Journal of Structural Geology, Vol. 5, No. 2, pp. 217 to 220, 1983
Printed in Great Britain

0191–8141/83 $3.00+0.00

Tectonic interpretations of enigmatic structures in the North Anatolian fault zone

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(*Received* 20 *December* 1982; *accepted in revised form* 5 *February* 1983)

Abstract—Two geometrically distinct groups of syn-sedimentary and post-depositional mesofaults and joints cut Neogene–Quaternary sediments in basins situated along the convex-northwards arc of the North Anatolian fault zone between Çerkes and Erbaa. One group comprises second-order fractures interpreted as having developed during episodes of right-lateral shear along the fault zone, while the morphologically identical fractures in the other group have been interpreted as secondary products of left-lateral shear; thus apparently implying one or more former episodes of eastwards motion of the Anatolian *scholle*. Because such a reversal of motion would be counter to the well-established westward escape of Anatolia the structures have been called anomalous or incompatible.

Alternative hypotheses which have been advanced to explain the development of the anomalous mesofractures include: localized reversals related to displacements of rigid blocks acting as buttresses within basins; selective operation of intra-pull-apart strike-slip faults; stress release; the coincidence of the present western sector of the fault with an older left-lateral fault zone; and the influence of a North Turkish neotectonic stress regime.

DESPITE numerous seismological analyses and conventional geological surveys of the North Anatolian fault zone (e.g. Ambraseys 1970, McKenzie 1972, 1978, Şengör 1979, Şengör *et al.* 1982), there have been few microtectonic investigations of the zone and hence our reports (Hancock & Barka 1980, 1981) of some anomalously orientated joints and mesofaults have attracted some interest (Hempton 1982, Şengör *et al.* 1983).

The approximately 1200-km long North Anatolian fault zone is an intracontinental transform linking the East Anatolian convergent zone with the Hellenic subduction zone (Şengör *et al.* 1982). Despite a lack of agreement about its date of initiation and cumulative offset most workers agree that it developed in the Neogene and that the right-lateral displacement is substantial, but may vary along its length (see Şengör 1979, Şengör *et al.* 1982; Barka & Hancock in press for reviews).

Continental clastic sediments in five Neogene–Quaternary basins (see Hancock & Barka 1981, fig. 1b) situated astride or adjacent to the main trace of the North Anatolian fault between Çerkes and Erbaa are cut by numerous sets of joints and mesoscopic-scale faults belonging to two geometrical groups distinguishable on the basis of their attitudes and senses of displacement with reference to the trend of the fault zone (Hancock & Barka 1980, 1981). The principal elements in each group of fractures are summarized in Table 1. The precise age of the Pontus Formation (Irrlitz 1972) is in some doubt but it probably ranges from the Tortonian to the early Pleistocene (see Şengör *et al.* 1983 for a fuller discussion).

Both group 1 and group 2 mesofractures include syn-sedimentary and post-depositional structures displaying an identical range of morphological characteristics, and hence, despite their different geometries it is not unreasonable to seek a common mechanism for their genesis. According to Hancock & Barka (1980, 1981) group 1 structures may be related to secondary directions of compression or extension presumed to have been generated by one or more episodes of left-lateral shear along the fault zone, while group 2 structures are interpreted as the second-order products of right-lateral shear. The explanation advanced for the group 2 fractures is not controversial because the inferred shear sense accords with that operating at the present day. However, in the context of a tectonic model involving the westwards escape of the Anatolian *scholle* (crustal splinter) along an approximately E–W trending northern boundary the attitudes of the group 1 mesofractures are anomalous (Hancock & Barka 1981) or incompatible (Şengör *et al.* 1983).

Six hypotheses (Fig. 1) have been published to explain the occurrence of group 1 (i.e. anomalous) mesofractures within the North Anatolian fault zone. Furthermore, it must be acknowledged that some group 1, and possibly some group 2, normal and reverse mesofaults may be related to adjustments or rotations in the wall rocks of macrofaults which are themselves secondary

