.6 - 18.3
		Dacite-Rhyolite-tuff	CA-SH	19.5 - 20.3
		Andesite-trachyandesite-dacite-tuff	CA	22.3 - 23.6
Ayvalik 10	Late Miocene	Basalt	A	
	Early Miocene	Rhyolite- dacite-andesite	CA	16.0
	Late Oligocene-Early Miocene	Andesite- dacite	CA	31.4
Bergama 11	Late Pliocene	Basalt	A	
	Late Miocene	Dacite- rhyolite (lava-tuff)	CA	13.6
	Middle Miocene	Andesite (lava-pyroclast)	CA	14.6, 15.2-15.6

Referenz to the locations cited in fig. 7	Time/Stratigraphy	Lithology	Geochemical Affinity	Radiometric Age (m.y.)
Dikili-Çandarlı 12	Late Pliocene Late Miocene Middle Miocene	Basalt Andesite (lava-pyroclast)	A CA	14.1-16.7 17.3-17.6
Menemen-Foça Izmir 13	Middle Miocene Early Miocene	Basalt- hawaiite- mugearite Latite-latitic andesite- rhyolite	A SH CA	 16.5-17.0 21.5
Çeşme-Karaburun 14	Middle Miocene Early Miocene	Andesite-latitic andesite- dacite-rhyodacite	CA	11.5-12 17-17.3- 18.2 19.2- 21.3
Urla-Cumaovası- Seferihisar 15	Middle Miocene	Basalt- hawaiite- mugearite- trachyte Alkali rhyolite	A	11.3-11.9- 12.5
Söke 16	Late Pliocene Early Pliocene- Late Miocene Miocene (?)	Basalt Trachybasalt Andesite latitic andesite- latite- dacite	A A CA	 6.99
Dursunbey- Orhaneli 17	Late Pliocene Late Miocene- Middle Miocene	Basalt Andesite- dacite- rhyolite	A CA	
Tavşanli 18	Pliocene Late Miocene (?)- Middle Miocene	Basalt Andesite (lava-pyroclast)	A CA	
Simav 19	Late-Middle Pliocene Late-Middle Miocene	Trachybasalt- hawaiite-mugearite- rhyolite Andesite- dacite- rhyolite	A CA	
Gördes 20	Late Miocene	Dacite-rhyolite-rhyodacite	CA	
Selendi 21	Quaternary- Late Pliocene Early Pliocene- Middle Miocene	Basalt-hawaiite Andesite- dacite- rhyolite	A CA	
Uşak 22	Late Pliocene Late Miocene Middle Miocene	Basalt Andesite-trachyandesite- dacite- rhyodacite Rhyolite (lava-tuff)	A CA CA	8.3-12.2
Kula 23	Quaternary- recent Pliocene	Basalt- hawaiite-tephritetuff Andesite	A CA	10.000- 300.000 1.4
Salarya granite	Early Miocene Late Oligocene	 Granodiorite	CA	23.5 20.3
Eybek granite	Late Oligocene	Granodiorite-quartzmonzonite Granite	CA	35.33-30.5 24.2-23.9 23.6
Kozak granite	Miocene- Late Oligocene	Granodiorite-monzonite- granite	 CA	16.5-19.5 25.7-24.2- 22.1 20.2
Alaçam granite	Early Miocene Late Oligocene	Monzogranite- monzonite Siyeno- monzogranite	CA CA A(?)	20.3 18.0-25.1
Eğrigöz granite	Early Miocene	Monzogranite	CA A(?)	20 21.2, 24.6

Table 1: Young volcanic and plutonic centres, the rock association, radiometric dating data from Western Anatolia.

Discussion and geological evolution

The major tectonic zones of Western Anatolia are displayed in Figure 1. The figure shows that the northern continental fragment, the Sakarya continent (Figure 2) and the southern continental fragment, the Tauride Anatolide platform of Şengör and Yılmaz (1981) are separated from one another by the remnant of the ocean floor (the Neotethys) that is known as the İzmir-Ankara melange zone. It sutures the two continental masses. According to the data available, the following geological evolution may be envisaged: during the Late Cretaceous, the Neo-Tethyan ocean floor began to be consumed by northward subduction under the Sakarya continent (Figure 9). It created a weakly-developed magmatic chain on the Sakarya continent, and a well-developed high pressure metamorphic belt, together with accretionary melange association, in front of the Sakarya continent. During this phase, the ophiolite slabs moved onto the leading edge of the Taurus platform. The ophiolites, which are presently observed on the metamorphic rocks of the Menderes massif and on the Tauride carbonate platform succession, are the remnant of this southernly transported nappe. The ophiolite nappe transport continued until the Eocene. The evidence for this is seen in the coarse-ophiolitic debris which were shed into the basin lying in front of the nappes. Later, the ophiolite were also moved and thrust onto this clastic succession.

