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Significance of the Volcanogenic Nilüfer Unit and Related Components of the Triassic Karakaya Complex for Tethyan Subduction/Accretion Processes in NW Turkey

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Abstract: The Tethyan Karakaya Complex extends east–west across northern Turkey from the Aegean coast to Iran (c. 1100 km), and is interpreted as a Mid–Late Triassic subduction/accretion complex. It comprises strongly deformed fragments of Triassic oceanic seamounts, mid-ocean ridge-type oceanic crust, trench-type sedimentary rocks (Ortaoba Unit) and Permian–Triassic continental fragments (Çal Unit). We focus on the Triassic Nilüfer Unit, which comprises altered basic volcanic and volcaniclastic rocks, volcanogenic sedimentary rocks, heterogeneous debris flow deposits, calciturbidites, siliceous pelagic sedimentary rocks and, in places, Triassic shallow-water limestones. The predominant lithologies are massive basalt and reworked basic pyroclastic deposits. Additional detrital lithologies include volcanogenic sandstone/siltstone/mudstone and volcanogenic breccia. These lithologies document the construction of one, or several, volcanic seamounts within the Triassic Tethyan ocean, removed from a supply of terrigenous detrital sediment. Whole-rock geochemical analysis of basalt and electron-microprobe analysis of clinopyroxene phenocrysts confirm a within-plate, "enriched" composition, without a detectable subduction influence. The Nilüfer Unit generally exhibits greenschist-facies metamorphism and locally also HP/LT (up to eclogitic) facies metamorphism. The structurally overlying Ortaoba (Hodul) Unit records the accretion of mid-ocean-ridge-type basalts, radiolarian chert and minor serpentinised ultramafic rocks in a trench-type setting where mainly arkosic sediments rich in altered silicic volcanic grains accumulated. Above this, the unmetamorphosed Çal Unit is dominated by blocks of Upper Permian neritic limestone associated with within-plate-type basalt. The bases of locally intact successions are commonly depositionally associated with micaceous shale of terrigenous origin suggesting the former presence of a continental substratum that was probably removed by subduction. One or more of such continental fragments were possibly rifted from the southern margin (Anatolides) and drifted northward across the Triassic Tethys before being accreted to the Eurasian margin. The direction of subduction related to initial tectonic accretion is assumed to have been northward although definitive structural evidence is lacking. The Karakaya Complex was finally emplaced northward over the leading edge of the Eurasian margin (Sakarya basement), possibly in response to the collision of the Çal continental fragment(s) with the subduction zone, prior to covering by shelf carbonate in middle Jurassic time.

Key Words: Nilüfer Unit, NW Turkey, Karakaya Complex, subduction/accretion, Triassic Tethys

Volkanojenik Nilüfer Birimi ve Karakaya Kompleksi'nin Diğer Birimlerinin Kuzeybatı Anadolu'da Tetis'deki Dalma-Batma/Eklenme Olayları Açısından Önemi

Özet: Karakaya Kompleksi kuzey Anadolu'da batıdan doğuya, Ege Denizi'nden İran'a kadar yaklaşık 1100 km bir dağılımı olan Orta–Geç Triyas yaşında bir dalma-batma-eklenme kompleksidir. Karakaya Kompleksi çok kuvvetli deformasyon geçirmiş Triyas yaşta okyanusal deniz adaları, okyanus-ortası-sırtı tipi kabuk, hendek tipi çökel kayalar (Ortaoba Birimi) ve Permiyen–Triyas yaşta kıtasal parçalar (Çal Birimi) içerir. Bu makalede, volkanik ve volkaniklastik kayalar, volkanojenik sedimenter kayalar, heterojen moloz akıntı çökelleri, kalsiturbidit, silisli pelajik sedimenter kayalar ve yer yer neritik Triyas kireçtaşlarından oluşan Nilüfer Birimine odaklanılmıştır. Nilüfer Birimi'nin baskın litolojisi massif bazalt ve bazik piroklastik kayalardır. Bunlara volkanojenik kumtaşı, silttaşı, çamurtaşı ve volkanojenik breş türü kırıntılı kayalar eşlik eder. Bu litolojiler, kıtasal etkilerden uzakta, Triyas yaşta Tetis okyanusu içinde bir veya birden fazla volkanik deniz adalarında ve çevrelerinde oluşmuştur. Bazaltlarda yapılan tüm kaya jeokimya analizleri, ve yine bazaltlardaki piroksenlerde yapılan elektron-mikroprob analizleri, Nilüfer Birimi bazaltlarının, herhangi bir dalma-batma zonu etkisi görülmeyen levha-içi bir karakterde olduğunu teyit eder. Nilüfer Birimi genellikle yeşilşist fasiyesinde, yer yer eklojite varan yüksek basınç/düşük sıcaklık fasiyesinde, bölgesel metamorfizma geçirmiştir. Nilüfer Birimi'nin yapısal olarak üstünde yer alan Ortaoba (Hodul) Birimi, okyanus ortası tipi bazaltların, radyolaryalı çörtlerin ve az oranda serpantinleşmiş ultramafik kayaların, hendek tipi çökeller olarak yorumlanan arkozik klastiklere eklendiği bir dalma-batma zonu ortamını tanımlar. Tektonik olarak daha üstte yer alan, ve metamorfizma geçirmemiş olan Çal Birimi, levha-içi bazaltlarla beraber bulunan Geç Permiyen yaşta neritik kireçtaşı bloklarından oluşur. Çal Birimi'nin yer yer korunmuş alt kesimleri, jeokimyasal olarak kıtasal kökenli olarak belirlenen mikali şeyller kapsar. Bu durum Çal Birimi'nin kıtasal bir kabuk üzerinde çökeldiği, daha sonra bu kabuğun dalma-batma ile yok olduğuna işaret eder. Bu tip bir veya birden çok kıtasal parça, Triyas Tetisi'nin güney kenarından (Anatolidler'den) riftleşme ile ayrılmış, kuzeye hareket ederek, Avrasya kıta kenarına eklenmiştir. Bu konuda kesin veri olmamasına rağmen, dalma-batma polaritesinin kuzeye doğru olduğu sanılmaktadır. Karakaya Kompleksi, daha sonra, muhtemelen Çal kıtasal parçasının Lavrasya kıta kenarı (Sakarya temeli) ile çarpışması sonucu, kuzeye Lavrasya kıta kenarı üzerine itilmiştir.

Anahtar Sözcükler: Nilüfer Birimi, KB Türkiye, Karakaya Karmaşığı, dalma-batma/eklenme, Triyas Tetisi

Introduction

The Permo–Triassic Karakaya Complex extends across Turkey from the Aegean Sea to Iran (> 1100 km) and is critical to an understanding of the Late Palaeozoic–Early Mesozoic palaeo-tectonic evolution of Tethys. It is a classic example of a mélange terrane interpreted as a subduction complex (Tekeli 1981) and can be taken as a reference for many other examples throughout the eastern Mediterranean region and elsewhere (Robertson 1994). Here, we focus on metamorphosed basic volcanogenic rocks (lavas and volcaniclastic sedimentary rocks), which form a key component of the Karakaya Complex in NW Turkey, known as the *Nilüfer Unit* (Figure 1). We also consider evidence from other units of the Karakaya Complex that are relevant to a discussion of the tectonic setting.

The Karakaya Complex, as defined by Bingöl *et al.* (1975), is dominated by a volcanic-sedimentary mélange, mainly composed of Permian and Triassic rocks preserved as an inferred subduction/accretion complex (Tekeli 1981; Pickett & Robertson 1996; Okay 2000). The Karakaya Complex is structurally underlain by a crystalline basement of high-grade metamorphic and granitic rocks, exposed in several deeply exhumed extensional core-complexes (Okay *et al.* 1991, 1996). The structurally lower levels of the Karakaya Complex, represented by the Nilüfer Unit, comprise kilometres-thick, strongly deformed and metamorphosed sequences of basic volcanic and volcanogenic sedimentary rocks, together with limestones in some areas. Our aim here is, first to infer the tectonic setting of formation of the Nilüfer Unit (i.e., its tectonic facies; Robertson 1994), and secondly to use the Nilüfer Unit to help test alternative tectonic models of the Triassic Tethys in NW Turkey in the light of regional data and modern oceanic comparisons.

The Karakaya Complex has been interpreted in various different ways, as summarised below:

1. A Permo–Triassic rift infilled with basic volcanics, volcanogenic sedimentary rocks, olistostromes and turbidites, forming a layer-cake sequence (Bingöl *et al.* 1975; Kaya *et al.* 1986, 1989; Kaya 1991; Wiedmann *et al.* 1992);
2. A narrow rifted back-arc basin generated by *southward* subduction of a "main" Palaeotethys beneath the northern margin of Gondwana (i.e., Anatolides/Taurides) (Şengör & Yılmaz 1981; Şengör *et al.* 1984; Genç & Yılmaz 1995; Göncüoğlu *et al.* 2000);
3. A fore-arc complex related to *southward* subduction of a "main Palaeotethys" with the Triassic volcanogenic Nilüfer Unit representing a subduction-related volcanic arc, flanking inter-arc and fore-arc basins (Okay *et al.* 1991, 1996; Akyüz & Okay 1996);
4. A back-arc basin related to *northward* subduction of a Palaeotethyan ocean located to the south of the present deformed and metamorphosed Anatolide carbonate platform and related units (Stampfli *et al.* 1998; Stampfli 2000);
5. A subduction complex related to Triassic *northward* subduction of Triassic oceanic crust (Pickett *et al.* 1995; Pickett & Robertson 1996; Robertson *et al.* 1996; Ustaömer & Robertson 1997, 1999; Okay 2000; Robertson *et al.* 2004). The Nilüfer Unit is interpreted as accreted oceanic sediments, whereas the Çal Unit is seen as one or several accreted continental fragments according to Pickett & Robertson (1996);
6. In this interpretation, the Karakaya Complex includes Upper Permian limestones (Çal Unit) that

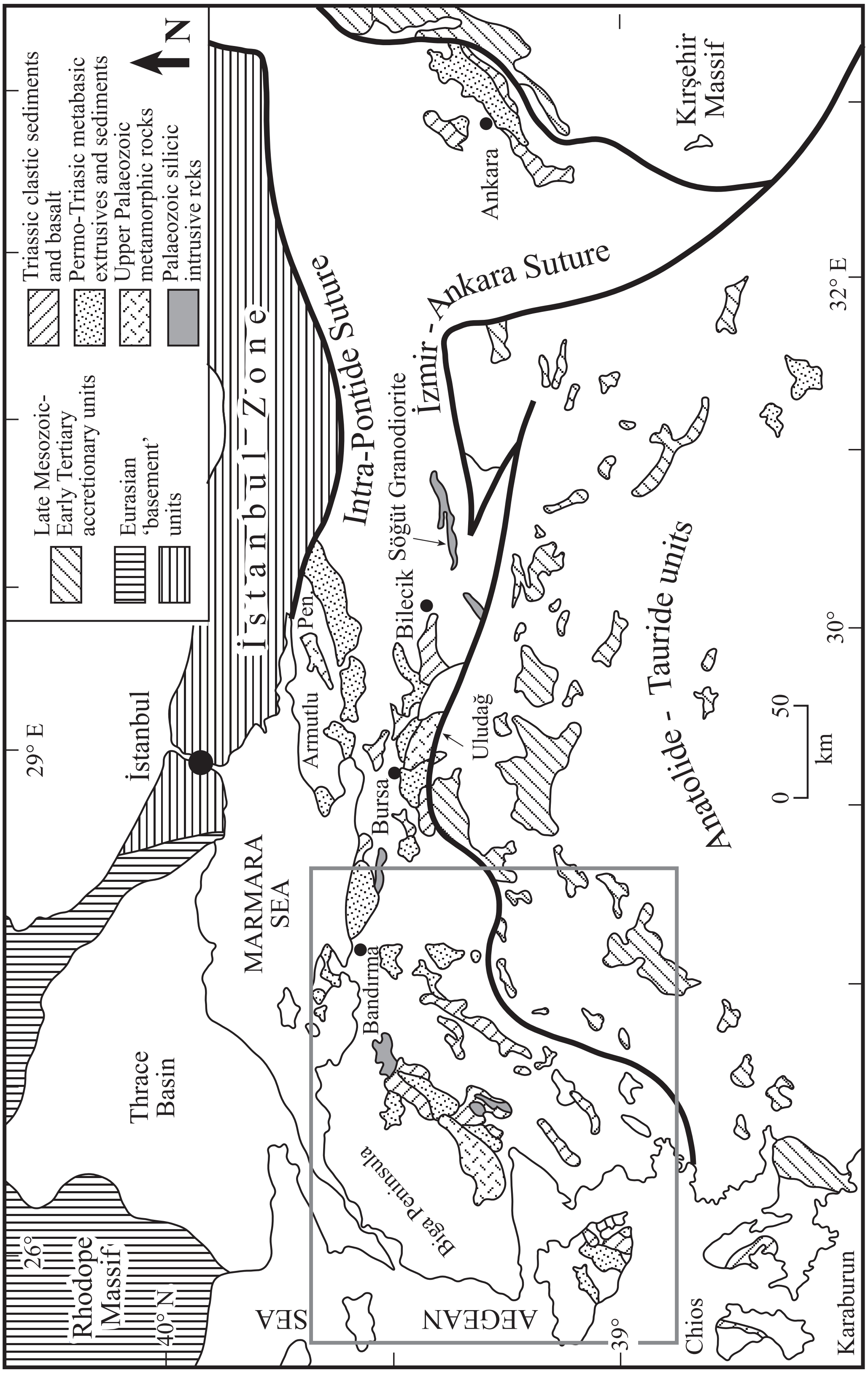


Figure 1. Outline tectonic map of NW Turkey showing the Biga Peninsula (in box) where the Triassic Nilüfer Unit crops out as part of the Karakaya Complex. The Permian and Triassic units cannot be accurately differentiated at this scale (see Figure 2) (modified after Okay 2000).

> were detached from an inferred continental fragment that itself originated by rifting from the southerly (Anatolide-Tauride) margin of the Triassic Tethyan oceanic basin. The subducting oceanic lithosphere was also possibly partly of pre-Triassic age since Permo–Carboniferous pelagic fossils, notably radiolarians, have been discovered within blocks in the Karakaya Complex (Kozur & Kaya 1994; Okay & Mostler 1994).

The accretion of the Karakaya Complex took place during Late Triassic time (215–200 Ma; Okay 2000), although in general accretionary processes appear to have been more long-lived along the Eurasian margin (Late Palaeozoic–Early Mesozoic). The Karakaya Complex is widely interpreted as being made up of units of mainly Permian and Triassic age that were emplaced northward onto the Eurasian margin in latest Triassic time and covered by Early Jurassic shelf carbonates (Bingöl *et al.* 1975; Okay *et al.* 1991; Pickett 1994). According to different authors, the Tethyan ocean in this region either completely closed during the latest Triassic "Cimmerian event" as a result of continental collision (Şengör *et al.* 1980; Şengör & Yılmaz 1981; Genç & Yılmaz 1995), or remained partly open between Eurasia and Gondwana-related units (i.e., Anatolides/Taurides) until latest Cretaceous–Early Tertiary time (Robertson & Dixon 1984; Dercourt *et al.* 1986, 1993; Ustaömer & Robertson 1993, 1997; Okay 2000; Robertson & Pickett 2000; Robertson *et al.* 2004).

Several authors suggested that the collision of oceanic igneous bodies (seamount(s) or oceanic plateau), or microcontinental fragments with the Eurasian active continental margin to the north played an important role. Pickett & Robertson (1996) proposed a model in which steady-state northward subduction culminated in collision of one or several igneous seamounts and microcontinental fragments with a trench located along the southern margin of Eurasia. The collision of a continental fragment triggered a localised reversal of subduction polarity, following which the Karakaya Complex was assembled as a pile of northward-verging thrust sheets. Okay (2000) suggested that this Cimmerian orogenic event was driven by the collision of a Large Igneous Complex (LIP) with the Eurasian active margin. This collision blocked steady-state subduction and deformed the accretionary wedge.

Thus, it is clear that the Nilüfer Unit had a critical role in the Triassic evolution of Tethys and the tectonic assembly of the Karakaya Complex.

Tethyan Nomenclature

The Karakaya Complex formed within part of the Tethyan oceanic system generally known as Palaeotethys by most Turkish workers. However, the term "Palaeotethys" has been defined differently by different workers and has genetic connotations. For Şengör *et al.* (1984), "Paleo-Tethys" represents a largely Late Palaeozoic–Early Mesozoic ocean basin between Eurasia and Gondwana-related units (Anatolide-Tauride platform) that closed prior to Early Jurassic time, leaving its root zone close to the Eurasian margin. This was followed by rifting of "Neotethyan" ocean basins in this region. By contrast, for Stampfli & Borel (2002), the root zone of "Paleotethys" lies further south, whereas "Neotethys" refers only to an oceanic basin formed south of the (Gondwana-related) Tauride-Anatolide platform unit. Both of the above definitions are related to quite different tectonic models. The genetic nature of this Tethyan nomenclature inhibits testing of alternative tectonic models based on new evidence. Here, we simply refer to Tethys by age (e.g., Triassic Tethys) in NW Turkey.

Regional Setting of the Nilüfer Unit

The unit is named after the Nilüfer River, between Bursa and Orhaneli (Okay *et al.* 1991) and is equivalent to the Çavdartepe Formation (Akyürek & Soysal 1983) and the Madradağ Formation (Kaya *et al.* 1986) of earlier stratigraphic schemes.

