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# Three-directional extensional deformation and formation of the Liassic rift basins in the Eastern Pontides (NE Turkey)

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**Abstract:** The Eastern Pontide magmatic arc (NE Turkey) was rifted by the polyphase extensional tectonic regimes in the Early Jurassic. While alternated volcanics and siliciclastic sedimentary rocks accumulated during the episodic tectonic subsidences, thermal subsidence is manifested by sedimentation of the red pelagic limestones of the Ammonitico Rosso during the Pliensbachian. The trends of the Liassic basins extending in NW-SE, E-W, NE-SW directions coincide with the gravity and magnetic lineament anomalies and corresponding fault zones that are responsible for the paleotectonic and neotectonic evolutions of the Eastern Pontide magmatic arc. These mutual relationships suggest that the faults making up the architecture of the Liassic basins might have operated during the Paleozoic, Mesozoic and Cenozoic times in different manners. Neptunian dikes, filled by the early rift siliciclastic and following fossiliferous red pelagic limestone implying the repeated extensional tectonic regimes, are also parallel to the main extensions of the Liassic basins. The poles of the contemporaneous neptunian dikes suggesting two or three extensional conjugate fracture systems are in accordance with the dip directions of the rift sediments accumulated in the same conjugate normal fault systems. Assuming that the Liassic basins with Ammonitico Rosso are coeval, multi-armed rift basins might have opened by the mode of the three-directional extension rather than reactivation of faults in the different times.

**Key words:** Eastern Pontides, Liassic rift basins, extension, gravimetry, magnetics, sedimentary dikes.

## Introduction

The Eastern Pontide orogenic belt extends along the southeastern coast of the Black Sea and comprises three subtectonic units from north to south: the northern (magmatic arc), southern and axial zones (back-arc) (Fig. 1). Jurassic multiple extension within the Eastern Pontide orogenic belt (NE Turkey) caused the formation of a failed triple rift system trending in NW, E-W and NE directions. First Liassic rifting of the magmatic arc is characterized by the asymmetrical half-grabens and accumulation bimodal volcanics and associated coarse clastics. However, during and subsequent to the first rifting, these rift-related basins experienced short-lasting thermal subsidence and so pelagic limestone of Ammonitico Rosso deposited as post rift sediments. The second rifting of the Jurassic began with second alternations of the bimodal volcanics and epiclastics. A following, second long-lasting thermal subsidence caused building up of the Upper Jurassic-Lower Cretaceous carbonate platform on the rift-related sediments. Though there are many sedimentological studies on the Liassic rifting of the Eastern Pontide magmatic arc (Yılmaz et al. 1996 and 2006), tectonic aspects of the rift-related basins are lacking. Therefore we intend to present some geological evidence and the outline of the geophysical properties of the Liassic basins to interpret the kinematic and dynamic analysis of Liassic rifting.

In this article, we also present some evidence for three-dimensional deformation of the Liassic rifting of the Eastern Pontides by using the Liassic neptunian dikes (Bektaş & Çapkınoğlu 1997; Bektaş et al. 2001), dip analysis of the Liassic bedding and possibly fault-related folding.

## The main geological features of the Eastern Pontide orogenic belt

The Eastern Pontides correspond to a part of the active continental margin extending 600 km along the eastern part of the Black Sea coast (Fig. 1). It remains debatable whether the Eastern Pontides were the northern active continental margin of Gondwana during the Cretaceous (Dewey et al. 1973; Bektaş et al. 1984; Bektaş 1986, 1987; Chorowicz et al. 1998), or the southern active continental margin of Eurasia during that time (Şengör et al. 1981; Adamia et al. 1981). According to Bektaş et al. (1999), the Eastern Pontide orogenic belt comprises three subtectonic units, from north to south: the northern (magmatic arc) zone, the southern zone and the axial zone (back-arc) (Fig. 1). Bouger gravity, magnetic and residual gravity

