Journal of Structural Geology, Vol. 11, No. 3, pp. 275 to 283, 1989
Printed in Great Britain

0191-8141/89 $03.00 + 0.00

Complex evolution of the Erzincan Basin (eastern Turkey)

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(*Received* 16 *February* 1988; *accepted in revised form* 5 *August* 1988)

Abstract—Two new tectonic models are presented to explain the pull-apart opening of the Erzincan Basin. Our field studies indicated that the Erzincan Basin is not a typical rhombic pull-apart basin; instead it has a rather complex, single- or two-stage pull-apart opening mechanism. The basin was initially formed as a result of a 4 km wide releasing stepover and a 15° divergence angle between segments 1 and 2 of the North Anatolian Fault Zone (NAFZ) along which the westward tectonic escape of the Anatolian Block has been taking place. The single stage model refers to the partitioning of the transtensional deformation by coeval normal and strike-slip displacements on parallel-trending faults which remained since their initiation. The two-stage model infers that the basin opening was modified later by the formation of the left-lateral Ovacık Fault which caused fragmentation of the Anatolian Block. The two-stage pull-apart basin opening mechanism accounts for the observed geometry of the Erzincan Basin. The present day geometry of the basin indicates that there had been 35 ± 5 km of right-lateral displacement along the NAFZ and 5 ± 2 km of left-lateral displacement along the Ovacık Fault.

INTRODUCTION

ALTHOUGH the 'pull-apart basin' concept was first introduced in the mid-1960s (e.g. Burchfiel & Stewart 1966), it has received attention from structural geologists since 1974 with the papers of Crowell (1974a, b) on the basins of Southern California. Within the last decade a large body of knowledge has been acquired through detailed geological and geophysical studies and significant progress has been made in understanding the formation and evolution of pull-apart basins in strike-slip regimes. A collection of papers are contained in two books (Ballance & Reading 1980, Biddle & Christie-Blick 1985), which are devoted to strike-slip basin formation and sedimentation, and these provide an excellent review of pull-apart basins.

The purpose of this paper is to discuss the origin and evolution of the Erzincan Basin. We will emphasize the importance of continental block kinematics in its formation, and present a new, complex pull-apart mechanism for basins in continental collision areas where tectonic escape prevails. The Erzincan Basin is situated on the North Anatolian Fault Zone (NAFZ). Its long axis strikes NW–SE parallel to the general trend of the fault zone (Figs. 1 and 2). The basin is approximately 50 km long and widens to the SE, reaching a maximum width of 15 km. Two other left-lateral faults, the Northeast Anatolian Fault and the Ovacık Fault obliquely intersect the NAFZ to the NW and SE of the basin, respectively (Figs. 1 and 2).

The Erzincan Basin has recently attracted considerable attention in the literature. Previously, the basin has been described as a typical rhombic pull-apart basin, bounded by two parallel master faults which are presumed to be the segments of the NAFZ (Figs. 3a & b), (Şengör 1979, Aydın & Nur 1982, Hempton & Dunne 1984, Şengör *et al.* 1985). However, our field studies have indicated that the Erzincan Basin is not a typical rhombic pull-apart basin, instead it has a rather complex pull-apart mechanism and basin evolution due to the critical role of the Ovacık Fault (Fig. 2). In the following sections we will present the stratigraphic and structural details of the Erzincan Basin based on field and aerial photo observations and then, we will use these investigations to explore the formation and evolution of the Erzincan Basin within a regional tectonic framework.

TECTONIC AND STRATIGRAPHIC SETTING

In this region, before the Eocene, there were two branches of the Neo-Tethys (Stöcklin 1974, Şengör & Yılmaz 1981). The northern branch which formerly separated the Pontides from the Anatolid/Taurid platform, closed in Eocene times, forming the Pontide–Anatolide/Tauride Suture Zone (PATSZ). Further south, continental collision between the Anatolide/Tauride platform and the Arabian plate occurred in mid–late Miocene (Hall 1976, Perinçek 1980, Şengör & Yılmaz 1981). This closure eliminated the southern branch of the Neo-Tethys forming the Bitlis Suture Zone (BSZ). The continental collision along the BSZ caused further deformation and modified the northern Pontide–Anatolide/Tauride suture zone along which, narrow E–W-trending compressional basins were formed (Fig. 2). These basins are bounded by mostly E–W-trending thrusts and their internal structures are also dominated by E–W-trending folds. As a result of the continued convergence following the continental collision along the BSZ, the North Anatolian, East Anatolian and Northeast Anatolian Fault Zones were formed in early Pliocene. These fault zones make up the boundaries of major continental blocks such as Anatolian and Northeast Anatolian blocks (Fig. 1). The