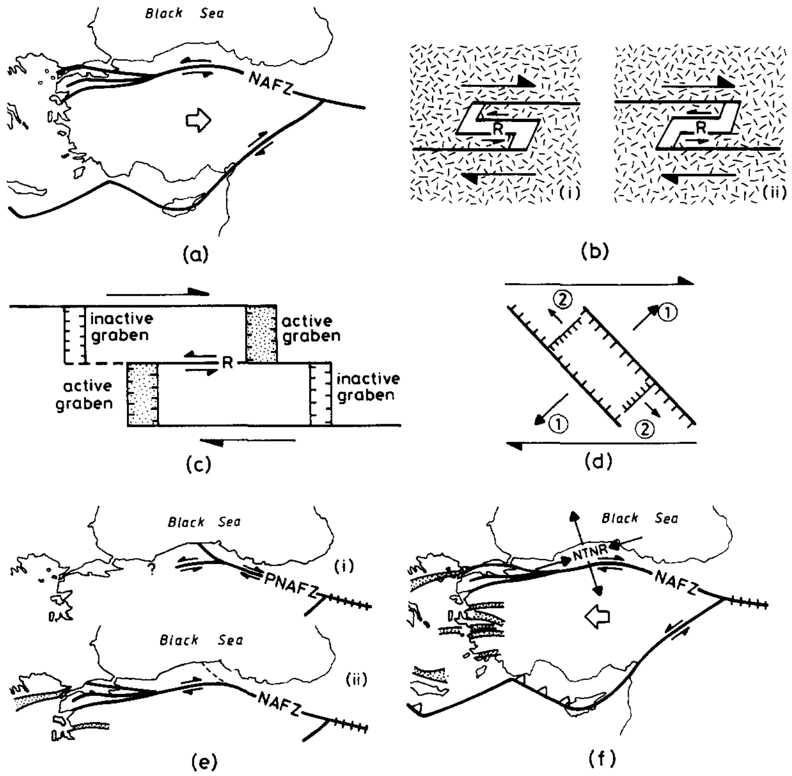

Fig. 1. Cartoons illustrating six hypotheses to explain the occurrence of group 1 (anomalous) mesofractures in the North Anatolian fault zone (NAFZ). (a) Regional reversal of motion of the Anatolian *scholle*. (b) Localized reversals (R) related to displacements of rigid blocks projecting as buttresses into basins which are (i) closing and (ii) opening. (c) Localized reversal (R) on an intra-pull-apart strike-slip fault. (d) Stress release. Thick lines depict older normal faults, thin lines show younger faults. (1), extension direction related to right-lateral shear along the North Anatolian fault zone; (2), extension direction during stress release. (e) Coincidence of western sector with an older left-lateral fault. (i) Tectonic regime during activity on the proto North Anatolian fault zone (PNAFZ), (ii) after the Plio-Pleistocene and establishment of the present-day North Anatolian fault zone. (f) Influence of a North Turkish neotectonic regime (NTNR) during the westwards escape of Anatolia.

structures in the North Anatolian fault zone. Such smaller faults may misleadingly be reverse in the wall rocks of larger normal faults, or normal in the wall rocks of larger reverse faults, as a consequence of the larger fault being (a) convex upwards (e.g. Mattauer 1973, fig. 6.55), (b) listric and normal, leading to back-rotation of pre-existing faults in the hanging-wall block (Jackson *et al.* 1982, fig. 4) or (c) a thrust displacing the ground surface with consequent hanging-wall collapse (e.g. Jackson *et al.* 1982, fig. 8). For these explanations to apply to the majority of the mesofaults in the North Anatolian zone it would be necessary to demonstrate a direct spatial association between the distribution of the mesofaults and macrofaults of appropriate geometry, for which there is no evidence.

(1) *Regional reversal(s) of motion before the late Pleistocene* (*Hancock & Barka* 1980, 1981)

A worthwhile attribute of this radical idea is that the morphologically identical fractures in both groups 1 and 2 are accounted for by the same mechanism; that is they are the secondary products of shear couples which operated in opposite senses at different times. However, as Hempton (1982) and Şengör *et al.* (1983) have persuasively argued, such an interpretation possesses profoundly unacceptable implications for current ideas about the neotectonic evolution of the entire Turkish–Aegean region, within which there is no known corroborative evidence in favour of there having been one or more reversals of the normal westwards motion of the Anatolian *scholle* (Fig. 1a). We note however that Tapponnier *et al.* (1982) consider that a change in the sense of motion can occur on some large continental strike-slip faults, such as the Red River fault in South East Asia.

(2) *Localized reversals related to displacements of rigid blocks acting as buttresses within basins* (*Hancock & Barka* 1981)

The proposal that displacements of pre-existing rigid blocks projecting into basins could cause localized reversals as a consequence of buttressing possesses the merits of not giving rise to unacceptable tectonic implications. However, as a mechanism for forming group 1 mesofractures it remains a highly speculative explanation because it is not possible to correlate the distribution of anomalous fractures with suitably arranged rigid blocks such as those illustrated in Fig. 1(b), which shows two purely hypothetical configurations. Hancock & Barka (1981) proposed that the absence of anomalous structures in sediments above the Pontus Formation could reflect the

Table 1. Summary of mesofracture sets in Neogene–Quaternary sediments in basins along the North Anatolian fault zone

	Stratigraphic range	Conjugate reverse mesofaults	Conjugate normal mesofaults	Strike-slip faults	Conjugate steeply-inclined joints	Vertical joints
Group 1	Pontus Formation	strike NW	strike NE	not observed	strike NE	conjugate sets enclose a NE-trending acute bisector and single sets strike NE
Group 2	Pontus Formation–Holocene	strike NE	strike NW	strike NE or parallel to main trace	strike NW	conjugate sets enclose a NW-trending acute bisector and single sets strike NW

waning influence of buttresses as their asperities were progressively eliminated during repeated episodes of right-lateral shear.