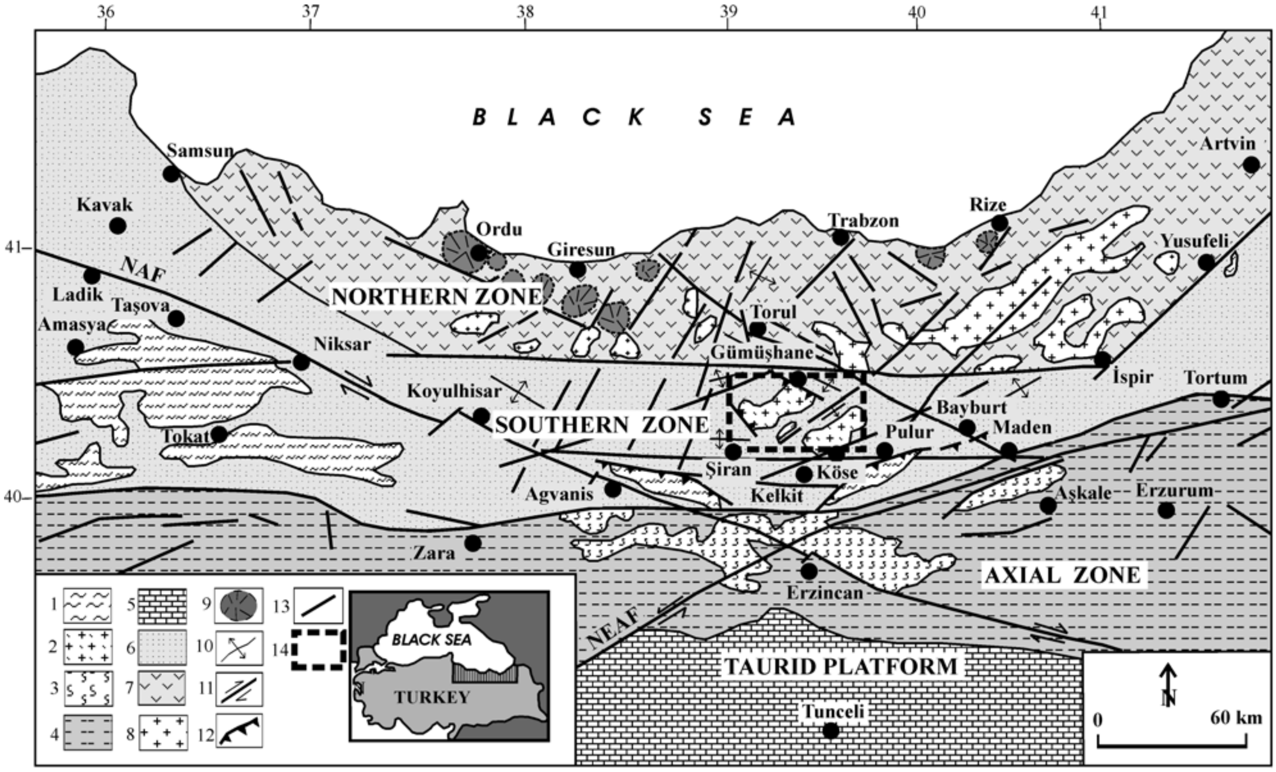

**Fig. 1.** Main tectonic features and tectonic zones of the Eastern Pontides. **1** — Paleozoic metamorphic basement, **2** — Paleozoic granites, **3** — serpentinite, **4** — undifferentiated Mesozoic and Cenozoic rocks, **5** — platform carbonates, **6** — mainly Mesozoic sedimentary rocks, **7** — Cretaceous and Eocene arc volcanics, **8** — Upper Cretaceous and Eocene arc granites, **9** — caldera or dome, **10** — orthogonal drape and drag folds **11** — fault, **12** — thrust fault, **13** — normal fault, **14** — study area. **NAF** — North Anatolian Fault, **NEAF** — Northeast Anatolian Fault.

anomalies (Fig. 8A,B,C) and geological map criteria imply that polygonal networks of the extensional faults with NW, E-W, NE directions are responsible for the formation of the Mesozoic basins in the Eastern Pontides. The blocks of the Hercynian basement in the southern and axial zones such as Agvanis and Pulur metamorphic massifs and Gümüşhane-Köse granites are rhomboid or lozenge-shaped in plan view and are framed by zig-zag shaped paleofault systems (Fig. 1). The alignment of the Upper Cretaceous calderas in the northern zone and of the Kop peridotites in the axial zone, are also controlled by these basement-involved fault systems. The fault framework of NW, E-W, NE directions makes up the block-faulted tectonic style of the Eastern Pontides. Block coupling along these three weakness zones produced a diagnostic en echelon arrangement of the orthogonal drag and drape folds (Schlische 1995), possibly reflecting the trace of the basement fault at the surface. The block fault framework formed the Mesozoic basins in three main distinctive weakness or tectonic zones on the Eastern Pontide magmatic arc evolved on the southward subduction zone of the Paleotethys (Bektaş et al. 1999). Neptunian dikes, exposed near Gümüşhane in the southern zone, were formed by the polyphase rifting of the magmatic arc during the Jurassic and Cenomanian (Fig. 2).

The first rifting is related to the break-up of the granitic basement of the Hercynian whereas the later two were related to the break-up or drowning of the carbonate platform of the Upper Jurassic–Lower Cretaceous (Fig. 2).

## Sedimentological pattern of the Liassic rift basins

During the Liassic, the Eastern Pontides were rifted in NW, E-W, NE directions (Figs. 1 and 3). These multi-directional rift basins are considered to be contemporaneous due to the Ammonitico Rosso facies in each basin. The syn-rift strata of the basins form asymmetric prism indicating deposition in half-grabens (Fig. 4). The prisms contain volcano-sedimentary clastics and pelagic sediments ranging from 0 to 1000 m thickness (Yılmaz 2002). The vertical columns of the rift sediments form two megacycles that thin and become more fine-grained upward (Fig. 2). Each megacycle ended with the accumulation of the red pelagic limestones (Ammonitico Rosso); this is interpreted as reflecting the filling of a marine basin created by faulting. Asymmetry of the sediment prism and facies changing within them indicate the position and dip direction of the normal faults varying in north, northwest, and northeast multi-directions indicating three-directional extensional deformation and formation of polygonal networks of extensional faults.