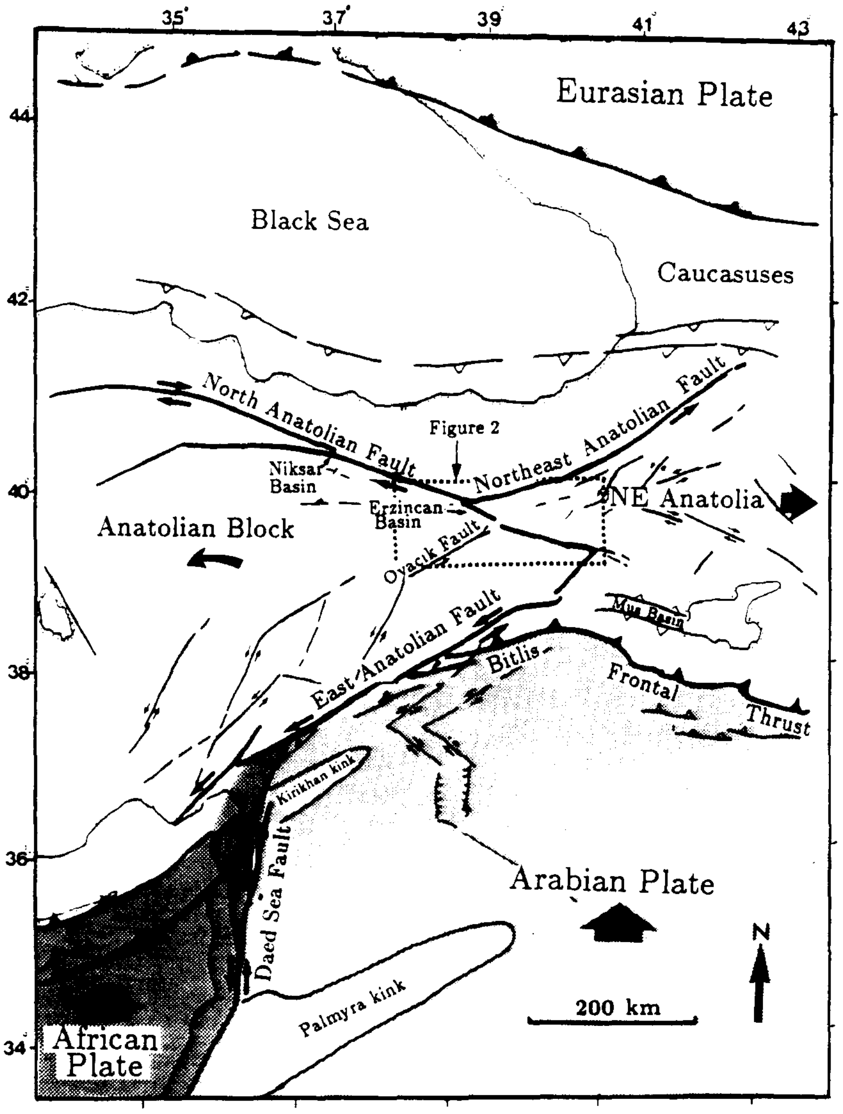

Fig. 1. Major tectonic elements of eastern Turkey, where the post-collisional N–S convergence between the Arabian Plate and the Pontides caused the escape of the continental blocks westward and eastward as indicated by large arrows. The study area is enclosed by dotted lines. Major faults are highlighted with thick lines. Other active faults are also shown (compiled from Şengör *et al.* 1985, Perinçek *et al.* 1987, Barka & Kadinsky-Cade 1988).

escape of continental blocks away from the maximum compression zone (Ketin 1948, McKenzie 1972, Gülen 1984, Şengör *et al.* 1985) tectonically overprinted some of the existing suture zones and basins, and also created new basins.

The stratigraphic characteristics of the Neogene–Quaternary sedimentary sequences in eastern Turkey indicate that there are three main stages of deposition. The first stage of sedimentation is associated with the wide-spread early Miocene transgression (Irrlitz 1972, Luttig & Steffens 1976, Şengör & Kidd 1979) which deposited sandstone/limestone lithologies passing upwards into shallow marine marls and reefal carbonates (Ketin 1950, Altınlı 1966, Şengör & Kidd 1979). This facies unconformably overlies older sedimentary units and ophiolitic melange of the Pontide–Anatolide/Tauride suture zone and its thickness has been estimated to be 750 m (Ketin 1950, Nebert 1961, Altınlı 1966). A marine regression took place towards the end of middle Miocene time, coeval with continental collision along the BSZ. This is indicated by increasing evaporitic intercalations and appearance of lacustrine and fluvial sediments in the stratigraphic record (Ketin 1950, Altınlı 1966, Kurtman *et al.* 1978, Bektaş 1981).

The second stage of deposition filled approximately E–W-trending narrow compressional basins located proximally to the suture zones (Fig. 2). The Muş Basin (Kurtman *et al.* 1978, Şaroğlu & Güner 1981, Şengör *et al.* 1985), Çayırlı-Tercan Basin (Ketin 1950, Irrlitz 1972) and the Mihar-Ahmediye Basin, which is situated to the NW of the Erzincan Basin (Figs. 2 and 4), are typical examples of this kind (Figs. 1 and 2). This stage is characterized by lacustrine and fluvial facies represented by evaporite/sandstone/marl/conglomerate lithologies, reaching up to 1750 m in thickness (Kurtman 1972, Tatar 1978). Nebert (1961) reported *Hipparion* fossils from these sediments, indicating the late Miocene age, which was also confirmed by Irrlitz (1972), in the Refahiye region, the western extension of the Mihar-Ahmediye Basin.

