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A geotraverse across northwestern Turkey: tectonic units of the Central Sakarya region and their tectonic evolution

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Abstract: In the Central Sakarya area of Turkey there are two main Alpine continental units, separated by a south verging ophiolitic complex which represents the root zone of the İzmir–Ankara Suture Belt.

The Central Sakarya Terrane in the north includes two 'Variscan' tectonic units in its basement. The Söğüt Metamorphic rocks represent a Variscan ensimatic arc complex and the Tepeköy Metamorphic rocks are characteristically a forearc–trench complex. The unconformably overlying Triassic Soğukkuyu Metamorphic rocks correspond to a part of the Karakaya Formation and are interpreted as a Triassic rift basin assemblage. These units are unconformably overlain by a transgressive sequence of Liassic–Late Cretaceous age that represents the northeastward deepening carbonate platform of the Sakarya Composite Terrane.

The middle tectonic unit (the Central Sakarya Ophiolitic Complex) comprises blocks and slices of dismembered ophiolites, blueschists and basic volcanic rocks with uppermost Jurassic–Lower Cretaceous radiolarite–limestone interlayers. Geochemical data from basalt blocks suggest mid-ocean ridge basalt (MORB)- and suprasubduction-type tectonic settings within the Neotethyan İzmir–Ankara Ocean.

The southern tectonic unit includes basal polyphase metamorphosed clastic rocks (Sömdiken Metamorphics), intruded by felsic and basic dykes and overlain by thick-bedded marbles. This assemblage is unconformably overlain by continental clastic rocks gradually giving way to thick-bedded recrystallized limestones, cherty limestones and pelagic limestones intercalated with radiolarites, and finally by a thick high pressure–low temperature (HP–LT) metamorphic synorogenic flysch sequence. This succession is identical to the passive continental margin sequences of the Tauride Platform. It is suggested that this passive margin was subducted during the Late Cretaceous in an intra-oceanic subduction zone and affected by HP–LT metamorphism. The emplacement of the allochthonous oceanic assemblages and the collision with the Central Sakarya Terrane was complete by the end of the Cretaceous.

Turkey is an east–west trending segment of the Alpine–Himalayan orogenic belt, and is located on the boundary between Gondwana in the south and Laurasia in the north. Within this belt, different continental and oceanic assemblages related to the opening and closure of the Palaeozoic and Mesozoic oceanic basins can be found. These oceanic basins are collectively named the Tethys Ocean.

One of the most critical problems on the Tethyan evolution of northwestern Turkey is the location of the oceanic suture root zones and the interrelations of Palaeo- and Neotethyan terranes. The Central Sakarya region (Fig. 1) is a key area where tectonic elements of both the Palaeo- and Neotethyan assemblages crop out.

It is frequently accepted that in this area three Alpine microplates occur (Şengör & Yılmaz 1981; Okay 1989; Göncüoğlu & Erendil 1990; Yılmaz 1990). The northernmost terrane is represented by the İstanbul Nappe of Şengör & Yılmaz (1981) or the İstanbul Zone of Okay (1989). It is separated from the Sakarya Microcontinent to the south (Şengör & Yılmaz 1981) by the Intra-Pontide Suture Zone. The major Neotethyan Vardar–İzmir–Ankara Suture Zone, on the other hand, separates the Sakarya Microcontinent from the Anatolides that represents the northern

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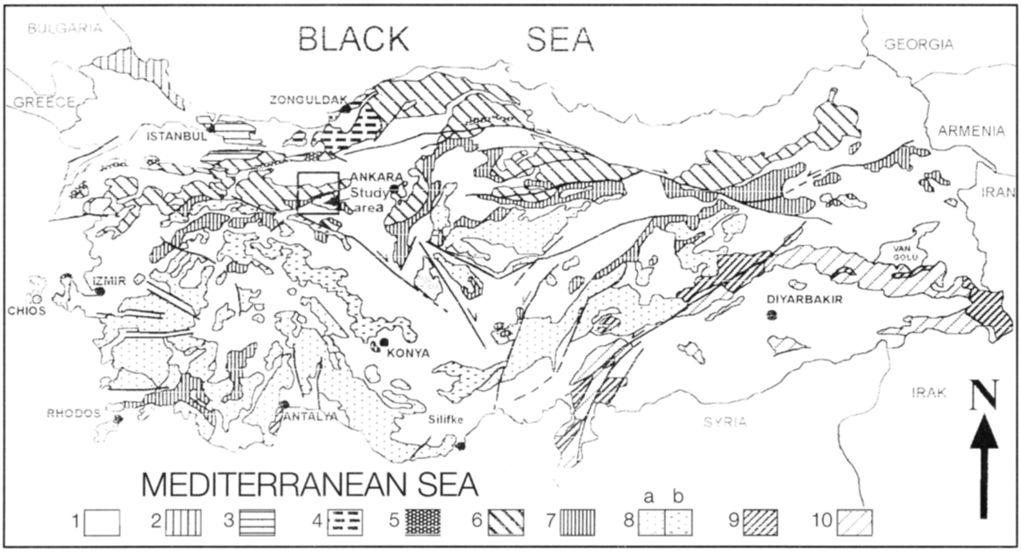

Fig. 1. Distribution of the main Alpine terranes in Turkey [after Göncüoğlu *et al.* (1996–1997)] and the location of the study area. 1, Tertiary cover; 2, Istranca Terrane; 3, İstanbul Terrane; 4, Zonguldak Terrane; 5, Intra-Pontide Suture Belt; 6, Sakarya Composite Terrane; 7, İzmir–Ankara–Erzincan Suture Belt; 8, Tauride–Anatolide Composite Terrane (a, undivided; b, Kütahya–Bolkardağ Belt); 9, Southeast Anatolian Suture Belt; 10, Southeast Anatolian–Arabian Plate.

margin of the Tauride–Anatolide Platform. Each of these Alpine units differ not only in their magmatic/metamorphic and depositional history but also in containing older units, and hence in their palaeogeographic positions during the Phanerozoic times.

Göncüoğlu *et al.* (1996–1997) recently reviewed the tectonic units of Turkey and described the Alpine fragments as 'terranes' or 'composite terranes' (*sensu* Howell 1989) with regard to their pre-Alpine history (Fig. 1).

According to this classification, the İstanbul Terrane in the north was probably located during the Palaeozoic at the passive margin of an isolated continental fragment within a Palaeozoic ocean to the north of Gondwana (Göncüoğlu 1997; Göncüoğlu & Kozur 1998). During the latest Mesozoic, it was attached to Laurasia and had an active margin setting to the north of the Neotethyan Intra-Pontide Ocean. The İstanbul Terrane overthrusts the Intra-Pontide Suture Zone (Göncüoğlu & Erendil 1990). The latter unit, located between the Sakarya Composite Terrane and the İstanbul Terrane, is characterized by ophiolites and a mélange complex with radiolarian cherts and pelagic limestones of Late Jurassic–Early Cretaceous age. It is thrust southward onto Upper Cretaceous flysch sequences of the Sakarya Composite Terrane. The Intra-Pontide Suture Zone probably extends westwards into the ophiolitic belt observed on Lesbos and the Eastern Rhodopian Ophiolites.

The Alpine 'Sakarya Composite Terrane', the Sakarya Zone of Okay *et al.* (1996), is generally accepted as an isolated carbonate platform in the Tethys during Middle–Late Mesozoic time. However, its pre-Alpine history is very complex and there is no consensus on the ages, extents and the geodynamic setting of more or less metamorphic tectonic fragments. These pre-Alpine elements mainly represent oceanic and continental fragments of Late Palaeozoic and/or Early Mesozoic age. The Central Sakarya 'Terrane' is one of these pre-Alpine units and will be one of the main topics of this paper.

The Vardar–İzmir–Ankara Suture Belt represents the northern branch of Neotethys. It is unequivocally accepted that huge allochthonous nappes of almost complete ophiolitic sequences and tectonic mélanges were generated during its closure and thrust southwards to the passive margin of the Tauride–Anatolide Platform. However, the location of the suture root zone in the Central Sakarya region has not been clearly identified (e.g. Monod *et al.* 1991), and will be evaluated in this paper. On the other hand, field and geochemical data from western Central Anatolia suggest that at least the İzmir–Ankara segment of the northern Neotethyan

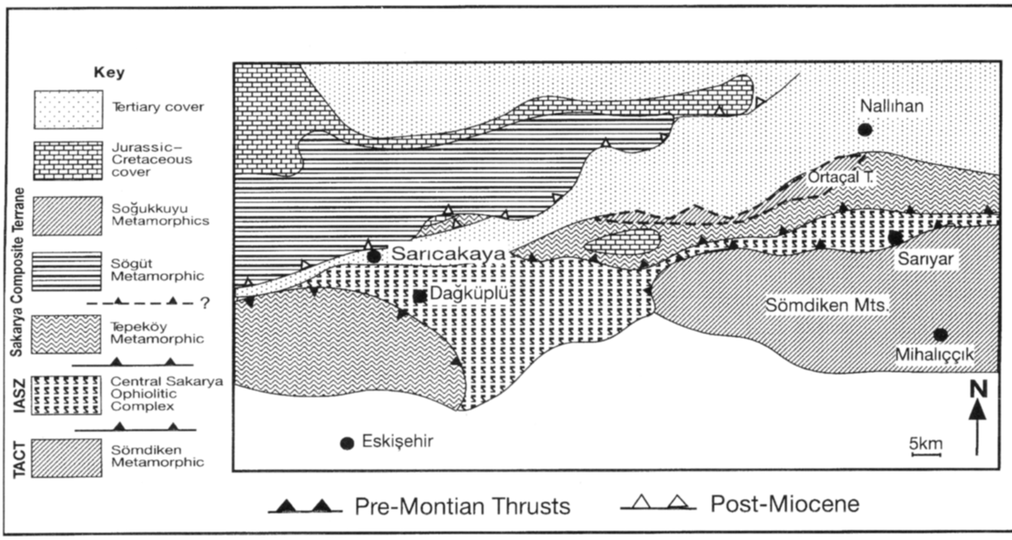

Fig. 2. Simplified structural map of the Central Sakarya area. TACT, Tauride Anatolide Composite Terrane; IASZ, İzmir–Ankara Suture Zone.

ocean was entirely consumed along a north dipping intra-oceanic subduction zone generating suprasubduction zone (SSZ)-type oceanic crust during early Late Cretaceous time (Göncüoğlu & Türeli 1993; Yalınız *et al.* 1996; Floyd *et al.* 1998). So, it is critically important to establish whether the intra-oceanic subduction had also played an important role during its closure in the western part of Anatolia as well.