Field observation carried out in the Gümüşhane (Fig. 3) and Kelkit areas imply that subsidence of the Liassic basins occurred in three stages: (1) an initial phase of the

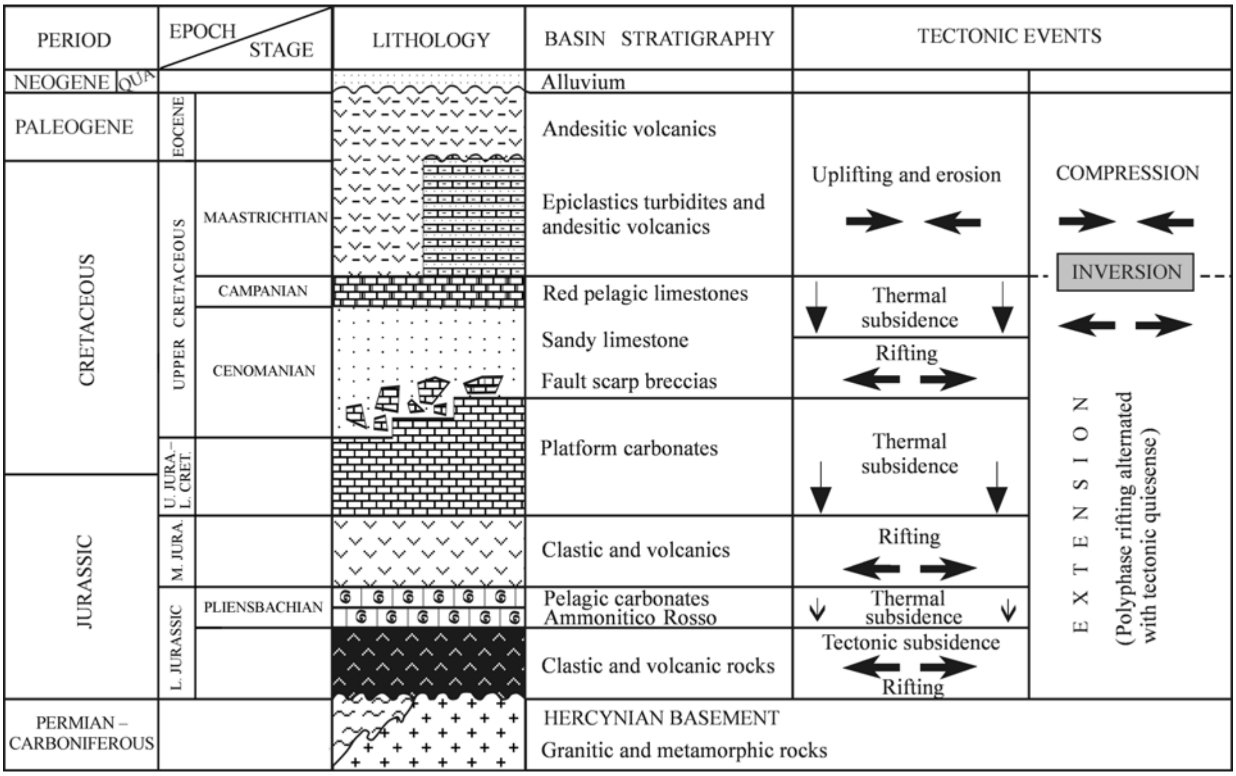

**Fig. 2.** Stratigraphic column showing rifting periods of the Mesozoic and inversion of the Cenozoic in the southern zone of the Eastern Pontides.

stretching or first tectonic subsidence gave rise to tilting of the blocks and formation of the asymmetric basins. As the basal coal-bearing sandstones accumulated in the southern depositional environment of a short-lived swamp area (Ravnas & Steel 1998) near Kelkit, a volcano-sedimentary package accumulated in the northern narrow deep troughs on the northward tilted block in the northern depositional area (Gümüşhane). (2) A subsequent phase of the gradual thermal subsidence, during which the depositional basins expanded to bury the earlier border faults and so progressively younger condensed sediments of Ammonitico Rosso onlapped onto the basement and formed neptunian dikes on the uplifted hanging wall of the normal faults (Fig. 4). (3) Recurrent tectonic subsidence deepened previous basins in which a second level of the coal-bearing sandstones accumulated at the end of the Liassic rifting in the Kelkit area. Failed Liassic rifting ends during the Late Jurassic, and rift-related sediments are overlain by the Upper Jurassic-Lower Cretaceous neritic carbonates during long-lived thermal subsidence (Fig. 2).

## Descriptive analysis of the Liassic neptunian dikes

Neptunian dikes are sedimentary dikes in which the infilling sediments are derived from above, in contrast to some sedimentary dikes with filling injected from below (Winterer & Sarti 1994). The passive continental margins of the Mesozoic Tethys in the circum-Mediterranean region display a great variety of neptunian dikes that are used for understanding the tectonic evolution of these margins (Bektaş et al. 2001). Liassic neptunian dikes, outcropping separately in the Hur and Kırıklı Valleys, 10 km south of Gümüşhane, were developed in the Hercynian granites and metamorphics and also in the early rift-related sandstones implying that Hercynian basement was deformed by the Liassic multiphase extensional regimes (Fig. 3). The dimensions of the mesoscopic neptunian dikes varies from 20 cm to 18 m in length and from 0.5 cm to 40 cm in width in the NW, E-W, NE directions parallel to regional fault systems of the Eastern Pontides. The fact that the granitic wall rocks of the neptunian dikes in the Hur Valley (Gökdere village) are not generally sheared though cross-cutting or conjugate shapes of the neptunian dikes may imply that some of them correspond to shear fractures included in the Paleozoic granites (Fig. 3). Some neptunian dikes are displaced by the younger cracks or faults. All the dikes outcropping in Gökdere village along the granitic contact are filled and covered by the pelagic limestones of Ammonitico Rosso suggesting that neptunian dikes developed during the thermal subsidence of the granitic horsts. Another neptunian dike exposure and some associated calcite veins are seen in an area of 1 $km^2$ on each side of the Kırıklı Valley near Kov village (Fig. 3). They are included in the basement Paleozoic metamorphic rocks and early Liassic sandstones. Successive neptunian dikes are filled with early rift-related sandstone and later pelagic limestones of Ammonitico Rosso

