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Different Modes of Stress Transfer in a Strike-slip Fault Zone: an Example From the North Anatolian Fault System in Turkey

OSMAN BEKTAŞ[1], YENER EYÜBOĞLU[1] & NAFIZ MADEN[2]

[1] Department of Geology, Karadeniz Technical University, Gümüşhane Engineering Faculty, TR–29000, Gümüşhane, Turkey (E-mail: eyuboglu@ktu.edu.tr)
[2] Department of Geophysics, Karadeniz Technical University, TR–61080 Trabzon, Turkey

Abstract: The dextral North Anatolian Fault System (NAFS) extends for well over 1000 km from the compressive tectonic domain of eastern Anatolia into the broad and diverse tectonic domain of the western Anatolian, Marmara and Aegean regions. These different tectonic regimes are characterized by a narrow deformation zone in the east and a much broader deformation zone with multiple sub-parallel fault zones in the west. The spatial and temporal distribution of large historical and modern earthquakes (Mw>5) shows two distinctive macro-seismic zones in the eastern and western parts of the NAFS. The eastern macro-seismic zone, between the towns of Erzincan and Bolu, has produced a successive linear earthquake series parallel to the fault system over the last 500 years, suggesting that stress transfer along the fault occurred in a manner of 'Static Coulomb failure stress changes' through the entire elastic crust. In contrast, the western macro-seismic zone of the NAFS, in the Marmara region, has produced successive *earthquake pairs* on the parallel faults, implying 'dynamic stress changes', involving large-scale flow in the aseismic lower crust and the mantle.

Key Words: North Anatolian Fault System (NAFS), strike-slip faulting, earthquake, stress transfer

Doğrultu Atımlı Fay Zonlarında Farklı Stres Transferleri: Kuzey Anadolu Fayı Sisteminden Bir Örnek, Türkiye

Özet: Sağ yönlü Kuzey Anadolu Fay Sistemi (KAFS), Doğu Anadolu'nun sıkışmalı tektonik rejimi ile, Batı Anadolu'nun genişlemeli tektonik rejimi arasında uzanmaktadır. Bu farklı tektonik rejimlerden dolayı Kuzey Anadolu Fay Sistemi, doğuda dar bir deformasyon zonuna, batıda ise yarı paralel faylardan oluşan daha geniş bir deformasyon zonuna sahiptir. KAFS'nin Erzincan-Bolu arasında kalan 'doğu makro sismik zonu' 500 yıllık süreç içerisinde fay zonuna paralel, birbirini takip eden lineer deprem serileri üretmiştir. Bu durum, deprem serilerini oluşturan stres transferinin bütünüyle elastik kabuk içerisindeki fay boyunca 'statik Coulomb kırılma stres değişimleri'nin sonucunda meydana geldiğini gösterir. Diğer yandan, Marmara Bölgesinde Kuzey Anadolu Fay Sistemi'nin 'batı makro sismik zonu' ise yarı paralel faylar (KAFS'nin kuzey ve güney kolları) üzerinde birbirini takip eden deprem çiftleri üretmiştir. Bu tür sismik özellik, asismik alt kabuk ve manto içindeki büyük ölçekli akmalar ile, paralel faylar arasındaki 'dinamik stres değişimlerine' işaret eder.

Anahtar Sözcükler: Kuzey Anadolu Fayı (KAFS), doğrultu atımlı faylanma, deprem, stres transferi

Introduction

Stress changes in tectonically active areas are important parameters for assessing the seismic potential of an area. However, our ability to evaluate stress changes via numerical simulation depends strongly on the assumed fault configuration (Cai & Wang 2001) and yet the nature of strike-slip faulting at depth is still poorly understood. Some strike-slip fault zones appear to be near vertical and penetrate deeply into, if not completely through, the crust, whereas others are confined to the upper crust above detachment horizons (Lemiszki & Brown 1988). The vertical crustal geometry of the strike-slip fault zones suggests that a significant amount of coupling occurs along the fault system between the brittle upper and ductile lower crustal regimes.

There is extensive support for an intracrustal viscoelastic layer as has been suggested for the San Andreas Fault System by Anderson (1971), Hadley & Kanamori (1977), Yeats (1981), Furlong (1993), Brocher *et al.* (1994) and Bürgmann (1997). According to Hadley & Kanamori (1977) an intracrustal decollement displaces the upper and lower portions of the San

Andreas Fault System. Arguments for this decollement were also given by Yeats (1981). Turcotte *et al.* (1984) emphasized the role of intracrustal ductility on the behaviour of major strike-slip faults. They suggested that an upper elastic plate extends to a depth of about 15 km, the depth of the deepest seismicity on, and adjacent to, the fault. Beneath this upper elastic plate they postulated that a soft, intracrustal 'asthenosphere' exhibits viscoelastic behaviour.

Lemiszki & Brown (1988) used seismic reflection profiles across strike-slip faults to reveal that intra-plate strike-slip fault systems are decoupled in the middle crust by sub-horizontal detachments. Such detachments in the middle crust may act to ease the rotation of upper-crustal blocks adjacent to strike-slip fault zones, as observed in palaeomagnetic studies by Garfunkel & Ron (1985), Tatar *et al.* (1995) and Piper *et al.* (1997). Brocher *et al.* (1994) postulated a lower crustal detachment between the San Andreas Fault System and Hayward Fault. The postulated existence of a quasi-horizontal detachment structure could facilitate more stress transfer between sub-parallel faults than would be expected from a stress change in an elastic medium, such as a change of the Coulomb failure function which is often calculated following large seismic events (Reasenberg & Simpson 1997). However, Parsons & Hart (1999) suggest that fault-plane reflections reveal that the San Andreas and Hayward faults actually dip toward each other below seismogenic depths at angles of 60 and 70 degrees, respectively, and persist to the base of the crust.

