Zeitschrift: Bulletin für angewandte Geologie

Herausgeber: Schweizerische Vereinigung der Petroleum-Geologen und –Ingenieure; Schweizerische Fachgruppe für Ingenieur-Geologie

Band: 5 (2000)

Heft: 2

Artikel: Geodynamics of the Marmara Sea region : recent tectonic activity and the role of fluids at the western end of the North Anatolian Fault Zone

Autor: Pfister, Martin / Greber, Emil / Schindler, Conrad

DOI: https://doi.org/10.5169/seals-222275

Bull. appl. Geol.	Vol. 5	No. 2	p. 155 – 176	December 2000

Geodynamics of the Marmara Sea region
Recent tectonic activity and the role of fluids at the western end of the North Anatolian Fault Zone

with 10 figures and 2 tables

MARTIN PFISTER[1], EMIL GREBER[2], CONRAD SCHINDLER[3], CHRISTIAN STRAUB[4], HANS-GERT KAHLE[5] & LADISLAUS RYBACH[6]

Zusammenfassung

Bei der Region Marmara handelt es sich um ein Gebiet mit erhöhter neotektonischer Aktivität. Die aktiven Bewegungen der Erdkruste treten auf in Kombination mit hoher Seismizität, zahlreichen Thermalwasservorkommen und Gasaustritten. Die Neotektonik ist stark durch den Grundwasserfluss und Fluids aus grosser Tiefe beeinflusst. Die wichtigsten neotektonischen Elemente sind: die dextrale Nordanatolische Bruchzone (NAFZ), grossräumige Verformungsmuster, Block Rotationen und die N-S-Extension des Ägäischen Raumes samt West-Anatolien. Basierend auf geologischen Daten belaufen sich die Raten der krustalen Bewegungen an der NAFZ seit Mittlerem Pliocän auf durchschnittlich 1.4–2.0 cm/a, was mit heutigen Raten aus GPS-Untersuchungen übereinstimmt. Die neotektonischen Strukturen folgen zumeist bereits bestehenden, älteren Bruchzonen oder Schwächezonen. Ihre Funktionen dagegen haben sich grundlegend geändert. Das von den GPS-Messungen abgeleitete krustale Deformationsmuster zeigt, dass heute die nördliche Zone der NAFZ, welche eine scharfe Grenze zwischen Eurasien und West-Anatolien bildet, am aktivsten ist. Im Süden verursacht Extension in der krustalen Lithosphäre eine erhöhte Wärmeflussdichte und Thermalquellen-Aktivität. Die meisten Thermomineralquellen sind meteorischen Ursprungs und nehmen Teil am hydrologischen Kreislauf. Bei einzelnen Quellen handelt es sich aber auch um Palaeowässer. Für die Existenz von metamorphen oder primordialen Wasserkomponenten aus grösserer Tiefe liegen keine Anzeichen vor. Es liegen deutliche isotopische Hinweise vor, dass ein Teil der Gase Kohlendioxid, Methan und Helium aus dem oberen Mantel oder tieferen Bereichen der Kruste aufsteigen. Die Fluid-Drucke der Thermomineralwässer des oberflächennahen Systems wie auch jene der aufsteigenden Tiefenfluids (v.a. Kohlendioxid) haben vermutlich einen bedeutenden Einfluss auf das Bruchverhalten und die Seismizität der Marmara Region.

Abstract

The Marmara Sea region is an area of exceptional neotectonic activity. Active crustal movements take place combined with very high seismicity and numerous outflows of thermal waters and gas outputs. Neotectonics is believed to be strongly influenced by groundwater circulation and fluids of deep origin

[1] Barerstrasse 53, D-80799 München
[2] magma AG, Langstrasse 62, CH-8004 Zürich
[3] Schwerzestrasse 7, CH-8618 Oetwil a.S.
[4] Swiss Re, Mythenquai 50/60, CH-8022 Zürich
[5] Institute of Geodesy, ETH Hönggerberg, CH-8093 Zürich
[6] Institute of Geophysics, ETH Hönggerberg, CH-8093 Zürich

in this area. The main neotectonic elements can be defined as: the dextral North Anatolian Fault Zone (NAFZ), regional faulting and tilting, block rotations, and the N-S extension of the Aegean realm including westernmost Anatolia. Since Middle Pliocene, rates of crustal movement along the NAFZ have averaged 1.4–2.0 cm/y based on geological data, close to the present rate of 2.2 cm/y determined from GPS (Global Positioning System) investigations. The neotectonic structures mostly follow pre-existing faults or zones of weakness. Their function, however, has changed completely. The GPS-derived crustal deformation pattern shows that the northern zone of the NAFZ is most active today, forming a sharp boundary between Eurasia and Western Anatolia. To the south, extension of continental lithosphere elevates terrestrial heat flow density and thermal spring activity. Most of the thermo-mineral waters are of meteoric origin and part of the modern hydrologic cycle, some are paleowaters. No evidence exists for involvement of metamorphic or primordial waters. Isotopic evidence suggests that carbon dioxide, methane and helium partly ascend from the upper mantle and lower crustal levels. The fluid pressures of the shallow thermo-mineral waters as well as of the deep-seated carbon dioxide probably play an important role in fault behavior and seismicity in the Marmara Sea region.

1. Introduction

The North Anatolian Fault Zone (NAFZ) forms the tectonic connection between the East Anatolian convergent zone and the Hellenic Arc, where the motion of Asia Minor is compensated by the consumption of oceanic crust (McKenzie 1972). The eastern part of the NAFZ is a narrow strike-slip zone, whereas further in the west, in the Marmara Sea region, the NAFZ splits into a complex fault pattern (Fig. 1). This branching is caused by the transition of the pure strike-slip regime in the east into a stress regime with additional N-S extension. The latter is typical for the Aegean region and responsible for the predominant E-W oriented graben structures in Western Anatolia.

In this paper, we describe the neotectonic activity of the Marmara Sea region. We especially focus on the interaction of neotectonics with groundwater circulation and fluids of deep origin (CO_2, He, CH_4, N_2) and then compare our findings with the situation along the San Andreas Fault System (SAFS).

The present work develops new aspects of the MARMARA Polyproject (Schindler & Pfister 1997).

2. Seismicity

In the Marmara Sea region, historic seismic activity is prominent (Ambraseys & Finkel 1991); many devastating earthquakes have occurred along the NAFZ. The instrumentally covered period shows that in the last decades seismicity of Western Anatolia has been highly active. Detailed investigations of low-magnitude earthquakes reveal swarm-type activity with remarkable clustering in space and time (Ücer et al. 1985, 1997, Sellami et al. 1997). The fault mechanisms of strong earthquakes are associated with major tectonic structures (Jackson & McKenzie 1988, Papazachos & Kiratzi 1996). According to various bulletins and sources the focal depths of the earthquakes range from 0 to 50 km. More accurate localization of selected earthquakes suggest focal depths no deeper than 10 to 15 km (e.g. Eyidogan & Jackson 1985). In the Bursa region, Sellami et al. (1997) located 90 % of the low-magnitude earthquakes in the uppermost 15 km, and only few earthquakes with depths between 15 and 60 km.
Based on the epicenters distribution of Western Anatolia, Crampin & Evans (1986)

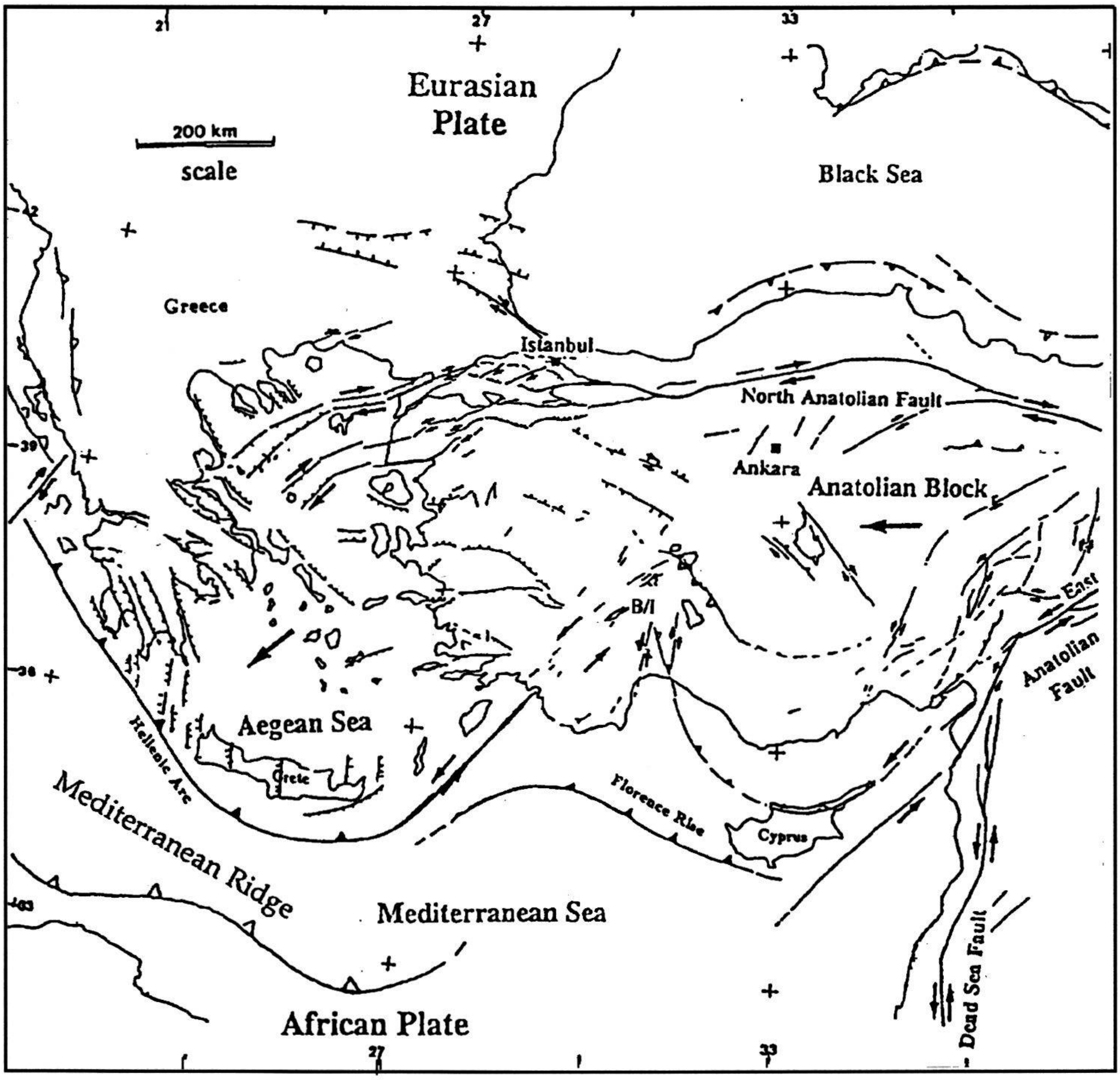

Fig. 1: Tectonic sketch map of the Aegean-Anatolian region, simplified after Mueller et al. (1997). B/I: Burdur / Isparta.

proposed a distinct seismotectonic unit, the Marmara Block. It is bordered by a highly seismic active zone extending from Izmir to Adapazari. It rotates and shears in order to accommodate the right-lateral motion of the NAFZ and the extensional tectonics of Southwestern Anatolia (Aegean).

