Late Cretaceous–Early Cenozoic tectonic evolution of the Eurasian active margin in the Central and Eastern Pontides, northern Turkey

SAMUEL P. RICE[1,2], ALASTAIR H. F. ROBERTSON[1] & TIMUR USTAÖMER[3]

[1]*Grant Institute of Earth Science, School of GeoSciences, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, UK*

[2]*Present address: CASP, Department of Earth Sciences, West Building, 181a Huntingdon Road, Cambridge CB3 0DH (e-mail: sam.rice@casp.cau.ac.uk)*

[3]*Istanbul University, Jeoloji Bölümü, Mineralojı-Petrografi Anabilim Dalı, 34850, Avcılar Istanbul, Turkey*

Abstract: The Izmir–Ankara–Erzincan suture zone (IAESZ) in the Central and the Eastern Pontides comprises a stack of thrust sheets of mainly Late Cretaceous–Early Cenozoic age that are restored as: (1) a subduction–accretion complex; (2) a continental-margin magmatic arc, plus an associated forearc basin; (3) a back-arc basin and its mainly sedimentary fill. Northward thrusting affected all of the Late Cretaceous units during latest Cretaceous (Campanian–Maastrichtian) time. This was followed by regional southward thrusting to form the present thrust stack during Mid-Eocene time. Alternative tectonic models are considered in the light of sedimentary, igneous geochemical and structural evidence, and global comparisons. We infer that the Northern Neotethys was subducted northwards beneath the Eurasian active margin during the Late Cretaceous. Subduction was associated with the genesis of a magmatic arc and a related forearc basin. The subduction zone retreated oceanwards, associated with the opening of a back-arc basin along the Eurasian margin, floored by oceanic crust and overlain by mixed terrigenous and volcaniclastic deep-marine sediments. Ophiolite genesis in a continental margin back-arc setting is suggested by the presence of screens of basement-type metamorphic rocks within an ophiolite-related sheeted dyke complex in the Eastern Pontides. During the latest Cretaceous closure of the inferred back-arc basin resulted in northward emplacement of ophiolitic and related units onto the Eurasian margin, as well exposed in the Central Pontides. In addition, accretionary mélange, volcanic arc, forearc and ophiolitic units were emplaced southwards onto the Tauride continent, represented by the Munzur platform in the Eastern Pontides, also during latest Cretaceous time. This incipient ('soft') collision was followed by widespread Paleocene–Early Eocene deposition of Nummulitic shelf carbonates and coarse clastic sediments on deformed and emplaced accretionary mélange, arc and ophiolitic units. Final closure ('hard collision') of the Northern Neotethys occurred during the Mid-Eocene, resulting in large-scale southward imbrication, together with northward backthrusting in some areas. Suture tightening and Plio-Quaternary strike-slip ensued.

During recent years most studies of the origin and emplacement of Tethyan ophiolites have focused on South Tethyan settings, where oceanic lithosphere (e.g. Semail and Troodos ophiolites) was emplaced onto Gondwana and its satellite microcontinents (e.g. Robertson 2002; Garfunkel 2006; Koller *et al.* 2006; Rassios & Moores 2006; Smith 2006). Many of these ophiolites formed in a suprasubduction-zone (SSZ) setting within a Southern Neotethyan oceanic basin (e.g. Parlak *et al.* 2004; Rızaoğlu *et al.* 2006). There have been few studies of ophiolites and related units that were formed in more northerly Neotethyan oceanic basins (Northern Neotethys) and emplaced onto the Eurasian continental margin. The Eurasian margin exhibits a long history of tectonic and magmatic events that can be mainly related to active margin processes, including subduction, accretion and arc volcanism (Şengör & Yılmaz 1981; Robertson & Dixon 1984; Dercourt *et al.* 1986; Stampfli *et al.* 2001).

Several workers have recognized that ophiolites were emplaced in the Pontides during Late Cretaceous–Early Cenozoic time and alternative tectonic scenarios have been proposed (Bergougnan 1975; Yılmaz 1985; Koçyiğit 1990; Tüysüz 1990; Okay & Şahintürk 1997; Ustaömer & Robertson 1997; Yılmaz *et al.* 1997). However, information on the age, structure and geochemistry of these units has remained sparse. To help address this deficiency we have studied the Izmir–Ankara–Erzincan suture zone (IAESZ) in two

From: ROBERTSON, A. H. F. & MOUNTRAKIS, D. (eds) 2006. *Tectonic Development of the Eastern Mediterranean Region*. Geological Society, London, Special Publications, **260**, 413–445.
0305-8719/06/$15.00

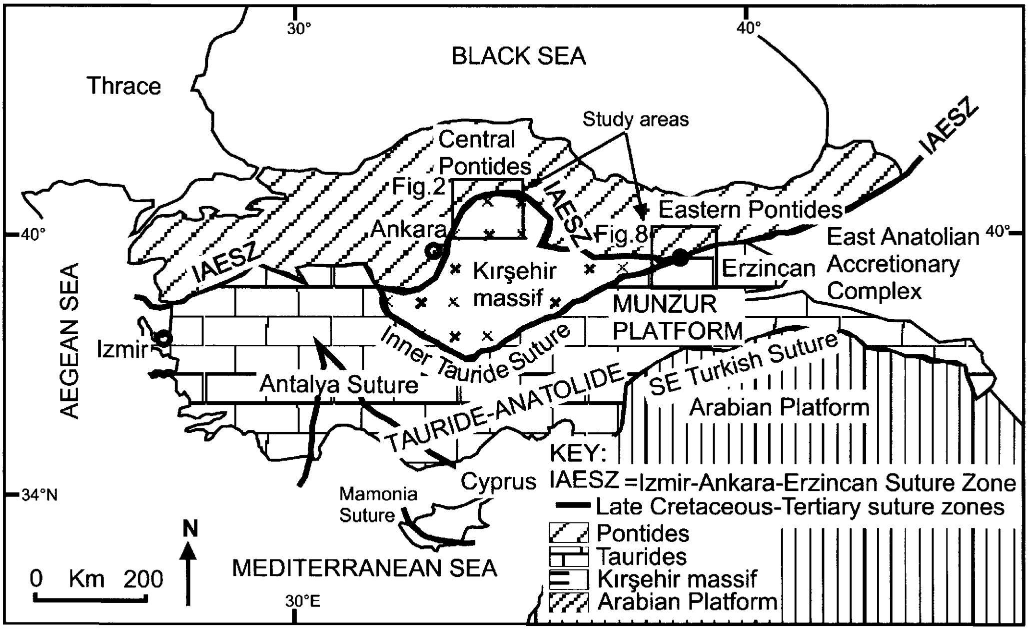

Fig. 1. Outline geological map of Turkey showing the regional settings of the Central and Eastern Pontide areas studied (marked with boxes).

specific areas of the Central and Eastern Pontides (Fig. 1).

The IAESZ separates Gondwana-derived (i.e. Tauride–Anatolide) blocks from Eurasia (i.e. Pontides) and records the closure of the main oceanic strand of the Northern Neotethys ocean (Şengör & Yılmaz 1981; Robertson & Dixon 1984; Dercourt *et al.* 1986; Okay *et al.* 2001). This suture zone is well exposed as a dominantly south-vergent thrust belt running across northern Anatolia (Fig. 1). In the north, Late Mesozoic units of the IAESZ are tectonically imbricated with Eurasia-related metamorphic basement rock, represented by the Karakaya Complex and related units. In the south these units structurally overlie continental units that were rifted from Gondwana, including the Munzur Platform (part of the Tauride–Anatolide Platform) in the Eastern Pontides, and the Kırşehir Massif (probably a separate microcontinent) in Central Anatolia (Fig. 1).

In this paper we will combine sedimentary, igneous, structural and palaeontological evidence to infer the tectonic settings of formation of the various units of mainly Late Cretaceous–Early Cenozoic age within the suture zone. More detailed information (e.g. detailed maps, sections and logs) has been given by Rice (2005). We will propose an interpretation involving northward subduction beneath the Eurasian margin during Late Cretaceous time, coupled with arc volcanism and the opening, then closure, of a marginal basin. We will also draw comparisons with modern and ancient marginal basins. The recently published time scale of the International Commission on Stratigraphy (Gradstein *et al.* 2004) is used throughout. Existing formation names are retained wherever possible but new names are introduced in several cases.

Central Pontides

Seven main tectonostratigraphic units of mainly Late Cretaceous age are identified in a well-exposed area of the Central Pontides (Fig. 2), as summarized below in upward structural order. Each of these units is bounded by south-vergent thrusts and is unconformably overlain by Neogene–Recent units.

Eskiköy Formation: cover of Pontide basement

The Eskiköy Formation (new name; Fig. 3a) (*c.* 150 m thick) rests with a low-angle unconformity on a thin unit of pisolitic bauxite that caps the schistose metamorphic basement of the Pontides (Kargı Complex; Ustaömer & Robertson 1997). This formation begins with thickly bedded

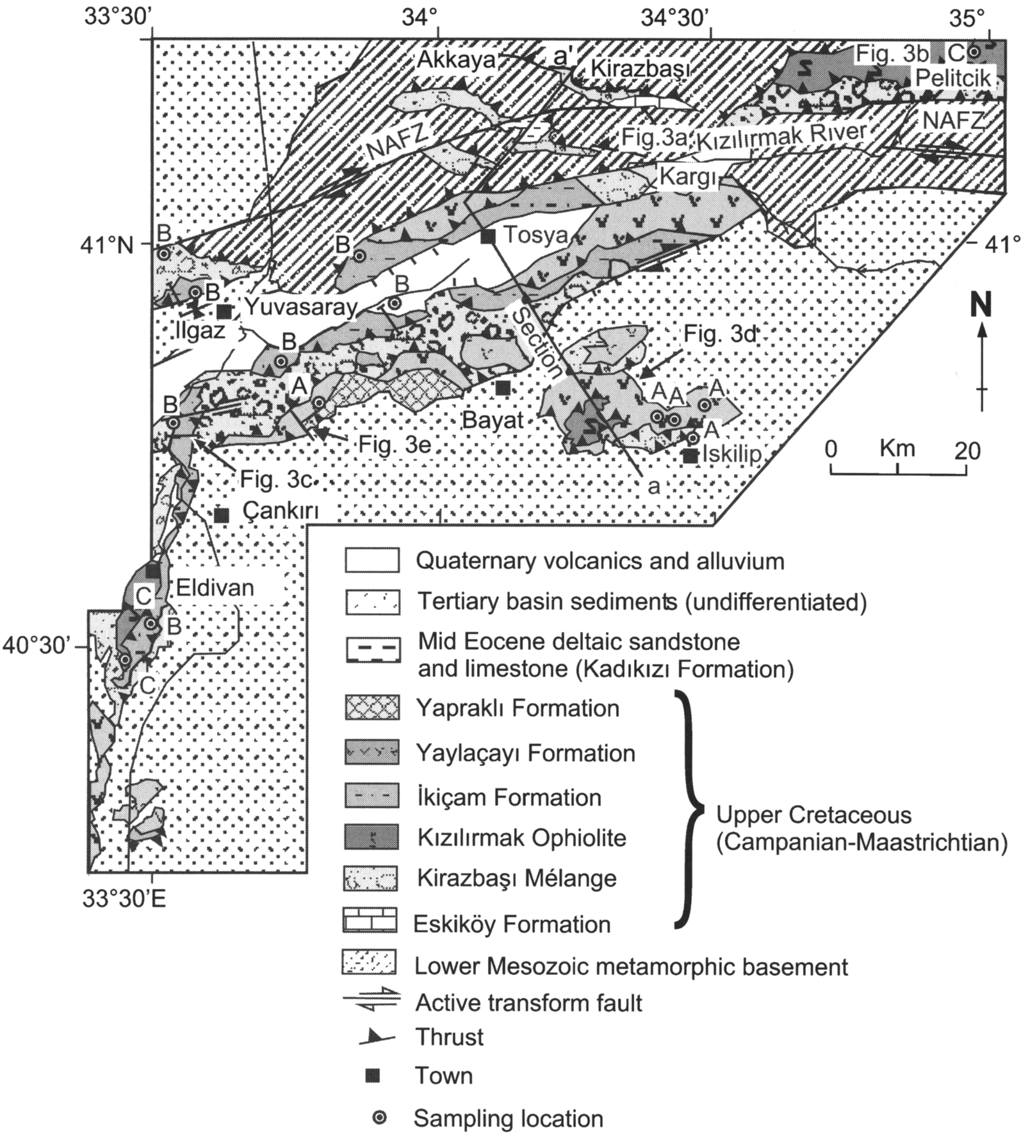

Fig. 2. Simplified geological map of the Central Pontides (see Fig. 1 for location). The locations of measured logs are shown (see Fig. 3a–e), also the line of section a–a' (see Fig. 4). The locations of sites sampled for geochemical analysis by XRF are also marked: A, Yaylaçayı Formation: B, İkiçam Formation: C, Kızılırmak Ophiolite (see also Fig. 6 and text for discussion).

(50 cm), grey microcrystalline pelagic limestones, *c.* 10 m thick, that contain planktonic Foraminifera (e.g. *Globotruncana* sp.) of Campanian age (Tüysüz *et al.* 1988). Sheared and isoclinally folded turbiditic sandstones with shaly partings, *c.* 150 m thick, include occasional poorly sorted, matrix-supported conglomerates (debrites). The sandstones exhibit flute casts and *Thalassinoides* sp. bioturbation. The conglomerates contain well-rounded pebbles of paraquartzite, presumably derived from the Pontide basement to the north. In thin section, the sandstones contain polycrystalline quartz, schistose lithoclasts and detrital white mica, indicating a metamorphic source. The succession passes upwards into thin-bedded red shale and radiolarian chert. Towards

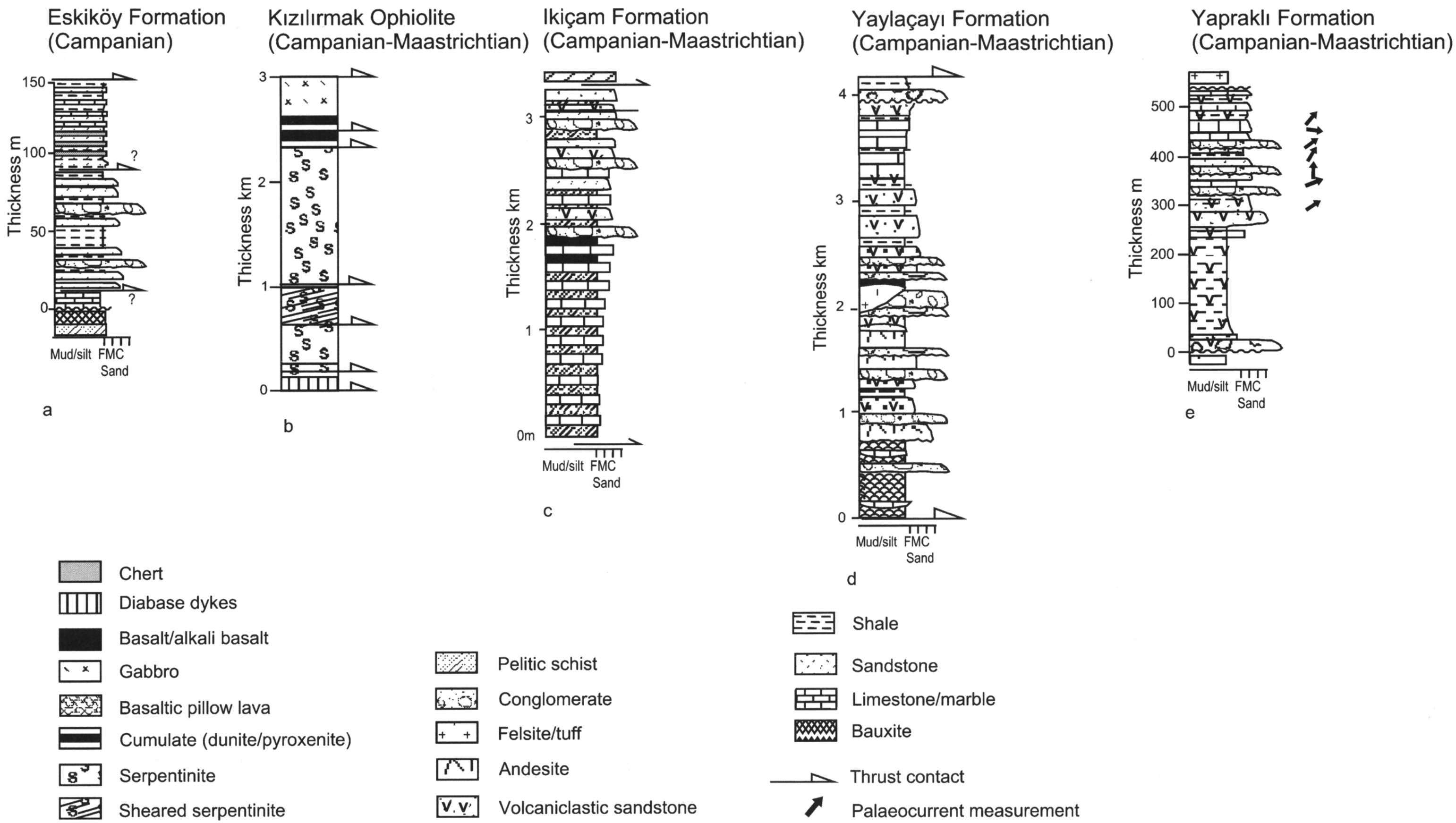

Fig. 3. Composite logs (**a**–**e**) of the Upper Cretaceous sequences in the Central Pontides, arranged from left to right according to structural position (**a**, highest; **e**, lowest). The differences in scale of individual logs should be noted. (See Fig. 2 for locations.)

the top of the formation the sediments are thrust-imbricated with ophiolitic mélange (Kirazbaşı Mélange; see below). The Eskiköy Formation is also exposed as thin (*c.* 40 m) thrust slices within more northerly outcrops of the mélange (e.g. near Ilgaz; Fig. 2).

The pelagic lower part of the Eskiköy Formation is interpreted to record subsidence of the Eurasian margin during Campanian time (83.5–70.6 Ma). The terrigenous gravity-deposited sediments were shed from the Pontide basement into a subsiding deep-water basin. This was probably a flexurally controlled foredeep, associated with the northward emplacement of ophiolites and related units onto the Eurasian margin.

Upper Cretaceous Kızılırmak Ophiolite

The Kızılırmak Ophiolite (Tüysüz 1990), *c.* 3.5 km thick, occurs at several different structural levels within the thrust stack (Figs 2 and 4). Outcrops of deformed ophiolitic rocks, 2–5 km thick, are found near Bayat and Eldivan, and also along the banks of the Kızılırmak River, at Pelitcik, near Kargı (Fig. 2). The ophiolitic complex includes serpentinized harzburgite, cumulate pyroxenite, dunite, isotropic and layered gabbro, and deformed greenschist-facies metabasaltic pillow lava (Fig. 3b). A Campanian–Maastrichtian age (83.5–65.5 Ma) for the ophiolite is indicated by the presence of *Globotruncana linneiana* (d'Orbigny) within pelagic limestones interbedded with basaltic pillow lavas (Tüysüz 1990) that are well exposed along the Kızılırmak river valley, north of Kamil (Aşıkbükü–Yukarı Zeytin section). Basalt from this locality was collected for analysis (see below).