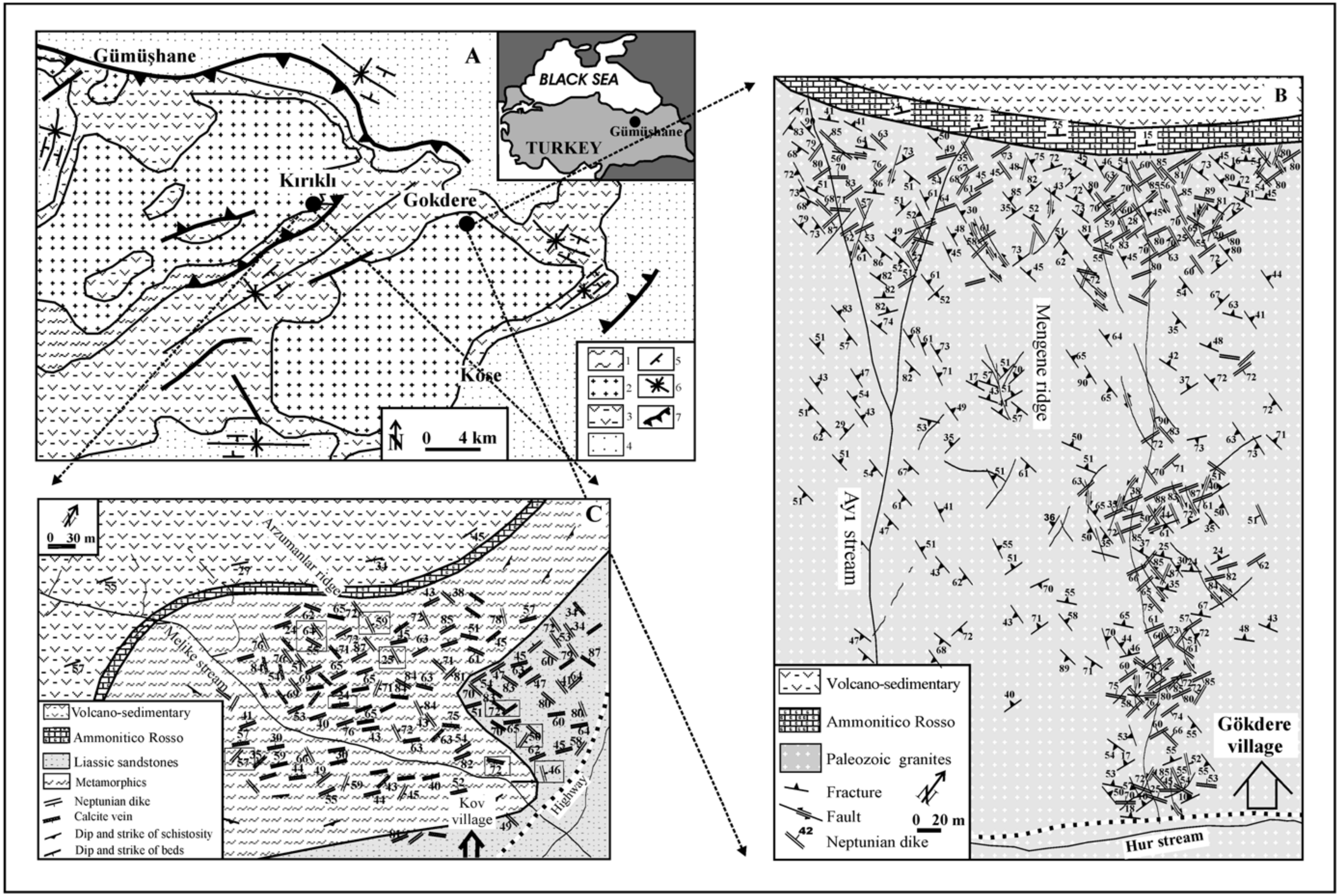

**Fig. 3. A** — Geological map of the Gümüşhane and Köse granites including Mesozoic extensional and compressional fault systems and their longitudinal and transversal drag-drape folds. **1** — Kırıklı metamorphics (Paleozoic), **2** — Gumushane and Kose granites (Paleozoic), **3** — Liassic volcanic and sedimentary rocks, **4** — Mesozoic and Cenozoic rocks, **5** — strike and dip direction of the beds, **6** — orthogonal drag and drape folds, **7** — thrust fault. **B–C** — Neptunian dike maps of the Gokdere and Kov villages, respectively.

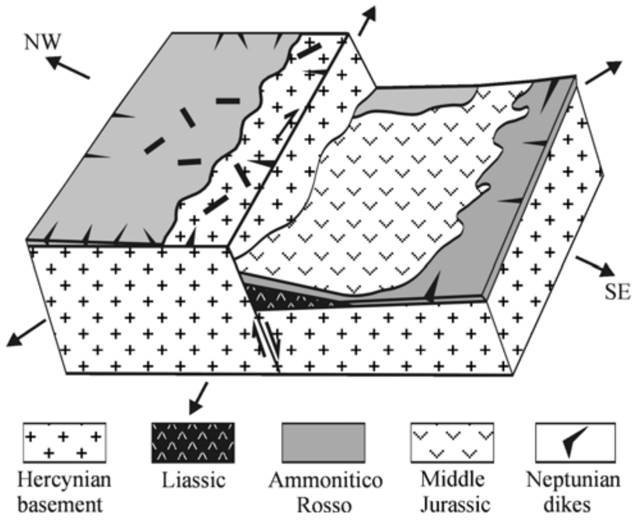

**Fig. 4.** Liassic tectonic and following thermal subsidences resulted in the formation of neptunian dikes in the granitic and metamorphic Hercynian basement.

of the Pliensbachian testifying to alternating extensional tectonic regimes during the Liassic.