The metamorphism of the Menderes massif may, in part, be ascribed to this obduction event (Fig. 8) resulting from the descent of the Tauride Anatolide platform (Şengör and Yılmaz 1981) into progressively hotter regions. Thus the radiometric age data show a spread of ages beginning with 60m.y. (Şengör et al. 1984).

Following the collision, the convergence between the two continents continued until the Miocene. Consequently, the platform began to be internally imbricated and the continental crust was shortened and thickened to reached over 60km. (Şengör et al. 1984).

Further burial of the platform unit created the peak metamorphism (the main Menderes metamorphism) 35m.y. ago. The grade of metamorphism reached to the amphibolite facies or perhaps even extended into the granulite facies (Akkök 1979, Ashworth and Evirgen 1984, Bozkurt and Park 1994, Candan et al. 1994). Southward thrust propagation continued in the Lycian Taurus in the Early Miocene.

As a result of the increasing tightening, the structure in Western Anatolia is dominated by composite nappe systems that become progressively younger in the direction of transport. The high grade core metamorphic rocks possibly thrust onto the low grade envelope rocks during this phase (Dora et al. 1992).

Some of these thrust planes may be the surface expression of the zone of separation between the lower and upper continental crust, which propagated to the surface as listic thrusts (Figure 8). An active example of this may be the low velocity zones in the cores of the orogens, as is the case beneath the central Alps (Mueller et al. 1976).

Thickness of the continental crust of Western Anatolia is calculated to be about 28-32km by different methods (Ezen 1993, Meissner et al. 1987, Makris and Stobbe 1984). Akkök (1979) estimates that at least a 15km envelope of rocks of the Menderes massif have been removed from its outer parts since its uplift.

Penecontemporaneous with the main metamorphic phase of the massif, anatectic melts were generated in the high metamorphic zones and formed migmatitic rocks (Dora et al. 1992). The granitic instrusions rose into shallow levels in the crust, where they formed shallow level and hypabissal intrusives (the granites are dated 30-35m.y). Partly coevally with these events, the first phase of young volcanic activity began in the region (dated 30m.y.) and widespread intermediate volcanic rocks of hybrid nature were formed as a result. These simultaneous events show clearly that the magma ascended through the potentially wide zone of anatexis at the lower levels in the crust.

