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Faulting and Stress Distribution in the Bolu Pull-apart Basin (North Anatolian Fault Zone, Turkey): The Significance of New Dates Obtained from the Basin Fill

ERGUN GÖKTEN[1], RAMAZAN DEMİRTAŞ[2], VOLKAN ÖZAKSOY[3], ERDAL HERECE[4], BAKİ VAROL[5] & UĞUR TEMİZ[6]

[1] Ankara University, Engineering Faculty, Geological Engineering Department, Tectonic Research Group, TR–06100 Ankara, Turkey (E-mail: Y.Ergun.Gokten@eng.ankara.edu.tr)

[2] Disaster and Emergency Management Presidency, Department of Earthquake, Eskişehir Yolu 9. km, Lodumlu, TR–06530 Ankara, Turkey

[3] Akdeniz University, Geological Engineering Department, Engineering Faculty, Dumlupınar Bulvarı, Kampus, TR–07058 Antalya, Turkey

[4] General Directorate of Minereal Research and Exploration (MTA), Geological Research Department, Balgat, TR–06800 Ankara, Turkey

[5] Ankara University, Engineering Faculty, Geological Engineering Department, TR–06100 Ankara, Turkey

[6] Bozok University, Engineering and Architectural Faculty, Geological Engineering Department, Atatürk Yolu, TR–66100 Yozgat, Turkey

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Abstract: The Bolu Basin in northwestern Turkey, situated in the western part of the North Anatolian Fault Zone (NAFZ), displays the neotectonic features of a pull apart basin. The long axis of the basin extends east–west, parallel to the fault zone and Bolu city, situated in the central part of this basin, was extensively damaged during the 17 August 1999 M= 7.4 and 12 November 1999 M= 7.2 earthquakes. The master strand of the North Anatolian Fault Zone cuts through the basin close to its southern edge and movement on this strand has caused tilting of the basin floor towards the south because of a small dip slip component. Almacık Mountain, to the west of the Bolu Basin, is interpreted as a plate flake and appears to play a role in the bifurcation of the North Anatolian Fault Zone around the Düzce Basin, to the west of Bolu. Thus the surface fracture associated with the right-lateral strike-slip Gölyaka-Kaynaşlı segment of the NAFZ (which caused the 12 November 1999 M= 7.2 earthquake in this region), can be traced along the northern flank of Almacık Mountain and may extend into the middle of the Bolu Basin from the west. The northern boundary of this basin is controlled mainly by an E–W-striking oblique-slip normal fault with a right-lateral strike-slip component but a major NE–SW-trending younger fracture (Kocasu Fault) has also influenced the kinematic behaviour of this sector of the NAFZ and the adjacent basin. It is concluded that the Bolu Basin opened as a pull-apart basin since the Early Pleistocene between the northern boundary faults and southern master strand, and within the complex stress-field reflected in this still-active fault regime. It has continued to develop in this style, despite the regional transpressional stress field prevailing in the western sector of the northwards-convex North Anatolian Fault Zone. New radiometric dates obtained from travertine deposits developed along the NAFZ master strand on the southern border of the Bolu Basin show that the basin is older than 3×10^5 years. Dip-slip normal faults observed in the poorly consolidated Quaternary fluvial sediments forming the basin floor display both ENE–WSW and N–S trends, in accordance with the transtensional kinematics of a pull-apart. The 4.5 metre co-seismic right-lateral displacement in the middle part of the Gölyaka-Kaynaşlı segment of the NAFZ that occurred during the 12 November 1999 earthquake appears to have loaded stress on to the eastern part of this segment, possibly causing it to propagate eastwards, into the middle of the Bolu pull-apart basin and creating an east–west-trending high strain zone north of Bolu city, suggesting the route of the possible continuation of the segment.

Key Words: Bolu, pull-apart basin, North Anatolian Fault Zone, recent faulting, 1999 earthquake, travertine dating

Bolu Çek-Ayır Havzasında Faylanma ve Gerilme Dağılımı (Kuzey Anadolu Fay Zonu, Türkiye): Havza Dolgusundan Elde Edilen Yeni Tarihlendirmelerin Önemi

Özet: Kuzeybatı Türkiye'de ve Kuzey Anadolu Fay Zonu'nun batı kesiminde yer alan Bolu Havzası bir çek-ayır havzanın özelliklerini sergiler. Uzun ekseni fay zonuna paralel yer alan havzanın ortasındaki Bolu şehri 17 Ağustos (M= 7.4) ve 12 Kasım (M= 7.2) 1999 depremlerinde ağır hasar görmüştür. Kuzey Anadolu Fay Zonu'nun ana kolu havzayı güney kenarından keser ve sahip olduğu küçük eğim atım bileşeni yüzünden havza tabanının güneye eğimlenmesine neden olur. Bolu Havza'sının batısında yer alan Almacık Dağı bir levha parçacığı gibi davranarak Bolu batısında ve Düzce Havzası dolayında fayın çatallanmasına yol açar. Kuzey Anadolu Fay Zonu'nun sağ yanal doğrultu atımlı Gölyaka-Kaynaşlı segmenti'nin (12 Kasım 1999 M= 7.2 depremine yol açan) yüzey kırığı Almacık Dağı'nın kuzey eteği boyunca izlenebilir ve Bolu Havza'sının batısına kadar uzanır. Havzanın kuzey kenarı başlıca D–B uzanımlı sağ yanal doğrultu atım bileşenli verev atımlı bir fay tarafından kontrol edilir, fakat bu kesimde KD–GB doğrultulu Kocasu fay zonunun kinematik davranışını etkiler. Bolu Havzası kuzeye bükümlü bir yay şeklinde olan Kuzey Anadolu Fay Zonu'nun genel olarak transpresyonel karakterde olan batı kesiminde yer almasına karşın olasılıkla Erken Pleyistosen'den beri zonun ana kolu ile kuzey kenar fayı arasında bir çek-ayır havza tarzında açılmakta olup karmaşık gerilme düzeni bu gelişimin devam etmekte olduğunu göstermektedir. Kuzey Anadolu Fay Zonu'nun havza güney sınırını oluşturan ana kolu üzerinde gelişmiş olan traverten oluşumlarından elde edilen radyometrik yaş verileri havzanın 3×10^5 yıldan daha yaşlı olduğunu göstermektedir. Havza tabanını oluşturan Kuvaterner yaşlı akarsu tortullarını etkileyen KD–GB ve K–G doğrultulu eğim atımlı faylar çek-ayır gelişime işaret ederler. 12 Kasım 1999 depreminde Kuzey Anadolu Fay Zonu'nun Gölyaka-Kaynaşlı segmenti'nin orta kesiminde meydana gelen 4.5 m'lik deprem eşzamanlı sağ yanal atım segmentin doğu kesimine bir gerilme yüklemiş olup Bolu şehrinin kuzeyinde meydana gelen yamulma zonu segmentin olası gelişme yolu hakkında da fikir vermiştir.

Anahtar Sözcükler: Bolu, çek-ayır havza, Kuzey Anadolu Fay Zonu, genç faylanma, 1999 depremi, traverten yaşlandırmada

Introduction

The right-lateral strike-slip North Anatolian Fault Zone is 1100 km long, extends in a northward convex arc across the northern part of the Anatolian plateau from Karlıova in the east to the North Aegean shear zone in the west. It is the most important seismogenic structure of Turkey (Figure 1). This structure coincides with the Inner Pontide suture marking the boundary between the Eurasian Plate to the north and the Sakarya Continent to the south. Since Ketin (1948a) recognized this structure as a major strike-slip fault, many studies have been carried out in different parts of the fault zone on its age, total offset and neotectonic properties (e.g., Taşman 1944; Ketin 1948a, b, 1957, 1968, 1969; Pavoni 1961; Öztürk 1968; Canıtez 1973; Tokay 1973; Tokay *et al.* 1974; Ambraseys 1975; Arpat & Şaroğlu 1975; Seymen 1975; Tatar 1975; Dewey 1976; Şengör 1979, 1980; Hankock & Barka 1980; Bergougnan & Fourquin 1982; Barka & Hankock 1984; Şengör *et al.* 1983, 1985; Şaroğlu 1985; Aktimur *et al.* 1986; Ambraseys & Finkel 1988; Koçyiğit 1988, 1989, 1990; Barka & Kadinsky-Cade 1988; Barka & Gülen 1990; Ikeda *et al.* 1991; Barka 1992; Dirik 1993; Barka & Wesnousky 1994; Demirtaş 1994, 2000; Okumura *et al.* 1994; Andrieux *et al.* 1995; Gökten *et al.* 1996, 1998; Sugai *et al.* 1997; Özaksoy *et al.* 1998; Demirtaş *et al.* 1998; Özaksoy 2000; Hitchcock *et al.* 2003; Herece 2005). While a synthesis of the neotectonics of Turkey has been presented by Bozkurt (2001), a complete history of the studies on the North Anatolian Fault Zone has recently been given by Şengör *et al.* (2004), who emphasised that the North Anatolian Fault Zone is a shear zone widening to the west. Theoretically, while the western part of the northward convex system creates a transpressive stress region, the eastern part is experienced by a transtensional stress regime which gives rise to some pull-apart basins such as Erbaa, Suşehri and Erzincan basins along its extent. But the widening character of the fault zone to the west, as a result of bifurcations, also caused the formation of some fault controlled basins, such as Bolu and Gölova basins (Koçyiğit 1990). Most recently Özden *et al.* (2008) examined the kinematic features of the North Anatolian Fault Zone along the southern boundary of the Bolu Basin.

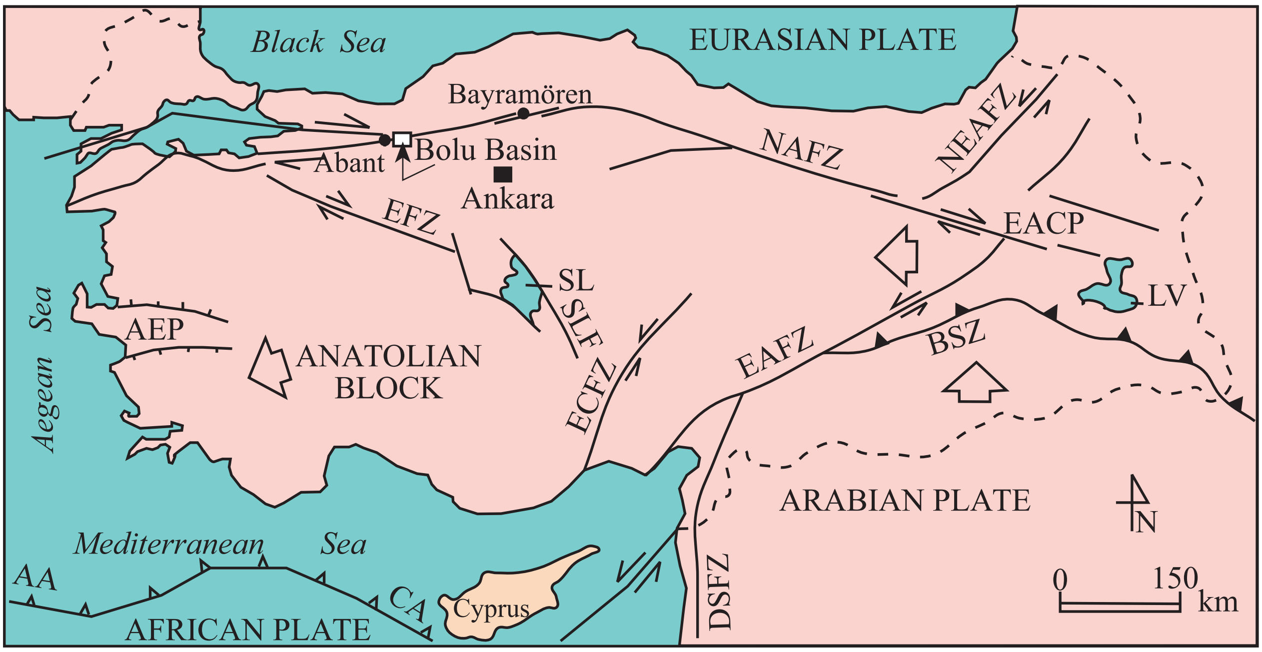

Figure 1. Simplified neotectonic map of Turkey and the location of the Bolu Basin (investigated area). AEP– Aegean Extensional Province, BSZ– Bitlis Suture Zone, DSFZ– Dead Sea Fault Zone, EACP– East Anatolian Compressional Province, EAFZ– East Anatolian Fault Zone, ECFZ– Ecemiş Fault Zone, EFZ– Eskişehir Fault Zone, LV– Lake Van, NAFZ– North Anatolian Fault Zone, NEAFZ– Northeast Anatolian Fault Zone, SL– Salt Lake, SLF– Salt Lake Fault.

