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SHORT NOTES

Neotectonics of the Pontides: implications for 'incompatible' structures along the North Anatolian fault

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Abstract—Data for the post-Serravallian, 'neotectonic' evolution of the Pontides in northern Turkey indicate predominant ENE–WSW shortening with complementary NNW–SSE extension. We present a new fault plane solution for the Bartın earthquake (3 September 1968) and compare its mechanism with the movement picture of other neotectonic faults in the Pontides and northern Greece together with that of the Thessaloniki earthquake (20 May 1978). The general strain pattern exhibited by these structures agrees remarkably well with that inferred from early Tortonian–early Pleistocene structures reported from within the North Anatolian fault zone, which have been interpreted as indicating a possible reversal of the sense of movement along the North Anatolian transform fault. Here, we argue that such 'incompatible' structures may be related to the overall E–W shortening of Anatolia and the southern parts of the Black Sea resulting from the sideways continental escape from around the African and the Arabian promontories, rather than to hypothetical reversal of motion along the North Anatolian fault, for which there is no evidence other than the above-mentioned 'incompatible' structures. This new model also has important implications for seismicity and earthquake risk in regions contained within the southern part of the Black Sea plate.

INTRODUCTION

IN ANATOLIA (Asia Minor), three major neotectonic (i.e. post-Serravallian; for a definition of neotectonic as commonly used in Turkey see Şengör 1980 in press) provinces have been recognized on the basis of their predominant structural styles and associated strain patterns (Şengör 1979, 1980). They are (1) the East Anatolian high plateau characterized by N–S shortening and accompanying E–W extension, (2) the Central Anatolian *ova* regime experiencing E–W shortening and N–S extension accomplished mainly on NE–SW striking oblique-slip faults and a subordinate fault set striking NW–SE and (3) the Aegean graben system dominated by N–S extension. The latter two provinces are bounded to the north by the right-lateral North Anatolian transform fault and its western substitute, the Grecian shear zone (Ketin 1948, Şengör 1979). The neotectonic regime of the areas lying north of the North Anatolian transform and comprising a major portion of the Pontide palaeotectonic unit (Ketin 1966) has not been studied in detail, largely because the neotectonic structures of the region are neither as active, nor as spectacular, nor as abundant as in other parts of Turkey. Indeed, the areas lying between the Black Sea shore and the north Anatolian transform (hereafter called the North Turkish region) have long been viewed as inactive and for this reason research is in progress to choose nuclear-power plant sites within the area. However, a study of the neotectonics of the North Turkish region is of critical importance for the solutions to a number of problems, such as the interpretation of the weak regional seismicity and the understanding of numerous, discontinuous, scattered neotectonic features recognizable on land, on ERTS images, aerial photographs, and in the field, and underwater on bathymetric charts and seismic reflection profiles.

The purpose of this note is to present a new fault plane solution for the Bartın earthquake and compare the associated faulting with other neotectonic features of the North Turkish region in an attempt to understand the nature of the dominant post-Serravallian regime in this area and to discuss its implications for the proposed reversals of the sense of motion along the North Anatolian fault.

THE BARTIN EARTHQUAKE AND ITS IMPLICATIONS FOR THE NEOTECTONICS OF THE NORTH TURKISH REGION

On 3 September 1968, at 10 h 20 min 36 sec GMT, the two small townships of Bartın and Amasra on the Black Sea coast of Turkey were shaken by an earthquake of magnitude 6.1. Although no fresh fault breaks were observed in the field following the earthquake, Ketin & Abdüsselâmoğlu (1970) noted that the coast near Amasra had been uplifted some 35–40 cm during the