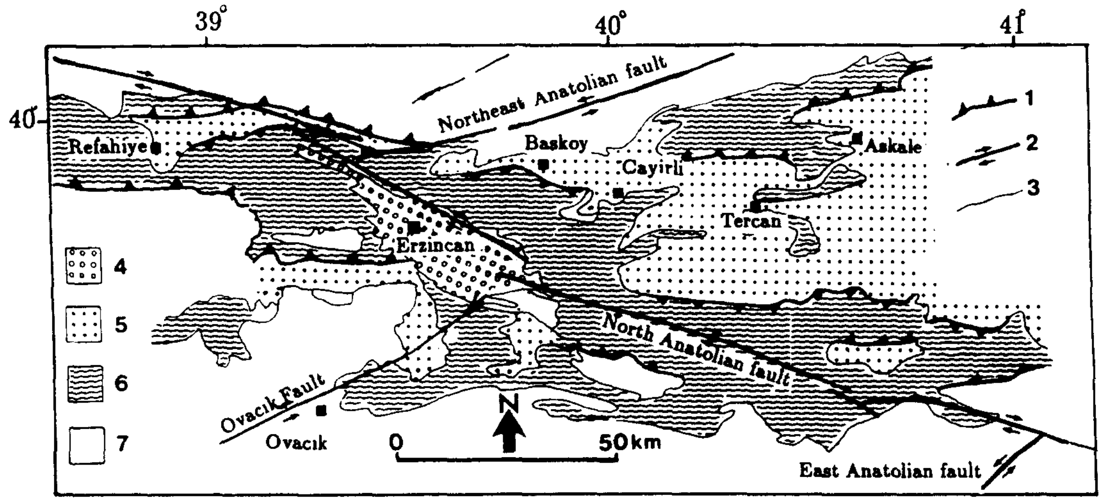

Fig. 2. Simplified geological map of the Erzincan area. 1; thrust, 2; strike-slip fault, 3; geological contact, 4; the Plio-Quaternary age Erzincan Basin, 5; late Miocene basins, 6; ophiolitic melanges representing Anatolide/Tauride–Pontide Suture zone, 7; other rock units (modified from the 1:500,000 scale geological map of Turkey). Notice that the NW–SE-striking Erzincan Basin which is subparallel to the North Anatolian Fault Zone differs from late Miocene basins, which strike E–W and are in thrust contact with the ophiolitic melanges. For more discussion see the text.

The third and final stage (Plio-Quaternary) of deposition produced mostly fluvial deposits (Fig. 4) within compressional basins as a continuation of the second stage (e.g. Muş Basin, Çayırlı-Tercan Basin, Figs. 1 and 2), or within newly formed basins along strike-slip fault zones (e.g. Erzincan Basin, Niksar Basin, see Fig. 1).

In the Erzincan Basin, all the exposed sediments belong to this third stage of deposition, which is characterized by Plio-Quarternary fluvial facies, that contain playa deposits, coarse clastics and basin margin conglomerates (Fig. 4). Conglomerates which are exposed along the NW margin of the basin are composed of ophiolitic melange clasts and Cretaceous–early Miocene carbonates. Occasional thin tephra and thick cross-bedded conglomerate layers are two characteristics of this sequence. The thickness of these unfossiliferous conglomerates reach up to 200 m and they have been considered to be of Pliocene–early Pleistocene age (Irrlitz 1972, Tatar 1978). The appearance of these ungraded, immature conglomerates and their sand to boulder size fragments suggest a rapid deposition in a tectonically active environment. Unfortunately, due to the absence of deep wells and seismic data, the total thickness of the Plio-Quaternary sediments in the Erzincan Basin is not known. For this reason thickness estimates of the basin fill range from 500–1000 m (Irrlitz 1972) to 2.5–3.5 km (Hempton & Dunne 1984).

In the Erzincan Basin, alluvial fans composed of recent debris flows and coarse-grained braided stream deposits are better developed along the steep northern margin. Along the southern margin, fan sediments and braided stream deposits are finer grained and contain no recent debris flows (Hempton & Dunne 1984). The central part of the basin is filled mostly by silts, sands, and gravels. The Euphrates River becomes a meandering type as soon as it enters the basin. A large salt playa abuts the meander plain at the lowest basin elevation containing thermal and soda springs. In contrast to the