The Bolu Basin is situated in the western part of the North Anatolian Fault Zone (NAFZ), in an area first mapped in detail by Öztürk *et al.* (1984), who did not interpret its neotectonic character. The pull-apart character of the basin was first emphasized by Gökten & Varol (2002, 2004). This basin is a densely inhabited area that includes Bolu city (Figure 1) in its centre. The east–west length of the basin is about 20 km, and its north–south width is about 5 km. The basin floor is gently inclined toward the south. The basin is bounded to north and south by lithological units of pre-Miocene age, while to the west the plain is bounded by the Bolu Massif and the east side is defined by a tectonic elevation that separates Yenicağ Lake from the Bolu Basin (east of No 16 in Figure 5). The floor of the Bolu Basin has been filled with unconsolidated to poorly consolidated pebbly and sandy deposits transported from the northern highlands as alluvial fans and by alluvium deposited by the Büyüksu stream flowing close to the southern edge of the basin. This tectonically controlled basin is characterized by high seismicity and was severely affected by the 1999 east Marmara earthquakes. The master strand of the North Anatolian Fault Zone extends along the southern edge of the basin. The aim of the study presented here is to describe the stratigraphic and structural attributes of the Bolu Basin, focusing on the geometry and kinematics of recent faulting, in order to interpret the present stress distribution and to discuss the age and evolution of the Bolu Basin, using new dates relating to the neotectonic behaviour of the NAFZ .

Geological Framework

Stratigraphic units of different ages and various lithologies crop out to the north and south of the Bolu Basin. These Palaeozoic to Miocene formations are termed the palaeotectonic units. Since the encroachment of the North Anatolian Fault Zone into the Bolu region during the Pliocene, the units formed under the control of this fault (post-Pliocene to Recent) are designated the neotectonic units, and these are the main basin-fill deposits. The lithostratigraphical terminology used here is taken from several previous studies (Blumenthal 1948; Canik 1980; Öztürk *et al.* 1984).

Palaeotectonic Units

The North Anatolian Fault Zone coincides with the 'Intra Pontide Suture' and delineates the boundary between İstanbul and Sakarya Zones (Okay 1989) in the Bolu region. Thus the stratigraphy in the northern and southern parts of the fault zone shows differences: for example no autochthonous Palaeozoic formations are seen in the southern sector. However, the basement rocks are not the main scope of this paper, they are described briefly because they form the basement of the basin, and especially because the master strand of the North Anatolian Fault Zone displays kinematic indicators in the basement rocks south of the basin.

Northern Sector – The northern and western margins of the Bolu Basin are formed by the Palaeozoic Bolu Massif, the Kızılağıl formation (Devonian), the Bayramışlar formation (late Cretaceous), the Arkotdağı mélange (late Cretaceous), the Lower to Middle Paleocene Sırakayalar formation and the Merkeşler formation (Eocene) (Öztürk *et al.* 1984) (Figure 2). These Palaeotectonic lithostratigraphical units are all depicted with the same symbol on the geological map (Figure 3).

Southern Sector– The Palaeotectonic formations exposed along the southern border of the Bolu Basin are the Kayı formation (Jurassic–Cretaceous), the Kuzviran formation (late Cretaceous), the Kıvaşı formation (Paleocene) and the mainly Neogene Köroğlu volcanic rocks of the Galatean Massif (Öztürk *et al.* 1984) (Figure 4).

Neotectonic Units

Salıbeyler Formation (Tps)– This formation is exposed north of the Bolu Basin, mostly in the area between the İstanbul-Ankara motorway and Salıbeyler village (Figure 2; UTM 36°N 381500, 4513400). The formation rests with an angular unconformity on Eocene turbiditic limestones of the Merkeşler formation. Because of tilting associated with the faulted southern boundary of the basin this lithostratigraphic unit is buried under younger sediments in the middle of the plain. The lower part of the formation comprises alternations of well-cemented thick conglomerate and sandstone, overlain by upper levels dominated by poorly-cemented sandstones and conglomerates, which are characterized by poorly sorted and angular granite, gneiss and limestone pebbles. The visible thickness of this fluvial unit is about 20 m. In the east of the Bolu plain the unit is capped by a thin, local, white limnic limestone layer (UTM 36°N 392800, 4511300). Most of Bolu city is built upon various levels of this formation. The upper levels of this unit also outcrops around the Üçtepeler pressure ridge, in the south of the Bolu plain (Figure 3) and here it has a typical fluvial character, with loose pebbly and sandy deposits. These upper levels of the formation alternate with local travertine occurrences just east of Üçtepeler. The radiometric age of these travertines exceeds 300 000 y BP. Because the unit rests unconformably upon the Eocene Merkeşler formation, the lower levels of the Salıbeyler formation may extend down to early Pleistocene time. However the age of the young cover series exposed in the Mudurnu valley near the Bolu Basin has been assigned to the Pliocene by Gözübol (1978) and Paluska *et al.* (1989), who presented a radiometric age data of 82 000 y BP for these series. Consequently we propose an Early Pleistocene–Late Pleistocene age range for Salıbeyler formation in this study.

Terrace Deposits (Qtr1)– This terrace level comprises the older alluvial deposits of the west-flowing Büyüksu stream in the northern and central parts of the basin as the second stage basin fill of the Bolu Basin (Figure 3). They cover the southern parts of the basin on the hanging wall of the Salıbeyler fault, which is why a clear relationship with the underlaying Salıbeyler formation cannot be seen. The visible thickness of the unit is about 60 m at outcrop but exceeds 100 m in boreholes drilled to the east of Bolu city (UTM 36°N 390500, 4510900). This unit is composed of alternating gravelly, sandy and silty deposits, which grade into each other laterally and vertically. The boundary of these terrace deposits is clearly defined by the step-like morphology in the northern part of the basin. Bolu city centre is built upon part of this alluvial level that has been tectonically elevated as a pressure ridge with the possibly underlying Salıbeyler formation. The age of this formation, as a product of

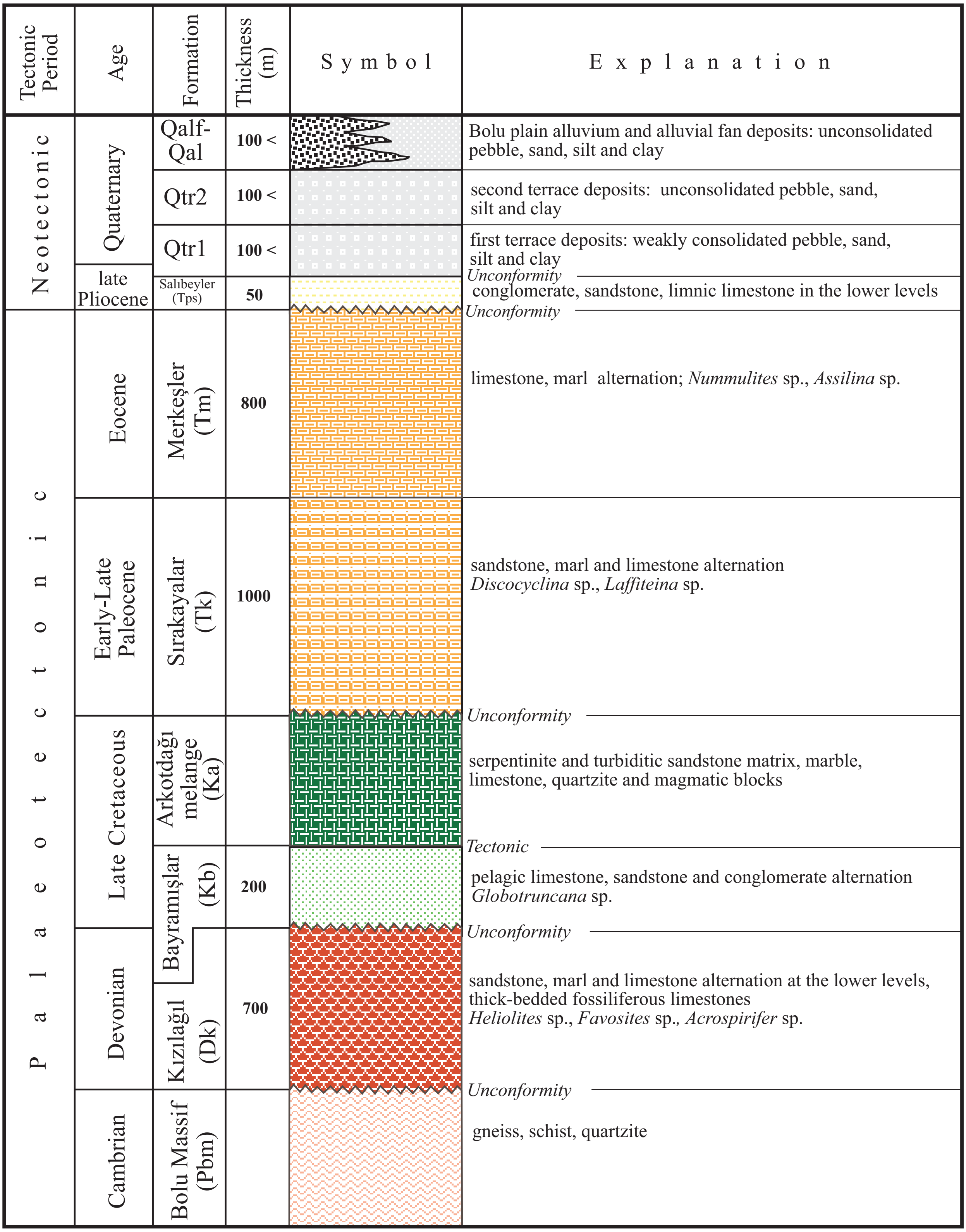

Figure 2. Generalized stratigraphic column for the northern margin of the Bolu Basin (after Öztürk *et al.* 1984).