The Kızılırmak Ophiolite is interpreted as an incomplete section of oceanic lithosphere of Late Cretaceous age. Supporting geochemical evidence is presented later in the paper.

Upper Cretaceous İkiçam Formation: marginal basin sediments

A very thick sedimentary unit, the İkiçam Formation (new name; >3000 m thick), is found within the middle to upper structural levels of the imbricate thrust stack (Fig. 4). A Late Cretaceous (Campanian–Maastrichtian) age is indicated by the presence of several species of *Globotruncana* (İ. Öngen, pers. comm.). The lower part (*c.* 2 km) of the formation comprises thinly bedded (beds <4 cm), buff-coloured micritic, to muddy limestones with thin grey pelitic schist partings and tuff (Fig. 3c). Higher levels of the succession comprise coarser-grained quartzo-feldspathic sandstones, volcaniclastic sandstones and sericitic shales. There are also interbeds of turbiditic calcarenites that contain volcanic grains and feldspars of probable magmatic origin (Fig. 5). Grains of undeformed quartz, polycrystalline quartz (i.e. quartzite) and schistose lithoclasts are also present. In the north the succession includes occasional igneous sills, massive lava flows and rare pillow lavas, as seen near Tosya (see below for chemical analysis). The lavas contain large (<2 cm) phenocrysts of biotite, analcite and salite (alkali pyroxene), suggesting a markedly alkaline composition. In the south the İkiçam Formation interdigitates with andesitic lavas and coarse andesitic volcaniclastic conglomerates and sandstones, correlated with the Yaylaçayı Formation, an Upper Cretaceous inferred volcanic arc unit, also exposed near Tosya (see below; Fig. 2). The more basic extrusive rocks within the İkiçam Formation were collected for chemical analysis (see below). However, extrusive rocks in the south are chemically too evolved to allow geochemical discriminant analysis, although their tectonic setting of eruption can be inferred from an interfingering relationship with the Yaylaçayı Formation inferred arc unit. The İkiçam Formation is unconformably overlain by sediments of Late Eocene or or younger age, which were deposited after the inferred suturing of the Northern Neotethys.

The Upper Cretaceous İkiçam Formation represents a volcanically active deep-water slope setting, with an increasing abundance of texturally immature volcanic and terrigenous sediments upwards. The turbiditic sandstones range from terrigenous, to volcaniclastic and calcareous in composition. The Pontide metamorphic basement to the north is the obvious source for the terrigenous material. The polycrystalline quartz is interpreted as metachert derived from pre-Jurassic accretionary complexes in the Pontides (Ustaömer & Robertson 1997). Deposition was accompanied by sparse alkaline–peralkaline volcanism in the north that could be extension related. In addition, the basaltic–andesitic composition of the interfingering volcanic rocks and coarse sediments in the south suggests that this material was derived from an adjacent magmatic arc unit. Overall, the İkiçam Formation is interpreted as the emplaced sedimentary–volcanic fill of a deep-water back-arc basin that formed between the Pontide continental margin to the north and an active volcanic arc to the south.

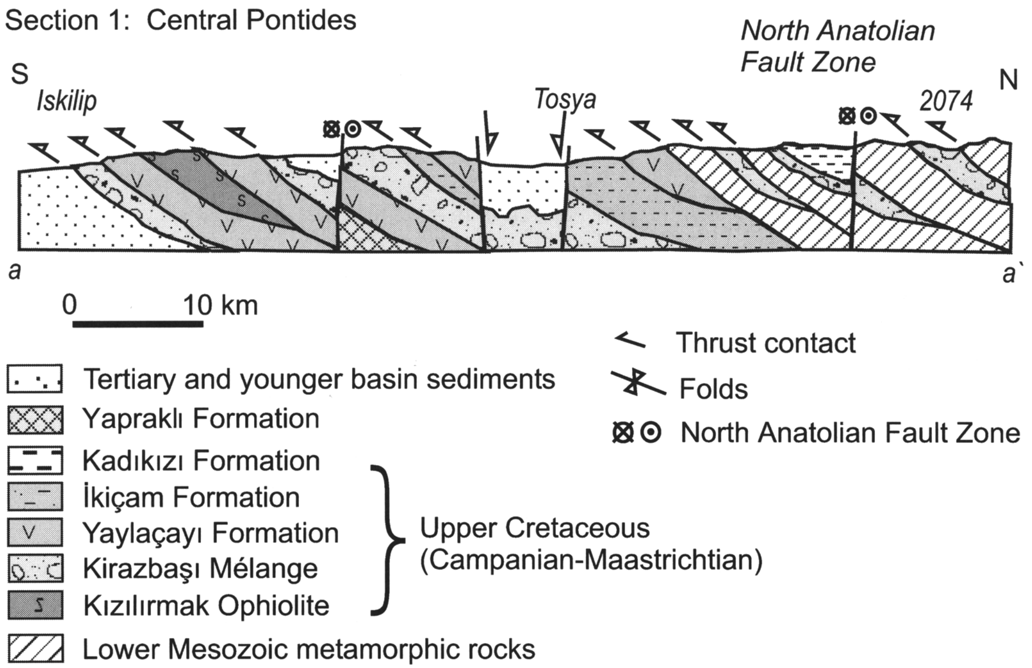

Fig. 4. Cross-section showing the main structural and stratigraphic relations in the Central Pontides. (See Fig. 2 for line of section). It should be noted that some variation is present along strike (see Fig. 2).

Upper Cretaceous Yaylaçayı Formation: volcanic arc unit

Two major thrust slices of volcanic and volcaniclastic rocks, each up to *c.* 4 km thick, occur at two different structural levels (Figs 2–4). The presence of several species of *Globotruncana* within interbedded sediments indicates a Late Cretaceous (Campanian–Maastrichtian) age for this unit (Tüysüz *et al.* 1995).

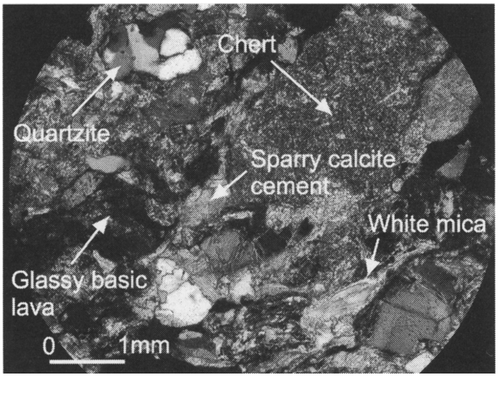

Fig. 5. Photomicrograph of Upper Cretaceous sandstone from the İkiçam Formation. The presence of terrigenous material (white mica, quartzite), glassy basic lava and chert should be noted.

The Yaylaçayı Formation (Yoldaş 1982) begins with basaltic pillow lavas and pelagic interpillow sediments and passes gradually upwards into a very thick succession (up to 3500 m in apparent thickness) of andesitic lava and coarse matrix-supported volcaniclastic conglomerates (Fig. 3d). Both the clasts and the matrix of these conglomerates are of intermediate composition, based on petrographic evidence. Felsic volcanic rocks, intrusive rocks and altered tuff are present in lesser amounts. Stratigraphically higher levels are dominated by volcaniclastic sandstones and shales that grade into pale grey thinly bedded shaly and micritic limestones. At higher levels of the thrust stack volcaniclastic and metavolcanic schists, also attributed to the Yaylaçayı Formation, exhibit well-developed metamorphic fabrics and a greenschist-facies mineral assemblage (i.e. epidote, talc, quartz, albite). The highest stratigraphic levels of the formation are transitional to pelagic limestones with *Globotruncana* in the İskilip area, whereas further west near Çankırı (Fig. 2) the formation is unconformably overlain by a shallow-marine sedimentary cover (Yapraklı Formation; see below).

Within the Yaylaçayı Formation, the volcanic rocks become generally more evolved stratigraphically upwards, from basaltic, to andesitic, then felsic (e.g. rhyodacite). Pelagic sediments are present between pillow lavas low in the succession but above this texturally immature volcaniclastic sediments predominate.

The formation is interpreted to record a fragment of a volcanic arc, which developed away from a supply of terrigenous sediment. A gradual passage from volcanic rocks to volcaniclastic sediments records a waning of volcanism, or a switch in the locus of volcanism to a more distal location. The arc edifice was eroded following cessation of volcanism. The pelagic limestones at the top of the Campanian–Maastrichtian succession indicate a reduced supply of volcaniclastic material, possibly caused by cessation of arc magmatism, tectonic subsidence, or a eustatic relative sea-level rise.

Upper Cretaceous Yapraklı Formation: arc apron–forearc basin

A sedimentary cover unit up to 500 m thick, known as the Yapraklı Formation (Birgili *et al.* 1975), unconformably overlies the arc-related Yaylaçayı Formation, as exposed near Çankırı (Figs 2 and 3e). A Late Cretaceous (Campanian–Maastrichtian; 83.5–65.5 Ma) age is indicated by the presence of planktonic foraminifera, including *Globotruncana linneiana* (d'Orbigny) (İ. Ongen, pers. com.). The formation begins with a thin basal conglomerate (*c.* 3 m), followed by grey volcaniclastic shales. The shale passes upwards into thick-bedded, coarse-grained calcarenites, volcanogenic shales, thick-bedded volcaniclastic sandstones and conglomerates, with minor grey fissile shaly partings. These sediments contain poorly sorted grains of mafic- and intermediate-composition volcanic rocks, quartz, feldspar, glauconite and abundant calcareous shell fragments. The detrital grains within individual samples range from subangular to well rounded and show evidence of textural inversion (i.e. well-rounded but poorly sorted grains). Large bivalves (< 10 cm; probably rudists) are locally present. Individual beds, up to 1.5 m thick, are commonly massive or graded and contain subrounded pebbles and boulders of feldspar-phyric andesite (up to 40 cm in diameter).

The unconformable base of the succession and the thin basal conglomerate together indicate that at least some erosion of the underlying volcanic arc unit has occurred, probably in a subaerial setting. This was followed by re-submergence and fine-grained deposition. The upward change from homogeneous grey shales to texturally immature lithologies suggests a relatively proximal source for the volcaniclastic and carbonate material. The large bivalves, well-rounded grains and the presence of glauconite suggest a shallow-marine setting. However, the existence of textural inversion confirms that some redeposition has occurred. The clastic sediments probably formed from sheet-like density flows within broad (*c.* 30 m) submarine channels. By contrast, the nature of the fine-grained shaly partings suggests low-energy background accumulation in a relatively deep-water setting. Measurements of cross-laminations and pebble imbrication yielded (dip-corrected) palaeocurrent directions towards the NE (Fig. 3e).

The Upper Cretaceous Yapraklı Formation is interpreted as part of the northern edge of a forearc basin that is mainly buried beneath the younger Çankırı Basin to the south (Kaymakçı 2000). Contemporaneous volcanogenic material (e.g. air-fall tuff) is absent. This unit probably records reworking of arc-derived material after arc volcanism had ended (at least locally), but prior to final tectonic emplacement. The shallow-water carbonate, including large bivalves, was derived from carbonate build-ups on, or around, arc edifices that were partially eroded after volcanism ended. Terrigenous sediment (e.g. metamorphic quartz) is notably absent, in common with the underlying arc unit.

Upper Cretaceous Kirazbaşı Mélange: ophiolitic mélange

An ophiolitic mélange unit, the Kirazbaşı Mélange (Tüysüz 1990), is widely distributed throughout several structural levels of the suture zone (Figs 2 and 4). In the north the mélange tectonically overlies the Upper Cretaceous Eskiköy Formation, interpreted above as a foredeep succession. The mélange is overlain unconformably by Eocene Nummulitic limestones and fluvio-deltaic sandstones; these belong to the Kadıkızı Formation, which postdates suturing. The mélange exhibits a block-against-block fabric without any matrix of sedimentary origin.

The most common lithologies of the mélange are serpentinized ultramafic rocks, basalt–metabasalt, dolerite, red radiolarian chert, pelagic–hemipelagic limestone, shale, volcaniclastic–terrigenous sandstone and neritic limestone. The size of the blocks ranges from centimetres to hundreds of metres. There are also dismembered thrust sheets up to several kilometres long. Locally, a red–brown matrix is present, which is poorly sorted and contains fragments of all of the above lithologies; this matrix is interpreted as of tectonic origin.

The extrusive and sedimentary blocks in the mélange occur as two main lithological associations: (1) basalt–chert; (2) basalt–volcaniclastic sediment–neritic carbonate. Calcareous microfossils from several of the blocks yielded ages ranging from Albian to Maastrichtian based on microfossils including *Pseudosiderolites vidali* Douville and *Rotalipora* sp. (İ. Ongen, pers. comm.). The formation of the mélange is assumed to be approximately coeval with the youngest known age of the blocks in the mélange (i.e. Late Maastrichtian). In addition, the exposed mélange predates unconformably overlying Eocene sediments (Kadıkızı Formation; see below).

The mélange is interpreted as an accretionary prism related to northward subduction of the Northern Neotethys. The pelagic sediments (radiolarites and rare pelagic carbonates), now present as blocks, were originally deposited on oceanic crust and were later accreted into the mélange. Accordingly, the age of the underlying oceanic crust was at least Albian–Late Maastrichtian (112–65.5 Ma). The blocks and slices of the basalt–chert lithological association and also serpentinite were accreted from Neotethyan oceanic lithosphere, whereas the blocks and slices of the basalt–volcaniclastic sediment–neritic carbonate association are interpreted as fragments of emplaced oceanic seamounts (Rojay *et al.* 2001). The dominance of oceanic material and the lack of a terrigenous matrix suggests that the accretionary wedge developed some distance from the Pontide continental margin to the north.

Middle Eocene Kadıkızı Formation: post-suture sediments

The oldest rocks above the Neotethyan IAESZ are represented by the Kadıkızı Formation of Mid-Eocene age. This formation overlies the Kirazbaşı Mélange with an irregular unconformity, as exposed north of Tosya (Fig. 2). The succession begins with Nummulitic limestones grading into calcarenites and shales, and then passes upwards into sandstones and lenticular conglomerates, which increase in abundance towards the top of the formation.

The sandstones are poorly sorted, terrigenous litharenites with well-rounded clasts, indicating reworking in a fluvial or shoreface environment. In addition, the presence of plant-derived material within these sediments suggests the proximity of fluvial input. The presence of coarse-grained Nummulitic calcarenites further indicates that this formation was deposited in a shelf-type setting. The conglomerates exhibit a lenticular geometry and an imbricated clast-supported texture, dominated by metamorphic lithoclasts, which suggests deposition in channels mainly fed from the Pontide continental margin to the north.

The overall regressive nature of the succession suggests a transition from a shallow carbonate-depositing shelf (<200 m: lower shoreface) to a proximal subaqueous delta that was constructed directly on the Kirazbaşı Mélange during Mid-Eocene time.

Unlike the Upper Cretaceous units described above, the Kadıkızı Formation is relatively undeformed. It lacks a penetrative cleavage and does not exhibit north-vergent deformational fabrics, as seen in the underlying units. This suggests that the emplacement of these underlying units took place prior to the Mid-Eocene.

Geochemistry of Central Pontide basaltic rocks and peridotites

Analytical methods

Samples of relatively unaltered basaltic rocks were collected from the Kızılırmak Ophiolite, the Kirazbaşı Mélange, the Yaylaçayı volcanic arc unit and from the İkiçam, inferred back-arc unit and were analysed for major and trace elements by X-ray fluorescence (XRF) at the School of GeoSciences, University of Edinburgh, using the method of Fitton *et al.* (1998).

In addition, chrome spinel grains from serpentinized harzburgites taken from both the mélange (several samples) and the Kızılırmak Ophiolite (one sample) were analysed using a Cameca SX100 electron microprobe at the School of GeoSciences, University of Edinburgh, using the method of Reed (1975). A focused beam of 20 nA was used. The instrument was fitted with five wavelength-dispersive spectrometers and operated with a gun potential of 20 kV. Probe current was measured using a Faraday cup. The analytical standards were a selection of Specpure metals, simple synthetic oxide crystals and simple silicates. Fe^{3+} concentrations were calculated stoichiometrically following the method of Droop (1987).

Results of basalt chemical analysis

The extrusive rocks are andesite, andesite–basalt, sub-alkali basalt and alkali basalt, as shown in Figure 6a. The compositions of the ophiolitic and volcanic arc basalts are also illustrated using normal-mid-oceanic ridge basalt (N-MORB)-normalized 'spidergrams' (Fig. 6b) (Pearce *et al.* 1984). Selected analyses are shown in Table 1.

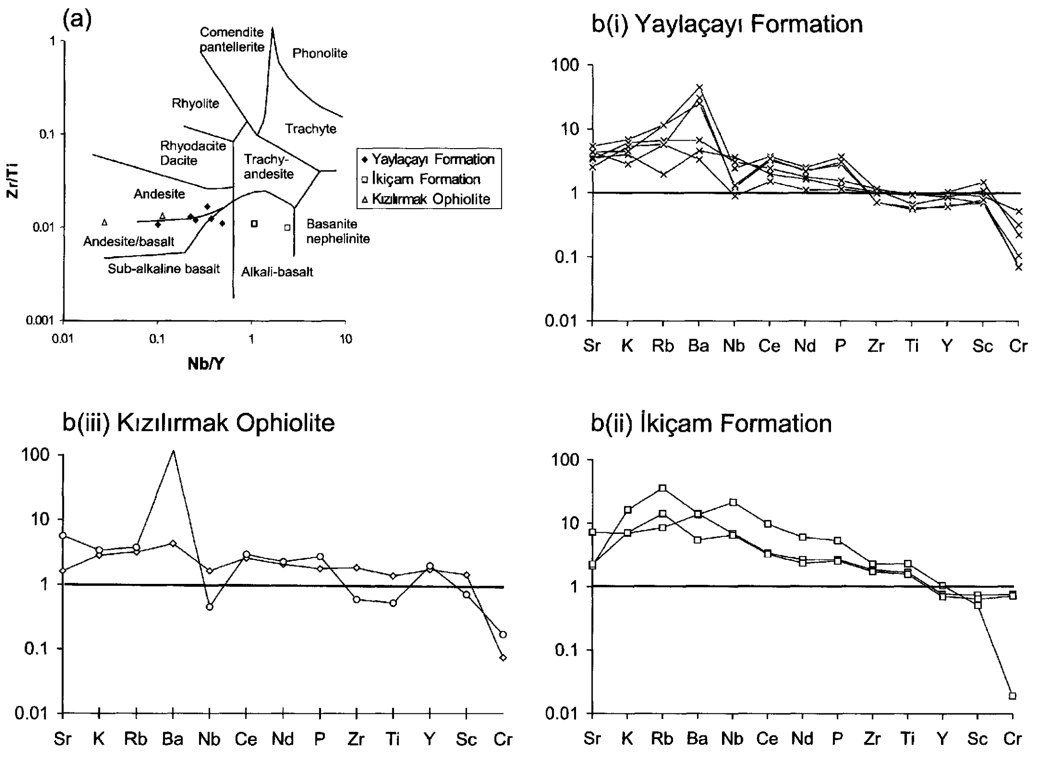

Fig. 6. Chemistry of Central Pontide basaltic rocks. (**a**) Zr/Ti v. Nb/Y diagram showing the range of lithologies present; (**b**) MORB-normalized trace-element patterns of basaltic rocks from the Central Pontides. (i), Yaylaçayı Formation (volcanic arc); (ii), Ikiçam Formation (marginal basin sediments); (iii), Kızılırmak Ophiolite (SSZ-type oceanic crust). Normalizing values: Sr, 120 ppm; K_2O, 0.15%; Rb, 2.0 ppm; Ba, 20 ppm; Nb, 3.5 ppm; La, 3 ppm; Ce, 10 ppm; Nd, 8 ppm; P_2O_5, 0.12% ; Zr, 90 ppm; TiO_2, 1.5%; Y, 30 ppm; Sc, 40 ppm; Cr, 250 ppm (Pearce 1982). (See Fig. 2 for sampling locations.)

