

Neotectonics of East Anatolian Plateau (Turkey) and Lesser Caucasus: implication for transition from thrusting to strike-slip faulting

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Abstract – The east Anatolian plateau and the Lesser Caucasus are characterised and shaped by three major structures: (1) NW- and NE-trending dextral to sinistral active strike-slip faults, (2) N-S to NNW-trending fissures and /or Plio-Quaternary volcanoes, and (3) a 5-km thick, undeformed Plio-Quaternary continental volcano-sedimentary sequence accumulated in various strike-slip basins. In contrast to the situation in the east Anatolian plateau and the Lesser Caucasus, the Transcaucasus and the Great Caucasus are characterised by WNW-trending active thrust to reverse faults, folds, and 6-km thick, undeformed (except for the fault-bounded basin margins) continuous Oligocene-Quaternary molassic sequence accumulated in actively developing ramp basins. Hence, the neotectonic regime in the Great Caucasus and the Transcaucasus is compressional–contractional, and Oligocene-Quaternary in age; whereas it is compressional–extensional, and Plio-Quaternary in age in the east Anatolian plateau and the Lesser Caucasus.

Middle and Upper Miocene volcano-sedimentary sequences are folded and thrust-to-reverse-faulted as a result of compressional–contractional tectonic regime accompanied by mostly calc-alkaline volcanic activity, whereas Middle Pliocene-Quaternary sequences, which rest with angular unconformity on the pre-Middle Pliocene rocks, are nearly flat-lying and dominated by strike-slip faulting accompanied by mostly alkali volcanic activity implying an inversion in tectonic regime. The strike-slip faults cut and displace dykes, reverse to thrust faults and fold axes of Late Miocene age up to maximum 7 km: hence these faults are younger than Late Miocene, i.e., these formed after Late Miocene. Therefore, the time period between late Serravalian (~ 12 Ma) continent–continent collision of Arabian and Eurasian plates and the late Early Pliocene inver-

sion in both the tectonic regime, basin type and deformation pattern (from folding and thrusting to strike-slip faulting) is here termed as the Transitional period.

Orientation patterns of various neotectonic structures and focal mechanism solutions of recent earthquakes that occurred in the east Anatolian plateau and the Caucasus fit well with the N–S directed intracontinental convergence between the Arabian plate in the south and the Eurasian plate in the north lasting since Late Miocene or Early Pliocene in places. © 2001 Éditions scientifiques et médicales Elsevier SAS

East Anatolian Plateau / Caucasus / neotectonics / ramp basin / strike-slip basin

1. Introduction

Eastern Turkey and neighbouring areas including west-northwest Iran, Nakhichevan, Armenia, and Georgia are seismically active, and geologically a very complex domain situated in the Alpine–Himalayan fold-thrust fault belt (*figure 1A, B*). From north to south, this domain is divided into several structural sub-domains. These are the Great Caucasus, the Alazani and Kura basins that form the Transcaucasus, the İzmir–Ankara–Erzincan and the Lesser Caucasus suture zones, the east Anatolian plateau, the Bitlis–Zagros suture zone, and the Arabian platform (*figure 2*). The latter forms the Arabian plate, while the formers altogether form the Eurasian plate. The northern branch of Neo-Tethys (north Anatolian–Lesser Caucasian ocean) was demised diachronically (Late Paleocene in the west, late Burdigalian in the

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east) by final collision and suturing of Eurasia in the north and the Anatolian–Iranian platform in the south [1–5]. However, the Bitlis Ocean (southern branch of Neo-Tethys) persisted by the late Middle Miocene (Serravalian) and then it was also closed and demised entirely by the continent–continent collision and suturing of the Arabian plate with the Eurasian plate [6, 7]. Due to the post-collisional intracontinental convergence along both the Lesser Caucasian and Bitlis–Zagros sutures, the intervening area was squeezed as a 2 km-high plateau, namely the east Anatolian–Iranian plateau as in the case of Tibetan plateau in Himalaya [8]. The intracontinental convergence and N–S-directed compressional–contractional tectonic regime remained at the end of Late Miocene and late Early Pliocene, in places along the Bitlis suture zone in eastern Turkey. It is indicated by E–W trending, north- to south-vergent thrust to reverse faults, and E–W trending folds. In late Early Pliocene, three major neotectonic structures, the dextral North Anatolian and sinistral East Anatolian Transform Faults and the Anatolian platelet, formed and the latter commenced to escape in WSW direction onto the oceanic lithosphere of the African plate [9, 10]. Thus, starting from late Early Pliocene onward, earlier compressional–contractional tectonic regime was replaced by the compressional–extensional tectonic regime, i.e., the extrusion tectonics [11] dominated by the conjugate strike-slip faulting. In contrast to this development, post-collisional intracontinental convergence or N–S directed compressional–contractional tectonic regime is still remaining in the Great Caucasus and the Transcaucasus. It is indicated by NNW- and E–W-trending thrust to reverse faults, folds, and high seismicity of thrusting origin (*figure 1B*) [12]. However, there is no comprehensive study of neotectonics of east Anatolia and Caucasus at a regional scale. Hence the present paper aims to document neotectonics and related structures of the east Anatolian Plateau and the Lesser Caucasus in the light of literature and new data obtained from field geological mapping carried out in both areas by the cooperation of the General Directorate of Mineral Research and Exploration (MTA) from Turkey, the State Department of Geology (SDG) and the Geological Institute of Academia of Sciences (GIN) from Georgia. In order to realize this goal, we will treat mostly the Plio-Quaternary compressional–extensional neotectonic regime and related structures shaping the east Anatolian plateau, because: (1) there is a considerable gap in the literature on the strike-slip faults, and (2) this neotectonic regime is much younger than the compressional–contractional neotectonic regime lasting since at least Oligocene in Great Caucasus and the Transcaucasus. In addition, a very short stratigraphical outline of both pre-Oligocene basement rocks and Oligocene–Quaternary cover sequences will first be given, to facilitate the understanding of this broad region's neotectonics.

2. Stratigraphical outline

2.1. Basement rocks

Caucasus is located at the junction of the Turkish and Iranian segments of the Alpine–Himalayan fold-thrust fault belt (*figure 1*). It is bordered by the Scythian platform in the north and the southern Armenian–Nakhichevan sub-platform in the south. The Scythian platform consists of Hercynian basement overlain by Late Hercynian molasse and calc-alkaline volcanic rocks succeeded by Mesozoic–Cenozoic epicontinental, marine, and lagoonal–continental deposits. The southern Armenian–Nakhichevan sub-platform is similar to the Taurus–south Anatolian zone, and characterised by a pre-Campanian granite-metamorphic basement overlain unconformably by monotonous shelf carbonates of Palaeozoic–Triassic age. Until the end of Palaeozoic, the southern Armenian–Nakhichevan sub-platform belonged to the Gondwana biostratigraphic province [13].

Caucasus is subdivided into three structural domains: (1) the Great Caucasus, (2) the Transcaucasus, and (3) the Lesser Caucasus (*figure 2*). The Great Caucasus consists of Hercynian granite-metamorphic basement transgressed by tightly folded and cleaved flysch sequences of Jurassic–Eocene age. It belonged to the Eurasiatic biostratigraphic province [13, 14], and experienced magmatism, metamorphism and deformation throughout the Palaeozoic and the Alpine orogeny. The Transcaucasus is directly linked with the Pontides and dominated by a Baikalian–Hercynian basement overlain unconformably by discontinuous shallow-marine to continental clastic rocks and carbonate sequences of Mesozoic–Cenozoic age. This older cover sequence contains thick calc-alkaline volcanic rocks ranging from Jurassic to Quaternary in age. The Lesser Caucasus is the present site of the northern Neo-Tethys and represented by a relatively narrow ophiolitic belt passing westwards into the İzmir–Ankara–Erzincan suture zone (*figure 1*). The Lesser Caucasus consists of tectonic slices of ophiolitic mélange of late Albanian–early Campanian age.

In both the Great Caucasus and the Transcaucasus, folded and thrust-to-reverse-faulted pre-Oligocene basement rocks are overlain with angular unconformity by a continuous and thick (up to 6 km), nearly undeformed (except for the fault-bounded basin margins) Oligocene–Quaternary sequence accumulated in ramp basins without influence of any igneous activity (*figure 3A*). This ramp basin infill consists of shallow-marine to continental clastic rocks, and contains two local and short-lived stratigraphic gaps implying that the sedimentation has continued under the control of a compressional–contractional neotectonic regime from the beginning of Oligocene till present [13]. In contrast to the situation in Great Caucasus and Transcaucasus, both the Lesser Caucasus and the east Anatolian plateau are dominated by several volcano-sedimentary sequences of differing age, facies and deformation pattern (*figures 3 and 4*).