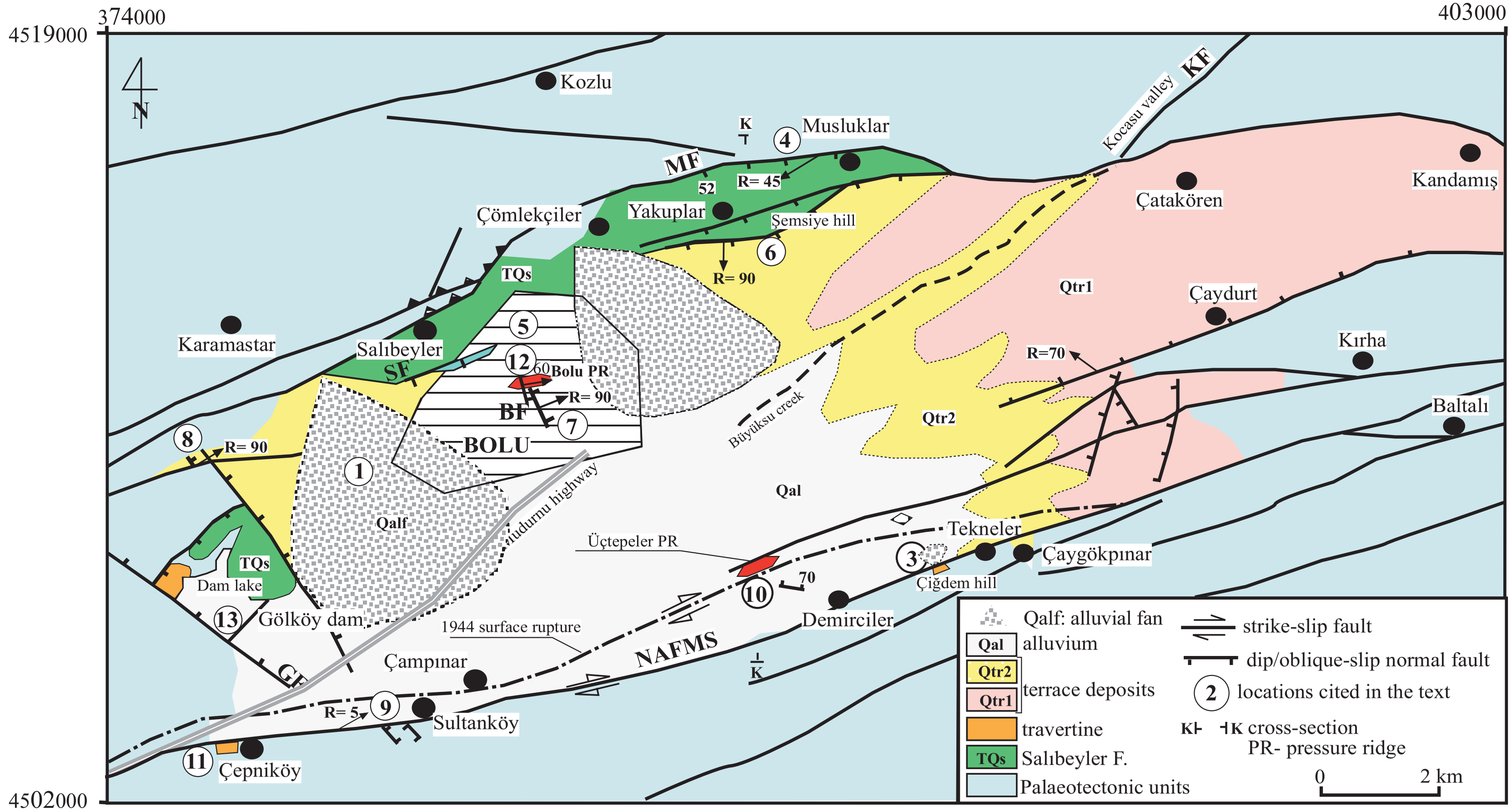

Figure 3. Map showing the main neotectonic features and structures in the Bolu Basin. NAFMS– North Anatolian Fault Zone master strand, KF– Kocasu fault, MF– Musluklar fault, GF– Gölköy fault, BF– Bolu fault, SF– Salıbeyler fault, 1–12 are the location numbers cited in the text.

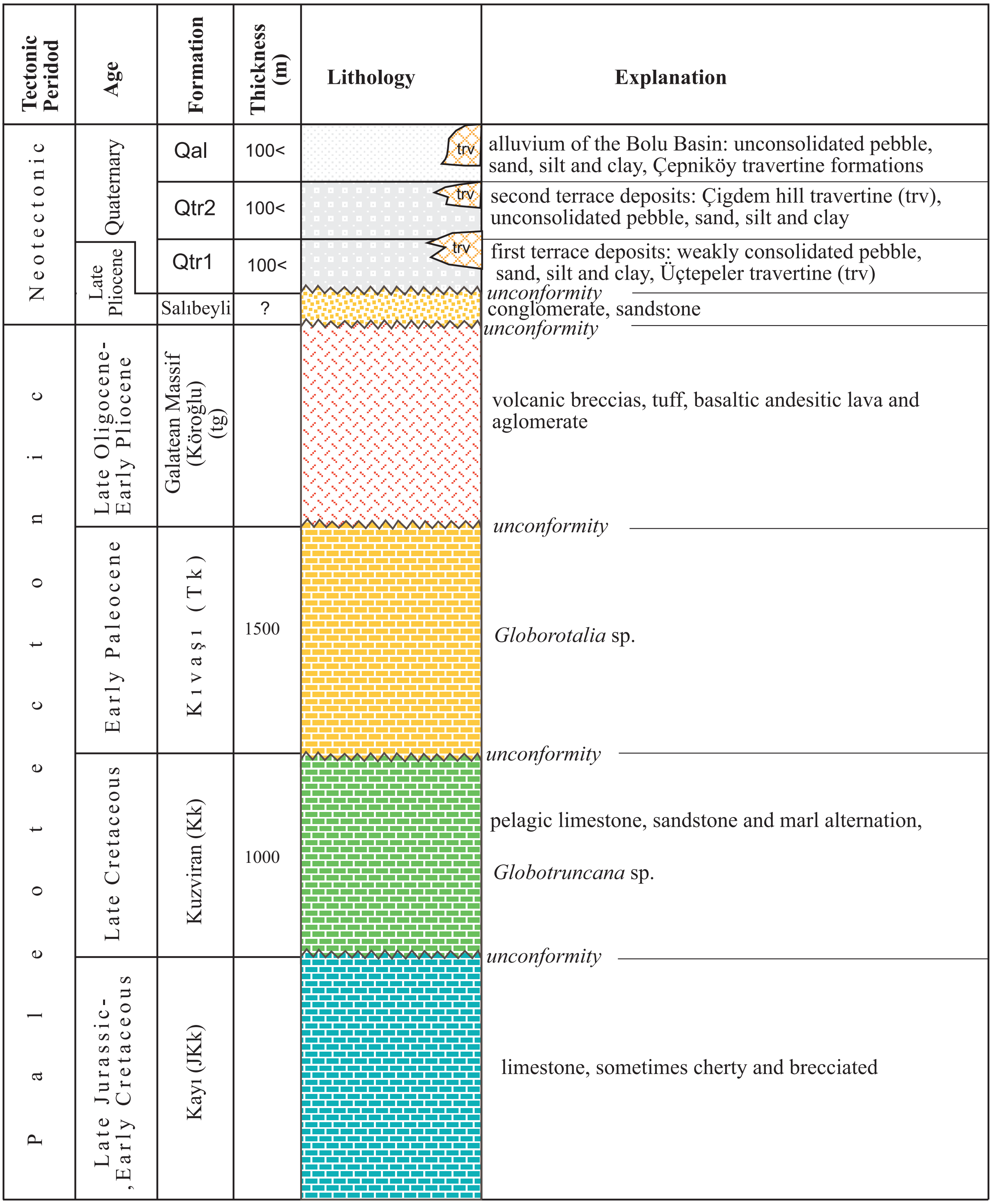

Figure 4. Generalized stratigraphic column for the southern margin of the Bolu Basin (after Öztürk *et al.* 1984).

geologically recent fluvial activity, is Late Pleistocene–Holocene.

Terrace Deposits (Qtr2)– This comprises the stratigraphically younger (Holocene) terrace deposits developed on the flood plain of the Büyüksu stream in the northeastern and central parts of the plain (Figure 3). It is composed of coarse clastic fluvial deposits, similar to those found in the first terrace deposits. The boundary between the first and second terrace levels is clearly defined by the step morphology.

Aluvial Fan Deposits (Qalf)– There are two major alluvial fan deposits in the Bolu Basin. The first fan (No 1 on Figure 3) is built from materials transported from the highland region northwest of the basin by south-flowing streams. The distal parts of the fan reach as far south as the Mudurnu road. The unconsolidated gravels, sands and silty deposits merge with the recent alluvium and clayey, silty and sandy deposits of the Büyüksu stream floodplain, flowing WSW towards the Mudurnu Valley (No 19 in Figure 5). The second large alluvial fan is in the north-central part of the Bolu Basin, northeast of Bolu city, and extends southwards from the high northern borderland (Figure 3). The lithological features and the thickness (25 m) of this fan can be observed in deep pits excavated for the disposal of rubbish from Bolu city. Most of the industrial establishments, workshops and buildings of Bolu city are constructed on the loose gravelly, sandy and silty lithologies of this alluvial fan.

Alluvium (Qal)– The floor of the Bolu Basin is gently inclined to the south, thus the gravels, sands and silty materials transported by the Büyüksu stream are ultimately deposited in the south of the basin as Recent alluvium. Similar recent deposits are seen just north of the state highway, in a densely populated part of Bolu city. The thickness of these Recent deposits exceeds 100 m in the southern part of the basin.

Travertine (trv)– Some travertine deposits have developed in the vicinity of the 1944 surface rupture of the North Anatolian Fault Zone in this region (Gökten & Temiz 2007). A few travertine outcrops also occur in the south of the Bolu Basin (Figure 4). One travertine formation is seen to the north of Çiğdem Hill (Figure 3) associated with a spring which provides some of the drinking water for Bolu city (No. 3 on Figure3; UTM 36°N 3990075, 4506996; Figure 6a). Two more travertine deposits are exposed in the southwest of the basin, on the main strand of the North Anatolian Fault Zone. One of these travertine bodies displays step-like morphology, presumably because of movements on the main fault, the surface trace of which can be seen in the adjacent basement rocks, near the southwest end of the basin. The travertine formation crops out northwest of the Gölköy Reservoir on the hanging block of the Gölköy fault, extending from northwest to southeast (Figure 3). Most importantly the travertine occurrences are seen interbedded with the lower levels of the basin-fill sediments in the east of the Üçtepeler region (No 10 in Figure 3)

The $^{230}Th/^{234}U$ dates obtained from travertine samples (Table 1) collected from the localities described above (see Table 1) are: 82,980±7960 y BP for the Çiğdem Hill locality (Bolu spring water on the table); ages in excess of 300,000 y BP for travertines exposed on the pressure ridge to the east of Üçtepeler (No 10 in Figure 3; UTM 36°N 389250, 4507400; Figure 6b) and 17,960±7410 y and 18,880±6380 y BP for two samples of the step-morphology travertines from Çepniköy, in the southwest corner of the basin (Figure 3; No 11; UTM 36°N 375132, 4503924; Figure 6c). The two samples from the Çepniköy region were vertically separated by two metres, which thus yields an average precipitation rate of 0.235 cm/y, at least for this geological interval. In addition, dates obtained from a travertine ridge further east, near Belemurlu Hill between the Bolu Basin and the Yeniçağa depression (UTM 36°N between 413912, 4512998 and 413912, 4513150) (Figure 5; No 16 on Figure 6d) range from 96,310±38,440 y to 52,650±8060 y BP. All these age data suggest that the inception of the Bolu Basin occurred more than 300,000 years ago.

Structural Geology

The Bolu Basin has developed under the influence of right-lateral strike-slip faults associated with the North Anatolian Fault Zone (NAFZ), which is the most seismically active tectonic structure in Turkey.