By using coda waves, Nishigami (2000) has interpreted the deeper image of the San Andreas Fault System. He argues that continuous slip across the deep plate boundary encounters a sub-horizantal detachment in the lower crust so that brittle fracture occurs along these faults and shear stresses are transferred horizontally to the bottoms of the San Andreas and Hayward faults. This suggests that sub-parallel active faults may be controlled by lower crustal detachments that facilitate the broadening of a shear zone. This kind of deep structure for the San Andreas Fault System is also suggested by Lemiszki & Brown (1988), and Lisowski *et al.* (1991). On the other hand Parsons & Hart (1999) suggest that the San Andreas and Hayward faults actually continue as faults beneath seismogenic depths. If these faults retain their observed dips at 60 and 70 degrees, respectively, they would converge into a single zone in the upper mantle 45 km beneath the surface, although they are currently only imaged in the crust.

The spatial and temporal variation of historic and modern earthquakes that have occurred along the dextral North Anatolian Fault System (NAFS) in Turkey can help to resolve the problem of stress transfer along strike-slip fault zones and in this study we show that different stress transfer models, namely 'static Coulomb failure stress changes' and 'dynamic stress changes involving large-scale flow in the aseismic lower crust and the mantle', are responsible for the formation of the earthquake series and earthquake pairs on the eastern and western part parts the NAFS, respectively.

Review of the North Anatolian Fault System (NAFS)

The NAFS is a morphologically distinct and seismically active strike-slip fault which extends for about 1200 km from Karlıova to the Gulf of Saros along the Black Sea mountains of North Anatolia (Figure 1). For most of its length, the transform has a typical strike-slip fault zone morphology, characterized by a narrow rift zone (Şengör 1979). Additionally, Şengör (1979) added that the crust along the fault zone is thinner than normal. The transform probably originated some time between the Burdigalian and the Pliocene and has offset of about 85 km. The North Anatolian transform fault system appears to have originated as a consequence of the Arabia-Anatolia collision during the Late (? Middle) Miocene, when the Anatolian Plate formed and was wedged out into the oceanic tract of the eastern Mediterranean from the converging jaws of Arabia and Eurasia to prevent excessive crustal thickening in eastern Anatolia. The westerly motion of Anatolia, with respect to Eurasia and Africa, caused a great change in the tectonic evolution of the eastern Mediterranean, giving rise to the Aegean extensional regime and to internal deformation of Anatolia (Şengör1979). Zhu *et al.* (2006) suggest that there is general trend of westward crustal thinning from 36 km in central Anatolia to 28–30 km in the central Menderes Massif to 25 km beneath the Aegean Sea (Figure 1). The reader is referred to Bozkurt (2001) and Şengör *et al.* (2004) for a more information on the NAFS.

In a review paper concerning the NAFS, Şengör *et al.* (2004) suggested that since the seventeenth century the NAFS has displayed cyclical seismic behaviour, with

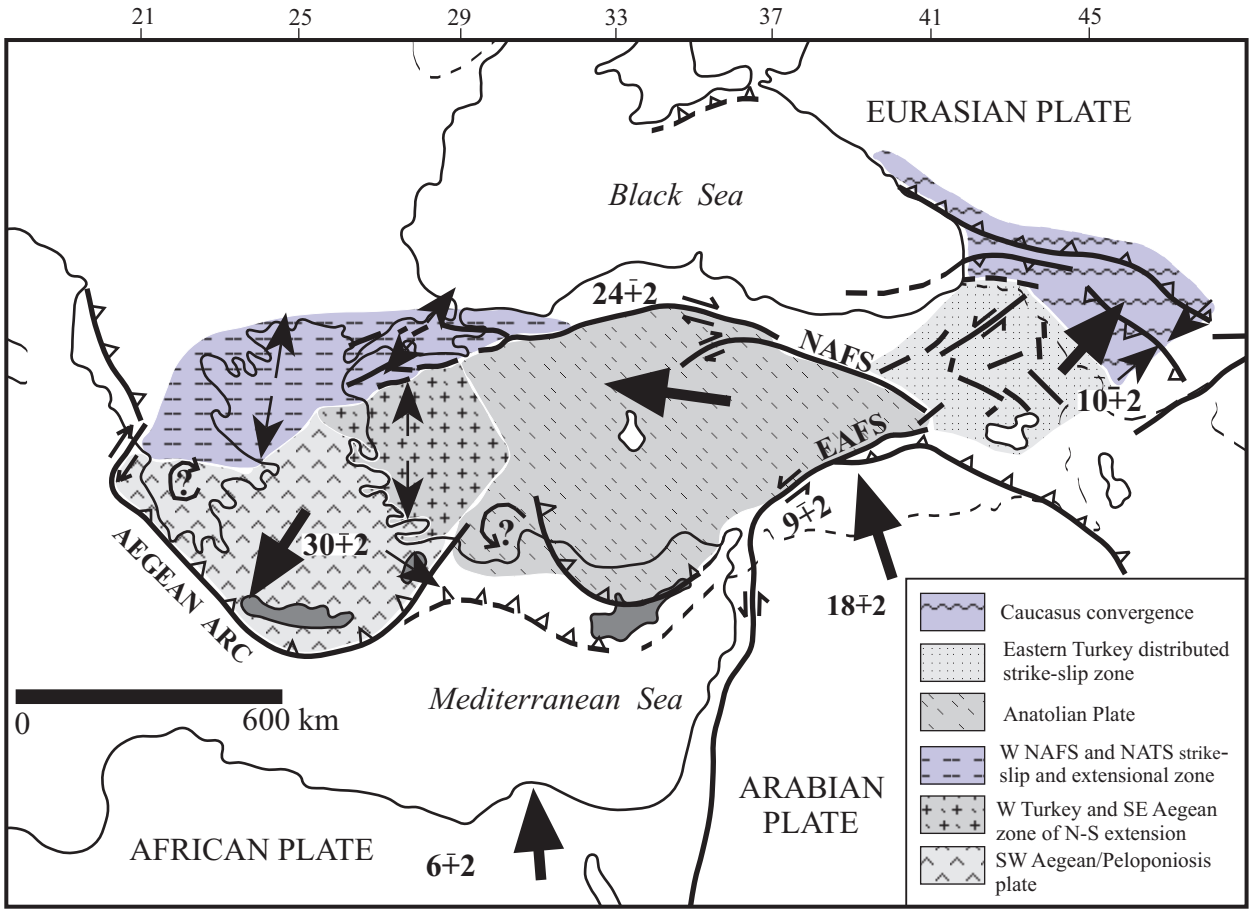

Figure 1. Plate tectonic framework and relative motions in Turkey and adjoining regions after McClusky *et al.* (2000).