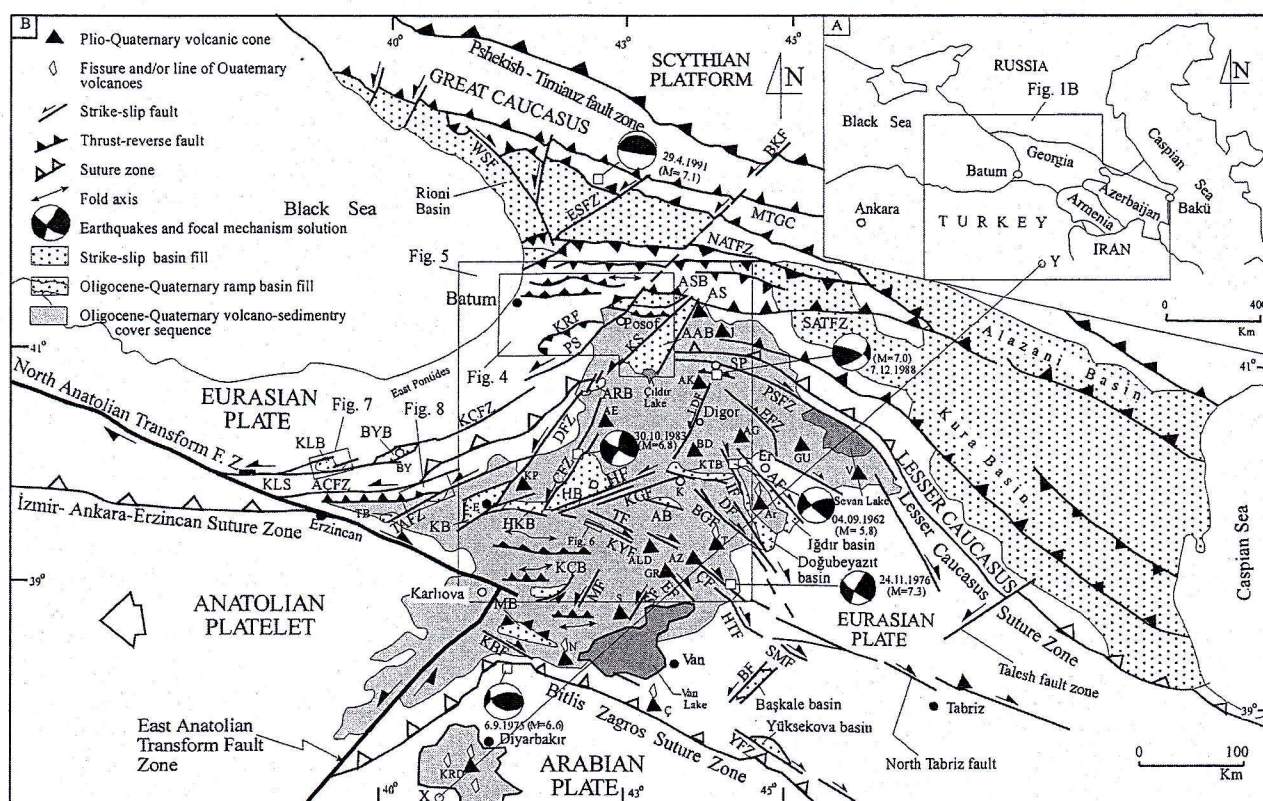


Figure 1. (A) Location map of the study area. (B) Simplified geological map showing major compressional and extensional structures. BY. Bayburt, E. Erzurum, Er. Erevan, K. Kağızman, and Sp. Spitak; AE. Allahuekber volcano, AG. Alagöz volcano, AK. Akbabadağ volcano, ALD. Aladağlar volcano, Ar. Ararat Mountain volcano, AS. line of Aboul-Samsar volcanoes, AZ. Azizan volcano, BD. Böğütlüdağ volcano, Ç. Çatak volcano and fissure, GR. Girekol volcano, GU. line of Guegam volcanoes, J. line of Javakheti volcanoes, KP. line of Kargapazan volcanoes, KRD. Karacadağ volcano, N. Nemrut volcano and fissure, S. Süphan volcano, and V. line of Vardinis volcanoes; AAB. Aktaş-Akhalkalaki basin, AB. Ağrı basin, ARB. Ardahan basin, ASB. Ahaltikhe basin, BYB. Bayburt basin, HB. Horasan basin, HKB. Hasankale basin, KB. Karasu basin, KÇB. Karaçoban basin, KLB. Kelkit basin, KTB. Kağızman-Tuzluca basin, MB. Muş basin, and TB. Tercan basin; ACFZ. Akdağ-Çayırılı fault zone, BF. Başkale fault, BGF. Balıkgözü fault, BKF. Borjomi-Kasbeg fault, ÇF. Çaldıran fault, ÇDS. Çobandede fault segment, ÇFZ. Çobandede fault zone, DF. Doğubeyazıt fault, DFZ. Dumlupınar fault zone, EF. Erciş fault, EFZ. Erevan fault zone, ESFZ. East Samegrelo fault zone, HF. Horasan fault, HTF. Hasantimur Lake fault, IF. Iğdır fault, KBF. Kavakbaşı fault, KÇFZ. Kelkit-Çoruh fault zone, KGF. Kağızman fault, KLS. Kelkit fault segment, KRF. Karçal reverse fault, KS. Kura fault segment, LDF. Leninakan-Digori fault, MF. Malazgirt fault, MTGC. Master thrust of Great Caucasus, NATF. North Adjar-Trialetian thrust fault zone, PS. Posof fault segment, PSFZ. Pambak-Seven fault zone, SATFZ. South Adjar-Trialetian fault zone, SF. Süphan fault, SMF. Salmas fault, TAFZ. Tercan-Aşkale fault zone, TF. Tutak fault, WSF. West Samegrelo fault, and YFZ. Yüksekova fault zone.

In the Lesser Caucasus, three volcano-sedimentary sequences occur (*figure 3B*). The oldest of these is 5.5 km thick and a coal-bearing volcano-sedimentary sequence of Late Eocene-Early Miocene age. This sequence consists of andesitic-basaltic volcanic rocks, shallow-marine sedimentary clastics and fluvio-lacustrine deposits intruded by dacite. This first sequence is overlain with angular unconformity by the second volcano-sedimentary sequence consisting of various volcanic rocks alternating with fluvio-lacustrine deposits of Late Miocene-Early Pliocene age [15, 16]. This second sequence is > 500 m thick and overlain with angular unconformity by the third volcano-sedimentary sequence of Late Pliocene-Quaternary age [17, 18]. The first two

sequences are folded and thrust-to-reverse faulted. Unlike to their deformation pattern, the third sequence, that is 1 km thick, undeformed, and represents a basin fill of the compressional-extensional neotectonic period.

Four cover sequences occur in the east Anatolian plateau. One of them is a sedimentary, but the rest are volcano-sedimentary sequences separated from each other by angular unconformities (*figure 3C*). The oldest sequence consists of basal conglomerate, siltstone, shale, gypsum, shallow-marine reefal limestone, lagoonal evaporite to mudstone alternation of Oligocene-Early Miocene age [19]. This sedimentary sequence is ~ 1500 m thick and overlain with angu-

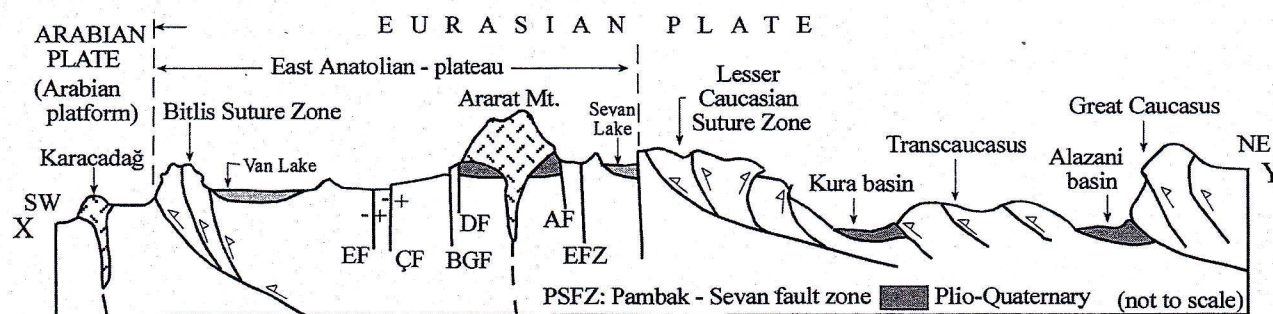


Figure 2. Simplified geological cross-section showing major compressional and extensional structures (See line X–Y in figure 1B for location). AF. Aras fault, BGF. Balıkgözü fault, ÇF. Çaldıran fault, DF. Doğubeyazıt fault, EF. Erciş fault, and EFZ. Erevan fault zone.

lar unconformity by the third sequence consisting of coal-bearing fluviolacustrine deposits and andesitic to basaltic rocks alternation of Late Miocene–Early Pliocene age [16,

19–24]. This third and 2400 m-thick volcano-sedimentary sequence is also overlain with angular unconformity by the 2000 m thick continental volcano-sedimentary sequence

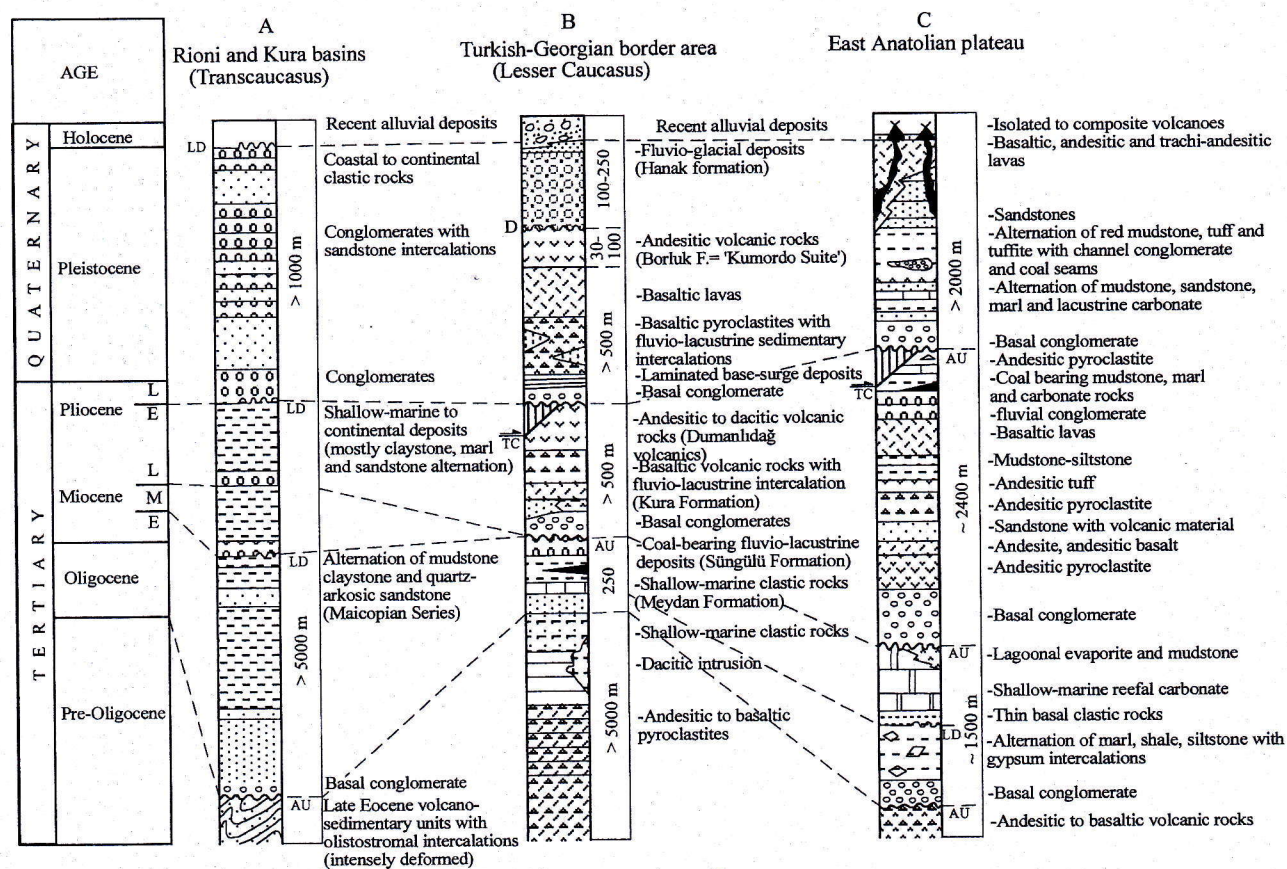


Figure 3. Simplified stratigraphical columns of Oligocene-Quaternary neotectonic fill in the Rioni–Kura basin, Turkish–Georgian border area (Ahalsikhe and Aktaş–Akhalkalaki basins) and east Anatolian basins. AU. Angular unconformity, D. Disconformity, E. Early, L. Late, LD. Local disconformity, M. middle, and TC. Thrust-to-reverse fault contact.