The Nilüfer Unit is well exposed in several different areas in the Biga Peninsula and surrounding areas (Figures 2 & 3). The Nilüfer Unit is mapped as regionally overlying the Sakarya crystalline basement in several large windows (i.e., Kazdağ, Uludağ and Kozak massifs). These are interpreted as Neogene core complexes (Pickett 1994; Okay & Satır 2000). The "Sakarya basement" includes Late Palaeozoic (Devonian–Early Permian) granodiorites and Carboniferous high-grade metamorphic rocks (e.g., Kazdağ gneiss; see Okay 2000 for a review). Locally, intrusive rocks are reported to overlie the Karakaya Complex tectonically with intervening mylonites (e.g., Söğüt Granodiorite; Figure 1).

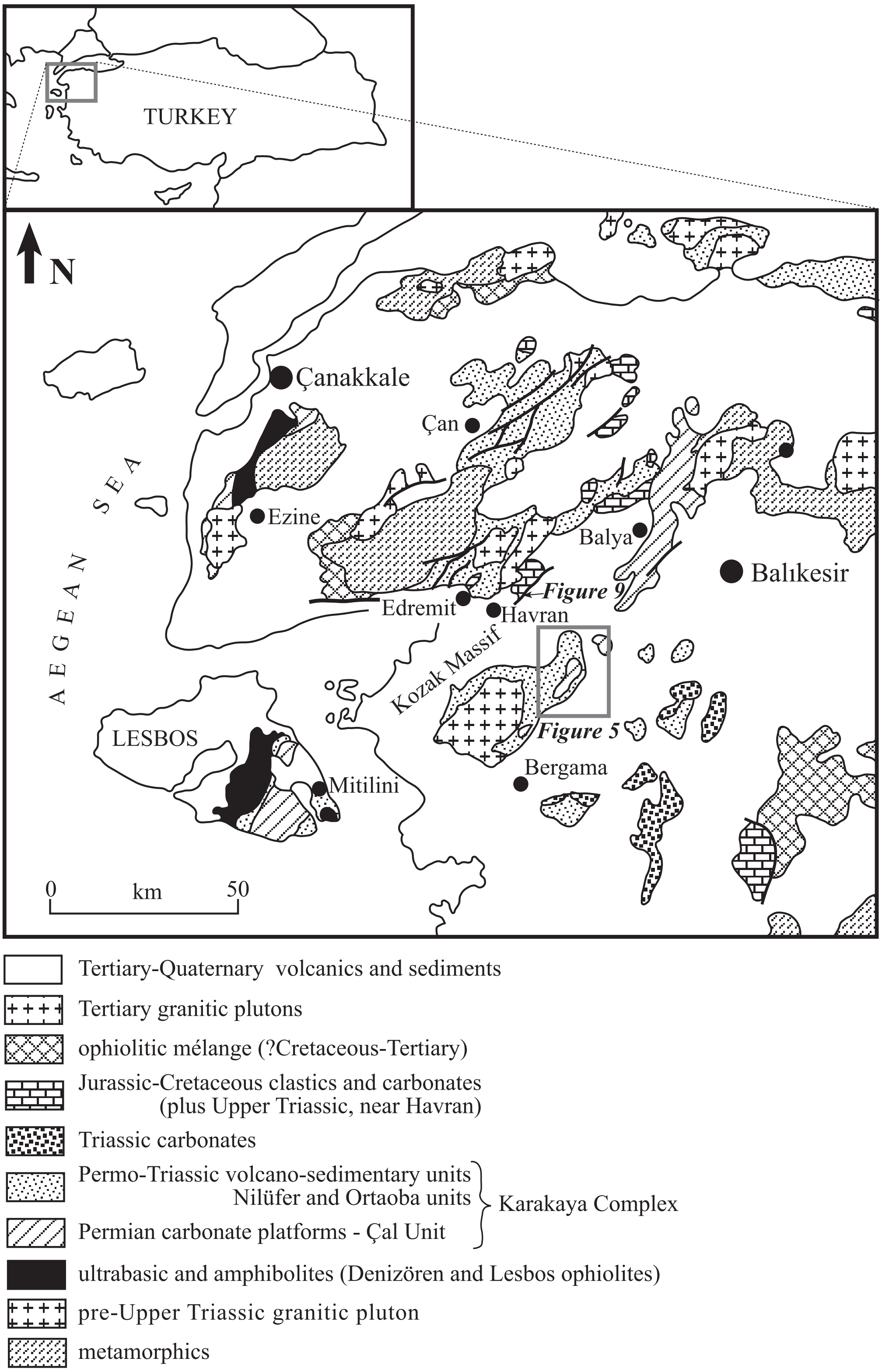


Figure 2. Simplified geological map of the Biga Peninsula. Note the occurrences of the Karakaya Complex. The Nilüfer Unit discussed here is included within the Permo-Triassic volcano-sedimentary units.

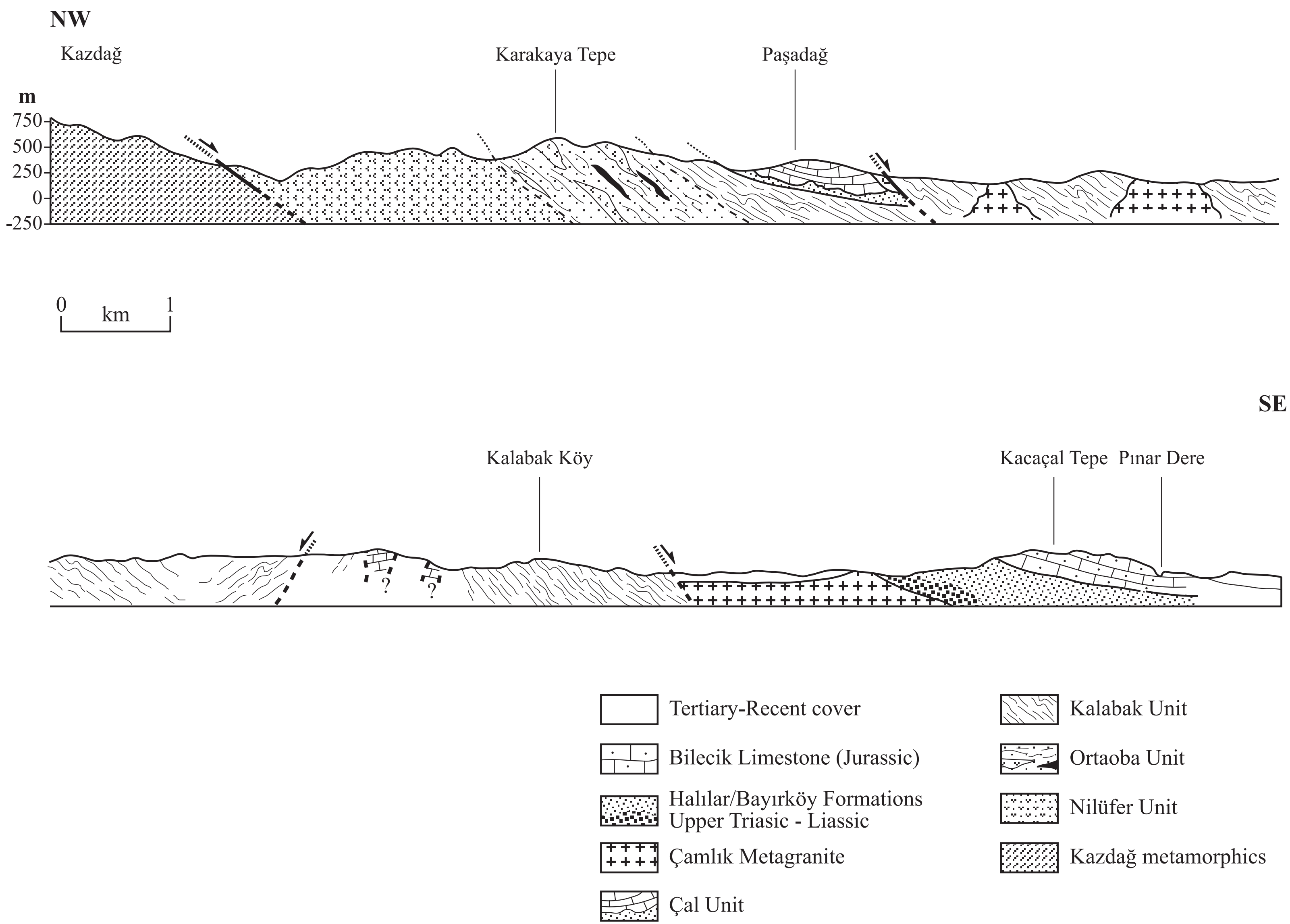


Figure 3. Cross-section through the Karakaya Complex in the Edremit area. Note the location of the Nilüfer Unit at the structural base in extensional fault contact with the Kazdağ metamorphic massif (modified after Aslaner 1965).

The Nilüfer Unit is dominated by basic volcanic and volcanogenic sedimentary rocks, with common matrix-supported conglomerates, detached blocks and occasional large sheets of limestone. The true thickness is unknown as no original basal contacts are exposed; however, the apparent thickness is commonly 1–2 km, to 7 km, locally. The Nilüfer Unit is structurally overlain by other units of the Karakaya Complex, as discussed later in the paper.

The lowest part of the Nilüfer Unit is sparsely fossiliferous. Kozur *et al.* (1996) reported the presence of Lower and Middle Scythian radiolarians, and H. Kozur (pers. com., 1998 to A. Okay 2000) also noted the existence of conodonts of Early Triassic age, south of Bursa. Conodonts of Middle Triassic age (Anisian/Ladinian boundary) were reported from basic volcanogenic sedimentary rocks in the upper part of the Nilüfer Unit in the Kozak Massif, south of Edremit (Kaya & Mostler 1992; see also Altıner & Koçyiğit 1993). A latest Triassic age of emplacement of the Nilüfer Unit is indicated by Ar-Ar dating of phengites in blueschists and eclogites north of Eskişehir (Monod *et al.* 1996; Okay *et al.* 2002).

The Nilüfer Unit as a whole can be considered to have undergone at least three metamorphic events: i.e., a pervasive low- to intermediate-temperature greenschist-facies metamorphism (spilitisation), a locally recognised blueschist/eclogite-facies metamorphism, and occasional high-temperature greenschist-facies metamorphism (Okay *et al.* 1991; Pickett 1994; Okay 2000). Spilitisation appears to have affected the Nilüfer Unit in the Kozak Massif, north of Bergama (Figure 2). Spilitisation was overprinted by high-greenschist facies metamorphism in the lower part of the Nilüfer Unit in the Edremit area, as characterised by an assemblage including hornblende, actinolite, albite, chlorite, epidote and garnet (Pickett 1994). In addition, high-greenschist- and blueschist/eclogite-facies metamorphism is widespread in the Bursa area, as shown by the presence of blue sodic amphiboles replacing kaersutite (Okay *et al.* 1991). Iron-rich metacherts with HP/LT mineral assemblages are also present locally (Okay *et al.* 1996). Furthermore, tectonic lenses (< 100 m in size) of sodic amphibole-bearing eclogites occur east of Bandırma (Okay *et al.* 1991; Okay & Monié 1997; Figure 4). A large slice of Nilüfer rocks has undergone blueschist/eclogite-facies metamorphism north of Eskişehir (Monod *et al.* 1996; Monod & Okay 1999; Okay *et al.* 2002; Figure 4).

The low-temperature alteration could reflect initial sea-floor alteration. The blueschist/ eclogite-facies metamorphism could then relate to later subduction subduction/underplating (followed by exhumation). The high-temperature greenschist-facies metamorphism might be the response of burial beneath a pile of thrust sheets related to regional crustal thickening. However, the precise tectonic settings of metamorphism remain poorly constrained.

Lithostratigraphy of the Nilüfer Unit

We focus on the Nilüfer Unit, focusing on volcanic-sedimentary relations in two areas of northwest Turkey, the Kozak Massif (or Kozak Range) north of Bergama and the Edremit area (c. 60 km apart; Figures 1 & 2).

Kozak Massif

We discuss the Kozak Massif first as it is better exposed than the Edremit area. Despite commonly intense deformation, relatively intact primary transitions are visible between massive lava flows, volcaniclastic flows, thin-bedded volcaniclastic rocks and siliceous sedimentary rocks. Middle Triassic conodonts occur within limestones interbedded with phyllites near the top of the unit (Kaya & Mostler 1992). The exposed succession begins with unfoliated lava flows, interbedded with volcaniclastic flows. Over an interval of 100–200 m there is a change to foliated and schistose grey-green phyllites, with local lenses of recrystallised limestone. The presence of a local slice of weathered dunite, 30 m across (near Köyyeri, Figure 5) confirms that the overall succession was tectonically assembled and cannot be simply a deformed layer-cake sequence.

Within the Kozak Massif the following main lithofacies are observed:

Massive Basalts with Primary Textures

Pale green, homogeneous basalt forms the exposed base of the Nilüfer Unit, as seen along the road from Köyyeri to Hacılar (Figure 5). The lavas include spherical degassing structures, with chlorite and epidote-filled vesicles, up to 2 mm in diameter, concentrated near the margins (Figure 15b). The massive lavas pass with a short transition (1 m) into the volcanogenic lithofacies described below.

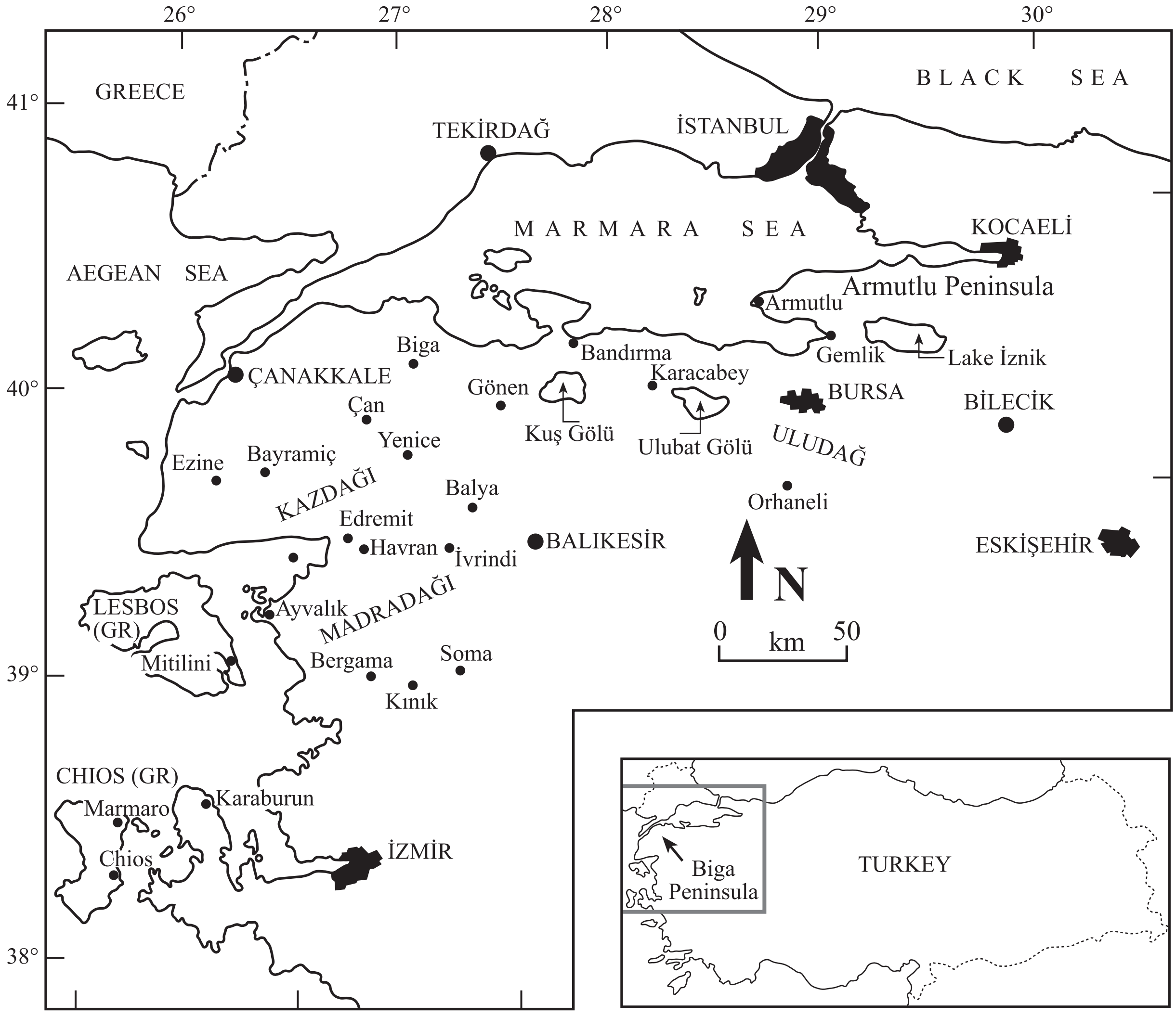


Figure 4. Location of places mentioned in the text.

Massive Hyaloclastite Flows

Some of the rocks exhibit a distinctive streaky appearance, with visible small clasts up to several millimetres in size. In thin section, these clasts are seen to be basaltic and are surrounded by devitrified glassy material. Other examples comprise isolated (former) glass fiamme in a chloritic matrix. The fiamme are commonly aligned parallel to the overall flow direction. This lithology is interpreted mainly water-lain glassy hyalotuff of primary eruptive origin.