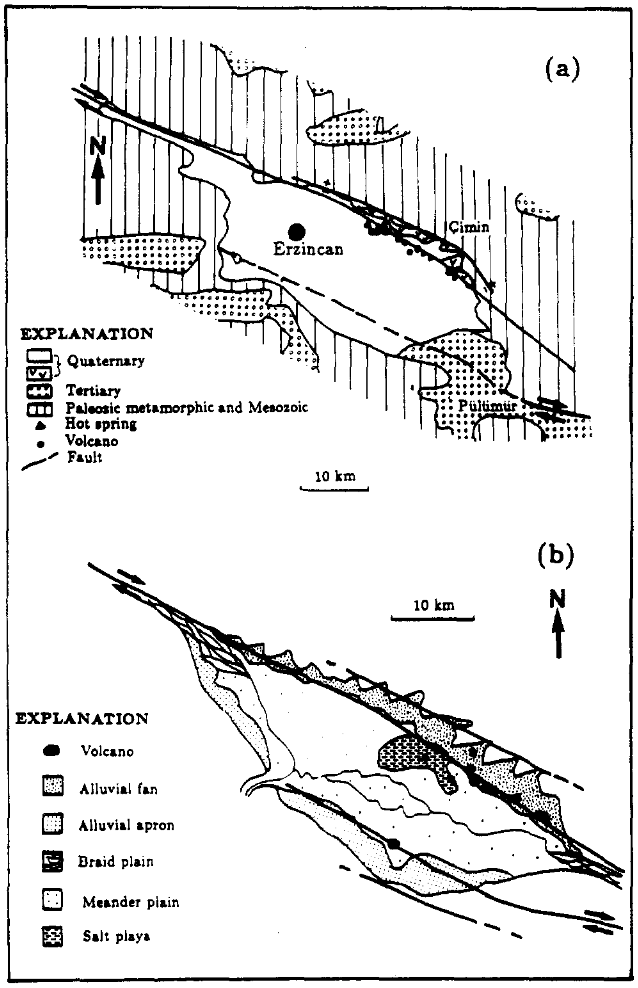

Fig. 3. Two previous pull-apart mechanism interpretations for the Erzincan Basin. (a) From Aydın & Nur (1982) depicting the Erzincan Basin as a typical rhombic pull-apart basin bounded by the en échelon NAFZ segments. (b) Hempton & Dunne's (1984) interpretation of the Erzincan Basin, which is quite similar to Aydın & Nur's (1982) above interpretation.

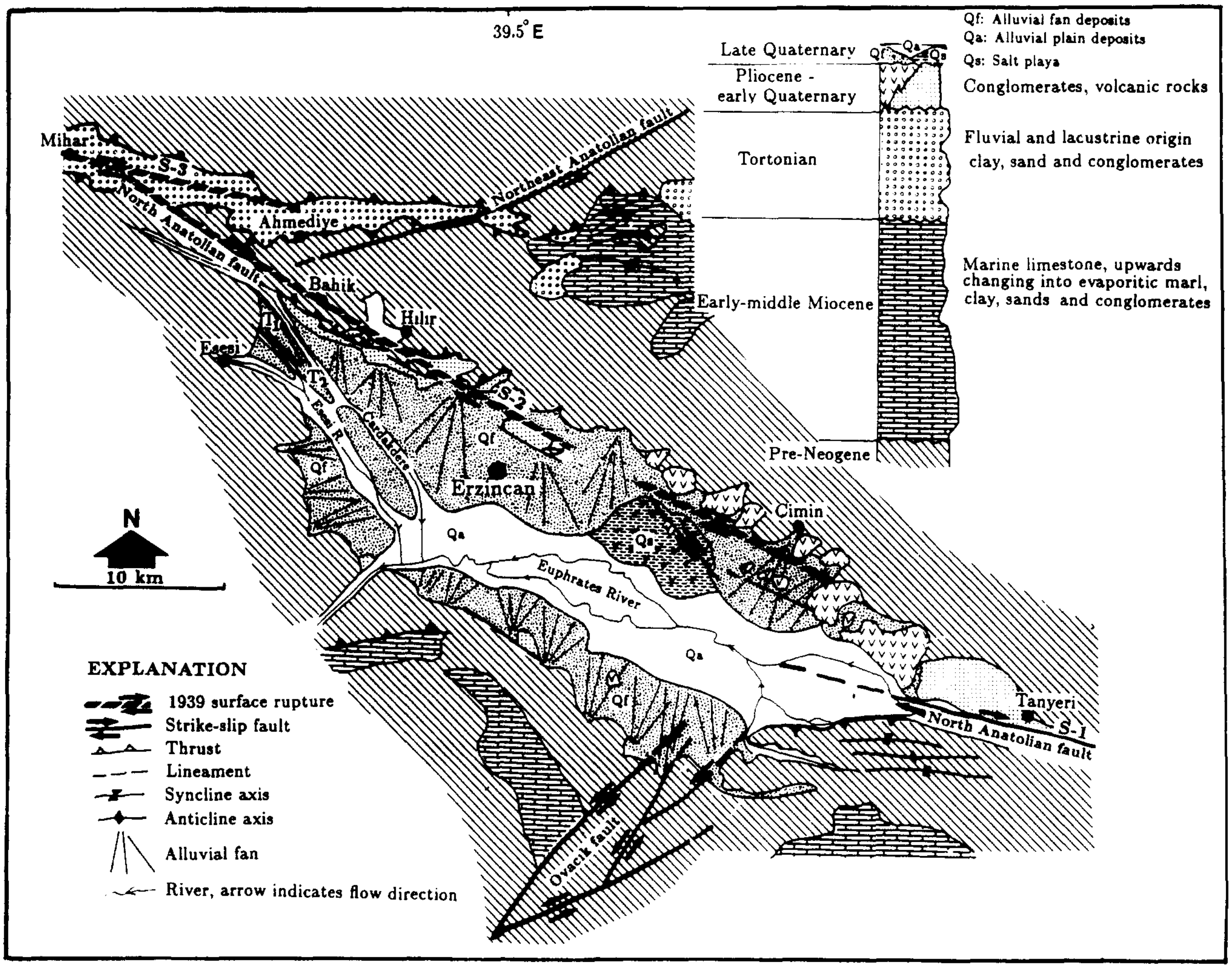

Fig. 4. Geological map of the Erzincan pull-apart basin and its vicinity. A generalized stratigraphic column is given as an inset. T1 and T2 denote the two levels of terraces, that are mapped along the Çardakdere and Esesi Rivers.

Euphrates River, the Çardakdere and Esesi Rivers (Fig. 4) preserve their braided character within the basin. Unlike the Euphrates, which has no river terraces, at least two levels of terraces are developed along these rivers. The upper terrace is about 40–50 m higher than the present river base.