century-long cycles beginning in the east and progressing westward. For earlier times, the record is less clear but does indicate a lively seismicity. The twentieth century record has been successfully interpreted in terms of a Coulomb failure model, whereby every earthquake concentrates the shear stress at the western tips of the broken segments leading to westward migration of large earthquakes. Following the 17 August and 12 November 1999, events, there is a ~50% probability of a major, M < 7.6, event on the segment(s) of the NAFS within the Marmara Sea within the next half century. Currently, the strain in the Marmara Sea region is highly asymmetric, with greater strain to the south of the Northern strand.

Different Macro-seismic Zones Along the North Anatolian Fault System

Comparative geological and geophysical studies between the well known San Andreas Fault System and North Anatolian Fault System (NAFS) may help us to understand and estimate seismic activity along these major intracrustal transforms. It is well established that the NAFS moves from a compressive tectonic domain in Eastern Anatolia into a diverse, dominantly extensional, tectonic domain in Western Anatolia (McClusy *et al.* 2000; Figure 1). These different tectonic regimes are the result of diffential indentation of the Anatolian accretionary collage by the northward movement of the Arabian Plate and the tectonic escape of these terranes by a combination of westward push and suction into the southward-retreating Aegean Trench. The spatial and temporal distributions of large historical and modern earthquakes (Mw> 5) would appear to make up two macro-seismic zones, one to the east of the NAFS and one to the west of the NAFS. These zones differ in style and express the different rheologic properties of the crust, thus implying different stress transfer mechanisms.

The Eastern Macro-seismic Zone and Earthquake Series of the NAFS

The eastern macro-seismic zone of the NAFS, between Erzincan and Bolu, has produced successive linear earthquake series parallel to the fault zone for at least 500 years (Figure 2). Five linear historical earthquake series with an interval of 100 years were produced between the 15th and 19th centuries. Each earthquake series consists of successive earthquake events migrating from east near Erzincan to Kastamonu city in the west (Stein *et al.* 1997; Soysal *et al.* 1981; Table 1). At the end of the 19th century the earthquake activity increased and a similar earthquake series with an interval of ~50 years occured on this zone (Figure 2). The first earthquake series of the 20th century began with the Erzincan earthquake (M= 7.9) in 1939, and has comprised seven earthquakes (Mw 6–7) migrating to the west (Figures 2 & 3). A possible second earthquake series, beginning in the 20th century, began with the Erzincan earthquake (M= 6.9) in 1992 and may be completed by westward migrating earthquakes over approximately the next 50 years (Figure 2). These successive earthquake series on the NAFS, which have a narrow expression in the 'eastern macro seismic zone' suggest that stress transfer along the NAFS has occurred within a high-viscosity crust exhibiting primarily elastic behaviour at all depths as suggested by Roy & Royden (2000). According to this interpretation, a significant fraction of the stress released on the fault is transferred to the remaining locked section after a major earthquake (Stein *et al.* 1997). This type of static stress transfer between the locked sections of the fault is compatible with the observed behaviour of the San Andreas Fault (Turcotte *et al.* 1984).

The Western Macro-seismic Zone and Earthquake Pairs of the NAFS

West of Bolu the NAFS splits into northern and southern sub-parallel branches in a broad extensional deformation zone incorporating the Marmara-northern Aegean region (McClusky *et al.* 2000). In contrast to the eastern macro-seismic zone, the western macro-seismic zone of the NAFS in the Marmara region, has produced seven historical (Mw> 7) and 12 modern (Mw 4.9–7) successive earthquakes (Ambraseys & Jackson 2000; Ambraseys 2002; Şaroğlu *et al.* 1999; Yaltırak *et al.* 2005) making up earthquake pairs on the northern and southern branches of the NAFS over the last 500 years (Figure 4). From 1912 to 2001, six destructive earthquake pairs occurred corresponding to the northern and southern branches of the NAFS around the margin of the Marmara Sea (Figure 5). The 1935 Mw 6.4 Erdek-Biga and 1943 Mw 6.6 Adapazarı-Hendek earthquake pair, the 1953 Mw 7.2 Yenice-Gönen and 1963 Mw 6.3 Çınarcık-Yalova earthquake pair, and the 1964 Mw 7 Manyas and 1967 Mw 6.3 Adapazarı earthquake pair are all characteristic paired earthquakes on parallel fault branches of the NAFS in the Marmara region. The 1983 Biga earthquake (Mw 4.9) on the southern branch was followed by the 1999 Yalova and Düzce earthquakes (Mw 7.4) on the northern branch including one of the recent catastrophic earthquake events in the Marmara region (Figure 5). Historical earthquakes with (Mw>7) in the Marmara region (Ambraseys & Jackson 2000) also make-up earthquake pairs on the northern and southern branches of the NAFS (Figures 4 & 5). Examples include the 1509 İstanbul earthquake–1556 Erdek earthquake, 1719 İzmit earthquake–1737 Biga earthquake, the 1766 Gelibolu earthquake–1855 Bursa earthquake and 1894 İzmit earthquake; in each case historical earthquake pairs have alternated on the two branches of the NAFS (Table 1). These historical and modern seismic patterns of the NAFS in the Marmara region suggest that the kinematics and geometry of the western part of the NAFS are controlled by large-scale flow in the aseismic lower crust. Thus shear stress is transferred horizontally to the bottom of the northern and southern parallel fault branches by a horizontal detachment so that brittle fracture has occurred successively on faults in the seismogenic upper crust. A dynamic stress transfer model involving mantle flow for the parallel branches of the NAFS in the Marmara region is applicable to explaining the occurrence of earthquake pairs such as the 1992 Mw 7.3 Landers and 1999 Mw 7.1 Hector Mine earthquake pair in California (Pollitz *et al.* 2001).