## Kinematic and dynamic analysis of the Liassic neptunian dikes

Because joints are kinematically enigmatic structures their interpretation has generated controversy (Hancock 1985). For example, Scheidegger (1983) regards many joints, especially those belonging to orthogonal vertical sets, as shears. The same sets have been interpreted as comprising extensional fractures. If we classify the shape of the neptunian dikes in Hur and Kırıklı Valleys (Figs. 5 and 6), they are grouped as I-shaped (possibly unidirectional extension jointing) and T-shaped (possibly two episodes of the orthogonal systematic extensional joints), and L-, V-, Y-, X-shaped conjugate or hybrid conjugate joints (Hancock 1985). So it might be concluded that neptunian dikes in both areas formed mainly in extensional fractures and less frequently in conjugate fracture systems. On the other hand the mesoscopic fracture systems of the neptunian dikes correspond to the macro-fracture systems of the Eastern Pontides. We interpreted regional extensional directions operating during the Early Jurassic by using the poles of the neptunian dikes in the Hur and Kırıklı Valleys as in the NE, N, and NW directions (Fig. 7). If we assume that two or three conjugate fracture systems of the Liassic neptunian dikes are coeval, these characteristic fracture systems arranged in orthorhombic symmetry (Oertel 1965; Reches 1983a,b) may be caused by three-dimensional strain rather than by multiple phases of faulting or pre-existing basement faults. Synchronous opening of the multi-direction Liassic rifts, in which characteristic limestone of the Ammonitico Rosso accumulated, testify to the triaxial extensional deformation of the Hercynian basement. On the other hand, multi-directional block-edge folds (Fig. 3), dogleg structures, trap-door block and angular unconformity caused by block tilting are evidence for the extensional fault style of the Liassic.

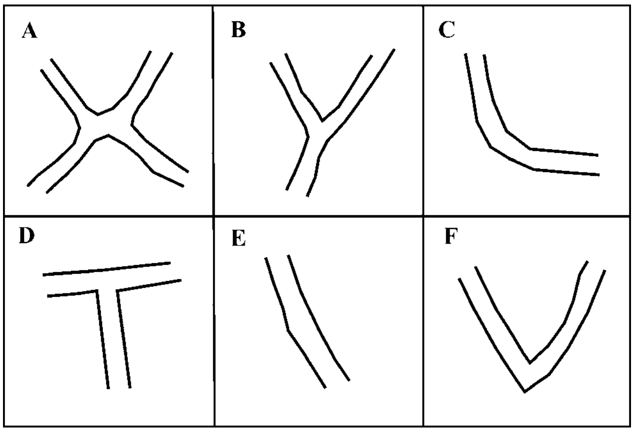

**Fig. 5.** Main geometric shapes of the neptunian dikes exposed in the Gokdere and Kov villages. **A** — X-shaped (Fig. 7E), **B** — Y-shaped, **C** — L-shaped (Fig. 7A), **D** — T-shaped, **E** — I-shaped (Fig. 7B,C,D,F and G), **F** — V-shaped (Fig. 7A).

## The dip direction method as a tool for estimating regional kinematics in extensional terranes

Scott et al. (1995) presented a stimulating and perhaps widely applicable method to determine the regional maximum extensional direction in extensional terranes on the basis of dip direction of the sediments (Ring & Betzler 1995; Moustafa 1996). Though the Eastern Pontide orogenic belt experienced a multi-stage extensional history during the Mesozoic and a reverse reactivation of the normal faults during the Cenozoic (Fig. 2), experimental and theoretical studies (Mandal & Chattopadhyay 1995) have shown that the dip direction of the normal faults and of bedding could not be changed significantly during inversion tectonics. So we established the poles to bedding of the Liassic rift-related sediments, and obtained the mean dip directions or multi-extensional directions as NW-SE, N-S, NE-SW (Fig. 7). These are consistent with those obtained from the neptunian dikes of the Liassic.

## Liassic rifting and inversion

Mesozoic basins in the southern zone of the Eastern Pontides evolved from the Liassic rifting through passive continental margin to the deep troughs with sea-floor spreading of the middle and Upper Cretaceous. Diachronous compressive tectonic regimes are responsible for the closing of these deep basins and inversion of the extensional faults before the Eocene. During inversion tectonics, regional contraction can reactivate pre-existing extensional faults as reverse faults (Cooper & Williams 1989; Williams et al. 1989; Letouzey et al. 1990). However, reverse reactivation may not take place in every do-

