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Cross-basin Faulting and Extinction of Pull-apart Basins in the Sea of Marmara, NW Turkey

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Abstract: Although offshore multi-channel seismic reflection and multi-beam bathymetric studies were intensively carried out in the Sea of Marmara especially after the August 17, 1999 İzmit earthquake (Mw 7.4), some basic problems remain unsolved, for example whether the seafloor was cut by a double fault system or just by a single fault. The researchers advocating the double fault system assumed that most of the deformation occurred along the margins of the basins and concluded that the classical model of pull-apart basin formation along releasing bends or stepovers within an east–west-trending dextral strike-slip system prevails. An alternative and completely different proposition proposed by some other researchers suggested that the seafloor was cut by a single, continuous strike-slip fault that does not coincide with the basin margins and hence does not fit the pull-apart model. These two apparently opposing ideas in fact, are not in conflict with each other; but instead define successive events. The fault geometry in the Sea of Marmara simply reflects a transition from complex pull-apart basins into single strike-slip faults. All the pull-apart basins in the world, regardless of offset geometry, evolve progressively from narrow grabens bounded by oblique-slip link faults to wider rhombic basins flanked by terraced basin sidewall fault systems. Field observations and analogue models show that in the later stages of this widening, the cross-basin faults cut the floor of the pull-apart basins and link the offset principal displacement zones. The jogs and therefore the pull-apart basins become extinct and strike-slip faults become straight as time passes. This development history of the faults and accompanying basins is valid also for the North Anatolian Fault and the basins in the northern Sea of Marmara as well as those in the Gulf of İzmit and for the other sections of the fault on land displaying two sets of faults, the older being inactive.

Key Words: The North Anatolian Fault, Sea of Marmara, pull-apart basin, cross-basin fault, strike-slip faulting, basin formation

Marmara Denizi'nde (KB Türkiye) Çapraz Faylanma ve Çek-ayır Havzaların Sönümlenmesi

Özet: Marmara Denizi'nde, özellikle 17 Ağustos 1999 İzmit depreminden sonra kıyı ötesi çok kanallı sismik yansıma ve çok ışınlı batimetrik inceleme çalışmalarının yoğun olarak yapılmış olmasına rağmen, deniz tabanının çift fay sistemi ile ya da tek bir fay ile kesilmiş olması ile ilgili bazı temel sorular cevapsız kalmıştır. Çift fay sistemini savunan araştırmacılar deformasyonun çoğunun havza kenarlarında olduğunu ve doğu–batı uzanımlı sağ yönlü bir doğrultu atımlı fay sistemi içinde açılan dirsekler ve aşmalar boyunca klasik çek-ayır modelinin halen geçerli olduğunu ileri sürmektedir. Öte yandan, diğer araştırmacılar tarafından tamamen farklı bir öneri savunulmaktadır: deniz tabanı, çek-ayır modeline uymayan, havza kenarları ile örtüşmeyen tek, sürekli bir doğrultu atımlı fay ile kesilmiştir. Birbiri ile karşıt gibi görülen bu iki fikir aslında çelişkili değildir ve bunlar birbirini takip eden olaylardır. Fay geometrisi bağlamında Marmara Denizi'nde gözlemlenen olaylar karmaşık çek-ayır sisteminden tek, doğrultu atımlı faylara geçişi işaret eder. Ötelenme geometrisine bakılmaksızın, tüm çek-ayır havzalar zaman içinde verev atımlı bağlantı fayları ile sınırlanmış dar grabenlerden daha geniş, basamaklı yan duvar fay sistemleri ile sınırlanmış baklava dilimi şekilli havzalara doğru evrilirler. Arazi gözlemleri ve analog modeller bu genişlemenin ileri aşamalarında çapraz havza faylarının çek-ayır havza tabanlarını kestiğini ve ana ötelenme zonlarını birleştirdiğini gösterir. Joglar ve daha sonra çek-ayır havzalar yok olur ve doğrultu atımlı faylar zaman içinde düz uzanımlı hale gelir. Fayların ve onlara eşlik eden havzaların bu gelişim süreci, Kuzey Anadolu Fayı boyunca Marmara Denizi'nin kuzey kesimlerinde yer alan, iki set fayın gözlendiği ve daha eski olanın artık inaktif hale gelmiş olduğu havzalar için de geçerlidir.

Anahtar Sözcükler: Kuzey Anadolu Fayı, Marmara Denizi, çek-ayır havza, çapraz havza fayı, doğrultu atımlı faylanma, havza oluşumu

Introduction

With its morphologically well-defined features and active seismicity, the North Anatolian Fault (NAF) is recognized as one of the most important active strike-slip fault systems in the world. It is a dextral strike-slip fault which extends for about 1500 km along the Black Sea mountains of northern Anatolia between Karlıova in eastern Turkey to the Gulf of Saros in the Aegean Sea (Şengör 1979; Şengör *et al.* 1985; Şaroğlu *et al.* 1987, 1992; Barka 1992) (Figure 1). It is roughly parallel with, but 100 km inland from the Black Sea coast of Turkey and is defined as the right-lateral fault zone taking up the relative motion between the Eurasian and Anatolian blocks which connects the east Anatolian convergent zone with the Agean trench through the complex plate boundary zone of the Aegean (Dewey & Şengör 1979; Şengör 1979). The most recent episode of seismic activity, which began in 1939 in the eastern sector of the North Anatolian Fault, has since gradually migrated westward along the fault. The latest events recorded on the fault are the 17.8.1999 İzmit and 12.11.1999 Düzce earthquakes (Figures 1 & 3A).

Along most of its length the North Anatolian Fault consist of a single fault zone, as in its eastern and central parts, but as it approaches the Aegean extensional regime in the west, it splits into two branches which demonstrate different kinematic and seismic features in the Marmara region (Figure 1). The northern branch enters the Sea of Marmara through the Gulf of İzmit and is responsible for the formation of the large strike-slip depression, the Marmara Trough, in the northern Sea of Marmara. The fault briefly emerges on land in southern Thrace before entering the northern Aegean Sea, where it is known as the Ganos fault which ruptured during the August 3, 1912 Şarköy-Mürefte earthquake (M 7.2). The August 17, 1999 İzmit earthquake (Mw= 7.4) is the last in the series of westerly migrating major shocks along the North Anatolian Fault leaving the segment in the Sea of Marmara as the only portion in the area that did not rupture during the 20th century. Tectonic features of this part of the fault are relatively less known in spite of its high potential for producing large earthquakes. While geometry and the nature of the fault under the sea is still a matter of debate, geodetic measurements have shown that the rate of dextral strike-slip motion along this segment is 24 mm/yr (Meade *et al.* 2002). The question this paper addresses, in relation to the geometry of the faults cutting the seafloor, is how this motion is transferred from the eastern and to western ends of the Sea of Marmara. Is this transfer made by marginal faults, the members of complex pull-apart mechanism or by a single east–west-trending continuous strike-slip fault? The answer is critical to understanding the seismic behaviour of the North Anatolian Fault in this region in terms of slip partitioning and in predicting future earthquakes in the area.

This paper aims to show that the two different models proposed for the definition of the active faults in the Sea of Marmara do not conflict since they are stages of a successive process, namely a transition from complex pull-apart basins into single strike-slip faults. The Main Marmara Fault (Le Pichon *et al.* 2001) is a cross basin fault formed as a consequence of this transition and, unlike the marginal faults is likely to be the causative active fault for the future earthquakes.