3. Neotectonics

In our terminology the term «Neotectonics» represents the period having a similar style of deformation, a comparable stress field and a paleogeography resembling today's conditions (compare Table 1). In general, the neotectonic deformation in the study area is still Alpine, but somewhat different from former Alpine events. In Northwestern Anatolia, the begin of the neotectonics took place between the final stage of Alpine compression in Aquitanian (ca. 22 m.y.) and the opening of the

Aegean and the Marmara Seas. Based on littoral sediments this transgression happened in Upper Serravallian (11–13 m.y.). Most authors place the start of neotectonics in the investigation area in the Middle Miocene (Le Pichon & Angelier 1981: 13 m.y., Mercier et al. 1989: 15–13.5 m.y., Yilmaz 1997: 15 m.y.). According to Mercier et al. (1989) a new subduction zone, the Hellenic Arc, has become active in the Langhian (16.6–15.1 m.y.).

	Stage (marine)	Age (m.y.)	Uncertainty (m.y.)	Main events	Max. displacement	Average rate
Quat.	Quaternary	1.6		Second phase activity NAFZ, W of Kuzuluk predominantly Northern zone + opening Marmara sea trough + 5° anticlockwise rotation + Extension in Aegean region 3-4m.y.	NAFZ northern zone + some along southern z. 55-60km	3m.y.: 1.8-2.0 cm/y 4m.y.: 1.4-1.5 cm/y
Pliocene	Late Pliocene	3.4	3–4		Opening Marmara trough 40km Aegean ext. unknown	3m.y.: 1.3cm/y 4m.y.: 1.0cm/y ?
	Early Pliocene	5.3	5–6	Gentle compression, folding, tilting. Previously and subsequently quiet periods. Extension in Aegean realm interrupted 1-3m.y., probably 1-2m.y.	?	?
Miocene	Messinian	6.5		First phase of NAFZ activity west of Kuzuluk, predominantlly southern zone, start of geothermal activity at Kuzluk + extension in Aegean region 2-5m.y., probably 2.5-4m.y.	NAFZ southern zone east of Bursa ~20km -5km(?) since Plioc.	2.5m.y.: 0.6cm/y 4m.y.: 0.4 cm/y
	Late Tortonian		8–11		Amount of extension unknown	?
	Early Tortonian	11.2		Extension in Aegean realm, start of geothermal activity at Tuzla 1-6m.y., probably 2-4m.y.	Amount of extension unknown	?
	Serravallian	15.1	12–14	Start of extension in Aegean realm? 25° anticlockwise rotation, breaking up, massive widespread faulting and tilting 2-5m.y., probably 3-4m.y.	Amount of extension unknown Marmara Sea ~90km dextral movement	? 3m.y.: 3cm/y 4m.y.: 2.25cm/y
	Langhian	16.6	16–17			
	Burdigalian	21.8		End of Paleotectonics Last Alpine orogeny		

Tab. 1: Stages of Neotectonics in NW Anatolia (MARMARA study areas and Thrace).

The main neotectonic elements of the Marmara Sea region are: the dextral NAFZ, regional faulting and tilting, block rotations and the N-S extension of the Aegean realm including westernmost Anatolia. The origin of the NAFZ is connected to the collision of the Arabian and African plates with Eurasia (Pavoni 1961, McKenzie 1972, Jackson & McKenzie 1984). In addition to tectonic escape (Meijer & Wortel 1996) of the Aegean micro-plate, additional driving mechanisms such as slab rollback and gravitational collapse must be invoked to account for the seismicity pattern and the pronounced spatial acceleration of motion. The Anatolian Block moves westward from the zone of intensive convergence in eastern Anatolia along the dextral NAFZ. East of 32°, the displacements are concentrated along a narrow fault zone whereas to the west, the zone progressively splits up and becomes wider (Fig. 1). Near Adapazari, the NAFZ definitively splits into two broad complex zones (Barka 1992, 1997). Barka further subdivided the southern zone into middle and southern branches. However, these are difficult to separate and show close interrelations. The activity of the NAFZ started during Late Serravallian (12 m.y.) in eastern Anatolia, the motion progressing from east to west (Barka 1992).

According to the results of paleomagnetism and geology, the zone north of the NAFZ has been stable since the start of neotectonics - at least in the region investigated in the MARMARA Polyproject between 25°30' and 31° E (Kondopoulos et al. 1996, Tapirdamaz & Yaltirak 1996, Michel et al. 1995). An anti-clockwise rota-

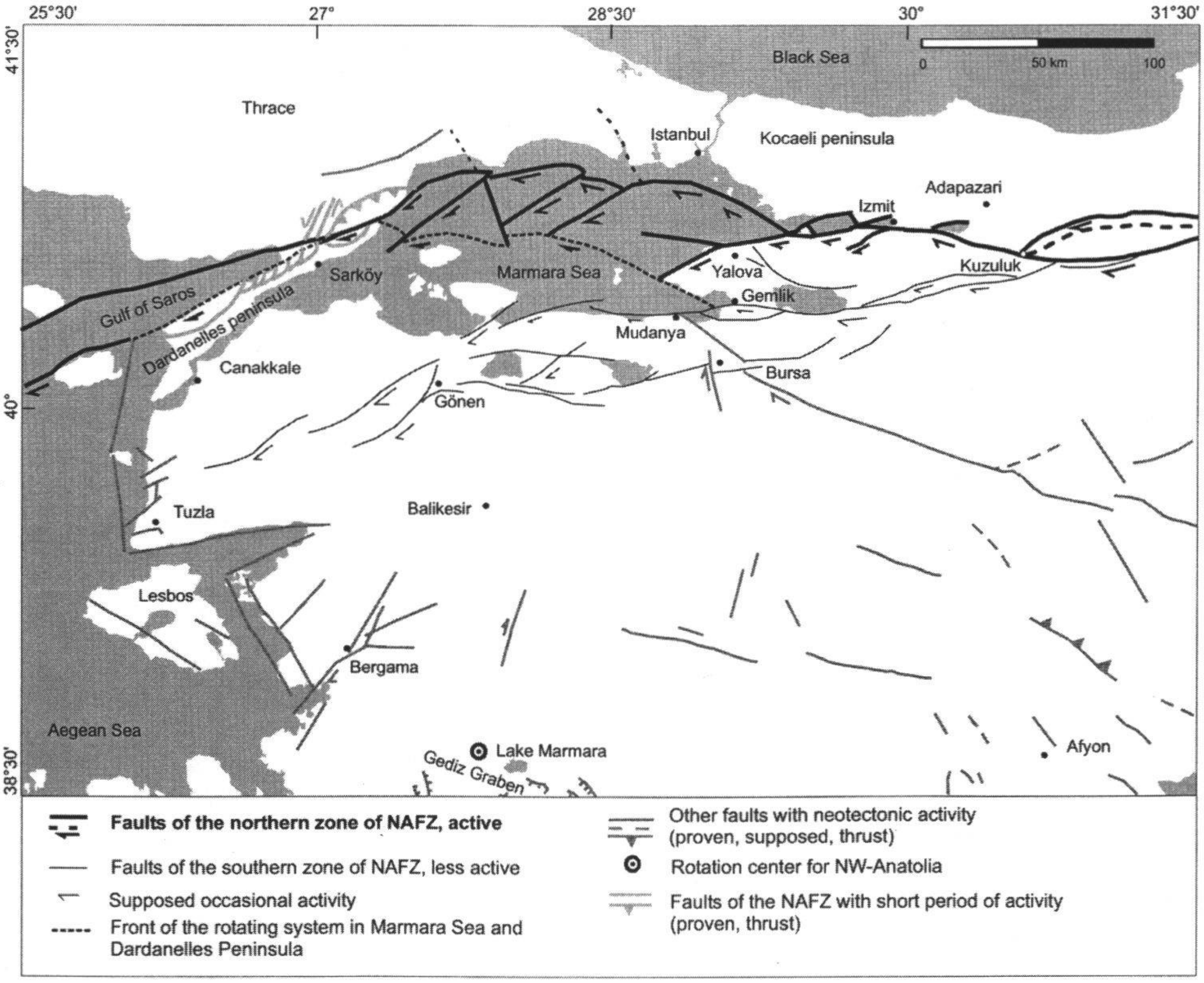

Fig. 2: Neotectonic activity in NW Anatolia since Pliocene.

tion of about 30° since Burdigalian is well established for the area between Canakkale and Izmir (Kissel et al. 1989, Isseven et al. 1995). To the south of Adapazari, Michel et al. (1995) found a rather small anti-clockwise rotation. Further to the east, unfortunately data are missing in the south of the NAFZ. In striking contrast, the Greek mainland west of the Strimon river and the north Aegean islands with the exception of Lesbos (no deviation?) experienced a distinct clockwise rotation (Kissel et al. 1989). A very important neotectonic structure follows the Aegean coast. The outskirts of this boundary were sketched (Fig. 2) based on the relief of the sea floor, by fault systems recognized on land and by the distribution of microseismic epicenters. Between the Dardanelles Peninsula and Mudanya the northern border of the rotated West Anatolian Block corresponds well to a sector of a circle if later fault displacements are eliminated (Fig. 2). The circle has a radius of 220 km. The center of it is located 60 km ENE of Izmir. Southeast of Mudanya this border splits, its prolongation was not investigated by the MARMARA Polyproject. We suppose that the limits of the block join the Burdur-Isparta triangle (Mueller et al. 1997 and Fig. 1) in an intricate way.

Table 1 outlines the sequence of neotectonic events which was derived for the northeastern Aegean area (mainly based on Mercier et al. 1989) and for NW Anatolia. A more detailed description is given by Schindler (1997).

3.1 Average rates of movements

Table 1 indicates the order of magnitude of the average movements only since neither the duration of the individual phases of the neotectonic history nor the exact amounts of displacements are known. The largest values are found along the northern border of the rotating West Anatolian Block during Middle Miocene (2.25–3 cm/y). For the NAFZ, the displacements during the Late Tortonian are modest (0.4–0.6 cm/y), concentrated in the southern zone and fade out to the west. Since Middle Pliocene the rates reach 1.4–2.0 cm/y and could even be higher if they were interrupted during the Early Quaternary. The values are in the range of the 2.2 cm/y resulting from the GPS investigations (Straub & Kahle 1995, 1997). Unfortunately, the average rates and the total amount of the Aegean extension cannot be deduced from our geological studies. Summing up all displacements along the NAFZ since the Late Miocene, we obtain 70–80 km of dextral movement for the region of Adapazari. This is in the same order as estimates published by Seymen (1975), Sengör (1979) and Westaway (1994).

3.2 Relationship between paleotectonics and neotectonics

Schindler (1997) reconstructed the paleogeography for the beginning of neotectonics (Figure 3). In there the original orientation of different paleotectonic structures are shown. The zone of the future NAFZ and the area south of it indicate a general E-W trend. Only the oldest elements, the highly metamorphic series of early Variscan (or Caledonian?) age, run WNW-ESE.