The 'Tauride–Anatolide units' represent the Gondwana continental platform between the Neotethyan İzmir–Ankara–Erzincan Ocean to the north and the Southern Branch of Neotethys to the south. It comprises three units; from north to south these are: the Kütahya–Bolkardağ Belt, representing the tectonic slivers of the northern margin of the platform; the Menderes–Central Anatolian Unit, representing the metamorphic central part, and the Tauride Belt, consisting of a package of mainly non-metamorphic nappes. During the closure of the Vardar–İzmir–Ankara Ocean, ophiolites and slivers of slope-type rocks were thrust southwards (Lycian–Bozkır Nappes) onto the platform, whereas the rest of the platform margin was deeply subducted (Göncüoğlu & Türeli 1993; Okay & Kelley 1994), which resulted in high pressure–low temperature (HP–LT) metamorphism in northern and northwestern Anatolia. However, HP–LT metamorphism is not restricted to the Alpine event. Some authors have also suggested that part of the blueschists in northwestern Anatolia were formed during the closure of the 'Palaeotethys' (e.g. Şentürk & Karaköse 1981; Tekeli 1981; Okay *et al.* 1996), which was also checked by the present authors' detailed work in the Central Sakarya region.

In this study, the geology of the tectonic units along a geotraverse across the Sakarya Composite Terrane, the İzmir–Ankara Suture Zone and the northern part of the Tauride–Anatolide Composite Terrane in northwest Anatolia are described, and their Late Palaeozoic and Mesozoic geodynamic evolution interpreted. This study is mainly based on many years field work in the Armutlu Peninsula (Göncüoğlu *et al.* 1987; Göncüoğlu & Erendil 1990), the Central Sakarya region (Göncüoğlu *et al.* 1996) and the Kütahya–Bolkardağ Belt (Göncüoğlu *et al.* 1992).

Main tectonic units and their structural relations

The study area along the Sakarya Valley between Sarıcakaya and Nallıhan includes parts of two former continental plates: the Sakarya Composite Terrane to the north and the Kütahya–Bolkardağ Belt of the Tauride Platform to the south. They are separated by the ophiolites and mélange assemblages of the Tethyan İzmir–Ankara Suture Zone (Fig. 2). The Sakarya Composite Terrane is subdivided into the Tepeköy Metamorphics and the Söğüt Metamorphics. Both units were tectonically

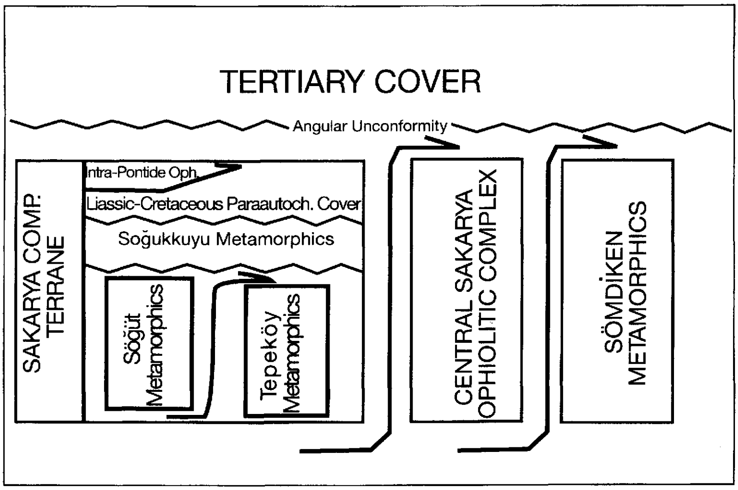

Fig. 3. Structural relations of the tectonic units in the Central Sakarya area.

superposed prior to Early Jurassic time (Fig. 3). The original contact between the Sakarya Composite Terrane and the Central Sakarya Ophiolitic Mélange is a south verging thrust fault that can be followed along-strike for > 75 km along the Central Sakarya Valley. The thrust plane is steep in the east (60–70° to the north), but in the west, the main body of the Tepeköy Metamorphics rests on the ophiolitic rocks with a thrust plane dipping north at *c.* 30°. The age of initial juxtaposition is probably post-Early Maastrichtian–pre-Middle Palaeocene, as molasse-type continental clastic rocks of Montian age unconformably cover both tectonic units. The original thrust planes must also have been reactivated during the Late Miocene compressional event, shown by north dipping inclined to overturned fold planes of the Lower–Middle Miocene Beypazarı Group and the thrusting of basement units on to the Palaeocene Kızılçay Group. The primary contact between the Central Sakarya Ophiolitic Mélange and Sömdiken Metamorphics of the Kütahya–Bolkardağ Belt (Tauride–Anatolide Platform) is again a south verging thrust, where ophiolitic rocks rest on a gently north dipping thrust plane overriding the metamorphic complex. In the eastern part of the study area, around Çalkaya Hill, the thrust plane is defined by a well-developed mylonitic zone.

Tectonostratigraphy

The structural relationship and generalized tectonostratigraphic features of the main tectonic units in the study area are summarized in Fig. 3.

The Central Sakarya Terrane

In the study area, the pre-Jurassic basement complex of the northern tectonic unit is represented by the Central Sakarya Terrane, a member of the Sakarya Composite Terrane. The latter is an east–west trending Alpine tectonic unit covering almost the whole of northern Anatolia (Fig. 1). It corresponds to a part of the Pontides of Ketin (1966) and the Rhodope–Pontide Fragment of Şengör *et al.* (1984). The Late Cretaceous closure of the Neotethyan oceanic basins and subsequent collisions of the microcontinents during latest Cretaceous–Palaeocene time has obscured the primary relationships of the pre-Alpine assemblages.

The Central Sakarya Terrane contains two metamorphic units termed the Söğüt Metamorphics and the Tepeköy Metamorphics, together with their cover, the Soğukkuyu Metamorphics (Fig. 3). The metamorphic units are exposed as east–west trending discontinuous tectonostratigraphic units along the Sakarya Valley.

The Söğüt Metamorphics. The Söğüt Metamorphics is the structurally higher unit in the basement of the Central Sakarya Terrane. It comprises paragneisses and granitic plutons. The gneisses comprise garnet amphibolites, sillimanite–garnet gneisses, biotite–amphibole

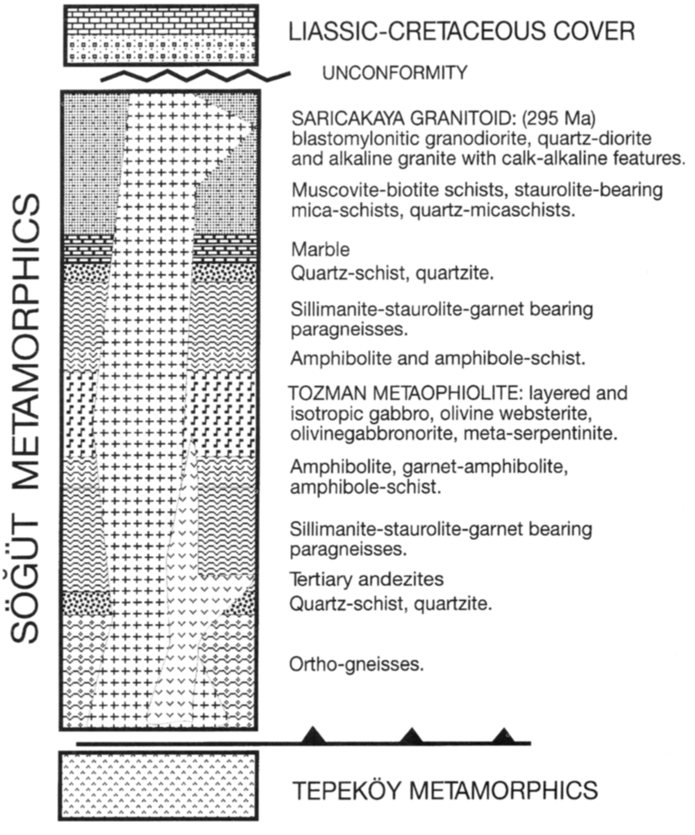

Fig. 4. Generalized stratigraphic section of the Söğüt Metamorphics.

gneisses, two-mica gneisses, sillimanite-bearing staurolite schists, and micaschists with very rare marble and quartzite interlayers (Fig. 4). Rapid alternations of different lithologies indicate that the protoliths of these rocks can be interpreted in terms of sedimentary and/or volcanogenic origin. Discontinuous, small and lens-shaped bodies of layered and cumulate metagabbros, associated with metaolivine pyroxenites (Tozman Metaophiolite; Göncüoğlu *et al.* 1997) and metaserpentinites, are generally concordant with the east–west trending foliation of the surrounding gneisses. These mafic–ultramafic lenses are rimmed by well-foliated amphibolites and high Mg-schists. The pre-Alpine metamorphism under medium–high amphibolite facies conditions of the Söğüt Metamorphics is suggested by the paragenesis: staurolite + almandine + biotite and biotite + almandine + sillimanite in the metapelites and the local presence of migmatites. Post-deformational thermal overprinting is represented by static andalusite porphyroblasts close to the contacts of the intruding calc-alkaline granitoids.

Numerous plutonic rocks of granitic–dioritic composition intrude the Söğüt Metamorphics (Yılmaz 1990). They form elliptical bodies with mylonitic–blastomylonitic textures, elongated east–west. Discordant stocks and dykes of granitoids cross-cut these rocks, and obviously postdate the main metamorphic and deformational event. Yılmaz (1979) recognized five different types of granitic rocks and indicated that they represent a magmatic arc. This suggestion is further supported by geochemical data (Kibici 1990). The granitoids yielded a zircon fission-track age of *c.* 295 Ma (Çoğulu *et al.* 1965). Development of cataclasis is related to late Alpine events.

The depositional age of the paragneisses in the Söğüt Metamorphics is suggested to be mid-Late Palaeozoic, based on regional correlations. Radiometric data from the intruding granitoids, and Lower–Upper Permian carbonates unconformably covering them in the Geyve area, clearly indicate that at least the main metamorphic event is pre-Permian in age (Göncüoğlu *et al.* 1987; Yılmaz 1990).