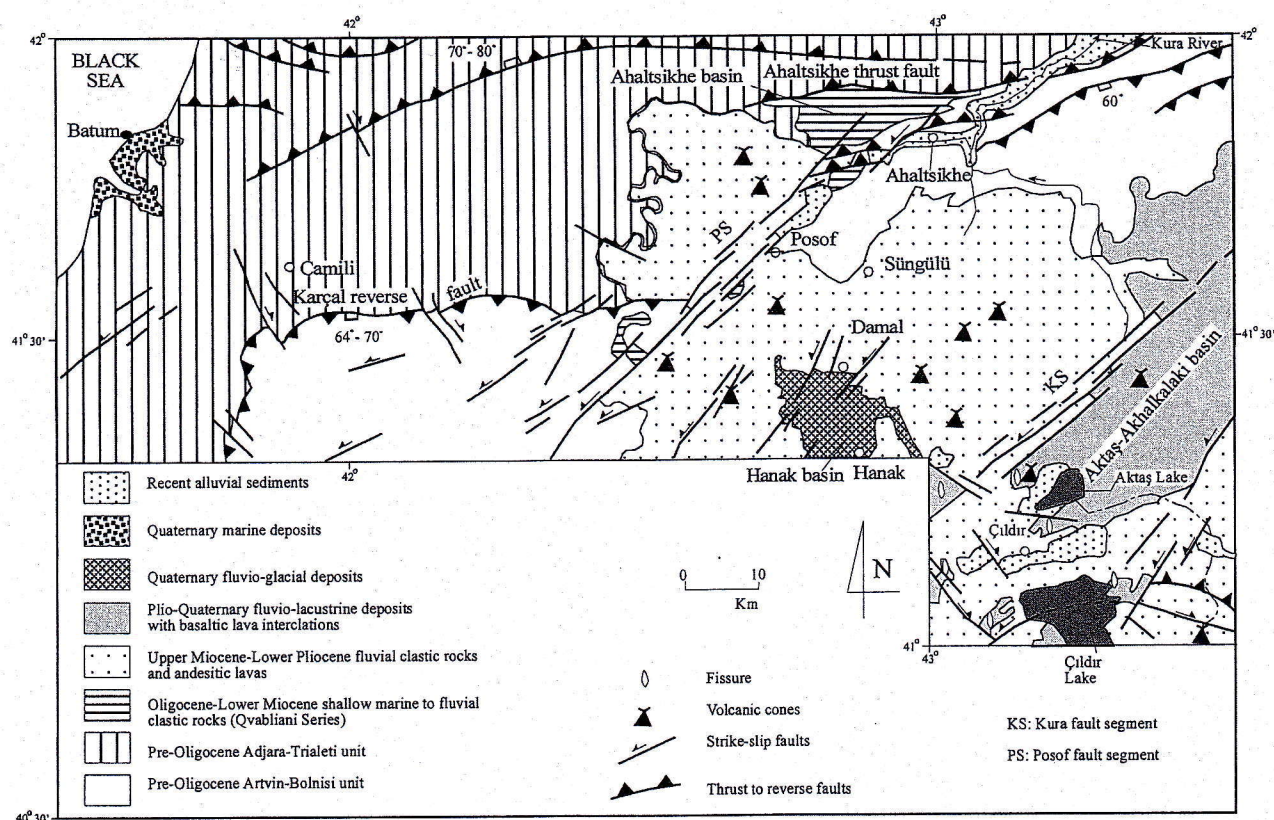


Figure 4. Simplified geologic map of the Turkish–Georgian border area.

dominated by isolated-to-composite volcanoes of Plio-Quaternary age [23–26]. The first three sequences of east Anatolian plateau are folded and thrust-to-reverse faulted, whereas the last Plio-Quaternary volcano-sedimentary sequence is undeformed, and represents basin fill of the compressional–extensional neotectonic period.

Consequently, Middle Miocene and Middle Pliocene erosional periods, angular unconformities and deformation of pre-MiddlePliocene sequences by folding and thrust-to-reverse faulting altogether reveal an inversion in tectonic regime and also a transition from earlier compressional–contractual palaeotectonic regime into the strike-slip-dominated compressional–extensional neotectonic regime in both the Lesser Caucasus and east Anatolian plateau.

3. Neotectonic structures

Starting from the southern foot of the Transcaucasus southwards, the nature of both the tectonic regime and the geological structures vary gradationally (figure 1). The N–S-directed compressional–contractual tectonic regime and related structures (folds, thrust-to-reverse faults and ramp

basins) are prominent in the north (Great Caucasus and the Transcaucasus), while the compressional–extensional tectonic regime and related structures (both the sinistral and dextral strike-slip faults, various strike-slip basins and N–S trending fissures to lines of volcanoes) become prominent in the south (the Lesser Caucasus and east Anatolian plateau) (figure 1). These structures will be described separately in more detail as the Caucasian structures and the east Anatolian structures, respectively.

3.1. Caucasian structures

3.1.1. Ramp basins

The most common examples of the ramp basins are the Rioni, the Ahalsikhe (ASB in figure 1), the Alazani and the Kura basins (figures 1 and 2). These are the WNW–ENE trending depressions located in the Transcaucasus and northern part of the Lesser Caucasus. These basins are bounded on one side or on both sides by the thrust-to-reverse faults, hence these are in the nature of half to full ramp basins characterised by a 6 km-thick shallow-marine and continental molassic sedimentary sequence of Oligocene–Quaternary age. This thick sedimentary pile shows facies zonation, from

coarsest near the fault-bounded basin margin, to finest at depocenter. Moreover, the degree of deformation (mainly folding) decreases in the direction opposite to the fault-bounded basin margins, and dies out at the centre of basins, i.e. basin fill is intensely deformed into tight-to-overturned folds along the basin margins; however, it is nearly flat-lying (undeformed) at the centre of basins. Some syn-depositional features such as olistostromes, slump folds and slump thrusts also occur frequently in the basin fill nearby the fault-bounded basin margins. The basin fill is nearly continuous from Oligocene to recent, except for a few local and short-lived stratigraphic gaps. All these field observations indicate a long-lived, thrust-to-reverse fault controlled sedimentation since Oligocene time, i.e. a compressional-contractional neotectonic regime has been active since Oligocene in the Transcaucasus and northern part of the Lesser Caucasus.

3.1.2. Thrust-to-reverse faults

Diagnostic structures of the Great Caucasus and the Transcaucasus are the margin-bounding faults of the ramp basins. These are divided into two categories: (1) WNW–ESE trending and south-verging thrust-to-reverse faults, and (2) E–W trending and north-verging reverse faults. Common examples of the first group of structures are the Pshekish-Tirniauz fault zone, the frontal thrust of the Great Caucasus, and the south Adjara-Trialeti fault zone (SATFZ in *figure 1*). These structures dip 45–50° NNE, and some of these determine northern margins of the Rioni and Ahalsikhe basins. Some others cut and deform both the northern and southern parts of the Kura basin (*figure 1*). Well-known examples of the second group of reverse faults are the north Adjara-Trialeti fault zone and the Karçal reverse fault (NATFZ and KRF in *figure 1*). These structures dip steeper (70–80°) than the south-verging faults, and are interpreted as the back-reverse faults (*figure 2*). Both the intense deformation of the basin fill along the fault-bounded basin margins and the recent seismic activities, such as the Spitak earthquake of 7 December 1988 in Armenia and the Rachat-Dzhava earthquake of 29 April 1991 in Georgia, obviously indicate that the compressional-contractional neotectonic regime and related structures (reverse faults) are still active. Fault plane solutions of these earthquakes also reveal that the earthquake-generating faults are reverse faults with minor amount of dextral strike-slip component [12, 27] (*figure 1*). One of the well-known and recently active compressional structures comprising the Lesser Caucasus is the Spitak reverse fault. It is 20 km long, 300° striking and 70° NE-dipping fault located just south of Spitak (*figure 1*). A large earthquake with a magnitude 7, the Spitak earthquake, took place at 07h41 UT on 7 December 1988 in Spitak and devastated northern Armenia. It moved the Spitak reverse fault and produced 13 km-long surface break with a scarp of 1.6 m reverse slip and 40 cm dextral slip [27].

3.1.3. Folds

The third group of structures of the Great Caucasus and the Transcaucasus are folds. These structures are confined to the fault-bounded margins of ramp basins, and trend parallel to sub-parallel the thrust and reverse faults. Folds are tight and south- to north-verging, overturned in nature nearby the basin margins, but they are converted into open folds away from basin margins, and finally die out at the axial part of basins implying the activity of the margin-bounding faults.

3.2. East Anatolian structures

The southern Lesser Caucasus and the east Anatolian plateau are characterised and shaped by three major groups of structures: (1) dextral to sinistral strike-slip faults, (2) strike-slip basins, and (3) N–S trending fissures and lines of Plio-Quaternary volcanoes (*figures 1, 2 and 5*).

3.2.1. Strike-slip faults

These structures cut across and displace fold axes, thrust-to-reverse faults, dykes, and sills of Late Miocene age. Therefore, strike-slip faults are younger than Miocene, i.e. these faults formed in a time after Miocene, most probably in Late Pliocene. In addition, the total offset measured on drainage systems, formation boundaries, and fold axes cut and displaced by strike-slip faults range from 100 m to 7 km.

Two systems of strike-slip faults occur in east Anatolian Plateau: (a) NW–SE trending dextral strike-slip faults paralleling the North Anatolian Transform Fault Zone (NATFZ) with the same sense of motion, hence these faults are here termed as the North Anatolian system; (b) NE–SW trending sinistral strike-slip faults paralleling the East Anatolian Transform Fault Zone (EATFZ) with the same sense of motion. These faults are termed as the East Anatolian system (*figures 1 and 5*). These two fault systems are same in age (Late Pliocene), and these are connected with a stress field linked to the N–S directed intracontinental convergence between the Eurasian and Arabian plates. Both the NATFZ and the EATFZ are conjugate, and intracontinental transform fault boundaries separate the wedge-like Anatolian platelet from the Eurasian and Arabian plates, respectively (*figure 1*). The NATFZ is a 1300 km long and 2–110 km wide dextral strike-slip fault system formed in Pliocene (4 Ma). It cuts across and displaces the Inner Tau-ride suture up to 50 km in a dextral direction that reveals a uniform slip rate of 1.3 cm·year⁻¹ since its creation. The EATFZ is a 600 km long and 1–25 km wide sinistral strike-slip fault system formed in Pliocene. It cuts and displaces some linear structures such as the antecedent Euphrates River and formation boundaries up to 15 km and 22 km, respectively in sinistral direction [28, 29]. These observations indicate a uniform slip rate of ~0.5 cm·year⁻¹ along the EATFZ since its creation. In general, the total horizontal displacement accumulated on each fault comprising both the north