Volcanogenic Sandstones and Thin Mudstones

Right-way-up successions (based on size grading) of fine- to medium-grained volcanogenic sandstone, with thin volcanogenic mudstone partings (2 mm – 2 cm) dominate the highest levels of the succession in the Kozak Massif (Figure 14d). The volcanogenic sandstone is well bedded (beds 3–20-cm thick), pale green and siliceous.

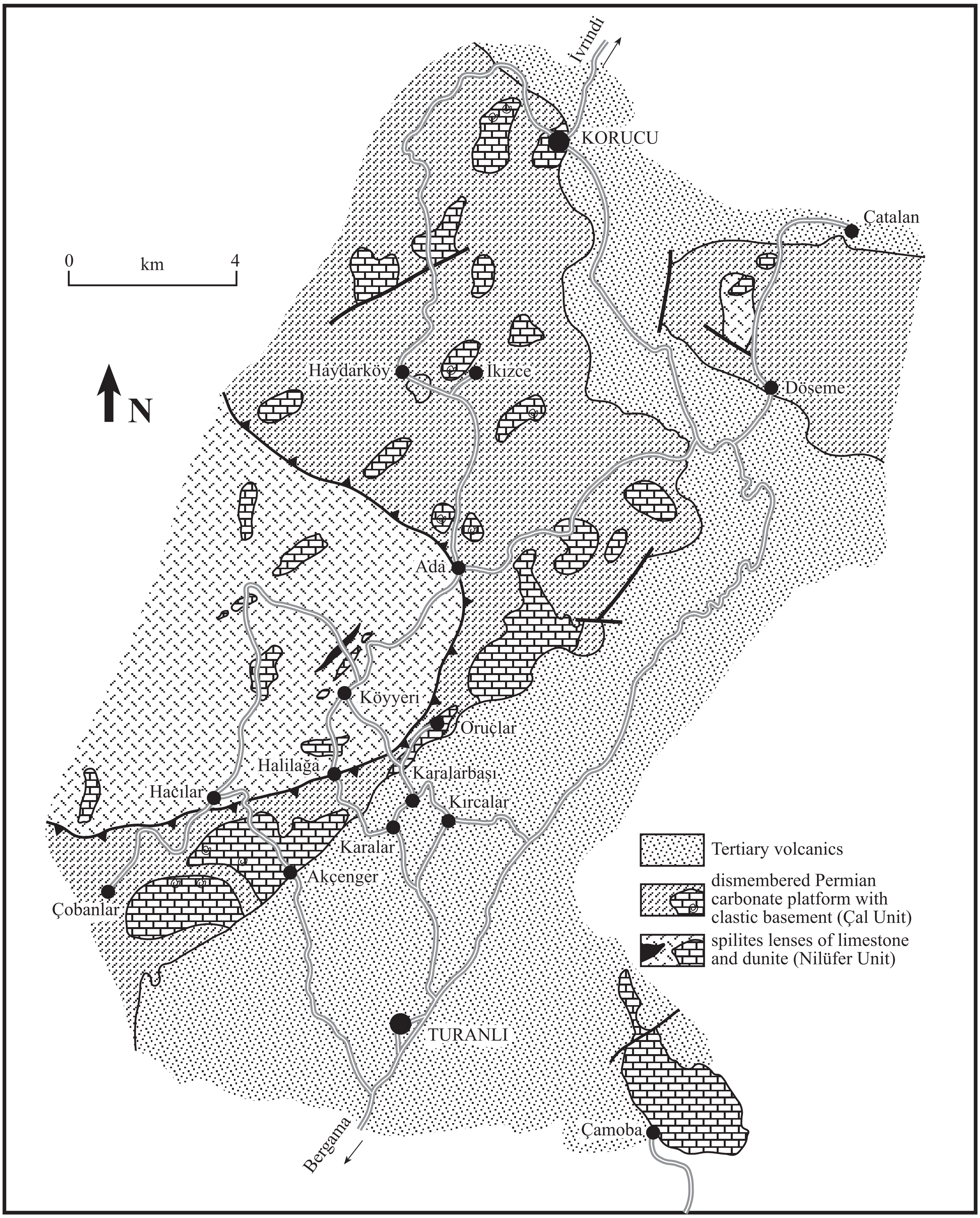


Figure 5. Geological map of the Kozak Range, north of Bergama (modified after General Directorate of Mineral Research and Exploration of Turkey – MTA – map sheet Balıkesir G4 with additional information from A. Okay – personal communication, 1992).

Redeposited Limestone and Volcanogenic Sedimentary Rocks

The succession includes intercalations of well-bedded limestones, traceable laterally up to 1 km (Figures 6 & 7). Individual beds range in thickness from 2 cm to 4 m and are commonly separated by thin (< 2 cm) partings of foliated green and purple mudstone. Despite extensive recrystallisation the limestone is seen to be of clastic origin. Flattened and fused lenticular shapes are visible, separated by sutured, stylolitic seams of fine-grained, green shaly material. The redeposited limestones are commonly intercalated with volcanogenic sedimentary rocks on a metre scale (e.g., NW of Köyyeri; Figure 5).

White Fine-Grained Metatuff

Green volcaniclastic sedimentary rocks locally pass upward into pale beige to white shale, interpreted as lithified volcanic material, as seen near the base of the exposed section at Ada Tepe (Figure 8). These tuffaceous sedimentary rocks are associated with lenticular tectonic lenses of feldspathic sandstone that belong to the structurally overlying Ortaoba (Hodul) Unit.

Edremit Area

The Nilüfer Unit is again well exposed northwest of Edremit (Figure 2), where considerable relief (> c. 1000 m) is created by neotectonic extensional faulting. The base of the Nilüfer Unit is a low-angle extensional fault, along which the underlying Kazdağ metamorphic massif was exhumed as a core complex (Pickett 1994; Okay & Satır 2000; Figure 9). A composite log is shown in Figure 10a. We carried out our most detailed work in this area (Figure 11), although exposures are fragmentary and no originally complete stratigraphical succession can be reconstructed.

We focused on a well-exposed valley running north of Uğu taşı, especially a small steep-sided, E–W-trending valley (marked by box A in Figure 11). Samples were collected for geochemical analysis mainly along a road running along the eastern side of the main valley. In this area, the Nilüfer Unit forms a major thrust sheet bounded by the Kazdağ metamorphic massif below and the Ortaoba (Hodul) Unit above (Figures 9 & 10). The Nilüfer Unit in this area is subdivided into a number of sub-units by poorly exposed contacts that are interpreted as thrusts. Sedimentary structures and primary igneous features are best preserved in the structurally higher, less deformed intervals.

The following lithofacies are recognised in the Edremit area.

Massive Basalt Flows

Where exposed along the N–S valley (north of Uğutaşı; Figure 11), basic lava flows grade laterally and vertically into volcaniclastic flows. In thin section, the primary flows exhibit subophitic, intergranular, amygdaloidal and porphyritic textures. Small pink clinopyroxene phenocrysts are commonly observed in a fine-grained sub-ophitic groundmass. More commonly, the lavas are strongly altered and display plagioclase albitisation, alteration of clinopyroxene to chlorite and complete

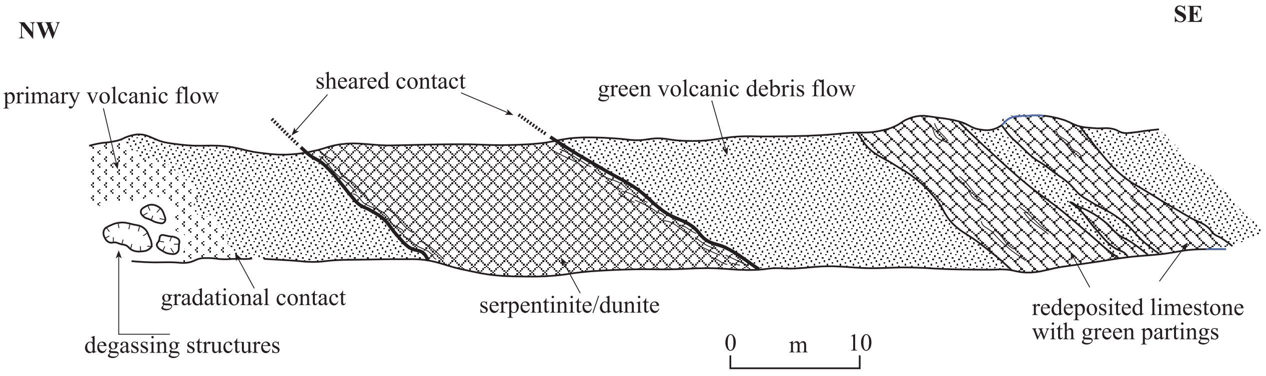


Figure 6. Field sketch of the Nilüfer Unit near Koyyeri, Kozak Massif, showing a section through the basaltic and volcaniclastic sequence. Note the tectonically intercalated dunite slice.

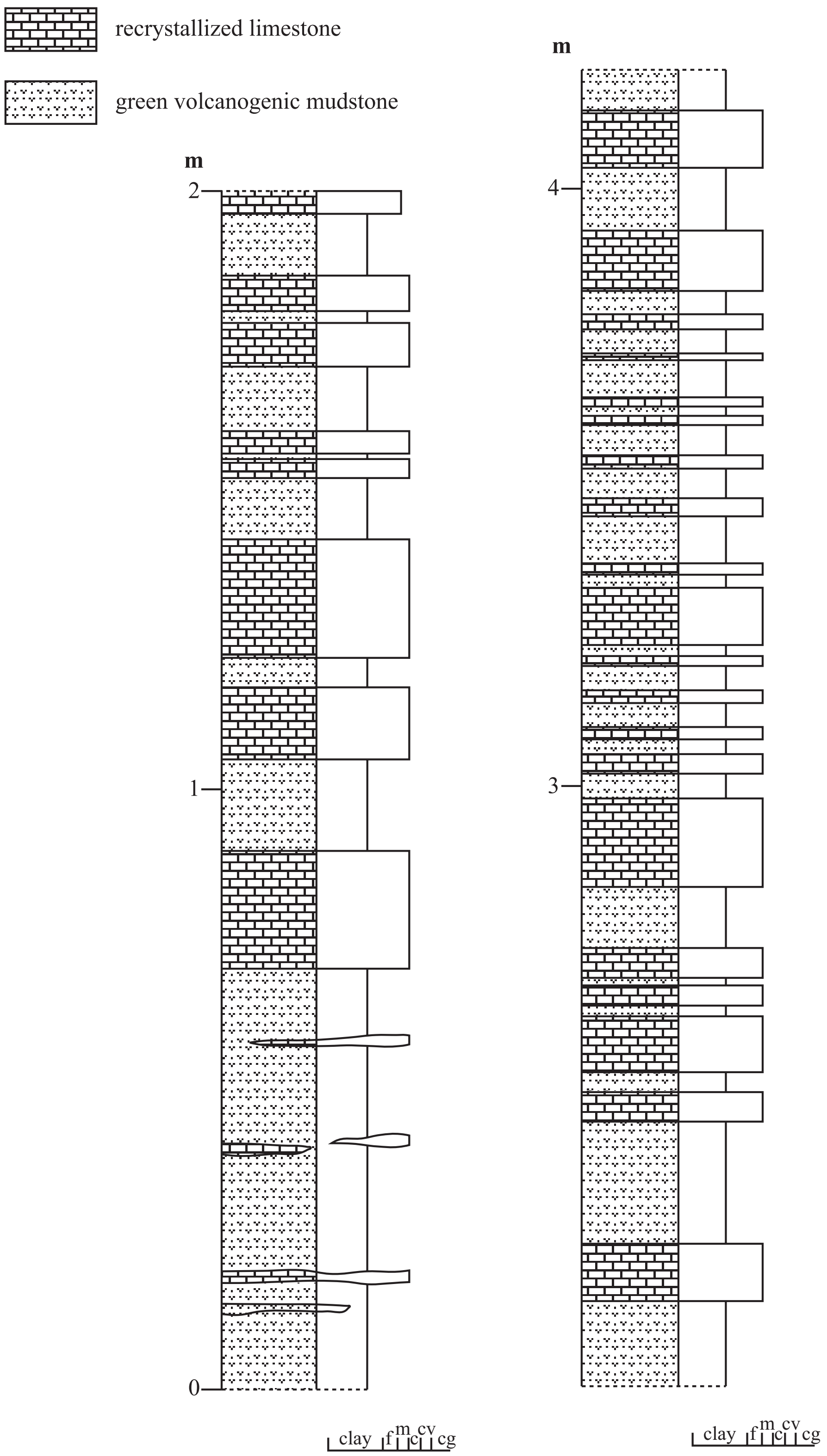


Figure 7. Representative log through the interbedded volcanogenic shale and limestone of the Nilüfer Unit, NW of Koyyeri, Kozak Massif.

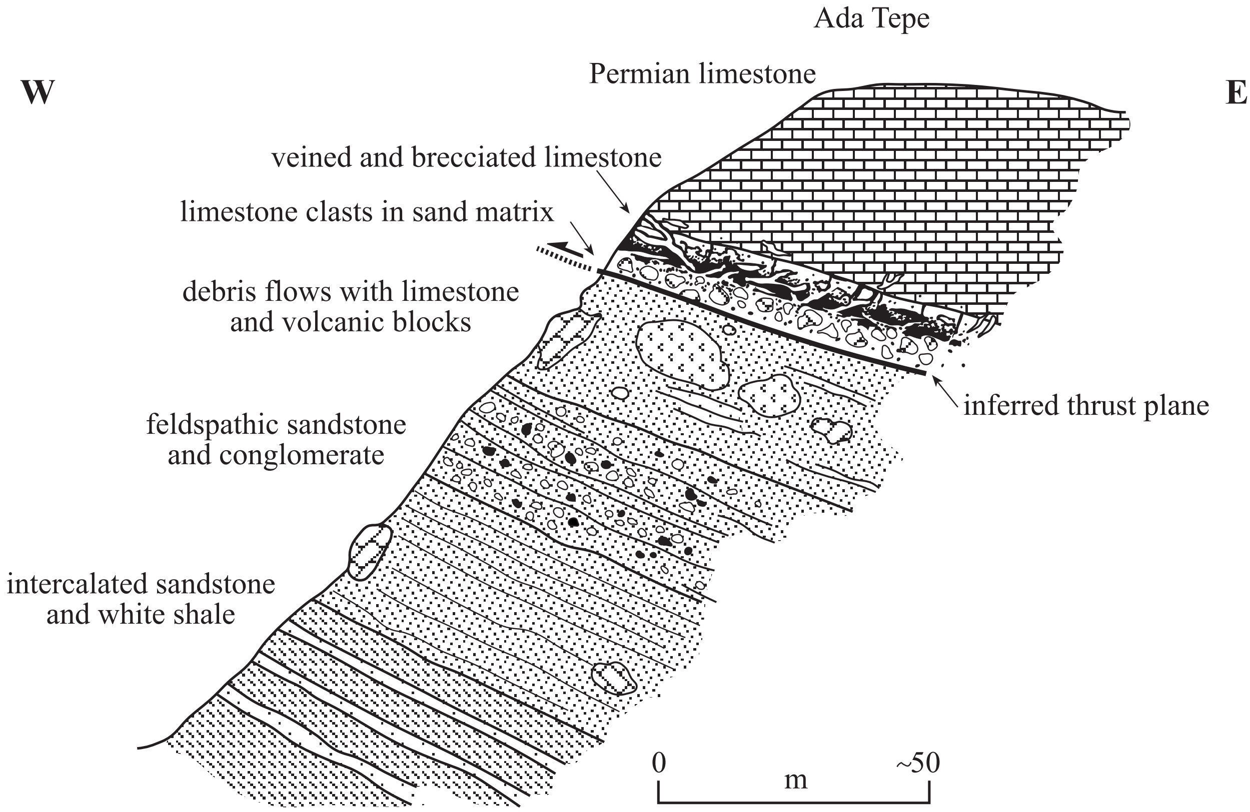


Figure 8. Field sketch showing an upward passage from white shale, interpreted as siliceous tuff, to coarse clastics and debris flows interpreted as within the uppermost part of the Nilüfer Unit (base of section). This is in turn tectonically overlain by Permian limestones of the Çal Unit (main part of section); Ada Tepe, Kozak Massif.

devitrification of glass. Vesicles are infilled with chlorite and calcite and are commonly rimed by epidote crystals. Locally, the entire rock is replaced by chlorite and actinolite, as seen in the structurally lower levels of the Nilüfer Unit.

Massive Waterlain Hyaloclastite Tuffs

These pyroclastic flows are identical to those of the Kozak Massif (Bergama region; see above) and are closely associated with basaltic flows (e.g., in the main valley north of Uğutaşı; Figure 11). These pyroclastic rocks have a streaky texture with small extrusive clasts up to a few millimetres in size. Glass-rich examples contain chlorite-filled vesicles and small clasts of fine-grained basalt (Figure 15a). Other examples are much less glass rich and comprise isolated glass fiamme in a chloritic matrix. A measured log is shown in Figure 10b.

Sheared Purple Volcanics

Where exposed (e.g., near the village of Pınarbaşı and along the road north from Mehmetalan; Figure 11), sheared purple basic volcanic rocks are associated with large blocks of white recrystallised limestone (Figure 11). In thin section, lath-like plagioclase crystals show a slightly preferred orientation. The recrystallised limestones include purple partings of haematite and reworked volcanogenic material that was possibly derived from the purple volcanic rocks.