About 15 small volcanic cones are aligned along the northern margin, while only one cone occurs close to the southern margin of the basin. They consist of dacites and rhyolites. The age of the volcanism is 0.25–3.1 Ma (Baş 1979, Hempton & Linneman 1984).

STRUCTURAL GEOLOGY

A general N–S compressional regime dominates the neotectonics of the whole of eastern Turkey due to the continuing active convergence following the late–middle Miocene continental collision along the Bitlis Suture Zone. For example, Miocene sediments are deformed (mostly thrusting and folding) throughout this region (Pamir & Ketin 1941, Altınlı 1966, Tatar 1978), as well as along the northern margin of the Arabian plate (Rigo de Righi & Cortesini 1964, Ketin 1969, Perinçek 1980, Özkaya 1981). As shown in Fig. 4, early–middle Miocene limestone units and the late Miocene sediments of the E–W-trending Mihar-Ahmediye Basin are folded with axial traces striking E–W and the basins are bounded by E–W-trending thrusts in the north and south (see also Fig. 2). Many other Miocene basins exhibit similar deformational styles in eastern Turkey (Kurtman *et al.* 1978, Şaroğlu & Güner 1981, Şengör *et al.* 1985, Barka & Gülen 1988). The Erzincan Basin differs from the above mentioned basins because of its NW–SE-trending long axis and its relatively young age (Fig. 2). The basin's NW-SE trend is parallel to the trend of the NAFZ which forms the entire northern boundary of the Erzincan Basin and serves as a master fault. The NAFZ consists of three major segments in this region (Figs. 2 and 4). The geometry and the interaction of these segments are extremely important for the understanding of the origin and evolution of the Erzincan Basin.

Segment 1

This eastern segment is about 75 km long and trends N110°E. The western half of the segment runs along the Euphrates valley where physiographic expressions are subdued due to the high rate of fluvial activity. The best fault expressions in this part are developed between

Tanyeri and Çaykomu (Fig. 4). In this area a long narrow side-hill ridge also demonstrates that the southern block is uplifted about 30 m relative to the northern block. The eastern half of this segment has very clear strike-slip fault expressions where the 26 July 1967 Pülümür earthquake, M = 5.6–6.2, occurred (Fig. 5b).

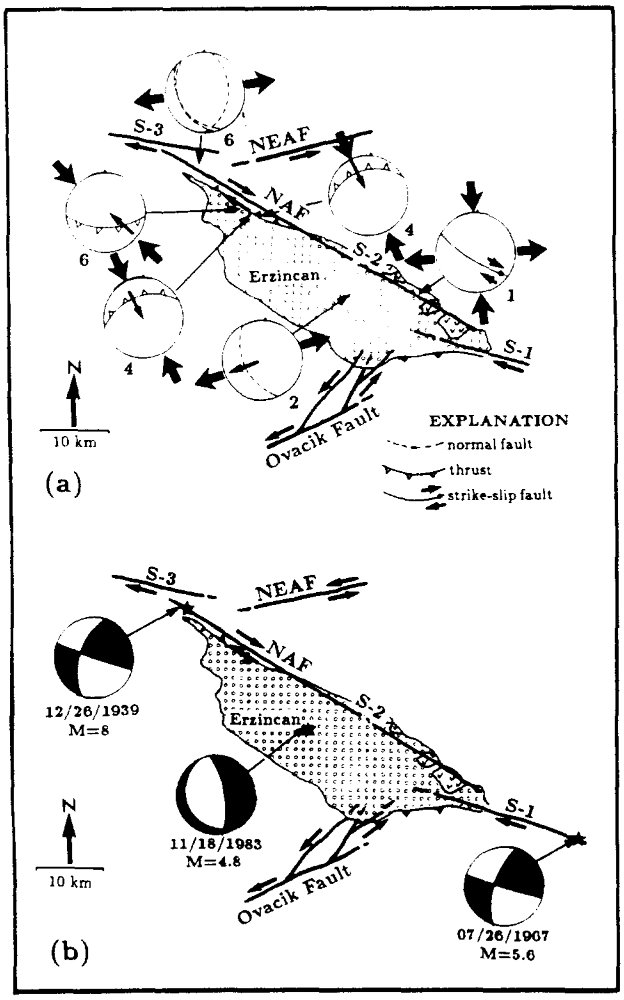

Fig. 5. Interpretation of tectonic structures in the Erzincan Basin. (a) Map showing analysis of mesoscopic scale faults measured within the Neogene–Quaternary sediments, illustrating NNW–SSE compression and ENE–WSW extension along the NAFZ (large arrows). Stereonets are equal-area, lower-hemisphere projection. The figures in the lower corners indicate the number of structures measured at each station. (b) Fault plane solutions clearly indicating the active opening of the Erzincan Basin. Solutions of 26 December 1939 and 26 July 1967 are from McKenzie (1972) and 18 November 1983 is from the International Seismological Centre Bulletin (1983). Magnitudes of the earthquakes are also given on the figure.