Discussion

It has been known for a long time that earthquake occurrence is non-random in space and time. Earthquakes induced by static or dynamic stress changes may trigger subsequent earthquakes. In addition to these, transient flow in the upper mantle is a fundamental component of the earthquake cycle (Pollitz *et al.* 2001).

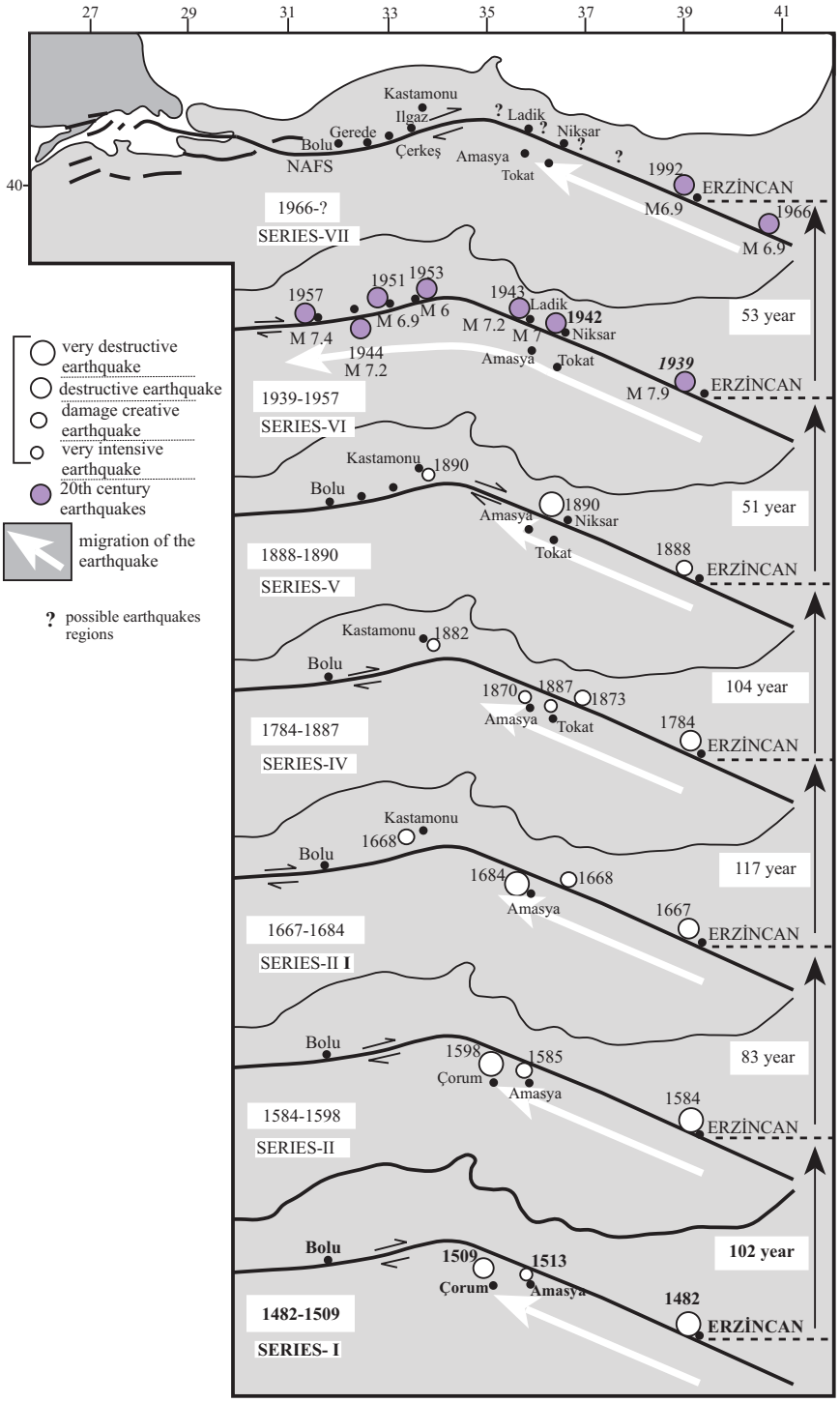

Figure 2. Historical and 20th century earthquake series on the segments of the North Anatolian Fault System between Erzincan and Bolu and possible future destructive earthquakes. The historical and 20th century earthquakes are taken from Soysal *et al.* (1981) and Şaroğlu *et al.* (1999), respectively.

Table 1. Intensity, date and locations of the historical earthquakes.

Intensity	Date	Location	Serie
IX	1482	Erzincan	
VI	1513	Amasya	
VIII	1509	Çorum	Series 1
?	1584	Erzincan	
VII	1585	Amasya	
IX	1598	Çorum	Series 2
VIII	1667	Erzincan	
IX	1668	Amasya-Tokat	
VIII	1668	Bolu-Kastamonu	Series 3
VIII	1684	Amasya	
VIII	1784	Erzincan	
V	1870	Amasya	
VII	1873	Niksar	
VI	1882	Tosya-Kastamonu	Series 4
VI	1887	Tokat	
VII	1888	Erzincan	
VI	1890	Niksar	Series 5
VI	1890	Kastamonu	

Static Stress Transfer and Formation of the Earthquake Series

Harris (1998) and Stein (1999) use calculations of a Coulomb stress increment calculated from an elastic-dislocation model of the main-shock to examine geographical pattern of subsequent earthquakes relative to pattern of change in Coulomb failure. The coseismic change in Coulomb failure function (CF) is given by

$$\Delta CF = \Delta_{\sigma s} + \mu(\Delta_{\sigma n} + \Delta p),$$

where $\Delta_{\sigma s}$ is the coseismic change in shear stress in the direction of the fault slip, $\Delta_{\sigma n}$ is the change in normal stress (with positive tension), Δp is the change in pore-fluid pressure, and μ is an assumed 'coefficient of internal friction'. This general method has shown that static Coulomb stress transfer is consistent with a pattern of 70–80% aftershocks for the studied events. According to Stein *et al.* (1997), there is progressive failure on the eastern part of the NAFS from east to west since 1939 by earthquake stress triggering. This progressive failure mode along the eastern part of the NAFS makes up the modern and historical *earthquake series* on the eastern macro seismic zone of the NAFS (Figures 2 & 3).