Clast-Supported Volcanogenic Conglomerate

Greenish (brownish where altered) conglomerates, well exposed in the small valley marked A in Figure 11, are mainly volcanic-derived, or volcaniclastic (Figure 12). The dominant clast type is rounded black "blebs" (up to 5 mm across), mainly composed of relict clinopyroxene crystals,

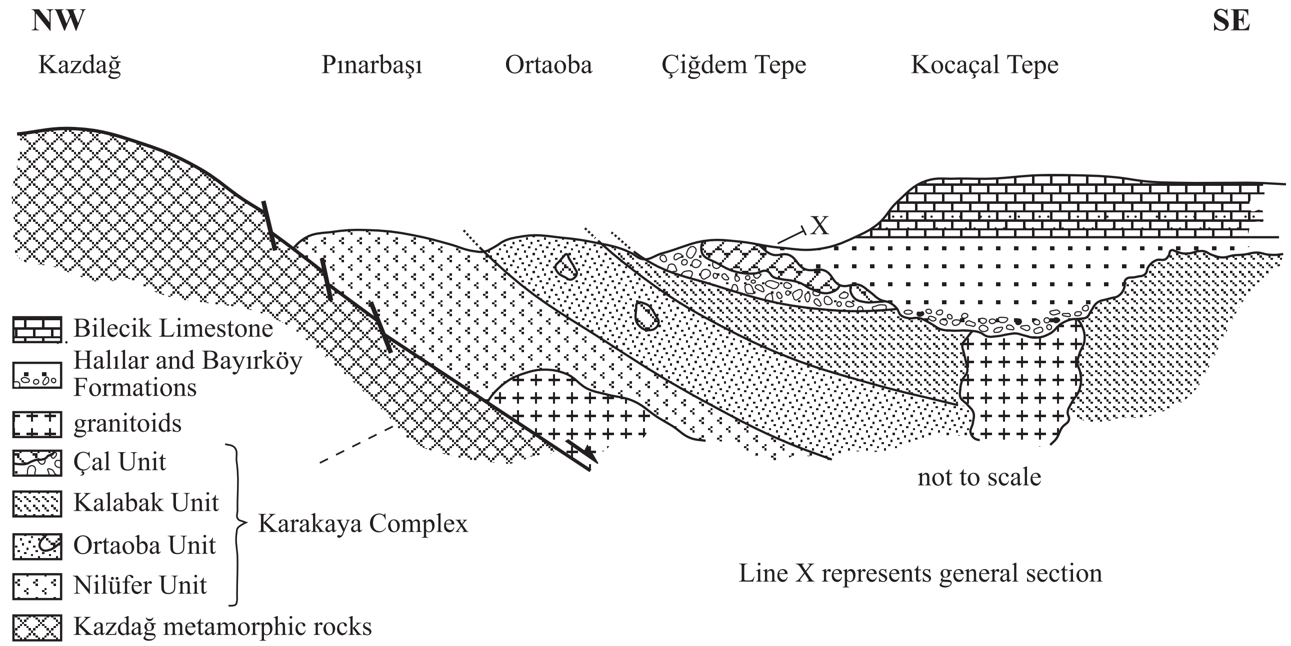


Figure 9. Schematic cross-section through the Karakaya Complex in the Edremit-Havran area. Note the low structural position of the Nilüfer Unit, the presence of Devonian plutons cutting the Kalabak Unit and the latest Triassic-Liassic (and younger) unconformable sedimentary cover (from Pickett & Robertson 1996).

or altered glass shards, set in a fine-grained groundmass. Additional clasts (Figure 14a) include recrystallised white limestone (rarely with internal kinked layering), amygdaloidal basalt, purple shale, fine-grained volcanogenic sandstone, pale green volcanic shale and rare red metachert. Volcaniclastic conglomerate clasts occasionally include calcite, or epidote veins, of inferred hydrothermal origin. The matrix is fine- to medium-volcaniclastic material, identical to many of the smaller clasts.

Bedded Volcanogenic Mudstone and Fine Sandstone

This subordinate lithofacies, as seen at the intersection of the valley with the road running north from Uğu Taşı (Figure 11), is made up of interbedded volcanogenic siltstone and sandstone. The finer grained beds are pale green and siliceous, whereas these sandstones are a slightly darker green and contain rare clasts of similar-composition sandstone, up to 3 cm in size.

Bedded Limestones and Volcanogenic Sedimentary Rocks

Mudstones and siltstones with small soft-sediment folds are locally intercalated with redeposited limestone. These lithologies are well exposed within a small E–W valley (to the east of the main valley north of Uğutaşı; i.e., box A of Edremit area map; Figure 11). Individual limestone horizons begin with flattened clasts of limestone, green spilite, fine-grained volcanogenic sandstone and siltstone and then pass upward into pale, grey recrystallised limestone. In addition, the volcanic/volcaniclastic succession locally contains intercalated limestones (Figure 13). There are also local interbeds of green volcaniclastic sandstones. We infer that the limestones originally formed part of a coherent volcanic-sedimentary succession (see below). Similar limestones and volcanogenic sedimentary rocks are exposed elsewhere in the Edremit area (e.g., north of Pınarbaşı; Figure 16) and in the Hacılar area (Figure 14c) and are inferred to occur mainly in higher levels of an original stratigraphic succession.

Limestone Thrust Sheets and Large Detached Blocks

The Nilüfer Unit in the Edremit area is intimately associated with large masses of recrystallised limestone. Large detached blocks (up to 1 km size) are exposed within volcanogenic debris flows directly west of the N–S

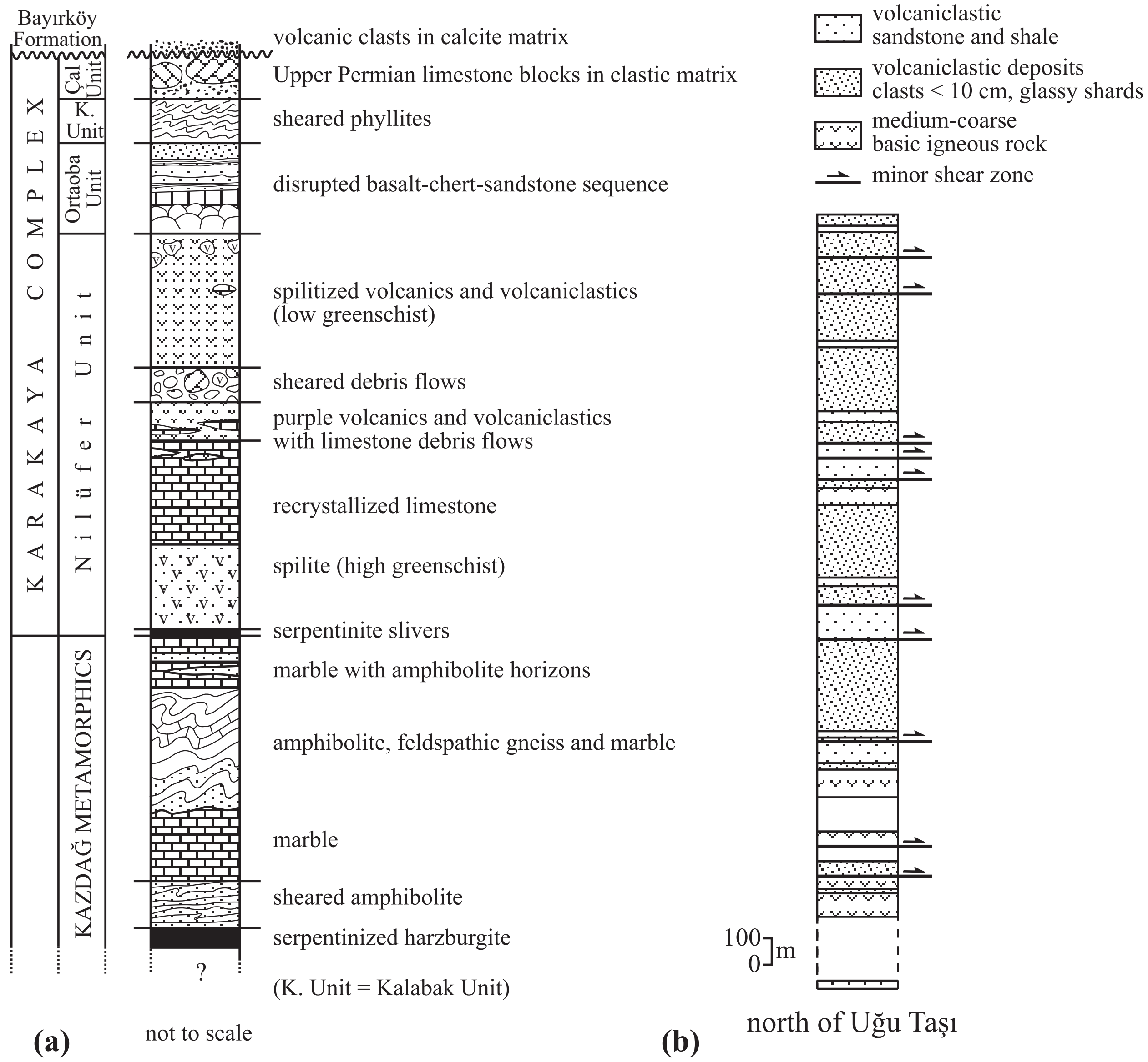


Figure 10. (a) Schematic stratigraphical column of the Karakaya Complex. Although based on the Edremit area, this tectono-stratigraphy is applicable to the Biga Peninsula as a whole (from Pickett & Robertson 1966); (b) measured log of the Nilüfer Unit near Edremit.

valley (north of Uğutaşı; Figure 11). A larger mass of similar limestone (> 3 km long) is exposed c. 1 km farther west (W of locality C on Figure 11). No intact depositional contacts are preserved between the limestones and the volcanogenic facies of the Nilüfer Unit and exposure is poor, especially in the north towards the exhumed Kazdağ Massif. However, comparable limestones are widely distributed as clasts throughout adjacent volcaniclastic debris flows (e.g., Figure 13). We, therefore, infer that the limestones formed part of an original Nilüfer Unit succession, as shown in Figure 10.

Associated Small Thrust Slices of Debris-Flow Deposits

Poorly sorted conglomerates form small tectonic slices (mainly < 10-m thick) within the volcanogenic units described above. These conglomerates range from clast supported to matrix supported, as seen east of

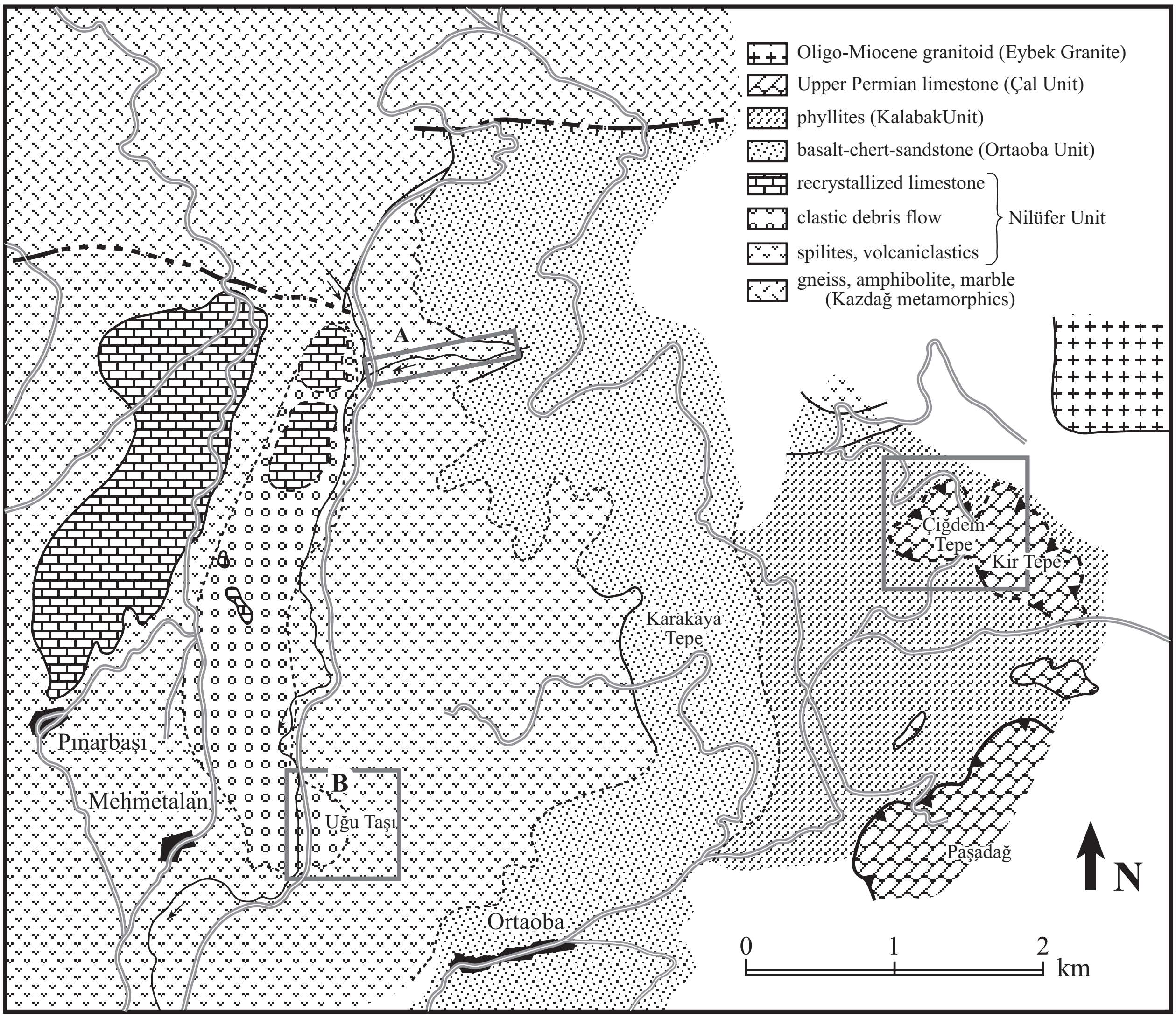


Figure 11. Geological map of the area north of Edremit. The areas within boxes A, B and C are discussed in the text; based on mapping by A. Okay (unpublished) and E. A. Pickett. Modified after Pickett & Robertson (1996).

Mehmetalan (Figure 11). Sub-rounded to sub-angular clasts (0.5–20 cm in size) are set in green volcanogenic mudstone. The volcanic clasts consist of porphyritic lava, green mudstone and volcaniclastic rocks. Other clasts include green hyaloclastite and fine-, medium- and coarse-grained sandstone. The debris-flow deposits also locally contain abundant clasts of pink quartzite, white and grey quartz, felsic extrusive rock and scarce granite. A few of these clasts are well rounded. Other clasts include dark grey limestone, grey fissile mudstone and streaky, laminated, recrystallised limestone, as seen as loose boulders (up to several metres in size) in a stream bed just east of Mehmetalan (Figure 14b).

Similar matrix-supported conglomerates are exposed between massive altered basalts north of Mehmetalan (Figure 11). These rudites are associated with deformed, interbedded feldspathic sandstone and shale. The debris-flow deposits are much finer grained than those east of Mehmetalan and commonly comprise clast-supported pebblestones (clasts < 5 cm), with clasts of mainly sedimentary rocks (mainly siltstone, grey mudstone, fine-

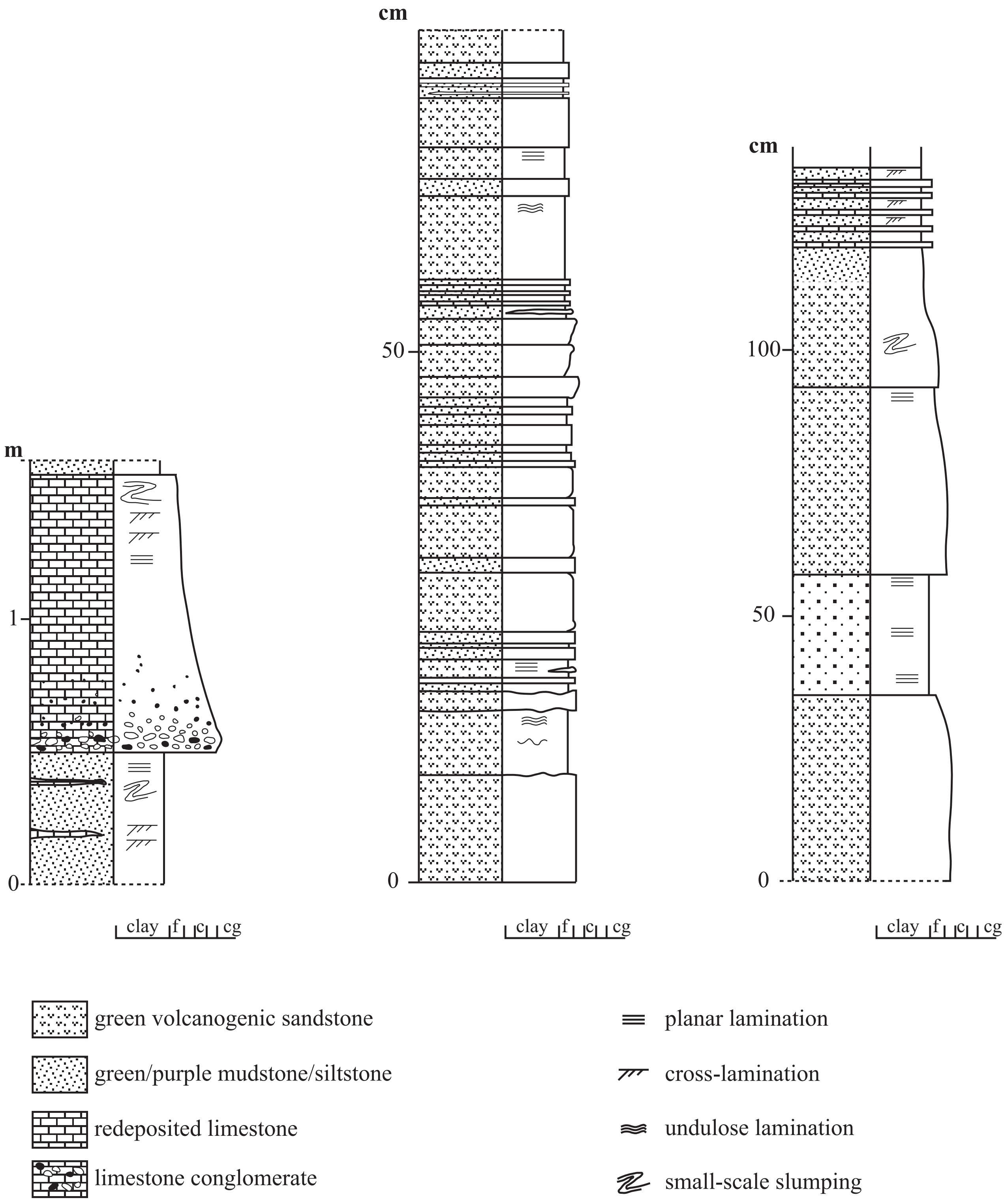


Figure 12. Representative logs through sedimentary facies of the Nilüfer Unit in the valley marked by Box A in Figure 11.