Segment 2

This segment forms the northern boundary of the Erzincan Basin. It is approximately 60 km long and trends N125°E. It consists of a number of small en échelon faults in its southern half, along which a series of volcanic cones are aligned. Fault traces and related right-lateral shear zone deformation are best observed in a stream valley west of Bahik. As shown in Fig. 6, the structures include folds, pressure ridges and extension cracks which are probably created by historical earthquakes. The strike-slip fault planes dip steeply to the south and the southern block is slightly uplifted. The pitch of the slickenside lineation is 10°SE from the strike of the fault. Stress analysis of the structures at this location indicates a dominant right-lateral strike slip along segment 2. Furthermore, along the northwestern half of this segment positive flower structures (Harding 1985) are also common. Both the 15° difference and the approximately 4 km wide releasing stepover between segments 1 and 2 are responsible for the initial opening of the Erzincan Basin.

Segment 3

This segment strikes N105°E and starts around Ahmediye and extends westward about 110 km to the Suşehri Basin (Figs. 2 and 4). The fault expression is best observed in the vicinity of Mihar. The 1939 Great Erzincan earthquake (M = 8.0) created surface ruptures not only on this segment, but also on segment 2, producing 4 m right-lateral slip and the southern block was uplifted 1 m (Pamir & Ketin 1941, Ketin 1969). The 20° difference in strike between segments 2 and 3 forms a restraining bend to the NW of the Erzincan Basin with the epicenter of the 1939 Erzincan earthquake in the vicinity of this restraining bend (Fig. 5b).

Ovacık Fault

The Ovacık Fault (Figs. 2 and 4) is a left-lateral strike-slip fault and was partly mapped by Arpat & Şaroğlu (1975). From 1 : 60,000 scale aerial photographs, the northeastern end of the Ovacık Fault was mapped in detail. This fault is obliquely oriented relative to the NAFZ (N60°E) and extends about 120 km southwest from the southeastern end of the Erzincan Basin and cuts the Quaternary fan deposits of the Ovacık Basin (located to the south of the study area, see Fig. 2). Field observation in the NE of the Ovacık Basin revealed that the fault plane dips steeply NW, with dominant left-lateral strike-slip and subordinate thrust components of the uplifted northern block. The Ovacık Fault splays into several branches near the Erzincan Basin. This may be due to fact that the fault enters an extensional regime.

Finally, the Northeast Anatolian Fault (Tatar 1978) is a major left-lateral strike-slip fault which defines the northern boundary of the eastward escaping Northeast Anatolian Block (Figs. 1, 2 and 4).

Relative stress directions are obtained from the analysis of conjugate faults and slickenside lineations (Hancock & Barka 1981, Angelier 1984, Hancock 1985) measured at six stations in the Neogene–Quaternary sediments (Fig. 5a). The analysis indicates that the area is under NNW–SSE compression and related ENE–WSW extension. This is in agreement with the stress field related to the right-lateral NAFZ.

The fault plane solutions of 26 December 1939 (M = 8.0), 26 July 1967 (M = 5.6) and 18 November 1983 (M = 4.8) earthquakes are given in Fig. 5(b). The first two solutions are consistent with right-lateral motion along segments of the NAFZ, but the solution

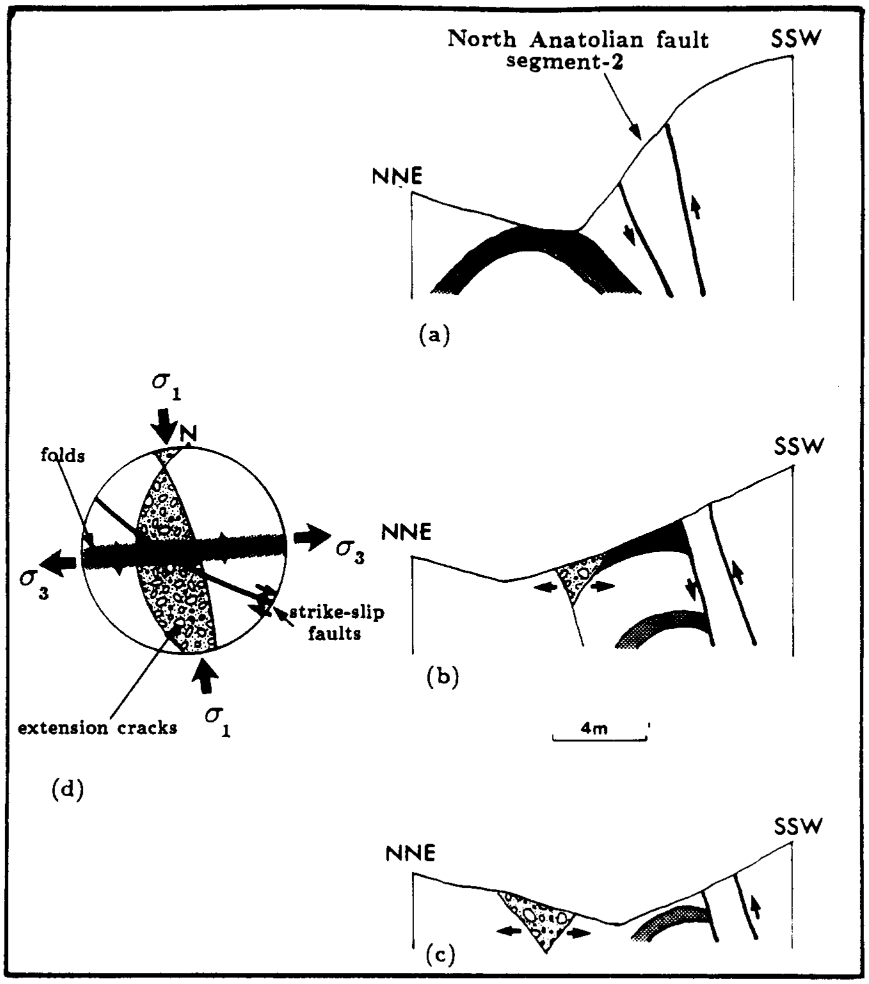

Fig. 6. (a)–(c) sketch of profiles along segment 2 of the NAFZ from a natural valley cut 100 m west of Bahik, where surface breaks of 1939 Erzincan earthquake passed through (looking in the SE direction), showing deformation patterns related to the fault zone such as fault planes, folds, pressure ridge and extension cracks. (d) Lower-hemisphere projection of the geometrical orientation of these structures and their relative stress directions.