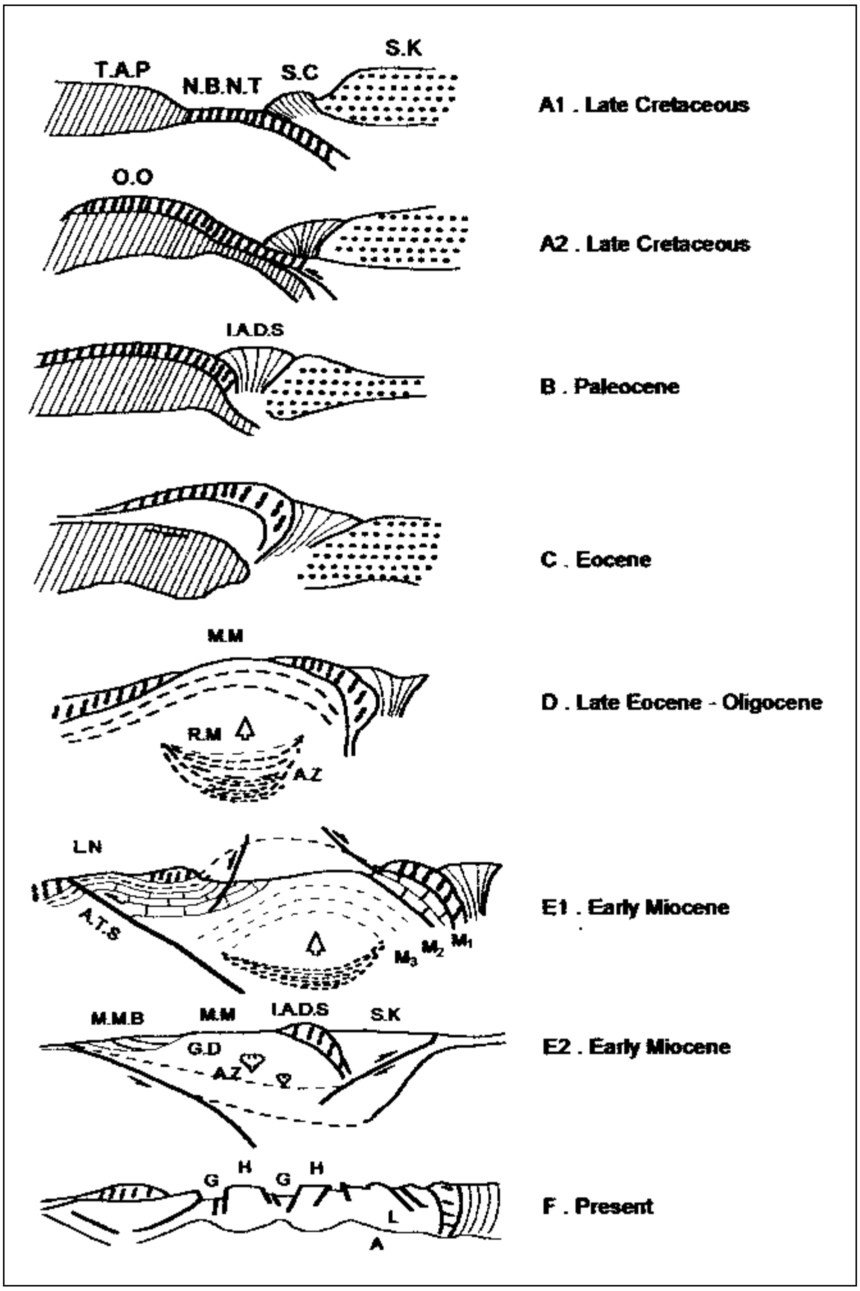

Figure 8: *Schematic sequential cross sections showing Late Mesozoic to the present, tectonic evolution of Western Anatolia.*
Abbreviations: TAP : Tauride-Anatolide platform, NBNT: northern branch of the neo-Tethyan ocean, SK: Sakarya continent, SC: subduction-acreation complex, OO: ophiolite obduction onto the Taurus carbonate platform, IADS: İzmir-Ankara ophiolitic suture zone MM: Menderes massif, AZ: zone of anatexis, RM: core rocks of the Menderes massif, M1, M2, M3: envelopes of the Menderes massif, GD: granitic diapirs, L: lithosphere, A: asthenosphere, G: graben, H: horst, LN: Lycian nappes, MMB: Miocene molasse basins.

During the ascent, this magma affected the continental crust and was itself affected by it. The main influence of the magma in the crust is thought to be an increase of the thermal gradient and a promotion of the crustal anatexis at progressively shallower levels. The sialic crust, on the other hand, affects the rising magma as a density filter and promotes the differentiation. This contributes to the higher silica mode of rocks, as attested to by the great variety of rocks from basic andesite to the dacite. As the magma ascended through it, the thickened continental crust may have permitted the magma to be selectively contaminated, in particular by radiogenic isotopes (Güleç 1991, Yılmaz 1989).

Extrusion of the intermediate magmas lasted to the end of the compressional regime and possibly extended to the beginning of the extensional regime, and then gradually died out with the beginning of the middle Miocene (approximately 15m.y. ago).

The Western Anatolian extensional regime followed the compressional system. This regime has been continuing since the middle Miocene and, as a result of this, the present structural features, represented by about 10 E-W oriented grabens, were developed.

The grabens are the most prominent morphological features of Western Anatolia. They control the drainage pattern and, thus, the sedimentation.

The N-S extension is calculated to be about 30 to 40mm/y by a variety of methods, including GPS measurements. The width of the most advanced grabens (i.e. the Büyük Menderes and Gediz graben) is only about 10km across. The graben sedimentary fills are about 2 to 2.8km thick (unpublished T.P.A.O. data). Using the different sets of data, the stretching factor has been calculated as varying from 1.3 to 1.5.