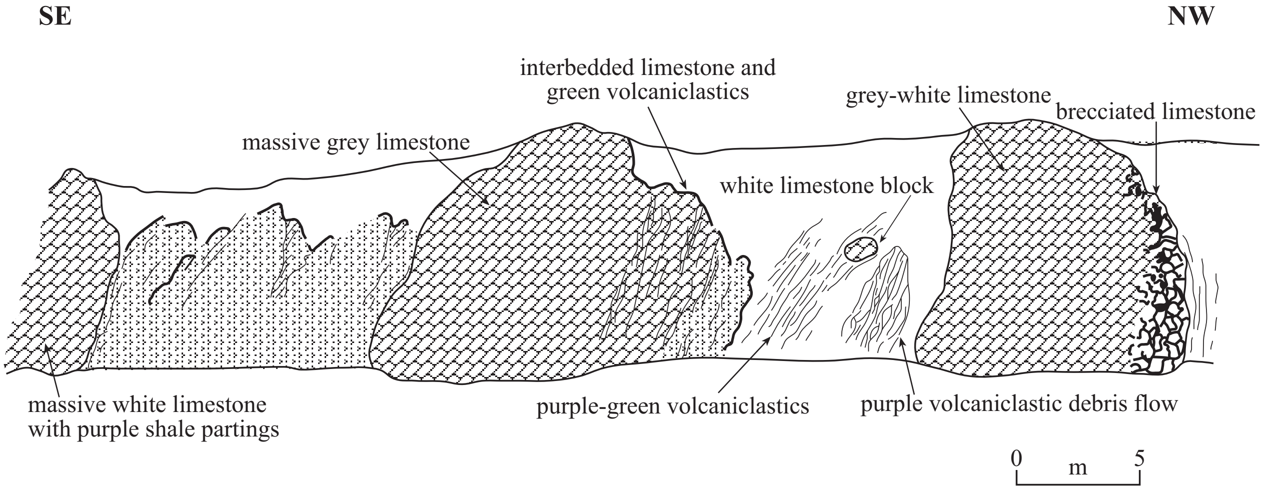


Figure 13. Field sketches of road section showing limestone blocks and intervening volcanics; location of Box C in Figure 11.

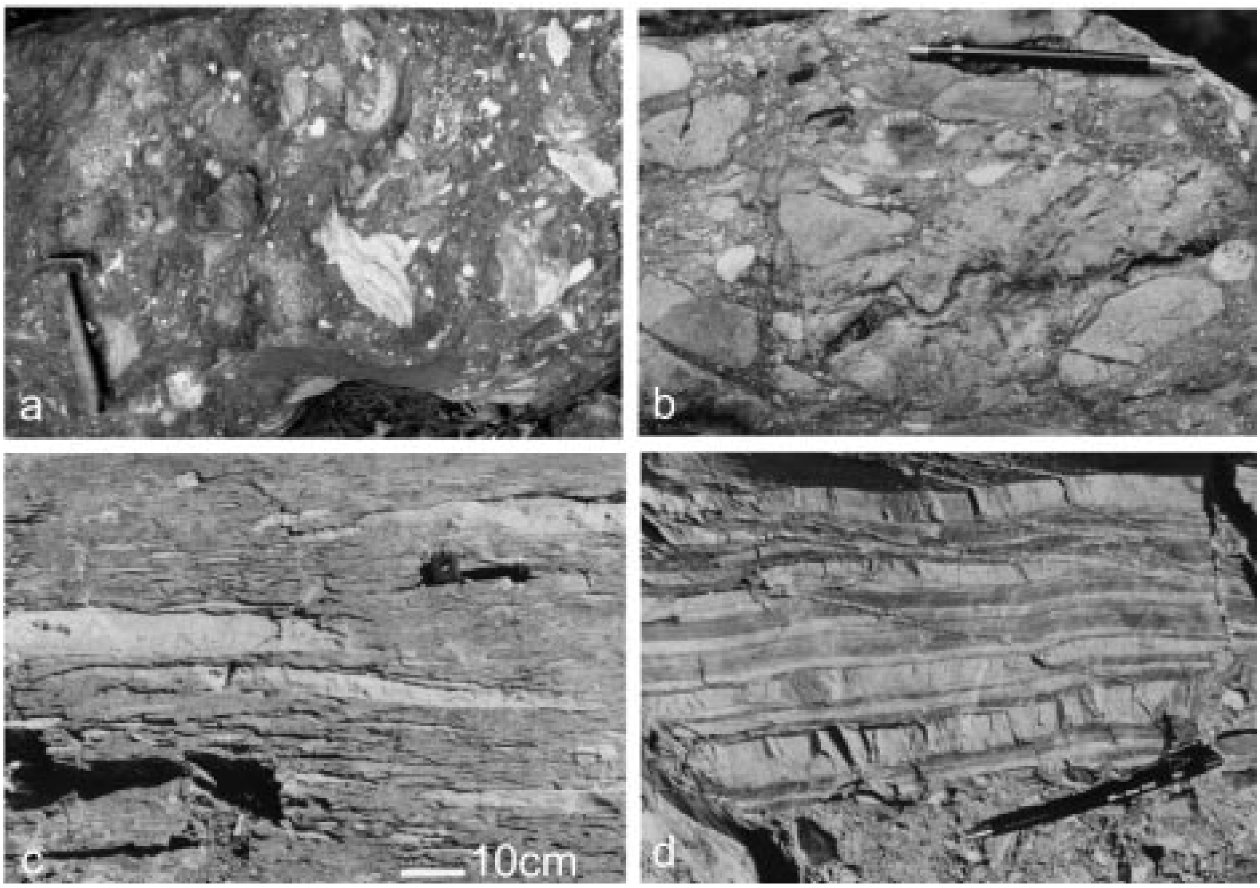


Figure 14. Field photographs of the Nilüfer Unit and associated exotic slices: (a) volcanogenic conglomerate with basaltic, volcanogenic sedimentary rocks and recystallised white limestone clasts. Note the relict lamination in the limestone clasts in the centre of the field of view. From the valley marked C in Figure 11; (b) poorly sorted conglomerate interpreted as a debris flow, exposed as boulders in the stream west of Uğu Taşı (see Figure 11). Note the heterogeneous and relatively well-rounded nature of clasts. These debris flows occur as thrust intercalations within the Nilüfer Unit; (c) lenses of recrystallised limestone (flattened clasts?) in foliated purple shale, near Hacılar; (d) fine-grained cherty sandstone interbedded with green and grey mudstone, possibly representing a distal facies; near Köyyeri.

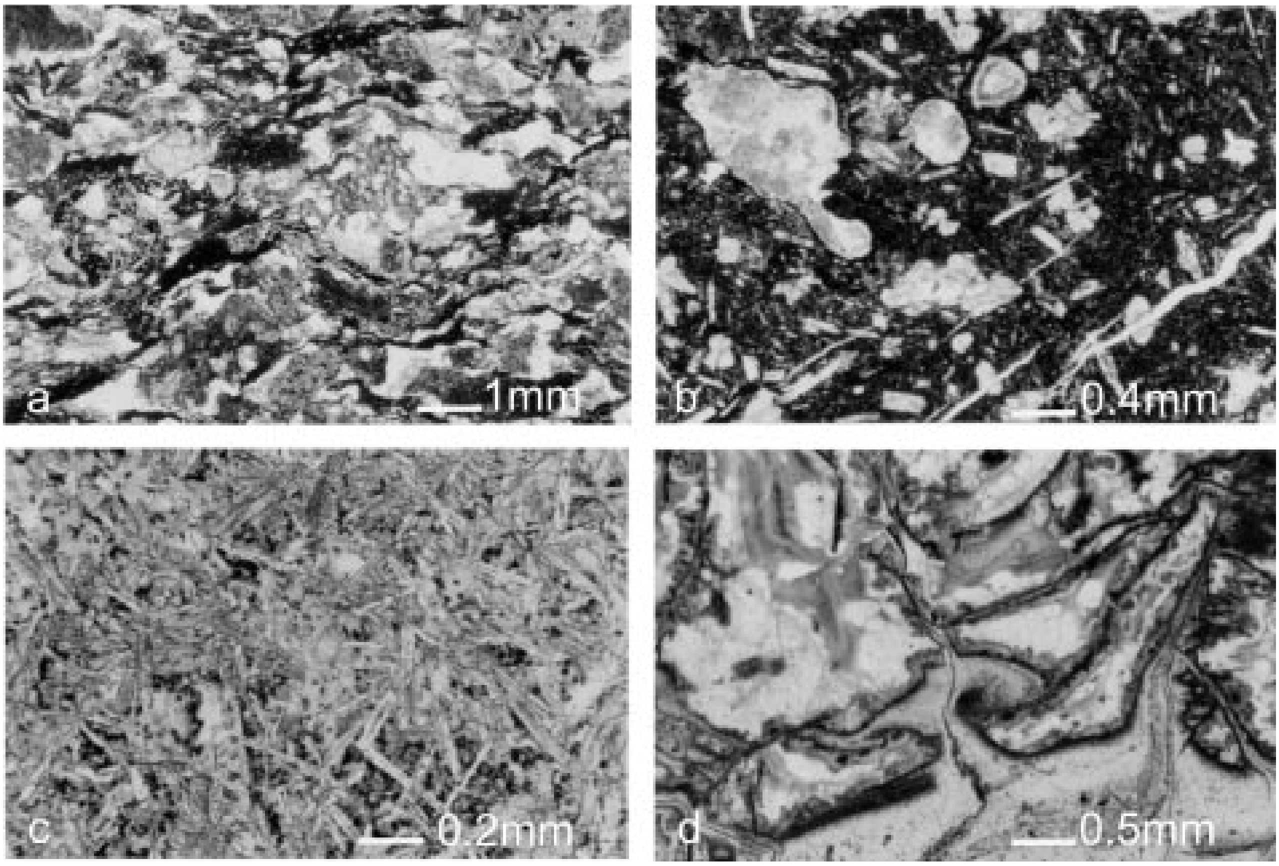


Figure 15. Photomicrographs of Nilüfer Unit and the Ortoaba Unit volcanic and volcaniclastic lithologies. **(a)** Basaltic clasts and glass fiamme, Nilüfer Unit north of Edremit (plane-polarised light; field of view 8.5 mm); **(b)** basalt showing clinopyroxene phenocrysts and variably sized plagioclase laths in a fine glassy goundmass. Rounded vesicles are infilled with epidote and chlorite; Nilüfer Unit, road section near Köyyeri (plane-polarised light; field of view 4 mm); **(c)** intersertal and subophitic textures in Ortaoba Unit pillow basalt (plane-polarised light). Albitised laths of plagioclase are enclosed in a groundmass of chloritised clinopyroxene and dark devitrified glass; **(d)** glassy quench textures in Ortaoba Unit pillow basalt (plane-polarised light). The glass is devitrified and mainly altered to chlorite.

grained sandstone and quartz). Rounded (deformed) granitic clasts are again rarely observed. Occasional horizons include rounded blocks of dark grey limestone (2–30 cm in size), together with grey mudstone clasts (2–4 cm). In addition, large limestone blocks (up to 2 m) are scattered within limestone-shale sequences. One such limestone block is mantled by a coarse limestone breccia of sedimentary origin.

The debris-flow deposits containing terrigenous clasts (e.g., granite, quartzite) occur only as small tectonic slices within the Nilüfer Unit and are not compatible with the composition of the Nilüfer Unit as a whole. We, therefore, infer that this exotic material relates to the tectonic emplacement of the Nilüfer Unit rather than to its genesis in an oceanic setting. The composition of the debris-flow deposits is suggestive of derivation from siliceous intrusive rocks and metamorphic rocks related to the Eurasian continental margin (i.e., Sakarya basement), as discussed later in the paper.

Nilüfer Unit in Other Regions

A reconnaissance study was made of exposures located adjacent to the type area of the Nilüfer Unit in the Biga Peninsula and from other areas. The main objectives were to determine the relationship to the underlying Sakarya basement and the internal tectono-stratigraphy of the Nilüfer Unit. We include additional information from areas south and southeast of Lake İznik obtained by the second author jointly with T. Ustaömer as part of their

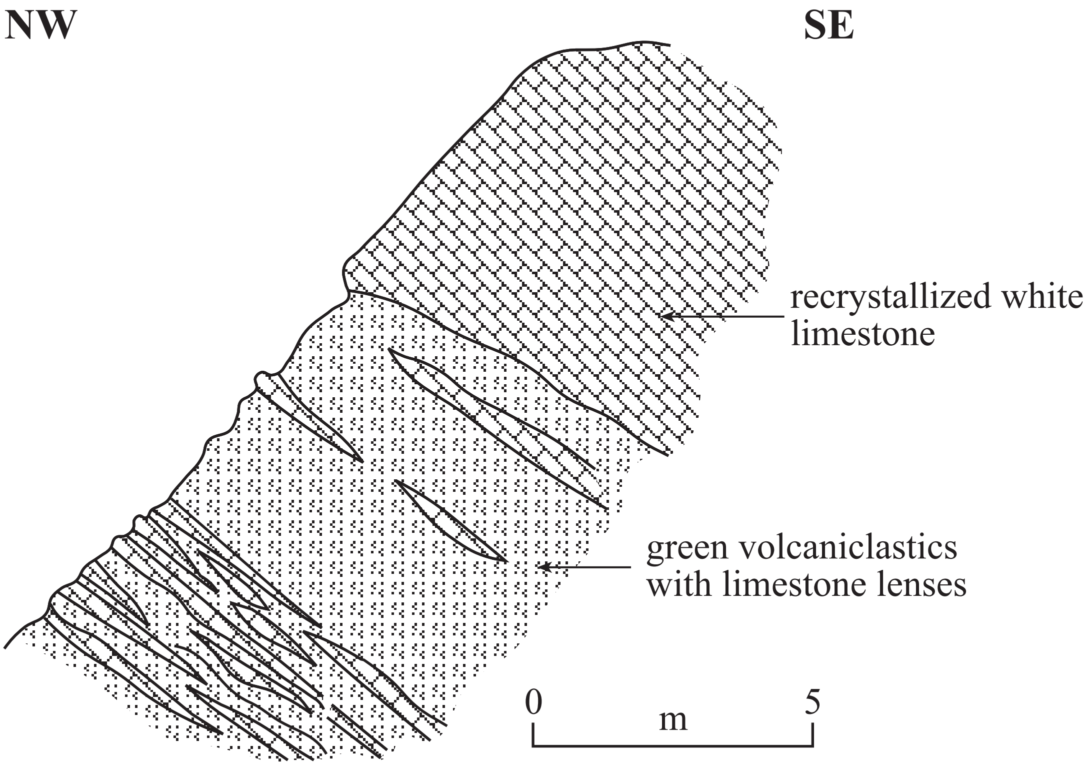


Figure 16. Field sketch of volcanogenic shale interbedded with recrystallised limestone, c. 1 km north of Pınarbaşı, Edremit area.

study of the Armutlu Peninsula and environs (Robertson & Ustaömer 2004).

Çan Area

In the Çan area in the central Biga Peninsula (Figure 4), the Nilüfer Unit crops out as foliated metatuffs, known as the Sazak Metatuffs (Okay *et al.* 1991) These rocks are foliated and silvery grey to beige, in contrast to the more massive green volcanics and volcanogenic sedimentary rocks elsewhere. Ti-augites are again present.