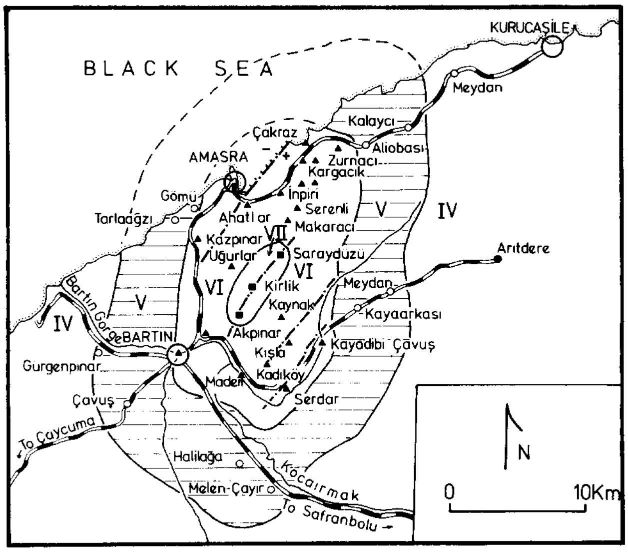


Fig. 1. Seismotectonic map of the epicentral region of the Bartın earthquake. For location of map area see boxed area in Fig. 3(a). Symbols are as follows: black squares are localities of highest damage, black triangles are those of much damage and white circles are those of little damage. Contours are isoseismal lines enclosing areas of varying intensities according to the Mercalli–Sieberg scale (roman numerals indicate intensities). Discontinuous heavy lines with dots in between are recent faults, the hachured one is along the uplifted coast near Amasra (hachures on the downthrown side). Redrawn after Ketin & Abdüsselâmoğlu (1970).

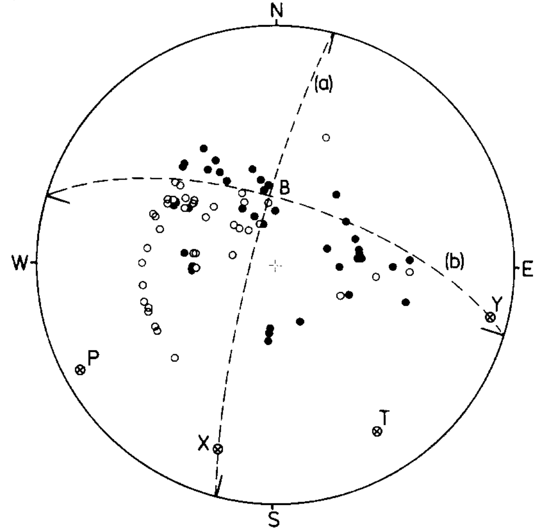
earthquake and that a number of NNE-striking faults located parallel with, but to the south of the raised coast line, may have moved as well (Fig. 1). As Fig. 1 shows, the isoseismals are concentric about the fault extending from Akpınar to Saraydüzü and they are elongate parallel with its trace. Ketin & Abdüsselâmoğlu (1970) concluded that the fault family shown in Fig. 1, or some subset of the family, must have been responsible for the earthquake.

McKenzie (1972, fig. 26n) provided a fault plane solution, based on long period WWSSN observations, indicating either NNE- or NW-striking thrusting with some strike-slip component. Figure 2 displays our new mechanism solution, which contains the short period observations of polarity published by the International Seismological Centre as well as the WWSSN observations from the same source. The compressional arrivals in the NW quadrant constrains the strike of the (b) plane which is closer to an E–W orientation than McKenzie's (1972) corresponding plane 2. Plane (a) in our figure is less well-constrained and is close in orientation to McKenzie's plane 1. Both our plane (a) and McKenzie's plane 1 have strikes very close to that of the Akpınar–Saraydüzü fault, and its thrust component is probably represented by the vertical motions observed (along the coast) and suspected (inland) by Ketin & Abdüsselâmoğlu (1970). We therefore take plane (a) as the fault plane. That vertical movements have been going on in this region during the latest Quaternary is indicated by Esen Arpat's (pers. comm. 1982) observation that the Kocaırmak river has dissected its terraces much more deeply than other streams flowing into the Black Sea. Arpat is of the opinion that this dissection occurred after the latest filling of the Black Sea (latest Pontian–Kimmerian; for a review of the debate on the timing of the latest filling of the Black Sea, see Hsü 1980 and Kojumdgieva 1980), that is, it is tectonically controlled.

Both our fault plane solution and that of McKenzie (1972) indicate an overall ENE–WSW shortening with NNW–SSE extension. It is difficult to interpret the Bartın earthquake as being related to the general deformation resulting from the activity of the nearby North Anatolian transform fault because the sense of movement during the Bartın earthquake was almost exactly the opposite of what one would have expected from the right-lateral north Anatolian fault.