In summary, south of Thrace and the Kocaeli Peninsula several major orogenies occurred, which have caused both brittle and ductile deformation since the late Variscan. Several of the major tectonic structures probably cut very deep into the lithosphere. All these events facilitated the initiation of systems of normal, transversal or oblique faults. As observed in the field, the rocks in Northwestern Anatolia show a high degree of often steeply dipping fracturing, but it is very difficult to determine the age and history of the individual fault systems. Many of them were active already before neotectonics started, proven by synsedimentary activity, by dykes or hydrothermal deposits or by datable displacements. Faulting along the Aegean coast at the start of neotectonics reactivated some of these systems. The northern border of the West Anatolian Block follows the Iznik Metamorphics Zone (ancient northern trough of Neotethys, metamorphised and closed during Late Cretaceous to the Intrapontide Suture) over a long distance (Fig. 3). More to the east it cuts obliquely into the hypothetical Karakaya zone (Genc & Yilmaz 1995).

East of Adapazari, the NAFZ presumably follows approximately the Intrapontide suture zone (e.g. Barka 1992). The main branch of the southern zone follows the southern border of Iznik metamorphics, other parts split to the northwest or southwest (Fig. 3). Cutting the border of the rotated block near Bursa, the fault lines reach more stable areas and become weaker. In contrast, the northern zone first meets more resistance as it misses the northern limit of the Iznik metamorphics zone for unknown reasons, but then joins and follows the margin of the rotated zone which had been already activated before (Middle Miocene).

The neotectonic structures mostly follow pre-existing faults or zones of weakness such as the borders of the Iznik metamorphics zone. The function of the old struc-

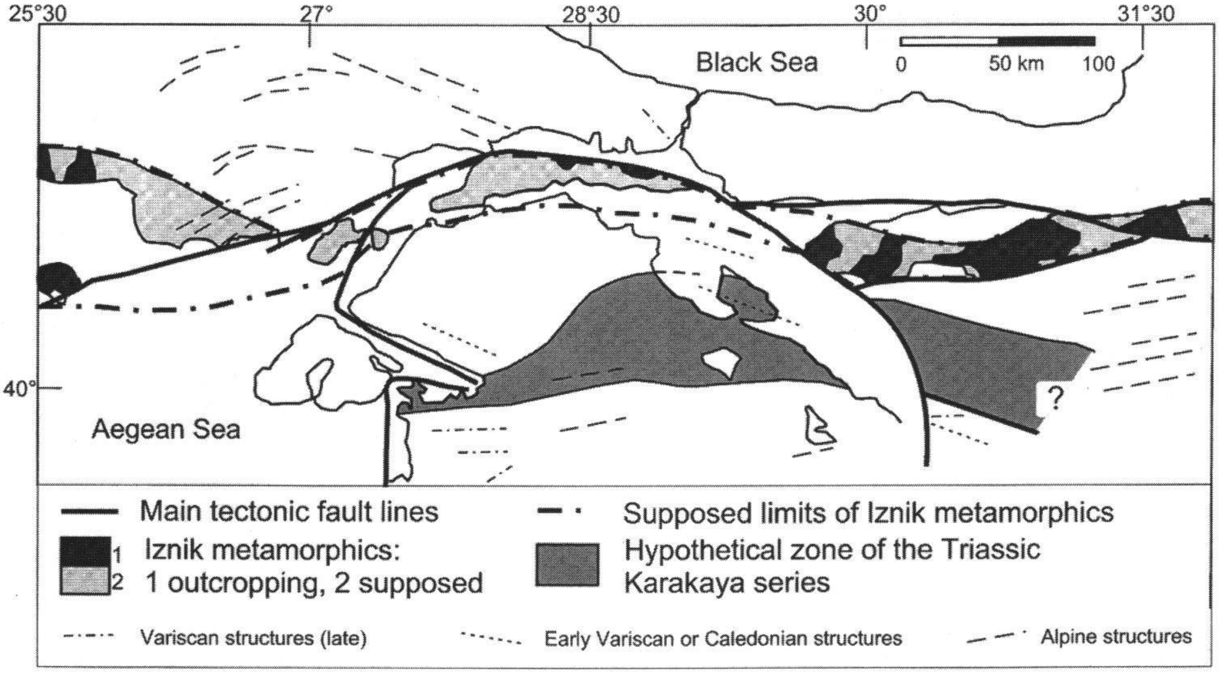

Fig. 3: Paleogeographic reconstruction at the start of neotectonics (Middle Miocene) showing the supposed extent of Iznik Metamorphics, main neotectonic lines and old structures. To simplify orientation, the shorelines and - north of the northern zone of NAFZ - the geographical grid correspond to the actual situation.

tures, however, has changed completely since the neotectonic period. Fracturing and brittle deformation have been going on since the Middle Miocene. Nowadays, most of the rocks of Northwestern Anatolia are cut intensively by various systems of joints, faults and shearing planes. This fact may help to explain why the displacements along the southern zone of the NAFZ disappear to the west, or how the conflicting situation between different influences can be solved between 28°30' and 29°30' E. Micro-seismicity observed in the Bursa region (Sellami et al. 1997) does not follow well-defined fault lines but shows a large variety of wandering clusters of epicenters.

4. GPS estimates of the tectonic activity

Recent space geodetic developments have fostered significant improvements in the understanding of lithosphere dynamics. They have made it possible to measure the deformation rates of the moving lithospheric plates over long distances (on the order of thousands of kilometres) even though the rates of displacement may be relatively small (millimetres per year).

In order to assess the deformation pattern of the Marmara Sea region, a dense network of 52 sites was installed and measured with the Global Positioning System (GPS) four times between 1990 and 1996. The analysis of the observations has revealed that the Anatolian Block is moving westwards at 22 mm/y relative to Istanbul (i.e. with respect to an assumed stable Eurasia). This value represents the average dextral strike-slip along the western part of the NAFZ. Around longitude 27.5°E, the strike of motion bends towards the west-southwest. The detailed analysis of the GPS data is compiled in Straub & Kahle (1997). These results are in excellent agreement with results from larger scale geodetic networks (e.g. Reilinger et al. 1997; Robbins et al. 1995).

Based on the displacement rates found, the strain rate field was calculated (Straub & Kahle 1995, 1997). The deformation pattern shows that the northern zone of the NAFZ (along a line connecting Kuzuluk, Izmit, Sarköy, Fig. 2) is by far the most active neotectonic unit. It forms a sharp boundary between the Thrace-Black Sea Block and Western Anatolia. This finding is of great importance since Istanbul is located close to this zone and confirms the great earthquake hazard for its inhabitants. The mean strain rates in the north (compression: 0.19 μstrain/y, extension: 0.16 μstrain/y) are roughly twice as large as the ones in the southern zone (compression: 0.08 μstrain/y, extension: 0.08 μstrain/y). The geologic results presented in the previous section corroborate the distinction between these two zones as well. The general shear motion in the northern zone is of a dextral sense and reaches values of up to 0.27 μstrain/y. The average shear strain over the whole area amounts to 0.11 μstrain/y. Summations of seismic moment tensors in the same area led to an average shear strain rate of 0.05 μstrain/y (e.g. Papazachos & Kiratzi 1996). We assume that there is a substantial amount of aseismic creep and / or accumulation of strain that may be released in future earthquakes.

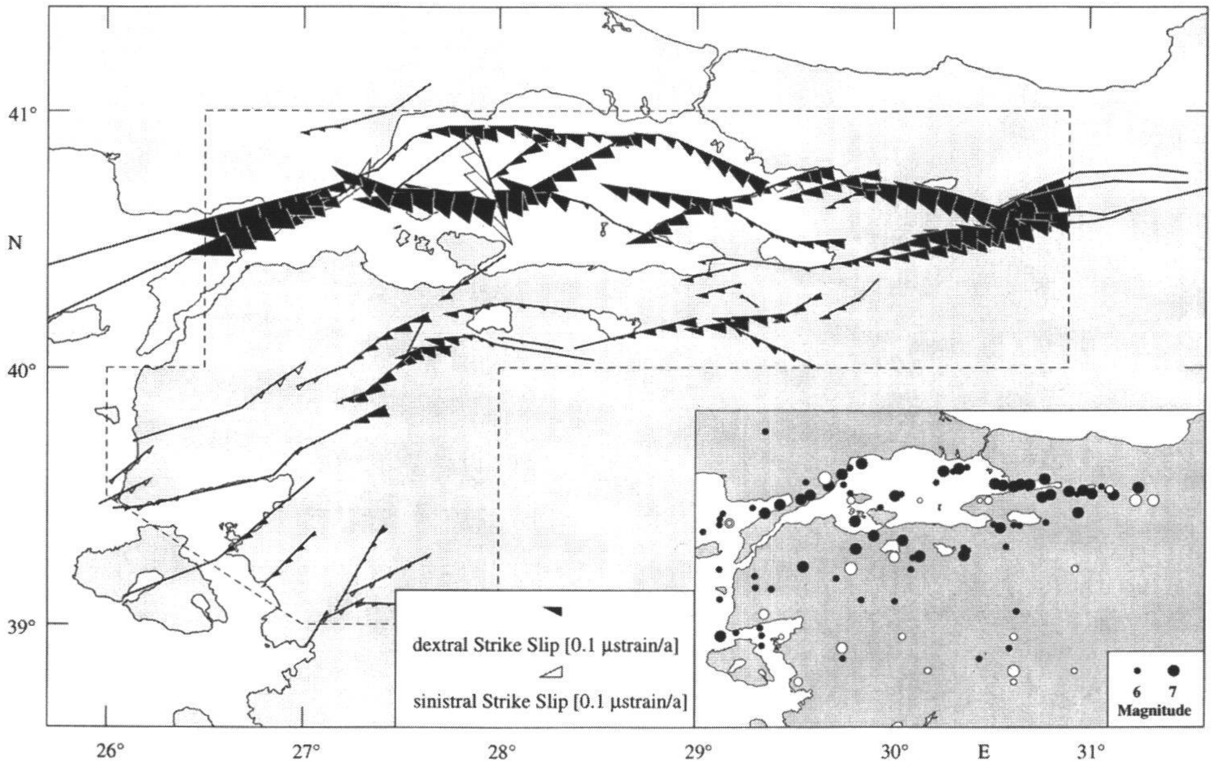

Fig. 4: GPS-derived crustal deformation of the Marmara Sea region (Straub and Kahle 1997): Scaled and oriented sense of strike along the fault lines. Most activity occurs along the northern zone of the NAFZ and shows dextral sense of motion. Less shear can be revealed along the southern zone. No continuation of the southern zone faults to the Aegean Sea is observable. The dashed line indicates the region investigated. (1 μstrain/y is equal to a relative motion of 1 mm/y over a distance of 1 km normal to the fault.)
Small inset: Long-term seismicity of the Marmara Sea region after Ambraseys and Finkel (1991) and NEIC (1990). Black circles show events before this century. Large circles indicate events with M ≥ 7, small circles show events with 7 > M ≥ 6. This century's events are given by white circles. Stronger activity is reported for the northern zone than for the southern one which reveals a diffuse pattern of seismic events.