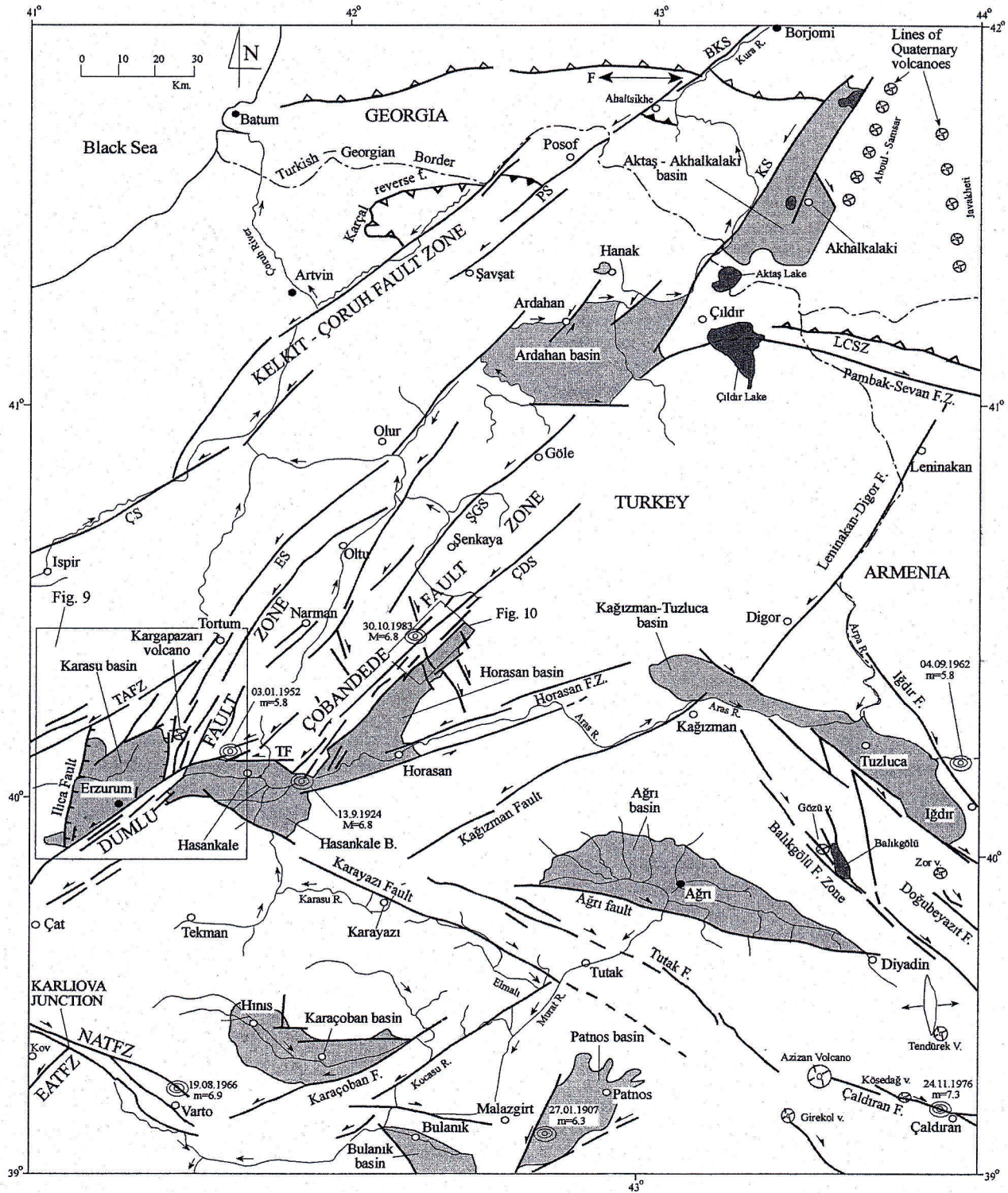


Figure 5. Simplified map showing major strike-slip faults, basins, Plio-Quaternary volcanoes and fissures. BKS. Borjomi-Kasbeg fault segment, ÇDS. Çobandede fault segment, ÇS. Çoruh Fault segment, EATFZ. East Anatolian Transform Fault Zone, ES. Erzurum fault segment, F. Fold, Kov. Karlıova, KS. Kura fault segment, NATFZ. North Anatolian Transform Fault Zone, SGS. Şenkaya-Göle fault segment, TAFZ. Tercan-Aşkale fault zone, and TF. Timur fault.

Anatolian and the east Anatolian fault systems is less (ranging from a few hundred meters to a maximum of 7 km) compared with those along the NATFZ and the EATFZ, because most of motions is being taken up by these two transform plate boundaries.

3.2.1.1. North Anatolian system

Outside of the Anatolian platelet, a series of dextral strike-slip faults and fault zones occurs in a 800 km wide area between Sevan Lake near the southern mountain front of the Lesser Caucasus in the northeast, and the southern coastal plain of Van Lake located north afoot the Bitlis-Zagros suture zone in the southwest (figures 1, 2 and 5). These structures are, from northeast to southwest, the Pambak-Sevan fault zone, the Eravan fault zone, the Aras fault, and the Iğdır, Doğubeyazıt, Balıkgözü, Tutak, Karayazı, Çaldıran, Erciş Hasantimur Lake, Kavakbaşı and the Yüksekova fault zones (figures 1 and 5). These faults and fault zones are 20–300 km long, a few hundred meters to 8 km wide shear zones consisting of several parallel to sub-parallel fault segments. On average, these faults strike NW–SE, however their strikes range from 280–340°, and faults gain considerable reverse or normal slip component as their strikes become close to the 270° (E–W) and 360° (N–S), respectively.

Outlines of faults are very obvious and continuous in the morphology, on both the aerial photographs and the topographical maps. They display a series of well-developed and preserved strong morphologic evidence indicating trace, strike-slip nature and recent activity of faults. Some of them are the fault scarps, triangular facets, break in slope, deep and long linear valleys, pressure ridges, sag-ponds, pull-apart basins of mesoscopic to mapable scale, line of degraded alluvial fans, hot-to-cold water springs, travertine occurrences, uplifted terrace deposits, and crushed zones. Moreover these faults cut and displace dikes, fold axes and thrust-to-reverse faults of Late Miocene age up to 3 km in dextral direction, implying that these strike-slip faults are younger than Late Miocene. Only three of these faults will be described in more detail below: because these were examined in detail, and one of the recent and largest earthquakes, the Çaldıran earthquake of 24 December 1976, moved one of them. These are the Pambak–Sevan fault zone, the Karayazı Fault and the Çaldıran Fault zone (PSFZ, KYF, ÇF in figure 1).

3.2.1.1.1. Pambak–Sevan fault zone

This is a 300 km long, 10 km wide and NW–SE trending dextral strike-slip fault zone located along the southern foot of the Lesser Caucasus (PSFZ in figure 1). The Pambak–Sevan Fault zone begins nearby the Çıldır Lake in the WNW (figure 5) and runs in ESE and SE directions through Spitak, northern margin of the Sevan Lake up to the NE–SW trending sinistral Talesh fault zone in the northern Iran in the SE. Rebai *et al.* [12] studied the Pambak–Sevan Fault zone in detail and they suggested that it is a dextral strike-slip fault

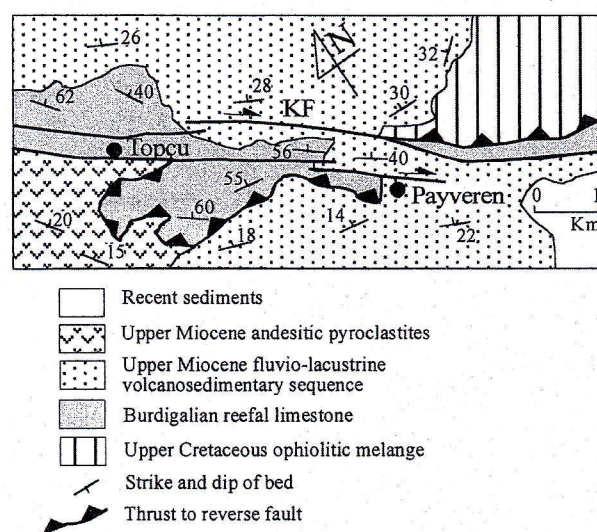


Figure 6. Geological map of the Topçu–Payveren (Karayazı) area. KF. Karayazı fault (see figure 1 for location).

system with an accumulated horizontal displacement of 1 km. The Pambak–Sevan Fault zone consists of numerous parallel to sub-parallel fault segments of dissimilar size. Two groups of structures are well observed along the master strand of this fault zone. These are the localized compressional structures (*en échelon* folds, pressure ridges, tilted blocks) and the localised extensional structures (pull-apart basins, normal faults) resulting from various geometrical complexities (step-overs, bifurcations and bends) along the master strand of the fault zone. The Pambak–Sevan Fault zone cuts and deforms Quaternary alluvial deposits and volcanic cones, which implies that it is an active structure.

3.2.1.1.2. Karayazı fault

This is an 80 km long and 295° striking dextral strike-slip fault located in the central part of the east Anatolian plateau [19] (KYF in figures 1 and 5). The northern block of the Karayazı Fault is 80 m morphologically higher than its southern block and consists of older rocks with respect to the southern block. The Upper Cretaceous ophiolitic mélangé and the Miocene volcanic rocks comprising the northern block of the Karayazı Fault are tectonically juxtaposed with the Quaternary basaltic lavas exposing only on the southern block along the eastern part of the fault. Moreover along the western part of the Karayazı fault, the reverse faults of Late Miocene age and some streams (Elmalı and Karasu rivers) are cut and offset in dextral direction 3 km and 1 km, respectively, by the Karayazı Fault (figures 5 and 6) implying that the Karayazı fault is younger than Miocene.

3.2.1.1.3. Çaldıran fault

This is a 290–315° striking, 60 km long and active dextral strike-slip fault. The Çaldıran Fault is located 40 km NE of the Van Lake nearby the Turkish-Iranian border (ÇF in *figure 1*). This starts eastern foot of the Late Miocene-Pliocene Azizan volcano in the WNW (*figure 5*) and follows a very straight fault trace on a distance of 25 km in ESE direction up to the Çaldıran County, where it bifurcates into two sub-branches, the northern and southern fault segments. The northern fault segment follows a similar strike (290°) for a few kilometres and then disappears beneath the Quaternary fill of the Çaldıran basin (a pull-apart basin). The southern fault segment follows a strike of 315° and cuts across both the Quaternary basaltic lavas of the Tendürek shield volcano and young fill of the Çaldıran basin, resulting in pressure ridges and sag-ponds occupied by swamps. Further ESE, the Çaldıran Fault enters an ophiolitic mélangé and then it cannot be observed in the vicinity of the Turkish-Iranian border. However on the Iranian side of the border some well-known and active dextral strike-slip fault zones, the North Tabriz Fault zone and the Salmas Fault are exposed and these follow approximately the same strike [30]: hence, the Çaldıran Fault, Hasantimur Lake Fault, and both the Balıkgölü and Doğubeyazıt dextral strike-slip fault zones together may be the northwest extension of both the North Tabriz Fault zone and the Salmas Fault, on which a large earthquake with magnitude of 7.4 occurred on 8 May 1930 [30] (ÇF, HTF, BGF and DF in *figure 1*).

The Çaldıran Fault displays strong morphological evidences of recent activity. These are 0.5–1 km horizontal offset stream channels (Deli and Bendimahı rivers), deep-narrow and long fault valleys developed across the Bemraz and Köseadağ volcanoes (*figure 5*), pressure ridges and pull-apart basins (Hıdırmentes and Çaldıran basins) resulting from both the right step-over and bifurcation of the Çaldıran Fault [31, 32]. A large earthquake, the Çaldıran earthquake with a magnitude of 7.3, occurred at 14h30 local time, on 24 November 1976 in Çaldıran and moved the Çaldıran Fault. It destroyed a broad area of 2000 km² around Çaldıran and produced an 55 km long zone of surface breaks along the Çaldıran Fault. The zone of surface breaks consists of numerous and well-developed open tensional cracks, right step-overs, outcrop-scale depressions (pull-apart basins) and intervening pressure ridges and reverse faults. All of these structures and the offset features obviously indicate the dextral strike-slip nature of the Çaldıran Fault. It cut various features such as the stream course, irrigation duck, road and basaltic lavas and displaced them dextrally 3.7 m, 2.06 m, 2.25 m and 2.5 m, respectively [31]. Displacement of the earthquake fault or zone of surface breaks decreases from 3.7 m in the WNW to 0.1 m in the ESE, implying that the propagation of the rupture has been initiated at the WNW tip of the Çaldıran Fault and continued towards its ESE tip.

3.2.1.2. East Anatolian system

A number of sinistral strike-slip faults occur in the area between the southern foot of the Transcaucasus in the north, and the northern side of the Erzincan–Van line in the south. These faults cut, displace and deform Plio-Quaternary basin fill and volcanic rocks of both the northwestern part of the east Anatolian plateau, and the east-southeastern parts of the east Pontides. Well-known examples of these faults are, from WNW to ESE, the Kelkit–Çoruh, Akdağ–Çayırılı, Tercan–Aşkale, Dumlu, Çobandede, Horasan, Kağızman, Leninakan–Digor, Malazgirt, Süphan and Başkale faults and/or fault zones (*figures 1 and 5*). The sinistral strike-slip faults and fault zones are 5–600 km long, a few hundred metres to 10 km wide shear zones consisting of a number of parallel to sub-parallel and discontinuous fault segments. These faults strike 25–85° and change from a few hundred metres to 160 km in length. These gain considerable normal-slip component when their strikes become close to N–S. Outlines of these faults are very clear in the morphology, and also on both the aerial photographs and the topographic maps. These display well-developed and preserved morphological evidence indicating their sinistral strike-slip nature and recent activity. Sinistral strike-slip faults cut and displace dykes, reverse-to-thrust faults and fold axes of Late Miocene age up to 7 km: hence these faults are younger than Late Miocene, i.e. these are sinistral strike-slip faults formed after Late Miocene, or these are older compressional structures reactivated as the sinistral strike-slip faults during the Plio-Quaternary neotectonic period. Most of the sinistral strike-slip faults are also seismically active. Four of them will be described in more detail below: because these were examined in detail in the field, and a recent earthquake with a magnitude of 6.8, the Horasan–Narman earthquake of 30 October 1983 moved one of them. These are the Kelkit–Çoruh, Tercan–Aşkale, Dumlu and the Çobandede fault zones (KÇFZ, TAFZ, DFZ and ÇFZ in *figure 1*).