In order to clarify the structural setting of the Bartın earthquake, we have looked at other neotectonic features in the North Turkish region. Prominent, well-studied structures are unfortunately few in this region, despite the existence of detailed, local geomorphological studies (e.g. Akkan 1970, 1975). The structures we could find both in northwestern Turkey (loc. 6, Fig. 3a, from Kopp *et al.* 1969) and in northern Greece (loc. 5, Fig. 3a, from Mercier *et al.* 1979) are consistent with an overall ENE–WSW to E–W shortening with roughly N–S extension. The fault plane solution of the 20 May 1978 shock of the 1978 Thessaloniki earthquake sequence is also given in Fig. 3(a) and comes from Soufleris & Stewart (1981). It exhibits predominant normal faulting with some strike-slip component, a picture in accord with NNW–SSE extension and ENE–WSW compression (Mercier *et al.* 1979).

Date: 03.09.1968
Time of origin: 08h 19m 53s
Epicentre: 41·81°N 32·39°E



	(a)	(b)		P	T	B	X	Y
Strike:	16°	104°	Azimuth:	242°	148°	356°	197°	102°
Dip:	82°	68°	Plunge:	9°	20°	66°	21°	8°

Fig. 2. Fault plane solution of the Bartın earthquake (by S.B.). Black circles are compressional, white circles are dilatational first arrivals. B. designates the null vector. A number of the incompatible observations may be due to the unreported reversed polarities in the local seismic stations reporting to the ISC. For further discussion see the text.

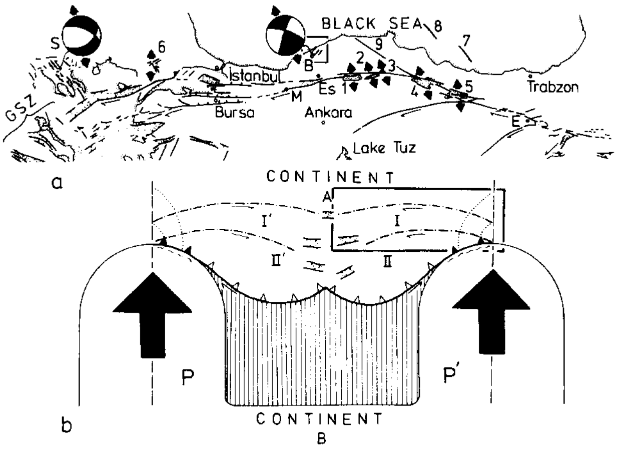


Fig. 3(a) Schematized neotectonic structures of northern Turkey and Greece. Black lines with hachures are normal faults (hachures in the downthrown block), those with black triangles are thrusts, and those with half-arrows are strike-slip faults. Stippled areas are extensional basins. Thick, short, black arrows indicate direction of extension accomplished by associated neotectonic features. Other directions of extension and associated structures that are also compatible with the proposed E–W shortening and corresponding N–S extension model are not shown, because they are not considered 'incompatible' with the present movement of the North Anatolian fault. GSZ is Grecian Shear Zone, S is the Thessaloniki area, B is Bartın, M is Mudurnu, Es is Eskipazar, E is Erzincan. 1 is Çerkes–Ilgaz basin, 2 is Tosya basin, 3 is Kargı basin, 4 is Havza–Ladik basin, 5 is Taşova–Erbaa basin and 6–9 are explained in the text. (b) Schematic diagram, modified from Tapponnier (1977), showing collision of continents A and B. P and P′ are the promontories corresponding with the African and the Arabian promontories of Argand (1924), respectively. The vertically lined area represents the intervening remnant ocean. Black toothed lines are sutures, whereas the white toothed line represents the subduction along which continental pieces II and II′ are moving onto the subductable oceanic area. The boxed area corresponds with the region illustrated in Fig. 3(a). The fault bounding domain I in the north has not developed as a distinct, throughgoing feature in the case shown in Fig. 3(a), probably because of very small and perhaps rather diffuse westerly motion. Fig. 3(b) is drawn symmetrically only for aesthetic reasons: the actual situation is naturally much more complex and asymmetric, but does not alter the arguments made in this paper.