Previous Ideas: Active Margin Faults of Pull-apart Basins Versus Long, Continuous, Through–going Strike-slip Fault

Although initial models for the evolution of the Sea of Marmara date back to the 1940s, modern studies of seafloor topography and seismic research began in the late 1980s. The most important debates still are about the geometry of the faults cutting the sea floor

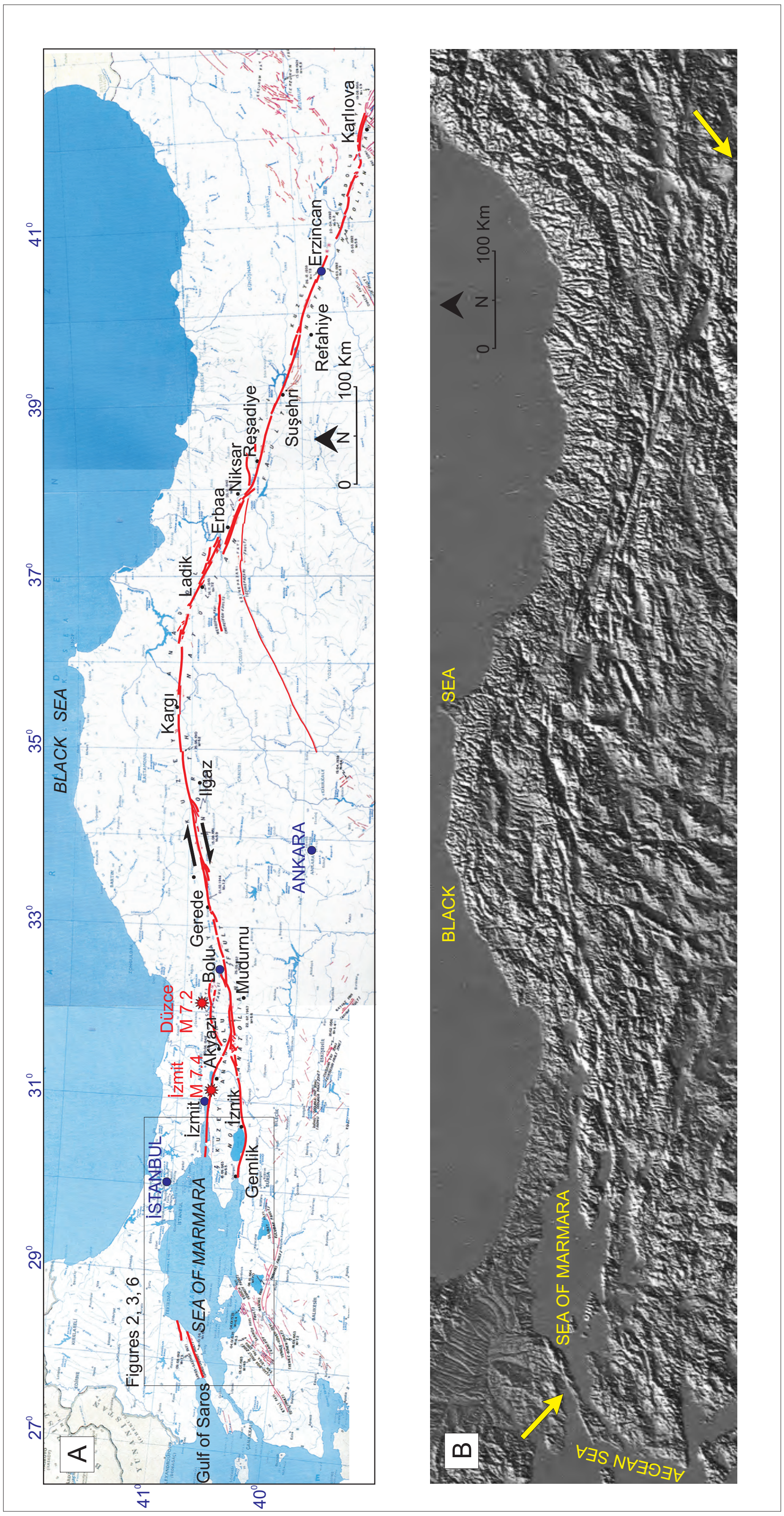

Figure 1. The North Anatolian Fault (NAF) as shown on the **(A)** Active Fault Map of Turkey (after Şaroğlu *et al.* 1992) and on a **(B)** DEM image of northern Turkey where the fault extends. The yellow arrows indicate the NAF.

despite the availability of widespread coverage of marine seismic and multi-beam data (e.g., Barka & Kadinsky-Cade 1988; Barka 1992; Ergün & Özel 1995; Wong *et al.* 1995; Armijo *et al.* 1999; Le Pichon *et al.* 1999, 2001, 2003; Okay *et al.* 1999, 2000; Parke *et al.* 1999; Aksu *et al.* 2000; İmren *et al.* 2001; Rangin *et al.* 2001; Yaltırak 2002; Armijo 2000; Demirbağ *et al.* 2003; Le Pichon *et al.* 2003) (Figure 2). These recent studies can roughly be classified into two groups in terms of fault geometry: (1) active margin faults in the northern Marmara trough (pull-apart models), and (2) a single and continuous, through-going fault system in the Sea of Marmara.

Active Margin Faults in the Northern Marmara Trough (Pull-apart Models)

In the beginning of the 20th century, before the use of seismic profiles, the first bathymetric survey revealed the presence of three deep basins and their intervening ridges in the Sea of Marmara (Andrusov 1901). Pfannensteil (1944) noted the rhombohedral shape of the deep Sea of Marmara basins and proposed that the ridges separating the basins represent horst blocks bounded by normal faults. Barka & Kadinsky-Cade (1988) used seismic data acquired by the Marathon Oil Company to suggest that the deep Sea of Marmara basins (their basins A, B and C which correspond to the Tekirdağ, Central Marmara and Çınarcık basins, respectively) were developed as pull-apart basins between splays of the North Anatolian Fault. There are two fault systems in this model: northeast–southwest-trending strike-slip faults and NNW–SSE or east–west-trending normal faults. Associating the pull-apart basins with bathymetric lows, concentrations of microseismicity and extensional focal mechanisms, the authors stated the need for new and extensive data to verify this model. Following this research, Ergün & Özel (1995) and Wong *et al.* (1995), on the basis of the same set of shallow seismic reflection data acquired by *R/V Piri Reis*, modified this pull-apart model to include compressional and tensional rhombohedral blocks bounded by short and discontinuous strike-slip faults to explain the three deep basins and two intervening transpressional push-up structures aligned oblique to the North Anatolian Fault in the Sea of Marmara. Wong *et al.* (1995) also emphasized the role of the two northeast–southwest push-ups as dextral transfer zones causing deformation within the basin between the extensional northern and southern margins.

Armijo *et al.* (1999) and Armijo (2000) proposed a simple geometric pull-apart model on the basis of purely topographic and geometric considerations (Figure 3A). According to this model, the Sea of Marmara opened uniformly as a pull-apart during the last 5 Myr and the present pattern of deformation is similarly governed by the pull-apart logic. The authors concluded that the long-term kinematics around the Sea of Marmara pull-apart are similar to present day kinematics as deduced from space geodesy (Meade *et al.* 2002). Within this large Marmara pull-apart, Armijo *et al.* (2002) defined the North Marmara Fault System (NMFS) as a smaller pull-apart system opened by an oblique submarine fault zone which links the two strike-slip branches that ruptured during the 1912 Şarköy-Mürefte and 1999 İzmit earthquakes on the Ganos and İzmit faults, respectively. Using the high-resolution data (multi-beam bathymetry and seismic reflection profiles using surface and deep-towed streamers) on the NMFS collected during the cruise of *R/V Le Suroit* in September 2000, Armijo *et al.* (2002) studied the region again and concluded that the active faulting along the NMFS is segmented and appeared to link the largest pull-apart basins (Çınarcık, Central and Tekirdağ basins) with the İzmit and Ganos faults on land, as anticipated previously by Barka & Kadinsky-Cade (1988).

A Single and Continuous, Through-going Fault System Through the Sea of Marmara

The first researcher discussing a single fault transecting the three basins suggested by Andrusov (1901) is Pınar (1943) who, based on the linear distribution of the epicentres, proposed that a single east–west-trending fault cuts the northern Sea of Marmara extending from the Gulf of İzmit in the east to near Mürefte in the west. The author also discussed a possible relation between the seismicity and meteorological conditions in the area. Later on Şengör *et al.* (1985), modelling the tectonic activity of the entire North Anatolian Fault, proposed a single shear zone in the Sea of Marmara for the first time.