3.2.1.2.1. Kelkit–Çoruh fault zone

This is a 600 km long, 10 km wide and 45–85° striking sinistral strike-slip fault zone. The Kelkit–Çoruh fault zone located on both sides of the Turkish–Georgian border area cuts across the pre-Oligocene basement rocks and the Oligocene–Quaternary basin fills of the Caucasus, the east Pontides and the east Anatolian plateau (KÇFZ in *figure 1*). This consists of four segments. These are, from SW to NE, the Kelkit, Çoruh, Posof and the Borjomi–Kasbeg fault segments (*figures 1 and 5*). These bifurcate, step over in both the sinistral and dextral directions, and produce strike-slip basins and push-ups that are diagnostic features resulting from strike-slip faulting.

The Kelkit segment (KLS in *figure 5*) splays from the North Anatolian Transform fault zone 100 km WNW of Erzincan. This strikes 85–80° and displays fault scarps, and well-preserved slickensides with slickenlines parallel the strike line of the fault. The Kelkit fault segment controls the Kel-

kit River and deviates its main course and tributaries in S-shaped pattern, sometimes offsetting them sinistrally up to 1.5 km. Around the town of Kelkit, this fault segment bifurcates and results in a fault-wedge basin (figure 7). Along the northern margin of this basin, a well-developed push-up occurs. It results from the right step-over of the margin-bounding sinistral strike-slip faults. This is indicated by the reverse faults that link two strike-slip fault segments to each other, and tilting of beds of sedimentary basin fill up to 55° along the northern margin (figure 7). In contrast to the situation on the northern margin, sedimentary fill is nearly horizontal along the southern margin. Moreover, travertine occurrences and terrace conglomerates of Early Quaternary age are uplifted, dissected and displaced sinistrally up to 400 m (figure 7). East of the town of Bayburt, the Kelkit segment jumps towards north, results in a left step-over and produces a pull-apart basin, the Bayburt basin (figure 1). Starting from the north of Bayburt, this fault follows a strike of $70\text{--}60^\circ$ and controls the Çoruh River, hence it is here termed as the Çoruh segment (figure 1 and ÇS in figure 5). The Çoruh fault segment also displays both the same morphologic and structural characteristics as the Kelkit segment, and makes a left step-over resulting in another pull-apart basin at its north-east tip. The northern margin-bounding fault of this basin strikes 050° and continues further northeast through the town of Posof and the Turkish–Georgian border area. This part of the Kelkit–Çoruh fault zone is here termed as the Posof segment (PS in figures 1, 4 and 5). The northeasternmost extension of the Kelkit–Çoruh fault zone is termed as the Borjomi–Kasbeg segment (BKS in figures 1 and 5). This is located on the Georgian side of the Turkish–Georgian border, and cuts and displaces sinistrally the Transcaucasian and the Great Caucasian compressional structures such as thrust-to-reverse faults and folds of Oligocene–Quaternary age [12, 27]. The morphological outline of the Borjomi–Kasbeg segment is not evident as much as for both the Kelkit, Çoruh and Posof segments. Although the Kelkit–Çoruh fault zone displays strong morphological evidences of recent fault activity, an intermediate or large historical to recent seismic event has not been recorded yet.

3.2.1.2.2. Tercan–Aşkale fault zone

This is a 150 km long, 2–4 km wide, $50\text{--}60^\circ$ striking and recently active sinistral strike-slip fault zone. The Tercan–Aşkale fault zone is located in the west of Erzurum close to the North Anatolian Transform fault zone (NATFZ in figure 1). This consists of numerous parallel to sub-parallel fault segments with a length of 2–20 km. Some of these fault segments cut across the brittle rocks, such as the Burdigalian shallow-marine carbonates, Upper Miocene andesitic lava, Lower Quaternary travertine, and displays well-preserved slickensides, in places (figure 8). These strike $60\text{--}62^\circ$, dip $85\text{--}87^\circ$ N and contain slickenlines indicating minor normal-slip component. The normal-slip component is also indicated by the pull-apart basin and uplifted terrace conglomerates along the strike-slip fault-bounded basin margins.

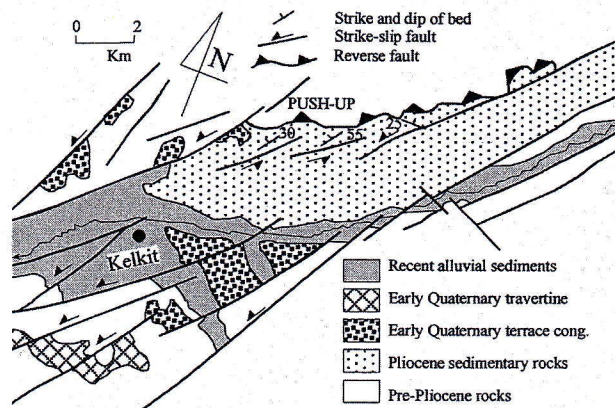


Figure 7. Simplified geological map of the Kelkit basin (see figure 1 for location). This was modified from figure 7 of Gürsay [42].

Fault segments also cut the Upper Cretaceous ophiolitic mélange, Oligocene–Miocene sedimentary sequence, E–W trending reverse-to-thrust faults and fold axes of Late Miocene age, Lower Quaternary travertine occurrences, and displace them sinistrally by 4 km (figure 8). Moreover, some streams (the Karasu River) and their tributaries are controlled and deviated in the shape of an ‘S’ or offset sinistrally by 5.5 km (figure 9A, B). These field observations obviously indicate that the Tercan–Aşkale fault zone is younger than Miocene. It is possibly Plio–Quaternary in age and seismically active as indicated by both the historical and recent earthquakes of 1268, 21 November 1939, 18 October 1980, and 19 April 1983 [33, 34].

3.2.1.2.3. Dumlu fault zone

This is a 350 km long, 4–14 km wide and NE–SW trending sinistral strike-slip fault zone, located between the Transcaucasus in the northeast and the North Anatolian Transform fault in the southwest (DFZ in figure 1). The Dumlu fault zone consists of two major segments: (1) Erzurum segment, and (2) Kura segment (ES and KS in figure 5). These two segments are linked to each other by the intervening Ardahan pull-apart basin (figures 1 and 5). The Erzurum segment comprises the southwestern part of the Dumlu Fault zone and occurs in discontinuous faults a few hundred metres to 50 km long running through Çat, Erzurum, Tortum, Narman, Oltu and Olur (figure 5). In the area of Çat–Erzurum–Tortum, the Erzurum segment consists of three fault sets, the 060° , the 025° and the 045° striking sets (1, 2 and 3 in figure 9). These sets cut across the Upper Cretaceous ophiolitic mélange, Eocene–Miocene volcanic rocks, Oligocene–Miocene continental red clastic rocks, Plio–Quaternary volcanic cones and basin fill and Miocene compressional structures (E–W trending thrust faults and fold axes). The 060° striking set is located very close to the North Anatolian Transform fault zone and determines southeastern margin of the Karasu pull-apart basin. In the east of Erzurum, this fault

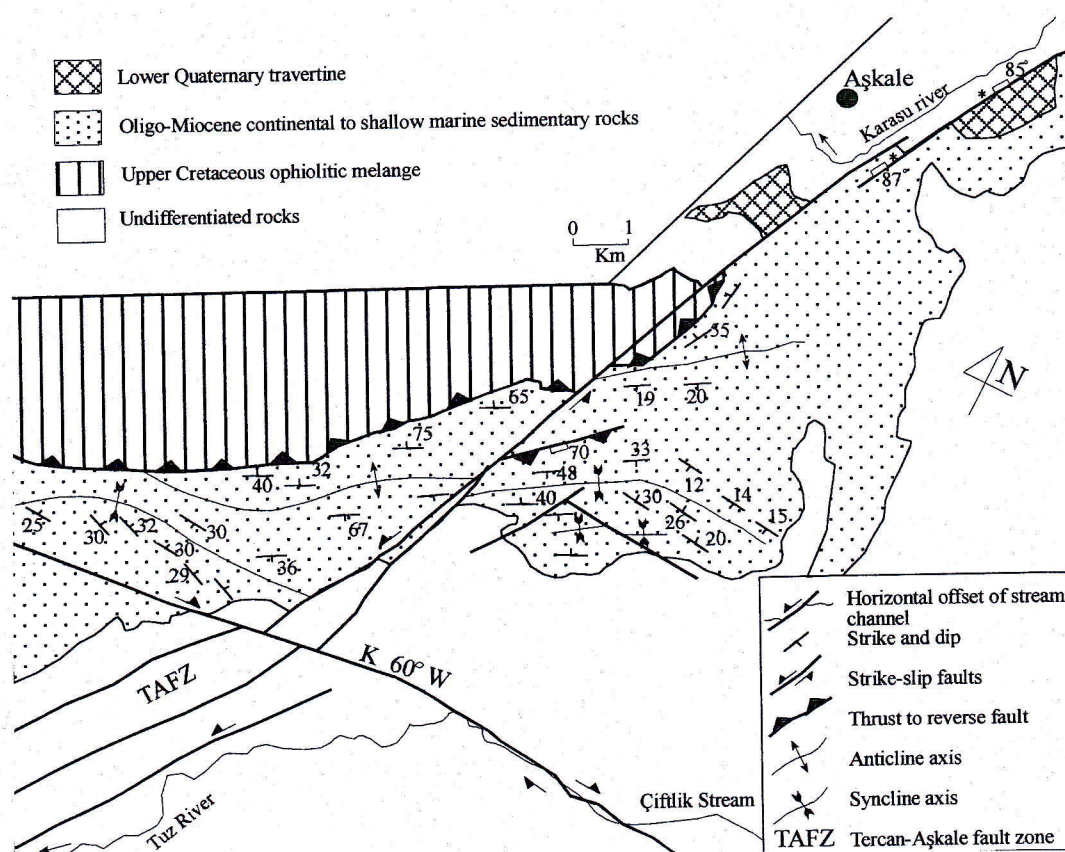


Figure 8. Simplified geological map of the Aşkale–Tercan area (see figure 1 for location). This was modified from figure 8of [43].

set bifurcates into a number of parallel to sub-parallel faults and results in both the Karasu and Hasankale pull-apart basins, and the 025° and the 045° striking sub-fault sets (figures 5 and 9). The 025° striking fault set determines the eastern margin of the Karasu basin and has a considerable normal-slip component. This is indicated by the Karasu pull-apart basin developed on its western block, the high relief (1.5 km) between the basin floor and the surrounding mountains and the faulted and uplifted Lower Quaternary terrace conglomerates. The 045° striking set that consists of 2–30 km long faults, deviates and offsets sinistrally the tributaries of the Aras River. One of these faults is the Timur Fault, which determines the north–northwestern margin of the Hasankale pull-apart basin (figures 5 and 9). The Hasankale (Erzurum) earthquake of 3 January 1952 occurred on this fault and destroyed several settlements located 10 km WNW of Hasankale County. Both the historical and recent earthquakes (1458; 5 September 1660; 2 December 1685; 4 April 1696; 1712; 4 October 1766; October 1769; 18 July 1784; 1859; 8 November 1901; 8 December 1906; 15 April 1960; 18 September 1984, and 20 July 1999) obviously indicated that the Erzurum segment of the Dumlu Fault zone is active [34–36].