Although roughly NW–SE oriented recent faults (localities 7–9, Fig. 3a) characterize the central part of the North Turkish region (Bergougnan *et al.* 1978) and its offshore extension (Neprochnov *et al.* 1974), no reliable evidence for the sense of neotectonic movement along them has yet been recorded.

On the other hand, Hancock & Barka (1980, 1981) have presented evidence for roughly ENE–WSW shortening with complementary NNW–SSE extension from five basins lined up along the North Anatolian fault zone between Çerkes (loc. 2, Fig. 3a) and Erbaa (loc. 5, Fig. 3a), an interpretation nearly identical to that deduced from the fault plane solutions of the Bartın earthquake and the other neotectonic structures farther west (Fig. 3a). Provided proper sense of movement can be demonstrated along them, the structures located farther east than the Bartın area (localities 7–9, Fig. 3a) could also take up roughly E–W shortening. It is noteworthy in this connection that the fault shown as 8 (Fig. 3a) has an associated weak seismicity.

An interesting aspect of Hancock & Barka's (1980, 1981) study, however, is their observation that the mesoscopic-scale structures indicating ENE–WSW compression with accompanying NNW–SSE extension are confined to sediments of the Pontus Formation. Pliocene–early Pleistocene according to Irrlitz's (1972) identification of the Lower Pontus as Pannonian and therefore early Pliocene. In the central Paratethyan domain, however, the Pannonian is now viewed to be equivalent to the Lower to Middle Tortonian (Dr. F. F. Steininger, pers. comm. 1982). Thus, the age of the Pontus Formation probably extends down into the early Tortonian, that is, roughly 11.5 Ma. On the basis of this observation, Hancock & Barka (1980, 1981) argued that because the strain picture given by the mesoscopic structures of the Pontus Formation is exactly the opposite of what one would have expected from the present sense of motion along the North Anatolian fault, it may have been reversed during that interval. Structures indicating this assumed reversal are here called 'incompatible' ('anomalously' oriented mesofractures in Hempton 1982). Along with possible regional or local reversals, Hancock & Barka (1981) considered the possibility of three purely mechanistic explanations, although they favour the hypothesis of local or regional reversals.

Şengör *et al.* (1982) have pointed out that a wholesale reversal of the motion along the North Anatolian fault would have had profound effects on the neotectonic evolution of the entire eastern Mediterranean area, for which there seems to exist no unequivocal evidence. A regionally more restricted reversal of the kind favoured by Hempton (1982) suffers from the fact that 'incompatible' structures are also observed in the Havza–Ladik and the Taşova–Erbaa basins where no reversal should have occurred according to Hempton's model and 'compatible' structures have been generated since the early Tortonian where movement should have been the opposite of what it is today until the early Pleistocene. The kinematic sequence described by Angelier *et al.* (1981) from southwest Turkey is based on limited observations and is thus an unconstrained model. Therefore, Hempton's (1982) correlation of the episodes described by Angelier *et al.* (1981) from western Turkey with his hypothetical periods of evolution of the North Anatolian fault do not necessarily support his ideas.

The indications, albeit few, that the entire North Turkish region may be under roughly E–W compression provide a novel framework within which to evaluate Hancock & Barka's observations. In the following section we develop a model that exploits this framework.

THE MODEL

The model proposed here to explain the rather feeble neotectonics of the North Turkish region is an extension of the collision models of McKenzie (1972) and Tapponnier (1977). Figure 3(b), modified from Tapponnier (1977), illustrates the collision of two continents A and B. Continent B has two promontories (P and P′) with an intervening oceanic area. Collision at the promontories P and P′ results in the driving away, from the loci of collision, of continental pieces I, II, I′ and II′ onto the subductable oceanic area. Because the continental pieces I and II and I′ and II′ move towards one another, they undergo E–W compression and accompanying N–S extension that may be partially relieved by the grabens depicted in Fig. 3(b).