Most of the basalts of the Yaylaçayı Formation, inferred arc unit are enriched in large ion lithophile elements (LILE; e.g. Sr, K, Rb, Ba) relative to the less mobile high field strength elements (HFSE; e.g. Ti, P, Zr, Nb). This enrichment is accompanied by a marked negative Nb anomaly in most samples (Fig. 6b, i). These features are characteristic of a mantle source that was chemically affected by subduction fluids (e.g. Pearce & Cann 1973; Pearce *et al.* 1984). The extrusive rocks of the Yaylaçayı Formation are chemically similar to those of modern subduction-related volcanic arcs (e.g. Mariana, SW Pacific; Pearce 1982). The LILE enrichment is attributed to the effects of fluids derived from the downgoing slab as it underwent *PT*-controlled phase changes and associated dehydration reactions (Anderson *et al.* 1978; Saunders *et al.* 1980).

By contrast, the samples of the İkiçam Formation, from the more northerly part of the inferred back-arc unit, do not exhibit any identifiable subduction-influenced geochemical signature and are compatible with a within-plate setting (e.g. rift-related or seamount; Pearce 1982; Fig. 6b, ii).

MORB-normalized plots of basaltic rocks from the Kızılırmak Ophiolite (Fig. 6b, iii) are slightly enriched relative to MORB, and show a slight negative Nb anomaly. The low Cr values suggest a fractionation effect. Chemically similar basalts are known from many Tethyan ophiolites (e.g. Pearce *et al.* 1984; Robertson 2002; Parlak *et al.* 2004). Basalts exhibiting similar MORB-normalized plots have been dredged from modern back-arc basins (e.g. Weaver *et al.* 1979; Taylor *et al.* 1992).

The basaltic rocks from the Kirazbaşı Mélange exhibit trace-element signatures that suggest a range of mid-oceanic ridge to within-plate-type settings not influenced by subduction (Rice 2005).

Table 1. *Representative analyses of the Late Cretaceous basaltic rocks from the Central Pontides*

	Yaylaçayı Formation			İkiçam Formation			Kızılırmak Ophiolite		
Sample: Location:	PO02/150 North of Iskilip	PO02/130 Suseki (N Iskilip)	PO02/182 Yapraklı	PO03/205 Yukarıberçin (NW Tosya)	PO03/221 Yukarıberçin (NW Tosya)	PO03/216 Yukarıberçin (NW Tosya)	PO02/82 Eldivan	TU89.33 North of Kargı	PO03/21 Eldivan
SiO_2	51.81	46.68	43.19	44.35	47.17	43.58	50.79	50.42	49.59
TiO_2	1.34	1.43	0.89	3.49	2.38	2.55	2.01	1.41	0.77
Al_2O_3	14.91	14.44	17.14	15.93	16.17	17.56	14.55	14.96	13.82
Fe_2O_3	12.00	9.82	12.18	12.64	12.41	13.55	13.29	9.58	4.13
MgO	6.41	7.76	7.95	4.12	6.80	6.75	4.67	8.36	1.46
CaO	7.16	10.54	10.44	8.61	6.31	5.38	7.86	7.54	13.96
Na_2O	3.92	3.50	2.69	4.42	3.59	2.52	3.87	2.86	4.38
K_2O	0.80	0.60	0.68	1.03	1.07	2.44	0.42	1.91	0.50
MnO	0.27	0.17	0.23	0.20	0.17	0.16	0.17	0.18	0.11
P_2O_5	0.14	0.15	0.37	0.65	0.31	0.32	0.21	0.14	0.32
LOI	1.42	4.85	3.68	4.15	3.68	5.04	1.66		10.38
Total	100.23	99.94	99.44	99.59	100.05	99.85	48.71		99.42
Zn	98.6	83.0	75.2	115.4	131.6	150.5	105.6	120.0	78.1
Cu	73.5	117.6	46.5	24.2	82.9	82.4	55.2	29.0	44.9
Ni	30.9	68.7	29.1	13.1	136.3	175.7	16.7	42.0	33.0
Cr	55.7	79.7	17.4	4.8	179.7	190.8	18.3	72.0	41.6
V	392.8	313.8	338.0	297.1	250.7	294.0	466.4	318.0	128.0
Ba	66.4	90.9	497.5	273.1	109.3	281.9	84.4	778.0	2350.9
Sc	59.2	43.5	31.5	20.6	26.0	29.9	56.1	39.0	27.8
Nb	3.1	12.7	4.6	75.0	22.8	24.2	5.6	5.0	1.6
Zr	89.4	94.3	63.8	208.2	157.2	167.6	162.3	120.0	52.5
Y	31.2	26.1	18.1	31.6	21.3	23.1	50.3	37.0	57.5
Sr	304.4	423.3	521.8	863.1	271.3	255.4	191.9	196.0	672.6
Rb	11.5	3.9	22.9	17.1	28.2	71.5	6.2	3.0	7.4
La	6.2	9.0	16.2	45.0	11.6	11.8	8.4	5.0	21.3
Ce	15.2	19.8	34.6	97.7	32.8	33.9	25.3	12.0	28.9
Nd	8.9	13.1	17.5	48.1	18.9	21.3	16.2	12.0	17.8

LOI, loss on ignition.
Sample locations are shown in Figure 2. GPS coordinates (where available): PO02/150, 1913814058; PO02/130, 2238617389; PO02/182, 6667615522; PO03/205, 8121242547; PO03/221, 7201843766; PO03/216, 7201843766; PO02/82, 3947983543; TU89.33, north of Kamil (Aşıkbükü–Yukarı Zeytin section); PO03/21, 378447779968.

Results of chrome spinel analysis

The harzburgitic composition of the ophiolitic peridotites from the Kızılırmak Ophiolite and from the mélange beneath implies the presence of highly depleted mantle, possibly resulting from hydrous melting related to a subduction zone (Pearce *et al.* 1984). In this context, the ratios of Cr-number ($Cr \times 100/(Cr + Al)$) and Mg-number ($Mg \times 100/(Mg + Fe^{2+})$ in spinels allow peridotites that formed in a MOR-type setting to be distinguished from those formed in an SSZ-type setting (Dick & Bullen 1984). The main constituents of spinel $(Mg,Fe^{2+})(Cr,Al,Fe^{3+})_2O_4$ behave differently during partial melting or crystallization, with Cr and Mg partitioning into solid phases, and Al into the melt.

The results of 273 analyses of 127 spinel grains from three samples of harzburgite from the Central Pontides (Table 2) were plotted on a Cr-number v. Mg-number diagram (Fig. 7a). In general, the observed high Mg-number values of the ophiolitic samples relative to abyssal peridotites could reflect low-temperature re-equilibration with olivine (Dick & Bullen 1984).

The grains analysed from the single sample from the Kızılırmak Ophiolite (OCP1) exhibit Cr-number values within the range for abyssal peridotites and are consistent with either MOR-type or a back-arc marginal basin setting.

The two samples of serpentinized harzburgite from the mélange (Fig. 7; MCP1, MCP2) plot in the higher Cr-number group, implying a higher degree of partial melting of the mantle source. The high Cr-number values are similar to those for SSZ boninite-type settings, including the Upper Pillow Lavas of the Troodos ophiolite (Dick & Bullen 1984). The most likely origin is that these harzburgites originated in a forearc setting and were later incorporated into the accretionary mélange beneath.

Eastern Pontides

Six tectonostratigraphic units of Late Cretaceous–Early Cenozoic age were identified in the well-exposed area of the IAESZ in the Eastern Pontides (Fig. 8). As for the Central Pontides, these units will be described from north to south in generally downward structural order. The Munzur Mountains (Tauride) platform unit in the far south, described last, is located at the lowest structural level (Figs 8 and 9).

Upper Cretaceous Refahiye Complex: Neotethyan oceanic crust

An ophiolitic unit termed the Refahiye Complex (Yılmaz 1985) crops out north and NW of Erzincan, mainly at a high structural level (Figs 1 and 8). Smaller ophiolitic exposures also occur at a much lower structural level, near the Munzur platform (Fig. 8). The base of the Refahiye Complex is a north-dipping thrust (Fig. 9); its upper boundary is an unconformity with overlying Eocene sediments (Sipikör Formation) or younger units. The complex, with an estimated apparent thickness of *c.* 8 km, is composed of >75% (by volume) serpentinized harzburgite, *c.* 20% diabase dykes and <5% trondhjemite (plagiogranite) dykes. The diabase includes thrust slices of sheeted dykes up to 1000 m thick. The boundaries of the individual thrust sheets of sheeted dykes are commonly zones of sheared serpentinite, up to *c.* 30 m thick. There are also isolated dykes, individually <2 m thick, within serpentinized harzburgite (Fig. 10a).

An important observation is that the sheeted dykes include numerous elongate screens, each up to *c.* 50 m thick, that are composed of highly strained metamorphic rocks. These screens locally dominate the dyke section in the SW of the complex (Fig 11) and include epidote–actinolite schist, metabasite, metaserpentinite and massive marble. The individual screens are intruded by swarms of diabase dykes, together with rare plagiogranite dykes and late-stage aplite dykelets, up to 30 cm wide (Fig. 11). Undisturbed primary igneous contacts are preserved between many of the dykes and the host rocks.

The exposure of the Refahiye ophiolitic complex in the north is interpreted as a dismembered section of oceanic lithosphere, of which the upper, extrusive levels are not now preserved. The metamorphic host rocks within the Refahiye Complex are lithologically comparable with the Late Palaeozoic–Early Mesozoic metamorphic basement of the Pontides (e.g. Domuzdağ Unit; Topuz *et al.* 2004), and are seen as fragments of country rocks that were rifted from the Pontide basement and incorporated into the ophiolite complex. An alternative origin as fragments of an older dyke-rich metamorphic basement, as known from some parts of the Pontides (eg. Artvin region; T. Ustaömer, pers comm.), is unlikely in view of the close association of the metamorphic rock screens with the nearby 100% sheeted dyke sections of the Refahiye Complex. An important implication of the dyke-rich metamorphic rock screens is that the Refahiye ophiolitic complex formed in a rifted continental margin, rather than an oceanic setting.

Upper Cretaceous Karadağ Formation: oceanic arc

This volcanic and volcaniclastic unit crops out at two structural levels, located west and SE of

Table 2. *Representative analyses of Cr-spinel grains from peridotites of the Neotethyan ophiolitic and mélange units in the Central and Eastern Pontides*

Sample	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	V_2O_3	FeO	MnO	NiO	ZnO	MgO	CaO	Na_2O	Total
Central Pontides													
Kızılırmak Ophiolite PO02/37 (Yalmansaray)													
Spinel 1	0.027	0.073	40.039	27.582	0.169	17.273	0.263	0.176	0.270	15.341	0.006	0.007	101.226
Spinel 2	0.041	0.046	38.946	29.106	0.162	17.748	0.247	0.173	0.306	14.946	0.000	0.009	101.731
Spinel 3	0.039	0.051	37.283	31.099	0.191	16.701	0.263	0.166	0.275	15.424	0.000	0.019	101.511
Spinel 4	0.044	0.035	38.888	29.946	0.212	15.885	0.240	0.179	0.271	15.835	0.000	0.021	101.556
Spinel 5	1.047	0.028	37.241	28.889	0.178	15.411	0.250	0.150	0.245	16.938	0.037	0.273	100.688
Kirazbaşı Mélange PO02/71 (Büyük Yayla)													
Spinel 1	0.060	0.021	15.206	53.923	0.384	21.583	0.440	0.054	0.315	9.415	0.007	0.027	101.435
Spinel 2	0.076	0.018	20.198	47.755	0.378	21.418	0.451	0.066	0.336	9.876	0.068	0.013	100.652
Spinel 3	0.064	0.020	13.800	56.486	0.369	19.933	0.430	0.044	0.240	10.141	0.000	0.037	101.563
Spinel 4	0.076	0.017	15.088	55.038	0.369	20.680	0.465	0.047	0.255	9.656	0.021	0.015	101.726
Spinel 5	0.064	0.026	13.942	56.423	0.371	19.658	0.447	0.075	0.240	10.399	0.013	0.014	101.672
Eastern Pontides													
Refahiye Ophiolite PO03/188 Sakultan Gecedi													
Spinel 1	0.027	0.039	38.246	30.401	0.176	16.020	0.268	0.176	0.263	15.698	0.008	0.000	101.320
Spinel 2	0.054	0.039	39.003	29.871	0.189	15.405	0.212	0.152	0.263	15.924	0.009	0.020	101.142
Spinel 3	0.039	0.051	37.283	31.099	0.191	16.701	0.263	0.166	0.275	15.424	0.000	0.019	101.511
Spinel 4	0.044	0.035	38.888	29.946	0.212	15.885	0.240	0.179	0.271	15.835	0.000	0.021	101.556
Spinel 5	1.047	0.028	37.241	28.889	0.178	15.411	0.250	0.150	0.245	16.938	0.037	0.273	100.688
Refahiye Ophiolite PO03/189 Sakultan Gecedi													
Spinel 8	0.045	0.102	8.384	51.862	0.198	31.702	0.538	0.098	0.188	7.756	0.019	0.017	100.909
Spinel 9	0.055	0.115	16.520	52.246	0.213	21.799	0.420	0.091	0.234	10.501	0.008	0.014	102.217
Spinel 10	0.050	0.127	16.920	52.143	0.203	21.343	0.439	0.063	0.228	10.643	0.014	0.021	102.194
Spinel 12	0.051	0.095	16.167	51.133	0.206	23.131	0.454	0.076	0.262	9.847	0.018	0.027	101.467
Spinel 13	0.040	0.113	16.522	51.703	0.193	21.881	0.415	0.049	0.226	10.355	0.001	0.009	101.507
Karayaprak Melange PO03/81 Avcilar													
Spinel 1	0.059	0.021	15.832	54.052	0.299	19.429	0.421	0.059	0.188	11.040	0.017	0.007	101.423
Spinel 2	0.076	0.011	16.177	53.738	0.299	19.429	0.417	0.069	0.203	11.155	0.003	0.016	101.592
Spinel 3	0.045	0.019	16.959	52.214	0.339	20.489	0.414	0.061	0.233	10.610	0.004	0.011	101.398
Spinel 4	0.444	0.013	19.229	45.875	0.342	23.824	0.441	0.068	0.437	10.211	0.000	0.026	100.909
Spinel 5	0.053	0.021	16.057	53.584	0.300	19.483	0.387	0.071	0.209	10.958	0.006	0.015	101.144

GPS coordinates: PO02/37, 5633065332; PO02/71, Büyük Yayla, *c.* 5 km north of Yapraklı; PO03/188, 1482314773; PO03/189, 1360214724; PO03/81, 7173588257.

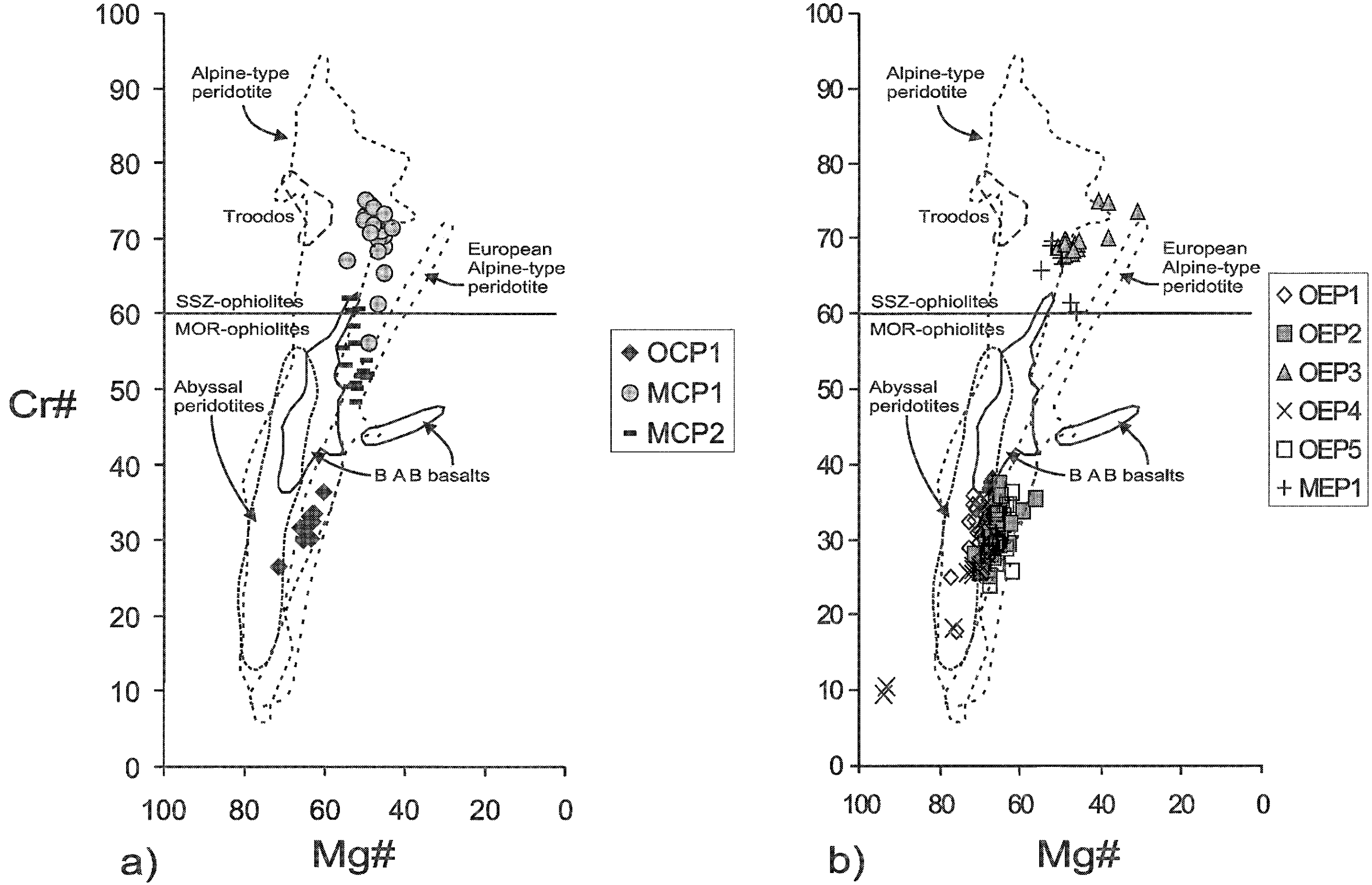

Fig. 7. Cr-number ((Cr × 100)/(Cr + Al)) v. Mg-number ((Mg × 100)/(Mg + Fe^{2+})) for spinels from serpentinized peridotites in the ophiolitic and mélange units of (**a**) the Central Pontides and (**b**) the Eastern Pontides. The marked fields are for Troodos, Alpine-type peridotites, abyssal basalts and back-arc basin basalts (BAB) (Dick & Bullen 1984). Sample locations in the Central Pontides: OCP1, Pelitcik; MCP1, between İlgaz and Çankırı; MCP2, south of Tosya (see Fig. 2 for location). Sample locations in the Eastern Pontides: OEP1, OEP3 and OEP5, Sakultan Geçidi; OEP2, Mercidiye; OEP4, Aktaş; MEP1, Avcılar (see Fig. 8).