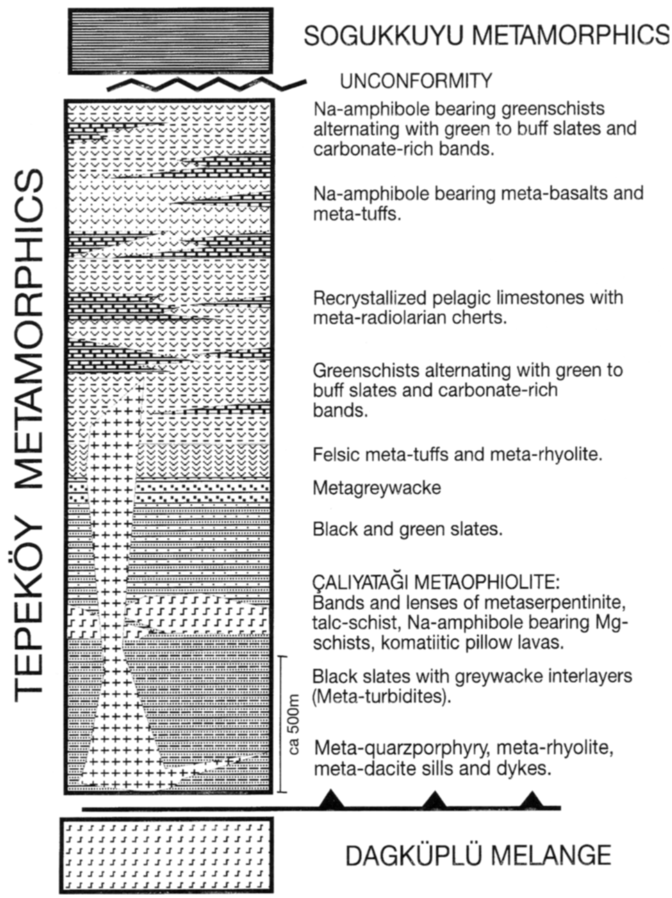

Fig. 5. Generalized stratigraphic section of the Tepeköy Metamorphics.

The variety of the metamorphic rock types, the presence of ophiolitic assemblages and the geochemical characteristics of the granitoids intruding them, strongly suggest an island-arc tectonic setting for the Söğüt Metamorphics.

The Tepeköy Metamorphics. This unit represents the lower tectonic slice of the Central Sakarya basement and comprises a belt > 100 km long extending along the Sakarya Valley (Fig. 2). Lithologically, it corresponds to the Sakarya Metabasites of Yılmaz (1979), the 'Greenschist–Marble Association' of Şentürk & Karaköse (1981). In northwestern Anatolia, a lithologically similar unit is known as the Nilüfer Unit (Okay *et al.* 1991).

The bulk of the Tepeköy Metamorphics is composed of metabasic rocks, metatuffs, metafelsic rocks, black phyllites, metagreywackes, metasandstones and recrystallized pelagic limestone with metaradiolarite interlayers (Fig. 5). The unit is > 3500 m thick and, in its lower part to the south-southwest of Nallıhan (where black and green phyllites and greywackes dominate), displays typical features of a 'sedimentary mélange' where depositional processes such as debris flows, gravity sliding and slumping, and tectonic deformation occur. Within these metaturbidites, pods and lenses of serpentinized mafic and ultramafic rocks (Çalıyatağı Metaophiolite; Göncüoğlu *et al.* 1996), and knockers of white, massive marbles are recognized to the northwest of the Sarıyar area. The upper part, along the Sakarya Valley, however, is represented by an alternation of metabasic rocks and carbonates. The carbonates (Eğriköyü Marbles; Göncüoğlu *et al.* 1996) are grey, medium- to thin-bedded and cut by diabase dykes and sills. Thin, dark red to black metachert interlayers are abundant in the upper part. The thickness of the recrystallized limestones locally reaches up to 150 m. The metabasic rocks make up > 75% of the upper part of the succession, including massive and pillowed lavas, volcanic breccia, and metatuffs interlayered with green to buff slates and carbonate-rich bands. The metafelsic rocks occur both as foliated intrusive rocks (quartz–porphyries and rhyolites–dacites) and volcaniclastic rocks.

The metamorphic mineral assemblage in the metagreywackes is actinolite (rimmed by Na-amphibole) + oligoclase + chlorite + epidote + white mica. The metabasalts and metadiabases contain relict phases of Ti-augite, olivine and brown hornblende, and metamorphic phases of actinolite + Na-amphibole + stilpnomelane + albite/oligoclase + epidote + garnet + chlorite. The Na-amphiboles occur both at the rim of actinolite, replacing primary hornblende, and along well-developed S_2 planes, where they are associated with stilpnomelane and chlorite. The basic metatuffs contain almost the same metamorphic mineral assemblage, but they are characterized by two sets of S planes, the younger one of which is represented by nematoblastic Na-amphibole. The metaultramafic blocks occur as lens-shaped bodies up to 200 m thick in the lower part of the unit and, in their core, contain relict primary mineral assemblages such as olivine, clinopyroxene, spinel and chromite. Towards the rim the metamorphic mineral assemblages – i.e. cummingtonite + anthophyllite + Mg-chlorite + gedrite + talc + chlorite + magnesite – dominate. The outermost rim is represented by Na-amphiboles replacing clino-amphiboles. Meta-olivine basalts, with relict porphyritic textures, occur within these meta-ultramafic blocks. These very peculiar glassy lavas display an earlier metamorphic mineral paragenesis of Mg-chlorite + cummingtonite (M_1) and a later one with Na-amphibole (M_2). Textural and mineralogical data strongly suggest an earlier regional upper greenschist facies metamorphism in the Tepeköy Metamorphics, followed by a HP–LT event producing the typical mineral paragenesis.

According to this group's preliminary geochemical data, the glassy lavas show typical geochemical features of boninites (TiO_2 < 0.5%; Zr < 15 ppm MgO $\cong$ 9%; Tokel, pers. comm.). The boninitic chemistry of the basic volcanic rocks, their association with radiolarian cherts and pelagic limestones, and the presence of felsic magmatic rocks intruding them all, suggest an intra-oceanic forearc setting for the Tepeköy Metamorphics. The appearance of mafic, ultramafic and pelagic limestone–chert blocks within a sedimentary complex, on the other hand, suggests an accretionary complex. Thus, it is assumed that the Tepeköy Metamorphics represents a forearc–trench complex. Tectonic units with similar rock assemblages are widespread in northwestern Anatolia. The HP–LT metamorphosed Nilüfer Unit of Okay *et al.* (1991, 1996) is interpreted as a subducted intra-oceanic arc to forearc sequence. Based on geochemical data, Pickett & Robertson (1996) interpreted the Nilüfer Unit, that consists of metamorphic (low to high greenschist facies) spilites and volcanogenic sediments, as a typical seamount sequence. In both units, continent-derived clastic material, and felsic volcanic and volcaniclastic rocks are noticeably absent. Disregarding the age constraints, the Tepeköy Metamorphics may be considered as a different metabasic unit due to the presence of a felsic volcanism.

No fossils have been reported yet in the Tepeköy Metamorphics, or similar units [e.g. the Nilüfer Unit of Okay *et al.* (1991)] in the western areas of the Sakarya Composite Terrane. Yılmaz (1981) proposed a Late Mesozoic formation age for the Tepeköy-type metabasic rocks just west of the study area. The Middle Triassic deposition age (Kaya & Mostler 1992), based on fossil findings, is probably not from Tepeköy type metabasites–metacarbonates but from the Soğukkuyu type sediments. In the study area, the primary contact between the Tepeköy Metamorphics and other units of the Central Sakarya Terrane is hard to recognize because of end Cretaceous and Early Miocene tectonics. However, southwest of Nallıhan (Ortaçal Tepe; Fig. 2), the Tepeköy Metamorphics are unconformably overlain by basal clastic rocks of the Soğukkuyu Metamorphics containing pebbles of the Tepeköy Metamorphics. In northwestern Anatolia, the contact between the Nilüfer Unit and the overlying Upper Triassic Hodul Unit has also been assumed to be a stratigraphic contact (Leven & Okay 1996). To the north of Central Sakarya, in the Geyve region, the basal clastic rocks of the Soğukkuyu Metamorphics rest on the Söğüt Metamorphics (Göncüoğlu *et al.* 1987) and their Permian cover. The same contact relations were reported by Genç (1992) and Genç & Yılmaz (1995) from west of Bilecik. On the other hand, the felsic magmatism in the Tepeköy Metamorphics is ascribed to the latest Carboniferous magmatic event observed in the Söğüt Metamorphics. This data indirectly suggest a pre-Permian formation and initial metamorphism ages for the Tepeköy and Söğüt Units. This suggestion does not exclude the presence of further metabasic rock units of

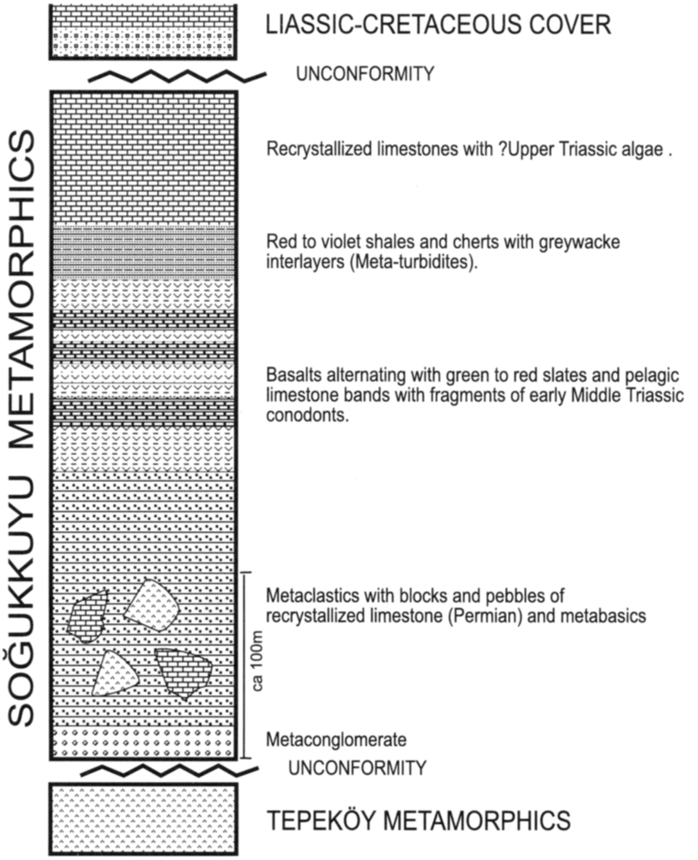

Fig. 6. Generalized stratigraphic section of the Soğukkuyu Metamorphics.