The boxed area in Fig. 3(b) corresponds with the situation shown in Fig. 3(a). The North Anatolian fault represents the strike-slip fault separating domains I and II, whereas the fault shown to bound the northern side of I has not developed as a distinct fault zone similar to the North Anatolian fault; nevertheless a seismically active line does delimit a very slow-moving (with respect to Eurasia) Black Sea plate to the north (McKenzie 1972, figs. 2 and 28). It is our contention that although by far the greatest portion of the continental escape from the converging jaws of Arabia and Eurasia is accomplished by the westerly and southwesterly motion of a number of *scholles* (i.e. crustal fragments and splinters that form, as a result of complex strain patterns during continental deformation, and by the virtue of their tectonic nature and behaviour cannot be termed 'plates') concave to the southeast (Şengör in press), comprising nearly all of Anatolia south of the North Anatolian fault. Regions north of the North Anatolian fault also take up a small portion of the N–S convergence along the meridian of eastern Turkey by westerly movement with respect to Eurasia. Because the motion is small, perhaps rather episodic, and probably diffused throughout the region between the North Anatolian fault and the northern shores of the Black Sea, it has not given rise to a distinct, narrow, dextral fault zone to form its limit against Eurasia.

Tapponnier (1977) has argued that the Tethyan ranges lying between the African and Arabian promontories (schematically P and P′, respectively in Fig. 3b) have been under strike-parallel shortening, related to the mechanism illustrated in Fig. 3(b), since the collision of those promontories with Eurasia. Şengör (1979, 1980, in press) has shown that considerable E–W shortening has occurred within what has been inappropriately termed the 'Anatolian plate'. If E–W shortening is also taking place north of the North Anatolian fault as proposed here, albeit on a much smaller scale than in the south, structures associated with this regime (i.e. the 'incompatible' structures) should occur along the North Anatolian fault together with those associated with dextral slip, because the North Anatolian fault as a whole would be moving in a medium being shortened E–W. There is, therefore, no reason to attribute them to a hypothetical reversal of the sense of motion along the North Anatolian fault.

The obvious difficulty this model encounters is the reported observation that the incompatible structures along the fault are confined to sediments older than the late Pleistocene. However, the parallel observation that structures compatible with the present sense of slip were generated throughout much of the history of the fault zone (Hancock & Barka 1981) indicates perhaps that right-lateral motion has been more or less continuous since at least the early Tortonian, whereas E–W compressive phase(s) generating the 'incompatible' structures may have been episodic. But, as the Bartın earthquake clearly shows, the regime responsible for the development of the 'incompatible' structures is by no means extinct. It seems that much more data, of the kind gathered by Hancock & Barka (1980, 1981) are necessary, both within and outside the fault zone, to formulate secure models to account for the origin of the 'incompatible' structures.

There is one additional, very attractive mechanism to account for the origin of incompatible structures of the kind reported by Hancock & Barka (1980, 1981) along major strike-slip faults in general. It may indeed apply to the North Anatolian fault, although from the extant data bank we cannot make a decision concerning its applicability. We discuss it briefly to show that within the framework of our model of continuous right-lateral slip along the North Anatolian fault since the time of its origin, local strike-slip segments with reversed sense of shear can be generated and yet this does not contradict the model of continuous dextral slip along the fault zone as a whole.

Aydın & Nur (1982) have argued that pull-apart basins may enlarge in width by the progressive formation and coalesence of a number of parallel pull-aparts placed side by side. Thus, a number intra-pull-apart strike-slip faults bounding pull-apart-within-pull-apart structures could develop as in the Koehn Lake composite pull-apart basin along the Garlock fault (Aydın & Nur 1982). In a possible geometry such as that illustrated in Fig. 4, if the graben pairs 1 & 3 and 2 & 4 are active alternately, the strike-slip fault segment α would have a sense of motion opposite to that of the main fault during the activity of the pair 2 & 4 (see Dewey 1977). Because pull-apart structures can be much longer than they are wide, as in the Cayman Trough (Macdonald & Holcombe 1978), contrary to the assertion of Aydın & Nur (1982), such graben-linking, intra-pull-apart strike-slip faults may be indistinguishable from parallel strands of the main fault, of the type described by Tokay (1973) from the North Anatolian fault zone between Gerede and Ilgaz. Because, during the reversal of the sense of shear along