On the other hand, different seismic patterns, earthquake series and earthquake pairs, on the eastern and western part of the NAFS, respectively, may not be simply explained by the static stress change of the successive earthquakes. For example, in series VII, (Figure 2), the static stress increase related to the 1966 earthquake M 6.9 in the area of the 1992 M 6.9 Erzincan earthquake, may be negligible due to the long distance, 125 km, between the epicentres of two earthquakes. Similarly, in the historical series IV and V, if we take into account the long distances between earthquakes or their intensities, it seems that static stress change can not be responsible for the earthquake series in the eastern part of the NAFS.

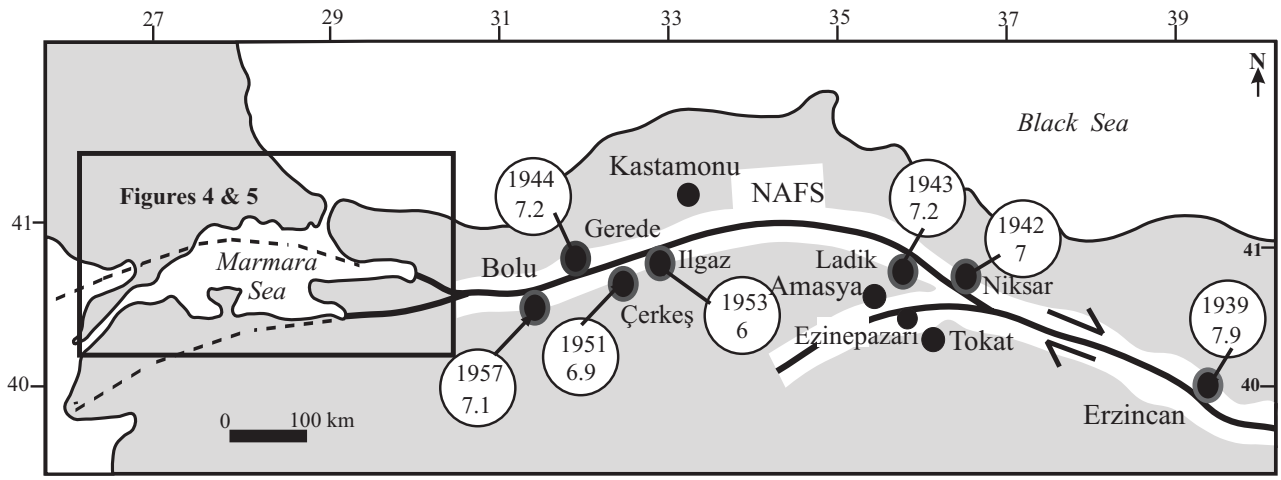

Figure 3. The eastern macroseismic zone of the NAFS located between Erzincan and Bolu, showing how an earthquake series of seven large earthquakes (M ~6–7.4) has migrated regularly from east to west during the 20th century.

So we can deduce that in addition to the static stress change, different crustal rheology played a considerable role in the formation of the earthquake series and pairs. Indeed, Roy & Royden (2000) suggested that brittle failure in a high viscosity crust is primarily focused along the narrow strike-slip fault zone forming earthquake series regardless of the time of the earthquakes. In contrast, when the elastic upper crust is underlain by a low-viscosity lower crustal layer, the deformation zone broadens in time to encompass many parallel strike-slip faults in an interacting network and their earthquake pairs.

In the modern series, VII (Figure 2) the region recovered from the stress shadow created by the 1939 M 7.9 earthquake via the 1992 M 6.9 Erzincan earthquake. We suggest therefore that this series may propagate westward from Erzincan city over the next ~50 years.

Fault Interactions in a Viscoelastic Earth and Formation of Earthquake Pairs

In addition to static stress changes, dynamic or transient stress changes may also be capable of triggering earthquakes. Lomnitz (1996) suggested that fault interaction including distant triggering is due to deep-seated flow in the earth in a response to the triggering earthquake. Alternatively, Harris (2000) considered that dynamic strains may be caused by distant triggering. Parsons (2005) suggests that dynamic stress transfer has a significant effect (potentially a minimum 40% of large triggered earthquakes globally from dynamic stress transfer) although the physics and timing of the dynamic triggering are acknowledged to be poorly understood.

Deep post-earthquake after-slip and viscoelastic relaxation of the lower crust and upper mantle may act to redistribute stress into the seismogenic crust over time (Pollitz *et al.* 2001). Stress transfer within elastic crust is static and immediate, whereas stress transferred by a large earthquake in the higher temperature lower crust and upper mantle is time dependent because strain occurs at depth by viscoelastic flow in response to a sudden stress change (Pollitz *et al.* 2001; Pollitz 2005). Deep post-seismic readjustment may impact the seismogenic crust and act to modify the coseismic static stress change. This process is known as stress diffusion, and appears to occur rapidly relative to the seismic cycle (Parsons 2002). Stress diffusion models were fitted to geodetic measurements made after the 1999 (Mw 7.1) Hector Mine, California and 1999 (Mw 7.4) İzmit, Turkey earthquakes (Hearn *et al.* 2002). The results emphasise that stress diffusion models more easily explain the 1992 Mw 7.2 Landers–1999 Mw 7.1 Hector Mine earthquake pair on the parallel faults rather than the classic static stress transfer model. Roy & Royden (2000) emphasize the effects of lower crustal flow on faulting at strike-slip plate boundaries. They show that when a low-viscosity lower crustal layer underlies a primarily elastic upper crust, the deformation zone broadens in time to