Triassic age within the Sakarya Composite Terrane, as will be discussed later within the framework of the geodynamic evolution of northwestern Anatolia.

The Soğukkuyu Metamorphics. This unit corresponds to part of the Karakaya Complex of Bingöl *et al.* (1975), and the Hodul and Çal Units of Okay *et al.* (1991).

In the Central Sakarya Area, the Soğukkuyu Metamorphics unconformably overlie both the Söğüt and Tepeköy Metamorphics (Fig. 6). Southwest of Nallıhan, the basal conglomerates include well-rounded pebbles of metabasalts, metacherts and recrystallized limestones. Southwest of Geyve, the basal clastic rocks of the Soğukkuyu Metamorphics consist of white arkosic sandstones with quartzite lenses (Göncüoğlu *et al.* 1987). The clasts are mainly derived from the underlying granitic rocks of the Söğüt Metamorphics. The basal clastic rocks are overlain by greywackes, debris flow conglomerates, and turbiditic siltstones–shales with knockers of metabasalts and recrystallized limestones of Permian age. The olistostromal unit, containing rare basaltic lava flows, is followed by a thick sequence where spilites, basaltic pillow lavas and red-violet mudstones alternate with pink-red pelagic limestones and pyroclastic rocks. Higher up, this volcano–sedimentary sequence grades vertically into thin-bedded pink-violet limestones, grey-white cherty limestones and, near the top, white, thick-bedded to massive recrystallized limestones with algae and gastropods (Ortaçal Tepe Limestone; Göncüoğlu *et al.* 1996). The pelagic limestones alternating with volcanic rocks contain poorly preserved conodont fragments of early Middle Triassic age (Keskin, pers. comm.), whereas the algae in the uppermost massive limestones resemble those in the Late Triassic (Kozur, pers. comm.).

The metamorphic mineral assemblage of basic volcanic rocks in the Soğukkuyu Metamorphics is chlorite + actinolite + epidote +

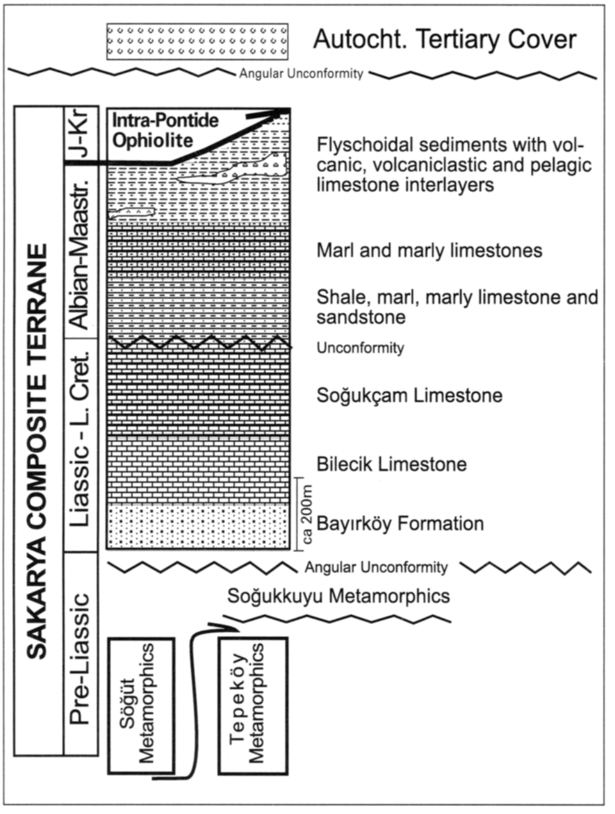

Fig. 7. Generalized stratigraphic section of Liassic–Upper Cretaceous cover units of the Central Sakarya Terrane.

albite, whereas the associated pelitic rocks contain only muscovite + chlorite. Only a single foliation and the absence of HP–LT paragenesis are characteristic features of the unit.

The rock units and their relations strongly suggest that Soğukkuyu Metamorphics were deposited in a rifted basin, which probably opened on the accreted Söğüt and Tepeköy Units and their Permian carbonate cover.

Jurassic–Cretaceous cover. The metamorphic basement units of the Central Sakarya Terrane are unconformably overlain by an unmetamorphosed sequence of Lower Jurassic and younger rocks (Fig. 7). This platform sequence has been mainly studied in detail in the Central Sakarya region (e.g. Altınlı 1975; Saner 1977; Altıner *et al.* 1991; Göncüoğlu *et al.* 1996).

The sequence starts with shallow-marine clastic rocks and carbonates of early Middle Liassic (Altıner *et al.* 1991; Göncüoğlu *et al.* 1996) age. They are followed by platform-type carbonates of Middle Jurassic–Early Cretaceous age that grade into slope-type deposits of Late Jurassic to Middle and Late Cretaceous age towards the northeast. During the Late Cretaceous (Maastrichtian), proximal turbidites with volcanic–volcaniclastic and calciturbiditic interlayers covered the northern part of the Central Sakarya Terrane. The upper part of this flysch succession, which represents a typical foreland sequence, is dominated by ophiolitic detritus. A slice of ophiolitic rocks (Intra-Pontide Ophiolites) overthrust the flysch rocks (Göncüoğlu & Erendil 1990; Yılmaz *et al.* 1995).

During the Middle–Late Mesozoic, the Central Sakarya Terrane as a whole represents a carbonate platform flanked by the Intra-Pontide Ocean in the north and the İzmir–Ankara Ocean in the south. Since the Middle Cretaceous, it was submerged and a foreland basin developed at its northern margin in front of the southward advancing ophiolitic nappes. The initial juxtaposition of the northern İstanbul–Zonguldak Terrane with the Central Sakarya Terrane was probably an oblique collision and

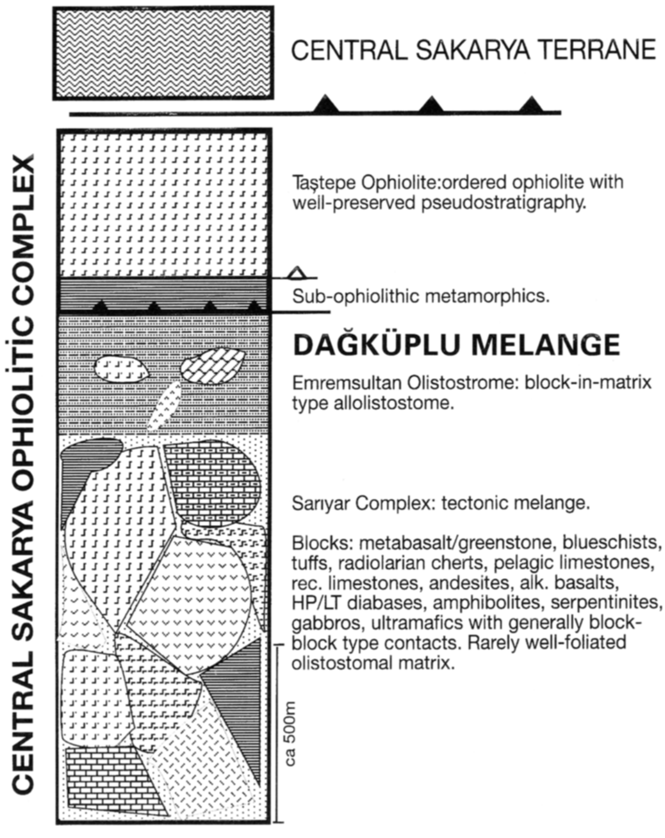

Fig. 8. Tectonostratigraphic section of the Central Sakarya Ophiolitic Complex.

must have taken place during the Early Senonian (Göncüoğlu & Erendil 1990).

The Central Sakarya Ophiolitic Complex. In the Central Sakarya region, the ophiolites and the mélange complex of the İzmir–Ankara Ocean are represented by an east–west trending tectonic sliver almost 100 km long. This ophiolitic complex is sandwiched between the Central Sakarya Terrane and the Tauride–Anatolide Composite Terrane, and represents the northernmost outcrops (and hence the root zone) of the İzmir–Ankara Suture in northwestern Anatolia (Göncüoğlu *et al.* 1997). The ophiolitic complex comprises an upper slice of more or less ordered ophiolite (Taştepe Ophiolite) with subophiolitic metamorphic rocks at its base and a lower disrupted slice (Dağküplü Mélange) (Fig. 8). The latter is further subdivided into mappable units (the Emremsultan Olistostrome and the Sarıyar Complex).

The Taştepe Ophiolite. This unit occurs as a nappe package almost 4 km thick which predominantly comprises slices of tectonites and mafic–ultramafic cumulates. The members of the dyke complex and lava sequence are only found as smaller slices between the main ultramafic body and the underlying mélange complex, or as huge blocks within the mélange. Discontinuous outcrops of metamorphic rocks, alternating garnet–amphibolites, and thin-bedded marble and metacherts, are exposed below the main ultramafic body. In the lowest part of the ophiolites, the dunites are relatively fresh. The partially serpentinized harzburgites contain pods and bands of chromite and display a distinct tectonite fabric defined by the alignment of the orthopyroxenes. The cumulates consist of dunite–clinopyroxenite/wehrlite–clinopyroxenite-gabbro bands. The layered gabbro, consisting of troctolites, two-pyroxene gabbros and gabbro-norites, in ascending order, is highly sheared. The upper part of the layered