Further in the NE, the Erzurum segment follows upstream of the Kura River around the city of Ardahan located close to the Turkish–Georgian border. In this area it jumps twice towards east, which results in right step-overs, cuts and offsets the Kura River 4–7 km, and then runs as the Kura segment located mostly in Georgia (figures 1, 4 and 5). The Kura segment is 035° striking sinistral strike-slip sub-fault zone comprising the northeastern extension of the Dumlu Fault zone. This consists of several parallel to sub-parallel faults occurring discontinuously within a zone 4 km wide and 70 km long including the Kura River and its tributaries. The Kura segment determines the WNW margin of a NNE-trending large depression, the Aktaş–Akhalkalaki basin (AAB in figures 1 and 5), along which Upper Miocene–Lower Pliocene and Plio-Quaternary volcano-sedimentary sequences are cut and deformed by the Kura segment. Moreover, Lower Quaternary terrace conglomerates of the Kura River have been faulted, dissected and uplifted as the fault terraces at the elevations of 50 m, 30 m, and 15 m above the present-day course of the river. These uplifted terrace conglomerates are interpreted as the record of normal-slip component of the Kura fault segment. This is also indicated by the Aktaş–Akhalkalaki basin and its eastern fault-bounded

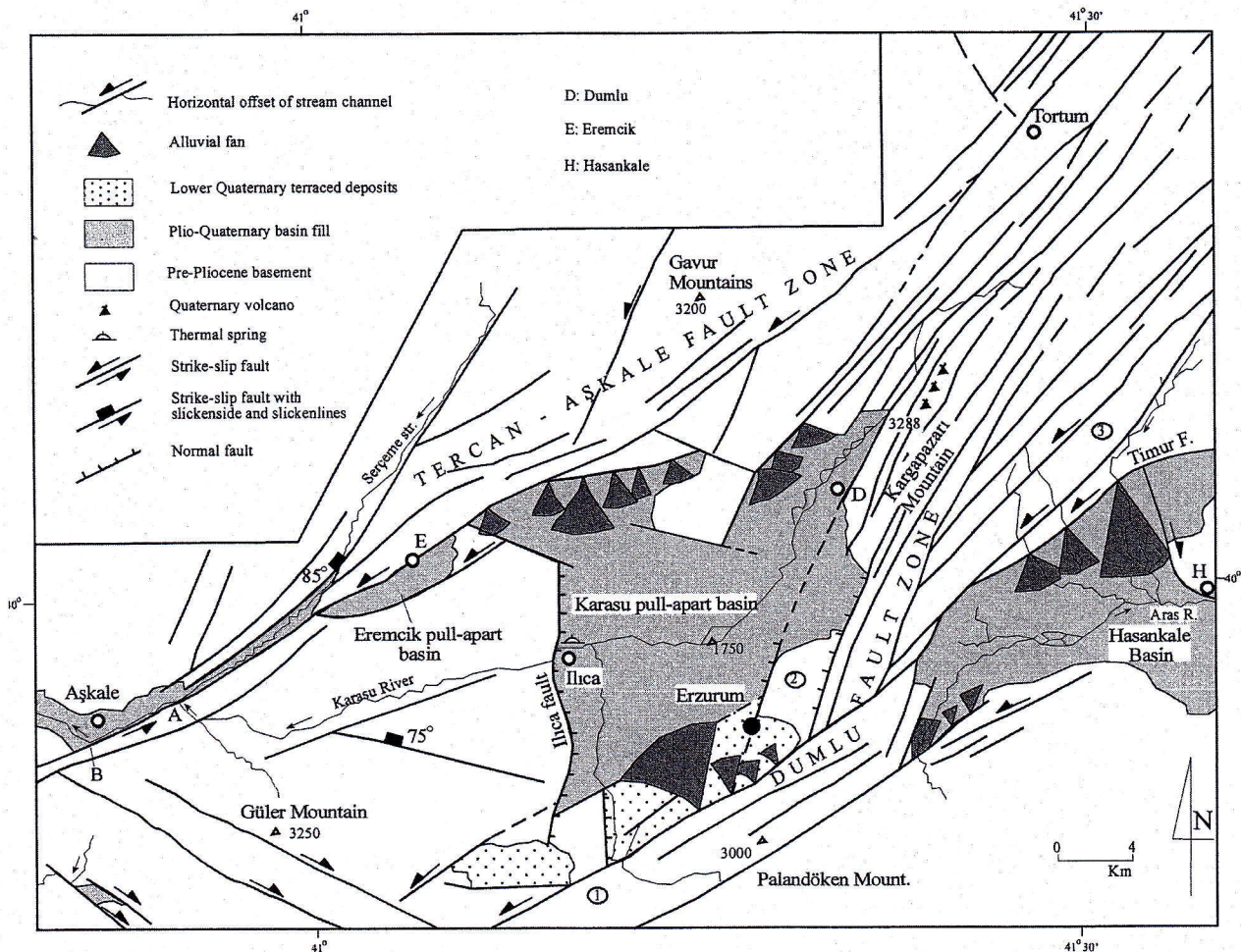


Figure 9. Simplified map of the Karasu and Hasankale basins (see figure 5 for location).

margin dominated by the 15–20° trending line of Plio-Quaternary volcanic cones (Aboul-Samsar volcanic mountain range) (figure 5) [12]. The Kura segment displays strong morphological evidence of recent activity, and cuts and displaces the WNW-trending Caucasian active compressional structures (ramp basins, thrust-to-reverse faults and folds) of Oligocene-Quaternary age: hence, the Kura segment of the Dumlulu Fault zone is also an active structure.

3.2.1.2.4. Çobandede fault zone

This is a 4–6 km wide, 130 km long and 030°–060° striking sinistral strike-slip fault zone with minor reverse-slip component as indicated by the Horasan-Narman earthquake of 30 October 1983. This consists of two major segments: (1) the Çobandede segment, and (2) the Şenkaya-Göle segment (ÇS and ŞGS in figure 5). The Çobandede segment occurs in numerous short to long (0.5–20 km) and discon-

tinuous faults within a 4–6 km wide and 100 km long shear zone, which determines the WNW margin of the Horasan basin (figures 1 and 5). The Upper Cretaceous ophiolitic mélange and the Eocene volcano-sedimentary sequence are juxtaposed tectonically with the intensely folded and reverse-faulted Miocene continental volcano-sedimentary sequence by the Çobandede segment (figure 10A). The folded and reverse-faulted Miocene sequence is overlain with angular unconformity by the undeformed Plio-Quaternary basin fill (figure 10B). The Çobandede segment, is a conjugate fault set consisting of 030°–060° striking sinistral and 300°–330° striking dextral strike-slip faults, that cut across each other, the Miocene fold axes, and displace them dextrally and sinistally 1 km (figure 10A).

At the southwest tip of the Çobandede Fault zone, around the town of Çobandede, both the Çobandede and the Horasan fault zones meet and result in a seismically interlocking area

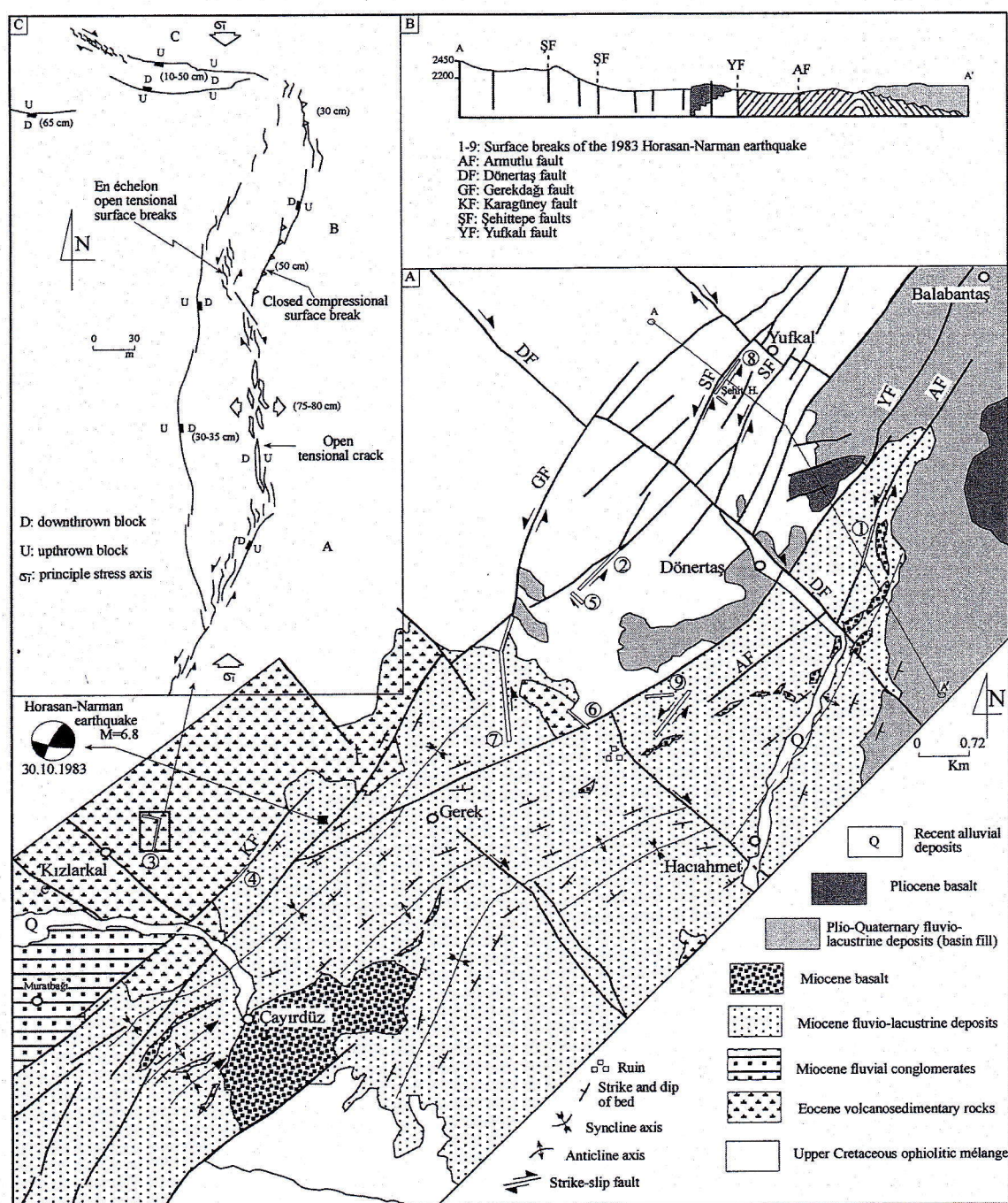


Figure 10. (A) Simplified geological map of the Çobandede fault zone and the Horasan basin. (B) Geological cross-section along the line A–A'. (C) Simplified map of the Çamlı Hill (Kızılarkale village) surface breaks consisting of 'en échelon' tensional and closed compressional cracks, reverse faults, N–S and WNW-trending two grabens (see 3 in figure 10A for location).

leading the accumulation of elastic strain energy as indicated by the Çobandede earthquake of 13 September 1924 (*figure 5*). The Çobandede earthquake with magnitude of 6.8

took place at the junction of these two fault zones and destroyed a large region within and adjacent to the Çobandede fault segment [34].