In a further step the kind and strength of motion along known fault segments have been determined by calculating and projecting the strain tensor components along these segments. Thus, the individual fault lines can be classified. Figure 4 depicts the major sense of shear motion occurring along the individual faults. Dextral shearing and extension govern the neotectonic pattern of the Marmara Sea region. Compression plays a major role at faults trending NE-SW (Fig. 5). Extension becomes more important as we go from east to southwest. The strain rates were transformed to stress parameters assuming an elastic behavior of the upper crust. The highest values of annual maximum shear stress accumulation (> 14 kN/m^2) are found along the northern zone. The compilation of the historical seismicity in the Marmara Sea region shows that the strongest events are aligned along the northern zone of the NAFZ whereas far fewer major earthquakes took place in the southern zone (small inset of Figure 4, based on Ambraseys & Finkel 1991). This correspondence suggests that the deformation pattern obtained from six years of GPS observations represents the long-term behavior of the neotectonic pattern of the Marmara Sea region.

The orientation of a fault segment controls the strain rate normal to it (WSW: compression, WNW: extension). Figure 4 shows the sense and strength of the shear processes occurring along known fault segments. It illustrates clearly that most of the shear occurs along the northern zone of the NAFZ. This GPS based deformation pattern is strongly supported by models of earthquake stress triggering along the NAFZ (Stein et al. 1997) which suggest a strong build up of stress in the area between Kuzuluk and the Gulf of Izmit. The southern zone undergoes far less shearing than the northern one. Significant dextral shear was detected only at Bursa and

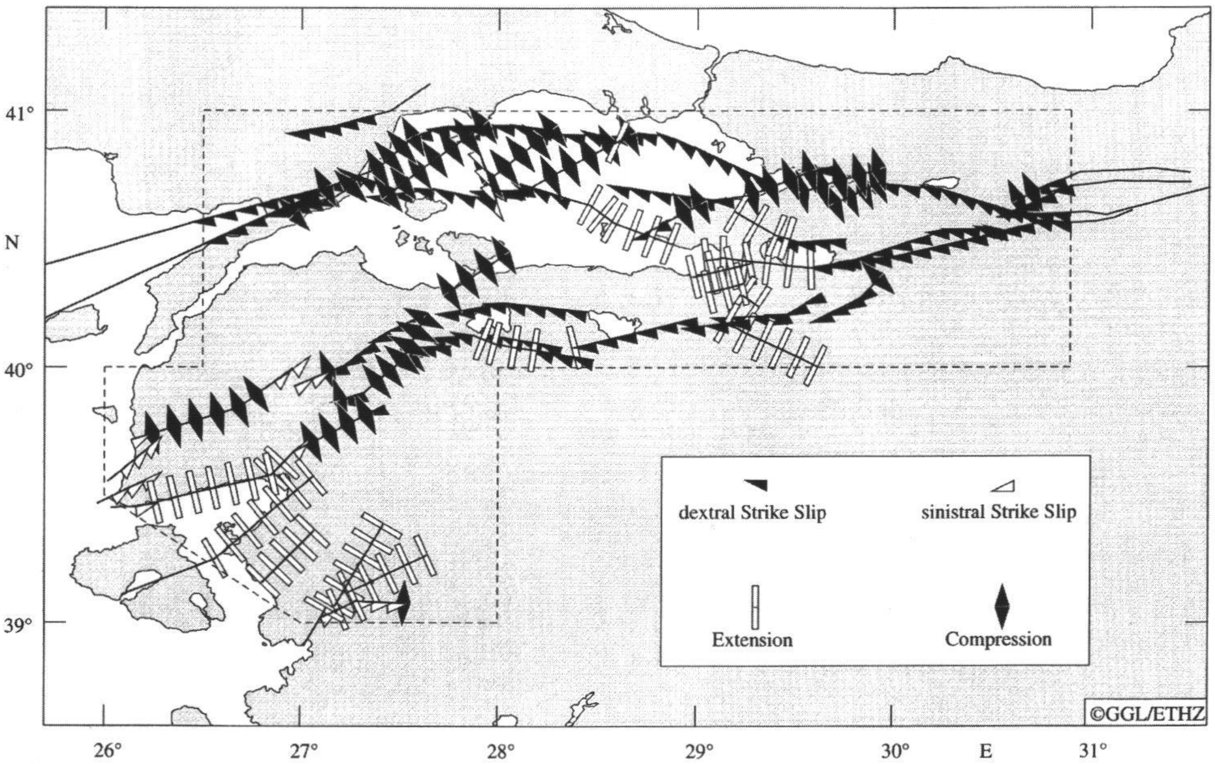

Fig. 5: Unscaled major kind of motion projected along the fault lines. The deformation pattern of the Marmara Sea region is governed by dextral strike-slip. WNW trending faults are characterized by extension, ENE trending faults show compression. The dashed line indicates the region investigated by GPS measurements.

around Gönen. Gönen lies in the area where the fault lines and the velocity field change their direction from E-W to ENE-WSW. We also compared the individual fault motions deduced from the GPS data with neotectonic and seismotectonic results and found a strong correlation both in the amount and direction of the independently derived strain rates (Straub et al. 1997).

5. Geothermal signatures

The distribution of thermal springs in the Marmara Sea region displays a clear pattern (Fig. 6). Large springs with several MW energy output occur in distinct areas. Estimates of the total thermal energy output in the study area from producing thermal wells amount to ca. 100 MW (Simsek & Okandan 1990), and to between ca. 60 and 130 MW from natural thermal springs. Added together, the possible amount of thermal energy output (230 MW) distributed over the investigation area (85,000 km^2) corresponds to a theoretical convective heat flow component of ca. 2.5 mW/m^2. Therefore, the geothermal areas of Northwestern Anatolia form significant anomalies locally.

As the energy output is considered, the aerial distribution of the thermal springs cannot be related to the terrestrial heat flow density field in the study area (Pfister et al. 1998). The occurrence of the springs is much more bound to active tectonic fault lines (Fig. 6). No significant thermal springs are found north of 41°N (Thrace, Istanbul area, northern Adapazari region, compare Fig. 2 for localities). Zones with significant compressional tectonics (e.g. Sarköy, Afyon) or regions with clear strike-slip tectonics (east of Kuzuluk) are characterized by no or lower thermal water activity. On the other hand, extensional tectonics is often associated with significant thermal spring activity (e.g. Bursa, Gemlik, Bergama, Tuzla, Lesbos). The largest springs flow out in active zones dominated by transtensional faults. This can be observed in detail at outcrops described by different authors (Eisenlohr 1997, Greber 1994, Imbach 1997, Jeckelmann 1996, Mützenberg 1997), or in a more regional sense (cf. Fig. 6).

Numerical thermo-hydraulic simulations of selected conceptual hydrogeological models suggest that precipitation water circulates into depths of between 2 and 5 km (Pfister et al. 1997a, Eisenlohr et al. 1997). From there, the warmed-up water quickly ascends along tectonic structures to the thermal discharge zones. An elevated background terrestrial heat flow is not necessarily involved in this process.

A comparison of the recent spatial distribution of micro-seismicity (Ücer et al. 1985, 1997) with the occurrence of thermal springs (Fig. 6) shows a positive correlation. Most significant geothermal sites lie near regions with elevated seismicity. Thus, a relationship between thermal spring energy on one side and seismic energy release and crustal deformation on the other side was postulated by Pfister et al. (1997b). Their analysis confirmed that huge thermal springs are significantly correlated with frequent seismicity and a certain amount of crustal extension. We have strong indications from field studies, as well as from hydrothermal modelling studies, that the thermal groundwater exhibits a constant flow behaviour over several decades, whereas the seismic swarm activity is variable in time and space (Sellami et al. 1997). It is still unclear how far the deep groundwaters or the temperature anomaly in the crust are responsible for opening or closing existing or new fault sys-

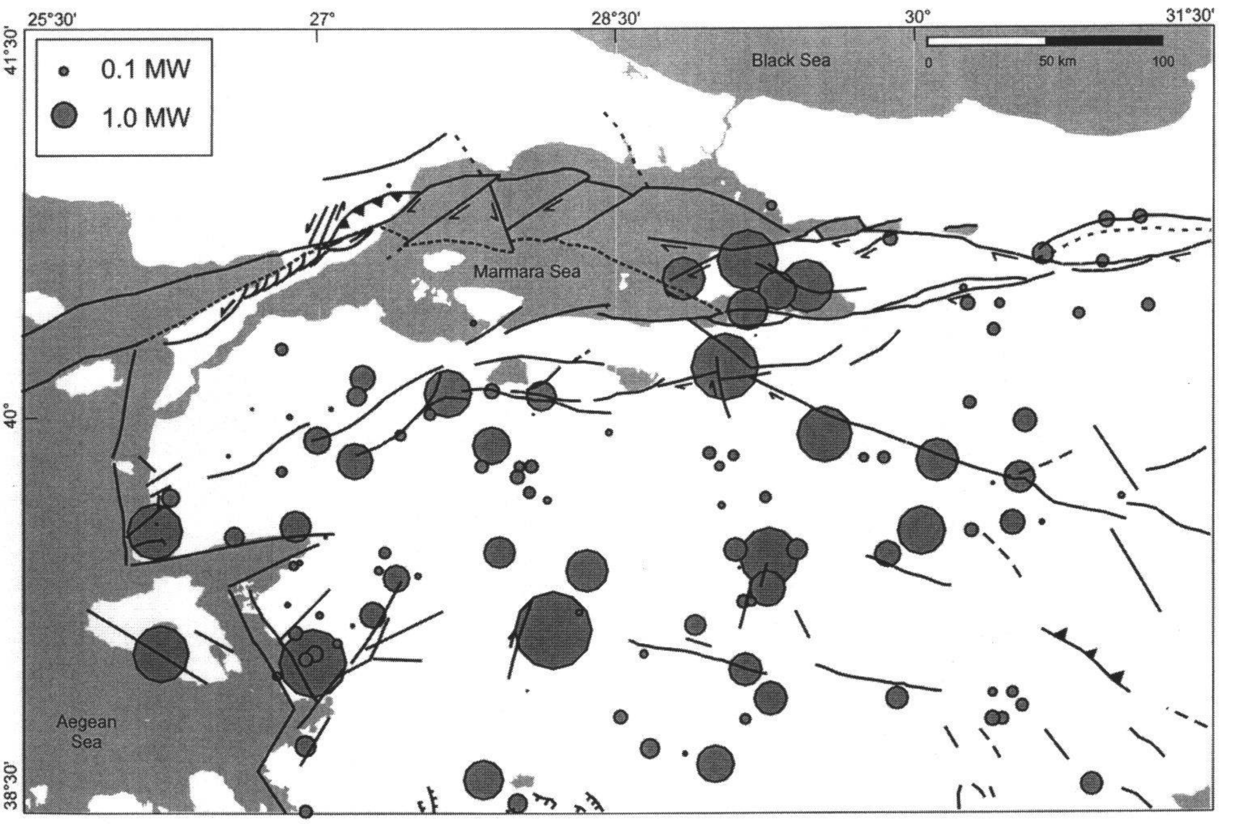

Fig. 6: Thermal spring distribution of the Marmara Sea region according to their energy output (circle size). North of the NAFZ no remarkable thermal activity can be observed, the main springs are bound to fault systems with transtensional character (compare Fig. 5).

tems. However, careful simultaneous observation of thermal water outflow and seismic behavior in such regions is highly promising to determine possible influences. No direct connections were observed between changes in thermal water discharge and nearby seismic events during the project period. However, older historical reports describe the influence of strong earthquakes on the flow rates and outflow locations of thermal springs.