obtained from the 18 November 1983 earthquake implies ENE–WSW extension, which is consistent with the active opening of the Erzincan Basin.

ORIGIN AND EVOLUTION OF THE ERZINCAN BASIN

In the Erzincan region, segments 1, 2 and 3 of the NAFZ form a releasing double bend. There is a 15° divergence angle and a 4 km wide releasing stepover between segments 1 and 2 (Fig. 8a). This small, secondary stepover and the 15° divergence angle were initially responsible for the westward pull-apart opening of the Erzincan Basin due to right-lateral displacement along the NAFZ (Fig. 8b). This pull-apart geometry is very similar to the Glynnwye Lake Basin along the Hope Fault, New Zealand (Freund 1971, see also Mann *et al.* 1983 for detailed discussion on divergent master faults). As is observed in the Glynnwye Lake Basin, this geometry of the master faults results in extensive normal faulting associated with progressive right-lateral motion (Figs. 7a and 8b).

In contrast to the northern margin of the Erzincan Basin, our field studies and aerial photo interpretations

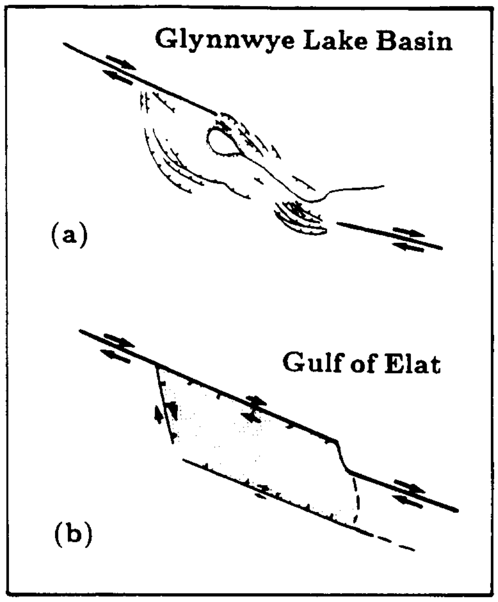

Fig. 7. Two examples of a single stage model to explain the evolution of the Erzincan Basin. (a) The Glynnwye Lake Basin (from Freund 1971). (b) Simplified and interchanged (from left- to right-lateral) geometry and structure of the Gulf of Elat (Ben-Avraham 1985).