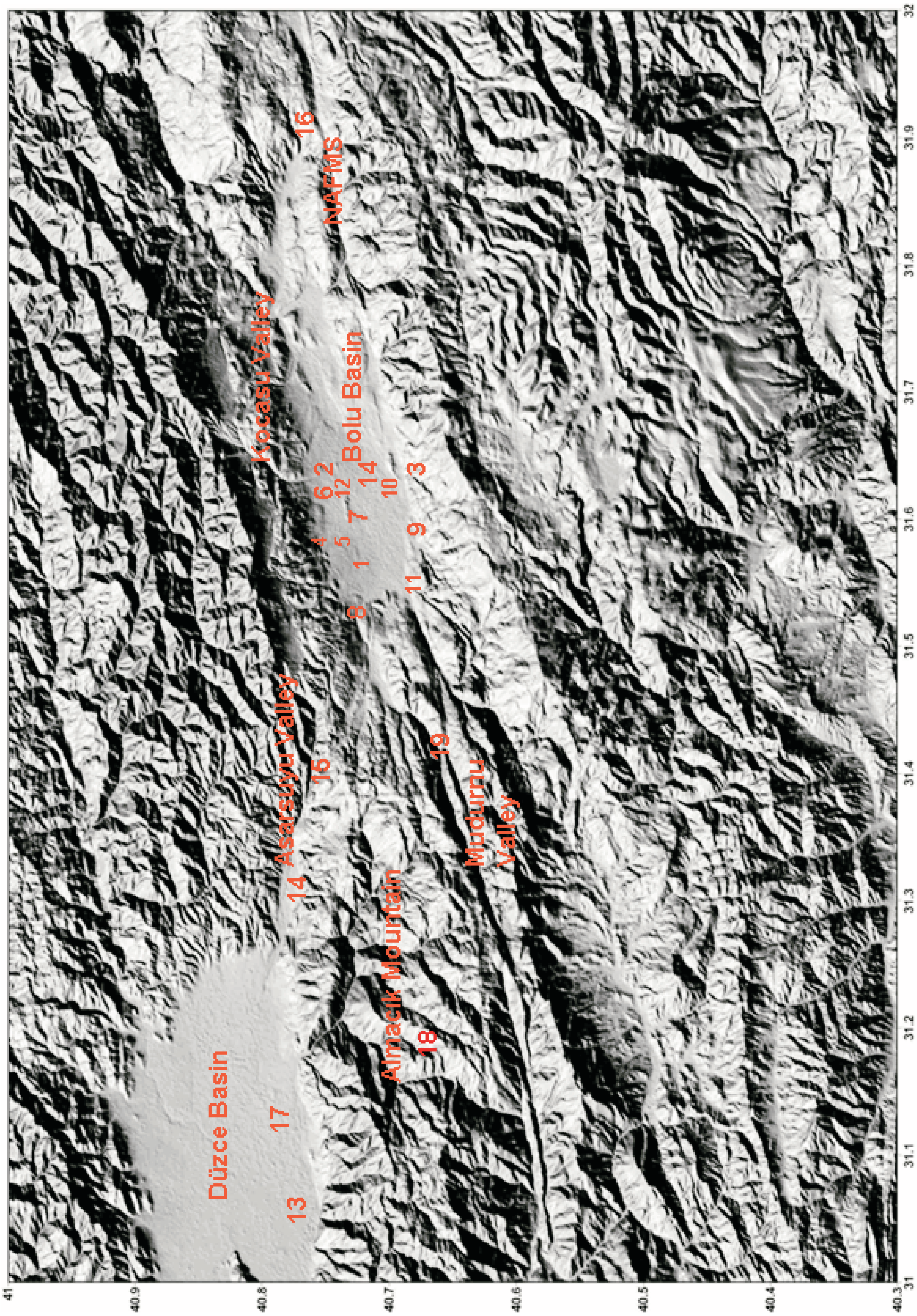

Figure 5. The DEM image of the Bolu and Düzce basins (USGS 2000; http://earthquake.usgs.gov/maps/strm). The numbers 1–18 are the localities cited in the text, NAFMS– North Anatolian Fault Zone master strand.

Table 1. Uranium series radiometric datings of the travertines of the Bolu Basin.
(Results of the U and Th isotope analysis)

Sample No	^{232}Th [mBq/g]	^{230}Th [mBq/g]	^{238}U [mBq/g]	^{234}U [mBq/g]	$(^{234}U/^{232}Th)_m$	$(^{230}Th/^{232}Th)_m$	^{230}Th/^{234}U age [y]	Error on age [y]
Bolu Basin pressure ridge	1.06	6.80	4.78	6.09	5.75	6.43	>300000	
Y-I-1 Yeniçağ-inner-1	0.007	0.73	1.60	1.36	194.30	104.3	82980	±7960
Y-I-2 Yeniçağ-inner-2	1.80	2.23	1.90	2.55	1.42	1.24	96310	±38440
Y-D-2 Yeniçağ-outer-2	0.03	1.56	3.06	2.83	94.33	52	85930	±7160
Y-D-1 Yeniçağ-outer-1	3.33	2.31	2.22	2.30	0.69	0.69	52650	±8060
B-I-3 Bolu spring water 3	0.01	1.07	2.34	1.20	120	107	82980	±7960
C-1 Çepni-1	0.52	0.65	0.74	1.40	2.69	1.25	17960	±7410
C-2 Çepni-2	0.54	0.70	0.87	1.52	2.81	1.30	18880	±6380

Faulting characterizes both the palaeotectonic and neotectonic periods in the northern and the southern parts of the basin. The neotectonic (post Mid-Pliocene) faults are the structures responsible for development of the pull-apart basin. One of the most important neotectonic fractures forming the northern boundary of the basin is the Musluklar fault, seen to the north of Musluklar village (No 4 on Figures 3 & 5; Figure 7a) (Demirtaş 2000; Gökten & Varol 2002, 2004). This is an oblique-slip normal fault with a right-lateral strike-slip component (N78°E, 52°SE; R= 45°SW). The throw of the fault is more than 20 m, so the basin floor forms a hanging wall that is drawn towards the southwest in this northern part of the basin (Figure 8a). The northern boundary fault of the NAFZ makes a restraining bend to the north of Salıbeyler and this bending is considered to be responsible for the high-angle reverse character of this sector of the fault (Figure 3). North of Çatakören village the northern boundary fault is cut by the Kocasu fault (possible southwest continuation of the Mengen fault in the northeast of the Bolu Basin), which has a N44°E trend (Figure 3). Displacement of the Quaternary basin-fill sediments observed along the southwest-trending Büyüksu stream in this region demonstrates that the Kocasu fault extends well into the Bolu Basin. The morphotectonic character of the fault is clear both in the northern plain and beyond the Bolu Basin, along the Kocasu Valley. In the northern Bolu Basin the straight alignment and related step-like morphology of the Quaternary terrace deposits along Büyüksu Creek provide the main evidence for the southwestwards continuation of the Kocasu Fault. In this study no new kinematic data have been obtained from the Kocasu Fault, but the characteristic straight alignment of the valley and left-lateral offsets of the tributaries imply that the Kocasu-Mengen sector of this fault is either a strike-slip or oblique-slip normal fault in character, with a left-lateral strike-slip component. West of the Kocasu junction the northern boundary fault contiues as a compound set

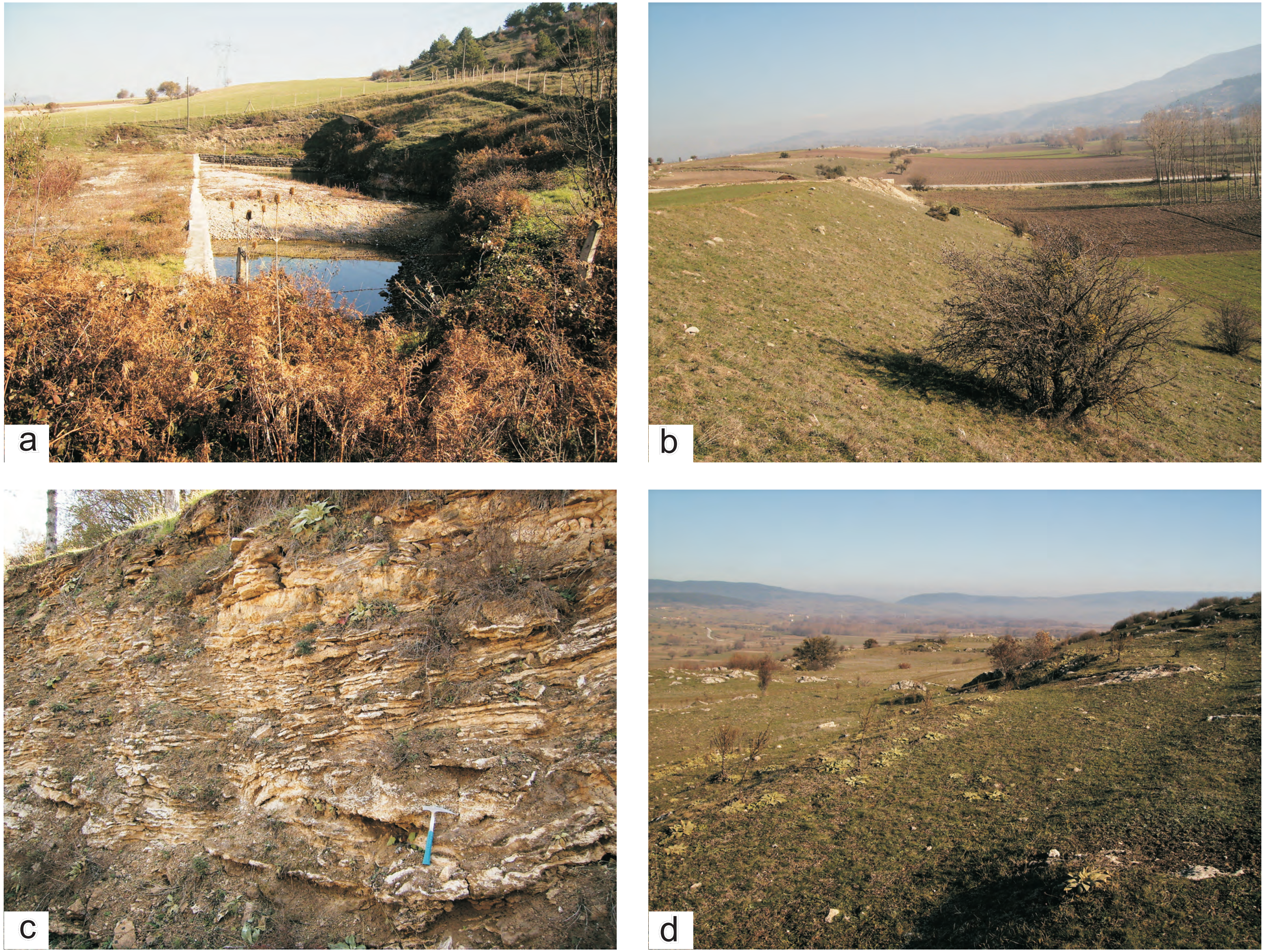

Figure 6. **(a)** Travertine formation around Çiğdem hill spring supplying drinking water to Bolu city, occurring on the main strand of the North Anatolian Fault Zone, looking east; **(b)** travertine formation exhumed on the Üçtepeler pressure ridge in the south of the Bolu Basin, looking east; **(c)** Çepniköy travertines in the southwest of the Bolu Basin; **(d)** Belemur hill travertines between the Bolu and Yeniçağa basins, looking west.