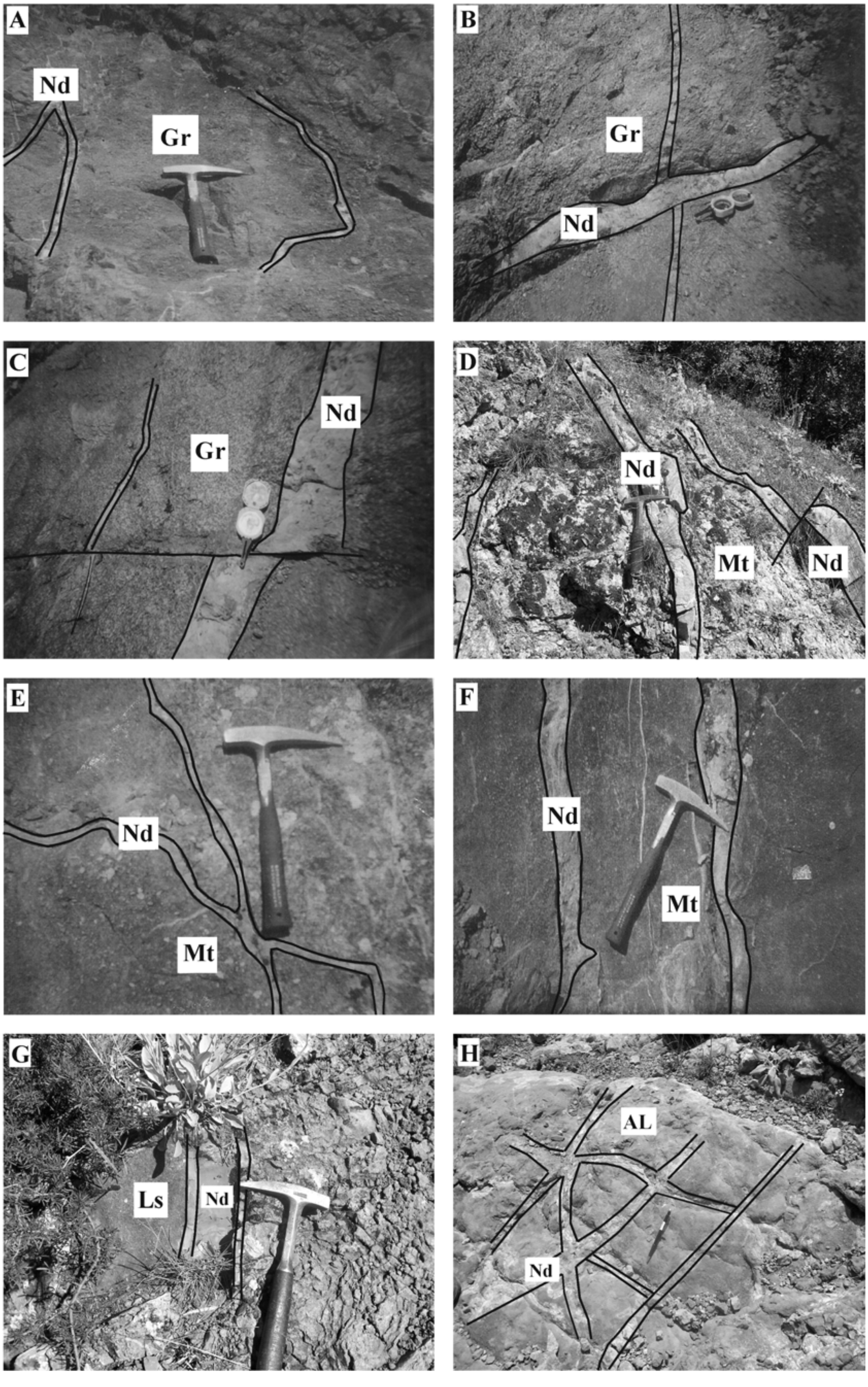

**Fig. 6.** Field photographs of the neptunian dikes. **Gr** — Paleozoic granites, **Mt** — Metamorphic rocks, **Ls** — Liassic sandstone, **AL** — Ammonitico Rosso limestone.

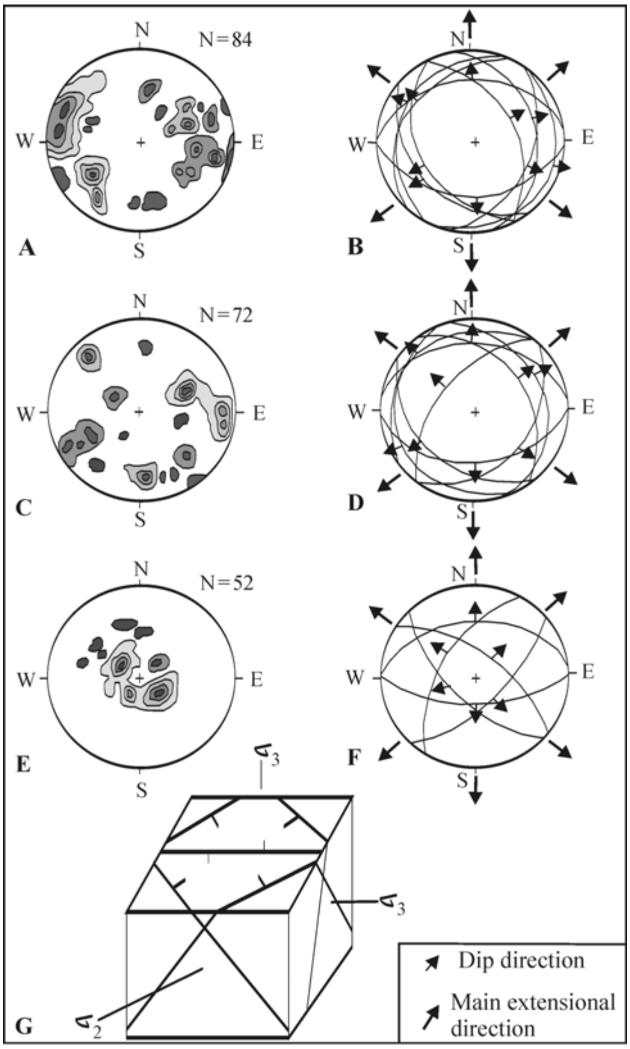

**Fig. 7.** Poles to Liassic neptunian dikes and their mean extensional directions (A and B: Gökdere village; C and D: Kov village). Poles to bedding and mean dip directions for the Liassic rift sediments (E and F). Dip analysis of the Liassic bedding and orientation of the Liassic neptunian dikes may imply three axial extensional deformation and formation of the three pairs conjugate normal faults (G).