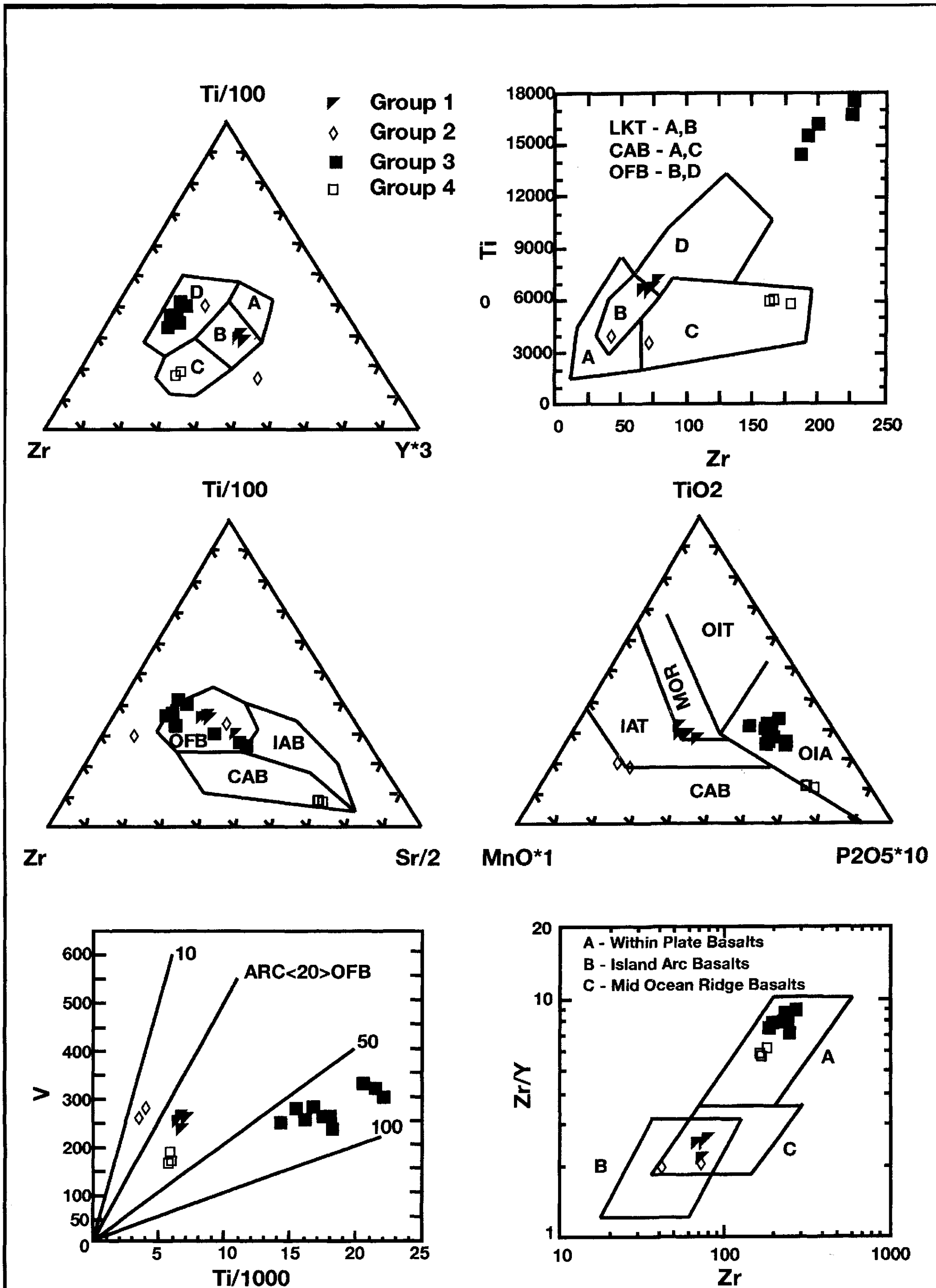

Fig. 9. Tectonic discrimination diagrams of the basic volcanic rocks of the Central Sakarya Ophiolite.

gabbro sequence contains low-grade metamorphic secondary phases such as uralite, chlorite, prehnite and pumpellyite (Asutay *et al.* 1989).

The Dağküplü Mélange. The Dağküplü Mélange is composed of the Sarıyar Complex and the Emremsultan Olistostrome. The former comprises blocks of spilitic metabasalts, glaucophane–lawsonite schists, radiolarian cherts, pelagic limestones, serpentinites and recrystallized neritic limestones of mainly Mesozoic age (Göncüoğlu *et al.* 1996). These lithologies make up *c.* 90% of the mélange blocks. Minor blocks are amphibolites, gabbros, pyroclastics and andesites–dacites (Fig. 8). The knockers are up to several kilometres across and, in general, display tectonic contacts. A well-foliated olistostromal matrix with south verging structural elements is only encountered southwest of Sarıyar. The Sarıyar Complex has a very complex imbricated internal structure with east–west trending shear zones and thrust faults, which is further complicated during subsequent compressional events masking its emplacement on to the Sömdiken Metamorphics and later events.

The neritic limestone blocks within the mélange are highly recrystallized, although their lithologies are very similar to the Middle Triassic–Jurassic carbonates of the Kütahya–Bolkardağ Belt of the Tauride–Anatolide carbonate Platform.

The dominant volcanic rock types are metabasalts. In different blocks of metabasic rocks, the metamorphic mineral assemblages range from typical parageneses of ocean-floor metamorphism to blueschist facies assemblages containing Na-pyroxene + Na-amphibole + lawsonite. The HP–LT parageneses are not restricted to the metabasalts, but were also observed in the metacherts and metatuffs. Na-amphibole nematoblasts were locally encountered in the highly sheared matrix.

Petrographical and geochemical investigations conducted on basic volcanic rocks within the mélange indicate the presence of four different compositional groups (Fig. 9) with distinctive magmatic affinities (Yalınız *et al.* 1998). The first group, represented by pillow lavas, displays geochemical affinity more akin to mid-ocean ridge basalts (MORB), with a flat pattern close to unity. The second group is made of HP–LT metamorphic pillow basalts, characterized by an island-arc tholeiite signature: strong depletion of high field strength elements (HFSE) and enrichment of large-ion lithophile elements (LILE) relative to MORB. The third group, the dominating block-type volcanic rocks, includes Ti-augite–phyric pillow basalts and breccias, and is characterized by signatures characteristic of within-plate alkaline magmatic series with enrichment of the more incompatible elements (e.g. Nb) relative to MORB. The fourth group, represented by olivine-poor, hornblende–clinopyroxene–phyric massive basalts, is characterized by a calc-alkaline signature, displaying a greater degree of enrichment in low field strength elements (LFSE) relative to MORB, depletion of Nb relative to LFSE and Ti relative to other LFSE and HFSE, and Ce and P enrichment relative to Zr, Ti and Y. The preliminary geochemical data therefore suggest the existence of a variety of magma types, ranging in composition from IAT to MORB to ocean island basalt (OIB) to CAB. The combination of these distinctive magma types suggests a subduction–accretion complex with blocks accreted from different oceanic settings, the most dominant one being an intra-oceanic suprasubduction zone environment.

The metabasalts alternate with radiolarian cherts that contain a rich radiolarian fauna. Spot samples from cherts associated with MORB-like basalts yielded *Dibolachras chandrika* Kocher, *Transhuum* sp., *Williriedellum* sp. aff. *W. carpathicum* Dumitrica, *Protunuma* sp. and *Stichocapsa* spp. *Amphipyndacidae indet.* of Late Bathonian–Early Tithonian age, and *Thanarla bruveri* TAN, *T. elegantissima* TAN and *T. gutta* JUD of latest Hauterivian–Early Aptian age (Tekin, pers. comm.). These age data suggest a Late Jurassic–Early Cretaceous age for the formation of MORB-type oceanic crust in the İzmir–Ankara oceanic branch of the Neotethys. The youngest ages obtained from the pelagic limestones within the mélange are Early Senonian (Asutay *et al.* 1989), indicating that the mélange formation, and hence the formation of the accretionary complex, lasted until the end of the Cretaceous.

The Emremsultan Olistostrome. The Emremsultan Olistostrome, a block-in-matrix-type allolistostrome, makes up the upper part of the Dağküplü Mélange and occurs mainly as a discrete tectonic sliver in the eastern part of the study area. It has a weakly deformed and greywacke-dominated matrix alternating with shales. The knockers are relatively small but are lithologically almost the same as in the Sarıyar Complex. The depositional features of the Emremsultan Olistostrome strongly suggest that it was formed in piggyback-type basins on the accretionary complex, represented by the Sarıyar Mélange.

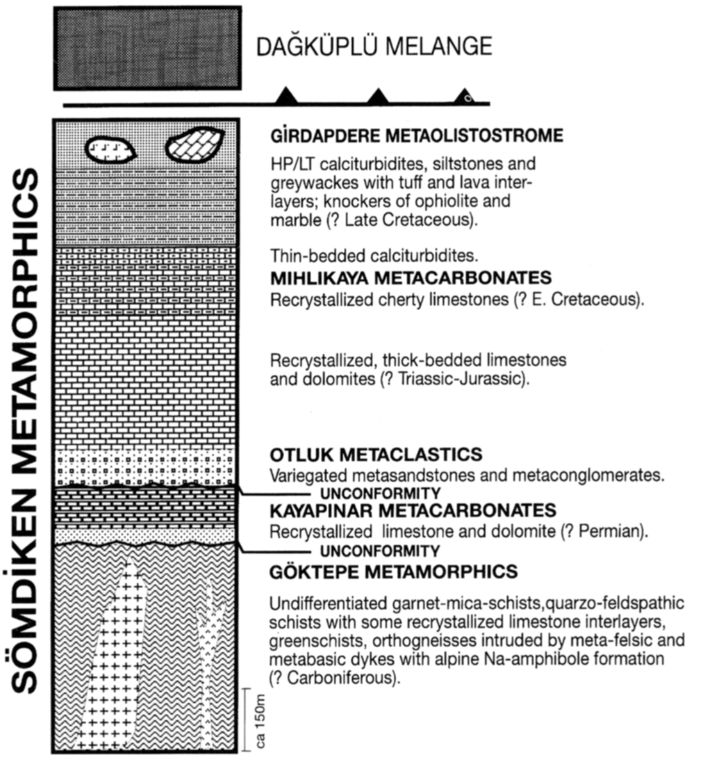

Fig. 10. Generalized stratigraphic section of the Sömdiken Metamorphics.

Sömdiken Metamorphics of the Tauride–Anatolide Platform

The Sömdiken Metamorphic rocks represent the lowermost structural unit in Central Sakarya. They are part of the Kütahya–Bolkardağ Belt that is characterized by slices of metamorphic units and represents the northern margin of the Gondwana Plate. Outcrops of the Sömdiken Metamorphics occur in a tectonic window southeast of the study area (Fig. 2). The generalized columnar section of this unit is given in Fig. 10.

The Göktepe Metamorphics. This unit occurs in the core of a south verging antiform in the Sömdiken Mountains (Fig. 2). It mainly comprises quarzofeldspathic gneisses in its lower part, overlain by quarzofeldspathic schists, pelitic micaschists with very rare carbonate and quartzite bands, and greenschists with a few lydite bands. The gneisses are blastomylonitic and display relict textures, indicating a granitic origin. The pelitic micaschists, > 2000 m thick, contain bands and lenses of greenschists. The whole sequence is cut by highly deformed basic and felsic dykes.