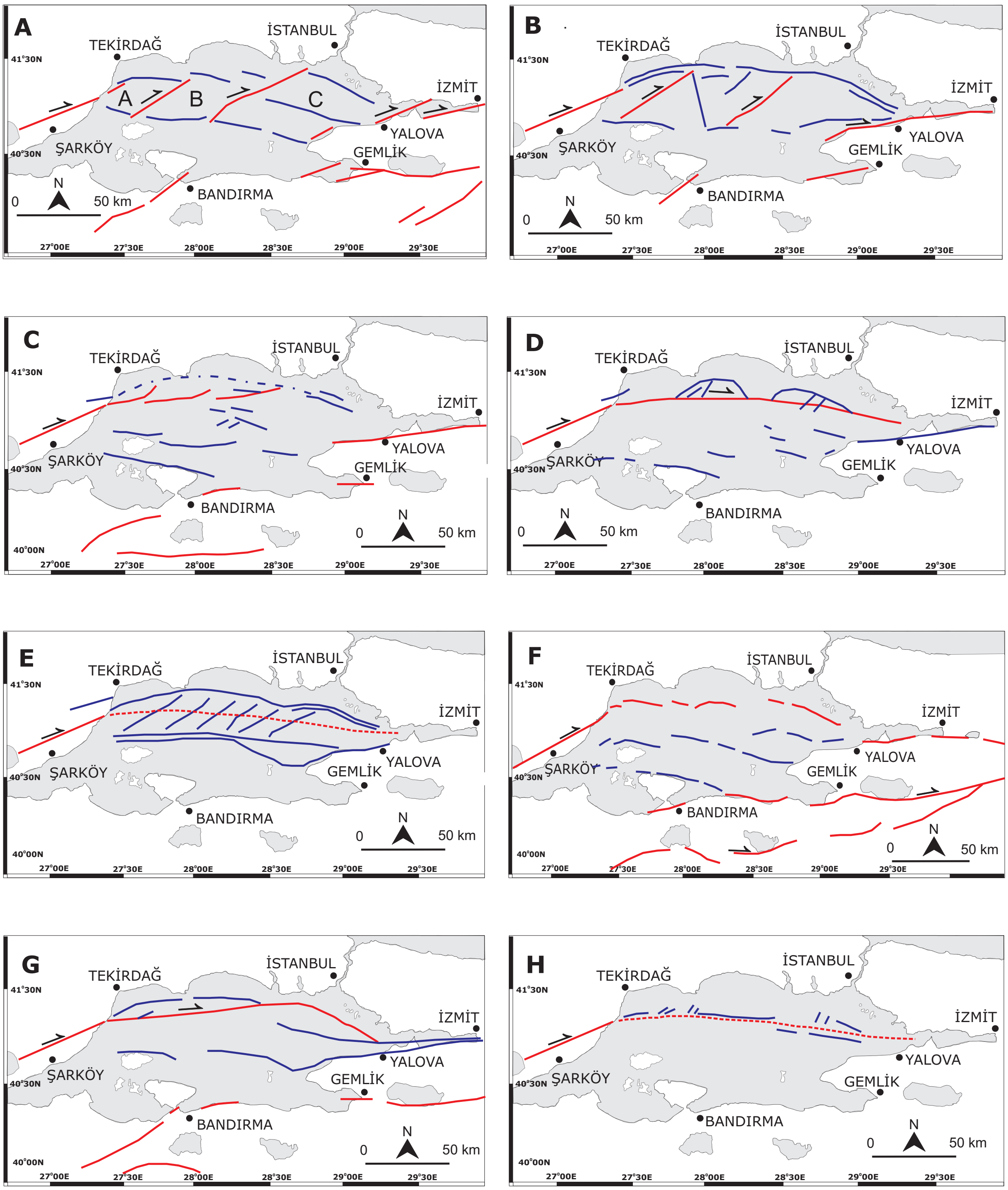

Figure 2. Tectonic models proposed for the Sea of Marmara. **(A)** Barka & Kadinsky-Cade (1988), **(B)** Ergün & Özel (1995) and Wong *et al.* (1995), **(C)** Parke *et al.* (1999), **(D)** Le Pichon *et al.* (1999), **(E)** Aksu *et al.* (2000), **(F)** Armijo *et al.* (2000), **(G)** Okay *et al.* (2000), **(H)** İmren *et al.* (2001).

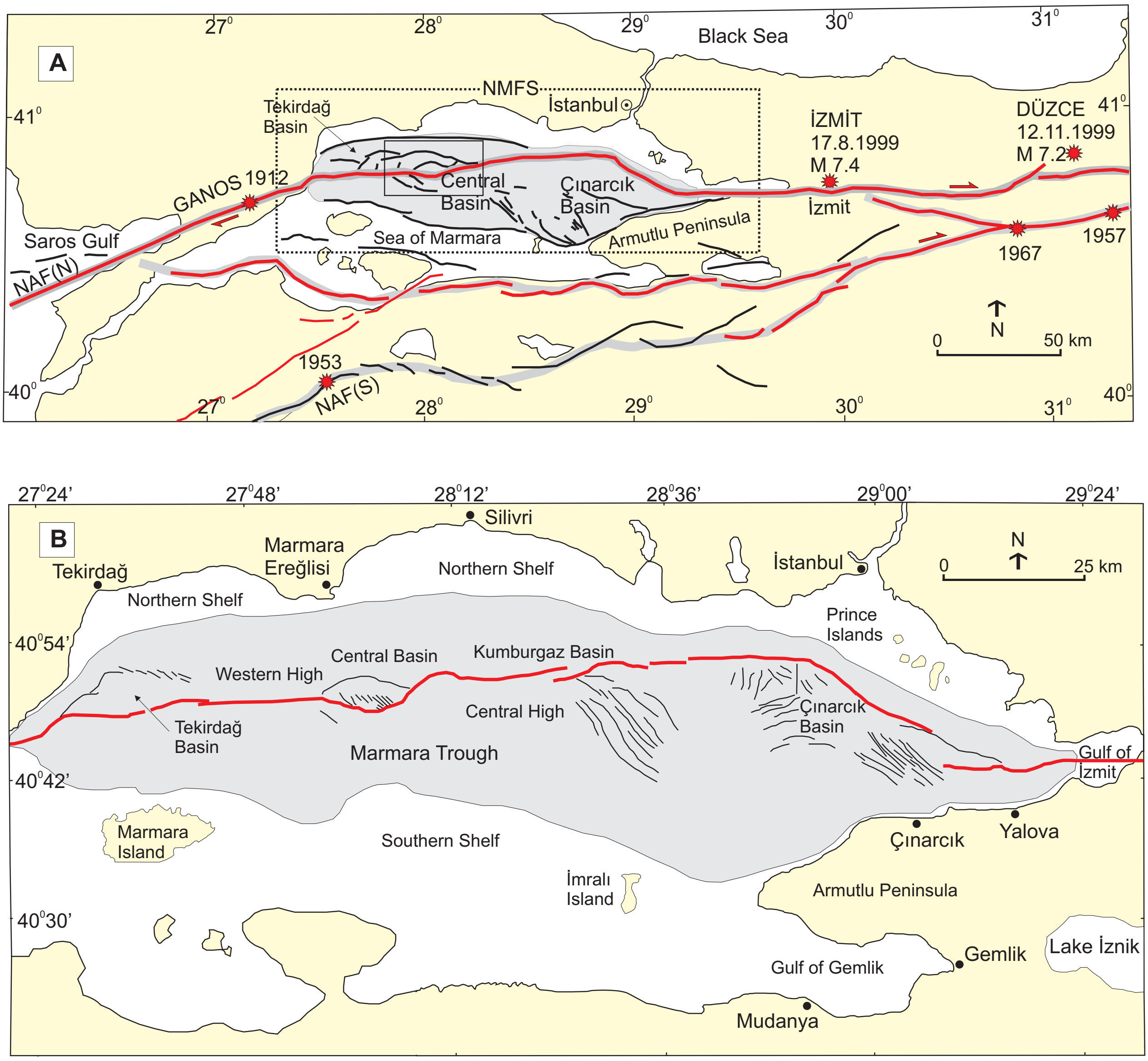

Figure 3. **(A)** Active tectonics in the Sea of Marmara pull-apart basin including the submarine faults. The North Anatolian Fault (NAF) splays westward into two main branches 100 km apart forming the larger pull-apart. Most of the lateral motion is transferred across the Sea of Marmara to the Northern branch (N). The sinuous branch (S) bypasses the pull-apart but accommodates much less motion. A smaller pull-apart called the North Marmara Fault System (NMFS) interconnects the deep northern basins (Tekirdağ, Central and Çınarcık basins) with two large strike-slip faults on land (İzmit and Ganos faults). Recent earthquake breaks are outlined (modified from Armijo *et al.* 2002). **(B)** Map of the Marmara trough (shaded area) with the main active structures. Thick red lines show main active faults. The width of the lines refers to the relative importance of the faults (modified from Le Pichon *et al.* 2001).