The Şenkaya–Göle segment is a 75 km long sinistral shear zone. This occurs in the area between Şenkaya and Göle 10 km west of the Çobandede fault segment. The Şenkaya–Göle segment trends parallel the Çobankaya segment and controls tributaries of both the upstream Çoruh and the Kura rivers. This also cuts and deforms the Miocene volcanic rocks.

One of the recent intermediate earthquakes, the Horasan–Narman earthquake of 30 October 1983 occurred at the junction of the Şenkaya–Göle and the Çobandede segments, but very close to the latter (*figures 1 and 10A*). It moved the Çobandede segment, destroyed a large region and produced a conjugate set of isolated surface breaks distributed in a zone 3 km wide and 11 km long (1 through 9 in *figure 10A*): 1) the 3–10 m wide, 150 m–2 km long and the 015°–050° striking zone of surface breaks, which was the prominent sinistral strike-slip set along which 120 cm sinistral strike-slip and 60 cm reverse-slip were measured; and 2) a few meters wide, 200–500 m long and 280°–330° striking zone of surface breaks with dextral strike-slip set. One of the conjugate zone of surface breaks was much more complex than others, because it occurred in two grabens trending WNW and NNE, respectively, and was bounded by both the normal and reverse faults with the maximum displacements of 50 cm and 30 cm respectively (*figure 10C*).

Consequently, orientations and patterns of the surface breaks, isoseismal and epicentral maps of aftershocks remarkably revealed that a conjugate strike-slip faulting occurred during the Horasan–Narman earthquake of 30 October 1983 [22, 33, 37]. This is also consistent with both the distribution pattern of the Çobandede fault segment and the regional stress pattern with a NNE-shortening and WNW-extension resulted from the intracontinental convergence between the Arabian and Eurasian plates.

3.2.2. Strike-slip basins

East Anatolian plateau and its boundary zones, namely the Bitlis–Zagros suture zone and the Lesser Caucasian suture zones are major structures of the Alpine–Himalayan convergent system [2, 7]. The intracontinental convergence, that is more severe within and near the suture, is still lasting throughout these structures in N–S direction. This resulted in a series of compressional features such as WNW-trending thrust to reverse faults, folds and ramp basins with the reverse fault-bounded margins within the east Anatolian plateau in Miocene (*figure 1*). An early weak and limited alkaline volcanism, but later strong and widespread calc-alkaline volcanism [23] also accompanied to the development of these compressional features, and they altogether started to shape the east Anatolian plateau during the Late Miocene transitional period between the pre-late Serravalian compressional–contractual palaeotectonic period and the Plio–Quaternary strike-slip faulting-dominated compressional–extensional neotectonic period.

Starting from the Middle Pliocene time (onset age of the strike-slip faulting-dominated neotectonic regime), southern part of the Eurasian plate was subdivided into a series of continental wedges bounded by the sinistral to dextral strike-slip faults (*figure 11*). One of them is the Anatolian platelet, that has been escaping along its boundary faults, the dextral North Anatolian and the sinistral East Anatolian Transform fault zones (NATFZ, EATFZ in *figures 1 and 11*) in WSW direction onto the easily subductable oceanic crust of the east Mediterranean Sea leaving the east Anatolian Plateau behind since the Middle Pliocene [9, 10]. This event is the remarkable record of the emergence of new tectonic regime (extrusion tectonics or escape tectonics) shaping the present-day configuration of the east Anatolian plateau and adjacent areas. Common escape tectonic structures, that characterise the east Anatolian plateau, are the dextral to sinistral strike-slip faults, which were described in detail above, strike-slip basins and fissures to lines of Plio–Quaternary volcanoes (*figures 1, 5 and 11*). Numerous strike-slip basins occur in the east Anatolian plateau (*figures 1 and 5*). They can be categorized, based on their age and type, into two groups: (1) Oligo–Miocene inverted basins or superimposed basins, and (2) newly formed pure strike-slip basins resulted from the geometric discontinuities including step-overs (offsets in fault traces), bends and bifurcations. Detailed description of each basin is outside of the scope of the present paper; instead of it, their general characteristics and examples will be summarized below.

3.2.2.1. Inverted basins (older basins)

These are generally large and WNW-trending troughs filled by continental and shallow marine deposits of Oligo–Miocene age. They began to develop during the last stage of the subduction of the Bitlis Ocean and persisted until the end of Late Miocene or rarely Early Pliocene transitional period of intracontinental convergence. These basins contain two sedimentary and/or volcano-sedimentary fills of dissimilar age, origin, lithofacies, internal structure and deformation pattern [38]. Their various stratigraphical and sedimentological characteristics were described above (C in *figure 3*). The lower and older fill is Oligo–Miocene in age and inherited from the last compressional–contractual palaeotectonic regime, hence it is highly deformed (folded and thrust-to-reverse-faulted). In contrast to the lower fill, the upper fill is Plio–Quaternary in age, nearly flat-lying or undeformed and rests with angular unconformity on the erosional surface of the lower fill (C in *figure 3*). The great discrepancy in deformation pattern of both fills and the angular unconformity separating them are remarkable records of an inversion in both the tectonic regime and basin type. Starting from Early Pliocene (sometimes Middle Pliocene), the earlier compressional–contractual regime and related structures were replaced and overprinted by the compressional–extensional tectonic regime (strike-slip faulting-dominated tectonic regime) and related structures. Hence, early-formed WNW-trending basins were deformed and dissected into iso-

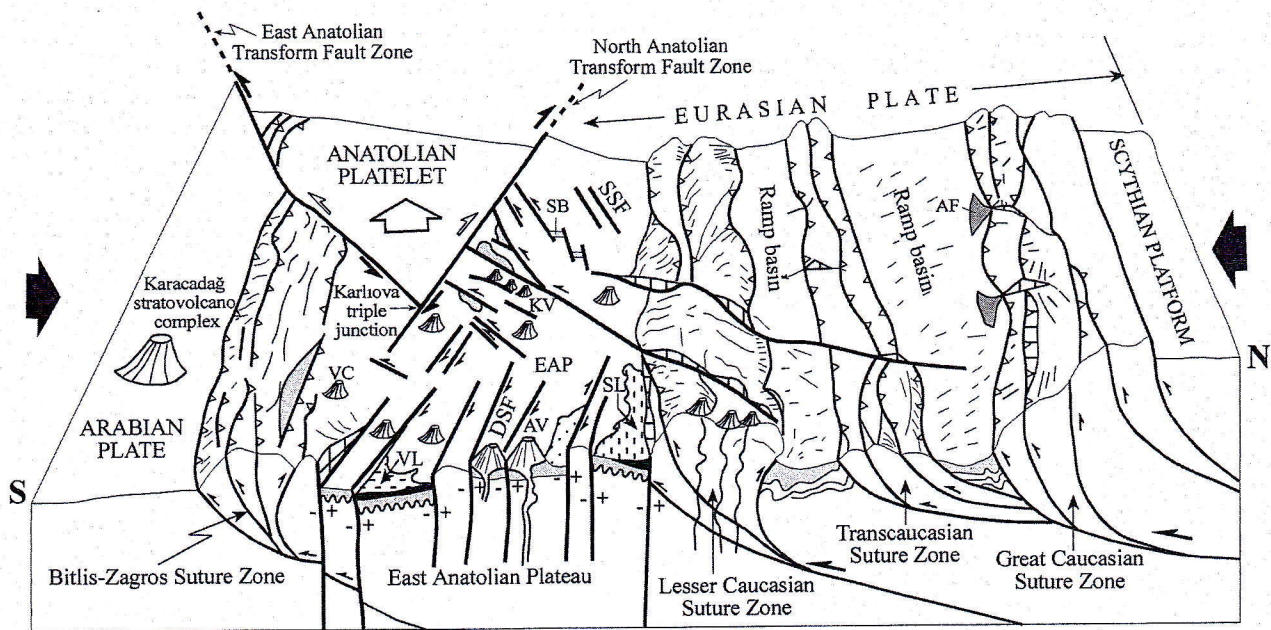


Figure 11. Block diagram depicting compressional and tensional neotectonic structures resulting from N–S convergence between the Arabian and Eurasian plates in the east Anatolian plateau and adjacent areas. AF. Quaternary alluvial fan, AV. Ağrı (Ararat) stratovolcano complex, DSF. Dextral strike-slip fault, Kv. line of Kargapazari volcanoes, SL. Sevan Lake, SB. Strike-slip basin, SSF. Sinistral strike-slip fault Vc. volcanic cone, and VL. Van Lake

lated smaller troughs rearranged obliquely or sub-parallel the margin-bounding faults of the newly-developing basins. Accordingly, compressional structures (WNW-trending fold axes, margin-bounding thrust to reverse faults) of older basins were cut, dissected and displaced dextrally or sinistrally and overprinted by newly developing basins and their margin-bounding strike-slip faults. Well-defined examples of the inverted basins are the Tercan-Aşkale, Karasu, Hasankale, Horasan, Karaçoban, Ağrı, Ardahan and the Aktaş-Akhalkalaki basins (figures 5, 8 and 9). Another largest and inverted structure is the Muş basin (figure 1). This is the deformed and dissected remnant of the WNW-trending Oligo-Miocene Muş–Van basin located at the northern foot of the Bitlis suture zone. Although the Muş basin seems to still retain its earlier nature of ramp basin, its northern margin-bounding reverse fault has a considerable dextral strike-slip component, implying an inversion in the nature of tectonic regime in Pliocene. Moreover, a strong and widespread Plio-Quaternary alkaline volcanism [23] that accompanied to the sedimentation, and the second-stage development of basins are also strong evidence of inversion in both tectonic regime and basin type.

3.2.2.2. Pure strike-slip basins

These are the basins developed during the Plio-Quaternary neotectonic period. The pure strike-slip basins are actively growing depressions resulted from the geomet-

ric complexities of both the dextral and sinistral strike-slip faults. These basins are smaller and younger compared with the inverted basins. The pure strike-slip basins contain a single basin fill of Plio-Quaternary age. This is nearly flat-lying except for the area nearby the fault-bounded basin margins. The basin fill rests with angular unconformity, in places, on the erosional surface of the pre-Oligocene rocks implying a long lived erosion took place in their present site before Pliocene.

Well-developed examples of the pure strike-slip basins are the Kelkit, Bayburt, Çaldıran, Patnos, Hanak, Kağızman-Tuzluca, Iğdır and the Sevan Lake pull-apart basins (figures 1, 4, 5 and 7). The Kağızman-Tuzluca basin is a NW–SE trending depression developed under the control of both the sinistral and dextral strike-slip faults (figure 5). It contains a 5.3 km thick continental basin fill of Plio-Quaternary age resting with angular unconformity on the erosional surface of the Eocene and older basement rocks. The basin fill is nearly horizontal and consists mostly of conglomerate, sandstone, mudstone and salt alternation capped conformably by the alternation of 5–15 m thick terrace conglomerate and various volcanic products of the nearby Mount Ağrı stratovolcano of Quaternary age. Both the Iğdır and Doğubeyazıt pull-apart basins bounded by the Iğdır, Doğubeyazıt and Aralık dextral strike-slip faults are also the southeastern extension of the Kağızman-Tuzluca basin, because these display

characteristics same as the Kağızman-Tuzluca basin, but their most parts were occupied by the sub-alkaline volcanic rocks (mostly basalt and its pyroclastites) of the Ararat stratovolcano with a relief of 5165 m. The bulk of the Ararat stratovolcano is isolated in an extensional area resulted from the right-stepover of both the Iğdır and Doğubeyazıt dextral strike-slip faults. The thick and young basin fill, uplifted terrace conglomerate and very large stratovolcano capping the lower part of the basin fill imply a considerable normal-slip component and high-rate subsidence along the margin-bounding faults, hence the Iğdır basin was previously interpreted as a graben [7].