	Balikesir, Bergama (Values in mW/m^2)	Thrace, Adapazari, Bursa (Values in mW/m^2)
Surface heat flow density	75 - 95 (q_0)	50 (q_0)
Paleoclimate correction	+15%	+20%
Crustal contribution	-25	-25
Basal heat flow from the mantle	**60 - 85** (q_R)	**35** (q_A)

Tab. 2: Heat budget through the crust. The stretched lithosphere shows significantly elevated basal heat flow by a factor of ca. 2 (q_R, Balikesir and Bergama) compared to the region not mainly influenced by extensional forces (q_A, Thrace, Adapazari) or less influenced (Bursa). The contribution of the crust to the budget was estimated using the seismic p-velocity depth distribution given by Alptekin et al. (1990) and the relationship between seismic velocities and crustal heat production (Rybach & Buntebarth 1982).

Two different heat flow regimes can be distinguished in the Marmara Sea region (Pfister et al. 1998). Increased heat flow values are measured in the area south of the Marmara Sea (Balikesir and Bergama). They correspond to a general transtensional tectonic regime of this region (Straub & Kahle 1995, 1997). Normal heat flow values occur in the northern and eastern part of the investigation area (Thrace, Adapazari and Bursa region), where the tectonic regime is either more stable or transpressional (Straub & Kahle 1995, 1997; Crampin & Evans 1986).

Thermal anomalies at the Earth's surface can be interpreted in terms of large-scale continental extension. The respective 1D-models were introduced by Lachenbruch & Sass (1978). We explain the regional extension south of the NAFZ with a simple stretching model of the continental lithosphere accompanied by accretion of crystalline material at mantle temperatures balancing isostasy (Pfister et al. 1997b). Following the heat budget defined in Table 2, the measured surface heat flow density q_0 has to be corrected for paleoclimatic influences and reduced by the crustal contribution to yield an estimate for basal mantle heat flow contribution. A ratio of ca. 2 results between regions dominated by a transtensional regime and regions dominated by a stable regime. Applying the simple stretching model (Lachenbruch & Sass 1978) this points to a crustal extension in the range of 0.01–0.03 μstrain/y with a lithosphere thickness of 40–60 km. Regional seismic tomographic results of the Aegean - Mediterranean area confirm the existence of a thin lithosphere (Spakman 1990).

The Marmara Sea itself may be underlain by an even thinner lithosphere. This assumption is supported by the Bouguer gravity anomaly of up to +60 mgal around the Marmara Sea (Klingele & Medici 1997). Partial melting might occur at shallow depth below the deep Marmara Sea trough, significantly influencing the thermal crustal structure and fluid migration.

6. Deep groundwater circulation

Fluids play a major role in the dynamics of active faults. The frequent and large thermal springs in the study region point to a significant potential influence. Therefore, thermal and mineral waters have been studied in detail to elucidate origin and circulation paths.

6.1 Main water characteristics

The mineral waters of the Marmara area show a large variety of chemical and isotopic compositions. By far the most prominent cation is sodium, while amongst the anions bicarbonate and sulfate prevail. TDS values (Total Dissolved Solids) normally range from 100 to several thousand mg/L. Elevated TDS contents of up to 60,000 mg/L in the areas of Tuzla and Bergama are explained by admixtures of brines. The chemical composition of the bulk of the waters can be readily explained by (1) dissolution of soluble rock minerals such as evaporites and carbonates, (2) hydrolysis of silicate minerals, (3) cation exchange in contact with clay minerals, (4) oxidation and dissolution of sulfide minerals, and (5) mixing of waters with different origins (Balderer 1997). CO_2 partial pressure was recognized as an important factor in water-rock interaction.

Oxygen and hydrogen isotopes show that most thermo-mineral waters are of mete-

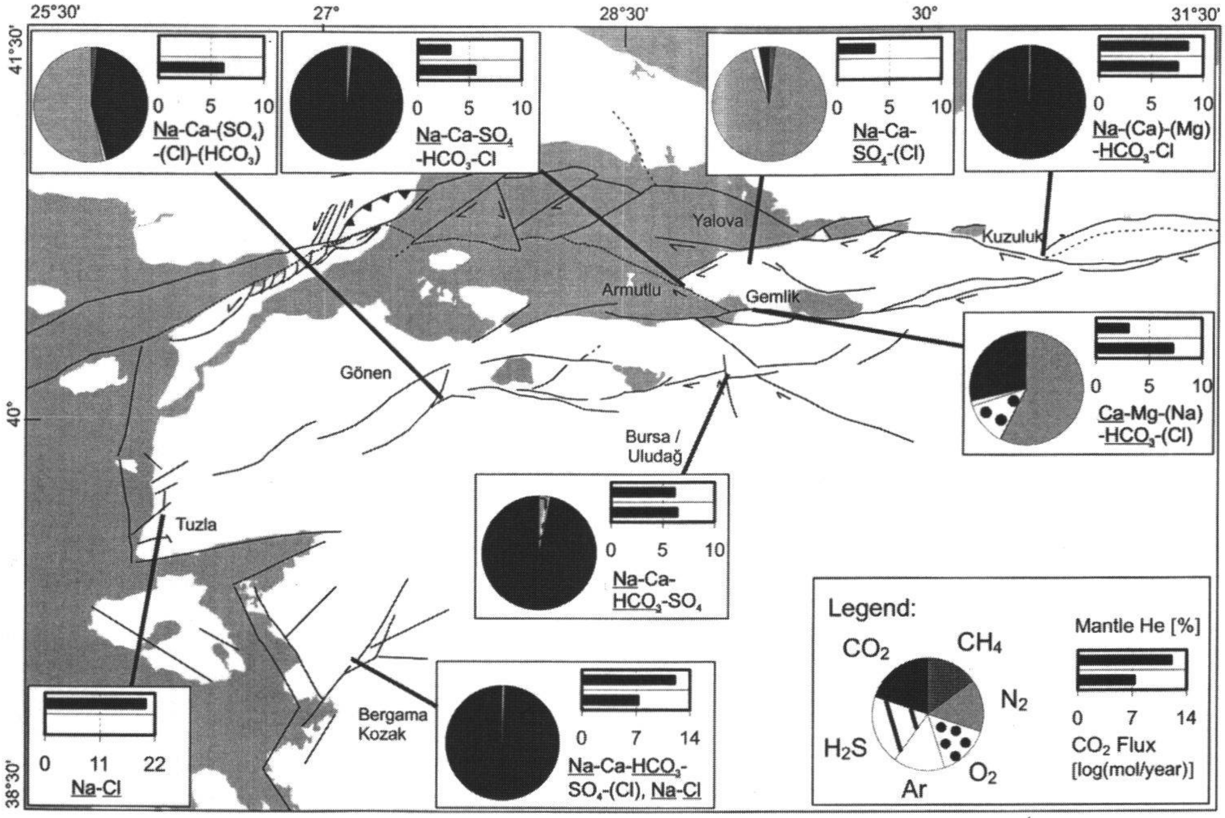

Fig. 7: The geothermal investigation areas are represented by selected thermal springs and their characteristics: gas content, main chemical characterization, mantle helium content and total CO_2 flux. The thermal springs show considerable mantle fluid contributions as well as high CO_2 contents. The latter is typical for tectonic active areas (Irwin & Barnes 1980).

oric origin and part of the modern hydrologic water cycle; only few indicate recharge under distinctly cooler climatic conditions. There are no signs of involved metamorphic or primordial waters.

Circulation depths can be estimated using geothermometers. The most consistent results were obtained applying chalcedony and $\delta^{18}O(SO_4\text{-}H_2O)$ thermometers. Highest temperatures in the range of 146–170°C were calculated in the Bergama area (Jeckelmann 1996). In a geothermal well at Tuzla a maximum water temperature of 175°C was measured (Mützenberg 1997). From these temperatures, maximum circulation depths of some 6 km are expected.

6.2 Main gas characteristics (Figure 7)

The main dissolved and free gases are CO_2 (0.1–100 vol%, average: 57 vol%, up to 2009 mg/kg) and N_2 (0–96.8 vol%, average: 38 vol%). However, the origin of most N_2 is interpreted to be atmospheric as elevated concentrations are always combined with high Ar contents. Thus CO_2 turns out to be by far the most prevalent non-superficial gas component. The Gemlik waters have indications for air admixtures from karstic cavities (Eisenlohr et al. 1997). There exist several indications for deep-seated inorganic CO_2 sources: (1) A positive logarithmic correlation between dissolved CO_2 contents and estimated reservoir water temperatures. (2) In most cases CO_2 portions make up more than 30 % of the total gas, which is indicative for an inorganic origin (e.g. Dai et al. 1996). (3) Most samples show $\delta^{13}CO_2$ values in the range of mantle CO_2 and/or decomposition of marine carbonates (Pfister et al. 1997b). Gases with mantle $\delta^{13}CO_2$ values are consistent with elevated mantle helium contributions and the occurrence of mantle methane in the corresponding waters.

The occurrence of CH_4 is less important as concentrations do not exceed 1.7 vol% (average: 0.2 vol%). However, its isotopic signature gives valuable information on the origin of this gas. Rather positive $\delta^{13}C$ values of three analysed samples from the Bergama area clearly indicate primordial CH_4. This finding coincides with the $\delta^{13}CO_2$ data of the same samples pointing to mantle origin.
As a third mantle fluid helium was detected at all thermal sites in the Marmara area by the means of $^3He/^4He$ ratios and neon measurements. From total He, up to 20.1% (average: 5.9%) originates from the Earth's mantle. Air-corrected R/R_a ratios vary between 0.27 at Yalova and 1.47 at Tuzla.

6.3 Fluid flow systems and CO_2 flux

Two different flow systems can be distinguished in the Marmara area: a «shallow» and a «deep» one (Fig. 10). In the shallow system, mostly meteoric waters circulate in the uppermost kilometers of the upper brittle crust. Residence times range between a few months and several tens of thousands of years. Advective forces as well as buoyancy effects due to gas occurrences, temperature and density differences are considered to be the main driving mechanisms. Preferential flow paths are along open fractures and discharge zones are restricted to extensional or transtensional stress regimes.

In contrast to the shallow flow system, the fluids of the deep flow system flow basically unidirectional, i.e. from the upper mantle and lower crustal levels towards the Earth's surface. Carbon dioxide, methane and helium are fluids of this system. They enter the base of the seismogenic zone at near lithostatic pressures and get concentrated within deep reaching (brittle) fault structures.

The shallow flow system is strongly overprinted by fluids of the deep system. Ascending CO_2 influences the chemical as well as the physical properties of the thermo-mineral waters, as hydrolysis is intensified and the specific density is lowered (Greber 1994).