From 1997 to 2000, *R/V MTA Sismik-1* collected 2200 km of multi-channel seismic reflection profiles across the whole Sea of Marmara. The data, independently processed in İstanbul Technical University and Cambridge University, were used in the papers revealing the existence of approximately east–west-trending faults crossing the two highs, midway between the two margins in the western and central parts of the sea, whereas the faults along the margins did not appear to be active (e.g., Le Pichon *et al.* 1999, 2001; Okay *et al.* 1999, 2000; Parke *et al.* 1999; İmren *et al.* 2001). Le Pichon *et al.* (1999), inferring the geometry of the continuation of the North Anatolian Fault across the Sea of Marmara on the basis of historical and present seismicity, published GPS measurements and seismic reflection data acquired by *R/V MTA Sismik-1*, concluded that this portion of the fault is a continuous dextral strike-slip segment that extends over a length of 175 km and along which slip accumulates. The authors, pointing out that the segment broke both during 1509 and 1766 earthquakes, proposed that its rupture during a single earthquake in the future should be expected.

In February 1999 *R/V Meteor* made the first multi-beam sounding survey that covered the Central Marmara High and Central Marmara Basin and, based on bathymetric data, first discovered the existence of an east–west-striking furrow, the eastward continuation of the dextral strike-slip Ganos Fault (Halbach *et al.* 2000, 2002; Kuşçu *et al.* 2008). This was the first solid evidence for the presence of an east–west-trending active fault that cut the Tekirdağ Basin, Tekirdağ Ridge and Central Marmara Basin, contrary to the models defending simple pull-apart mechanism at the time. Methane was shown to be venting from this furrow and this was interpreted as a sign of the activity of this fault. Sub-bottom profiler data obtained during this study also revealed the active faults in the area and in the north of the Çınarcık Basin in the eastern Sea of Marmara (Inthorn 2000).

The Department of Navigation, Hydrography and Oceanography (SHOD) of the Turkish Navy carried out a multi-beam bathymetric survey covering the axial region of the deep Marmara Trough. The resulting bathymetric chart revealed the existence of a continuous fault extending eastward from the Ganos Fault across the western two thirds of the Sea of Marmara (Demirbağ *et al.* 2000; Le Pichon *et al.* 2000). Studying the multi-channel seismic reflection data acquired by *R/V MTA Sismik-1* in 1999, Okay *et al.* (2000) concluded that the fault consists of a single major continuous fault zone; although it is not a single segment but comprises four segments, namely the Ganos, Central Marmara, North Boundary and İzmit segments. These segments, that do not follow the margins, are not compatible with the pull-apart model. İmren *et al.* (2001), Le Pichon *et al.* (2001) and Demirbağ *et al.* (2003), using the data collected by *R/V MTA Sismik-1, R/V Le Suroit* and the Department of Navigation, Hydrography and Oceanography (SHOD) of the Turkish Navy, obtained evidence supporting Le Pichon *et al.* (1999), who had proposed the existence of a continuous fault across the Sea of Marmara, termed by Le Pichon *et al.* (2001) the Main Marmara Fault (Figure 3B), which does not coincide with basin margins and does not fit the simple pull-apart model. Rangin *et al.* (2004), in their paper studying the inactivated pull-apart system in the Sea of Marmara, proposed that, before the full activation of the Main Marmara Fault, there was a period during which transtension (pull-apart) and then transpression inverting these depocentres delineated a wide shear zone in the Sea of Marmara. During the evolution of this shear zone, former transfer faults bounding the depocentres were inverted just before and (or) while the newly forming Main Marmara Fault propagated within the basin. Using seismic profiles they demonstrated the waning of extensional activity along the NE and SW margins of the Sea of Marmara pull-apart system. Their analysis of a large marine geophysical data set showed that most of the 120°E-trending normal faults that they interpreted as the transfer faults of the pull-apart system, framing a succession of depocentres and highs cut by the Main Marmara Fault, are now inactive as they are sealed by an average thickness of 300 m of sediments.

Through a microseismic experiment with 48 stations distributed around the Sea of Marmara, Gürbüz *et al.* (2000) obtained new data on the microseismicity within the Sea of Marmara. Their results showed a linear distribution of microseismicity closely related to the continuous fault crossing the western two thirds of the sea. The fault plane solutions are either strike-slip or compressional and the stress tensor is compatible with pure strike-slip on the approximately east–west-trending fault system. However, Örgülü & Aktar (2001), studying the large aftershocks of the August 17, 1999 İzmit earthquake showed that, in the Çınarcık Basin, movement was purely strike-slip along both the northern and the southern margins. In another study of microseismicity in the region, Sato *et al.* (2004), using ocean bottom seismometers, analysed the microearthquake seismicity and focal mechanisms within the Sea of Marmara and concluded that microseismicity mainly occurred along the Main Marmara Fault. Their studies revealed that composite focal mechanisms showed a strike-slip regime on the western Main Marmara Fault and complex faulting (strike-slip and normal faulting) on the eastern Main Marmara Fault.

To summarize, in the pull-apart model, the Sea of Marmara opened uniformly as a pull-apart and the present pattern of deformation is similarly governed by the pull-apart logic. Consequently, one should expect strike-slip segments at both the western and eastern extremities and *en échelon* oblique extension segments on both the northern and southern margins. As a result, the two margins of the Marmara Trough should contain several active segments with an important extensional component, none being longer than 50 km. This model assumes that most of the deformation occurs along the margins of the basins. However, this was known to be incorrect because extensive seismic reflection work in the Sea of Marmara revealed significant deformation within the basins. Some researchers (Le Pichon *et al.* 1999, 2001; Okay *et al.* 2000; İmren *et al.* 2001) suggested that the İzmit segment may be joined to the Ganos segment through the Sea of Marmara along a single fault. They considered that the pull-apart structure was no longer active and the basin was cut by a single, continuous strike-slip fault that may rupture along its length as during the earthquakes of 1509 and 1766.

Pull-apart Basins and Cross-basin Faults

Pull-apart basins, a modification of the older concept of rhombochasms (Carey 1958) were first defined by Burchfiel & Stewart (1966) in their interpretation of Central Death Valley, California. Many debates about the formation and development processes of pull-apart basins and push-up bulges have ensued since the introduction of the term. Characteristically, strike-slip faults tend to have straight traces and steep or vertical dips, although most do contain bends and stepovers that result in formation of both extensional and contractional structures. If the crust is pulled apart along a *bend* in a strike-slip fault system, the resulting structure is termed an *extensional* or *releasing bend* (Christie-Blick & Biddle 1985). Similar terminology can be applied to *stepovers* between two faults, where one strike-slip fault ends and another en échelon fault with the same sense of displacement begins (Sylvester 1988; Twiss & Moores 1992). At releasing bends or steps, pull-apart basins may form topographic depressions that commonly become sites of deposition for large thicknesses of alluvial and/or evaporitic deposits having lacustrine and marine facies with variable depth. Basins formed in this way are usually rhombohedral in shape in plan view and are bounded at their ends by high-angle faults with normal- to oblique-slip components (e.g., Crowell 1974; Mann *et al.* 1983; Woodcock & Fischer 1986; Twiss & Moores 1992; McClay & Bonora 2001). Pull-apart basins are proposed to form along (1) long strike-slip boundary zones between continental plates, (2) strike-slip systems in active arcs, and (3) strike-slip systems bounding fault wedges in convergent zones (Mann *et al.* 1983). A variety of structural models for development and evolution of pull-apart basins have been proposed and reflect the regional or experimental bias of the individual workers (e.g., Quennell 1958; Clayton 1966; Crowell 1974; Freund 1971; Koide & Bhattacharji 1977; Rodgers 1980; Schubert 1982; Garfunkel 1981; Aydın & Nur 1982; Mann *et al.* 1983).