Bandırma Area

Relatively high-grade metamorphosed lavas crop out in the Kapıdağ Peninsula, jutting out into the Marmara Sea, northwest of Bandırma along the shores of the Marmara Sea farther east (Figure 4) and on Marmara island. In general, green foliated metavolcanic rocks exhibit few primary structures. Altered metalavas are intercalated with strongly folded marble bands on the Kapıdağ Peninsula. In addition, weathered green volcanic and volcanogenic sedimentary rocks exist as scattered outcrops south and east of Bandırma. At the latter locality, Okay & Monié (1997) recorded tectonic lenses of Upper Triassic sodic amphibole-bearing eclogites, up to 100-m long.

In addition, T. Ustaömer (pers. com., 2004) has noted the following sequence in the Kapıdağ Peninsula. There is a lower unit of metaclastic psammites and pelites with rare marble lenses, overlain by sheared serpentinite. Above this, there is a metavolcanogenic sequence of dominantly metavolcaniclastic rocks with occasional volcanic breccia, phyllite and calcschist interbeds. Thicker marbles occur at the top of the sequence. A similar metavolcanogenic unit is exposed on Marmara Island, to the northwest of the Kapıdağ Peninsula. The metabasic rocks are overlain by a thick unit (> 1000 m) of metacarbonates that are possibly equivalent to the Orhangazi Marble and the Fındıklı Formation exposed in the Armutlu Peninsula farther north (T. Ustaömer, pers. com., 2004; see Robertson & Ustaömer 2004).

Bursa to Western Uludağ Area

Thick sequences of green metabasic igneous rocks are well exposed around the Uludağ metamorphic massif, south of Bursa city, specifically around the Nilüfer dam and along the main roads from Bursa and Orhaneli (Figure 4). The volcaniclastic rocks are similar to those of the Bergama and Edremit areas, although the state of alteration and metamorphic grade appear to be higher. Mainly dark green volcaniclastic sedimentary rocks with little structure, other than a faint foliation, are locally exposed along the road to Orhaneli (Figure 4). Ti-augite and kaersutite are present in the lavas, the latter mineral being locally replaced by incipient blue amphibole (Okay *et al.* 1991). Some of the volcaniclastic sedimentary rocks are seen in thin section to be hyaloclastites, with well-preserved clinopyroxene crystals, interpreted as relict phenocrysts, within a streaky chlorite and amphibole groundmass.

South of Lake İznik

The Karakaya Complex is also widely exposed to the south of Lake İznik and bordering the Uludağ metamorphic massif, extending towards Bilecik (Figure 4). Mapping by Genç (1987) revealed the following tectono-stratigraphy in this area: (1) crystalline rocks of the Uludağ Massif; (2) a unit of basic metamorphic rocks, marble, amphibolite and metaultrabasic rocks; (3) sandstone, altered basic volcanic rocks and limestone including Lower Triassic conodonts and Permian limestone olistoliths ("blocked series"), in turn unconformably overlain by (4) the Jurassic Bilecik Limestone. In his field guide Genç (1987) states (p. 25) "The relation between the metamorphic formation and sandstone is tectonical. Also the relation between the blocked series and metamorphic series is always seen and tectonical". However, Genç & Yılmaz (1987) later reinterpreted the field relations to indicate the presence of Sakarya basement (units 1 and 2 above), unconformably overlain by continental conglomerates and sandstones (Kandili Formation) passing depositionally upwards into Triassic volcanogenic units of the Karakaya Complex. This was cited as support for an origin of the Karakya Complex in a back-arc rift setting. Two main localities were re-examined.

First, south of Lake İznik (near Karamca) poorly exposed, highly altered schist and gneiss, correlated with the Sakarya basement (Genç 1987) are tectonically overlain by a gently inclined disrupted limestone thrust sheet. The contact zone, estimated as 10-m thick, includes a highly sheared tectonic mélange with sigmoidal blocks of very coarse limestone in a matrix of volcanogenic shale and phyllite. The contact zone is overlain first by micaceous shale and reddish siliceous shale, then by a dismembered thrust sheet of irregularly bedded grey recrystallised limestone with traces of shells and microbial carbonate. The marble is then tectonically overlain, with a south-dipping contact, by a disrupted thrust slice of strongly sheared serpentinised peridotite. In this area, the Karakaya Complex is overlain, transgressively, by the Jurassic Bilecik Limestone. This limits the outcrop available for study. We interpret the key relations in this area as a tectonic contact (probably extensional) between crystalline basement correlated with the Uludağ metamorphic massif and with an overlying unit equivalent to the Nilüfer Unit.

Correlatives of the Nilüfer Unit are well exposed structurally above and to the northeast of the Uludağ towards Lake İznik (Genç & Yılmaz 1995). In this area (e.g., along the Mahmudiye-Yenişehir road), we observed the following overall tectono-stratigraphy. A lower unit of meta-siliciclastic rocks comprises calc-schists, psammites, phyllites and minor metacarbonates near the top, where NE-vergent folds are present. Above are several thrust sheets, of which the lowest comprises metabasic rocks, overlain by black cherts, calciturbidites, then phyllites. An overlying thrust sheet begins with metalavas that are overlain by foliated metabasic rocks interbedded with chert. A stretching lineation is orientated NE–SW but no polarity was determined. Imbricated small thrust sheets with a northerly vergence follow, composed of schists, phyllites and meta-basic rocks. This is followed by imbricate thrust sheets (at least 6) composed of metacarbonates, metaphyllites and metabasic rocks, with gently plunging nearly N–S-orientated folds. In places, an early foliation is cut by NW-facing small reverse faults.

Several points can be made about the area north of Uludağ. (1) Most contacts between lithologies are tectonic, marked by shear zones, and no intact primary succession is preserved; (2) the dip of internal shear zones, like the unit as a whole, is relatively gentle (30° or less); (3) greenish "tuffs" are interpreted as sedimentary rocks of mainly detrital, epiclastic origin; (4) the metacarbonate thrust sheets were commonly subjected to extreme layer-parallel shortening; (5) limited structural data point to top-north to top-northwest tectonic displacement; (6) more work (including geochemistry) would be needed to assign the metabasic rocks to either the Nilüfer Unit or the Ortabağ unit.

Southeast of Lake İznik

Farther east (east of İnegöl; at Dede Tepe near Koyunköy; see Genç 1987), poorly exposed, very weathered mica schist is overlain by white arkosic sandstone and minor conglomerate (Kendirli Formation). A locally exposed section, c. 40-m thick, shows clastic sedimentary rocks, with small (< 5 cm) intraformational shale and limestone clasts, passing depositionally upwards into several interbeds of limestone. This is followed by sheared alternations of limestone, shale, volcanogenic debris flows with small limestone clasts and then vesicular volcanic rocks. Elsewhere in this area the clastic sedimentary rocks (Kendirli Formation) are absent and the contact with metamorphic rocks below is a 20-m-wide shear zone marked by phacoidal blocks of sandstone in a highly sheared phyllite matrix or tectonic breccia. The shear zone is overlain by altered basalt or pink pelagic limestone of inferred Triassic age. Structurally overlying units are well exposed several kilometres farther north (near Abadiye; Genç 1987), where massive Permian limestone (locally north dipping) passes depositionally upwards into an intact succession of sheared debris flows with volcanic and lithoclastic sandstone and limestone clasts. This is followed by massive vesicular lavas and lava breccias (grey, green and purple), up to c. 200-m thick, although no primary contact is exposed. We interpret this area (SE Lake İznik) as an underlying unit of high-grade metavolcanogenic rocks (possibly correlative with the Nilüfer Unit), tectonically overlain by a relatively unmetamorphosed equivalent of the Triassic Nilüfer Unit, and equivalents of the overlying Permian Çal Unit (not yet fully distinguished). The unusual feldspathic clastic rocks (Kendirli Formation) might represent clastic sediments that formed by erosion of the Sakarya metamorphic “basement” that were later tectonically emplaced into the Karakaya Complex.

In summary, from reconnaissance of the northernmost exposures we conclude that there is no evidence of a depositional contact with the underlying Sakarya crystalline rocks and also that the field relations of the Triassic Nilüfer Unit are compatible with those in the type area of the Biga Peninsula.

Nilüfer Unit elsewhere in Turkey

Similar lithological assemblages to those in the Biga Peninsula occur within the Karakaya Complex farther east (Okay 2000). These include occurrences in NW Turkey, north of Eskişehir (Okay *et al.* 2002; Figure 4), outside the scope of our study. There are also extensive exposures in central Anatolia; notably forming part of the Ankara Mélange (Norman 1984). Additional exposures are present in the eastern Pontides of NE Turkey, notably the 4.5-km-thick Ağvanis Group in the Sivas area (Okay & Şahintürk 1997), and in the Pulur Massif, Bayburt area (Okay 1996; Okay & Leven 1996; Okay & Şahintürk 1997). In general, within the eastern Pontides greenschist meta-lavas, with some minor pillow lavas are intercalated with green phyllites. These include marble clasts, "metatuffs" and white marble with thin chlorite- and/or epidote-rich layers. The lithological assemblage is very similar to the Nilüfer Unit of the type area in NW Turkey, although acidic metatuffs appear to be more abundant in the easterly areas. Many of these units in NE Turkey areas remain to be accurately dated.

Structure of the Nilüfer Unit

The Nilüfer Unit forms the structurally lowest unit of the Karakaya Complex in the type area of NW Turkey. Structural studies are inhibited by metamorphism and strong shearing. Although way-up criteria were commonly observed in the logs measured, associated folds are scarce.

In the Kozak Massif, the Nilüfer Unit forms a single, mainly south-dipping thrust sheet, up to 1000-m thick. Clasts within this unit are commonly flattened sub-parallel to a crude foliation, as a result of strong layer-parallel extension to create classic phacoidal fabrics, typical of tectonic mélange and other strongly sheared units. Farther north, in the Edremit region, the Nilüfer Unit forms a mainly SE-dipping thrust slice located between the metamorphic Kazdağ Massif below and higher thrust slices of the Karakaya Complex above. However, dips are locally variable. Shale-rich volcaniclastic sedimentary rocks exhibit rare small-scale folds but these lack consistent orientation (Pickett 1994). Locally (west of Karakaya Tepe), folds do show a general dip of axial planes towards the NE quadrant, whereas the associated fold axes plunge either N or E/SE. An outcrop of volcanogenic mudstone exposed in an E–W-trending valley (Box A in Figure 11) shows well-developed folding, veining and development of incipient cleavage along attenuated fold limbs. Schists south of Mehmetalan (interpreted as part of the Nilüfer Unit) exhibit both north- and south-dipping axial planes; fold axes plunge at a shallow angle to the NE and SW. Feldspathic sandstones north of Mehmetalan exhibit NW-dipping axial planes and fold axes with variable plunge directions (including N and S). Rod-like structures, trend or plunge to the north or south, with a wavelength of 0.5–1 m.

Elsewhere, in the Bursa area, Okay *et al.* (1991) reported the existence of tight to isoclinal folds with steep, mainly north-dipping axial planes. Similar features were noted in the areas S and SE of Lake İznik by the second author (with T. Ustaömer). Also, in the Bandırma area, on the western coast of the Kapıdağ Peninsula, sheared, altered metavolcanic rocks are tightly folded and verge southwards, but facing directions are unknown in the absence of reported way-up evidence. The fold axial planes dip NNE and fold axes plunge generally ESE, implying tectonic transport to the SSW, assuming the sequence is the right way up. In addition, large-scale thrust imbrication of the Karakaya Complex, including the Nilüfer Unit, is inferred north of Eskişehir, where a slice (4 km x 2 km) of high-pressure blueschist/eclogite-facies rocks structurally underlies a slice of low-pressure, greenschist-facies metamorphic rocks (Okay *et al.* 2002).

In summary, the Nilüfer Unit is characterised by layer-parallel extension, as observed in many accretionary prisms worldwide (e.g., Jurassic Franciscan Complex, California; Cloos 1984). There are hints of southward vergence, consistent with northward subduction, followed by possible re-thrusting that could relate to final northward emplacement onto the Eurasian margin (Sakarya basement). Such polyphase deformation could explain the scattered nature of the structural data collected in the Edremit area. However, additional structural data are needed to test the above tentative interpretation.

Geochemical Discrimination of Basalts

We have previously reported the main results of extensive whole-rock geochemical analysis by X-ray fluorescence (XRF) of basaltic rocks of both the Nilüfer and Çal units (Pickett *et al.* 1995; Pickett & Robertson 1996). The analysis was carried out at the Grant Institute of Earth Science according to a widely used method, described elsewhere (Fitton *et al.* 1998). Most of the samples of the Nilüfer Unit were collected from the Kozak Massif (near Bergama) and the Edremit area, where the basalts are relatively unaltered and retain clear relict textures. The basalts from the Edremit, Bergama and Bursa regions reveal a within-plate basalt (WPB) signature, consistent with an origin in an oceanic seamount and/or rift setting (Figure 17a–d). WPB-patterns are also seen in MORB-normalised "spider" plots, as indicated by persistent enrichments in Nb, P, Zr, Ti and LIL (large-ion lithophile) elements (Figure 17e–g). Representative analyses from each area are given in Table 1.

In the Kozak Massif, samples of greenish basalts were collected from road cuttings around the villages of Köyyeri and Ada. A single sample is relatively MORB-like, but has enrichment of Ti relative to Y, as in WPB basalts. In the Edremit area, two distinct basalt types are identified. The first, tectonically lower, type comprises mainly fragmental, purple, little-altered lava, as exposed along short stretches of the road north of Mehmetalan (marked C in Figure 11). The second, higher in the tectono-stratigraphy, is greenish and more altered (spilitic), and is exposed in road cuttings in the river valley north of Mehmetalan (Figure 11). Geochemical patterns of both lava types are similar to basalts of oceanic seamounts and oceanic islands (e.g., Azores; Peace *et al.* 1984). In addition, a few samples were collected from beside the dam in the Nilüfer River, south of Bursa and from a sheared outcrop several kilometres north of Karacabey, east of Bandırma on the Marmara Sea (Figure 4). These basalts are chemically indistinguishable from those of the Kozak Massif and the Edremit area, discussed above.

In addition, clinopyroxenes from the "green suite" in the Edremit area were analysed by electron microprobe at the Grant Institute of Earth Science. Representative analyses from each area are given in Table 2. The crystals

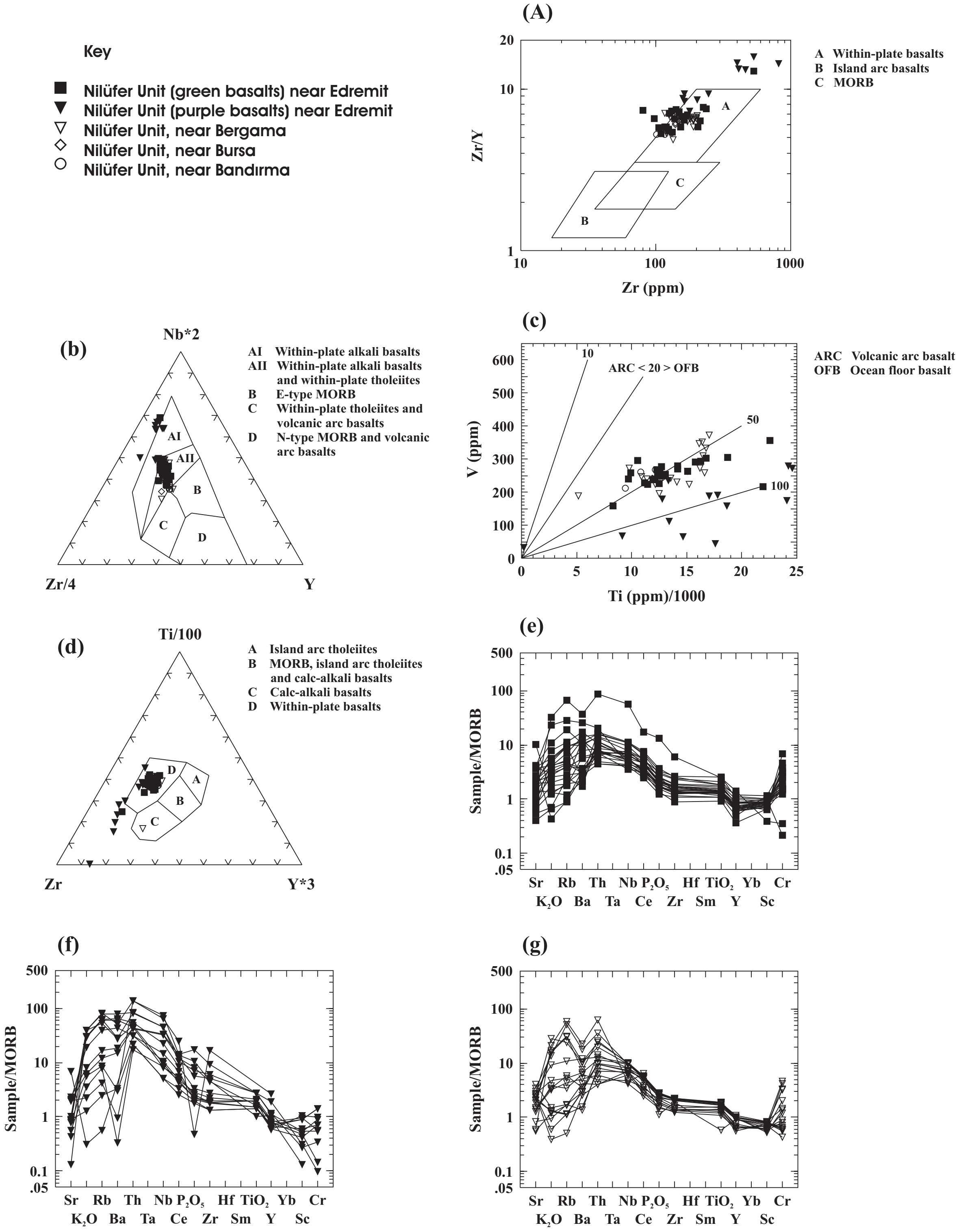


Figure 17. Geochemical plots for all samples from the Nilüfer Unit. (a) Zr/Y vs Zr; (b) Nbx2 vs Zr/4 vs Y; (c) V vs Ti/1000; (d) Ti/1000 vs Zr vs. Yx3; (e) MORB-normalised "spider" plots of green basalts, Edremit area; (f) MORB-normalised plots of purple basaltic suite, Edremit area; (g) MORB-normalised plots of basalts from the Bergama area. Normalising values from Pearce (1982). The analyses were carried out as specified by Fitton *et al.* (1998).