The dissolution of calcite with CO_2 gas and water liberates Ca and HCO_3 ions. Half of the HCO_3 originates from CO_2, the other half from calcite. As shallow waters generally are dominated by calcite dissolution, these waters plot close to the line of electroneutrality resulting from the above reaction (Fig. 8). The only HCO_3-depleted thermo-mineral waters are the formation waters of Tuzla and the purely crystalline waters of Yalova. At both places no CO_2 outgassing was observed. Most thermo-mineral waters, however, plot to the left of that line. This deviation indicates that most HCO_3 must be attributed to the dissolution of CO_2 gas in water. As HCO_3 is the dominant carbon species under the pH ranges considered, dissolved amounts of CO_2 ($CO_{2(d)}$) can be approximately calculated according to $[CO_{2(d)}] = [HCO_3^-] - [Ca^{2+}]$, where $[HCO_3^-]$ and $[Ca^{2+}]$ are measured ions in mol/L. CO_2 values calculated with this method highly correlate with *measured* concentrations of dissolved CO_2. By multiplying the resulting CO_2 content by the discharge, the CO_2

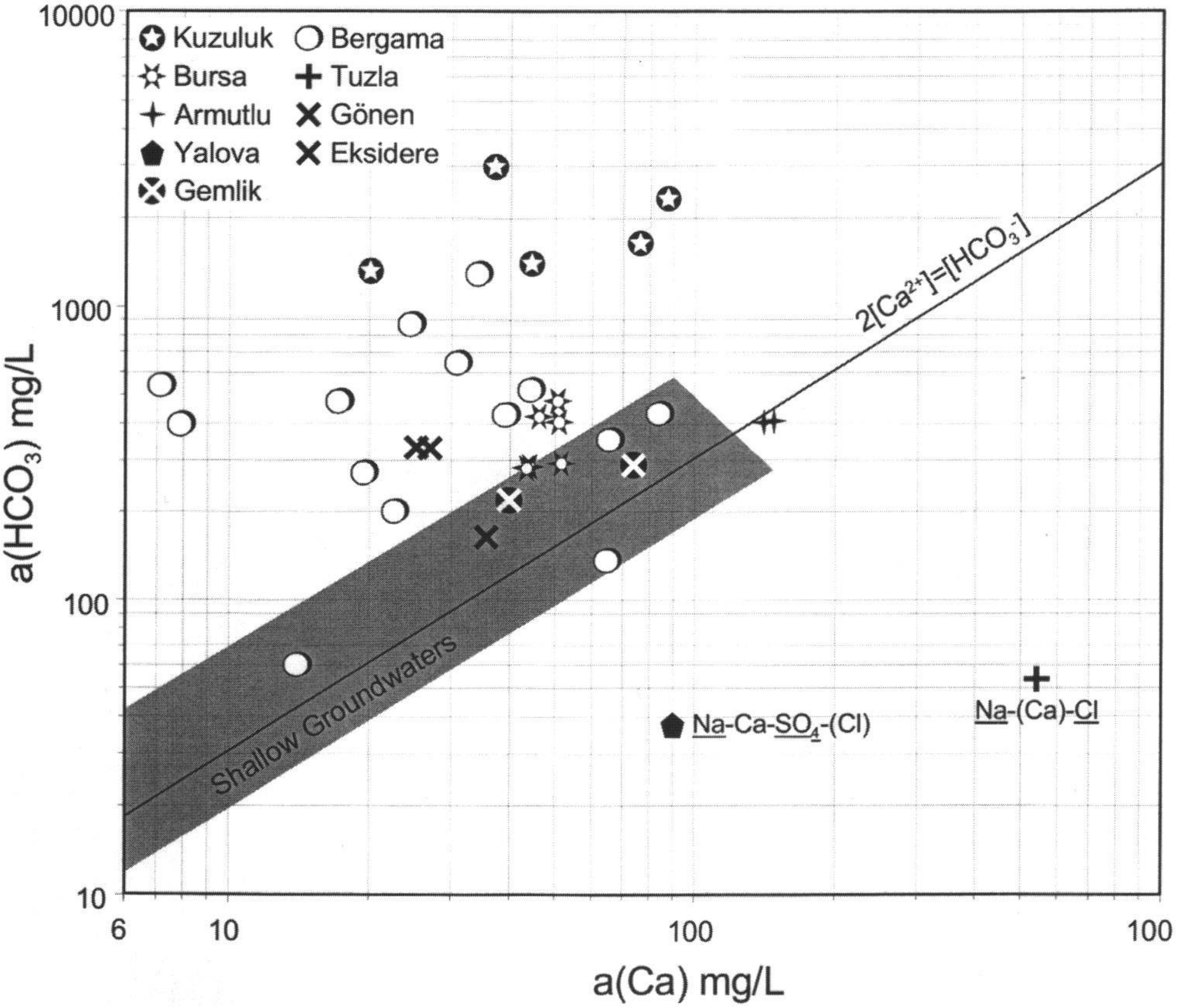

Fig. 8: Ca vs. HCO_3 activity. In contrast to the shallow groundwaters, the process of calcite dissolution is of subordinate importance for the thermo-mineral waters of the Marmara area. Instead of that, they are dominated by hydrolysis processes controlled by large amounts of CO_2 gas, ascending from deeper crustal and upper mantle levels. The thermal springs of Tuzla and Yalova are chemically not influenced by CO_2. The first are interpreted as mainly formation waters, the second as crystalline waters.

flux of a specific spring or well can be estimated. Ninety thermo-mineral springs and wells were evaluated in this way. CO_2 fluxes of each thermal area can be drawn from Fig. 7 . The total CO_2 flux calculated for the 90 thermo-mineral springs of 7.3 x 10^7 mol/y is considered a minimum value, as (1) not all CO_2-rich springs of the Marmara area are included, (2) besides HCO_3 there are other important carbon species such as H_2CO_3, dissolved and free CO_2 gas, and (3) CO_2 outgassing occurs also in areas without CO_2-rich springs (Greber 1992).

7. Discussion and conclusions

The principal axes and the values of compressional and extensional strain rates calculated from the GPS velocity field, yield insight into the major features subjected to the stress pattern at the western end of the NAFZ. The calculation of extension-

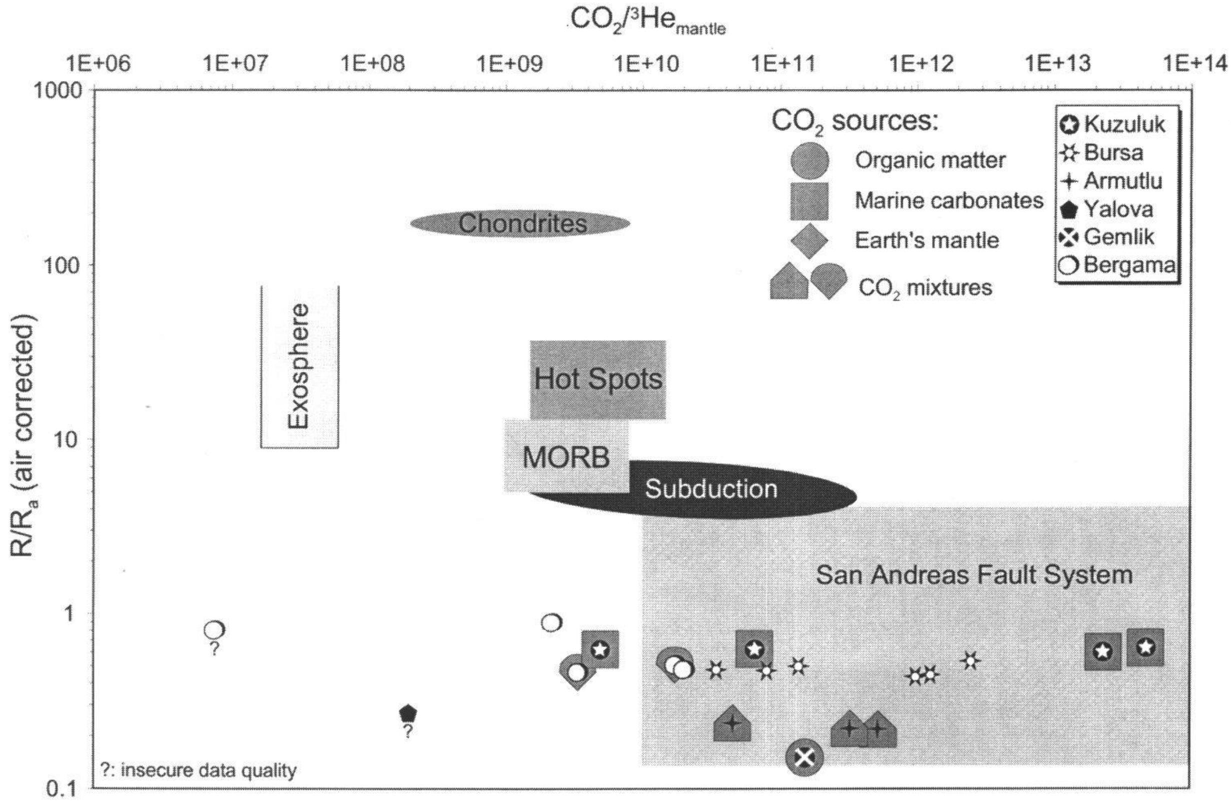

Fig. 9: Plot of $CO_2/^3He_{mantle}$ ratio vs. air-corrected helium isotopic ratio R (normalised to atmospheric ratio R_a). Also indicated are sources of CO_2 based on $\delta^{13}CO_2$ gas measurements. An upper limit for R/R_a values seems to exist for San Andreas as well as Marmara tectonics. Along the San Andreas fault, springs with higher mantle helium values than in the Marmara area are observed. The Marmara thermo-mineral waters show a wide range of $CO_2/^3He_{mantle}$, from values close to MORB to more than 10,000 higher, similar to the thermo-mineral waters of the San Andreas Fault System (Kharaka, written communication). The likely sources of the additional CO_2 are mainly mantle outgassing and marine carbonates.

al, compressional and shear strain components projected onto the major fault systems shows that dextral-type of shear dominates in the Marmara Sea region. This is a clear manifestation of the westward motion of Anatolia. The GPS strain rate results corroborate previous results on stress trajectories determined from marine geophysical data (Lyberis 1984). The dextral strike-slip motion is frequently combined with compressional and extensional forces and occurs along the so-called northern zone of the NAFZ. The area north of this zone, the Kocaeli Peninsula and Thrace, are stable at the present time. Based on the highly coherent regional deformation pattern (e.g. Reilinger et al. 1997), we assume that the geodetically observed deformation rates are representative for the bulk of the Earth's crust in the investigated area. The thermal springs distinctly are related to NAFZ structures; thermal water activity is extremely low to the north. This is interpreted by the conceptual model of a rather sharp plate boundary.

Large-scale extension is observed mainly within the Marmara Sea as well as south of it. This extension is manifested by an elevated terrestrial heat flow density. Stretching of the lithosphere is the responsible tectonic process there and isostasy is balanced by accretion of crystalline material at mantle temperatures. Local extension starts at Kuzuluk and is wide-spread further west of it.

The southern zone of the NAFZ is less active. At present, it mainly experiences a reactivation of older tectonic structures. The orientation of the individual faults has a predominant influence on the deformation style. Elevated thermal spring activity is a sign of transtensional tectonics. The carbon isotopes of CO_2 and the $CO_2/^3He_{mantle}$ ratios of the Bergama thermal springs (Fig. 9) indicate a predominant mantle origin of CO_2, which demonstrates the strongest influence of extension in this area.

The zonation of the current neotectonic activity is interpreted in a geological model as a rotating West Anatolian Block. The sense as well as the amount of faulting has been quite constant since the Late Pliocene. The E-W oriented deformation rate of 22 mm/y along the northern zone of the NAFZ relative to Thrace agrees well with the geologically derived rates. Several different phases of deformation were active before this recent phase. The southern zone experienced its strongest activity during the Miocene, when the rotation as well as the extension in the Aegean realm started and persisted. The function of these old fault structures has changed completely during the neotectonic period up to now. However, it is remarkable that the thermal springs at Tuzla and Kuzuluk have been active since the Middle / Late Miocene (c.f. Tab. 1).