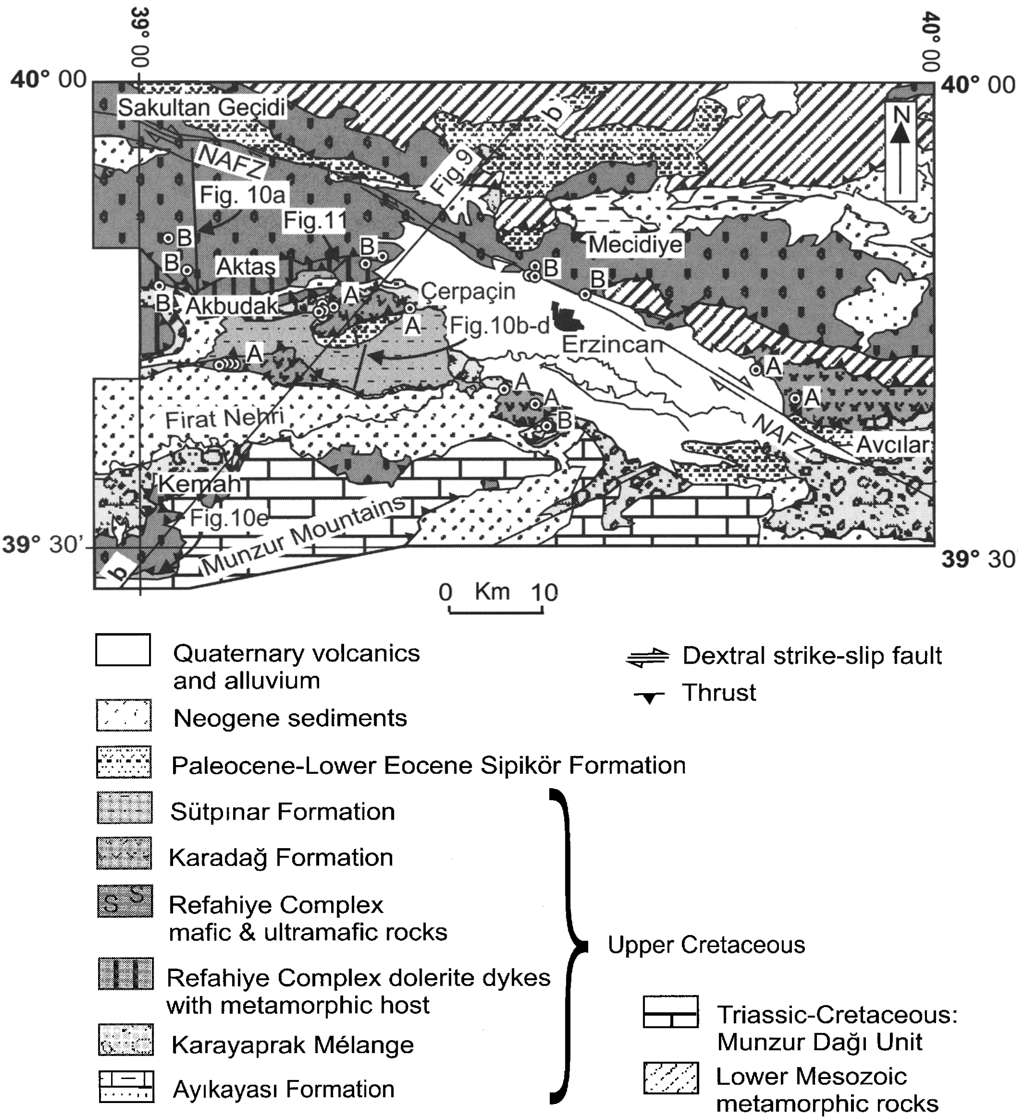

Fig. 8. Simplified geological map of the Eastern Pontides (see Fig. 1 for location). Line of section b–b' (see Fig. 9). The locations of sites sampled for geochemical analysis by XRF are marked: A, Karadağ Formation; B, Refahiye Complex (see Fig. 12). The Ayıkayası Formation is too thin and localized to show here (see Fig. 10).

Erzincan (Figs 8 and 9). The lower contact is a north-dipping thrust, whereas the upper boundary is an unconformity overlain by sediments of Early Eocene age or younger. The formation takes the form of large wedge-shaped thrust slices, individually up to 20 km long and *c.* 3 km thick. The total outcrop in the Erzincan area is estimated as *c.* 250 km^2. The presence of microfossils, including *Globotruncana*, within thin limestones interbedded with volcanic rocks indicates a Late Cretaceous (Campanian–Maastrichtian) age (K. Taşlı & N. İnan, pers. comm.).

The Karadağ Formation comprises a thick (*c.* 3 km), disrupted succession of hornblende- and plagioclase-phyric basaltic to andesitic lavas, interbedded with coarse-grained volcaniclastic conglomerates (Fig. 10b). In addition, volcaniclastic sandstones, shales and tuffs are present in lesser amounts. Higher-level thrust sheets are

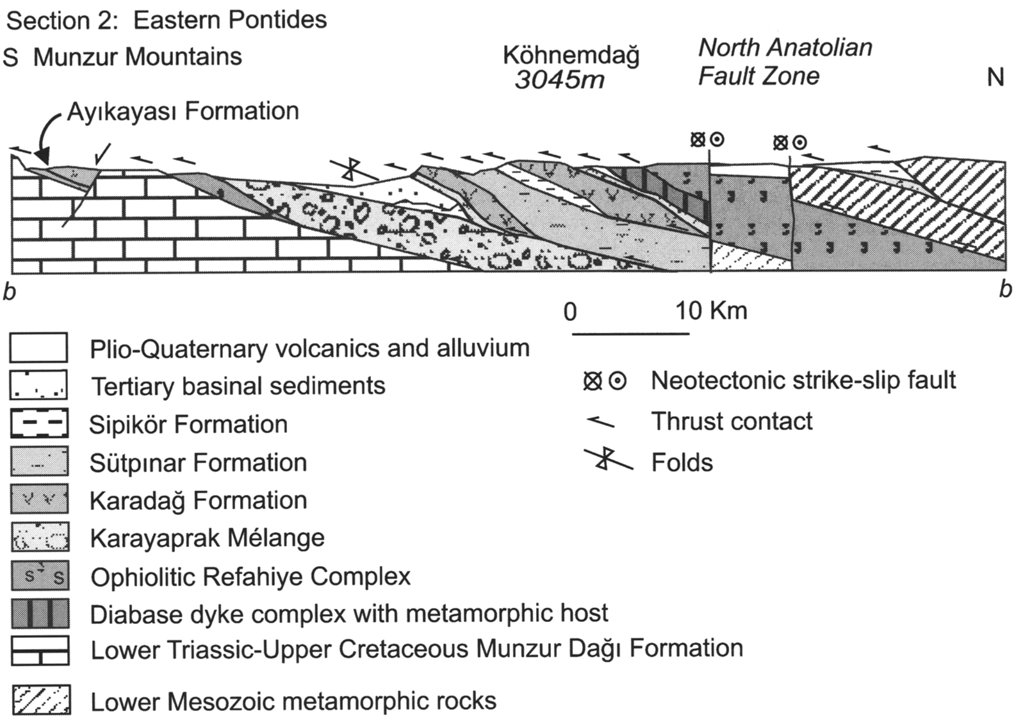

Fig. 9. Cross-section showing the main structural and stratigraphic relations in the Eastern Pontides. (See Fig. 8 for the line of section.)

mainly schistose and include metabasic and meta-andesitic flows (>70% by volume), individually 2–3 m thick, interbedded with volcaniclastic, tuffaceous and calcareous schists. Rare hemipelagic *Globotruncana*-bearing limestones are also present. The mineral assemblage quartz + epidote + plagioclase + chlorite + calcite is indicative of greenschist-facies metamorphism.

The Karadağ Formation is interpreted as part of a Late Cetaceous volcanic arc, dominated by andesitic volcanic rocks and volcaniclastic sediments, with an open-marine pelagic microfauna and little or no terrigenous input.

Upper Cretaceous–Palaeogene Sütpınar Formation: forearc basin

This coarsening-upward sedimentary unit, *c.* 1500 m thick, crops out in the mid-levels of the thrust stack (Figs 8 and 9), mainly east of Erzincan. The stratigraphic base is not exposed. North-dipping thrust faults imbricate the formation with other units. Planktonic Foraminifera (e.g. *Globotruncana*) in the lower part of the succession indicate a Late Cretaceous age, whereas benthic Foraminifera (e.g. *Alveolina*) in the higher part of the formation are indicative of an Early Eocene age (K. Taşlı & N. İnan, pers. comm.). The Sütpınar Formation (Fig. 10c) passes conformably, and probably diachronously, into facies similar to the Sipikör Formation in some areas (see below).

The lower *c.* 800 m of the succession comprises thin- to medium-bedded (10 cm–1.5 m) quartz- and feldspar-bearing calcareous sandstones. Individual beds are typically amalgamated and exhibit planar and convolute lamination, with partings of mud, shale and marl. In places, the succession is dominated by thinly bedded, fine-grained, dark volcaniclastic shale, or by more thickly bedded, pale calcarenites with rare andesitic lava flows and volcaniclastic debris-flow conglomerates. The upper *c.* 600 m of the succession exhibits an increase in the abundance and thickness of volcaniclastic sandstones and conglomerates.

The lower part of the Sütpınar Formation formed in a deep-marine setting, marked by low-energy background deposition of volcaniclastic mud and pelagic carbonate. Subordinate intercalations of coarser-grained clastic sediments were deposited from turbidity currents. The volcaniclastic lithologies higher in the succession are

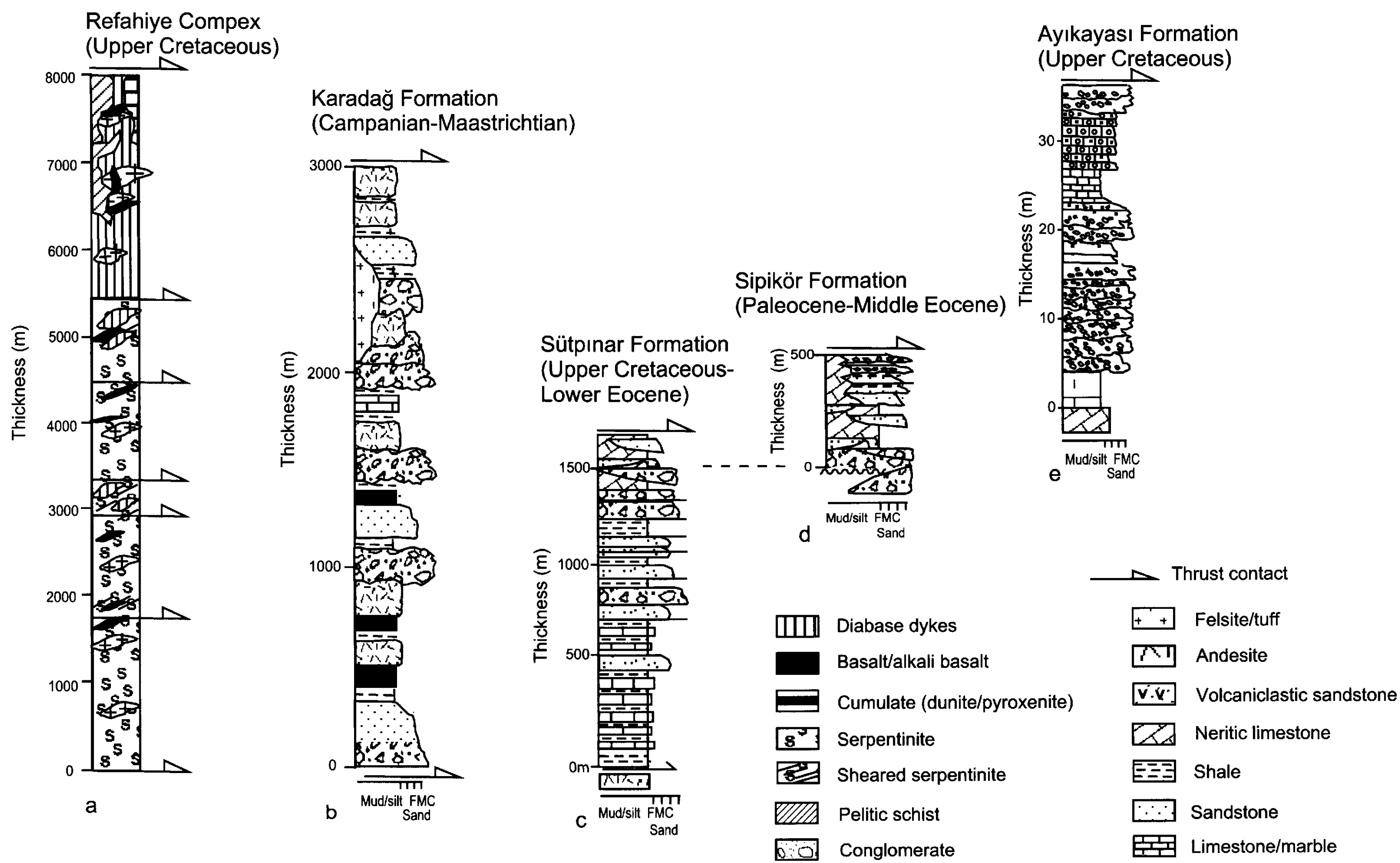

Fig. 10. Composite sedimentary logs (**a**–**e**) of the Upper Cretaceous–Lower Cenozoic sequences in the Eastern Pontides, arranged from left to right according to structural position (**a**, highest; **e**, lowest). (See Fig. 8 for locations.)

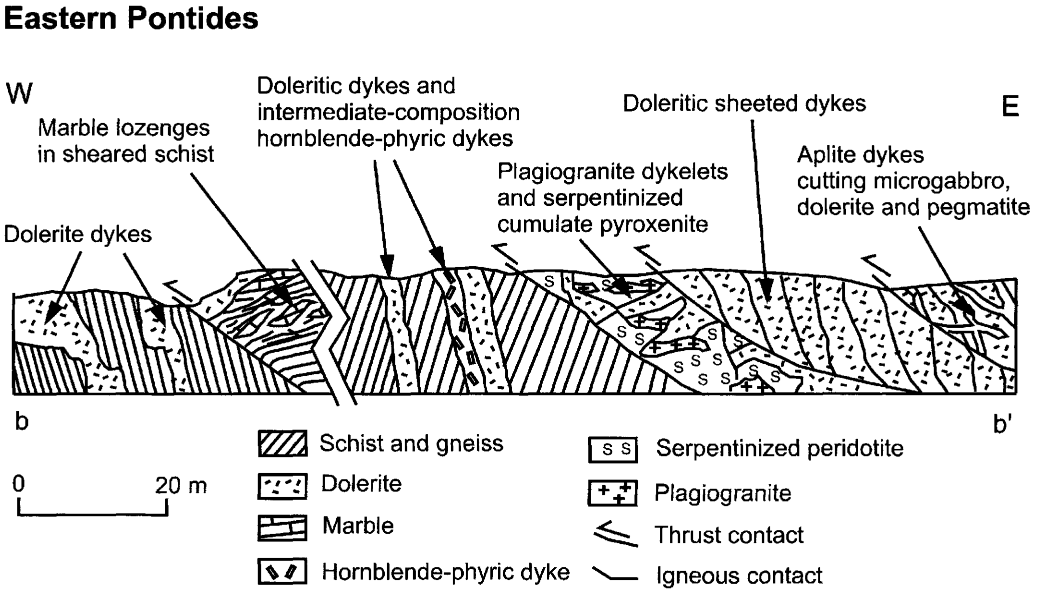

Fig. 11. Screens of marble, schist and gneiss intruded by doleritic dykes within the Refahiye ophiolitic complex. (See text for explanation.)

very similar to those of the Karadağ, inferred arc unit, suggesting that these were intergradational. Volcanogenic material is mainly detrital and coeval lava flows rarely occur. The coarse carbonate sediment was redeposited from a shelf-depth setting, rich in *Nummulites* sp. Increasing amounts of coarse, reworked ophiolitic and metamorphic material appear towards the top of the formation, grading into the Sipikör Formation (see below). An increase in depositional energy and source proximity is confirmed by reduced textural maturity upwards. Overall, the Sütpınar Formation is interpreted as a Late Cretaceous–Early Cenozoic regressive forearc basin, in which detritus was being supplied from an uplifted mélange, a volcanic arc, an ophiolite and continental basement units. By this time only very minor arc-related volcanism persisted, at least in this area.

Palaeogene Sipikör Formation: post-emplacement sediments

In the area studied this varied sedimentary unit rests unconformably on all of the Upper Cretaceous units (including ophiolitic rocks) with the sole exception of the inferred forearc basin unit (Sütpınar Formation), with which it is intergradational and partly coeval (see above). The Sipikör Formation is widely exposed around Erzincan, especially to the north of the city (Fig. 8). In the south, the formation unconformably overlies the Munzur Limestone Formation and to the north it unconformably overlies the Pontide metamorphic basement (Topuz *et al.* 2004; Figs 8 and 9). The Sipikör Formation, up to 500 m thick, is dated as Paleocene–Eocene based on planktonic and benthic Foraminifera (e.g. *Nummulites*) (K. Taşlı & N. İnan, pers. comm.), in agreement with previous workers (Okay & Şahintürk 1997; Topuz *et al.* 2004).

In the area studied, the Sipikör Formation (Fig. 10) comprises lenticular polymict conglomerates with well-rounded clasts, together with poorly bedded to massive, fine- to coarse-grained sandstones. These lithologies interdigitate with very fine-grained, dark grey, hard, massive foraminiferal limestones, forming lenses up to *c.* 50 m thick. The clastic content is varied and includes metamorphic lithoclasts. In places, medium- to thick-bedded oncoidal and *Nummulites*-bearing bioclastic limestones are present, together with rudist bivalves, microbial carbonate and large sponges. The limestones are interbedded with massive, poorly sorted, lenticular sandstones, conglomerates and thin (*c.* 2 m) layers of anhydrite. There also local interbeds of red siltstones that contain thin (*c.* 5 cm) layers of caliche (palaeosols).