main of the thrust belt. Letouzey et al. (1990) have shown that reverse slip occurs along the deeper segments of the normal faults but not along shallower fault segments, which typically dip more steeply. Some field investigations (Hatcher 1981) have shown that many normal faults have not been reactivated, and that contraction is accommodated by new low-angle thrust. Normal faults reactivated only in areas subjected to large extension prior to contraction. Mandal & Chattopadhyay (1995) have shown experimentally that there are two modes of reverse reactivation which depend on dip and spacing of faults. In Mode 1 fault blocks undergo rigid rotation during the late contraction and pre-existing normal faults are reactivated as reverse faults. In Mode 2 faults are reactivated in reverse movements without rigid block rotation. As a result, the dips of faults and layers do not change during contraction. Unlike Mode 1 reactivation, the layers remain tilted even after fault offsets vanish. If we assume that Mode 1 and 2 are applicable methods for the reactivation of the Liassic extensional faults in the Eastern Pontides, we can deduce maximum extensional directions and dip directions of faults in extensional terranes on the basis of dips of the rift-related sediments.

Modern seismicity of the Eastern Pontides is mainly controlled by the faults corresponding to the lineament of the gravity and magnetic anomalies and extensions of the Mesozoic–Cenozoic basins implying that active faults are superimposed on the paleofaults (Figs. 1 and 8). The multiple directions of the Mesozoic–Cenozoic folds have mutual relationships with faults suggesting that the folds were formed by the faults in the extensional and/or compressional deformations.

## Fault-related folding in the Eastern Pontides

Fold orientations in NW, E-W, NE-SW, that are parallel to the fault systems are the main characteristic features of the Eastern Pontide structural style. This mutual relationship between faults and folds strongly suggests that folds were formed by the extensional and compressional fault systems during the opening and closing of the Mesozoic and Cenozoic basins, respectively. The overall size, shape, and trend of the fold in the Mesozoic and Cenozoic sediments reflects the size, shape, and trend of the basement blocks, such as the Hercynian Gümüşhane-Köse granites around Gümüşhane city (Fig. 3). On the other hand, the reactivation of synrift normal faults of the paleo-Atlas rifts inverted previous half-grabens into anticlinal structures, with the axis of the half-graben centred below the axis of the inverted anticline. The resulting inverted fold geometries are controlled by the geometries of the extensional planar or listric faults (Beauchamp et al. 1996). Therefore, if we take into account the opening and closing of the Liassic grabens extending in the NW-SE, E-W, NE-SW directions, it can be concluded that longitudinal Liassic synclines and anticlines in the same directions as faults, may correspond to the Liassic extensional folding and formation of the half-grabens (drag folds or rollover folds, Schlische 1995) and to later compressional folding and closing of the half-grabens (Mitra 1993).

## Interpretation of the gravity and magnetic anomaly maps of the Eastern Pontide orogenic belt

The characteristic magnetic and gravity features of the Eastern Pontides orogenic belt are summarized as follows:

1 — The large variations in amplitude and steep gradients in both gravity (Bouger and residual gravity map) and magnetic data define distinct northern, southern and axial zones, as seen in the geological map of the Eastern Pontides, and are compatible with the structures of the block fault tectonics (Fig. 1).