Worldwide CO_2 discharges are concentrated along major zones of seismicity (Irwin & Barnes 1980). In the Marmara Sea region, the discharges are partly related to the interaction of the Eurasian Plate with the Anatolian Block, and partly to the extensional tectonics at the transition zone between the Aegean Sea and the Anatolian Block. As CO_2 can generate pore pressures approaching lithostatic loads, effective stresses are lowered and faults weakened (e.g. Rice 1992). Water-rock interaction is believed to play an important role not only in the rheology of the fault zones, but also in the various aspects of the earthquake cycle because mineral dissolution and precipitation are strongly influenced by grain size, pore fluid pressures and mechanical stress (Sibson 1992). High fluid pressures are postulated to be the reason for the anomalous weakness of the SAFS (Irwin & Barnes 1975, Zoback et al. 1987, Rice 1992). The maintenance of the supposed high fluid pressures within the fault core is still a question of debate (Scholz 1996, 1998). The most recent data from Kennedy et al. (1997) and Kharaka et al. (in prep.) show that fluids of mantle origin take part in the groundwater circulation at the SAFS. These fluids could be responsible to maintain high pore pressures within the fault core.

For comparison, the CO_2 flux of the SAFS is estimated at 10^{11} mol/y (Kennedy et al. 1997), the global flux at 3×10^{12} mol/y (Bredehoeft & Ingebritsen 1990). The highest CO_2 flux in the Marmara Sea region is observed at Kuzuluk in an extensional structure in an overall transpressive stress regime. Other high fluxes are reported from Gemlik and Bergama, two pronounced (trans)tensional areas. It is interesting to note that at Tuzla, where more than 20 % of the helium is primordial, no CO_2 is outgassing.

Figure 9 shows the $CO_2/^3He_{mantle}$ ratio vs. the air-corrected helium isotopic ratio R. An upper limit of R/R_a ratios seems to exist for the San Andreas zone as well as for the Marmara neotectonics. This limit is clearly below the other main tectonic realms, which demonstrates restricted influence of mantle melts. On the other hand, $CO_2/^3He_{mantle}$ values show a wide range, close to MORB to more than 10,000 times higher.

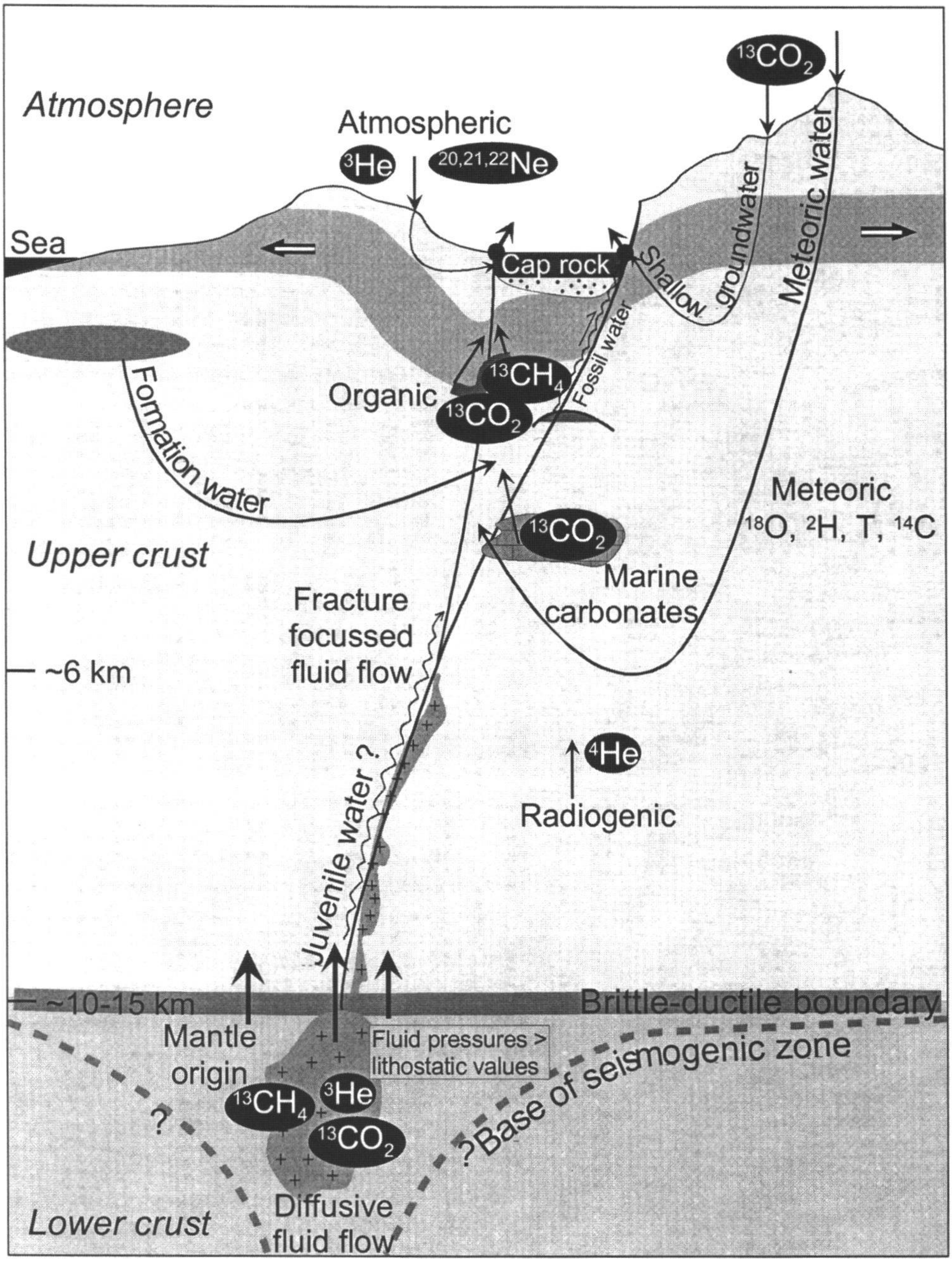

Fig. 10: Conceptual model of main fluid processes in the upper and lower crust: two different flow systems can be distinguished, a shallow and a deep one. Fluid reservoirs are indicated as they are in the atmosphere, in different crustal levels as well as in greater depths like in the mantle. Fluid migration differs: fracture focused fluid flow in the upper crust, more diffusive fluid flow in the lower crust. The base of seismogenic zone is influenced by rising fluids. Brittle-ductile boundary is variable according to the thermal profile of the crust.

Although no data on the strength of the NAFZ is available, fluid pressures might play an important role on fault behavior in the Marmara area. Both, the shallow and the deep flow systems have to be considered (Fig. 10): (1) Meteoric and connate water can be drawn into the fault zone and become trapped by mineral reactions. The high fluid pressures to weaken the fault are reestablished by compaction of the sealed fault-zone materials (Byerlee 1990 and 1993, Sleep & Blanpied 1993). In the Marmara Sea area this fluid circulation occurs in the upper 6 km of the crust. (2) Fault-weakening fluid pressures are generated by a high flux of deep crustal or mantle fluid that are continuously supplied to the seismogenic zone from the ductile lower crust at superlithostatic pressures. In the Marmara area, CO_2 is the relevant fluids to build up high pressures, while helium and methane exhibit more indicative character as mantle sources can properly be identified.

Acknowledgements

The MARMARA Poly-Project was financed and supported by the Swiss Federal Institute of Technology (ETH Zürich). We would like to thank Prof. R. Hütter, former ETHZ vice-president, and the research commission of the school for their broadmindedness and confidence. Generous support came from the Istanbul Technical University. Thanks go to all colleagues at the ETHZ and the ITU involved within the project. Many thanks also to Prof. T. Edwards for critical reading of the manuscript and for helpful suggestions for its improvement.

Literature

ALPTEKIN, Ö., ILKISIK, O.M., EZEN, Ü. & ÜCER, S.B. 1990: Heat flow, Seismicity and the crustal structure of Western Anatolia. *in* Proceedings, International earth sciences congress on Aegean regions, 1–6 October, Izmir; Turkey.

AMBRASEYS, N.N. & FINKEL, C.F. 1991: Long-term seismicity of Istanbul and of the Marmara Sea region. Terra Nova, v. 3, p. 527–539.

BALDERER, W. 1997: Mechanisms and processes of groundwater circulation in tectonically active areas. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 417–448.

BARKA, A.A. 1992: The North Anatolian fault zone. Annales Tectonicae, Special Issue, Supplement to Volume VI, p. 164–195.

BARKA, A.A. 1997: Neotectonics of the Marmara region. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 55–87.

BREDEHOEFT, J.D. & INGEBRITSEN, ST.E. 1990: Degassing of Carbon Dioxide as a Possible Source of High Pore Pressures in the Crust. *in* Bredehoeft, J.D. & Norton, D. L., eds., The role of fluids in crustal processes, Nat. Acad. Press Washington D.C., p. 158–164.

BYERLEE, J. 1990: Friction, overpressure and fault normal compression. Geophysical Research Letters, v. 17, no. 12, p. 2109–2112.

BYERLEE, J. 1993: Model for episodic flow of high-pressure water in fault zones before earthquakes. Geology, v. 21, p. 303–306.

CRAMPIN, S. & EVANS, R. 1986: Neotectonics of the Marmara sea region of Turkey. Journal of the Geological Society, London, v. 143, p. 343–348.

DAI, J.X., SONG, Y., DAI, CH.S. & WANG, D.R. 1996: Geochemistry and accumulation of carbon dioxide gases in China. AAPG Bulletin, v. 80, no. 10, p. 1615–1626.

EISENLOHR, TH. 1997: The thermal springs of the Armutlu Peninsula (NW Turkey) and their relationship to geology and tectonic. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 197–227.

EISENLOHR, TH., PFISTER, M. & BALDERER, W. 1997: Environmental isotope study and 2-D-modelling of cold and thermal karst within the Gemlik (Bursa) area of Northwestern Turkey. *in* Günay, G. & Johnson, A. I., eds., Karst Waters & Environmental Impacts, Balkema, Rotterdam, p. 231–237.

EYIDOGAN, H. & JACKSON, J. 1985: A seismological study of normal faulting in the Demirci, Alasehir and Gediz earthquakes of 1969–1970 in Western Turkey: implications for the nature and geometry of deformation in the continental crust. Geophys. J.R. Astron. Soc., v. 81, p. 569–637.

GENC, S.C. & YILMAZ, Y. 1995: Evolution of the Triassic continental margin, Northwest Anatolia. Tectonophysics, v. 243, p. 193–207.

GREBER, E., 1992: Das Geothermalfeld von Kuzuluk/Adapazari – Geologie, aktive Tektonik, Hydrogeologie, Hydrochemie, Gase und Isotope. Ph.D. thesis, ETH Zürich, No. 9984, 213 p.

GREBER, E. 1994: Deep circulation of CO_2-rich paleowaters in a seismically active zone (Kuzuluk/Adapazari, Northwestern Turkey). Geothermics, v. 23, no. 2, p. 151–174.

IMBACH, TH. 1997: Geology of Mount Uludag with emphasis on the genesis of the Bursa thermal waters, Northwest Anatolia, Turkey. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 239–266.