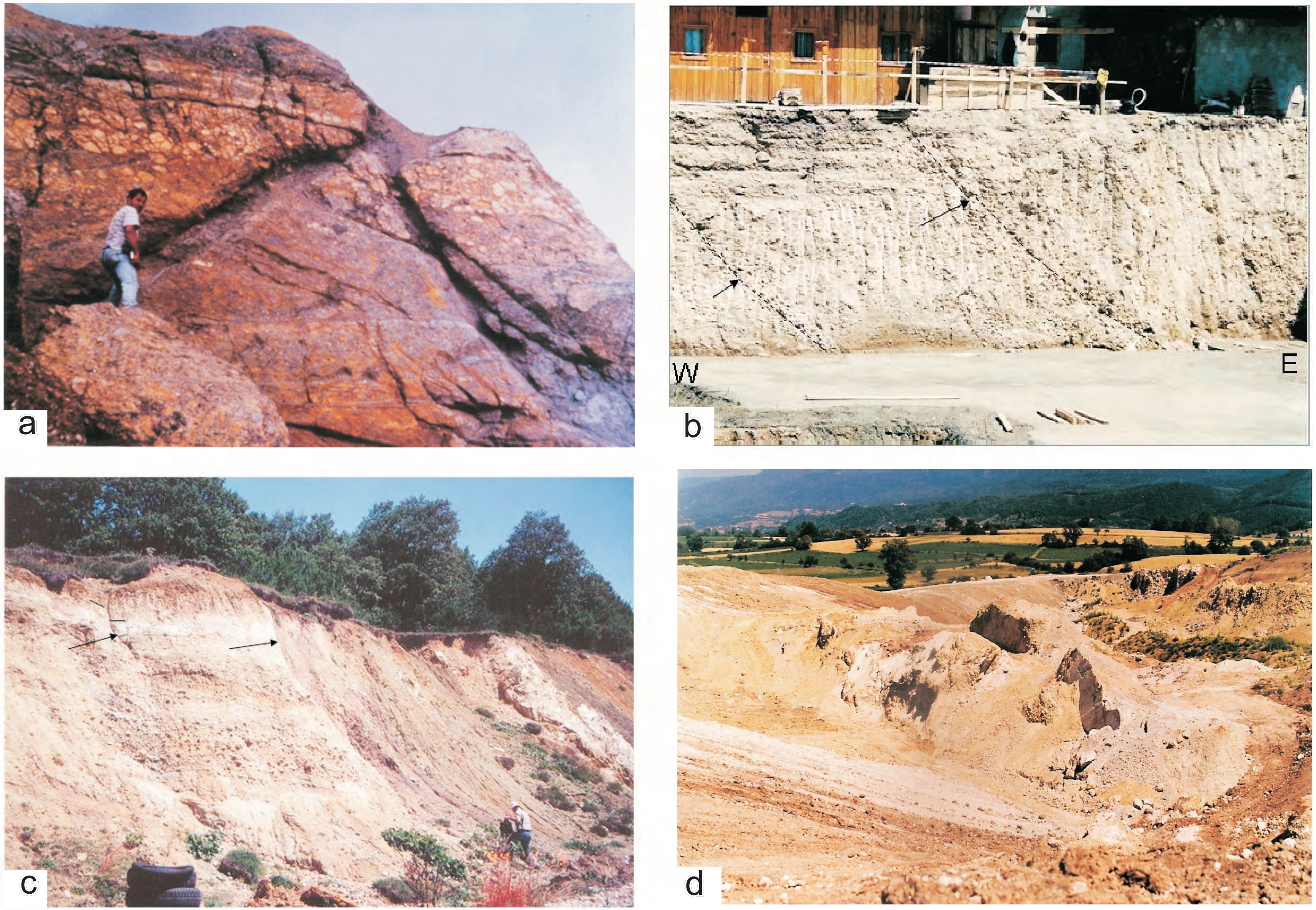

Figure 7. **(a)** Fault plane of the Musluklar fault, north of Musluklar village, looking north (see No 4 on Figure 3 for location); **(b)** dip-slip normal fractures of the Bolu fault, developed in Quaternary alluvial fan sediments in the central part of Bolu city, looking north; **(c)** dip-slip normal faults cutting Quaternary alluvial fan sediments near the D-100 State highway in the western part of the Bolu Basin; looking northeast; **(d)** fault plane of the NAFZ master strand developed in upper Jurassic–lower Cretaceous limestones on the southern margin of the Bolu Basin, Sultanköy quarry (No 9 on Figure 3), looking south.

of faults, mostly dip-slip normal faults in character (Öztürk 1968). Although the NAFZ northern boundary fault clearly extends further east from this junction, the Kocasu Fault may play a significant role in the evolution both of the NAFZ and the Bolu Basin by disrupting the right-lateral movement of the northern boundary fault at this location, and transferring the overall control of basin-extension to the NAFZ master strand controlling the southern boundary.

Another important fracture system which has contributed to the shaping of the northern part of the basin occurs south of Salıbeyler village as a set of dip-slip normal faults (R= 90°) that strike N80°E with a 85°SE dip (No 5 on Figures 3 & 5). This Salıbeyler fault has exhumed Eocene turbiditic sandstone beds from under the Quaternary sediments of the Bolu Basin fill (e.g., locality UTM 36°N 381600, 4512350), and is also responsible for the regional southwards inclination of the basin floor, with the assistance of accompanying *en échelon* faults (Gökten *et al*. 1998) (Figures 8b & 9). South of Yakuplar village, in the northern part of the basin, another step-like morphotectonic feature with a northeast–southwest trend reveals the Şemsiye Hill dip-slip normal fault, where Quaternary terrace deposits overlying the Pliocene consolidated sediments have been elevated by about five metres relative to the basin floor (No 6 on Figure 3; UTM 36°N 386850, 4513900). In addition, deep excavations cut into the alluvial fan in the northeast of the basin (No 2 on Figure 3) and in the center of Bolu city have revealed some N30°W, 45°NE-trending young faults developed in the semiconsolidated fluvial conglomerate and sandstones that display 30 to 50 cm of dip-slip displacement, indicating northeast–southwest extension of the basin floor simultaneously with the north–south widening (Figure 8c; No 7 on Figures 3 & 5; Figure 7b; UTM 36°N 382700, 4510225). The last mentioned point was a foundation excavation for a big state department building. So in the centre of the Bolu Basin it is very difficult to find any other kinematic data which will show the deformational trend of the basin floor besides this one. A similar situation is seen on the state highway in the western part of the Bolu Basin. Here some *en échelon* dip-slip normal faults trending NNW–SSE cut Quaternary coarse alluvial fan sediments (No 8 on Figures 3 & 5; Figure 7c; UTM 36°N 375700, 4511650).

The main strand of the North Anatolian Fault Zone (known here as the Bayramören-Abant segment; Figure 1) extends along the southern boundary of the Bolu Basin. The width of the zone does not exceed a few hundred metres here and the *en échelon* faults, mainly of oblique-slip normal character, occur very close to the main fault. These faults can be seen in the quarries in this part of the region. Details of the several types of deformational structures accompanying the fault zone have been given by Demirtaş (2000). The surface of the master fault is well displayed in the indurated Late Jurassic–Early Cretaceous rocks on the southwestern margin of the Bolu plain, in a quarry south of Sultanköy, where it displays transtensional character, as revealed by the 05° east-dipping rake observed on the 75° north dipping fault surface striking in N70°E trend (No 9 on Figure; Figures 7d & 8d). This sector of the NAFZ is characterized by second order faults of varied trends and origins, associated with the main strand. The North Anatolian Fault Zone master strand makes two bends south of the Bolu Basin. The first bend, in the western half of the south of the basin between Çepniköy and Demirciler villages, is convex to the south, forming a releasing bend, while in the eastern half of the south of the basin a bend convex to the north creates local restraining bend conditions. In the western parts of the master strand the second order structures are interpreted either as strike-slip dominated conjugate structural elements of the master strand (Figure 8e) or conjugate dip-slip normal fault sets trending N40–45° W (Figures 8f & 10). In this area the Sultanköy quarries are unique places to observe the kinematic features of the North Anatolian Fault Zone master strand in the south of the Bolu Basin. However, because the crushed upper Jurassic–lower Cretaceous limestones in the fault zone are used in road constructions as ready material by the municipality, the quarry face changes continously, and it is not now possible to see several characteristics of the zone in studies especially carried out after 2000 (Figure 11a). From Demirciler village (Figure 3) to the eastern end of the basin some compressive structures, such as sets of reverse

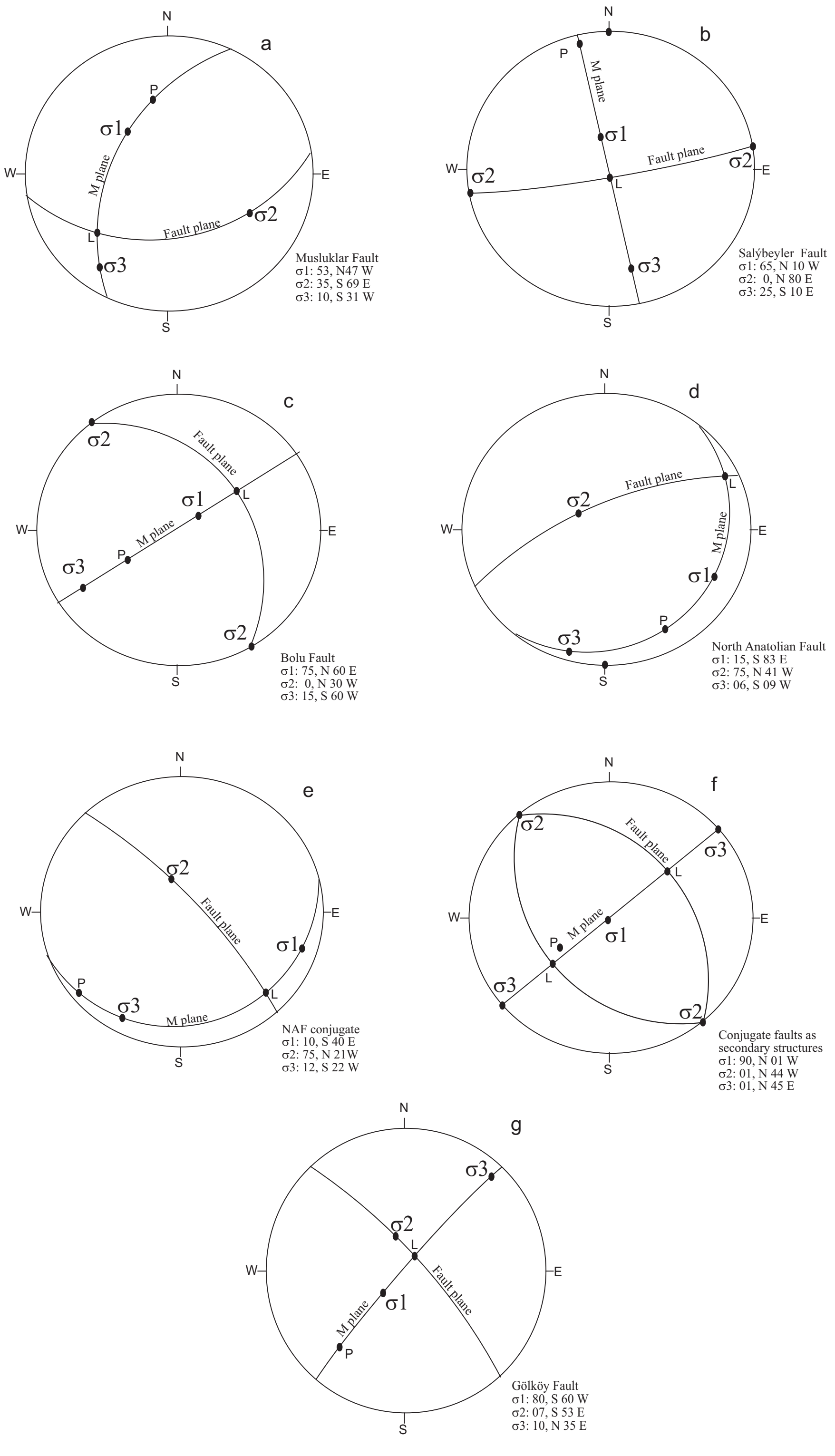

Figure 8. Fault plane solutions for the main neotectonic faults of the Bolu Basin; **(a)** Musluklar fault, **(b)** Salıbeyler fault, **(c)** Bolu fault, **(d)** NAF, **(e)** NAF conjugate, **(f)** Secondary conjugate faults, **(g)** Gölköy fault; equal area lower hemisphere projection (see Figure 3 for locations).