(3) *Localized reversals on intra-pull-apart strike-slip faults (Şengör* et al. 1983)

In common with hypothesis (2) an advantage of this idea (Fig. 1c) is that no regionally significant implications follow from it, but as with hypothesis (2) it is not possible to relate the distribution of group 1 mesofractures to that of the controlling major structures. In this instance these are two pairs of grabens, situated at the ends and on the opposite sides of an intra-pull-apart strike-slip fault. If activity on diagonally opposed grabens is alternating this will result in alternating episodes of left-lateral and right-lateral slip.

(4) *Stress release after episodes of right-lateral shear (Hancock & Barka* 1981)

If the anomalous structures are interpreted as a result of stress release (Fig. 1d) there are no unwelcome tectonic implications. Nevertheless the hypothesis does not account for the observed lack of anomalous structures in sediments younger than the Pontus Formation. Assuming that a mechanical process should operate after each episode of slip why are group 1 structures less common in the east, and why is the proportion of faults to joints in group 1 (19%) not much less than in group 2 (25%)? Stress release is more likely to form joints than faults.

(5) *Coincidence of the western sector of the present fault zone with an older left-lateral fault (Hempton* 1982)

The idea that the western sector of the modern fault zone may have developed along the outcrop of a former left-lateral ENE-trending fault has been proposed by Hempton (1982). He thinks that during the Mio-Pleistocene most of the right-lateral displacement on the northern part of the eastern sector, which formerly extended to the Black Sea, was transferred to the western sector (Fig. 1e). The outcrop of the former WNW extension, postulated by Bergougnan *et al.* (1978), should pass through or close to several Neogene–Quaternary basins. Because there are no published accounts of structures in these basins it is not known whether they contain group 2 mesofractures which support the idea of there having been right-lateral shear. Furthermore, despite the elegance of Hempton's model it fails to explain why there are some group 1 mesofractures in the two eastern basins, and likewise why synsedimentary group 2 mesofaults occur in the lower part of the Pontus Formation in the two western basins. During the early phases of deposition of the Pontus Formation the western sector should, according to Hempton's model, have been undergoing only left-lateral shear.

(6) *Superimposition of a North Turkish neotectonic regime (Şengör* et al. 1983)

This notion, the most plausible alternative to hypothesis (1), interprets group 1 mesofractures as products of episodic ENE–WSW shortening and complementary NNW–SSE extension in a North Turkish neotectonic regime superimposed on the strike-slip regime of the North Anatolian fault (Fig. 1f). The North Turkish regime is thought by Şengör *et al.* (1983) to be related to compression generated by constraints imposed in the Aegean region during the westwards escape of the Anatolian *scholle.* Although the explanation avoids the unacceptable implications of the reversal model it also possesses regional connotations of its own. Products of the regime should not be confined to, or necessarily most abundant in, the North Anatolian fault zone. Excepting the small number of faults and the earthquake focal mechanism solution discussed by Şengör *et al.* (1983) there are few reports of other structures whose orientations are consistent with their development in the postulated neotectonic regime. The apparent lack of such structures in the Pontides may be an artefact of the small number of investigations. The observations that group 1 mesofractures are less abundant in the two eastern basins is compatible with the notion of a North Turkish neotectonic regime, the influence of which is likely to decrease eastwards away from the Aegean region where it is generated.

The lack of observed group 1 structures in sediments younger than the Pontus Formation may be a function of the difficulty of detecting them, relatively few faults having been developed by such episodic activity in the short time interval since the end of the early Pleistocene. Even group 2 (i.e. compatible) mesofaults are uncommon in sediments younger than the Pontus Formation and are generally restricted to a narrow belt adjacent to the main active fault trace.

We conclude that although on theoretical and intuitive grounds it is possible to reject the idea of a wholesale reversal of shear on the North Anatolian fault it is less easy, in the absence of critical field evidence, to select an alternative explanation. We recommend that additional detailed structural studies in Neogene–Quaternary basins both within and external to the North Anatolian fault zone should be undertaken. Such investigations will be of benefit not only to tectonicians but also to engineers and planners working in a country of high seismic risk.

Acknowledgements—We are most grateful to Dr. A. M. C. Şengör for his comments on a draft of this note.

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