Table 1. Examples of major and trace element analyses of basalts from the Nilüfer Unit in NW Turkey

	Edremit (green basalts)			Edremit (purple basalts)			Bergama			Bursa	Bandırma
wt %	44C/90	46A/90	53E/90	17/9-F	17/9-H	17/9-R	21/9-18b	21/9-19c	21/9-19h	Nil 1	30/8/92-3
SiO_2	46.25	44.50	46.82	45.64	47.00	44.55	45.20	46.43	45.66	46.63	48.80
Al_2O_3	11.57	16.99	9.76	19.06	18.77	15.25	11.23	14.09	14.19	12.80	13.71
Fe_2O_3	13.52	12.75	12.12	15.11	16.07	16.02	11.37	13.14	13.98	13.14	12.01
MgO	13.09	8.42	14.85	1.95	3.73	5.69	15.40	6.95	7.49	10.00	5.94
CaO	5.87	5.20	7.41	2.82	0.45	4.44	7.40	7.54	7.51	7.58	10.04
Na_2O	2.65	2.04	2.22	2.06	1.02	3.81	2.10	1.59	2.54	2.81	2.47
K_2O	0.195	3.492	0.099	4.460	5.918	0.856	0.179	4.177	2.493	0.510	0.291
TiO_2	2.083	1.757	1.909	3.115	2.936	2.131	2.030	2.693	2.847	2.144	2.024
MnO	0.149	0.128	0.156	0.162	0.089	0.104	0.158	0.146	0.162	0.171	0.142
P_2O_5	0.231	0.203	0.201	0.404	0.270	0.231	0.228	0.316	0.332	0.258	0.254
LOI	4.58	4.90	4.48	5.00	3.84	6.82	4.59	2.82	2.77	3.59	3.76
Total	100.19	100.38	100.02	99.78	100.09	99.88	99.89	99.90	99.98	99.62	99.45
ppm											
Nb	16.5	15.7	14.6	78.5	32.9	17.7	24.4	33.4	35.1	21.1	15.6
Zr	131.8	125.1	115.9	247.5	177.6	118.5	127.1	189.9	199.1	154.0	130.9
Y	18.0	22.2	20.0	26.4	24.4	20.6	19.1	29.4	30.4	24.5	24.6
Sr	77.9	469.3	48.6	100.4	15.7	92.2	66.9	318.2	246.0	377.2	277.6
Rb	2.4	57.5	1.8	125.1	104.8	17.4	3.3	47.4	61.5	6.3	4.9
Th	1.5	4.1	0.9	11.1	9.5	4.3	0.8	4.0	4.8	2.0	1.3
Pb	1.6	1.0	-0.8	6.3	3.0	2.2	0.7	0.6	3.0	1.9	0.2
Zn	117.2	112.1	82.3	118.9	110.5	110.0	102.2	128.3	132.8	119.3	100.8
Cu	123.9	97.9	187.2	10.8	11.9	12.9	83.6	151.6	148.3	102.7	100.9
Ni	567.3	233.3	692.7	42.0	120.9	179.1	595.2	84.1	87.1	335.9	86.1
Cr	782.0	388.1	1151.9	221.4	138.4	353.5	839.1	147.1	157.0	492.9	163.2
Ce	31.1	35.7	29.8	84.1	43.0	33.4	28.1	53.2	58.2	50.3	41.1
Nd	16.9	19.6	14.9	36.2	23.9	18.0	16.8	29.3	30.2	23.2	20.1
La	8.2	8.8	8.9	45.0	10.7	10.4	12.6	19.9	18.9	13.6	8.2
V	226.2	296.6	223.8	159.4	44.5	178.8	223.2	347.1	373.7	245.7	267.7
Ba	43.0	510.2	54.5	1284.1	544.9	60.1	83.4	202.4	212.6	107.3	64.8
Sc	30.8	25.8	31.5	20.9	37.6	35.1	27.5	30.8	32.3	32.6	38.3

chosen for analysis were mainly small phenocrysts, although a few may represent interstitial groundmass material. Despite their dark brown and dusty appearance the clinopyroxenes are relatively fresh and, when analysed, gave good totals between 99 and 101%. Where possible, both cores and rims of phenocrysts were analysed and plotted as circles (cores) and triangles (rims). The results for both cores and rims (Figure 18) plot mainly in the non-alkali and non-orogenic field, respectively on the clinopyroxene discrimination diagrams of Leterrier *et al.* (1982). These clinopyroxenes are thus closely related to transitional or tholeiitic basalts and, more precisely, to non-orogenic tholeiites. This characterisation is in good agreement with the whole-rock geochemistry of the spilites.

Correlative units of the Nilüfer Unit farther east in Turkey include basalts in the older (pre-Jurassic) part of

Table 2. Examples of microprobe analyses of clinopyroxenes (cores and rims) from Nilüfer Unit basalts in the Edremit area

	48A/90		49C/90		56B/90		58B/90		102C/90	
	core	rim	core	rim	core	rim	core	rim	core	rim
Si	49.34	49.65	50.85	51.19	50.04	48.68	50.00	50.83	51.76	52.30
Ti	1.45	1.45	1.10	1.05	1.24	1.00	1.29	1.07	0.80	0.68
Al	3.29	3.35	3.33	3.06	3.77	3.30	3.98	3.17	2.70	2.53
Cr	0.00	0.00	0.45	0.36	0.02	0.02	0.56	0.50	0.12	0.15
Fe	10.71	10.80	7.18	7.03	11.53	17.49	7.20	7.27	7.13	6.87
Mn	0.26	0.26	0.17	0.17	0.29	0.46	0.16	0.14	0.19	0.17
Mg	13.98	14.11	15.16	15.37	14.53	12.78	14.95	15.45	16.40	16.47
Ca	20.11	19.89	21.38	21.46	18.37	15.63	21.47	21.10	20.38	20.46
Na	0.38	0.34	0.32	0.32	0.28	0.31	0.30	0.32	0.30	0.34
Total	99.52	99.85	99.94	100.01	100.07	99.67	99.91	99.85	99.78	99.97
	0=6	0=6	0=6	0=6	0= 6	0= 6	0=6	0=6	0=6	0=6
Si	1.87	1.87	1.89	1.90	1.87	1.87	1.86	1.89	1.91	1.93
Ti	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.03	0.02	0.02
Al	0.15	0.15	0.15	0.13	0.17	0.15	0.17	0.14	0.12	0.11
Cr	0.00	0.00	0.01	0.01	0.00	0.00	0.02	0.01	0.00	0.00
Fe	0.34	0.34	0.22	0.22	0.36	0.56	0.22	0.23	0.22	0.21
Mn	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.01
Mg	0.79	0.79	0.84	0.85	0.81	0.73	0.83	0.85	0.90	0.90
Ca	0.82	0.80	0.85	0.85	0.74	0.64	0.86	0.84	0.81	0.81
Na	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Sum	4.03	4.03	4.01	4.01	4.02	4.03	4.02	4.02	4.01	4.01

the Ankara Mélange (Çapan & Floyd 1985; Floyd 1993). There are also thrust slices of basalt in the central Pontides farther north, within the Kargı Massif and the structurally underlying Domuzdağ-Saraycıkdağ Complex; these show similar WPB-type chemical compositions (Ustaömer & Robertson 1999). Taken together, the chemical data support the conclusion of Pickett & Robertson (1996) that the Nilüfer basalts are the remains of seamounts, although a rift origin could not be excluded from these data alone, and additional evidence, as discussed earlier is needed to reach this conclusion.

Interpretation of the Nilüfer Unit as Volcanic Build-ups

Depositional and Eruptive Settings

The Nilüfer Unit in the areas studied generally comprises > 80% volcaniclastic rocks of both pyroclastic (i.e., primary eruptive) and epiclastic (secondary reworked type). Distinguishing *in situ* from redeposited pyroclastic deposits is not always possible. Many of the apparently massive flows, as seen in the Edremit area, when studied in thin section were found to be fragmental volcaniclastic sedimentary rocks, such that the volume of massive flows relative to fragmental sedimentary rocks has been overestimated in the past.

The massive lava flows, where present, are interpreted as sub-aqueous sheet flows. These are rarely more than several metres thick. Pillow basalts are scarce in the areas we studied, although some may have been obscured by strong shearing. Pillow lavas have been reported from counterparts of the Nilüfer Unit, as in the central Pontides (Ustaömer & Robertson 1997). The existence of inferred spherical degassing structures with large vesicles in the Kozak Massif is suggestive of eruption in relatively shallow water (< hundreds of

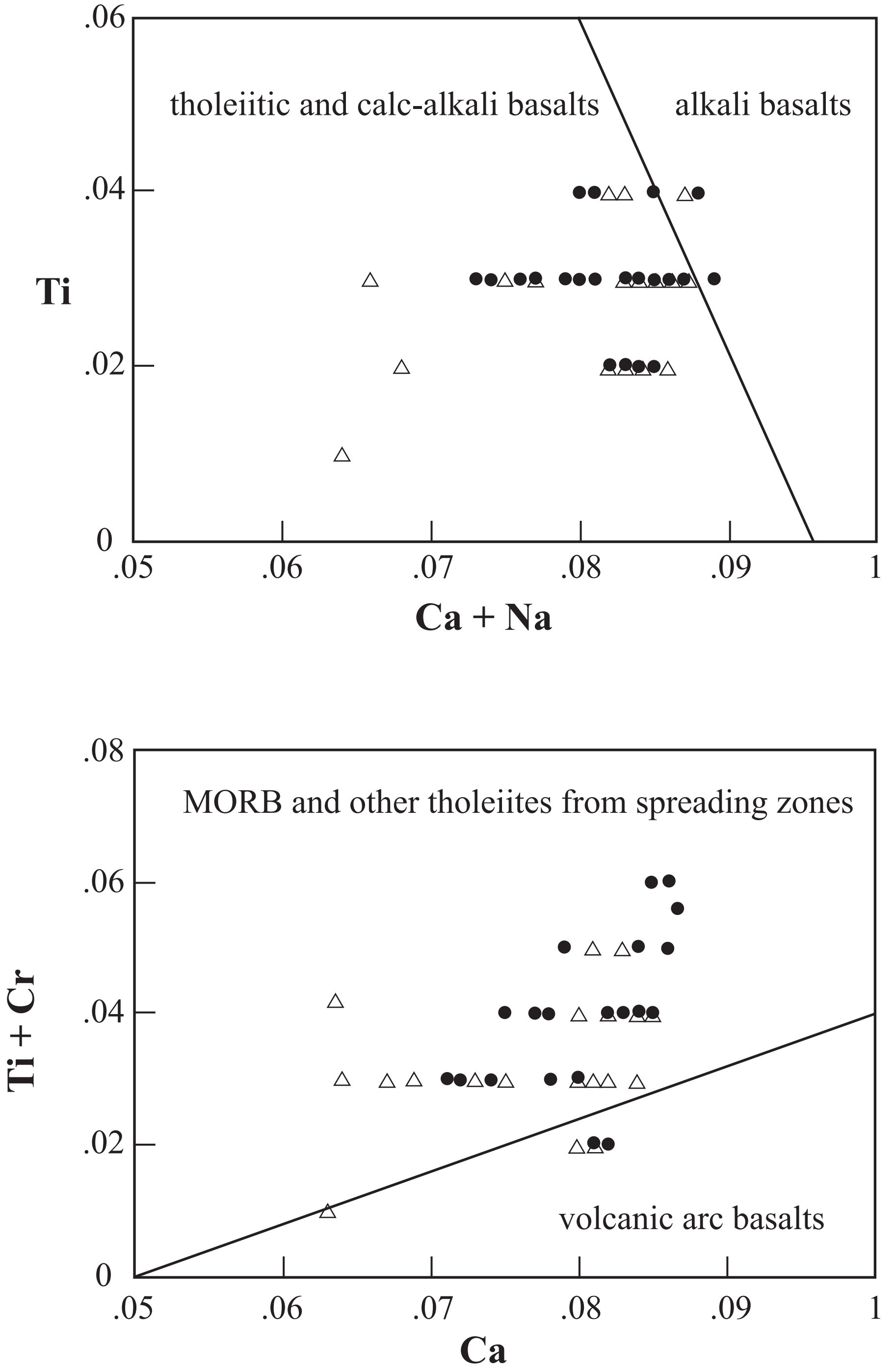


Figure 18. Tectonic discrimination diagrams for clinopyroxene from the "green suite" of the Edremit region. **(a)** Ti vs (Ca+Na) plot showing the fields for alkali basalts and tholeiitic and calc-alkali basalts; **(b)** (Ti+Cr) vs Ca plot showing the fields for MORB and other tholeiites from spreading zones and volcanic arc basalts; fields from Leterrier *et al.* (1982). Clinopyroxene compositions are expressed in cations per six oxygens. Circles represent phenocryst cores and triangles represent rims.

metres). Abundant reworked pyroclastic deposits are interpreted as mainly hyalotuff and hyalobreccia formed by chilling of basalt in contact with seawater. This material was later reworked down-slope by mass flow processes.

Widespread epiclastic breccias are interpreted as volcanic-derived talus that accumulated as sub-aqueous debris flows. Associated limestone clasts were probably derived from contemporaneous carbonate build-ups as polymict debris flows. Some igneous clasts show evidence of earlier hydrothermal veining (calcite and epidote veining). The presence of rare metachert clasts shows that lithified pelagic sedimentary rocks existed in the source area and were reworked downslope. Associated sandstones are interpreted as volcaniclastic turbidites. The volcaniclastic siltstones are commonly partly silicified which may relate to hydrothermal alteration. Scarce white shale in the Kozak Massif is assumed to have originated as air-fall ash.

Construction of Seamounts

The Nilüfer Unit is interpreted to record the *construction* of one, or several, seamounts in an oceanic setting (Figure 19). The volcanic pile is inferred to have built up near, or locally above, sea-level allowing tuffs and coarser-grained pyroclastic deposits to form. Carbonates accumulated locally in settings ranging from pelagic to neritic. Partial successions in some areas can be restored as a composite succession of basic lavas and volcaniclastic sedimentary rocks. In the Edremit area, these lithologies were overlain by one, or several, thick, shallow-water carbonate build-ups. These limestones probably capped the Nilüfer volcanic succession, shedding limestone clasts, which mixed with volcanogenic debris flows on the flanks of a volcanic edifice. Later, these limestones were detached and emplaced as blocks or thrust sheets within the Nilüfer Unit, as seen in the Edremit area. Pyroclastic sediments (e.g., hyaloclastites; flow-front breccias) and carbonates were redeposited downslope on the flanks of one, or several, large edifices as epiclastic conglomerates, sands, silts and muds, limestone talus and calciturbidites. Siliceous sedimentary rocks are assumed to have accumulated in more distal deep-water settings. The volcanic build-up(s) are assumed to have been constructed on Triassic oceanic crust that was not preserved due to subduction. Minor serpentinite intercalations may record remnants of this oceanic basement.

Comparable Modern and Ancient Accreted Seamounts

An origin as one, or several seamounts, is consistent with the WPB-type geochemistry of the basalts (Pickett & Robertson 1996). The seamounts were mainly constructed from basalt, volcanic breccias, volcaniclastic sandstones and hyaloclastite. Intrusive rocks are rare. However, in the lower part of the tectono-stratigraphy (e.g., Uğu Taşı), deformed and recrystallised relatively coarse basic igneous rocks are likely to include sills and other minor intrusions locally. Pyroclastic sedimentary rocks (e.g., tuff) may form explosively when a seamount nears, or breaches, sea level, owing to reduced hydrostatic pressure, or build-up of volatiles in the magma (Jones 1966). Massive lava flows may also erupt subaerially, as in many volcanic islands (e.g., Canary and Hawaii islands). Large volumes of epiclastic sedimentary rocks can be generated by shallow-marine processes (waves and tides) and subaerial erosion. This material is then carried downslope by gravity processes, ranging from debris flows, to turbidity currents to form large talus aprons. After volcanism ends, carbonate build-ups develop, followed by thermal subsidence, as in the Pacific Emperor Seamounts (Winterer & Metzle 1984).