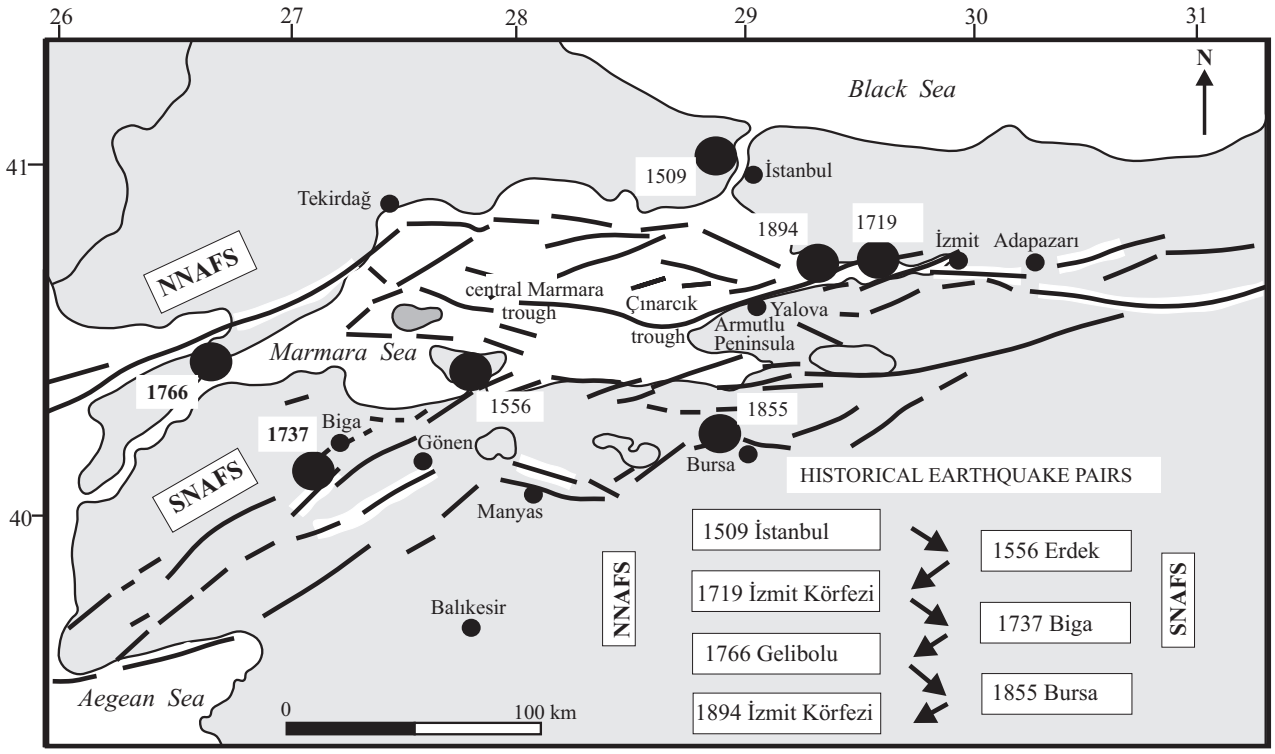

Figure 4. Alternating historical and large earthquakes pairs with magnitude of ≥7 on the northern (NNAFS) and southern (SNAFS) branches of the North Anatolian Fault System in the Marmara region. The historical earthquakes are taken from Ambraseys & Jackson (2000), the fault map from Koçyiğit (1988).

encompass many parallel strike-slip faults in an interacting network such as in the San Francisco Bay area and in the Marmara region of the NAFS. In contrast, when the entire crust behaves elastically, the deformation zone remains narrow as in the eastern part of NAFS, and becomes focussed on a single plate-bounding fault. In their model, the maximum depth of faults is limited by stress relaxation and large-scale viscous flow in the lower crust, which confines brittle failure to shallow and midcrustal levels. Cai & Wang (2001) test fault models with numerical simulation and propose two distinct tectonic models for the faults in central California. In one model (Figure 7, model a), no basal detachment is assumed. In another model (Figure 7, model b), a master detachment is assumed to be present below the seismogenic layer and connects the San Andreas Fault System with the other faults in the system. The authors suggest that model b, the presence of a basal detachment, may facilitate the transfer of shear deformation from the base of the lithosphere. Hence the stresses predicted by the two models are notably different and lead potentially to different assessments of the seismic potential in a given region. When we consider earthquake alternations on sub-parallel faults of the NAFS in the Marmara region we predict that model b is an appropriate explanation for the sub-parallel faults on the western seismic zone of the NAFS.

Primary interpretation of this work in relation to the NAFS suggests that the kinematics and geometry of the fault system and their earthquake pairs in the Marmara region is consistent with the presence of large-scale flow in the aseismic lower crust and contrasts with the eastern seismic zone of the NAFS. Thus historic and modern earthquake pairs on the parallel faults of the NAFS in the Marmara region are explained by a stress diffusion model rather than by a static stress transfer model.