The Sipikör Formation accumulated in varied shallow-marine, lagoonal, deltaic to fluvial settings and was sourced from a wide variety of lithologies in the area, including ophiolitic, arc-related and terrigenous (continental) units.

The Sipikör Formation in the area studied lacks north-vergent tectonic structures, as seen in all of the structurally underlying units. The formation in this area is interpreted as a transgressive cover, deposited after north-vergent deformation and emplacement of the underlying Upper Cretaceous units. The timing of north-vergent deformation in this area is, therefore, constrained to predate the Sipikör Formation (i.e. pre- or syn-Paleocene–Eocene).

Elsewhere (e.g. 90 km westwards), similar coarse clastic sediments of Paleocene age (Taşdemir Formation) are unconformably overlain by Paleocene–Eocene Nummulitic limestones. This unit is structurally overlain by a thrust sheet of limestone (i.e. Çimendağ Nappe) that was presumably emplaced northwards in this area. Similar clastic sediments structurally underlie another thrust sheet to the east of the study area (İmalidağ Nappe; Okay & Şahintürk 1997). Also, further east again in the Artvin area, Mid-Eocene, coarse non-marine clastic sediments are structurally overlain by Upper Cretaceous and older units. It is, therefore, probable that additional northward thrusting took place during Mid-Eocene time, approximately contemporaneously with the development of the south-vergent thrust wedge as a whole.

Karayaprak Mélange: ophiolitic mélange

This ophiolitic mélange unit occurs at several different levels within the thrust stack, forming discrete slices up to 4 km thick (Figs 8 and 9). In the south, near Kemah (Fig. 8), the mélange tectonically overlies the basinal latest Cretaceous Ayıkayası Formation above the Munzur carbonate platform. The mélange is unconformably overlain by Paleocene–Eocene clastic sediments of the Sipikör Formation (Fig. 10d) that postdate Mid-Eocene suturing, as seen in small exposures to the north and south of Erzincan (Figs 8 and 9).

The mélange is a tectonized mixture of blocks and slices that individually are up to *c.* 2 km in size. The blocks exhibit three main lithological associations: (1) altered basaltic pillow lavas commonly interbedded with red radiolarian chert, pelagic limestone and mudstone (i.e. basalt–pelagic sediment association); (2) very large blocks (> 1 km) of pale grey massive crystalline limestone commonly associated with basalt (i.e. basalt–neritic limestone association); (3) blocks of serpentinite, gabbro and diabase (i.e. ophiolitic association). Less common lithologies include volcaniclastic shale, volcaniclastic sandstone and rare amphibolite. Fissile, sheared serpentinite also occurs along shear zones and as a matrix to mafic and ultramafic blocks in some areas.

Pelagic carbonate blocks in the mélange yielded planktonic foraminifera and calpionellids (e.g. *Globotruncana linneiana* (d'Orbigny), *Archaeoglobigerina* sp., *Calpionella alpina* (Lorenz), *Calpionella elliptica* (Cadish)) of Early Cretaceous (Berriasian) age (K. Taşli & N. İnan, pers. comm.).

The basalt–pelagic sediment association is interpreted as accreted abyssal sediments that originally accumulated on oceanic crust. By contrast, the basalt–neritic limestone association is indicative of deposition above the carbonate compensation depth (CCD), probably on seamounts that were later detached from the ocean floor and accreted into the mélange. In addition, relatively rare deformed blocks of volcaniclastic and polymict sediments possibly represent accreted trench-fill sediments. The absence of terrigenous sediments suggests that the accretionary wedge developed away from a supply of continentally derived sediment.

Upper Cretaceous Ayıkayası Formation: foredeep unit

At the base of the thrust stack in the south (Fig. 9), Triassic–Cretaceous shallow-water limestones of the Tauride Munzur platform (Munzur Dağı Unit) are overlain, with a sharp, but conformable, contact by a relatively thin (tens to several hundred metres thick) unit of pelagic carbonates, known as the Ayıkayası Formation (Özgül & Turşucu 1984). Small exposures in the south (too small to show on the regional map) reveal that this unit unconformably overlies the northern margin of the Munzur Dağı Unit. A Late Cretaceous (Campanian–Maastrichtian) age for the Ayıkayası Formation is indicated by the presence of Late Cretaceous planktonic foraminifera (e.g. *Globotruncana* sp.) (K. Taşlı & N. İnan, pers. comm.). The upper stratigraphic boundary of this formation has been cut out by south-vergent thrusting of Early Cenozoic age.

The Ayıkayası Formation includes buff–grey, thin-bedded pelagic limestones, interbedded with redeposited oolitic and bioclastic calcarenites (Fig. 10e). The limestones include scattered lithoclasts of basic igneous rocks. The succession passes upwards into poorly sorted, coarse, clast-supported, lenticular graded conglomerates and breccias, containing angular to sub-rounded clasts of neritic limestone, red mudstone and chert within a matrix of calcarenite.

Conglomerate beds exhibit scoured erosive bases and appear to be channelized.

The sharp stratigraphic base of the formation implies an abrupt change from a shallow-water carbonate platform to a deeper marine setting during Campanian–Maastrichtian time. The foundering of the carbonate platform is interpreted as the result of flexural loading of the Munzur carbonate platform, ahead of southward emplacing Neotethyan units, including mélange and ophiolite (Özer *et al.* 2004). This subsidence was accompanied by an increased input of coarse detrital sediments as high-energy gravity flows derived from both the advancing Neotethyan units (e.g. basic igneous and ultramafic material) and the collapsing Munzur carbonate platform (e.g. redeposited carbonate material).

Geochemistry of the Eastern Pontide basalts and peridotites

As for the Central Pontides, samples of relatively unaltered basaltic rocks were collected from the ophiolitic, arc-type and mélange units in the Eastern Pontides. The Karadağ arc-related basalts plot in the andesite–basalt field on the Zr/Ti v. Nb/Y plot (Fig. 12a). On MORB-normalized plots (Fig. 12b, i) these basalts show enrichments in the more incompatible LILE relative to HFSE, and a distinct negative Nb anomaly in several samples. The patterns are comparable with those of modern magmatic arc basalts (Pearce 1982). Several samples show strong depletion of immobile elements (Nd, P, Zr, Ti, Y; see Table 3) suggestive of high-degree melting (Saunders & Tarney 1984).

When plotted on a MORB-normalized diagram (Fig. 12b, ii) the dykes from the Refahiye ophiolitic complex range from near-MORB with slight Nb depletion, to more depleted patterns with a distinct negative Nb anomaly.

The compositions of spinels from six samples of serpentinized harzburgite in the Eastern Pontides were plotted on a Cr-number v. Mg-number diagram (Fig. 7b). Multiple analyses were made of the cores and the rims of 12 or more individual spinel grains in each sample (Table 2). One sample of peridotite from the mélange (MEP1), as for the mélange from the Central Pontides (see above), exhibits a high Cr-number typical of Alpine-type peridotites. Of five samples from the intact Refahiye Ophiolitic Complex, four (OEP1, OEP2, OEP4 and OEP5) fall within or close to the field of abyssal spinel peridotites; one other sample from the ophiolite (OEP3) exhibits a much higher Cr-number.

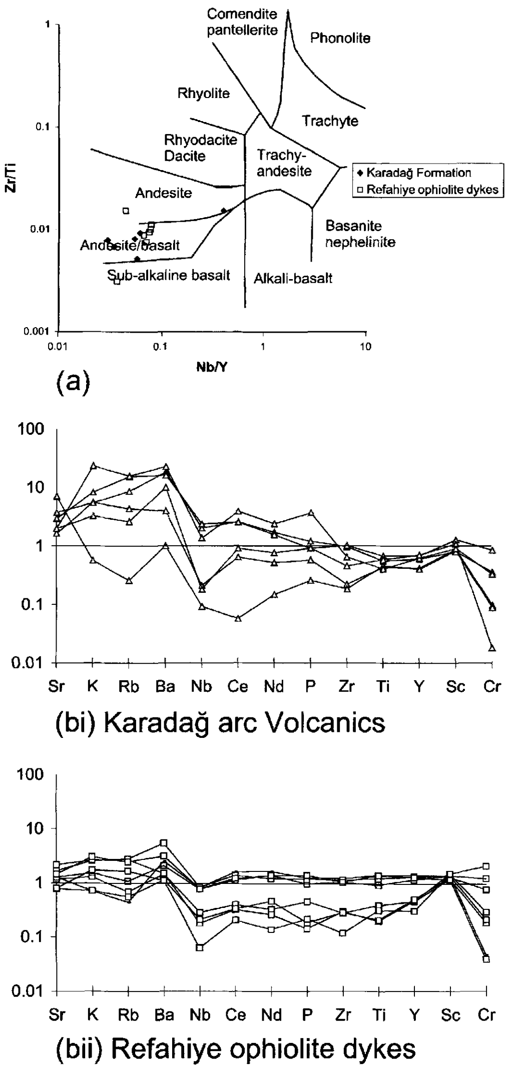

Fig. 12. Whole-rock geochemistry of basaltic rocks from the Eastern Pontides: **(a)** Zr/Ti v. Nb/Y diagram; **(b)** MORB-normalized trace-element patterns of basaltic rocks from the Eastern Pontides: (i) volcanic arc (Karadağ Formation); (ii) dolerite dykes from the ophiolitic Refahiye Complex. Normalizing values: Sr, 120 ppm; K_2O, 0.15%; Rb, 2.0 ppm; Ba, 20 ppm; Nb, 3.5 ppm; La, 3 ppm; Ce, 10 ppm; Nd, 8 ppm; P_2O_5, 0.12%; Zr, 90 ppm; TiO_2, 1.5%; Y, 30 ppm; Sc, 40 ppm; Cr, 250 ppm (Pearce 1982). (See Fig. 8 for sample locations.)

Samples OEP1, OEP3 and OEP5 were collected from a 3 km long transect of a single peridotite thrust sheet. Multiple grains were analysed from samples from this unit. Each sample clearly falls within one of the two petrogenetic types (i.e. Alpine-type or abyssal peridotite). A marked

Table 3. *Representative analyses of the Late Cretaceous basaltic rocks from the Eastern Pontides*

	Karadağ Formation (north)			Karadağ Formation (south)		Refahiye Ophiolite			
Sample: Location:	POO3/144 Avcılar	PO03/101 Köhnemdagı	PO03/183 Köhnemdagı	PO01/118B Karadağ (nr Doğan)	PO02/E30 Karadağ (Doğan)	PO03/148 Işıkpınar	PO01/119 Işıkpınar	PO02/E16 Kedek	PO03/149 Işıkpınar
SiO_2	45.88	50.29	50.21	48.71	47.77	51.65	53.47	47.55	51.32
TiO_2	0.65	0.60	0.87	0.83	1.01	0.46	0.57	2.04	2.03
Al_2O_3	18.88	14.61	17.52	17.21	15.86	14.82	16.25	14.47	14.85
Fe_2O_3	9.62	8.08	12.46	9.74	10.63	10.14	9.71	13.97	13.60
MgO	4.55	7.44	4.26	5.96	7.26	9.08	6.41	4.29	4.40
CaO	8.98	6.33	7.80	5.79	9.74	10.13	9.00	12.42	7.83
Na_2O	3.25	1.73	2.19	5.35	1.77	2.34	2.79	3.02	4.43
K_2O	0.83	3.51	0.49	0.81	1.23	0.26	0.19	0.11	0.45
MnO	0.21	0.18	0.22	0.17	0.15	0.18	0.16	0.22	0.25
P_2O_5	0.07	0.44	0.11	0.14	0.11	0.03	0.05	0.15	0.16
LOI	6.67	6.18	3.30	5.11	4.02	1.11	0.91	1.16	0.41
Total	99.58	99.40	99.43	99.83	99.55	100.19	99.52	99.40	99.73
Zn	104.0	64.3	96.0	113.9	86.4	73.7	74.4	105.0	87.0
Cu	83.7	171.7	82.2	104.4	108.4	13.9	72.4	70.6	60.2
Ni	10.0	31.3	3.3	77.8	119.3	121.9	39.9	32.9	7.2
Cr	24.2	82.6	4.6	89.3	212.3	503.8	45.7	11.7	9.7
V	350.1	315.2	364.9	311.9	379.4	341.5	288.1	573.5	382.9
Ba	79.1	458.3	199.4	367.6	324.5	22.1	29.1	50.7	62.8
Sc	34.8	36.1	43.5	31.9	51.0	58.1	46.6	52.7	45.4
Nb	0.7	4.8	0.6	7.1	8.3	0.2	1.0	2.8	2.7
Zr	19.9	58.3	40.9	87.6	91.4	10.5	24.9	106.9	91.3
Y	12.6	18.5	20.9	18.0	20.3	9.0	13.5	41.2	37.3
Sr	196.9	239.9	238.9	447.1	355.3	95.8	141.2	154.0	174.4
Rb	8.6	31.6	5.2	17.0	30.6	3.3	1.4	0.9	4.9
La	1.1	21.8	2.4	13.6	11.2	0.3	3.0	4.2	0.6
Ce	6.5	39.1	9.1	25.9	25.6	2.1	4.0	15.9	12.1
Nd	4.2	19.2	6.2	13.7	12.5	1.1	2.6	13.0	10.9

LOI, loss on ignition.
Sample locations are shown in Figure 8. GPS coordinates (where available): PO03/144, 150 m south of Çardaklı village (*c.* 40 km east of Erzincan); PO03/101, 1987600272; PO03/183, 1968900455; PO01/118B, Karadağ Mountain, *c.* 5 km north of Doğan village; PO02/E30, 0922894690; PO03/148, 4132705182; PO01/119, *c.* 1 km NE of Işıkpınar; PO02/E16, 0342309673; PO03/149, 4180705640.

compositional variation is thus present within this one thrust sheet. Such variation is consistent with variable depletion and enrichment trends found in chromites within peridotites dredged from back-arc basins (e.g. Dietrich *et al.* 1978; Saunders & Tarney 1984; Barker *et al.* 2003).

Structural vergence of units

The structural vergence recorded within individual units is critical to an understanding of the emplacement history of both the Central and the Eastern Pontides. All of the Upper Cretaceous units within the IAESZ in both of these areas preserve shear fabrics, folds and faults exhibiting a relatively early top-to-the-north kinematic sense of movement. Selected, representative outcrops are illustrated in Figure 13a–d. For example, in both regions the serpentinized harzburgites show a strong sigmoidal shear fabric indicating top-to-the-north movement.

In the Eastern Pontides, near Akbudak (Fig. 8), the tectonic contacts between lithological units are locally southward dipping but with top-to-the-north shear fabrics (e.g. small sigmoidal shear-pods) (Fig. 13a). The Upper Maastrichtian, inferred forearc succession (Sütpınar Formation) exhibits north-vergent asymmetrical folds (Fig. 13b) within large north-dipping thrust slices.

In the Central Pontides, at Akkaya (Fig. 2), similar structural relationships are seen. For example, the Kirazbaşı ophiolitic mélange exhibits a strong top-to-the-north shear fabric (Fig. 13c). Downward-facing asymmetrical folds with north-dipping axes are also locally preserved, also suggesting top-to-the-north vergence, as seen near Ilgaz, at Yuvasaray (Figs 2 and 13d). Following north-vergent displacement, units in both the Central and the Eastern Pontides were regionally deformed associated with the development of south-vergent thrusts, folds and shear zones. The initial vergence was, therefore, northwards, followed by southward vergence.

The transgressive Sipikör Formation of Paleocene–Eocene age is the oldest unit in the Eastern Pontides to lack evidence of north-vergent deformation in the area studied. We, therefore, see the north-vergent deformation as a mainly Late Cretaceous event in the area studied although, as noted earlier, there is evidence from adjacent areas of further north-verging displacement in the Mid-Eocene. In general, the south-vergent thrusts are capped by clastic units of Late Eocene age (Çankırı Basin; Central Pontides), which are interpreted to post-date final suturing of the Northern Neotethys. These Eocene and younger sediments were further deformed by further south-vergent thrusting of pre-Plio-Quaternary age, which is seen as the result of post-collisional suture tightening.

Comparison of the Central and Eastern Pontides

It is important to decide whether the Central and Eastern Pontide units of the IASZ exhibit a similar tectonic evolution.

Two large slices of inferred Upper Cretaceous volcanic arc units are present in both areas (Fig. 14a and b), associated with emplaced accretionary complexes and dismembered ophiolites. However, the Upper Cretaceous mixed terrigenous–volcaniclastic–volcanic unit (Ikiçam Formation), interpreted as a back-arc marginal basin, is exposed only in the Central Pontides. On the other hand, a thick succession of inferred forearc basin sediments (Sütpınar Formation) is widely exposed only in the Eastern Pontides, probably because its Upper Cretaceous counterpart in the Central Pontides (Yapraklı Formation) has been largely concealed by the post-suturing Çankırı Basin. Ophiolitic units crop out far more extensively in the Eastern Pontides (Refahiye unit) than the Central Pontides (Kızılırmak units). Ophiolitic volcanic rocks are well represented in the Central Pontides but not exposed in the Eastern Pontides.