The most important and less investigated aspect of the evolution of pull-apart basins is the extinction of these basins. Combining with associated topographic and sedimentary features, Zhang *et al.* (1989) studied the inactive faults, active faults and the surface ruptures of the historic earthquakes along the left-lateral Haiyuan fault and its associated pull-apart basins in north-central China and established the evolutionary history of the pull-apart basins. They described the geometric pattern and deformational style of pull-apart basins along the Haiyuan fault zone as in the extinction stage of their development (Figure 4). While mapping the pull-apart basins along the Haiyuan fault zone, they discovered that the formation of new strike-slip faults played an important role in halting the development of the pull-apart basins. Examples from several pull-apart basins along the fault zone showed that they may become inactive in several ways (Zhang *et al.* 1989): (a) strike-slip faults develop along one of the pre-existing bounding normal faults of the pull-apart basin, (b) a discontinuous strike-

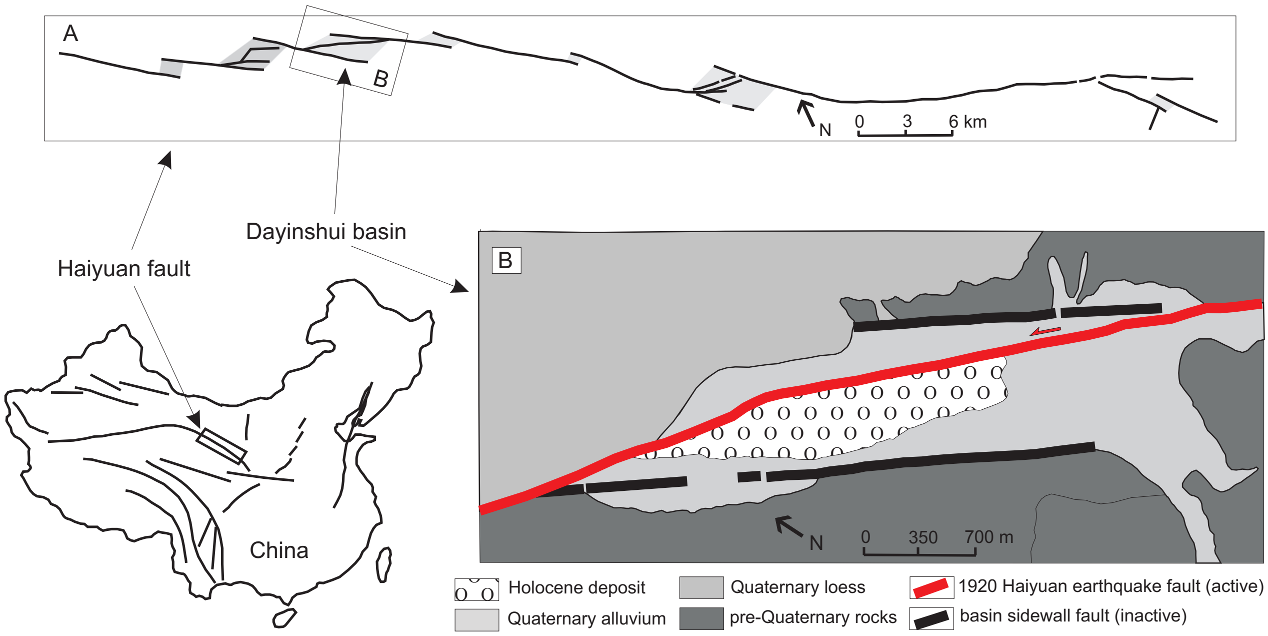

Figure 4. **(A)** Haiyuan fault zone and its associated pull-apart basins. **(B)** Simplified geological map of Dayinshui basin. Thick black lines are basin bounding faults. The red line indicates the surface ruptures associated with the 1920 Haiyuan earthquake (after Zhang *et al.* 1989).

slip fault system develops within the pull-apart basin, (c) strike-slip faults develop along the diagonal of a pull-apart basin [*cross-basin faults* (McClay & Dooley 1995)], and (d) strike-slip faults migrate toward the basin centre. The authors concluded that the extinction of a pull-apart basin probably represents a tendency for a strike-slip fault to straighten itself. Barnes *et al.* (2001), on the other hand, integrated seismic reflection profiles and multi-beam data to analyze the structure of the 25-km-long strike-slip Dagg Basin associated with the marine section of the Alpine Fault in Fiordland, New Zealand. The authors proposed that the present through-going releasing bend at the northern end of the basin might have evolved from a more complex pull-apart basin that developed between separate segments of the Alpine Fault and that the through-going trace at the releasing bend has some similarities to cross-basin faults that have been modelled (Dooley & McClay 1997) and observed in earthquake ruptures (Zhang *et al.* 1989) in mature pull-apart basins. Thus, the Dagg Basin is interpreted to be a hybrid case where a pull-apart basin developed at a stepover in the Alpine Fault and later evolved into a simpler releasing bend along the principal displacement fault zone (Barnes *et al.* 2001). The Suwa Basin in Japan is a typical rhomboidal pull-apart basin located along the central portion of the Itoigawa-Shizuoka tectonic line (Fujimori 1991) where active traces migrated from the basin margins to the basin centre and the size of the jogs decreased. Such migration of a fault trace is considered to be a feature of the evolution of strike-slip faults, in which eventually jogs and their related pull-apart basins will become extinct (Yoshioka 1996).

Analogue Modelling of Pull-apart Basins

Scaled sandbox models successfully simulate the geometries and progressive evolution of pull-apart basins from a narrow graben bounded by oblique-slip link faults to wider rhombic basins flanked by terraced basin sidewall fault systems. Dooley & McClay (1997) used scaled sandbox modelling to simulate the geometries and progressive evolution of pull-apart basins developed in a weak sedimentary cover above right-stepping (releasing) dextral strike-slip fault systems in rigid basement. Figure 5A and B illustrate the progressive evolution and final geometry of experiment W-45, a 30° releasing sidestep (Dooley & McClay 1997). After 1–2 cm of dextral strike-slip displacement on the basement faults, the initial deformation at the surface of the model is localized above the basement sidestep, forming two dextral, oblique-extensional fault segments bounding a narrow, elongate depression (faults 1 and 2, Figure 5B-a). With increased displacement, dextral strike-slip and oblique-slip faults appear above the main strands of the basement faults, forming the principal displacement zones (PDZ, Figure 5A-b & B-b). The PDZ are flanked by pop-up (or push up) structures generated between the left-stepping fault segments (Figure 5A-b & B-b). As displacement on the underlying basement faults increases, the initial oblique faults (faults 1 and 2) are carried outward and form the sidewalls to the developing pull-apart basin. These sidewalls are linked by a cross-basin fault zone (fault 3, Figure 5A-b & B-b). After 5–6 cm of dextral displacement (Figure 5A-c & B-d), the pull-apart basin is well defined, but it is still not bounded by faults. Intrabasinal deformation is characterized by a cross-basin fault zone that links the stepped PDZ (Figure 5A-c, d). This fault zone has dextral offset and forms a basin-floor ridge. At the end of the experiment (10 cm displacement, Figure 5A-e & B-e), the pull-apart basin is fully developed with a length/width aspect ratio of nearly 2.5:1. The sidewall fault zones consist of a lazy-Z shaped fault system that exhibits some terracing and kinking, forming internal fault blocks bounded by steep oblique-slip extensional faults (seen predominantly on the left sidewall of Figure 5A-e & B-e). The PDZ are characterized by linked dextral-slip faults that form an anastomosing fault zone (Figure 5A-e & B-e) (Dooley & McClay 1997).

The Sea of Marmara Case

Despite the limitations inherent in these analogue models, the results of the experiments show strong similarities in form, structural architecture, and dimensions to natural examples from a wide range of strike-slip fault systems in a variety of tectonic settings. The smaller pull-apart basin within the larger Marmara pull-apart that links the two strike-slip faults branches (Ganos and İzmit faults), termed the North Marmara Fault System (NMFS) by Armijo *et al.* (2002), is a good natural example for the above model (Figure 6). The Ganos and İzmit faults represent the basement (master) fault in Figure 5A-a, and PDZ in Figure 5 B-a to e. The faults bounding the NMFS in the south and the north and the cross-basin fault extending from west of the Tekirdağ Basin to east of the Kumburgaz Basin correspond to the faults 1, 2 and 3, respectively and form the lazy-Z shape in Figure 5B-b to d. Intrabasinal deformation is characterized by this cross-basin fault zone that links the stepped PDZ (Figure 5A-c, d). This fault zone has dextral offset and forms a basin-floor ridge (the Central Marmara High, in the Sea of Marmara). The overall geometry of the NMFS is very similar to Figure 5B-e, the final step of the experiment in which the elements of a mature, decreasingly active pull-apart basin are observed. The Gulf of İzmit and the Gulf of Saros were first formed as negative flower structures (Yaltırak *et al.* 1998; Kurt *et al.* 2000; Kuşçu *et al.* 2002) and correspond to the PDZ-negative flower structures in Figure 5B-e.