IRWIN, W. P. & BARNES, I. 1975: Effect of geologic structure and metamorphic fluids on seismic behavior of the San Andreas fault system in central and northern California. Geology, v. 3, p. 713–716.

IRWIN, W.P. & BARNES, I. 1980: Tectonic Relations of Carbon Dioxide Discharges and Earthquakes. Journal of Geophysical Research, v. 85, no. B6, p. 3115–3121.

ISSEVEN, T., TAPIRDAMAZ, C., ÖZCEP, F., HISARLI, M. ORBAY, N. & SANVER, M. 1995: Tectonics of Northwest Anatolia and Paleomagnetic Results. Jeofizik, v. 9, no. 10, p. 201–212.

JACKSON, J.A. & MCKENZIE, D.P. 1984: Rotational mechanisms of active deformation in Greece and Iran. *in* Dixon, J. E. & Robertson, A. H. F., eds., The Geological Evolution of the Eastern Mediterranean, The Geological Society, Blackwell Scientific Publications, p. 743–754.

JACKSON, J.A. & MCKENZIE, D.P. 1988: The Relationship between Plate Motions and Seismic Moment tensors & the rates of Active Deformation in the Mediterranean and the Middle East. Geophys. J. R. Astr. Soc., v. 93, p. 45–73.

JECKELMANN, CH. 1996: Genese lokaler Thermalwasservorkommen in der Region Bergama / W-Türkei. Ph.D. thesis. ETH Zürich, Nr. 11990, 199 p.

KENNEDY, B.M., KHARAKA, Y.K., EVANS, W.C., ELLWOOD, A., DEPAOLO, D.J., THORDSEN, J., AMBATS, G. & MARINER, R.H. 1997: Mantle Fluids in the San Andreas Fault System. California, Science, v. 278, p. 1278–1281.

KHARAKA, Y.K., THORDSEN, J.J., EVANS, W.C. & KENNEDY, B.M. in prep.: Geochemistry and hydromechanical interactions of fluids associated with the San Andreas fault system, California. *in* Haneberg and others, eds., Faults and Subsurface Fluid Flow (submitted).

KISSEL, C., LAJ, C., MAZAUD, A., POISSON, A., SAVASCIN, Y., SIMEAKIS, K., FRAISSINET, C. & MERCIER, J.L. 1989: Paleomagnetic study of the neogene formations of the Aegean area. *in* Sengör, A. M. C., eds., Tectonic evolution of the Tethyan region, NATO ASI Series, Mathematical and Physical Sciences, v. 259, p. 159–189.

KLINGELE, E. & MEDICI, F. 1997: Gravimetric studies of the Marmara sea region. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 487–501.

KONDOPOULOS, D., ATZEMOGLOU, A. & PAVLIDES, S. 1996: Paleomagnetism as a tool for testing geodynamic models in the North Aegean: convergences, controversies and a further hypothesis. *in* Morris, A. & Tarlin, D., eds., Paleomagnetism and Tectonics of the Mediterranean Region, Geol. Soc. Special Publications, no. 105, p. 277–288.

LACHENBRUCH, A.H. & SASS, J.H. 1978: Models of extending lithosphere and heat flow in the Basin and Range province. Geological Society of America, Memoir 152, p. 209–250.

LEPICHON, X. & ANGELIER, J. 1981: The Aegean Sea. Phil. Trans. R. Soc. Lond., A 300, p. 357–372.

LYBERIS, N. 1984: Tectonic evolution of the N. Aegean Trough. *in* Dixon, J. & Robertson, A., eds., The Geological evolution of the Eastern Mediterranean, Geol. Soc. London, Blackwell Scientific Publications, Oxford, London, Edinburgh, p. 709–725.

MEIJER, P. & WORTEL, M. 1996: Temporal variation in the stress field of the Aegean region. Geophys. Res. Letters, v. 23, no. 5, p. 439–442.

MERCIER, J., SOREL, D., VERGELY, P. & SIMEAKIS, K. 1989: Extensional tectonic regimes in the Aegean basins during the Cenozoic. Basin Research, v. 2, p. 49–71.

MCKENZIE, D. 1972: Active Tectonics of the Mediterranean Region. Geophys. J. R. Astron. Soc., v. 30, p. 109–185.

MICHEL, G.W., WALDHÖR, M., NEUGEBAUER, J. & APPEL, E. 1995: Sequential rotation of stretching axes and block rotations: a structural and paleomagnetic study along the North Anatolian Fault. Tectonophysics, v. 243, p. 97–118.

MUELLER, ST., KAHLE, H.-G. & BARKA, A.A. 1997: Plate tectonic situation in the Anatolian-Aegean region. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 11–28.

MÜTZENBERG, ST. 1997: Nature and origin of the thermal springs in the Tuzla area, Western Anatolia, Turkey. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 301–320.

PAPAZACHOS, C.B. & KIRATZI, A. 1996: A detailed view of the active crustal deformation in the Aegean and surrounding area. Tectonophysics, v. 253, p. 129–153.

PAVONI, N. 1961: Die nordanatolische Horizontalverschiebung. Geologische Rundschau, v. 51, p. 122–139.

PFISTER, M., RYBACH, L. & SIMSEK, S. 1997a: Geothermal reconnaissance of the Marmara Sea region. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 504–535.

PFISTER, M., BALDERER, W., GREBER, E., KAHLE, H.-G., MAYER-ROSA, D., MUELLER, ST., RYBACH, L., SCHINDLER, C., SELLAMI, S. & STRAUB, CH. 1997b: Synthesis of the MARMARA Poly-Project. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 540–565.

PFISTER, M., RYBACH, L. & SIMSEK, S. 1998: Geothermal reconnaissance of the Marmara Sea region (NW Turkey): surface heat flow density in an area of active continental extension. Tectonophysics, v. 291, no. 1–4, p. 77–89.

REILINGER, R., MCCLUSKY, S., ORAL, B., KING, R., TOKSÖZ, M., BARKA, A.A., KINIK, I., LENK, O. & SANLI, I. 1997: GPS measurements of present-day crustal movements in the Arabia-Africa-Eurasia Plate collision zone. J. Geophys. Res., v. 102, no. B5, p. 9983–9999.

RICE, J. R. 1992: Fault Stress States, Pore Pressure Distributions, and the Weakness of the San Andreas Fault. *in* Evans, B. & Wong, T.-F., eds., Fault Mechanics and Transport Properties of Rocks, Academic Press, San Diego, p. 475–503.

ROBBINS, J., DUNN, P.J., TORRENCE, M.H. & SMITH, D.E. 1995: Deformation in the Eastern Mediterranean. *in* Sahin, M. & Cross, P. A., eds., Proceedings of the First Turkish International Symposium on Deformations 1994, p. 738–745.

RYBACH, L. & BUNTEBARTH 1982: Relationships between the petrophysical properties density, seismic velocity, heat generation, and mineralogical constitution. Earth and Planetary Science Letters, v. 57, p. 367–376.

SCHINDLER, C. 1997: Geology of Northwestern Turkey: Results of the Marmara Poly-Project. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 329–373.

SCHINDLER, C. & PFISTER, M. 1997: Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology. vdf Zürich, ISBN 3 7281 2425 7, 570p. http://www.upress.de/abstracts/3-7281-2425-7.html

SCHOLZ, CH.H. 1996: Faults without friction?. Nature, v. 381, p. 556–557.

SCHOLZ, CH.H. 1998: Earthquakes and friction laws. Nature, v. 391, p. 37–42.

SELLAMI, S., PAVONI, N., MAYER-ROSA, D., MUELLER, ST., EYIDOGAN, H., AKTAR, M., GÜRBÜZ, C., BARIS, S., POLAT, O. & YALCIN, N. 1997: Seismicity and Seismotectonics of the Bursa region. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 449–485.

SENGÖR, A.M.C. 1979: The North Anatolian transform fault: its age, offset and tectonic significance. J. geol. Soc. Lon., v. 136, p. 269–282.

SEYMEN, I. 1975: Tectonic characteristics of the North Anatolian Fault zone in the Kelkit valley. PhD thesis. Istanbul Tech. Univ.

SIBSON, R.H. 1992: Implications of fault-valve behavior for rupture nucleation and recurrence. Tectonophysics, v. 211, p. 283–293.

SIMSEK, S. & OKANDAN, E. 1990: Geothermal energy development in Turkey. Geothermal resources council Transactions, v. 14, Part 1, p. 257–266.

SLEEP, N.H. & BLANPIED, M.L. 1993: Ductile creep and compaction: A mechanism for transiently increasing fluid pressure in mostly sealed fault zones. Pure and Applied Geophysics, v. 143, p. 9–40.

SPAKMAN, W. 1990: Tomographic images of the upper mantle below central Europe and the Mediterranean. Terra Nova, v. 2, no. 6, p. 542–553.

STEIN, R., BARKA, A.A. & DIETERICH, J. 1997: Progressive earthquake failure on the North Anatolian fault since 1939 by stress triggering. Geophys. J. Int., v. 128, p. 594–604.

STRAUB, CH. & KAHLE, H.-G. 1995: Active Crustal Deformation in the Marmara Sea Region, NW Anatolia, Inferred from GPS Measurements. Geophysical Research Letters, v. 22, no. 18, p. 2533–2536.

STRAUB, CH. & KAHLE, H.-G. 1997: Recent crustal deformation and strain accumulation in the Marmara Sea region, NW Anatolia, inferred from repeated GPS measurements. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 417–447.

STRAUB, CH., KAHLE, H.-G. & SCHINDLER, C. 1997: GPS and geologic estimates of the tectonic activity in the Marmara Sea region, NW Anatolia. J. Geophys. Res., v. 102, no. B12, p. 27'587–27'601.

TAPIRDAMAZ, C. & YALTIRAK, C. 1996: Results of Paleomagnetic study on young Volcanics in Thrace. Jeofizik, v. 9,no. 10, p. 213–218.

ÜCER, S.B., CRAMPIN, S., EVANS, R., MILLER, A. & KAFADAR, N. 1985: The MARNET radiolinked seismometer network spanning the Marmara Sea and the seismicity of Western Anatolia. Geophys. J.R. astr. Soc., v. 83, p. 17–30.

ÜÇER, B., EYIDOGAN, H., GÜRBÜZ, C, BARKA, A. A. & BARIS, S. 1997: Seismic investigations of the Marmara region. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 89–99.

WESTAWAY, R. 1994: Present-day kinematics of the Middle East and eastern Mediterranean. Journal of Geophysical Research, v. 99, no. B6, p. 12'071–12'090.

YILMAZ, Y. 1997: Geology of Western Anatolia. *in* Schindler C. & Pfister, M., eds., Active Tectonics of Northwestern Anatolia - The Marmara Poly-Project, A multidisciplinary approach by Space-Geodesy, Geology, Hydrogeology, Geothermics and Seismology, vdf Zürich, p. 31–53.

ZOBACK, M.D., ZOBACK, M.L., MOUNT, V.S., SUPPE, J., EATON, J.P., HEALY, J.H., OPPENHEIMER, D., REASENBERG, P., JONES, L., RALEIGH, C.B., WONG, I.G., SCOTTI, O. & WENTWORTH, C. 1987: New evidence on the state of stress on the San Andreas fault system. Science, v. 238, p. 1105–1111.