One of the other pure strike-slip basins is the Sevan Lake depression in Ermenia (*figure 1*). It is located on the southern block of the master strand of the Pambak-Sevan dextral strike-slip fault zone and has a 1.5 km thick Plio-Quaternary basin fill [12]. Around the Sevan Lake, the Pambak–Sevan fault bifurcates into numerous and southward concave splay faults in the pattern of extensional horsetail structure as indicated by the Sevan Lake fault wedge basin and the NNW–SSE trending lines of Quaternary volcanoes (Guegam and Vardinis volcanoes).

3.2.3. Fissures and lines of volcanoes

The third group of structures characterising the east Anatolian plateau is the fissures and lines of volcanoes. Fissures or local extensional normal faults are well exposed at the summits of large isolated-to-composite strato-volcanoes of Plio-Quaternary age, because these have not experienced yet enough long-lived erosion. These occur as an isolated and NNW-trending single crack, or a zone of cracks ranging from 30 m to 2 km in width and 400 m to 50 km in length. Well-defined examples of the fissures are seen at the summits of the Karaalan (Çatak), Nemrut, Tendürek and Mount Ağrı volcanoes (*figure 1*) along which less viscous magma has poured out and flowed down the steep slopes of volcanoes into the nearby basins [32, 39].

Plio-Quaternary volcanoes also display linear mountain chains consisting of numerous volcanic cones. In general, isolated and strato-volcanoes occur inside the geometrical discontinuities (extensional bends, step-overs, bifurcations and tips) of both the dextral and sinistral strike-slip faults. Well-defined examples of these volcanoes are the Girekol, Azizan, Köseadağ, Gözü, Zor and Mount Ağrı volcanoes (*figures 1 and 5*). However line of volcanoes or linear volcanic chains occur along the shoulders of fault-bounded margins of the strike-slip basins such as the Karasu, Aktaş-Akhalkalaki and the Sevan Lake basins (*figures 1, 5 and 9*). Well-defined examples of this group of volcanoes are the Kargapazarı, Aboul-Samsar, Javakheti, Guegam and the Vardinis lines of volcanoes, the latter two lines of volcanoes are located on southern margin of the Sevan Lake basin, while the formers are located eastern margins of the Karasu basin and the Aktaş-Akhalkalaki basin, respectively (*figure 5*).

Consequently both the NNW-trending fissures and lines of Plio-Quaternary volcanoes having the same orientation as the fissures (extensional normal faults) are also consistent with a regional strain pattern of NNW-shortening and ESE-extension resulting from the intracontinental convergence between the Arabian and Eurasian plates (*figure 11*).

4. Discussion and conclusion

Some of earlier studies [6, 7, 25, 40] reported that the neotectonic regime of the east Anatolia is compressional in nature and commenced in the late Serravalian time. They also claimed that main structures characterising the neotectonic period are E–W trending folds, thrust-to-reverse faults, NW- and NE-trending strike-slip faults and N–S trending fissures. Moreover, Yılmaz et al. [23] agreed with these authors on the nature of neotectonic regime and related structures, but they also claimed that the neotectonic regime initiated in Early Miocene. In contrast to the ideas of these authors, our field studies carried out in a broad area covering both the east Anatolian plateau and some parts of Caucasus indicate that the neotectonic regime of both the east Anatolian plateau and the Lesser Caucasus is the strike-slip faulting-dominated compressional–extensional regime commenced in Pliocene as indicated by the clear and regional inversions in the types of basins (from E–W trending compressional ramp basins to NW- and NE-trending strike-slip basins), the style of deformation (from thrusting to conjugate strike-slip faulting), the nature of volcanism (from strong and regional calc-alkaline post-collisional volcanism to alkaline volcanism), and the epirogenetic elevation changes (regional uplift and subsidence) [12, 16, 22, 23, 36]. Moreover there is a relatively long-lived transitional period (Late Miocene–Early Pliocene) between the pre-late Serravalian compressional–contractional palaeotectonic period and the Plio-Quaternary compressional–extensional neotectonic period. The same kind of transitional tectonic periods have also been reported for various parts of Europe [41]. The east Anatolian plateau experienced a transitional period in Late Miocene–Early Pliocene before the neotectonic period, however, this is still continuing in Caucasus.

The east Anatolian plateau and its boundary zones, namely the Bitlis–Zagros and the Lesser Caucasian suture zones, are major structures of the Alpine–Himalayan convergent system [2, 7]. The intracontinental convergence, that is much more severe within and nearby the suture, is still continuing throughout these structures in NNW–SSE direction. It resulted in a series of E–W trending compressional features such as the WNW-trending reverse-to-thrust faults, folds and ramp basins with the reverse fault-bounded margins in the east Anatolian plateau during the Miocene time. An early weak and limited alkaline volcanism, but later a strong and widespread calc-alkaline volcanism [23], also accompanied the development of these compressional features during the

Late Miocene–Early Pliocene transitional period that separates the pre-Serravalian palaeotectonic period from the Plio-Quaternary neotectonic period.

Starting from Middle Pliocene onwards, the southern part of the Eurasian plate was subdivided into a series of continental wedges bounded by the sinistral to dextral strike-slip faults (figure 11). One of these is the Anatolian platelet, which has been escaping along its boundary faults, the dextral North Anatolian and the sinistral East Anatolian Transform fault zones (NATFZ, EATFZ in figure 11), in WSW direction onto the oceanic crust of the east Mediterranean Sea since Middle Pliocene [9, 10]. The emergence and westward escape of the Anatolian platelet have taken up considerable amount of NNW-directed compression and compensated further shortening of the east Anatolian plateau. Thus, with the beginning of westward escape of the Anatolian platelet, the overthickened crust started to return to normal as indicated by the inversion in the nature of volcanism, from an earlier calc-alkaline to a newly developing alkaline type [23]. This event is one of the remarkable records of the onset of the neotectonic regime (extrusion or escape tectonics), which produced the present-day configuration of the east Anatolian plateau and adjacent areas. Common structures of the escape tectonics dominating the Plio-Quaternary neotectonic period of both the east Anatolian plateau and the Lesser Caucasus are the approximately NW-trending dextral and NE-trending active sinistral strike-slip faults, older superimposed and younger pure strike-slip basins (pull-apart basins), and numerous N–S trending fissures of dissimilar size, and/or line of Plio-Quaternary volcanoes.

Older inverted or superimposed basins [38] began to develop during the final stage of the subduction along the Bitlis and the Lesser Caucasian oceans, and persisted until the end of Late Miocene to Early Pliocene transitional period. These basins are generally E–W and WNW-trending depressions having two sedimentary and/or volcano-sedimentary fills of dissimilar age, origin, facies, internal structure and deformation pattern [38]. The lower older fill is Oligo-Miocene in age and inherited from the last palaeotectonic regime, hence this is highly deformed (folded and thrust-to-reverse faulted). Unlike this, the upper fill is Plio-Quaternary in age, nearly flat-lying and rests with angular unconformity on the erosional surface of the lower fill. The great discrepancy in their deformation patterns, and the angular unconformity separating them are again the remarkable records of the inversion in the nature of both tectonic regime and type of basins. Palaeotectonic regime and related compressional structures were replaced and overprinted by the strike-slip faulting-dominated neotectonic regime and its structures after the Late Miocene–Early Pliocene transitional period. So, early formed E–W and WNW-trending Oligo-Miocene basins were deformed and dissected into isolated troughs, rearranging in an oblique or sub-parallel way the newly developing strike-slip basins. Accordingly, the compressional structures (margin-bounding thrust-to-

reverse faults and fold axes) of the older basins (inverted basins) were cut, dissected and displaced dextrally and sinistrally, and overprinted by the strike-slip basins and their margin-bounding strike-slip faults. The pure strike-slip basins are Plio-Quaternary depressions originating from the geometrical complexities, including step-overs, bends and bifurcations of strike-slip faults. These are smaller compared with older superimposed basins and have a single, nearly flat-lying and 5.3 km maximum thick basin fill resting with angular unconformity on the erosional surface of mostly pre-Oligocene basement rocks.

In contrast to the situation in both the east Anatolian plateau and the Lesser Caucasus, the neotectonic regime in the remainder parts of Caucasus is still compressional-contractional in nature. This is indicated and dominated by numerous E–W and WNW-trending folds that are confined to the area nearby the thrust-to-reverse faulted basin margins, the ramp basins with a 6 km maximum thick and nearly continuous Oligocene-Quaternary molassic basin fill, and active thrust-to-reverse faults. Both the historical and recent seismicity of reverse faulting origin is one of the other evidences of the compressional-contractional neotectonic regime in both the Great Caucasus and the Transcaucasus [27].

Consequently, the neotectonic regime in both the east Anatolian plateau and the Lesser Caucasus is compressional-extensional in nature and Plio-Quaternary in age (figure 12). It is dominated by NW- and NE-trending dextral and sinis-

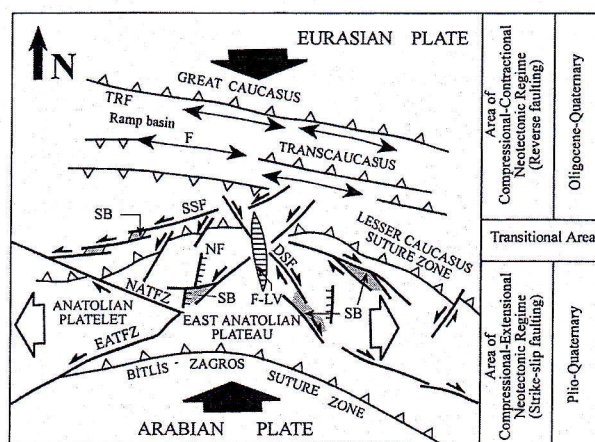


Figure 12. Sketched map showing neotectonic outline of the east Anatolian plateau and the Caucasus. The orientation of various neotectonic structures consists with a regional strain pattern of NNW–SSE shortening (closed large arrows) and WSW–ENE extension (open large arrows) as a result of the intracontinental convergence between the Arabian and Eurasian plates. DSF. Dextral strike-slip fault, EATF. East Anatolian Transform Fault Zone, F. Fold, F–LV. Fissures and/or line of Plio-Quaternary volcanoes, NATF. North Anatolian Transform Fault, NF. Normal fault, SB. Strike-slip basin, and TRF. Thrust-to-reverse fault.

tral active strike-slip faults, pure strike-slip basins, N–S and NNW-trending fissures and/or lines of Plio-Quaternary volcanoes and high seismicity of strike-slip faulting origin. Whereas the neotectonic regime in both the Great Caucasus and the Transcaucasus is still compressional–contractional in nature, and this has been lasting since Oligocene (figure 12). Moreover, there is a transition from thrusting to strike-slip faulting along the southern foot of the Lesser Caucasus (figure 12). The orientation of structures dominating the neotectonic regimes, and the focal mechanism solutions of recent earthquakes that occurred in the east Anatolian plateau and the Lesser Caucasus fit well with a regional stress pattern of NNW-shortening and ENE-extension resulting from the N–S directed intracontinental convergence between the Arabian and Eurasian plates (figure 12).

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