The Central Marmara Basin itself is another example of a pull-apart basin cut by a cross-basin fault. It was opened as an internal pull-apart on the large basin-floor ridge of the NMFS pull-apart basin which covers the Tekirdağ High and the Central Marmara High. The Central Marmara Basin is bounded by normal faults in the north and south and a cross-basin fault forming distinct *en échelon* fault scarps enclosing a younger pull-apart with a characteristic rhomb-shape links the strike-slip faults in the east and the west (Figure 7). These faults form a lazy-Z shape very similar to that discussed in Figures 5A and 4B and in the NMFS pull-apart basin in the Sea of Marmara. With the formation of the cross-basin fault, the activity of the basin-bounding faults decrease or simply become inactive, as seen in similar cases (Yoshioka 1996) of transition from complex pull-aparts to single strike-slip faults.

The fault geometry described in the above experimentary model (Dooley & McClay 1997) and observed in the Tekirdağ and Central Marmara basins implies that the long, through-going strike-slip faults are slicing through the earlier set of faults that developed in a broader shear zone. Development of a shear zone requires organization

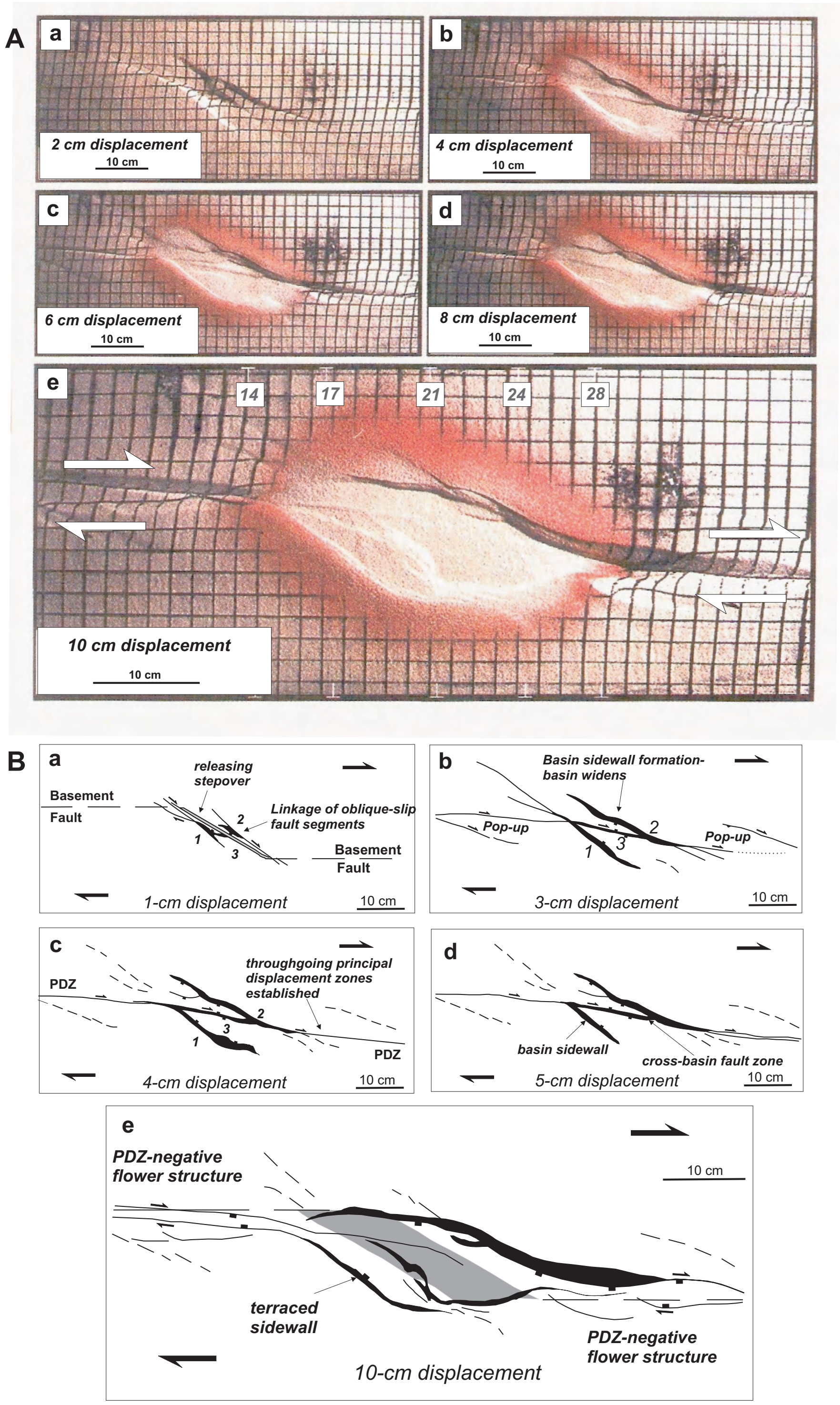

Figure 5. **(A)** Evolution and final plan views of experiment W-45, 30° releasing sidestep for 2, 4, 6, and 10 cm displacement done by Dooley & McClay (1997). **(B)** Interpreted plan view evolution of experiment W-45, 30° releasing sidestep, for 1, 3, 4, 5 and 10 cm of displacement (after Dooley & McClay 1997). See text for discussion of the models.

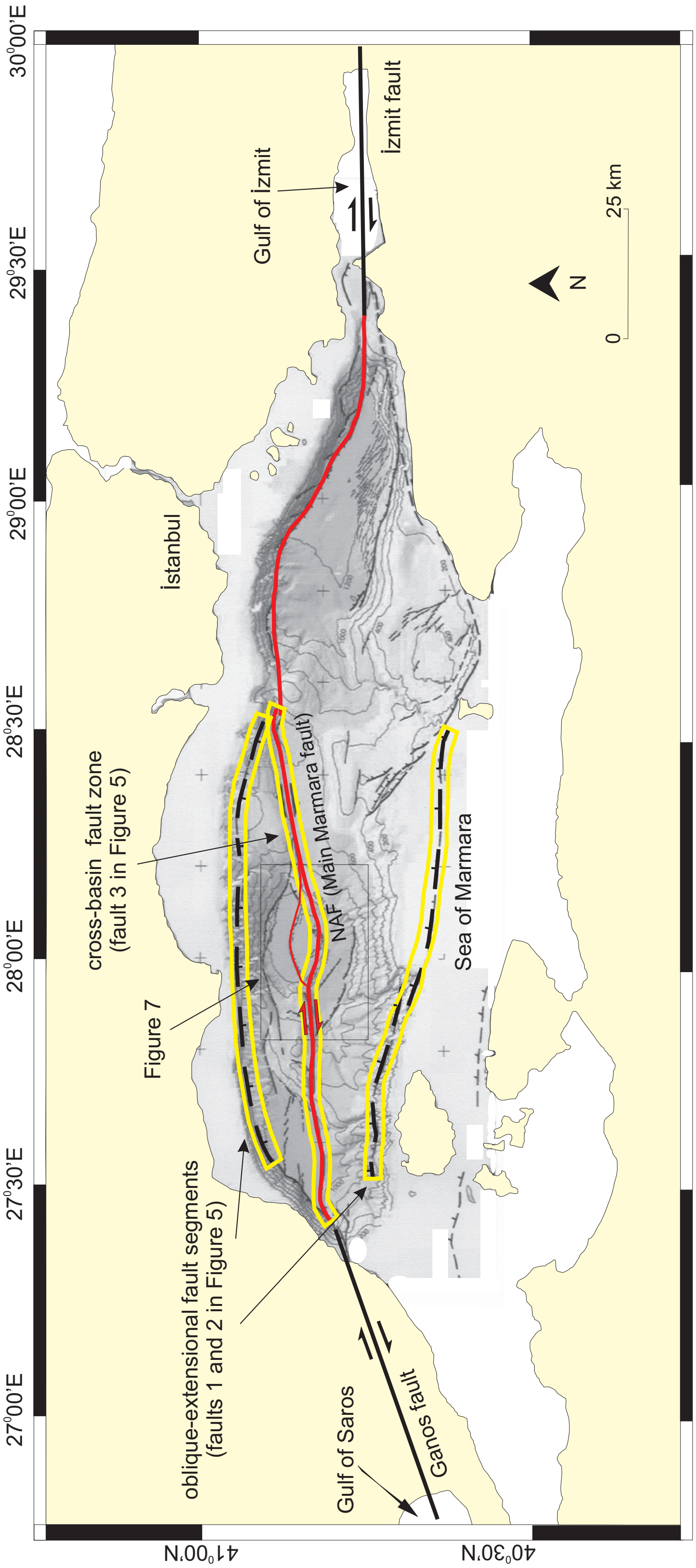

Figure 6. Strike-slip fault (cross basin fault) developed along the diagonal of the NMFS pull-apart basin (base map after Armijo *et al.* 2002).