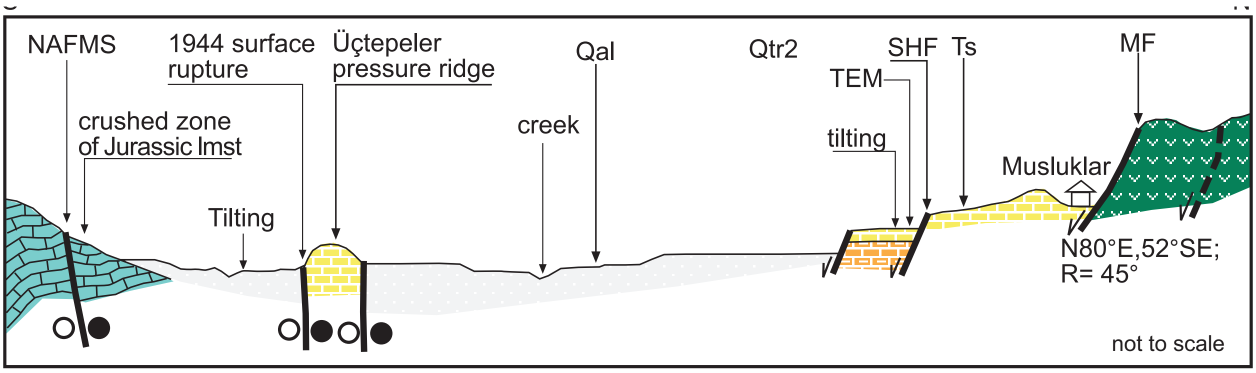

Figure 9. North-south geological cross-section of the Bolu Basin. NAFMS– North Anatolian Fault Zone master strand, SHF– Şemsiye hill fault, MF– Musluklar fault, TEM– Trans European Motorway, Ts– Salıbeyler formation. Filled circles show approaching block.

faults trending approximately N15°E, and related positive flower structures caused by the restraining character of the master strand were seen (Figures 11b & 12; Çaygökpınar quarry). All these kinds of structure have been developed in the fault crush zone in upper Jurassic–lower Cretaceous limestones. Unfortunately, because of the reason mentioned above, all these structures have been concealed today by the road constructions of the Bolu municipality.

The N70°E-trending surface rupture of the 1944 earthquake developed in the unconsolidated basin-fill sediments close to the fault scarp in the south (No

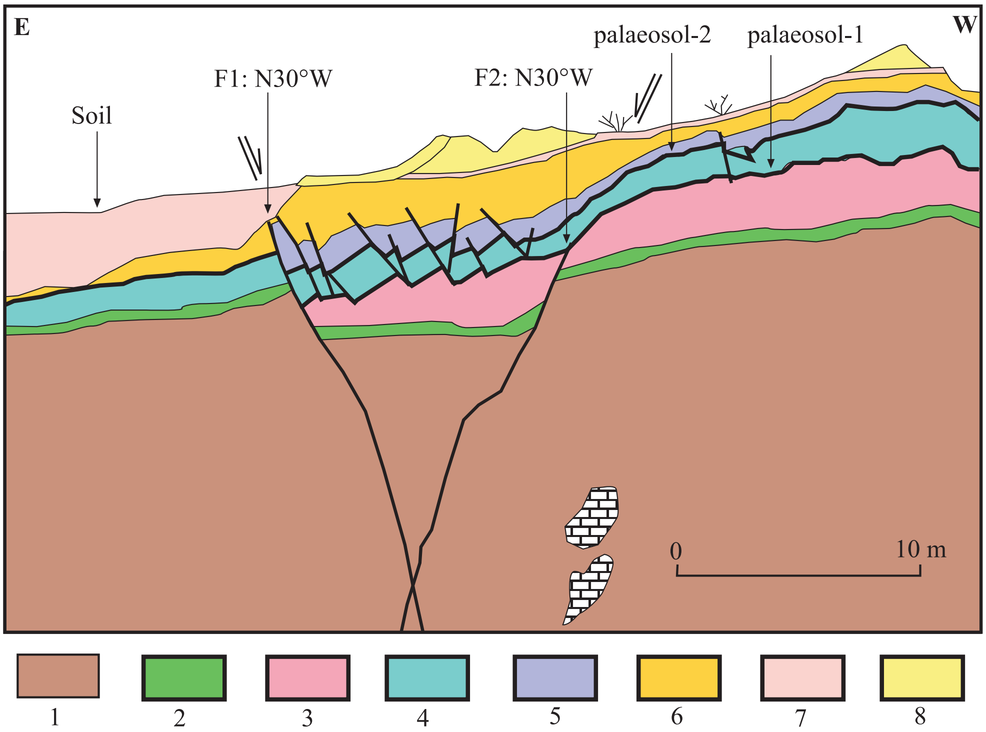

Figure 10. Secondary structures in the releasing bend sector of the North Anatolian Fault Zone master strand. 1– brecciated limestone, 2– pebble horizon, 3– silt and clay, 4– silty level, 5– sandy level, 6– altered zone, 7– soil, 8– carried material. Each palaeosol level possibly indicates an event (from Demirtaş 2000).

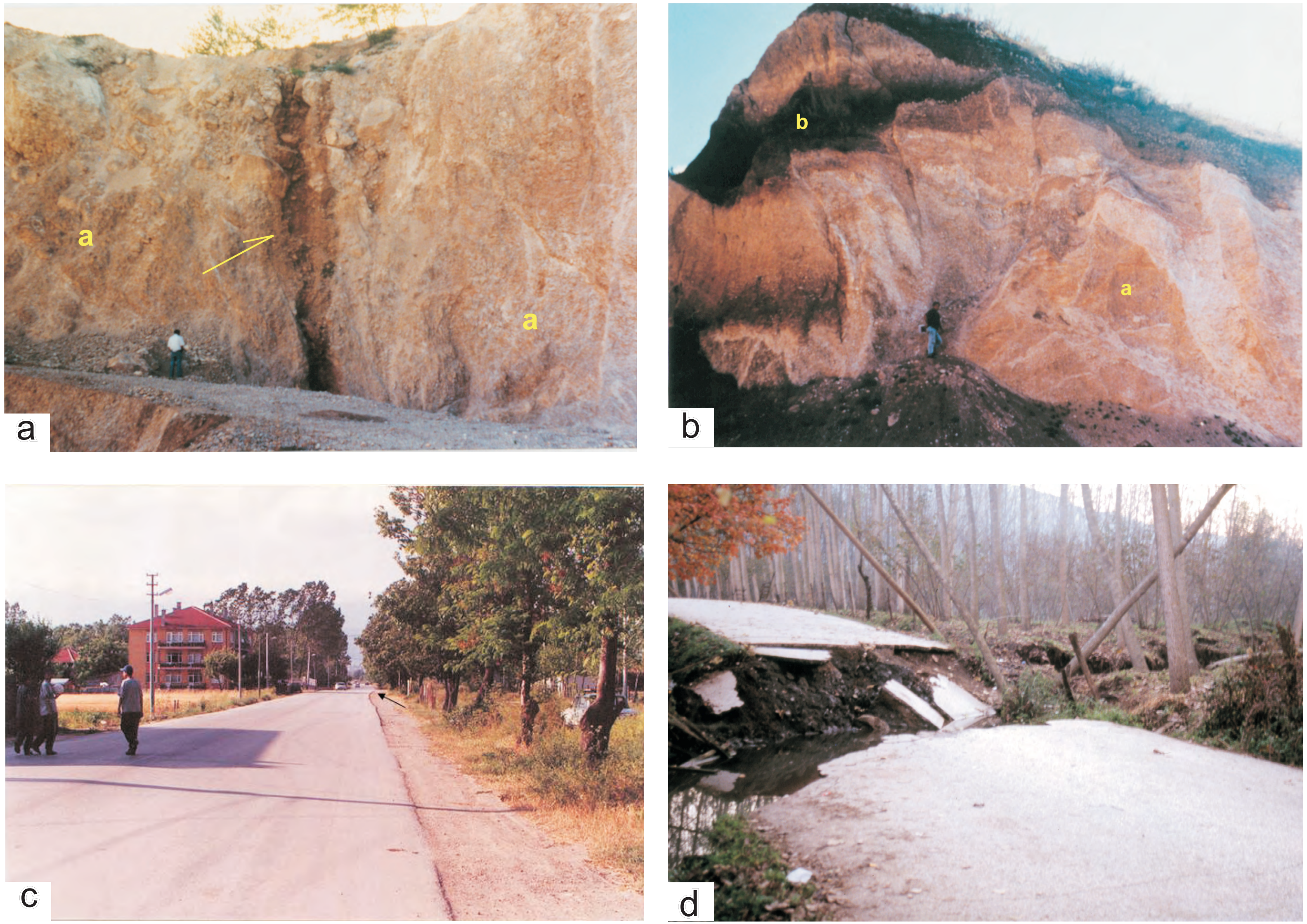

Figure 11. **(a)** Crushed zone of the master strand of the North Anatolian Fault Zone developed in the upper Jurassic–lower Cretaceous limestones, looking west in the west of the Sultanköy quarry; **(b)** positive flower structure developed in the restraining eastern part of the North Anatolian Fault Zone master strand in the south of the Bolu Basin, Çaygökpınar quarry, looking southwest (see Figure 3 for the location); **(c)** right-lateral offset of road leading to Bolu municipality hot springs, cut by NAFZ during the 1944 earthquakes. Road runs approximately north–south looking north; **(d)** 12 November 1999 earthquake 10 km overlapped the surface rupture of the 17 August 1999 earthquake and created a 2.65 m right-lateral offset on the road at Aydınpınar at the end of the surface rupture of 17 August 1999.

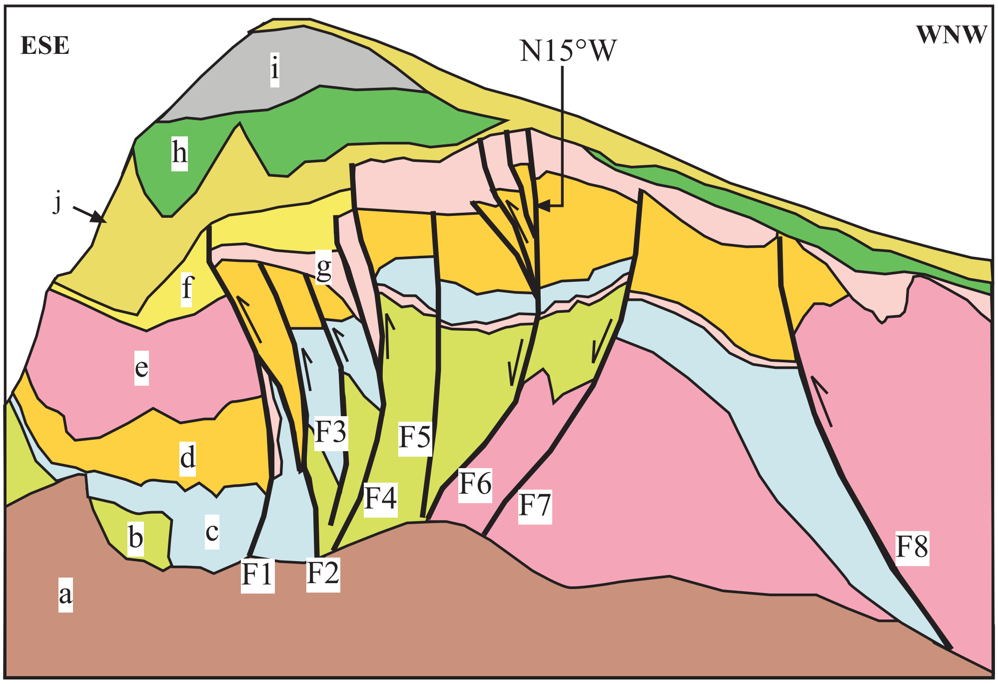

Figure 12. Compressive structure (positive flower structure) from the restraining sector of the North Anatolian Fault Zone master strand, Çaygökpınar quarry, looking southwest. a– crushed upper Jurassic–lower Cretaceous limestone, b– fine pebble, c– pebbly silt and clay, d– sandy pebble level, e– coarse sandy pebble level, f– pebble, h– pebbly sand and clay level, i– medium pebble level, j– soil (from Demirtaş 2000).