Each of the above Upper Cretaceous units occupies a distinct structural position within the suture zone (Fig. 14a and b). The ophiolitic units in both the Central and Eastern Pontides occur towards the top of the thrust stack. As an exception, relatively small exposures of ophiolitic rocks are present in the southern part of the Eastern Pontide area; these could represent large tectonic blocks within accretionary mélange. In both areas two thrust slices of inferred volcanic arc rocks occur towards the middle of the thrust stack. The upper of these two slices is more deformed in both areas. Metamorphic minerals and textures are better developed in the upper slice, suggesting a slightly higher metamorphic grade, although a greenschist-facies mineral assemblage is present in both of the inferred arc units. In addition, the ophiolitic mélange is distributed throughout the thrust stack in both areas. In the Central Pontides, thrust slices of the thick, Upper Cretaceous, inferred marginal basin unit (İkiçam Formation) mainly occur towards the top of the structural pile. The Upper Cretaceous forearc-type sediments (Yapraklı Formation) that locally unconformably overlie the inferred arc unit (Yaylaçayı Formation) occur at

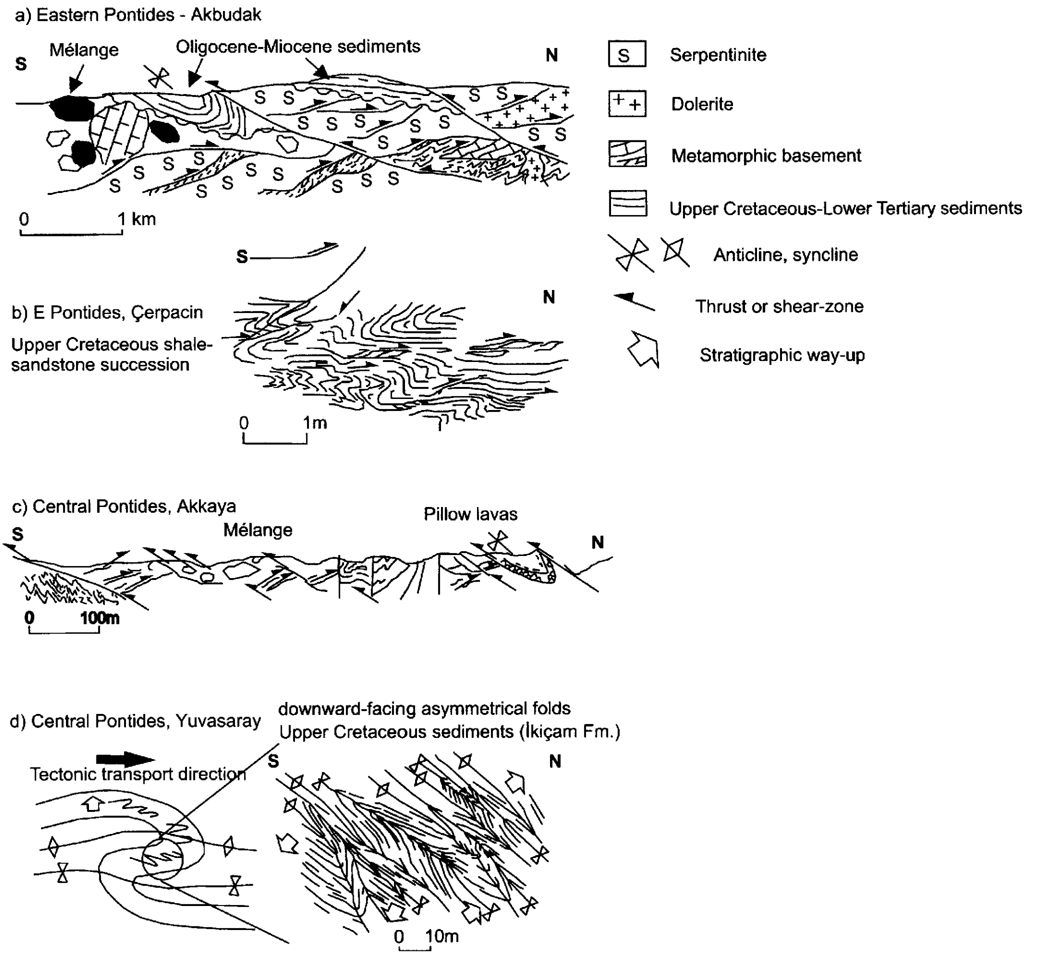

Fig. 13. Selected exposures from the Eastern Pontides (**a**, **b**) and the Central Pontides (**c**, **d**) showing the northward kinematic vergence within Upper Cretaceous–Lower Cenozoic units. (See text for explanation.)

a low level in the thrust stack (Fig 14a). The thick Upper Cretaceous inferred forearc basin succession in the Eastern Pontides (Sütpınar Formation) is also located at a low to mid-level in the thrust stack, where it is tectonically imbricated as two slices of the volcanic arc unit.

Basalts from the volcanic arc units in both areas (Karadağ and Yaylaçayı Formations) fall into the fields of island-arc and calc-alkali basalts, as summarized in Figure 15. A single sample from the Central Pontides (Yaylaçayı Formation) plots just within the field of within-plate type basalts. The ophiolitic basaltic dykes from the Eastern Pontides (Refahiye Complex) lie within the fields of ocean-floor basalts and island-arc basalts. The basaltic rocks analysed from the Kızılırmak ophiolite in the Central Pontides are ocean-floor basalts or island-arc basalts. Basalts from the mélange (not shown) exhibit MORB and WPB geochemical signatures in both areas (Rice 2005).

In summary, the above comparisons indicate that there are sufficient similarities between the Late Cretaceous–Early Cenozoic tectonostratigraphy of the Central and the Eastern Pontides to suggest that both originated in a similar overall tectonic setting, *c.* 600 km apart along strike from each other. The two areas can thus be taken together when considering possible tectonic models (see below). Little useful information is available from the intervening areas, which are generally less well exposed.

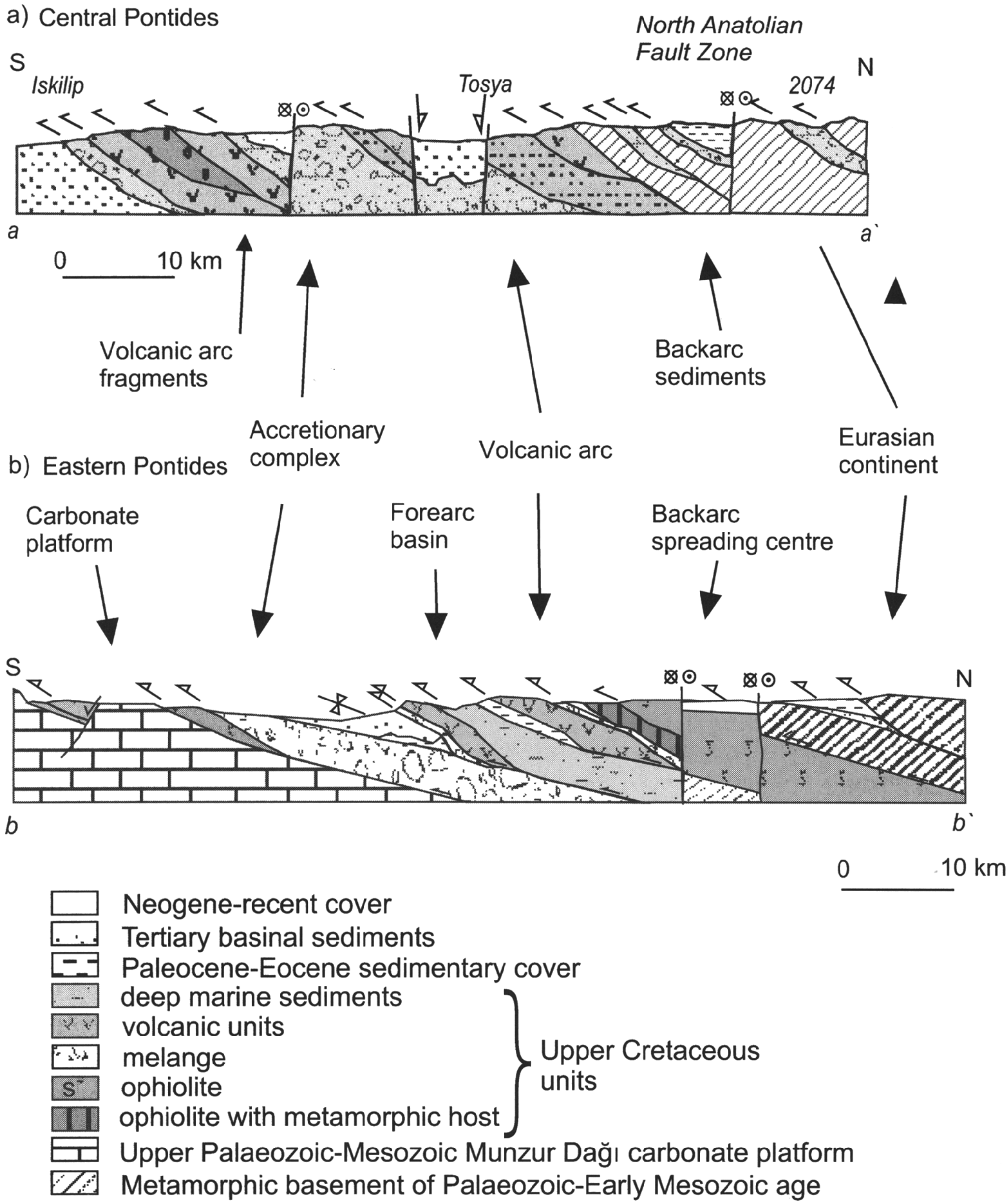

Fig. 14. Interpretative cross-sections of tectonostratigraphic units within **(a)** Central Pontides, and **(b)** Eastern Pontides. (See text for explanation.)

Comparison with adjacent areas of the Eurasian margin

The evolution of the Eurasian continental margin can be documented from the relatively autochthonous Pontide basement to the north. In the Eastern Pontides, Cretaceous–Eocene calc-alkaline volcanic rocks of the Eastern Pontide arc (up to 4 km thick) are exposed *c.* 50 km north of the suture zone, extending eastwards. These volcanic rocks are traditionally interpreted as part of a continental margin-type magmatic arc related to northward subduction of the Northern Neotethys (Şengör & Yılmaz 1981;

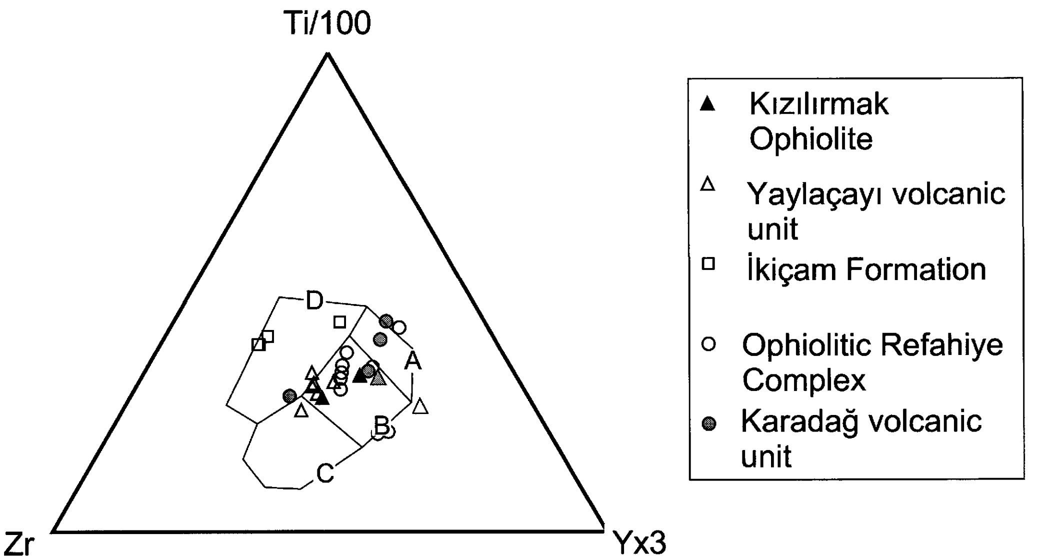

Fig. 15. Summary of the compositions of Central and Eastern Pontides basalts plotted on a Ti–Zr–Y diagram (Pearce & Cann 1973). Ocean-floor basalts, field B; island-arc basalts, fields A and B; calc-alkaline basalts, fields B and C; within-plate basalts, field D.

Akıncı 1984; Robertson & Dixon 1984; Okay & Şahintürk 1997; Yılmaz *et al.* 1997). Subduction-related volcanism in the Eastern Pontides arc began in the Turonian (Taner & Zaninetti 1978), or at the Late Coniacian–Santonian boundary (Yılmaz *et al.* 2003) according to different views. The arc-related volcanic rocks are overlain by Campanian pelagic limestones (Akıncı 1984), which in turn are overlain by Eocene volcanic rocks including high-K andesites (Bektaş *et al.* 1999). It was recently suggested that the Eastern Pontide arc might instead relate to southward subduction of oceanic crust within the Black Sea region to the north, based on geochemical evidence (Bektaş *et al.* 1999). Southward subduction of Western Black Sea lithosphere has also been proposed based on the interpretation of seismic data (Hossack 2004). However, this interpretation is yet to be supported by independent structural or stratigraphical field evidence. Also, it is not clear whether the Eocene volcanic rocks relate to a subduction-related setting or a syn- to post-collisional tectonic setting.

Another relevant unit, located much further west, is the Galatean Volcanic Province in the Central Pontides. The lower part of this unit, known as the Saraçköy Volcanic Suite, is located *c.* 80 km SW of the area studied. This suite of lavas was radiometrically dated at 76.4 ± 2.4 Ma (Late Campanian), and inferred to represent an extensional back-arc setting (Koçyiğit *et al.* 2003). By contrast, most of the overlying Galatean Volcanic Province represents post-collisional magmatism of Oligocene–Miocene age. The Saraçköy Volcanic Suite is geochemically similar to the Campanian–Maastrichtian Yaylaçayı Formation and might represent a more southwesterly extension of this inferred volcanic arc unit. By contrast, a back-arc marginal basin, interpreted by us as a Late Cretaceous marginal basin, restores to a more northerly position behind the Yaylaçayı volcanic arc unit.

In addition, kilometres-thick sedimentary basins of latest Cretaceous to Mid-Eocene age, for example in the Haymana–Polatlı region, near Ankara (e.g. Koçyiğit 1991) are widely interpreted as forearc basins related to northward subduction of the Northern Neotethys that persisted until Mid-Eocene time (Görür *et al.* 1984). However, there is little regional evidence of steady-state subduction after latest Cretaceous time when regional northward thrusting took place; for example, an Early Cenozoic accretionary prism is not known to exist. It is, therefore, likely that the Haymana–Polatlı basin and other parts of the Central Anatolian basin complex developed in a regional setting of incipient collision ('soft collision') in the latest Cretaceous (Campanian–Maastrichtian), followed by final collision ('hard collision') during Mid-Eocene time (Clark & Robertson 2002).

Comparisons with modern settings

Useful insights into the tectonic development of the Pontides can also be gained from comparisons with a range of modern and ancient convergent margin settings, including accretionary prisms, arcs and back-arc basins.

The Pontide mélanges are comparable with many examples of accretionary mélange, including those associated with ophiolite emplacement (e.g. Late Cretaceous Oman mélange; Searle & Cox 1999; Robertson 2002, 2006), and those formed in active continental margin settings (e.g. Franciscan Complex, USA; Cloos 1982). The Pontide inferred arc and back-arc units are generally similar to other examples including the Dras–Kohistan arc (Robertson & Degnan 1994; Clift *et al.* 2002) and the associated Shyok back-arc basin in the Himalayas (Robertson & Collins 2002), although these units appear to have formed in a more oceanic setting, far from the Eurasian margin.

Useful comparisons can also be made with both ancient (e.g. Western USA; Eastern Mediterranean; Southern Andes) and extant back-arc basins (e.g. Japan Sea; South Atlantic Bransfield Strait).

Several Eastern Mediterranean examples are directly relevant. The Late Palaeozoic–Early Mesozoic Küre marginal basin in the Central Pontides opened by rifting of the Eurasian continental margin in response to inferred northward subduction during Late Palaeozoic–Early Mesozoic time (Ustaömer & Robertson 1994, 1997), and later collapsed prior to Late Jurassic time related to southward underthrusting. Opposing subduction also features in our preferred tectonic model for the areas studied (see below). The ophiolitic extrusive rocks of the Küre Basin are of near-MORB composition, with a small negative Nb anomaly (Ustaömer & Robertson 1999). Further west, in northern Greece, a Guevgueli ophiolite formed within a rifted continental unit (Serbo-Macedonian zone) during Mid–Late Jurassic time (Bébien *et al.* 1987). This ophiolite retains primary intrusive contacts with metamorphic rocks, comparable with the screens of country rock within the Eastern Pontide ophiolitic dykes. The ophiolitic extrusive rocks are mainly of MORB-type but locally show a minor subduction influence. The back-arc ophiolite was bordered on its oceanic side by a rifted continental fragment, capped by a Jurassic magmatic arc (Brown & Robertson 2003). These comparisons indicate that subduction-related processes were active along the Eurasian margin prior to Late Mesozoic time.

Within the circum-Pacific region, the Jurassic Josephine marginal basin rifted along a pre-existing accretionary margin during Mid–Late Jurassic time. The back-arc basin was bordered on its oceanward side by an active arc (Chetco arc). The back-arc crust was overlain by mainly terrigenous but locally volcaniclastic sediments (Galice unit). This marginal basin closed, oceanwards, beneath the arc, resulting in the emplacement of oceanic lithosphere (Josephine Ophiolite) onto the continental margin (Harper 1984). A similar model is favoured for the Pontide areas studied.

Another comparable ancient continental margin back-arc basin setting is the Rocas Verdes mafic complex (Sarmiento and Tortuga ophiolites) in southern Chile (Dalziel *et al.* 1974; Rabinowitz & La Breque 1979; Weaver *et al.* 1979; Dalziel 1986; Dilek & Flower 2004). This comprises discontinuous exposures of gabbros, sheeted dykes and pillow basalts (> 3 km thick), interpreted as deformed, uplifted (but relatively autochthonous) marginal basin crust. The presence of pillow basalts overlain by tuffs, volcaniclastic sediments and cherts suggests proximity to an active volcanic arc. The Andean ophiolites formed between Palaeozoic basement to the east and an Early Cretaceous andesitic arc to the west (Patagonian Batholith). The ophiolitic rocks locally intrude metamorphic basement, supporting an intra-continental origin (Dalziel *et al.* 1974). Deformational structures within the Andean ophiolites indicate eastward displacement, towards the continental interior. N-MORB-normalized trace-element patterns from the ophiolitic basalts (Sarmiento and Tortuga) show a general enrichment in LILE relative to HFSE and a negative Nb anomaly, suggestive of a subduction influence. In contrast to the Pontide examples, the Southern Andean marginal basin formed well within the continental borderland and a large continental fragment was rifted.

A comparable modern-day intracontinental marginal basin is the Bransfield Strait, South Atlantic. This is inferred to have formed in a suprasubduction-zone setting, with the development of a back-arc spreading centre related to trench rollback (e.g. Keller & Fisk 1992). The arc rocks are exposed on the South Shetland Islands, where the oldest extrusive rocks are mostly low-K, high-alumina basalts, basaltic andesites and low-silica andesites of Aptian age. Cogenetic gabbros, tonalites and granodiorites are also exposed. Samples dredged from the centre of the Bransfield Strait are geochemically variable and plot in the combined field of ocean-floor, island-arc and calc-alkaline basalts (Keller & Fisk 1992). The Upper Cretaceous ophiolites of the

Central and Eastern Pontides are likely to have formed in a similar setting to the Bransfield Strait.

In general, oceanic subduction zones may either retreat (roll-back) towards the ocean associated with an extensional stress field in the upper plate (Mariana-type subduction; Uyeda & Kanamori 1979; Uyeda 1982), or instead advance towards the hinterland, resulting in compression. Intra-oceanic trench retreat can accommodate the opening of back-arc basins (e.g. Mariana and Lau basins). 'Retreating accretionary orogens' characterize the Western Pacific region; e.g. Mariana (Karig 1971), Sea of Japan (Uyeda 1982), Scotia Sea (Saunders & Tarney 1984) and the Bransfield Strait (Keller & Fisk 1992). A change from a retreating orogen to an advancing one can be triggered by local, regional, or global factors, including: (1) changes in the forces acting on the subducting lithosphere as its angle of descent changes (Royden 1993); (2) changes in regional-scale relative plate motions (Dalziel *et al.* 1974; Smith 2006); (3) lateral mantle flow (Flower 2003); (4) arrival of a large bathymetric feature (e.g. seamount) at the trench (Cadet *et al.* 1987). In the Pontides, a switch from a 'retreating orogen' to an 'advancing orogen' was triggered by the arrival of the Tauride continental margin (e.g. Munzur Platform) at the subduction trench, as discussed below.