There is a debate concerning the age of development of the E-W trending graben system in Western Anatolia. Contrary to the earlier suggestion of Şengör and Yılmaz (1981), Seyitoğlu and Scott (1991a, b) claim that the extension began during the Late Oligocene and has been continuing since then for the last 35m.y. They also suggested that all of the magmatic rocks that were formed from the Oligocene onwards were generated under the extensional regime. Seyitoğlu and Scott base their main arguments on the observations that the earliest sedimentary rocks resting on the metamorphic rocks of the Menderes massif date back to the Early Miocene.

In the light of such conflicting views, the development of the E-W trending grabens will be evaluated using three lines of evidence:

- direct evidence (the data derived from the present E-W oriented graben system) (a).
- direct evidence dating the final phase of the previous N-S compressional regime of Western Anatolia (b).
- indirect evidence, taking into consideration the rate of the active tectonic processes and making inferences from this set of data (c).

a) The sampling from the earliest sedimentary fills of the E-W oriented graben system is presently difficult because they are mostly under the younger sedimentary cover. The data presented from the Büyük Menderes graben and Gördes graben to document age of the graben's opening seem to be dubious because it is uncertain that these sediments are the product of E-W oriented graben infill, as they outcrop more extensively than the graben areas. Therefore, their relations to the present graben systems have not been established with relevant data.

b) The first phase of the cover sedimentary units of Western Anatolia has no apparent relation to the present graben system. The final phase of the compressional system of Western Anatolia, as exemplified by the Lycian nappe emplacement, lasted to the middle Miocene and ceased in the Langhian (Hayward 1984). Previously, the Kale-Tavas basin fills, which are regarded to seal the thrust contact between the Lycian nappes and the Menderes massif (Delaune-Mayere et al. 1977), have been re-examined (Gutnic et.al. 1979) and it has been concluded that the so-called seal units were transported passively on the massif during its southward movement. It has now been shown that the Tortonian coarse clastic rocks are the real seal, formed after the thrusting (Hayward 1984). The compressional structural features of the Aegean islands, agreeing with data of Western Anatolia, also occurred during the Early Miocene (Robertson and Dixon 1984) until the Langhian (Bonneau 1984). Immediately after the regional metamorphism, the Menderes massif was thermally domed and its cover began to be removed by erosional processes. This phase was possibly followed by the thermal collapse of the regional dome, as suggested by Dewey et al. (1986). This is believed to have created an initial extensional regime producing radially distributed grabens with respect to the centre of the dome. Maybe it was during this phase that the first fault-bounded basins of Western Anatolia began to develop. Therefore, this phase of basin development is independent of that of the N-S extension related late grabens. The younger grabens cut and were partly superimposed upon the older grabens. The Akhisar and Gördes grabens may be examples of the older grabens and the Gediz graben of the major young graben.

c) When the initiation of the extension in Western Anatolia is estimated using the various geophysical data, the total amount of the extension may be calculated to have taking place during the last 5m.y. The data for this are the paleomagnetic rotations around the graben systems (Kissel and Laj 1988), the relationship between the strain rate ($\beta 1,5$) and total amount of the extension ($\cong$10km), the kinematic approach (Le Pichon and Angelier 1981) and seismic moment rates (Main and Burton 1989).

The direct and indirect evidence discussed above do not favour initiation of the E-W grabens in the Oligocene-early Miocene period. Our on-going research in the extreme north (the Bayramiç graben) in the centre (the Bergama-Bakırçay graben) and in the extreme south (the Kerme graben; Görür et al. 1995) of Western Anatolia reveal, partly in agreement with the geophysical data, that the present E-W oriented graben system began very late, possibly after the middle Miocene period. The field evidence indicates that the grabens were mainly developed during the Late Miocene-Pliocene period.

During the N-S extension regime, the Menderes massif together with the surrounding regions, were extended considerably. The total extension is estimated of more than 50% since its beginning (Şengör et al. 1984). Such an extension is thought to have been accommodated by regional shear zones, along which high-grade metamorphic rocks were produced. They were accompanied by syntectonically formed anatectic melts (Verge, personnel communication, 1994).

During the more advanced stage of the extension, under the subhorizontal flow regime, basaltic melts were liberated from the underlying mantle, possibly due to the adiabatic upwelling of the mantle and extension-induced pressure release. For this, small melt fraction is thought to have played an important role in enriching the source region in the upper "lithospheric" mantle (Mc Kenzie and Yılmaz 1991). The wide diversity in geochemical composition of this late phase of basaltic magmas (Yılmaz 1989) may be related to the heterogeneous source region, which has in part been metasomatised prior to or during extension.

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