9–10 on Figures 3 & 5). The surface rupture of the 1944 earthquake enters the Bolu Basin around Çepniköy village in the southwest of the basin. The 2.5 m right-lateral displacement along the surface rupture can still be seen south of Çampınar village in the offset of the bed of a north-flowing creek and the offset of a row of old trees (Figure 3; UTM 36°N 381150, 4505560). East of this point this rupture offsets the road to the hot spring facilities of Bolu municipality, south of Bolu city near the Forestry Service buildings (Figure 3; UTM 36°N 383350, 4505000) (Figure 11c). The surface rupture of the 1944 earthquake continues eastwards, passing south of the Üçtepeler region which is the morphotectonic expression of a pressure ridge (No 10 on Figures 3 & 5). The 1944 rupture then leaves the Bolu Basin in the Çaygökpınar region (Figure 3) in the southeast corner of the Bolu Basin and enters another small pull-apart basin further east, in the Yeniçağa Lake region (east of No 16 in Figure 5).

The western boundary of the Bolu Basin is delineated by a series of dip-slip normal faults with N33–53°W trends. The most important of these is the Gölköy Fault (N53°W, 80°NE) which demarcatess the southwest border of Gölköy Reservoir (No 13 on Figures 3). Here the fault is expressed by a strongly aligned scarp and travertine formation covers the hanging wall. This fault kinematically confirms the NE–SW stretching of the basin floor in this region (Figure 8g) and is thus consistent with the general geometry and theoretical configuration of the structures expected in a pull-apart basin. The location and behaviour of the Gölköy fault and its associates are also consistent with a right overstep of the regional fracture system, from the Gölyaka-Kaynaşlı segment (adjacent to the Düzce Basin) in the north, to the North Anatolian Fault Zone master strand that forms the southern border of the Bolu Basin.

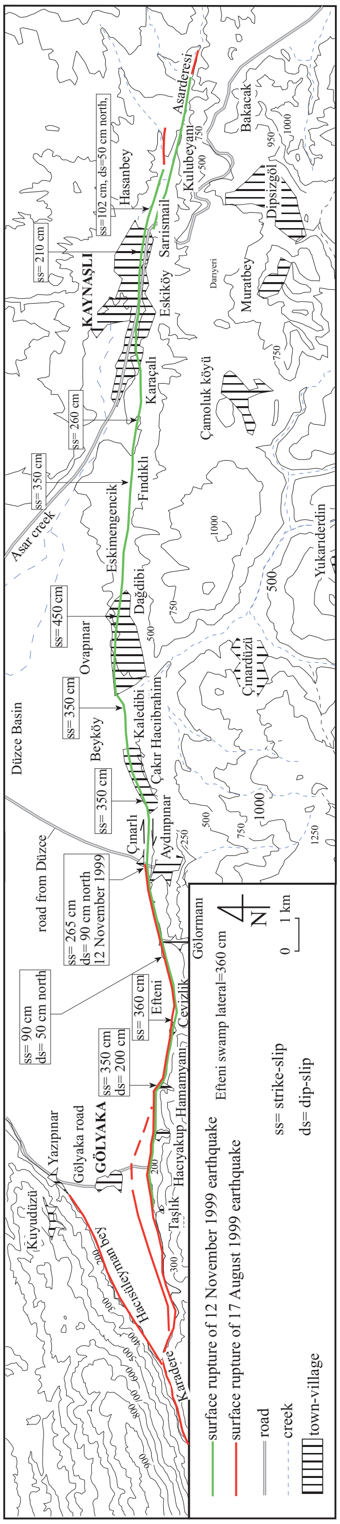

Figure 13. The alignment of the surface rupture of the Düzce-Kaynaşlı segment and the co-seismic slip distribution measured just after the 12 November 1999 earthquake.

The surface rupture that appeared during the 12 November 1999 Düzce earthquake extends from south of Gölyaka, in the south of the Düzce Basin, to Kaynaşlı in the east (Nos 14–17 on Figure 5), and passes along the northern flank of Almacık Mountain (No 18 on Figure 5) (plate flake), becoming unclear in the Asarsuyu Valley (No 15 on Figure 5). The surface rupture of the 17 August 1999 earthquake ends on the road in Aydınpınar village, 10 km south of Düzce (Gökten *et al.* 1999, 2000; Çemen *et al.* 2000; No 17 on Figure 5; Figure 13). In this area, the surface rupture of the 12 November 1999 earthquake 10 km overlapped the surface rupture of the 17 August 1999 earthquake and created a 2.65 m right-lateral offset on the road in Aydınpınar at the end of surface rupture of 17 August 1999 (Gökten *et al.* 1999) (Figure 11d). This active fault, which also might have caused earthquakes in historical times (Hitchcock *et al.* 2003), may continue into the middle of the Bolu Basin. However, there are no reliable morphological data to prove this and trenches excavated on the possible route of the fault revealed no evidence for faulting (Başokur *et al.* 2004). Nevertheless, since much of Bolu city has been founded on an east–west-trending ridge, interpreted as a pressure ridge (No 12 on Figures 3 & 5; UTM 36°N 382850, 4510400), the eastwards continuation of the Gölyaka-Kaynaşlı segment may pass close to Bolu city with a dextral strike-slip displacement. Besides this, a high strain zone created by the 12 November earthquake immediately north of the above-mentioned pressure ridge also indicates a possible continuation route of the segment into the Bolu Basin.

Discussion and Conclusions

The northern boundary of the Bolu Basin is mainly controlled by an oblique-slip normal fault with a dextral strike-slip component. This Musluklar fault strikes N70°E and dips 52°SE. The rake of the slickenlines is 45°SW. In the northwest of the basin associated faults also display a thrust component along a short restraining bend sector of the boundary. Thus the adjacent hanging wall, which is the basin floor here, has been displaced in a broadly S25°W direction.

Between the northern boundary fault and Bolu city the basin floor is cut by en échelon, dip-slip normal faults with approximately N70°E trends. The net slip on these faults is generally less than two metres. Thus the basin floor dips broadly southwards. Further south, the city centre of Bolu is situated on a conspicuous, broadly E–W-trending pressure ridge. The right-lateral Gölyaka-Kaynaşlı segment and the associated surface rupture from the 12 November 1999 earthquake appear to terminate in the Asarsuyu Valley, to the northwest of the Bolu Basin (No 15 on Figure 5). The eastern continuation of this fault, presumably caused pre-1999 earthquakes, as pointed by Hitchcock *et al.* (2003), has not been determined in the Bolu Basin by trench studies. However, following this event a conspicuous, roughly E–W-trending high strain zone was measured just north of the Bolu city pressure ridge, and it is likely that this feature represents the continuation of the Gölyaka-Kaynaşlı seismic segment into the Bolu Basin. In summary, these observations confirm that right-lateral strike-slip and transtensional tectonics prevail in the northern part of the Bolu Basin (Figure 14). The Bolu Basin has in fact been developed in the western part of the northward convex North Anatolian Fault Zone. This part of the fault zone theoretically creates overall a broad transpressional stress region. The characteristic pull-apart basins have been built in the eastern half of the system which the detailed informations about these basins have been given in the paper of Barka *et al.* (2000). But because the shear zone of the North Anatolian Fault (Şengör *et al.* 2005; their North Anatolian shear zone, NASZ) becomes wider west of Karlıova, small basins like Bolu can be developed between the structural elements in the widening western parts of the fault zone. This widening is most probably related to the anticlockwise rotation of the Anatolian block deduced from GPS measurements (Allmendinger *et al.* 2007). However Şengör *et al.* (1985) interpreted that there were no pull-apart basins between Havza and Adapazarı in this western half of the North Anatolian Fault Zone (Figure 1) in their previous paper on strike-slip related basins of Turkey by depending on the imperfection of the intersecting zones of convergent strain along the course of the fault zone in this part. They evaluated the small Yeniçağa Basin as a fault-wedge basin situated just east of Bolu by accepting that the bifurcation of the fault zone started by the east of Yeniçağ. But the pull-apart character of the Bolu Basin has also briefly been touched on by Şengör *et al.* (2004) in their recent comprehensive paper without giving any structural details.

The southern boundary of the Bolu Basin is defined mainly by the master strand of the North Anatolian Fault Zone, with a roughly N70°E trend. The direction of the compressive stress tensor here is S55°E (125°), which is consistent with development of the Bolu Basin as a pull-apart basin by a process of right overstepping between the right-lateral strike-slip northern and southern boundary faults. Radiometric dating of travertines intercalated with the basin-fill sediments and associated with the (southern) master strand of the NAFZ demonstrates that basin inception in this area commenced prior to 300 000 years B.P.

Of special significance are the new observations, reported here, of NNW–SSE-trending dip-slip normal faults cutting recent alluvial sediments near Bolu city (No 5 on Figure 3). The orientation and kinematic attributes of these fractures reveal that the basin floor is currently being stretched and displaced by ENE–WSW extension, thus confirming the pull-apart character of the basin (Figure 12). Özden *et al.* (2008) asserted that the Bolu Basin and surrounding region has been affected by two strike-slip faulting regimes and the regime changed from transpressional to transtensional with time. However slight bending of the master strand in a short period, especially in the southeast of the basin, gave rise to a short transpressional zone, although there is no indication of an earlier overall transpressional period in the basin development. The formation of the Bolu Basin can be interpreted as a wrench-related basin by referring to Minster & Jordan (1978 from Şengör 1994) and by considering that the basin is developing along the strike-slip North Anatolian Fault Zone master strand. But the Bolu Basin is also controlled from northern and southern boundaries by strike-slip and strike-slip dominated faults. According to Hans Becker's (1934 from Şengör 1994) interpretation, wrench-related basins develop along strike-slip faults with a zero component of net