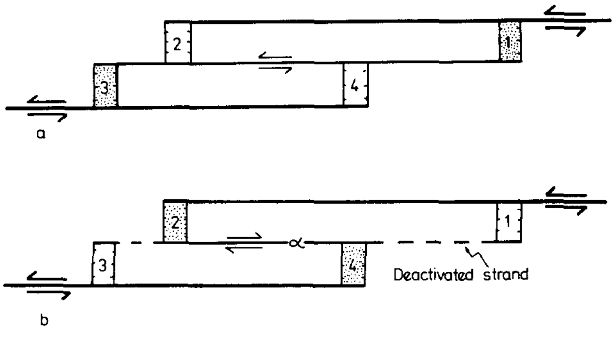


Fig. 4. Pull-apart-within-pull-apart mechanism to accomplish movement reversal along strike-slip fault strands. (a) Shows 'normal' whereas (b) shows reversed motion along the middle strand (α), while movement along the main fault zone remains unchanged. Stippled areas represent active grabens.

an intra-pull-apart strike-slip fault, the sense of movement along the main fault zone is not changed, 'incompatible' structures associated with the intra-pull-apart strike-slip fault can develop simultaneously with 'compatible' structures associated with the strands of the main fault zone, as seems to be the case along the North Anatolian fault (Hancock & Barka 1981).

CONCLUSIONS

(1) During the nectectonic evolution of Turkey, the North Turkish region, defined as that region lying north of the North Anatolian fault and having a transitional, diffuse northern limit, has had a weak, almost intraplate-type tectonic activity and seismicity, characterized dominantly by roughly E–W to ENE–WSW compression and correspondingly NNW–SSE extension, as shown, for example, by the fault plane solutions of the Bartın earthquake. Locally, geomorphological studies indicate areas of increased tectonism in the recent past, as in the case of the deeply entrenched Kocaırmak river (Fig. 1).

(2) Incompatible structures of early Tortonian to early Pleistocene age mapped in basins along the North Anatolian fault in its central segment between Çerkes and Erbaa (localities 1 and 5, Fig. 3a) and indicating ENE–WSW compression accompanied by NNW–SSE extension are interpreted as products of a North Turkish tectonic regime superimposed on those of the strike-slip regime of the North Anatolian fault. Their confinement to the early Tortonian–early Pleistocene Pontus Formation may reflect abrupt intensity fluctuations of the E–W compressional regime and/or inadequate sampling. The postulated reversals of the sense of movement along major segments or the whole of the North Anatolian fault inferred from the presence of the 'incompatible' structures are believed to be unnecessary. Such reversals of the sense of shear may take place, however, along local, intra-pull-apart strike-slip faults, without any change of the sense of motion along the major fault zone.

(3) The roughly E–W compressive neotectonic regime of the North Turkish region is believed to be the result of a limited continental escape westwards from the east Anatolian/Caucasian syntaxis. This westward motion is resisted in the west by crustal segments escaping eastwards from around the African promontory as suggested by Argand (1924) and Tapponnier (1977), resulting in E–W compression. Such movements are extremely small in regions lying north of the North Anatolian fault. Because they are small, the deformation they cause is very similar to intraplate activity both in intensity and distribution (e.g. Sykes & Sbar 1973). Associated neotectonic features are small compared with those in the remainder of Turkey, are discontinuous and display very reduced activity.

(4) Studies on earthquake prediction and nuclear-power plant siting in the North Turkish region must have, as a base, very detailed geomorphological/neotectonic maps to detect areas of past recurrent activity amidst its diffuse, feeble and irregularly distributed neotectonic features.

(5) Great caution should be exercised in interpreting mesoscopic structures indicating apparent abrupt and short-lived reversals along and across large-scale structures in terms of the evolution of the latter. Such 'incompatible' structures often result from local complications (e.g. Jackson *et al.* 1982) or from the superposition and/or interference of two or more overlapping tectonic regimes in which stress orientations are likely to be unstable over very short time intervals as McKenzie (1978) has shown. Real, abrupt and short-lived reversals along major structures, particularly if they are repetitive, are rare events. Many of the observations reported in their favour are artefacts stemming from misinterpretation of field data, as Jackson *et al.* (1982) have shown for the Aegean.

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