Though some earthquake pairs (1983–1999; 1964–1967) are separated by more than 200 km, they are also located in the broader Marmara deformation zone of the NAFS. If the model we suggested above is

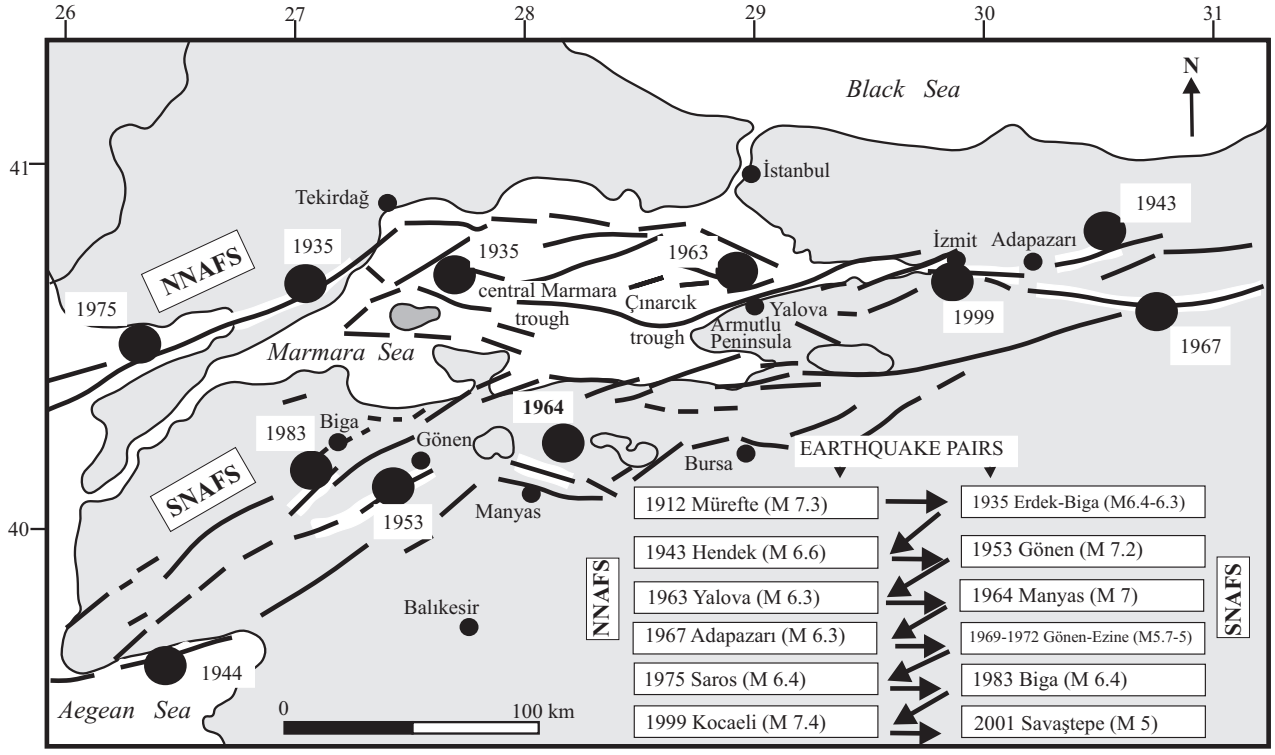

Figure 5. The western macro-seismic zone of the NAFS includes 6 earthquake pairs (M 6.1–7.4) that have alternated on distinct parallel fault segments of the NNAFS and SNAFS in the Marmara region during the 20th century (NNAFS: northern branch, SNAFS: southern branch, of the North Anatolian Fault System).

correct we can say that the sub-parallel faults of the NAFS, on which earthquake pairs occurred, may be controlled by the lower detachment that facilitates the broadening of the deformation zone.

However, Hubert-Ferrari *et al.* (2000) and King *et al.* (2001) examined earthquake interactions since 1900 in the Marmara Sea. They showed that 23 out of 29 earthquakes (M> 6) over an 85 year period could be related to earlier events. In a similar way, they showed that historical earthquakes, between 1700–1900, migrated westward and eastward on the northern and southern branches of the NAFS, respectively, in the Mamara Sea.

Similarly, Parsons *et al.* (2000) argue that the 1999 M 7.4 İzmit earthquake, as well as most background seismicity of the Marmara Sea, occurred where the failure stress is calculated to have increased 1–2 bars by M 6.5 earthquakes since 1939. The İzmit event, in turn, increased the stress beyond the east end of the rupture by 1–2 bars, where the M 7.2 Düzce earthquake struck, and by 0.5–5 bars beyond the west end of the 17 August rupture, where a cluster of aftershocks occurred (Parsons *et al.* 2000). However, a critical question related to this hypothesis is: why did the 1999 İzmit fracture not continue westward into Marmara Sea instead of eastward to Düzce (e.g., King *et al.* 2001; Hartleb *et al.* 2002)?

The hypothesis mentioned above contrasts with both the modern and historical earthquake pairs models we suggested in the text (Figures 4 & 5) for the Marmara Sea. Though we used all of the 12 modern earthquakes (M>5) since 1912, we had to use the historical earthquakes of M> 7 with dates between 1700 and 1900 (Ambraseys & Jackson 2000). According to King *et al.* (2001) the M> 7 events broke two or more segments while the smaller earthquake occurred on a single segment.