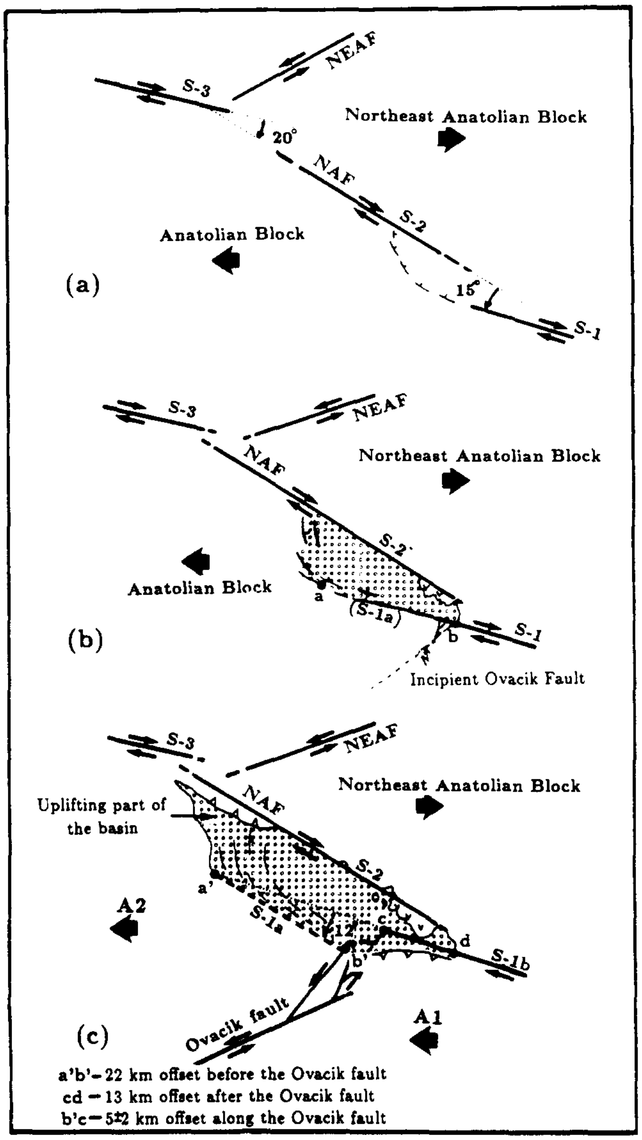

Fig. 8. Tectonic evolution stages of the Erzincan Basin. (a) The releasing double bend formed by segments 1–3. (b) Initial pull-apart opening (about 22 km right-lateral displacement) of the Erzincan Basin (basin area shaded) between non-parallel master (divergent) faults (S-1 and S-2), due to the tectonic escape of the Anatolian and Northeast Anatolian blocks westward and eastward, respectively. Volcanic activity also starts at the eastern part of the basin during this stage. (c) Two-stage model to explain the evolution of the Erzincan Basin. The formation of the left-lateral strike-slip Ovacık Fault divides eastern part of the Anatolian Block and segment 1 of the NAFZ into two; A1, A2 and S-1a, S-1b segments, respectively. At present, S-1a forms the southern basin boundary and the geometry of the basin indicates a 5 ± 2 km total left-lateral strike-slip offset for the branches of the Ovacık Fault (see the text for further explanation).

which extend southeastward, well outside of the basin, show no evidence that the southern margin is controlled by an active strike-slip master fault (compare the extents of fault segments 1 and 2 in Fig. 3 and Figs. 2 and 4), as suggested by Şengör (1979), Aydın & Nur (1982) and Hempton & Dunne (1984). It is true that some part of the southern boundary is linear, however on the whole it is quite different from the northern boundary. These tectonic differences between the margins can be inferred from the slopes of alluvial fans (i.e. along the northern margin they are at least twice as steep than those along the southern margin). A possible explanation for this observation is that the total vertical displacement is taken up mainly by the segment 2 master strike-slip fault along the northern margin, whereas it is partitioned among a number of buried normal faults which cause the formation of lower angle slopes along the southern margin.

The above mentioned arrangement of segments 1 and 2 can open only a westward widening pull-apart basin (Fig. 8b), however, the present day geometry of the basin indicates that the eastern part of the basin is also widening, where the pull-apart stepping is narrow. Based on the geometry of the basin and the participation of the Ovacık Fault in the opening of the basin, we suggest two different models for the origin and the evolution of the Erzincan Basin.

(a) *Single-stage model*

Two examples of a single stage model can be proposed to account for the geometry and structure of the basin without participation of the Ovacık Fault. The first one is the Glynnwye Lake Basin (Fig. 7a), with normal faults at the SE part of the basin which may widen the basin to the south. The second example is taken from studies by Ben-Avraham (1985) of the Gulf of Elat (Fig. 7b). According to this model the pull-apart basin is widened by a coeval normal fault trending parallel to the master strike-slip faults. Although, these two examples of single-stage model are very similar, the first one is more consistent with the geometry of the fault segments (Fig. 7a).

(b) *Two-stage model*

We believe that this initial stage was interrupted by the formation of the left-lateral Ovacık Fault which also caused further division of the eastern part of the Anatolian block into two wedge shaped blocks, A1 and A2 (Fig. 8c). As a result of this, the southern boundary master fault (segment 1, Fig. 8b) was offset and slightly rotated by the Ovacık Fault. This relict fault (segment 1a, Fig. 8c) appears to be acting as a breakaway zone for the Erzincan Basin. In other words, the current breakaway zone which is expressed by the linearity of the southern margin of the Erzincan Basin is in fact modified from the original strike-slip/normal fault segment. This two stage evolution and geometry of the basin indicates a total of 35 ± 5 km of right-lateral displacement along the NAFZ (Fig. 8c), 22 ± 3 km of which belongs to the first stage and the rest to the second stage, and 5 ± 2 km total left-lateral displacement along the Ovacık Fault (Fig. 8c). The first stage 22 km right-lateral displacement along the NAFZ could only have been possible, if there was no initial overlap between segments 1 and 2.

Although, the examples of single-stage model are far simpler and involve no rotation and offset of segment 1, and faults remain essentially strike-slip and normal since their initiation, the above described two stage model appears to explain our field data better, and we cannot neglect the existence and active participation of the Ovacık Fault.

Finally, the presence of positive flower structures in the vicinity of the restraining bend area segments 2 and 3, and the occurrence of river terraces along the Esesi and Çardakdere Rivers (Fig. 4) indicate that the northwestern half of the basin was contracting while this complex opening was in progress in the southeastern half of the basin. The contraction is caused mainly by N–S regional compression which results in side escapes of continental blocks. The existence of the restraining bend along segments 2 and 3 can be an another reason for the formation of these compressional features.

To summarize, we conclude that the Erzincan Basin was initially a non-parallel master fault type of pull-apart basin and it was formed between the segments of the NAFZ. Later, the opening of the basin was modified by the left-lateral Ovacık Fault which defined a new wedge shape westward escaping Anatolian block (A2). This model is based on only field geology data, but future deep drilling and seismic profiling may reveal the details of the subsurface structure in the basin.

Acknowledgements—The field work studies were supported by the ITIT joint project (No. 8212) between the Mineral Research and Exploration Institute of Turkey (M.T.A.), the Geological Survey of Japan, NASA grant No. NAG5-753 and U.S. Geological Survey contract No. 14-08-0001-G1151. We would like to thank Dr H. Kato for his assistance in collecting the data. Two anonymous referees and Dr D. J. Sanderson are acknowledged for reviewing the paper before publication.

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