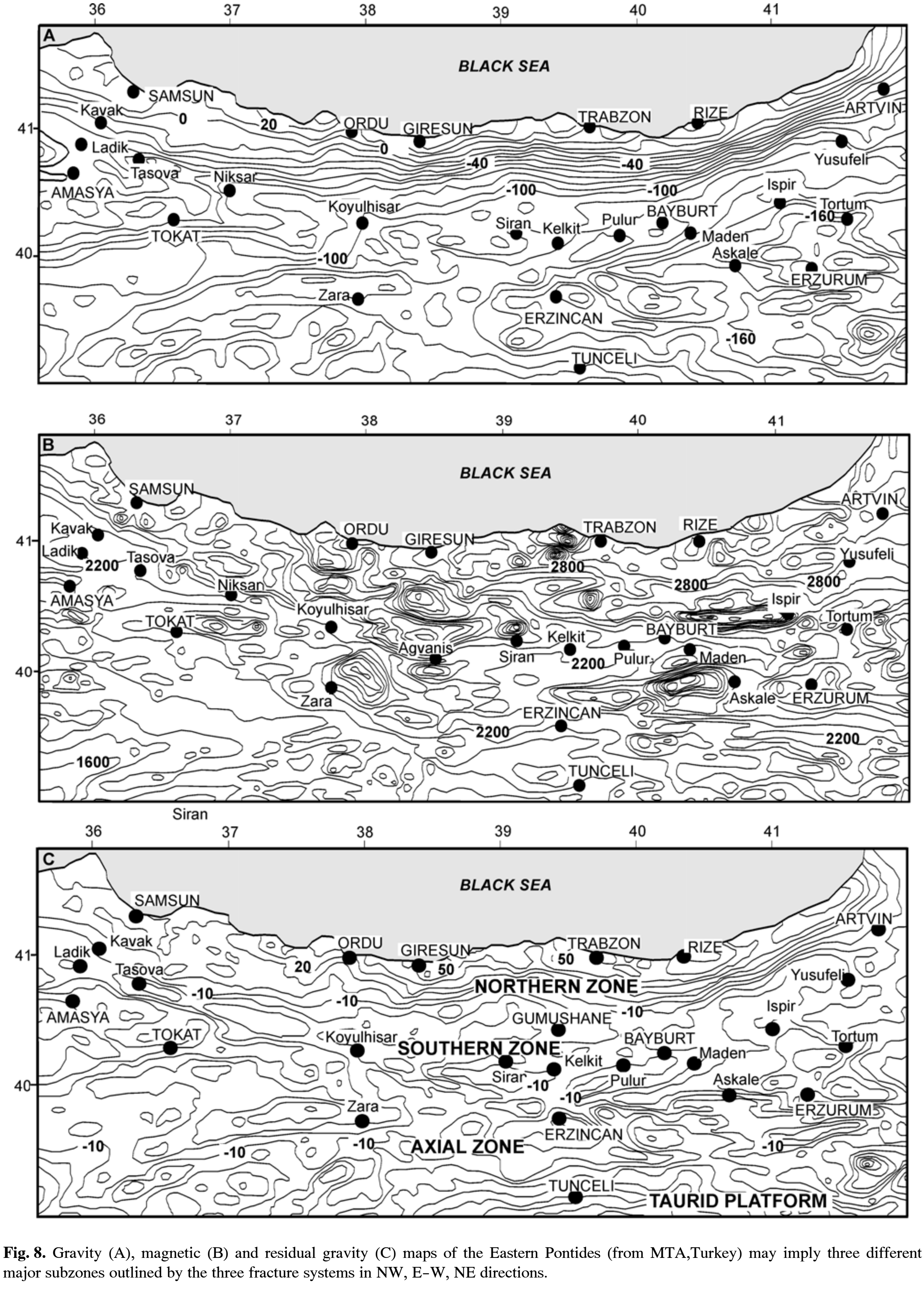

**Fig. 8.** Gravity (A), magnetic (B) and residual gravity (C) maps of the Eastern Pontides (from MTA,Turkey) may imply three different major subzones outlined by the three fracture systems in NW, E–W, NE directions.

2 — In contrast to the southern zone, which has negative residual gravity anomalies, the northern and axial zones have positive residual gravity anomaly. These imply that the Eastern Pontide orogenic belt had horst and graben structures or block-fault tectonics in Mesozoic and Cenozoic times (Fig. 8C).

3 — Lineaments which are expressed as linear magnetic and gravity anomalies in NW, E-W, NE directions are interpreted as originating from fault zones. The trends of the fault zone are parallel to the ultramafic, metamorphic and granitic massifs implying that the emplacements of the massifs are controlled by these faults.

4 — Basins of the Mesozoic and Cenozoic correspond to the magnetically calm areas which constitute the belts, a maximum of 30–40 km wide and 100–150 km long, in NW, E-W and NE directions. They coincide approximately with the edge of the blocks as defined by the gravity anomalies.

5 — A series of strong positive circular magnetic anomalies are seen especially in the northern zone. They are clearly granites and/or calderas that have been emplaced along the zones of faults.

## Discussion and conclusion

Models of rift basins commonly depict a relatively simple geometry produced during a single, sometimes protracted episode of extension (Gibbs 1987).

In recent years, many studies show four or six sets of faults with orthorhombic symmetry (Freund & Merzer 1976; Reches 1983a) or a zig-zag and polygonal pattern of normal faults in extensional regions (Lonergan et al. 1998; Lonergan & Cartwright 1999; Nieto-Samaniego 1999; Tikof & Fossen 1999). Such patterns are also observed from small-scale faults to the regional zig-zag pattern of the rift valleys (Collby & Susanne 1998). These patterns of faults were classically explained as the results of multiple phases of faulting or as being due to pre-existing basement faults. However, in some cases penecontemporaneous development of three or four sets of faults is either evident or very probable. Such a fault pattern was produced by (Oertel 1965) in a clay cake subjected to stretching in a three-dimensional strain field. Similarly, Reches (1983b) produced such patterns in cubes of sandstone, granite and limestone that were subjected to compression in a three-dimensional field. According to Reches's slip model, fault patterns such as defined above can form in a single phase of faulting, as the effect of a three-dimensional strain field. As three-dimensional states of strain are common in nature, it seems that the present analysis of the zig-zag shaped Liassic faulting of the Eastern Pontides (Fig. 1) is an appropriate approach for the interpretation of faults in the field.

The Eastern Pontide magmatic arc was rifted in NW, E-W and NE multi-directions during the Early Jurassic. As the characteristic red pelagic limestones of the Ammonitico Rosso deposited at the same stratigraphic level in the zig-zag shaped rift basins, it is considered that the openings of the rift system with multi-directions were synchronous. Distributions of the poles to the Liassic neptunian dikes filled and covered with Ammonitico Rosso imply that extensional deformation of the Liassic rift basins occurred in a three-dimensional strain field rather than multiple phases of the faulting. Extensional block tilting and dip direction of the Liassic sediments in NW-SE, N-S, NE-SW directions testify that Liassic rifting occurred by three pairs of conjugate normal faults parallel to the multi-direction rift, or three-directional deformation is responsible for the Liassic rifting.

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