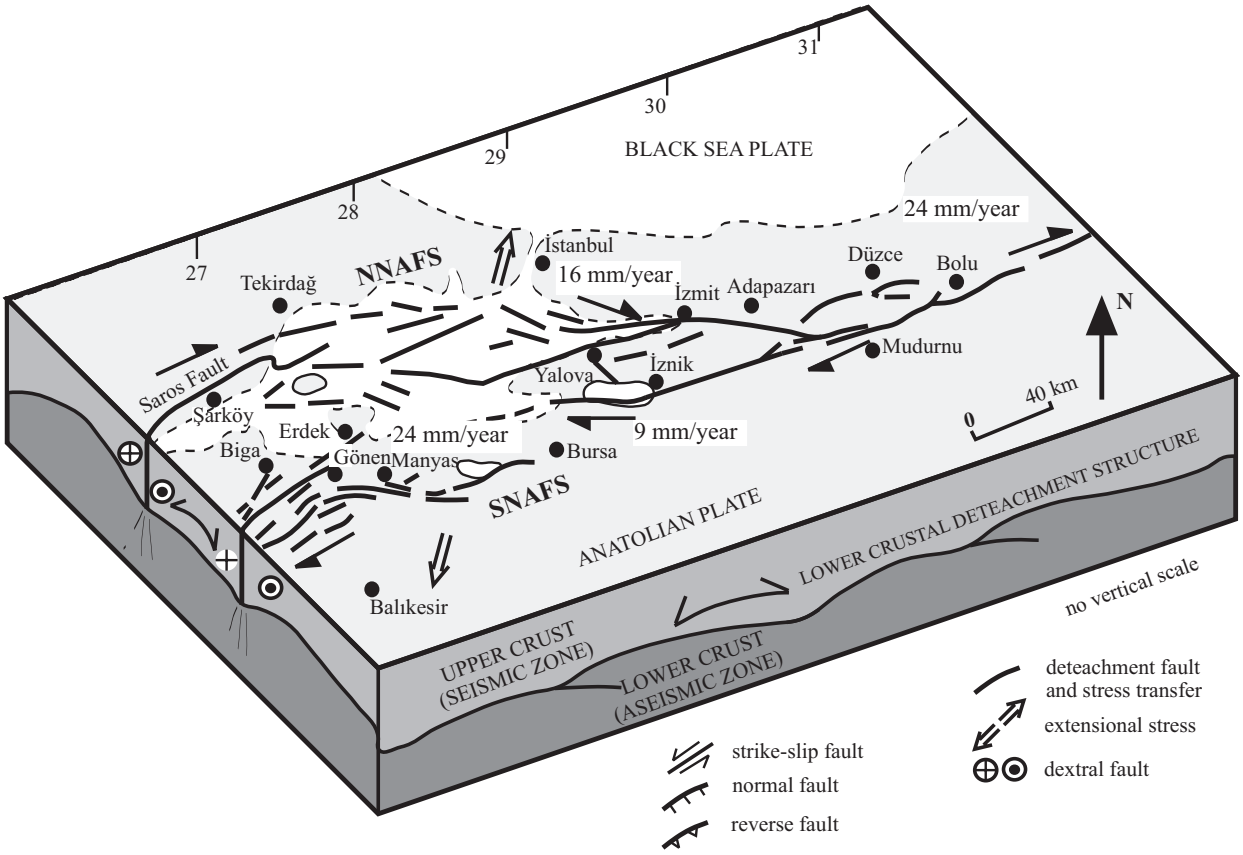

Figure 6. Schematic block diagram depicting sub-horizontal detachment between the lower and upper crust with shear stress transferred horizontally to the bottom of the northern and southern branches of the NAFS in the Marmara region as in Figure 7 model b century (NNAFS: northern branch, SNAFS: southern branch, of the North Anatolian Fault System).

Conclusion

Spatial and temporal variations of seismicity in the eastern and western parts of the NAFS make up two different macro-seismic zones, reflecting different crustal rheologies and stress transfer in two distinct tectonic domains as illustrated by the tectonic models discussed above (Lemiszki & Brown 1988; Nishigami 2000; Roy & Royden 2000; Cai & Wang 2001; Parsons 2004). The eastern macro-seismic zone of the NAFS, located between Erzincan and Bolu, has produced a series of seven modern large earthquakes (Mw 6–7.4) which have migrated regularly from east to west by the Coulomb static stress transfer (Figures 2 & 3). This modern earthquake series running parallel to the narrow NAFS zone suggests that stress transfer and migration of the earthquakes along the fault has occurred within a high-viscosity crust exhibiting primarily elastic behaviour at all depths (Roy & Royden 2000). This type of static stress transfer between the locked sections of the fault is consistent with observed behaviour on the San Andreas Fault (Turcotte *et al.* 1984).

West of the town of Bolu in the western macro-seismic zone the NAFS splits into northern and southern sub-parallel branches in a broad extensional deformation zone within the Marmara-northern Aegean region. During the last century, seismic activity in this zone has included six earthquake pairs (Mw 6.1–7.4) alternating on the distinct parallel fault segments of the northern and southern branches of the NAFS (Figure 5). This type of seismic activity may imply that there is a lower crustal sub-horizontal detachment fault that may facilitate more dynamic stress transfer between sub-parallel faults of the NAFS than would be expected from a static stress transfer in an elastic medium (Figure 6). However, so far,

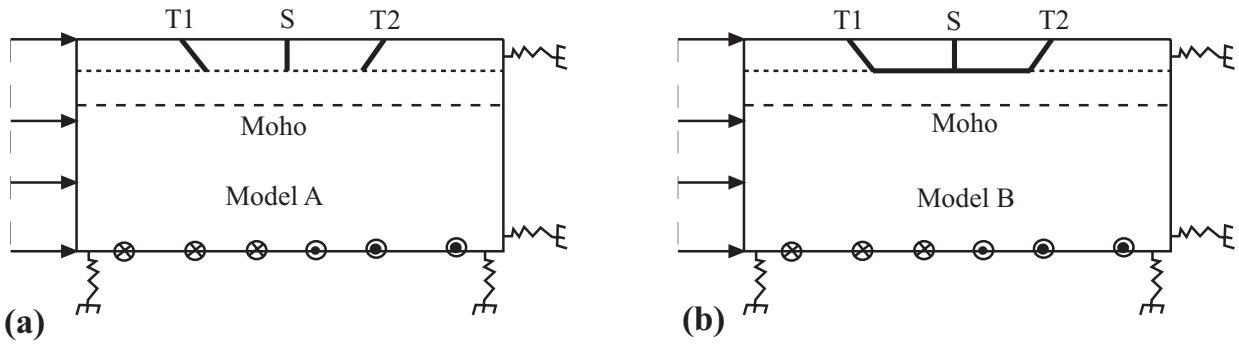

Figure 7. Schematic drawings of two different fault configurations showing (a) all faults terminating at the base of the seismogenic layer and (b) all faults connecting to a detachment at the base of the seismogenic layer. (⊗) shear out of page; (⊙) shear in the page (after Cai & Wang 2001).

in seismic hazard evaluations, or earthquake predictions, faults in the Marmara Sea are simulated as dislocations in a half-space where no basal detachment has been assumed. We conclude that the static stress transfer model in the eastern part of the NAFS and the dynamic stress transfer model among the parallel branches of the NAFS to the west provide the significant parameters for predicting seismic hazards on the NAFS.

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