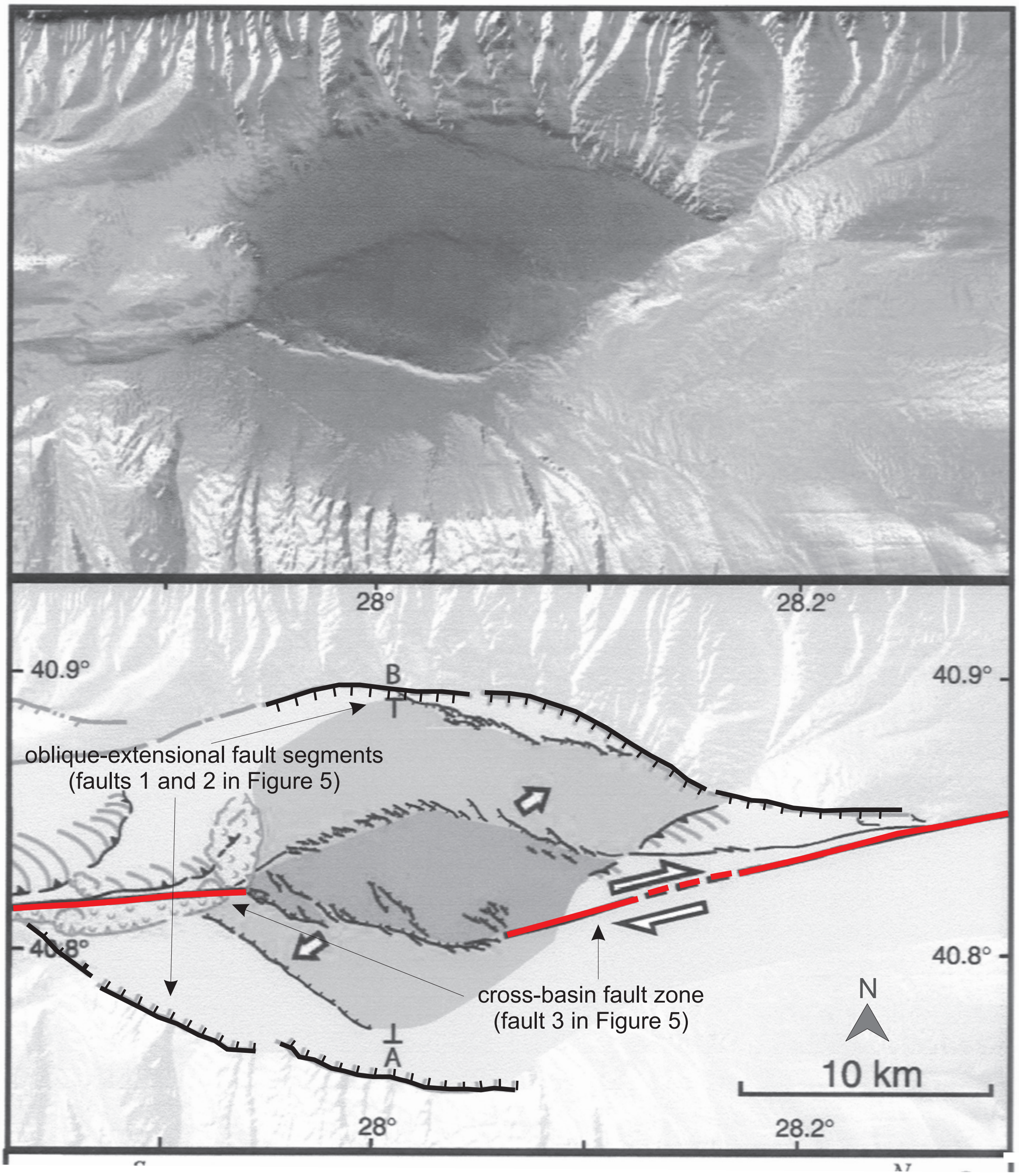

Figure 7. Strike-slip fault (cross basins fault) developed along the diagonal of the Central Marmara Basin (base map after Armijo *et al*. 2002).

by developing long, through-going, pure strike-slip faults that cut through earlier, shorter fault families bounding the alternating pull-apart basins and push-up ridges (Tchalenko 1970; Şengör 1995; Şengör *et al.* 1999; Kuşçu *et al.* 2002). Le Pichon *et al.* (1999) proposed the same evolution of the geometry of the northern Sea of Marmara basins and referred to an earlier pull-apart stage of the basins.

Discussion

Evolution of Pull–apart Basins

Like most other structures in the earth's crust, pull-apart basins do not suddenly come into existence but evolve through a sequence of closely related stages. A single pull-apart basin, as it is exposed today represents only one time frame in its development. The evolution of pull-apart basins can be separated into three stages depending on structures associated with their developmental stage: incipient, early, and mature (Rahe *et al.* 1998). *Incipient* pull-apart basins are characterized by closely spaced boundary faults that form parallel to the step angle between the main strike-slip zones (Figure 5B-a). The beginning of the *early* stage in the evolution of pull-apart basins is marked by the formation of the cross-basin strike-slip faults which begin to transect the interior of the developing pull-apart basin (Figure 5B-b, c). At this point in the models' development, boundary faults and cross-basin faults are not linked. Progressive widening of pull-apart basins is accommodated by formation of additional normal faults. During the early stage of development, progressive strike–slip displacements eventually cause displacement on cross-basin faults to shift toward the centre of the basin and link strike-slip fault segments to produce a through-going strike-slip fault. Pull-apart basins attain their *mature* stage of development once cross-basin faults link the main strike-slip displacement zones (Figure 5B-d, e). It must be noted that, although cross–basin faults in the analogue models form early in the sequence of faulting and remain active for the duration of each simulation, other researchers (Mann *et al.* 1983; Zhang *et al.* 1989) suggest that cross-basin faults are produced at mature stages in the process of pull-apart basin growth. Probably, at incipient and early stages cross–basin faults may simply be covered by the alluvial fill commonly associated with pull-apart basins (Rahe *et al.* 1998).

Construction of Cross-basin Faults and Extinction of Pull-apart Basins

Strike-slip faults with releasing bend geometries show tendencies toward straightening by constructing cross-basin faults (Zhang *et al.* 1989; Dooley & McClay 1997). A cross-basin fault, therefore, can be considered as a contributing factor to the extinction of a pull-apart basin (Zhang *et al.* 1989; Rahe *et al.* 1998). At an early stage of development, cross-basin faults form as separate, small faults having orientations and sense of slip similar to those of Riedel shear fractures in strike-slip settings. With further displacement, strike-slip displacement is concentrated toward the centre of the basin developing a linkage between the main strike-slip zones at the tips of the basin. During this process, normal faults bounding the pull-apart basin on the sides experience less absolute displacement (with respect to the basement) and typically become inactive and do not cut late synkinematic fill. In the extinction model of Zhang *et al.* (1989), development of a single cross-basin fault is coupled with the extinction, or inactivity, of extensional faults bounding the basin. The analogue models also indicate that the extinction of bounding normal faults occurs during the mature stages of the development of pull-apart basin (Rahe *et al.* 1998).

Rangin *et al.* (2004), on the other hand, defined the Marmara pull-apart as a now-inactive system. Analyzing a large data set that included multichannel seismic lines, sparker and deep towed high resolution seismic profiles, they stated that most normal faults framing the depocenters are now inactive as they are sealed by an average thickness of 300 m of sediments, implying that the pull-apart system was probably inactivated quite recently and certainly within the last few hundred thousand years. They proposed that the depocentres and push-ups are the relicts of former pull-apart basins and that transfer fault systems accommodated the motion of the North Anatolian Fault prior to the formation of the Main Marmara Fault in the Sea of Marmara.