The Göktepe Metamorphic rocks have a polyphase metamorphic history. The micaschists are characterized by an earlier metamorphic assemblage comprising muscovite + biotite + chloritoid + garnet + chlorite, whereas the interlayered greenschists contain chlorite + epidote + actinolite + garnet. The later event, represented by a non-penetrative foliation in the micaschists, is characterized by the paragenesis muscovite + chlorite + albite, whereas the greenschists include Na-amphibole + phengite + stilpnomelane + albite. The basic dykes cutting the Göktepe Metamorphics are only affected by the latter HP–LT paragenesis.

The Göktepe Metamorphics are almost identical with the lower grade metamorphic İhsaniye Metamorphics of the Kütahya–Bolkardağ Belt in the Kütahya and Konya areas (Özcan *et al.* 1988; Göncüoğlu *et al.* 1992). In the latter localities, a low-grade metamorphic sequence with lydite-rich turbidites, felsic pyroclastics, olistostromes with fossiliferous Lower Silurian–Lower Carboniferous limestones and chert blocks are associated with metatrachyandesites, metadolerites and metagabbros, intruded by metagranites. Geochemical data on the trachyandesitic and doleritic rocks display a combination of within-plate and continental-arc settings, whereas metagabbros show MORB character (Kurt 1996). The sequence is unconformably overlain by Permian platform-type carbonates. Based on the lithologies of the fossil-bearing sedimentary rock associations, their depositional features and the geochemistry of the volcanic rocks, the İhsaniye Metamorphics were interpreted to be the product of a Carboniferous back-arc system (Özcan *et al.* 1988). The same tectonic setting is accepted for the Göktepe Metamorphics.

The Kayapınar Metacarbonates. A *c.* 150 m thick sequence of metacarbonates unconformably overlying the Göktepe Metamorphics is known as the Kayapınar Metacarbonates (Göncüoğlu *et al.* 1996). The lower part of the sequence is represented by 25 m thick quartzites with chloritoid-bearing micaschist and marble interlayers. The main body of the unit is made up of medium- to thick-bedded marbles with interlayers of calcareous schists.

Similar limestones to the Kayapınar Metacarbonates are well known in the Kütahya–Bolkardağ Belt (Eldeş Formation; Özcan *et al.* 1988) and in the Taurides (Özgül 1984), where they contain a rich fauna indicating a Middle–Late Permian depositional age.

The Otluk Metaclastites. The slightly metamorphosed epicontinental clastic rocks overlying the Göktepe and Kayapınar Formations, with angular unconformity, are named the Otluk Metaclastics. At the base there are red, violet and brownish massive conglomerates, with pebbles of orthogneiss, micaschists and marble, which pass upwards into an alternation of arkosic metasandstone, quartzite and metasiltstone. The metaclastites are *c.* 160 m thick and grade upwards into the Mıhlıkaya Metacarbonates. This very characteristic metaclastic unit occurs throughout the Kütahya–Bolkardağ Belt at the same stratigraphic level and has been dated in the Kütahya area as Scythian (Özcan *et al.* 1988). In this locality, the entire unit is interpreted as a transgressive sequence, starting with proximal alluvial fans and subsequently grading into meandering stream and coastal plain deposits, ending with intertidal sediments. Göncüoğlu *et al.* (1992) suggested that the deposition of these coarse clastic rocks was related to rapid uplift at the northern margin of the Tauride–Anatolide Unit, related to the initial rifting and subsequent opening of the İzmir–Ankara Branch of Neotethys during the Early Triassic.

The Mıhlıkaya Metacarbonates. This unit is represented by a *c.* 700 m thick carbonate sequence, which in the lower part contains medium- to thick-bedded, grey, white and black recrystallized limestones and dolomites. The upper part comprises an alternation of grey, beige and pink, thin-bedded recrystallized cherty limestones and cherts, that grade into a *c.* 50 m thick succession of pink and greenish grey cherts with thin-bedded reddish calc-schist and slate interlayers. This thick carbonate-dominated sequence grades upwards into Girdapdere Metaolistostrome. The carbonates of the unit are recrystallized and only yielded ghost fossils in the study area. However, the Gökçeyayla Limestone in the Kütahya area has an identical stratigraphy and yields fossils indicating continuous carbonate deposition from Anisian to Late Jurassic time (Göncüoğlu *et al.* 1992). The cherty limestones and radiolarian cherts in the upper part of the unit, on the other hand, have been dated as Early Cretaceous–early Late Cretaceous. The same carbonate sequence is the most representative unit along the northern margin of the Tauride–Anatolide Platform. It is interpreted as a platform sequence on the north-facing margin of the Gondwanan Plate. The upper part of the sequence, represented by pelagic–hemipelagic condensed sediments, indicates foundering from platform to slope, and afterwards to basinal conditions.

The Girdapdere Metaolistostrome. The uppermost unit of the Sömdiken Metamorphics is represented by a *c.* 3000 m thick olistostromal sequence. The transitional lower part of the unit is characterized by a very thick succession of calciturbidites. The main body of the unit is made up of metamorphosed greywackes, calciturbidites, shales, siltstones, metatuffs, radiolarites, pelagic cherty limestones, turbiditic sandstones–conglomerates, and blocks of metabasalts, metaandesites–metadacites, recrystallized limestones and serpentinites. The Girdapdere Metaolistostrome is tectonically overlain by the Central Sakarya Ophiolitic Complex. It has undergone a HP–LT metamorphism, together with the rest of the Sömdiken Unit, with the development of three successive deformational phases. Textural data from the metatuff horizons suggest an earlier phase (S_1) with actinolite + epidote + chlorite formation, the second one (S_2) with syntectonic albite blasthesis and the last phase (S_3) with

Na-amphibole + albite + stilpnomelane + zoisite ± phengite ± lawsonite.

The unit is interpreted as a synorogenic metaclastic sequence formed on the northern margin of the Tauride–Anatolide Platform, in front of the advancing ophiolitic nappes derived from the closing İzmir–Ankara oceanic seaway. The depositional age of the olistostrome is only suggested by the presence of ?Lower Senonian ghost *Globotruncana* from the pelagic cherty limestone bands. However, in the Kütahya region, the lowest part of the synorogenic olistostromal sediments (Çoğurler Olistostrome; Özcan *et al.* 1988) yielded a rich microfauna indicating an early Late Maastrichtian depositional age. This may imply that the deposition of the flysch sediments became younger toward the south.

The presence of HP–LT assemblages implies that part of the continental margin has been deeply subducted, as previously suggested by Okay (1984) for the Tavşanlı area, west of the study area.

Post-tectonic cover

The oldest non-metamorphic sediments that unconformably overlie all the main tectonic units in the Central Sakarya area are represented by red continental conglomerates [Kızılçay Formation of Altınlı (1975)]. The lowest part of this unit contains boulder to block size clasts, derived from the Söğüt Metamorphics, the Dağküplü Mélange and the Sömdiken Metamorphics. The conglomerates are overlain by red to green mudstones, with dacitic to andesitic lavas and volcaniclastic rocks. Several plugs and dykes of dacitic composition occur within the sequence. Geochemical data of Kibici (1990) suggests a continental source and a post-collisional tectonic setting. The upper part of the unit is represented by fossiliferous marly limestones of Early Eocene age. For its lower part, Nebert *et al.* (1986) suggest a Palaeocene depositional age, which was confirmed by Göncüoğlu *et al.* (1996) who found fossils (*Laffitteina bibensis*, *L. mengaudi*, *Mississippina* sp., etc.) of Early Palaeocene age. This clastic-dominated unit is interpreted as a molasse-type depositional product.

These sediments are unconformably overlain by Middle Eocene–?Oligocene continental, shallow-marine sediments associated with andesitic volcanic rocks. The distribution of the sediments along east–west trending troughs, exhibiting very rapid lateral facies, changes strongly suggests that a transtensional system controlled the deposition.

The Miocene is characterized by continental sedimentation in two east–west trending basins, separated by a palaeohigh. The northern basin is characterized by the deposition of coarse clastics and shales, whereas the southern basin, around Beypazarı, is filled with conglomerates, marls and evaporites that contain lignite and trona deposits.

Tectonic evolution of the Central Sakarya area

The field, palaeontological and petrological data, outlined in previous chapters, indicate that the Central Sakarya area is composed of various tectonic units, which record four main orogenic events. The better known Alpine assemblage includes rocks from two oceanic seaways and three continental microplates. These are, from north to south: the İstanbul–Zonguldak Composite Terrane; the Intra-Pontide Suture; the Sakarya Composite Terrane; the İzmir–Ankara Suture; and the Tauride–Anatolide Composite Terrane. However, all of these tectonic units incorporate previous tectonic elements of Early Palaeozoic, Late Palaeozoic and Early Mesozoic events, respectively. The resulting picture is a very complex tectonic mosaic, involving not only continental microplates but also fore- and back-arc complexes, oceanic islands and subduction complexes. In the following section, the available data from northwestern Anatolia and the surrounding areas are interpreted to unravel this complicated history, starting with the Late Palaeozoic event. The northernmost tectonic unit considered in this scenario is the İstanbul Terrane. It differs from the İstanbul Nappe of Şengör *et al.* (1984) and the İstanbul unit of Okay (1989) in excluding the Zonguldak Terrane. The Early Palaeozoic history of the latter unit, involving a Cadomian event, has briefly been outlined by Göncüoğlu (1997) and Kozur *et al.* (1998). In this unit, the basement rocks are represented by an earliest Palaeozoic (*c.* 550 Ma; Ustaömer & Kipman 1997), intra-oceanic arc complex, unconformably overlain by Lower Ordovician–Upper Silurian platformal sediments. It was attached to the Moesian Platform during the Late Palaeozoic but has a quite different geological history (Göncüoğlu & Kozur 1998) to the İstanbul Terrane.