Alternative tectonic models

We now consider alternative tectonic interpretations for the Late Mesozoic–Early Cenozoic development of the Central and Eastern Pontides in the light of the modern and ancient comparisons.

Previous models

In a simple tectonic model, envisaged by Şengör & Yılmaz (1981; Fig. 16a) a single north-dipping subduction zone consumed MOR-type Northern Neotethyan oceanic lithosphere. This subduction generated the Eastern Pontide arc and eventually resulted in southward ophiolite emplacement onto the Tauride–Anatolide platform related to trench–margin collision. This model does not, however, explain the emplacement of Neotethyan ophiolitic units northwards onto the Eurasian margin. Also, the available geochemical evidence suggests that the Pontide ophiolites formed in a Late Cretaceous SSZ setting rather than at a mid-ocean ridge. Furthermore, the presence of screens of dyke-intruded metamorphic basement rock within the Eastern Pontide ophiolite suggest that this unit formed by rifting of the Eurasian continental margin.

A second model (Fig. 16b) envisages two subduction zones, one developing beneath the Pontide margin and another within the ocean to the south (Tüysüz 1990); however, the polarity and timing of this intra-oceanic subduction were not clearly specified.

A third model postulates a subduction polarity reversal (Okay & Şahintürk 1997): ophiolites were first emplaced northwards onto the Pontide basement as a result of trench–margin collision during Cenomanian–Turonian (*c.* 93 Ma; Fig. 16c, i); subduction then flipped to consume remaining oceanic crust beneath the Eurasian margin, creating the Eastern Pontide magmatic arc during the Palaeogene (Fig. 16c, ii). The main problems here are that (1) Eastern Pontide arc volcanism began as early as the Turonian (Taner & Zaninetti 1978), or Coniacian (Yılmaz *et al.* 1997), rather than Palaeocene as would be expected in this interpretation; (2) the model does not explain the southward emplacement over the collapsed Munzur Dağı carbonate platform during the latest Cretaceous; and (3) the model assumes that the Eocene volcanic rocks of the Eastern Pontides relate to normal subduction when they may instead have erupted in a syn- or post-collisional setting.

In a fourth alternative (Fig. 16d), Neotethyan oceanic crust was subducted northwards related to opening of a marginal basin along the Eurasian margin; this basin later collapsed and ophiolites were emplaced northwards onto the Pontide margin (Ustaömer & Robertson 1997). However, the timing and processes involved were not clearly specified.

Proposed new model

The interpretation that best fits our new information is shown in Figure 17. Northward subduction is seen as initiating within the Northern Neotethys adjacent to the Eurasian margin during the Late Cretaceous (Cenomanian–Turonian?). This led to the construction of a Late Cretaceous (Santonian?–Campanian) marginal volcanic arc (Fig. 17a) and an accretionary prism made up of mainly Cretaceous-aged fragments of oceanic crust, deep-sea sediments and seamounts. In addition, tectonic erosion of the forearc could explain the presence of SSZ-type harzburgite blocks and slices in the mélange (e.g. Beccaluva *et al.* 2004).

It is possible that the subduction zone trended at an oblique angle to the Eurasian margin. As a result, the belt of arc volcanism was located well inboard to the east within the Eastern Pontides (Artvin region), but then intersected with and

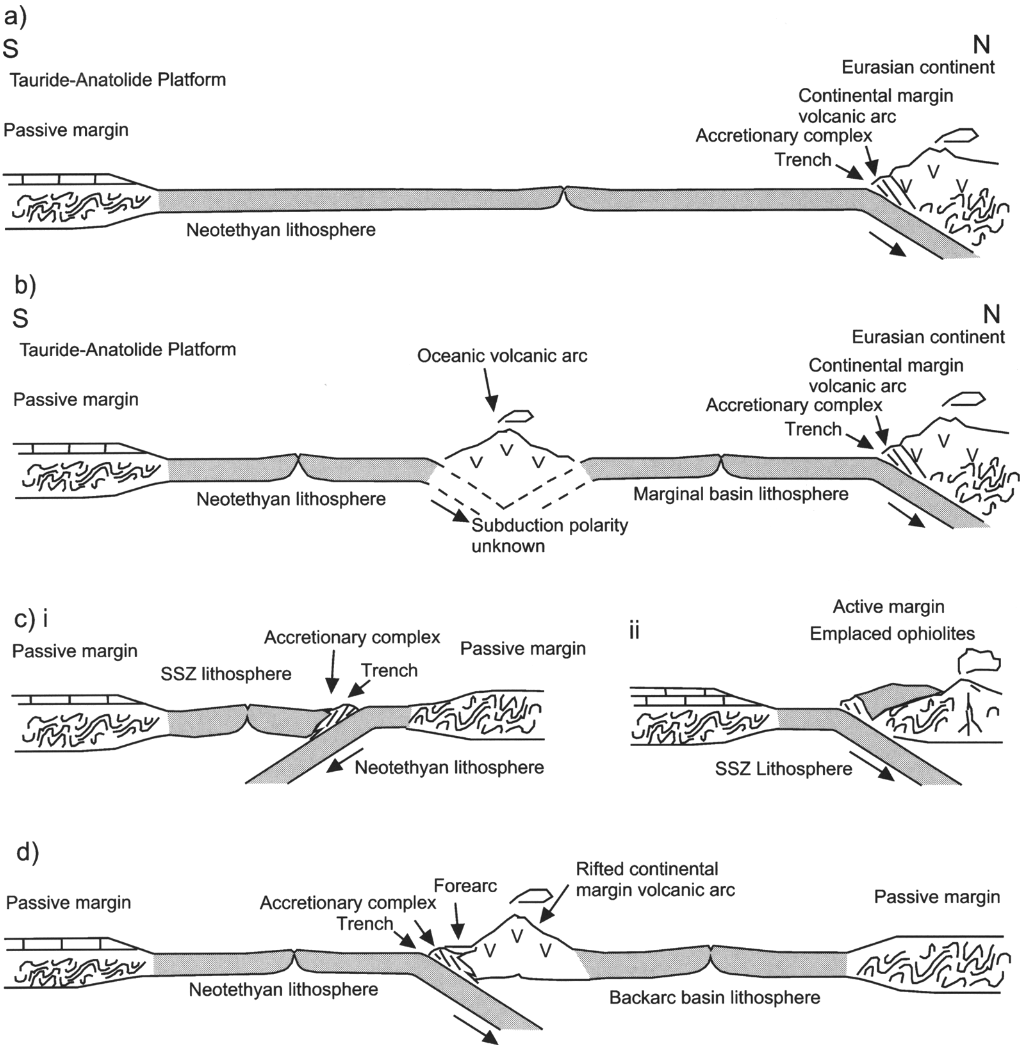

Fig. 16. Published tectonic models for the Late Cretaceous–Early Cenozoic tectonic assembly of the suture zone in the Pontides, generally: (**a**) single northward-dipping subduction zone (Şengör & Yılmaz 1981); (**b**) two northward-dipping subduction zones (polarity of oceanic arc not specified; Tüysüz 1990); (**c**) southward-dipping subduction, followed by reversal of subduction direction (Okay & Şahintürk 1997); (**d**) single northward-dipping subduction zone with the genesis and emplacement of a marginal basin (timing not specified; Ustaömer & Robertson 1997). (See text for discussion.)

straddled the continental margin further west in the Eastern and Central Pontide areas studied. Further west the arc was possibly located some distance out into the Northern Neotethys, which would explain the apparent absence of Late Cretaceous arc volcanic rocks on the Eurasian margin in the Western Pontides.

A back-arc basin (mainly Campanian) rifted along the south Eurasian margin within the Pontide continental basement (Fig. 17b), explaining the inclusions of metamorphic rocks within the Refahiye ophiolite in the Eastern Pontides. As the back-arc basin opened (Fig. 17c) the active arc migrated oceanwards, switching off the Eastern Pontide arc prior to the Campanian. Subduction of the Northern Neotethys continued in latest Cretaceous time (Campanian–Maastrichtian) until the trench began to collide with the leading edge of the Tauride continent, represented in the Eastern Pontides by the north-facing Munzur platform. The resulting collision drove the southward emplacement of the

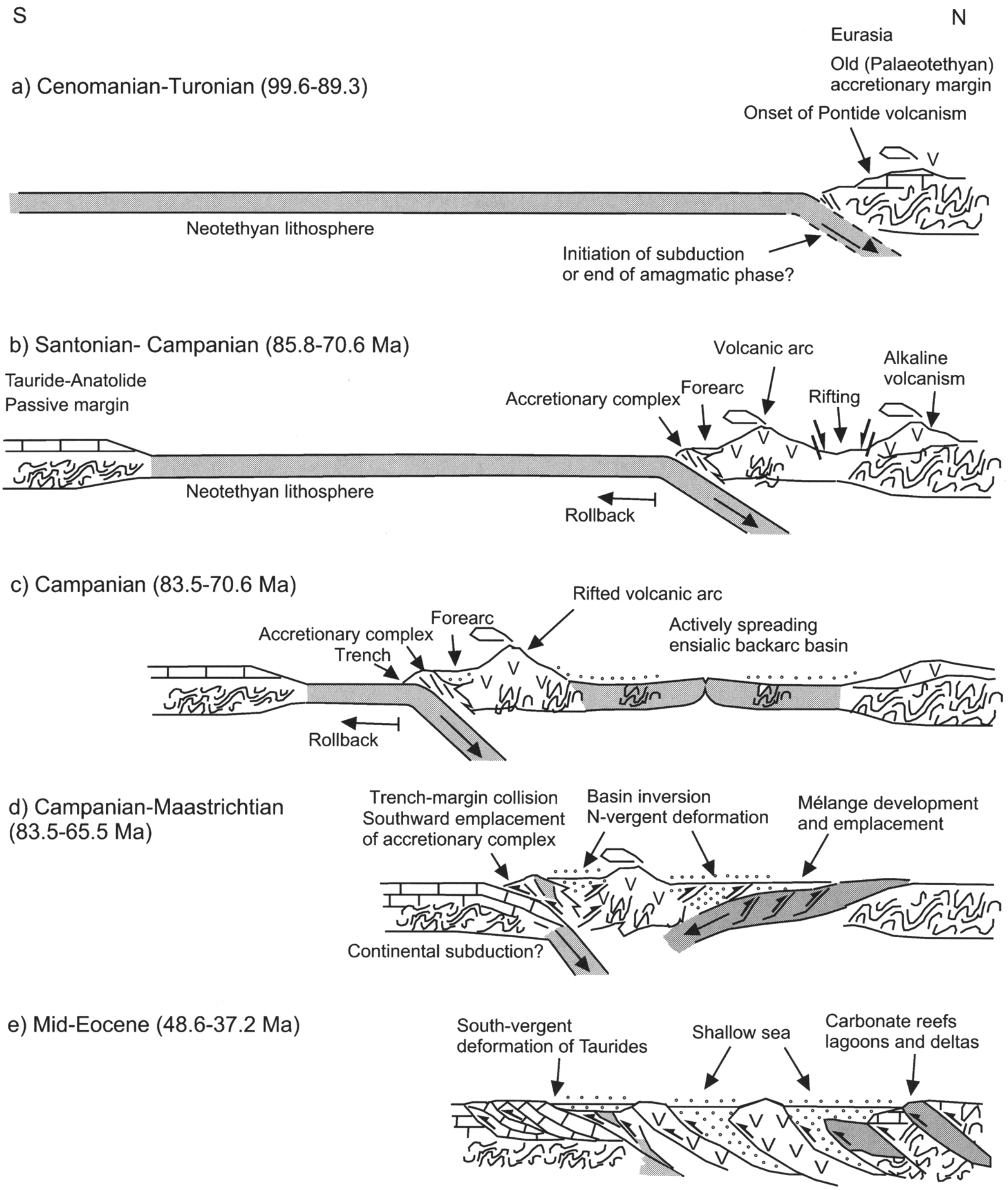

Fig. 17. Proposed new tectonic model for the development of the suture zone in the Pontides. (See text for explanation.)

Neotethyan accretionary mélange, arc and ophiolitic units onto the Munzur carbonate platform, which by then had collapsed (Fig. 17d).

The Late Cretaceous oceanic crust within the back-arc marginal basin was then subducted southwards until the convergence zone collided with the Eurasian margin, still during Campanian–Maastrichtian time, as best documented in the Central Pontides. This explains the initial northward emplacement of ophiolites and related units onto the Pontide basement prior to the Paleocene in the areas studied. It is interesting to note that seismic tomographic studies reveal a high-velocity slab (i.e. a high-Q body) dipping southwards beneath the region (Koulakov *et al.* 2002), which could relate to a south-dipping subduction zone.

Because allochthonous oceanic units were emplaced onto both the Eurasian and Tauride margins during the Campanian–Maastrichtian (e.g. Eastern Pontides) it is likely that the Northern Neotethys was in the process of closing completely by this time ('soft collision'). However, during the Paleocene–Early Eocene some oceanic crust persisted between the Taurides and Pontides, especially within embayments, and this was presumably subducted northwards.

During the Mid-Eocene the Tauride margin underwent attempted subduction beneath the Eurasian margin. During the collision that ensued ('hard collision') the entire thrust stack was re-imbricated and thrust southwards (Fig. 17e). The northward thrusting in some area can be seen as a related phase of backthrusting. Further south-vergent folding and thrusting, documented within Oligocene and Miocene sedimentary basins, are seen as a response to post-collisional suture tightening.

The main difficulty we see with the above tectonic model is that much of the tectonic development took place during Campanian–Maastrichtian time; a period of *c.* 18 Ma that at present cannot be adequately resolved. Thus, tectonic processes that appear to be broadly contemporaneous may in reality have been discrete, sequential events (e.g. back-arc opening and closure).

Conclusions

The Izmir–Ankara–Erzincan suture zone in the Central and Eastern Pontide regions exposes Upper Cretaceous units that record the development of an accretionary complex, a volcanic arc, a forearc basin and a rifted back-arc basin.

The following Late Cretaceous–Early Cenozoic stages of tectonic development are inferred.

Late Cretaceous (Cenomanian–Coniacian; c. *99.6–85.8Ma).* Neotethyan oceanic crust was subducted northwards beneath the Eurasian continental margin, represented by the Pontide metamorphic basement, leading to the initiation of the Eastern Pontide arc. A frontal accretionary prism developed composed of fragments of pelagic sediments, basalt and seamounts (e.g. basalt–limestone–chert). Serpentinite was possibly derived from the overriding forearc. Subduction–accretion persisted until Campanian–Maastrichtian time, but there is no evidence of Palaeogene accretion.

Santonian–Campanian (85.5–70 Ma). A volcanic arc was constructed bordering the Eurasian continental margin in the Central and Eastern Pontides. Subduction zone 'rollback' triggered back-arc rifting, giving rise to subduction-influenced volcanism and minor extension-related alkaline magmatism in the north (Central Pontides). Metamorphic basement was incorporated into an extension-related dyke complex (Eastern Pontides). A back-arc marginal basin opened, floored by oceanic lithosphere and overlain by redeposited terrigenous, volcaniclastic and pelagic sediments. The activity of the Eastern Pontide arc ceased prior to the Campanian, whereas arc volcanism continued in a more outboard location. Deep-water pelagic and volcaniclastic sediments accumulated in associated fore-arc basins to the south.

Campanian–Maastrichtian (85.8–65.5 Ma). The Tauride continent (e.g. Munzur carbonate platform) collided with the subduction trench. With continued convergence the leading edge of the Tauride continent entered the trench, and the accretionary complex, the arc and its related forearc basin were thrust southwards over the collapsed platform margin. In response, the forearc basin rapidly shallowed and filled. Further north, the inferred back-arc marginal basin was subducted (underthrust) southwards, resulting in the marginal basin ophiolite and its deep-sea sedimentary and volcanogenic cover being thrust northwards onto the Eurasian margin during Campanian–Maastrichtian time (e.g. Central Pontides), initiating a 'soft collision'.

Paleocene–Mid-Eocene (65.5–48.6 Ma). Shallow-marine to non-marine clastic and carbonate sediments accumulated on deformed and emplaced units. There is little evidence of convergence in the areas studied during this time. However, it is assumed that some Northern Neotethyan oceanic lithosphere persisted during this time and was subducted until a regional 'hard collision' took place.

*Mid–Late Eocene (*c. *48.6–37.4 Ma).* In response to the attempted northward subduction of the Tauride continental margin beneath the Eurasian margin the entire Northern Neotethyan thrust stack was re-imbricated and thrust southwards. Northward backthrusting also affected some areas.

Late Eocene–Late Miocene (37.4–5.33 Ma). The suture zone was largely emergent during the Oligocene, and then transgressed by shallow-water carbonates in some areas during the Miocene. Further compression and southward thrusting relates to post-collisional suture tightening.

Plio-Quaternary. Segments of the suture zone experienced left-lateral displacement (by up to 80 km) along the North Anatolian Fault Zone in both the Central and the Eastern Pontides, and this must be taken into account in any tectonic reconstruction.

S. R. acknowledges the financial support provided by an NERC PhD studentship. He also acknowledges Ö. Karslıoğlu, Y. Aydar and L. Meston for invaluable assistance in the field. A.H.F.R. acknowledges the Carnegie Trust for the Scottish Universities for financial assistance with fieldwork. Palaeontological determinations for this work were kindly provided to A.H.F.R. by N. İnan and K. Taşlı (Mersin University), mainly for the Eastern Pontides. Additional data were provided to T.U. by İ. Öngen (İstanbul University) mainly for the Central Pontides.

References

AKINCI, Ö. T. 1984. The Eastern Pontide volcano-sedimentary belt and associated massive sulphide deposits. *In*: ROBERTSON, A. H. F. & DIXON, J. E. (eds) *The Geological Evolution of the Eastern Mediterranean Region*. Geological Society, London, Special Publications, **17**, 415–428.

ANDERSON, R. N., DELONG, S. E. & SCHWARZ, W. H. 1978. Thermal model for subduction with dehydration in the downgoing slab. *Journal of Geology*, **86**, 731–739.

BARKER, D. H. N., CHRISTESON, G. L., AUSTIN, J. A., JR & DALZIEL, I. W. D. 2003. Backarc basin evolution and cordilleran orogenesis: insights from new ocean-bottom seismograph refraction profiling in Bransfield Strait, Antarctica. *Geological Society of America Bulletin*, **31**(2), 107–110.

BÉBIEN, J., BAROZ, J., CAPERDI, S. & VENTURELLI, G. 1987. Magmatisme basique associées à l'ouverture d'un basin marginal dans les Hellénides internes au Jurassic. *Ofioliti*, **12**, 53–70.

BECCALUVA, L., COLTORTI, M., GIUNTA, G. & SIENA, F. 2004. Tethyan vs. Cordilleran ophiolites: a reappraisal of distinctive tectono-magmatic features of supra-subduction complexes in relation to the subduction mode. *Tectonophysics*, **393**(1–4), 163–174.