Migration of Fault Traces

Along the North Anatolian Fault the oldest basin-fill deposits are Middle to early Late Miocene (ca 10 Ma; Şengör *et al.* 1985). This indicates that these sedimentary basins were formed simultaneously with the fault generation. The fault topography described by Yoshioka (1996), however, clearly shows that the locations and the sense of deformation of recently active faults are usually incoherent with major topographic scarps at basin margins along the transform active fault, meaning that these basins did not form as a result of recent fault displacements. However, lack of offset on the outer basin margins indicates that the accumulated displacement on the recent faults is at most a few kilometres. The fault traces must have been migrating (Figure 8). The most recent traces in the basins pass straight through each basin floor and have become almost straight, implying that these basins had stopped subsiding and the modern topography of the basin floor results from erosion (Yoshioka 1996). Such migration of the fault traces is considered to be one of the features of the evolution of strike-slip faults, and therefore jogs and their related basins will become inactive (Wesnousky 1988).

Conclusions

Following the disastrous Mw 7.4 1999 İzmit earthquake, there is great concern that the next big earthquake hazard is in İstanbul and the surrounding area. The August 17, 1999 İzmit earthquake (Mw= 7.4) was the latest in a series of westerly migrating major shocks along the North Anatolian Fault, leaving the segment in the Sea of Marmara as the only portion in the area that did not rupture during

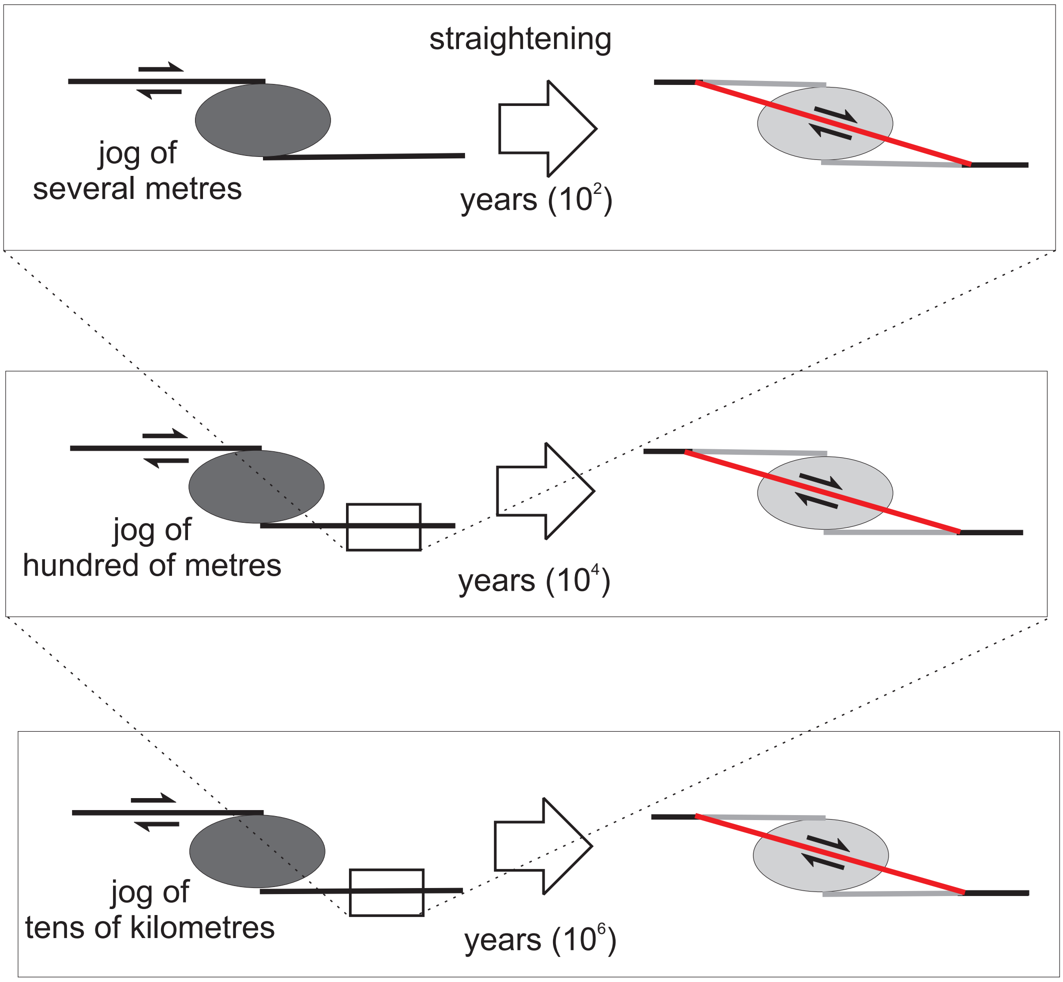

Figure 8. Schematic diagram showing the evolution of releasing jogs on dextral strike-slip faults. Grey lines are inactive faults. Red lines show the migrated faults (after Yoshioka 1996).

the 20th century. Also, the considerable body of information about active faults in the Sea of Marmara leads to the conclusion that major earthquakes are likely in the near future. Considering that the preceding shocks have a high potential of triggering the next earthquake along the North Anatolian Fault (Stein *et al.* 1997; Nalbant *et al.*1998) and the sequential westward migration of major earthquakes in the past, it is highly probable that the next earthquake is expected along the segments of the fault under the Sea of Marmara. GPS data, historical earthquake records and Coulomb modelling also suggest that there is a significant earthquake risk in the Sea of Marmara (Hubert-Ferrari *et al.* 2000; Parsons *et al.* 2000). The calculated probability of a M>7 earthquake at the bottom of the sea is 62±15% for the next 30 years (Parsons *et al.* 2000).

Identifying the *causative fault* of the next big earthquake in the Sea of Marmara is the present-day problem. Because the Marmara region is home to a large part of Turkey's population and a large part of her industrial activity, the Sea of Marmara itself and its surroundings have been intensely studied by many researchers, especially since the 1999 earthquakes. The offshore multi-channel seismic and multi-beam bathymetric studies provided extensive data to evaluate the fault geometry and the development of the strike-slip basins in the Sea of Marmara. Nonetheless, some basic problems remained unsolved, such as whether the seafloor was cut by a double fault system or just by a single fault. The researchers advocating the double fault system assumed that most of the deformation occurred along the margins of the basins and concluded that the classical model of pull-apart basin formation along releasing bends or stepovers within an east–west-trending dextral strike-slip system prevails. On the other hand, a completely different approach was stated by other researchers: namely that the seafloor was cut by a single, continuous strike-slip fault that does not coincide with the margins and does not fit the pull-apart model by providing any evidence for significant active normal faulting in the northern Sea of Marmara basins.

These two different ideas in fact do not necessarily conflict: instead they record successive development stages. In the Sea of Marmara the fault geometry simply records a transition from complex pull-apart basins into single strike-slip faults. All the pull-apart basins, regardless of offset geometry, evolve progressively from narrow grabens bounded by the oblique-slip link faults to wider rhombic basins flanked by terraced basin sidewall fault systems. The cross-basin faults that are characteristic of all experimental models cut the floor of the pull-apart basins and link the offset PDZ. Basin cutoff by such fault systems may lead to pull-apart inactivity and a gradual smoothing of the strike-slip fault zone similar to that described by Wesnousky (1988) as asperity cutoff. This development history of the faults and accompanying basins along the faults is valid for the North Anatolian Fault and the basins in the Sea of Marmara. It can be said that the Sea of Marmara pull-apart basin (NMFS) is at its extinction stage in its evolution with a well-developed cross-basin fault (the Main Marmara Fault) and with the margin faults (the Northern and the Southern Boundary Faults) that are now inactive. Earthquake rupture along strike-slip faults may be arrested by incipient and early pull-apart basins because of fault discontinuity. After the mature stage of evolution, cross-basin faults link the main strike-slip displacement zones and create individual faults with much larger surface areas. Because of their large surface areas, these faults may be capable of producing large-magnitude earthquakes (Rahe *et al.* 1998). Therefore, the single, through-going strike-slip fault (the Main Marmara Fault) that has developed as a cross-basin fault, should be considered as the likely *causative fault* for the next big earthquake in the Sea of Marmara, rather than the margin faults. The deformation patterns in the basins along the northern depression of the Sea of Marmara, microseismicity experiments, the distribution of the aftershocks of the 1999 İzmit earthquake and the epicentral distribution of the recent earthquakes in the region provide supporting evidence for this idea.

Further detailed research, however, to reveal whether the cross-basin faults link the main strike-slip displacement zones, and whether this single, through-going fault will break during a single earthquake, as suggested by Le Pichon *et al.* (1999), as in the cases of past 1509 and 1766 earthquakes or along the segments proposed by Okay *et al.* (2000), is needed for a detailed and better understanding of the causative fault in the Sea of Marmara.

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