Late Palaeozoic (Variscan) events

It is commonly accepted that the İstanbul Terrane represents a south facing Palaeozoic

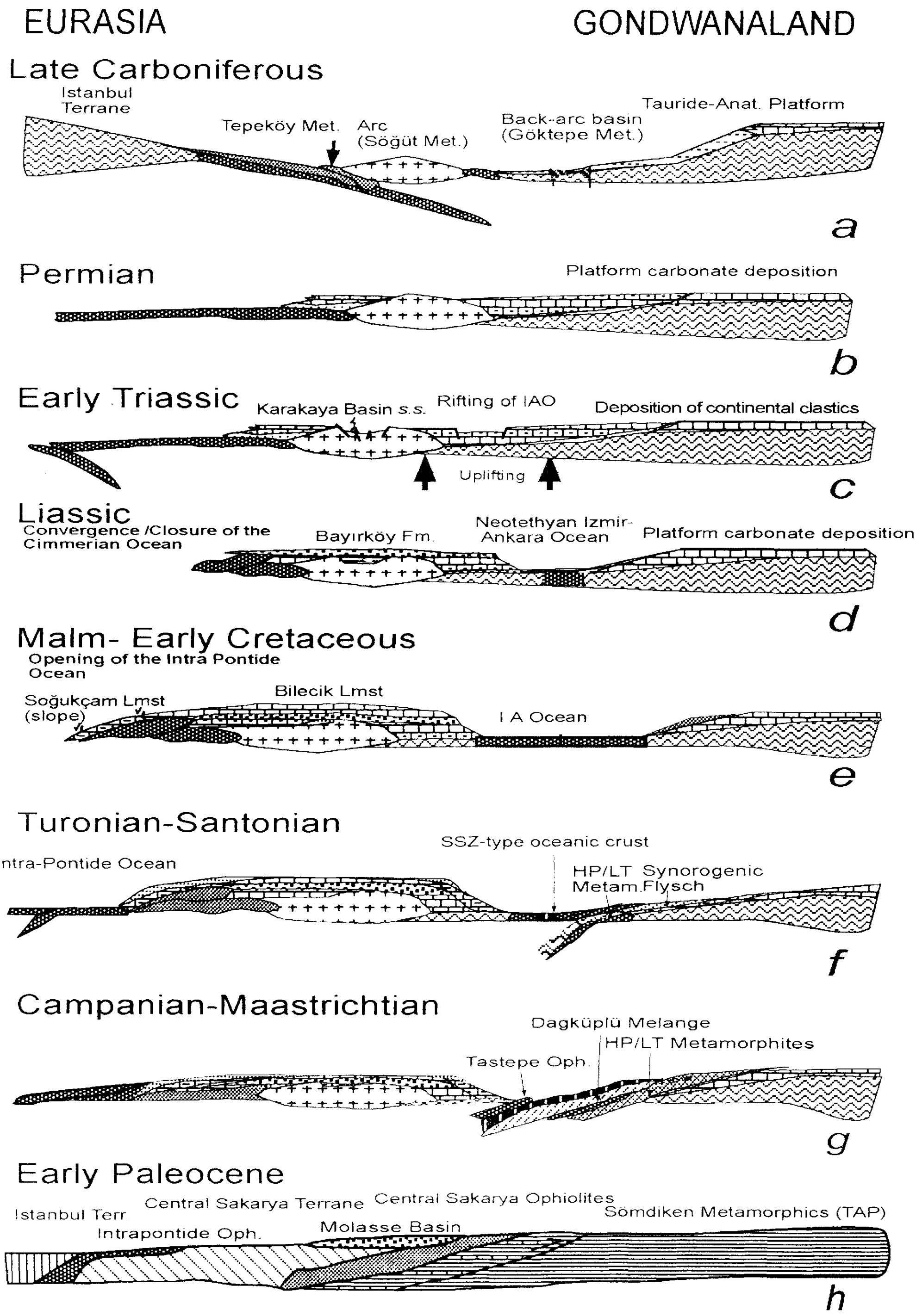

Fig. 11. Late Palaeozoic–Mesozoic evolution of the Central Sakarya region and its surroundings.

platform (Şengör *et al.* 1984), adjacent to a Palaeozoic oceanic branch (southern branch of the Rheic Ocean or Early Palaeozoic Tethys) that separated some Peri-Gondwanan microplates (e.g. Tauride–Anatolide, Balkan and Central Iran Terranes) from a mosaic of smaller ones, to which the İstanbul Terrane belonged (Göncüoğlu 1997). The Carboniferous rocks in this unit are synorogenic flysch deposits resting on the Devonian platform-slope carbonates, indicating a passive margin setting (Fig. 11a).

The intra-oceanic southward subduction within the Tethys during the Late Carboniferous is responsible for the arc- and forearc-type assemblages, represented by the Söğüt and Tepeköy Metamorphics of the Central Sakarya Terrane (Fig. 11a). Still further south, on the northern margin of the Tauride–Anatolide Carbonate Platform, a back-arc basin developed. The rock units of this basin occur at the base of the Sömdiken Unit (Göktepe Metamorphics) in the Central Sakarya region, as well as in most tectonic slices of the Kütahya–Bolkardağ Belt (e.g. the İhsaniye Metamorphics in the Kütahya area; Göncüoğlu *et al.* 1992; the 'turbidite–olistostrome unit' in the Karaburun Peninsula; Kozur 1997; and the Halıcı Formation at Konya; Özcan *et al.* 1988). Further south, on the Tauride–Anatolide Platform, carbonate deposition continued without any major change from the Devonian to the Permian, except for a rapid deepening and the influx of volcanic detritus during the lowest Carboniferous. Hence, during the Middle–Late Carboniferous, the Söğüt and Tepeköy arc–forearc units became attached to the northern margin of the Tauride–Anatolide Terrane. It was probably an accretion, or a gentle docking, rather than a forceful collision, evidenced by the weak deformation and metamorphism of the pre-Permian units (Kütahya–Bolkardağ Belt) of the Tauride–Anatolide Platform.

Autochthonous Lower Permian rocks, unknown in northwestern Anatolia, occur only on the Tauride Platform. However, the early Late Permian was a period of regional transgression on both the northern Tauride–Anatolide and Central Sakarya Units, implying that the Permian carbonate platform in the south also covered the northern units (Fig. 11b). It is not clear whether the İstanbul Terrane collided with the southern assemblages or whether the oceanic realm remained open during this period. However, the presence of latest Permian pelagic limestone blocks within the Triassic 'Karakaya Complex' (Kozur 1997) suggests the presence of a deep basin to the north of the Central Sakarya Terrane at this time.

Early Mesozoic (Cimmerian) events

In the Central Sakarya area, Triassic deposition is represented by the Soğukkuyu Metamorphics, which unconformably overlie the pre-Triassic units and are interpreted as a rift sequence. At the initial phase of rifting, coarse clastic rocks and associated rift-related volcanic rocks (Genç & Yılmaz 1995) were formed (Fig. 11c). In the north, the closure of the Late Palaeozoic–Triassic ocean gave way to a very complex system involving subduction–accretionary complexes, ocean islands and/or intra-oceanic arcs, which were subsequently accreted to the Central Sakarya Terrane (Tekeli 1981; Okay *et al.* 1991; Genç & Yılmaz 1995; Pickett & Robertson 1996). The subduction polarity and the palaeogeographic positions of the microplates in northwest Anatolia are a matter of debate. Pickett & Robertson's (1996) model postulates that the Late Palaeozoic–Triassic ocean was located between the main trunk of Gondwana in the south and Gondwana derived continental fragments with Upper Permian carbonate platforms (e.g. the Sakarya Microcontinent) in the north. It closed by southward subduction, generating a subduction–accretion complex (the Karakaya Complex). The ophiolites [the Denizgören Ophiolite of Okay *et al.* (1991)] and the subduction–accretion assemblages were then emplaced northward, onto the Permian platform sequences [the Karadağ Unit of Okay *et al.* (1991)]. Recent work (Okay *et al.* 1996), however, has shown that the age of the intra-oceanic decoupling of the Denizgören Ophiolite is Early Cretaceous. Okay *et al.* (1996) also suggested that, during the Permian, the Sakarya Microcontinent was still attached to the Moesian Platform to the north and separated from the main body of Gondwana by the intervening Palaeotethyan oceanic basin. The formation of the Karakaya forearc–accretionary complex was attributed to southward subduction during the Triassic, followed by obduction of the accreted units onto the Sakarya Microcontinent prior to the Early Jurassic. In this study, the Late Palaeozoic–Triassic oceanic basin is located between the İstanbul Terrane and the Central Sakarya Terrane. The main evidence for a southerly location of the latter is its Late Palaeozoic evolution, indicating a continuity with the northern margin of the Tauride–Anatolide Unit prior to the Middle–Late Triassic opening of the Neotethyan branches. In the model presented here (Fig. 11c), the southward subduction model of Şengör *et al.* (1984) is adopted, and it is suggested that the Soğukkuyu Metamorphics were formed in rift-related marginal basins in the Central Sakarya Terrane. The presence of Nilüfer type oceanic assemblages, *sensu* Okay *et al.* (1991) with a latest Triassic HP–LT metamorphic event in northwestern Anatolia (phengite Ar–Ar ages of 192–214 Ma; Monod *et al.* 1996), does not conflict with the proposed model. Moreover, it may further support a deep intra-oceanic subduction to the north of the Central Sakarya Terrane, followed by accretion and southward backthrusting of the subduction–accretion assemblages towards the south prior to the Early Jurassic. The termination of this orogenic event is marked by deposition of Lower Jurassic epicontinental sediments unconformably covering the orogenic assemblages.

Early Triassic rifting in the Central Sakarya Terrane was accompanied by the formation of basin-and-range-type narrow continental basins on the northern Tauride–Anatolide Platform. Deposition of continental coarse clastics (Otluk Metaclastics) in the Sömdiken Unit, and similar formations further south, marks this event. These data do not support the model of Şengör & Yılmaz (1981), who postulated Jurassic rifting that gave way to the opening of the İzmir–Ankara Ocean. The rift basin north of the Sömdiken Unit, and hence at the northern margin of the Tauride–Anatolide Platform, must have evolved into an oceanic basin during the Middle–Late Triassic. The upper Middle–lower Upper Triassic carbonates in the Kütahya area are characteristically open-shelf to slope-type deposits which do not include rift-related volcanic rocks. However, rift-related and transitional MORB-type volcanic rocks, with basinal sediments of Carnian–Norian age, are found in the Lycian Nappes. It is unequivocally accepted that these nappes were derived from the northernmost margin of the Tauride–Anatolide Platform and emplaced during the closure of the İzmir–Ankara Ocean to the south. Thus, the original location of these nappes should be more internal than the Sömdiken and Kütahya Units.

Another important clue that during the Early Jurassic the Tauride–Anatolide Terrane was already separated from the Central Sakarya Terrane by the intervening İzmir–Ankara Oceanic basin is that the Early Mesozoic (Cimmerian) deformation is nowhere recorded on the Tauride–Anatolide Terrane. All the ‘Cimmerian events’ in the northwestern part of the Taurides are either based on structural misinterpretations or inaccurate age dating (e.g. Tavşanlı area: Akdeniz & Konak 1979). The ‘Cimmerian orogenic events’ of Monod & Akay (1984, fig. 2, locations 4–11) in the Taurides *s.s.*, on the other hand, are probably related to intraplatformal tectonic events.