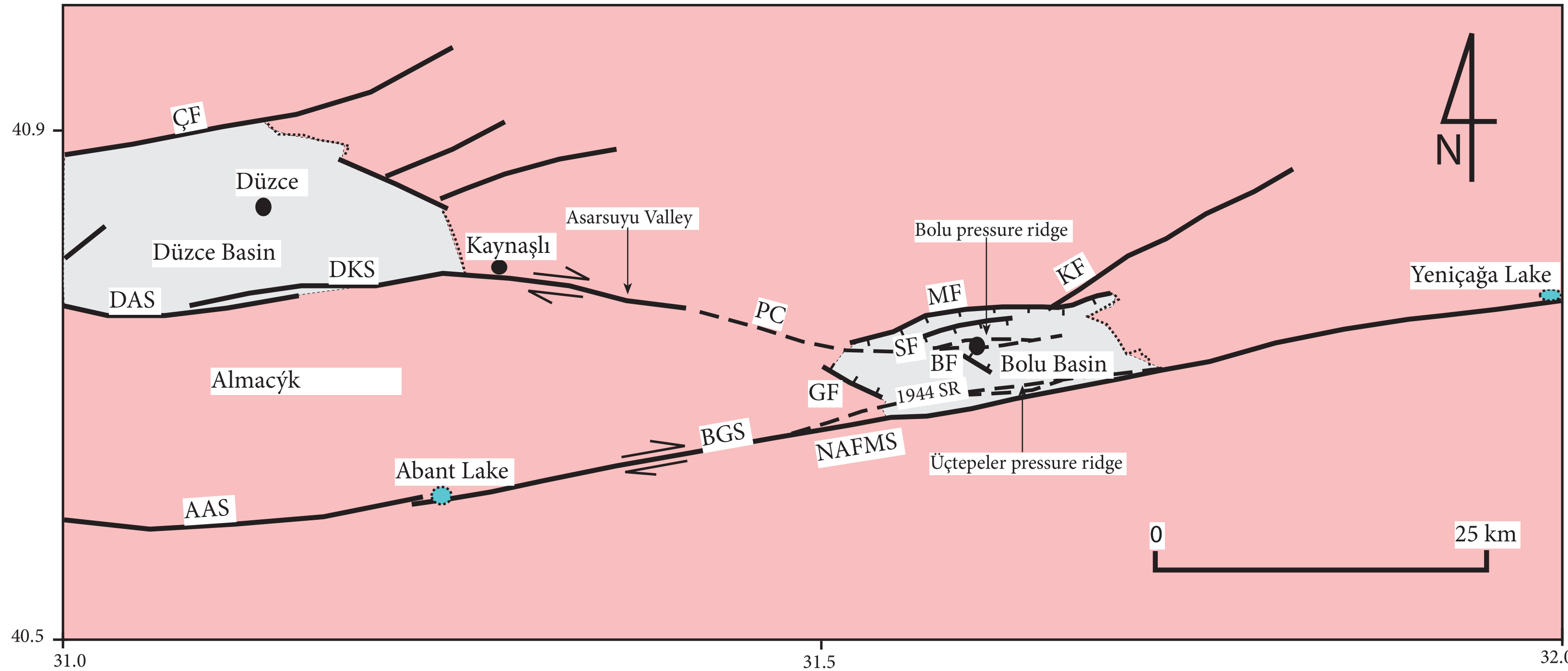

Figure 14. General kinematic map of the Bolu Basin and surroundings. AAS– Arifiye Abant, BF– Bolu fault, BGS– Bolu-Gered segment, ÇF– Çilimli fault, DAS– Düzce-Arifiye, DKS– Düzce-Kaynaşlı, GF– Gölköy fault, KF– Kocasu fault, MF– Musluklar fault, NAFMS– North Anatolian Fault Zone master strand, PC– possible continuation, SF– Salıbeyler fault, SR– surface rupture.

extension across the wrench fault. However the net extension is clearly seen in the Bolu Basin, in a north–south trend across the fault zone, by the existence of the Salıbeyler *en échelon* fault set (Figure 3). Also, as mentioned above, the basin floor is also stretched in a NNE–SSW direction by the Bolu fault (Figure 15). Based on these structural properties it can also be concluded that the central part of the basin between the master strand to the south and the Salıbeyler fault to the north is the overlapping younger part of the initial basin (cf. Barka *et al*. 2000) and may reflect a two stage widening in the basin development. Several previous studies have shown the complexity and variety of the sedimentary basins associated with the shear zones of the strike-slip faults, including pull-apart basins (e.g., Ingersol & Busby 1994), and it has been stated that all the possibilities may not be apparent in every experiment done relating to this proccess (Wilson 1960; Tchalenko 1970; Wilcox *et al.* 1973; Bartlet *et al*. 1981; Naylor *et al*. 1986: from Şengör 1994). The basin is not located at the ends of two overstepping strike-slip faults and that is why both the shape and the mechanism just do not fit the classical form of pull-apart basins (e.g., Mann *et al.* 1983), except at the western end, where the orientation of the Gölköy fault completely fits the the shape of a pull-apart basin. Consequently the data obtained confirm overall the pull-apart character of the basin rather than it resulting solely from a wrench-related rift mechanism.

Gürbüz & Gürer (2008) overviewed the pull-apart basins formed along the North Anatolian Fault Zone in their recent paper without giving detailed information. They summarized Rahe *et al.* (1998)'s view about the development stages of the pull-apart basins and briefly touched on the migration of the master strand of the North Anatolian Fault Zone towards the centre of the basin, which indicates the cessation of the pull-apart development of this sort of basin in general. But Rahe *et al*. (1998) proposed that the migrating strike-slip fault is also a straight aligning structure. However the 1944 surface rupture has appeared a few hundred metres north of the master strand, which is only seen in the middle of the basin in a northward convex arc: in the east and west ends of the basin it continues on its usual course. The Bolu dip-slip normal fault, cutting very young basin-fill sediments in the centre of the basin, clearly shows that the roughly E–W stretching of the basin is still going on. Thus the cessation of the pull-apart development of the Bolu basin is not evident.

East of the intersection point of the Kocasu fault with the NAFZ, the blocking effect of the Kocasu fault on the right-lateral movement of the northern boundary faults appears to have resulted in transfer of the overall movement of the basin floor on to the southern master strand. Hitchcock *et al*. (2003) showed by trench studies excavated close to the eastern end of the Düzce fault that the Düzce fault on the northern side of Almacık Mountain has repeatedly ruptured before the 12 November 1999 Düzce Kaynaşlı earthquake. They asserted that the Düzce fault is separated into the Bakacak and Elmalık faults by 1.0–1.5 km wide right stepovers near the Asarsuyu valley (No 15 on Figure 5). According to Hitchcock *et al*. (2003) these two faults are the structural connections between the Düzce fault and the North Anatolian Fault Zone master strand, delineating the southern boundary of the Bolu Basin. But in our study neither trench studies excavated on the possible continuation of the Düzce fault into the middle parts of the Bolu Basin nor north–south seismic studies across the basin (Başokur *et al*. 2004) revealed any faulting. In spite of this, the pressure ridge (No 12 on Figure 5) a bit further north, on which the central parts of the city have been built, shows the locations of the active faults beside the northern boundary fault of the basin (Musluklar fault). Additionally, an east–west-trending highly strained zone was created north of this pressure ridge during the 12 November earthquake (Gökten *et al.* 1999). However the northwest–southeast-trending Gölköy fault which bounds the east of the Bolu Basin (Figure 3) may play a role in transferring the overall movement on to the master strand in the south: after the Bakacak and Elmalık short right stepping segments, the main role of transferring the overall movement to the south possibly belongs to the Kocasu fault because of the existence of the north-south widened Bolu Basin.

The Gölyaka-Kaynaşlı segment surface rupture propagated as far as the Bolu tunnel in the northwest

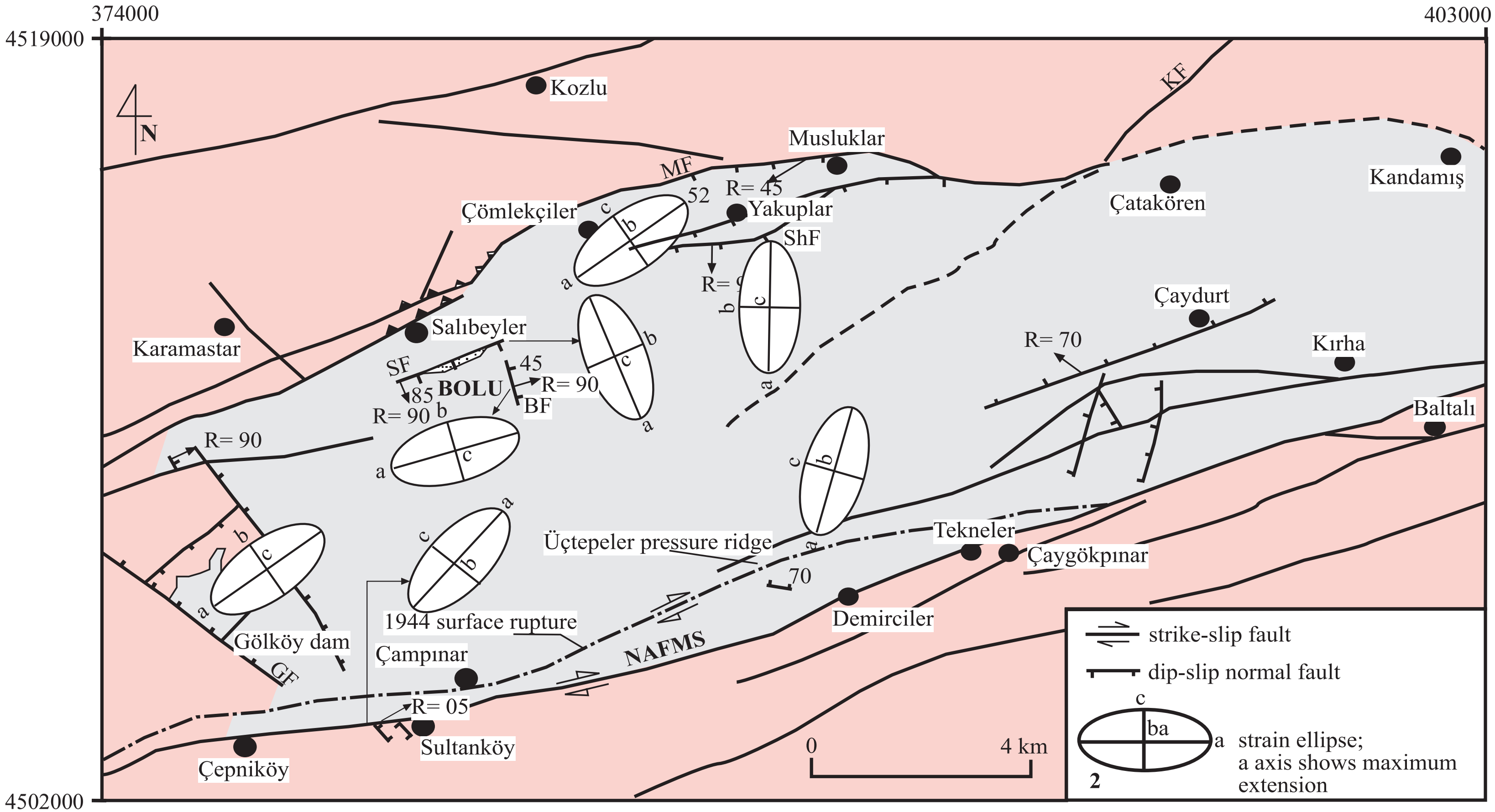

Figure 15. Recent stress distribution in relation to neotectonic structures in the Bolu Basin. BF– Bolu fault, GF– Gölköy fault, KF– Kocasu fault, MF– Musluklar fault, NAFMS– North Anatolian Fault master strand, SF– Salıbeyler fault, ShF– Şemsiye hill fault.

of the Bolu Basin during the 12 November 1999 earthquake. The route of the possible extension of this segment into the Bolu Basin is not clear, as mentioned above, but during this event an east–west-trending zone of high strain developed close to the centre of the city. This situation has given an impression about the possible propagation route of the fault to the east and earthquake risk related to this. The actual northeast–southwest stretching and north–south widening of the basin floor relating to its pull-apart character make this region critical in terms of city planning and housing.

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