BEKTAŞ, O., ŞEN, C., ATICI, Y. & KÖPRÜBAŞI, N. 1999. Migration of Upper Cretaceous subduction-related volcanism towards the back-arc basin of the Eastern Pontide magmatic arc (NE Turkey). *Geological Journal*, **34**, 95–106.

BERGOUGNAN, H. 1975. Relations entre les édifices pontique et taurique dans le Nord-Est de l'Anatolie. *Bulletin de la Societé Géologique de France*, XVII, 7(6), 1045–1057.

BİRGİLİ, Ş., YOLDAŞ, R. & ÜNALAN, G. 1975. *Çankırı–Çorum havzasının jeolojisi ve petrol olanakları*. MTA Enstitüsü, Rapor, **5621**.

BROWN, S. A. M. & ROBERTSON, A. H. F. 2003. Sedimentary geology as a key to understanding the tectonic evolution of the Mesozoic–Early Tertiary Paikon Massif, Vardar suture zone, N Greece. *Sedimentary Geology*, **160**, 179–212.

CADET, J.-P., KOBAYASHI, K., AUBOUIN, J., *et al.* 1987. The Japan Trench and its juncture with the Kuril Trench: cruise of the Kaiko project, Leg 3. *Earth and Planetary Science Letters*, **83**, 267–284.

CLARK, M. S. & ROBERTSON, A. H. F. 2002. The role of the Early Tertiary Ulukışla Basin, southern Turkey in suturing of the Mesozoic Tethys ocean. *Journal of the Geological Society, London*, **159**, 673–690.

CLIFT, P. D., HANNIGAN, R., BLUSZTAJN, J. & DRAUT, A. E. 2002. Geochemical evolution of the Dras–Kohistan Arc during collision with Eurasia: evidence from the Ladakh Himalaya, India. *The Island Arc*, **11**, 255–273.

CLOOS, M. 1982. Flow mélange, numerical modelling and geological constraints on the origin of the Franciscan Complex, California. *Geological Society of America Bulletin*, **93**, 330–345.

DALZIEL, I. W. D. 1986. Collision and Cordilleran orogenesis: an Andean perspective. *In*: COWARD, M. P. & RIES, A. C. (eds) *Collision Tectonics*. Geological Society, London, Special Publications, **19**, 389–404.

DALZIEL, I. W. D., DEWIT, M. J. & PALMER, K. F. 1974. Fossil marginal basin in the southern Andes. *Nature*, **250**, 291–294.

DERCOURT, J., ZONENSHAIN, L. P., RICOU, L. E., *et al.* 1986. Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. *Tectonophysics*, **123**, 241–315.

DICK, H. J. B. & BULLEN, T. 1984. Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. *Contributions to Mineralogy and Petrology*, **86**, 54–76.

DIETRICH, V., EMMERMANN, R., OBERHANSLI, R. & PUCHELT, H. 1978. Geochemistry of basaltic and gabbroic rocks from the West Mariana basin and the Mariana trench. *Earth and Planetary Science Letters*, **39**, 127–144.

DILEK, Y. & FLOWER, M. F. S. 2004. Arc–trench rollback and forearc accretion; 2. A model template for ophiolites in Albania, Cyprus and Oman. In: DILEK, Y. & ROBINSON, P. T. (eds) *Ophiolites in Earth History*. Geological Society, London, Special Publications, **218**, 43–68.

DROOP, G. T. R. 1987. A general equation for estimating Fe^{3+} concentrations in ferromagnesian silicates and oxides from microprobe analyses, using stoichiometric criteria. *Mineralogical Magazine*, **51**, 431–435.

FITTON, J. G., SAUNDERS, A. D., LARSEN, L. M., HARDARSON, B. S. & NORRY, M. J. 1998. Volcanic rocks from the southeast Greenland margin at 63°N: composition, petrogenesis and mantle sources. *In*: SAUNDERS, A. D., LARSEN, H. C. & WISE, S.W. JR (eds) *Proceedings of the Ocean Drilling Program, Scientific Results, 152*. Ocean Drilling Program, College Station, TX, 331–350.

FLOWER, M. F. J. 2003. Ophiolites, historical contingency, and the Wilson cycle. *In*: DILEK, Y. & NEWCOMB, S. (Eds) *Ophiolite Concept and the Evolution of Geological Thought*. Geological Society of America, Special Papers, **373**, 111–136.

GARFUNKEL, Z. 2006. Neotethyan ophiolites: formation and obduction within the life cycle of the host basin *In*: ROBERTSON, A. H. F. & MOUNTRAKIS, D. (eds) *Tectonic Development of the Eastern Mediterranean Region*. Geological Society, London, Special Publications, **260**, 301–326.

GÖRÜR, N., OKTAY, F. Y., SEYMEN, İ. & ŞENGÖR, A. M. C. 1984. Palaeotectonic evolution of the Tuzgölü Basin complex, central Turkey: sedimentary record of a Neotethyan closure. *In*: DIXON, J. E. & ROBERTSON, A. H. F. (eds) *The Geological Evolution of the Eastern Mediterranean*. Geological Society, London, Special Publications, **17**, 467–482.

GRADSTEIN, F. M., OGG, J. G., SMITH, A. G., *et al.* 2004. *A Geological Time Scale 2004*. Cambridge University Press, Cambridge.

HARPER, G. D. 1984. The Josephine ophiolite, northwestern California. *Geological Society of America Bulletin* **95**, 1019–1026.

HOSSACK, J. 2004. The tectonic evolution of the Black Sea. *In*: BEACH, A., BUTLER, R., GRAHAM, R., KNIPE, R., MCCLAY, K., RIES, A. & STEWART, S. (eds) *Continental Tectonics: Discussion Meeting in Memory of the Life and Work of Mike Coward*. Geological Society, London (abstracts).

KARIG, D. E. 1971. Origin and development of the marginal basins in the Western Pacific. *Journal of Geophysical Research*, **76**, 2542–2561.

KAYMAKÇI, N. 2000. *Tectono-stratigraphical evolution of the Çankırı Basin (Central Anatolia, Turkey)*. PhD thesis, University of Utrecht.

KELLER, R. A. & FISK, M. R. 1992. Quaternary marginal basin volcanism in the Bransfield Strait as a modern analogue of the southern Chilean ophiolites. *In*: PARSON, L. M., MURTON, B. J. & BROWNING, P. (eds) *Ophiolites and their Modern Oceanic Analogues*. Geological Society, London, Special Publications, **60**, 155–169.

KOÇYİĞİT, A. 1990. Structural relationships of three suture zones to the west of Erzincan (NE Turkey): Karakaya, Inner Tauride and Erzincan sutures. *In*: *8th Petroleum Congress of Turkey, Turkish Association of Petroleum Geologists UCTEA Chamber of Petroleum Engineers*, 152–161.

KOÇYİĞİT, A. 1991. An example of an accretionary forearc basin from northern Central Anatolia and its implications for history of subduction of Neo-Tethys in Turkey. *Geological Society of America Bulletin*, **103**, 22–36.

KOÇYİĞİT, A., WINCHESTER, J. A., BOZKURT, E. & HOLLAND, G. 2003. Saraçköy volcanic suite: implications for the subductional phase of arc evolution in the Galatean Arc Complex, Ankara, Turkey. *Geological Journal*, **38**, 1–14.

KOLLER, F., HOECK, V., MEISEL, T., IONESCU, C., ONUZI, K. & GHEGA, D. Cumulates and gabbros in southern Albanian ophiolites: their bearing on regional tectonic setting. *In*: ROBERTSON, A. H. F. & MOUNTRAKIS, D. (eds) *Tectonic Development of the Eastern Mediterranean Region*. Geological Society, London, Special Publications, **260**, 267–299.

KOULAKOV, I., TYCHKOV, S., BUSHENKOVA, N. & VASILEVSKY, A. 2002. Structure and dynamics of the upper mantle beneath the Alpine–Himalayan orogenic belt, from teleseismic tomography. *Tectonophysics*, **358**, 77–96.

OKAY, A.I. & ŞAHİNTÜRK, Ö. 1997. Geology of the Eastern Pontides. *In*: ROBINSON, G. (ed.) *Regional and Petroleum Geology of the Black Sea and Surrounding Region*. American Association of Petroleum Geologists, Memoirs, **68**, 291–311.

OKAY, A. I., TANSEL, I. & TÜYSÜZ, O. 2001. Obduction, subduction and collision as reflected in the Upper Cretaceous–Lower Eocene sedimentary record of western Turkey. *Geological Magazine*, **138**(2), 117–142.

ÖZER, E., KOC, H. & OZSAYAR, T. Y. 2004. Stratigraphical evidence for the depression of the northern margin of the Menderes–Tauride Block (Turkey) during the Late Cretaceous. *Journal of Asian Earth Sciences*, **22**(5), 401–412.

ÖZGÜL, N. & TURŞUCU, A. 1984. Stratigraphy of the Mesozoic carbonate sequence of the Munzur Mountains (Eastern Taurides). *In*: TEKELI, O. & GÖNCÜOĞLU, C. (eds) *Geology of the Tauride Belt, International Symposium, Ankara*, 173–180.

PARLAK, O., HÖCK, V., KOZCU, H. & DELALOYE, M. 2004. Oceanic crust generation in an island arc tectonic setting, SE Anatolian Orogenic Belt (Turkey). *Geological Magazine*, **141**, 583–603.

PEARCE, J. A. 1982. Trace element characteristics of lavas from destructive plate boundaries. *In*: THORPE, R. S. (ed.) *Andesites*. Wiley, New York, 525–548.

PEARCE, J. A. & CANN, J. R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis. *Earth and Planetary Science Letters*, **19**, 290–300.

PEARCE, J. A., LIPPARD, S. J. & ROBERTS, S. 1984. Characteristics and tectonic significance of supra-subduction zone ophiolites. *In*: KOKELAAR, B. P. & HOWELLS, M. F. (eds) *Marginal Basin Geology*. Geological Society, London, Special Publications, **16**, 77–94.

RABINOWITZ, P. D. & LA BREQUE, J. 1979. The Mesozoic South Atlantic Ocean and evolution of its continental margins. *Journal of Geophysical Research*, **84**, 5973–6002.

RASSIOS, A. H. E. & MOORES, E. M. 2006. Heterogeneous mantle complex, crustal processes, and obduction kinematics in a unified Pindos–Vourinos ophiolitic slab (northern Greece). *In*: ROBERTSON, A. H. F. & MOUNTRAKIS, D. (eds) *Tectonic Development of the Eastern Mediterranean Region*. Geological Society, London, Special Publications, **260**, 237–266.

REED, S. J. B. 1975. *Electron Microprobe Analysis*. Cambridge University Press, Cambridge.

RICE, S. P. 2005. *The Role of an Upper Cretaceous Volcanic Arc in the Tectonic Assembly of the Tethyan Suture Zone: Pontides, Northern Turkey*. PhD thesis, Unversity of Edinburgh.

RIZAOĞLU, T., PARLAK, O., HÖCK, V. & İŞLER, F. 2006. Nature and significance of Late Cretaceous ophiolitic rocks and their relation to the Baskil granitic intrusions of the Elazığ region, SE Turkey. *In*: ROBERTSON, A. H. F. & MOUNTRAKIS, D. (eds) *Tectonic Development of the Eastern Mediterranean Region*. Geological Society, London, Special Publications, **260**, 327–349.

ROBERTSON, A. H. F. 2002. Overview of the genesis and emplacement of Mesozoic ophiolites in the Eastern Mediterranean Tethyan region. *Lithos*, **65**, 1–67.

ROBERTSON, A. H. F. 2006. Contrasting modes of ophiolite emplacement in the Eastern Mediterranean region. *In*: GEE, D. & STEPHENSON, R. A. (eds) *European Lithosphere Dynamics*. Geological Society of London, Memoir **32** (in press).

ROBERTSON, A. H. F. & COLLINS, A. S. 2002. Shyok Suture Zone: late Mesozoic–Tertiary evolution of a critical suture zone separating the oceanic Ladakh arc from the Asian continental margin. *Journal of Asian Earth Sciences*, **20**, 309–351.

ROBERTSON, A. H. F. & DEGNAN, D. J. 1994. The Dras arc Complex: lithofacies and reconstruction of a Late Cretaceous oceanic volcanic arc in the Indus Suture Zone, Ladakh Himalya. *Sedimentary Geology*, **92**, 117–145.

ROBERTSON, A. H. F. & DIXON, J. E. 1984. Introduction: aspects of the geological evolution of the Eastern Mediterranean. *In*: DIXON, J. E. & ROBERTSON, A. H. F. (eds) *The Geological Evolution of the Eastern Mediterranean*. Geological Society, London, Special Publications, **17**, 1–74.

ROJAY, B., YALINIZ, K. M. & ALTINER, D. 2001. Tectonic implications of some Cretaceous pillow basalts from the North Anatolian ophiolitic mélange (Central Anatolia–Turkey) to the evolution of Neotethys. *Turkish Journal of Earth Sciences*, **10**, 93–102.

ROYDEN, L. H. 1993. The tectonic expression of slab pull at continental convergent boundaries. *Tectonics*, **12**(2) 303–325.

SAUNDERS, A. D. & TARNEY, J. 1984. Geochemical characteristics of basaltic volcanism within back-arc basins. *In*: KOKELAAR, B. P. & HOWELLS, M. F. (eds) *Marginal Basin Geology*. Geological Society, London, Special Publicatios, **16**, 59–76.

SAUNDERS, A. D., TARNEY, J. & WEAVER, S. D. 1980. Transverse geochemical variations across the Antarctic Peninsula: implications for the genesis of calc-alkaline magmas. *Earth and Planetary Science Letters*, **46**, 344–360.

SEARLE, M. P. & COX, J. 1999. Tectonic setting, origin and obduction of the Oman ophiolite. *Geological Society of America Bulletin*, **111**, 104–122.

ŞENGÖR, A. M. C. & YILMAZ, Y. 1981. Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics*, **75**, 181–241.

SMITH, A. G. 2006. Tethyan ophiolite emplacement, Africa to Europe motions, and Atlantic speading. *In*: ROBERTSON, A. H. F. & MOUTRAKIS, D. (eds) *Tectonic Development of the Eastern Mediterranean Region*. Geological Society, London, Special Publications, **260**, 11–34.

STAMPFLI, G., MOSAR, J., FAURÉ, P., PILLEVUIT, A. & VANNAY, J.-C. 2001. Permo-Mesozoic evolution of the western Tethys realm: the Neotethys East Mediterranean basin connection. *In*: ZIEGLER, P., CAVAZZA, W., ROBERTSON, A. H. F. & CRASQUIN-SOLEAU, S. (eds) *Peri-Tethys Memoir No. 5 Peri-Tethyan Rift/Wrench Basins and Passive Margins*. Mémoires du Muséum National d'Histoire Naturelle, **182**, 51–10.

TANER, M. F. & ZANINETTI, L. 1978. Etude palaéontologique dans le Cretacé volcano-sedimentaire de Güneyce (Pontides orientales, Turquie). *Rivista Italiana di Paleontologica e Stratigrafica*, **84**, 187–198.

TAYLOR, R. N., MURTON, B. J. & NESBITT, R. W. 1992. Chemical transects across intra-oceanic arcs: implications for the tectonic setting of ophiolites. *In*: PARSON, L. M., MURTON, B. J. & BROWNING, P. (eds) *Ophiolites and their Modern Oceanic Analogues*. Geological Society, London, Special Publications, **60**, 117–132.

TOPUZ, G., ALTHERR, R., SATIR, M. & SCHWARZ, W. H. 2004. Low-grade metamorphic rocks from the Pulur complex, NE Turkey: implications for the pre-Liassic evolution of the Eastern Pontides. *International Journal of Earth Science (Geologische Rundschau)*, **93**, 72–91.

TÜYSÜZ, O., 1990. Tectonic evolution of a part of the Tethyside orogenic collage: the Kargı Massif, northern Turkey. *Tectonics*, **9**, 141–160.

TÜYSÜZ, O., YİĞİTBAŞ, E. & SERDAR, H. S. 1988. Vezirköprü–Boyabat dolayının jeolojisi. Turkish Petroleum Company (TPAO) Report, **55**.

TÜYSÜZ, O., DELLALOĞLU, A. A. & TERZİOĞLU, N. 1995. A magmatic belt within the Neo-Tethyan suture zone and its role in the tectonic evolution of northern Turkey. *Tectonophysics*, **243**, 173–191.

USTAÖMER, T. & ROBERTSON, A. H. F. 1994. Late Palaeozoic marginal basin and subduction–accretion: evidence from the Palaeotethyan Küre Complex, Central Pontides, N. Turkey. *Journal of the Geological Society, London*, **151**, 291–305.

USTAÖMER, T. & ROBERTSON, A. H. F. 1997. Tectonic–sedimentary evolution of the north Tethyan margin in the Central Pontides of northern Turkey. *In*: ROBINSON, A. G. (ed.) *Regional and Petroleum Geology of the Black Sea and Surrounding Region*. American Association of Petroleum Geologists, Memoirs, **68**, 255–290.

USTAÖMER, T. & ROBERTSON, A. H. F. 1999. Geochemical evidence used to test alternative plate tectonic models for pre-Upper Jurassic (Palaeotethyan) units in the Central Pontides, N. Turkey. *Geological Journal*, **34**, 25–54.

UYEDA, S. 1982. Subduction zones: an introduction to comparative subductology. *Tectonophysics*, **81**, 133–159.

UYEDA, S. & KANAMORI, H. 1979. Back-arc opening and the mode of subduction. *Journal of Geophysical Research*, **84**, 1049–1061.

WEAVER, S. D., SAUNDERS, A. D., PANKHURST, R. J. & TARNEY, J. 1979. A geochemical study of magmatism associated with the initial stages of back-arc spreading. The Quaternary volcanics of

Bransfield Strait, from South Shetland Islands. *Contributions to Mineralogy and Petrology*, **68**, 151–169.

YILMAZ, A. 1985. Basic geological characteristics and structural evolution of the region between the Upper Kelkit Creek and the Munzur Mountains. *Bulletin of the Geological Society of Turkey*, **28**, 79–92.

YILMAZ, Y., TÜYSÜZ, O., YİĞİTBAŞ, E. CAN GENÇ, Ş. & ŞENGÖR, A. M. C. 1997. Geology and tectonic evolution of the Pontides. *In*: ROBINSON, A. G. (ed.) *Regional and Petroleum Geology of the Black Sea and Surrounding Region*. American Association of Petroleum Geologists, Memoirs **68**, 183–226.

YILMAZ, C., ŞEN, C. & ÖZGÜR, S. 2003. Sedimentological, palaeontological and volcanic records of the earliest volcanic activity in the Eastern Pontide Cretaceous volcanic arc (NE Turkey). *Geologica Carpathica*, **54**(6), 377–384.

YOLDAŞ, R. 1982. *Tosya (Kastamonu) ile Bayat (Çorum) arasındaki bölgenin jeolojisi.* PhD thesis, Istanbul University.