In short, Triassic time designates the closure of the main oceanic branch to the north of the Sakarya Composite Terrane (Şengör *et al.* 1984; Ustaömer & Robertson 1993; Okay *et al.* 1991; Yılmaz *et al.* 1995), the opening and closure of the aborted ‘Karakaya Rift Basin’ on the Central Sakarya Terrane, and the opening of the Neotethyan İzmir–Ankara Branch between Central Sakarya and the Tauride–Anatolide Terrane by back-arc spreading.

Late Mesozoic (Alpine) events

From the Jurassic, the configuration of the Neotethyan plates is less ambiguous (Fig. 11d and e). One exception is the problem whether the Triassic ocean to the north of the Sakarya Composite Terrane was totally eliminated during the Cimmerian events or whether part of it remained open to develop into the Neotethyan Intra-Pontide Ocean. The former interpretation is supported here and it is proposed that the ocean reopened during the late Middle Jurassic, evidenced by the development of Upper Jurassic slope sequences in the northern Armutlu Carbonate Platform (Önder & Göncüoğlu 1989) and in the northeastern margin of the Central Sakarya Platform (Altıner *et al.* 1991). In any case, during Jurassic–Early Cretaceous time, the Central Sakarya Terrane represents a carbonate platform limited by the Intra-Pontide Branch in the north and by the İzmir–Ankara Branch in the south. The MORB-type basaltic volcanic rocks associated with Upper Triassic–Lower Cretaceous radiolarian cherts (Göncüoğlu & Erendil 1990; Rojay *et al.* 1995; Bragin & Tekin 1996; the fossil data in this paper) indicate active spreading within these oceanic basins from the Late Triassic to the Early Cretaceous. The platform-type carbonate deposition on the northern margin of the Tauride–Anatolide Platform continued in the Jurassic with a slight change from open-shelf to open-slope conditions towards the end of the Jurassic and Early Cretaceous.

During the Early Cretaceous, the change in relative convergence between Gondwana and Eurasia to a more north–south orientation resulted in a convergence in the Intra-Pontide and İzmir–Ankara Branches of the Neotethys. The events relating to the closure of the Intra–Pontide Ocean have been evaluated by Göncüoğlu & Erendil (1990) and Yılmaz *et al.* (1995). Data from the northern part of the Central Sakarya area suggest that the regional subsidence was represented here by slope-type sediments of early Late Cretaceous age, followed by synorogenic flysch of Maastrichtian age containing ophiolitic detritus. The flysch sediments are overthrust by ophiolitic nappes derived from the Intra-Pontide Ocean. While it is generally accepted that the Intra-Pontide Ocean closed by northward subduction, the age of final collision of the Central Sakarya and İstanbul Terranes, however, is disputed. Based on field data, Göncüoğlu *et al.* (1987) suggested a Late Cretaceous age of collision, whereas Okay *et al.* (1994) preferred an Early Eocene collision.

During the Early Cretaceous convergent regime, within the İzmir–Ankara Branch and away from the passive margin of the Anatolide–Tauride Platform, northward intra-oceanic subduction was initiated (Fig. 11f) in Early–Middle Cretaceous times (Göncüoğlu & Türeli 1993). SSZ-type ophiolites were formed above this intra-oceanic subduction by the partial melting of the already depleted MORB-type İzmir–Ankara oceanic lithosphere during early Middle Turonian–Early Santonian times (Yalınız *et al.* 1996). The SSZ geochemical character of the basaltic rocks from the Dağküplü Mélange in the Central Sakarya area (Yalınız *et al.* 1998; this study), from the Kütahya region (Önen & Hall 1993) and from Central Anatolia (Yalınız *et al.* 1996), support this suggestion.

The subophiolitic amphibolites of the İzmir–Ankara Suture Zone from western Central Anatolia yielded mineral and isochron ages ranging from 101 to 90 Ma (Önen & Hall 1993; Harris *et al.* 1994), clearly indicating an early Late Cretaceous initial decoupling of oceanic crust. The upper level gabbros and dykes of SSZ-type oceanic crust in the Kütahya area, on the other hand, yielded isochron ages of *c.* 85 Ma (Önen & Hall 1993), which suggests that the formation of these ophiolites is penecontemporaneous with, or postdated, the deep intra-oceanic subduction and related HP–LT metamorphism. Due to their tectonic setting within the hanging wall, they probably escaped deep subduction (Fig. 11f), which would also explain the general absence of very HP parageneses in the SSZ-type ophiolites in both the study area and in Central Anatolia.

The blueschist-facies metamorphism related to this subduction has been the topic of copious studies in northwestern Anatolia (Yılmaz 1981; Okay *et al.* 1998 and refs cited therein). The HP–LT metamorphism recorded in the Dağküplü Mélange and the Sömdiken Group in the Central Sakarya area indicate, as in northwestern Anatolia, that not only the subduction–accretionary complex but also part of the passive continental margin was deeply subducted. In the Girdapdere Metaolistostrome, in this study area, the latest deformational phase is characterized by metamorphic conditions of *c.* 6 kbar and 200°C, which would correspond to a 20 km thick overburden of allochthonous material emplaced onto the passive margin of the Tauride–Anatolide platform.

The HP–LT metamorphism of the passive margin sequences in northwestern Anatolia [radiometric age data of Önen & Hall (1993) *c.* 90 $\pm$ 3 Ma is confirmed by Okay *et al.* (1998) who found Ar–Ar ages of *c.* 88 Ma] occurred in the Coniacian. However, the progressive southward younging of the metamorphosed synorogenic flysch sediments indicates that the emplacement of the oceanic material, subduction of the margin sequences, their metamorphism, exhumation and incorporation into foreland-type basins lasted until the Early Maastrichtian (Fig. 11g). The youngest flysch sediments unaffected by HP–LT metamorphism occur in the Kütahya area and were dated as early Late Maastrichtian–Early Palaeocene. In the Central Sakarya area, the molasse-type deposits of Middle Palaeocene (Montian) age unconformably cover all the main tectonic units (Fig. 11h). This indicates that the closure of the İzmir–Ankara oceanic basin, and the collision of the Central Sakarya Microcontinent and the Tauride–Anatolide Terrane occurred prior to the Middle Palaeocene.

The Middle Palaeocene–early Middle Eocene period in the Central Sakarya area is dominated by a tensional–transtensional regime, characterized by post-collisional magmatism and deposition of continental to shallow-marine sediments in fault-controlled basins. The Late Palaeogene in the study area is dominated by andesitic volcanism and deposition of alternating marine and terrestrial sediments. Renewed compression at the end of Miocene resulted in deformation of the Neogene basins and southward thrusting of the basement units.

Conclusions

The Late Palaeozoic–Mesozoic orogenic evolution (Fig. 11) of the Anatolian region and its surroundings can be summarized as a history of continuous convergence and divergence of microplates within the same main ocean, i.e. the Tethys. The durations, locations and names of the single branches (e.g. Prototethys, Palaeotethys, Karakaya Ocean, Neotethys, etc.) of this main ocean, as well as the nomenclature of the orogenic products, are still a matter of debate and beyond the scope of this study.

The Central Sakarya area is a key region in understanding the pre-Alpine and Alpine evolution of northwestern Anatolia. Along a north–south traverse in the Central Sakarya region, five different Alpine terranes were distinguished; from north to south these are: the İstanbul Terrane; the Intra-Pontide Suture Belt; the Sakarya Composite Terrane; the İzmir–Ankara Suture Belt; and the Tauride–Anatolide Composite Terrane. Among these, all of the continental units include amalgamated tectonic elements of Variscan and Cimmerian orogenic events.

The pre-Permian the Central Sakarya Terrane basement comprise two tectonic units: the Söğüt and Tepeköy Metamorphics. The former represents a Late Palaeozoic ensimatic arc complex whereas the latter is interpreted as a forearc–trench complex. These two basement units were juxtaposed during the 'Variscan' Orogeny due to the closure of a Palaeozoic oceanic branch by southward subduction. This subduction also produced a back-arc basin at the northern margin of the Peri-Gondwanan Tauride–Anatolide Platform. The Permian carbonates overlying this 'Variscan' orogenic assemblage characterize a period of platformal conditions prior to the Early Triassic rifting.

Triassic rifting is represented by a regional uplift and formation of the rift-basin assemblages (e.g. Soğukkuyu Metamorphics in Central Sakarya) or basin-and-range-type troughs in the northern margin of the Tauride–Anatolide Platform, filled with continental clastics. The rifting is related to the southward subduction of the 'Palaeotethyan' (*sensu* Şengör *et al.* 1984) oceanic crust. Starting from Middle–Late Triassic, one of the extensional basins on the northern Tauride–Anatolide Platform evolved in to the İzmir–Ankara Ocean and separated the Central Sakarya Terrane from the main body. In the north of the Central Sakarya Terrane, continuing subduction resulted in collision and amalgamation of oceanic assemblages to the northern margin of the Central Sakarya Terrane during Late Triassic and completed the 'Cimmerian' Orogeny.

Jurassic–Early Cretaceous time is represented in both microcontinents as a period of stable platform deposition. The only important event is Late Jurassic subsidence north of the Central Sakarya Terrane, probably related to the opening of the Intra-Pontide Ocean. In the Early Cretaceous, both branches of the northern Neotethys began to close by northward subduction.

Within the İzmir–Ankara oceanic seaway, northward intra-oceanic subduction was initiated in Early–Middle Cretaceous times, and SSZ-type ophiolites were formed in the upper plate during the early Late Cretaceous. First the subduction–accretionary complex, and later the passive margin of the Tauride–Anatolide Platform, were deeply subducted and affected by HP–LT metamorphism. Geological and geochronological data suggest that the subduction, blueschist metamorphism, exhumation and incorporation of ophiolite nappes onto foreland-type basins lasted until the Early Maastrichtian. The earliest post-tectonic molasse-type deposits in the Central Sakarya area are of Middle Palaeocene age, indicating that closure of the İzmir–Ankara oceanic basin, and collision of the Central Sakarya and the Tauride–Anatolide terranes predated the Middle Palaeocene.

Post-collisional compression and magmatism in the study area continued until the end of the Palaeogene, and the propagation of southward younging thrusts produced an immense crustal thickening which, in turn, gave rise to the metamorphism of the Menderes Massif.

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