Numerous ancient examples of emplaced seamounts are recognised within accretionary setting elsewhere (see Robertson 1994, 2002), including other parts of Turkey (e.g., Late Mesozoic part of the Ankara Mélange). Other examples are documented in both NW Greece (Jones & Robertson 1991) and SE Greece (Clift & Robertson 1989). Similar examples are widespread in the circum-Pacific region (e.g., Tomodo & Fujimota 1983), including central Honshu, Japan (e.g., Sano *et al.* 1992; Jones *et al.* 1993) and the Franciscan Complex of California (Cloos 1984). Similar eruptive and epiclastic processes are also well documented in Palaeozoic orogenic belts, notably the Ordovician Ballantrae Complex, SW Scotland, where WPB-type volcanics are constructed an oceanic pile of massive lava, pillow lava, hyaloclastite and volcaniclastic (i.e., epiclastic) sediment (Bluck 1982).

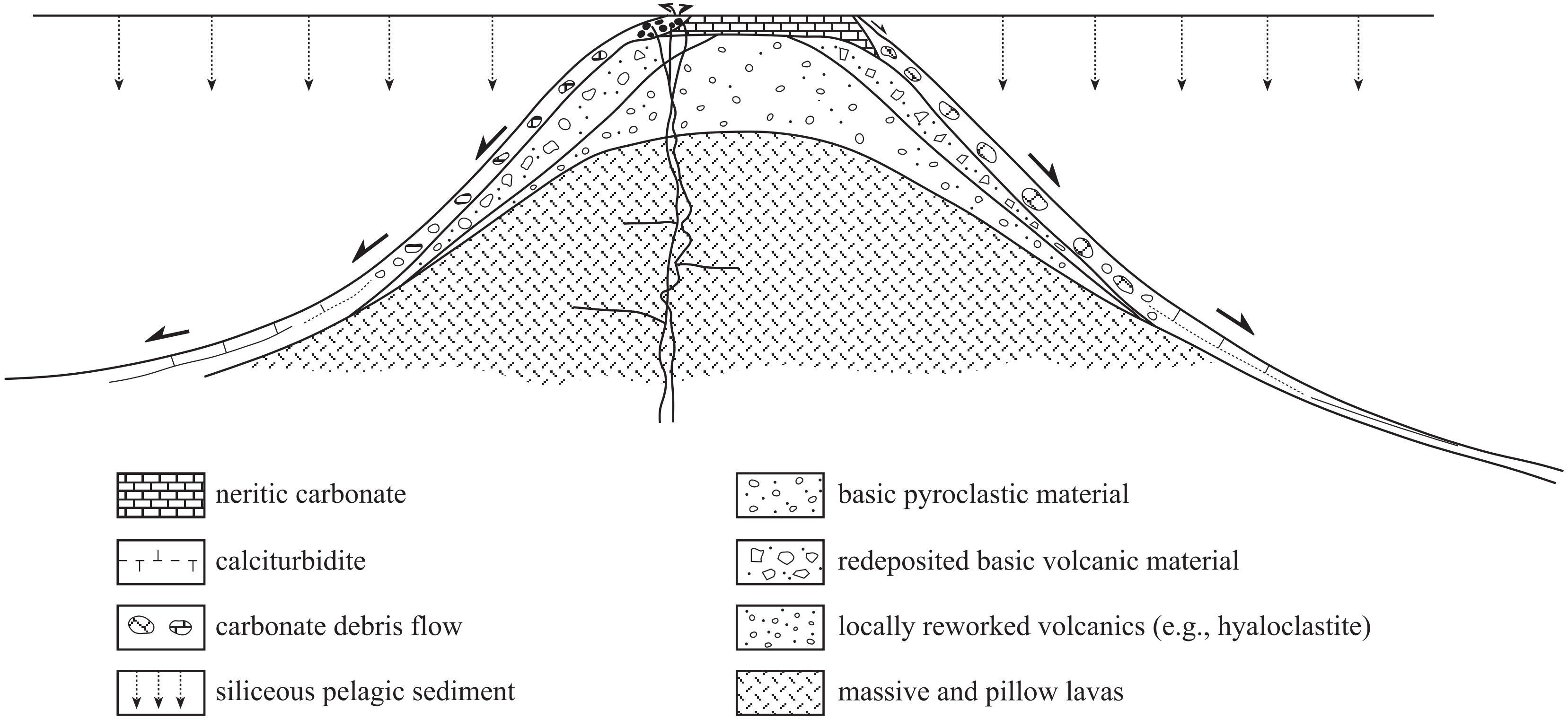


Figure 19. Reconstruction of a seamount as inferred for the Nilüfer Unit. See text for explanation.

Other Interpretations of the Nilüfer Unit

As discussed above our combined field and geochemical evidence supports the formation of the Nilüfer Unit as one or several oceanic volcanic build-ups, probably seamounts. However, the Nilüfer Unit has also been interpreted in several different ways, which we consider below.

Rift Origin

In one view, the Nilüfer Unit (and indeed the Karakaya Complex as a whole) represents a Triassic continental rift (Kaya 1991; Figure 20a). A rift origin is compatible with the WPB-type, non-orogenic chemical composition of the basalts, and with the presence of volcaniclastic sedimentary rocks, which might have formed along a rifted margin. However, a major problem is that the clastic sedimentary rocks, including mudstones, are volcanogenic, rather than terrigenous in origin. A further problem is that proximal rift-related volcanics and related volcaniclastic sedimentary rocks form along fault lineaments. The Nilüfer Unit exhibits similar slope-related features within a tectonically thickened unit wherever it occurs over vast outcrop areas. These could not *all* be representative of an originally linear rift setting. There is, for example, no evidence of the proximal-distal relations of volcanic or sedimentary rocks that could relate to a localised rift origin.

Ocean Plateau Origin

It has been suggested that the Nilüfer Unit represents an emplaced Large Igneous Province (LIP; Okay 2000; Figure 20e) on a scale equivalent to the entire Karakaya outcrop in Turkey (c. 1100-km long x > 80 km across). It was noted that the Nilüfer Unit does not preserve its entire original thickness, which was removed during tectonic emplacement (possibly by “subduction erosion”). A seamount origin is supposed to be less likely than a LIP in view of the long outcrop width across Turkey, which in turn might suggest a requirement for the former existence of tens of normal-sized seamounts. Until now, an age diachroneity suggestive of a hot-spot trail, similar to Hawaii and the Emperor Seamounts, has not been detected (although few of the Nilüfer volcanic-sedimentary units are yet well dated). A Nilüfer LIP would be on the scale of the Columbia River Basalts, the Deccan Traps, or the Ontong-Java Plateau (Okay 2000).

LIPs remain relatively poorly known because they mainly lie deep in the oceans and only several have been studied in any detail by ODP (i.e., Kerguelen and Ontong-Java). However, based on available information, LIPs are diverse in eruptive style, chemical composition and geological history (Coffin & Eldholm 1994; Saunders *et al.* 1996) and thus comparisons are difficult.

LIPs can be regarded as subaqueous equivalents of continental flood basalts (e.g., Cretaceous Deccan Traps), which erupt sheet flows of hundreds of kilometres in extent. In the oceans, LIPS, up 10-km thick, overlie oceanic crust and pre-existing pelagic sedimentary rocks. Part of the Ontong-Java LIP is exposed in the Solomon Islands (e.g., Malaita Island), where the succession is dominated by stratiform basaltic lavas and sills, with minor coarser-grained basic plutonic rocks but with very little intercalated pelagic sedimentary rock. The lavas are transitional in chemical composition from tholeiitic N-MORB to more enriched E-MORB. The igneous pile in the Solomon Islands is overlain by relatively deep-water pelagic carbonates, with minor alkaline lavas (Petterson *et al.* 1998).

Elsewhere, fragments of LIPs are widely emplaced onto continental margins as in the Caribbean region (Donnelly *et al.* 1973; Kerr *et al.* 1998) and its periphery, including Central America and the Andes. Basic extrusive rocks in these areas range from near MORB (transitional tholeiites) to highly magnesian, the latter recording high fusion temperatures (Mahoney *et al.* 1993; Mahoney & Coffin 1997). Highly magnesian lavas are also exposed on Gorgona Island (Dietrich *et al.* 1981), Curacao (Netherlands Antilles; Kerr *et al.* 1997) and in the Chilean Andes (Spadea *et al.* 1989). Other examples of emplaced LIPs include those in Japan and western USA, including the Marin Heads, San Francisco (Ben-Avraham *et al.* 1981).

The above information suggests that the Nilüfer Unit is not similar to most LIPs as presently understood for several reasons: (1) The Nilüfer Unit comprises c. 80% fragmental volcaniclastic sedimentary rock in the areas studied, whereas LIPS (e.g., Ontong-Java) are dominated by sheet flows up to tens-of-metres thick with minimal intercalated pelagic or volcaniclastic sedimentary rocks; (2) the uniformly enriched WPB chemistry of the Nilüfer Unit contrasts with the N-MORB, to E-MORB, to high-Mg character of most LIP magmas; (3) the Nilüfer Unit examined by us documents relatively steep slope settings

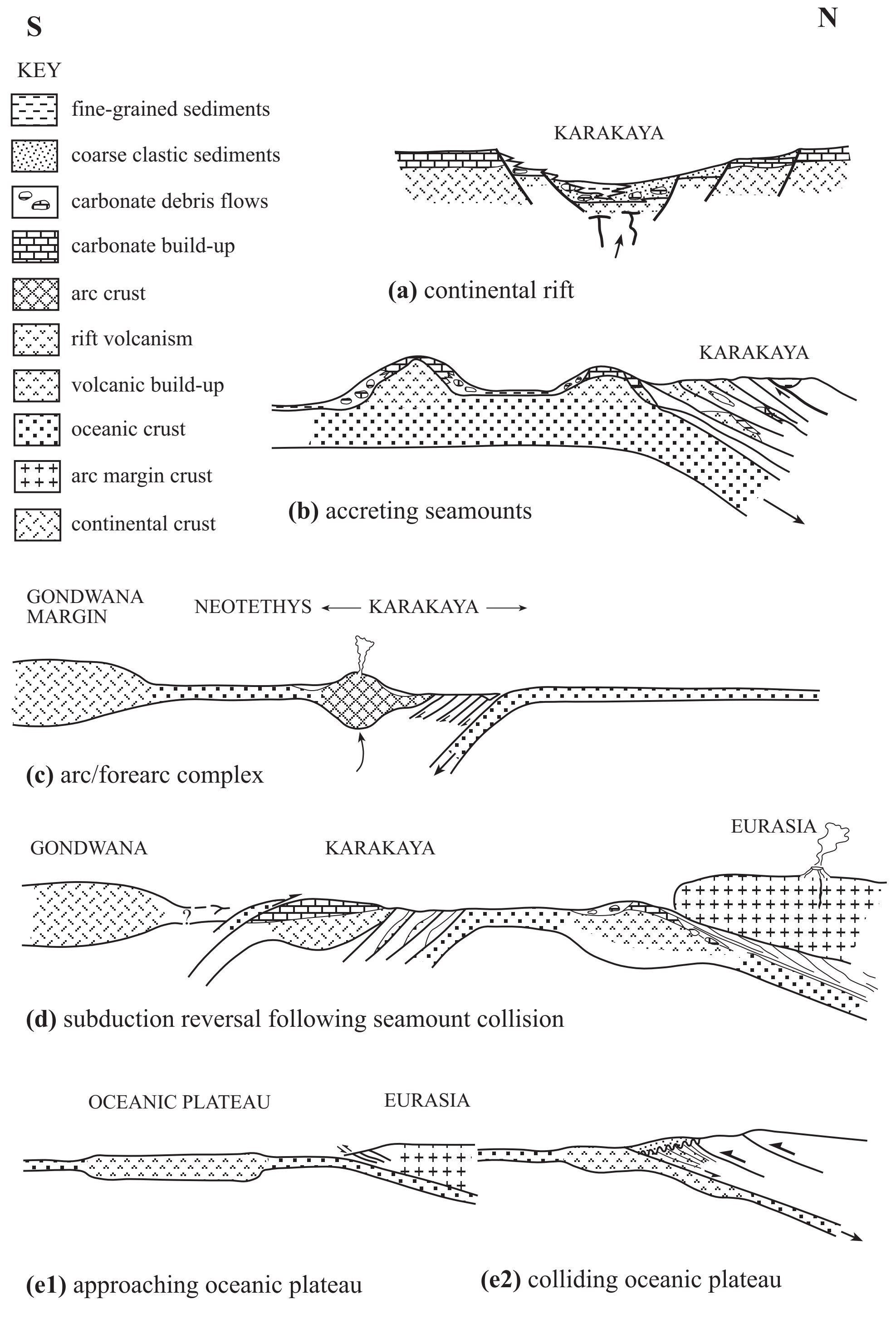


Figure 20. Published tectonic models for the Karakaya Complex; (a) Continental rift (Kaya *et al.* 1986, 1989); (b) as an accretionary prism with oceanic seamounts (Pickett *et al.* 1995); (c) as a marginal basin and magmatic arc formed above a southward-dipping subduction zone (Okay *et al.* 1991, 1996); (d) northward-dipping subduction followed by collision of a seamount complex or microcontinent with a trench reversing subduction (Pickett & Robertson 1996); (e) formation and then collision of an oceanic plateau with a N-dipping subduction zone (Okay 2000).

with ubiquitous gravity deposition, whereas typical LIPs are dominated by vast, low-relief plateaus; (4) most oceanic LIPs remained deeply submerged after eruption ended (e.g., Ontong-Java), whereas the Nilüfer Unit in the Edremit area includes neritic limestone and reworked marginal carbonate talus showing that the volcanic edifice reached near, or above, sea-level.

In summary, the field relations and lithological composition oppose a continental-rift origin for the Nilüfer Unit. Also, the geochemistry and field relations favour a seamount rather than LIP origin. The Nilüfer Unit is strongly deformed and tectonically imbricated and it is possible that a number of seamounts originally existed, possibly related to a hot-spot trail within the Triassic Tethys which remains to be elucidated. It was recently argued that widespread occurrences of chemically "enriched" basalts of WPB-type in many parts of the eastern Mediterranean, Middle Eastern and Himalayan regions (e.g., Cyprus, Greece, SW Cyprus, SW Turkey, Oman, Ladakh) reflect plume-related activity bordering the northern margin of Gondwana (Pe-Piper 1998; Dixon & Robertson 1999; Robertson 2002). Plume effects within the modern oceans range from LIPs of different size, to large island chains (e.g., Hawaii-Emperor Seamounts), to smaller seamounts that are ubiquitous throughout the Pacific Ocean (e.g., Malamud & Turcotte 1999). In reality, seamounts and LIPs may well be intergradational in chemical composition and size; indeed, the Nilüfer Unit shows some features that are compatible with either of these settings, although a seamount origin best fits the evidence from NW Turkey.

Accretionary Model for the Nilüfer Unit

The Nilüfer Unit was emplaced by the accretion of one, or several, large volcanic edifices in a subduction-trench setting (Pickett *et al.* 1995; Pickett & Robertson 1996; Figure 20c). The volcanic pile converged on the trench, subsided, tilted and broke up, resulting in mass wasting of the neritic carbonate cover to form limestone-dominated matrix-supported polymict conglomerates, as seen in the Edremit area. The clasts were probably derived from the adjacent Sakarya continental basement (e.g., quartz, granite) and associated units, possibly including previously accreted units (e.g., chert). The tectonically interleaved debris flows with exotic clasts (e.g., granite) are therefore interpreted to relate to tectonic mixing at the toe of the accretionary wedge in a fore-arc setting. Components of the Nilüfer Unit that experienced only low-grade metamorphism remained in the toe of the accretionary wedge. However, some part of the Nilüfur Unit were subducted and underplated beneath the fore-arc, resulting in HP/LT (locally eclogitic) metamorphism. Some of this material was exhumed to the seafloor by earliest Jurassic time.

A close comparison can be made between the inferred accretion of the Nilüfer Unit and the destruction of the Daiichi-Kashina Seamount in the Japan Trench (Cadet *et al.* 1987; Taira *et al.* 1989; Dominguez *et al.* 1998; Figure 21). This seamount is cut by two normal faults, along which the landward block is subsiding into the trench. Limestone breccia was observed between the seamount and the inner trench wall. Seamount material was also noted on the landward slope of the trench, above the level of the down-faulted seamount block. This suggests that tectonic mixing is taking place between seamount-derived and fore-arc (trench-wall)-derived material. The intercalation may relate to thrusting in the lower part of the slope, implying that accretionary processes were active in the toe of the accretionary wedge (Kobayashi *et al.* 1987). Other examples of seamounts converging with, or already emplaced beneath, subduction trenches include the Kyushu-Palau Ridge/Nankai Trough intersection, along the Mariana/Bonin convergent margin, and the western part of the Mediterranean Ridge.

Other Units of the Karakaya Complex in NW Turkey

Any interpretation of the Nilüfer Unit in its regional context must take account of the adjacent units in the pile of thrust sheets making up the Karakaya Complex. In the following section we summarise our evidence obtained from study of these units which structurally overlie the Nilüfer Unit in NW Turkey.

Ortaoba Unit: Clastic Rocks, Cherts and MORB-Lavas

The Nilüfer Unit in the Edremit area is overlain by a less metamorphosed, generally thinner (1–2-km thick), thrust sheet made up of a basalt-chert-sandstone association, known as the Ortaoba Unit (Pickett 1994; Figures 2, 3, 9 & 10). This unit is generally equivalent to the Hodul Unit of Okay *et al.* (1991). Some undeformed clastic sedimentary rocks of the overlying cover unit (Havran area) and limestone debris flows (near Balya) were

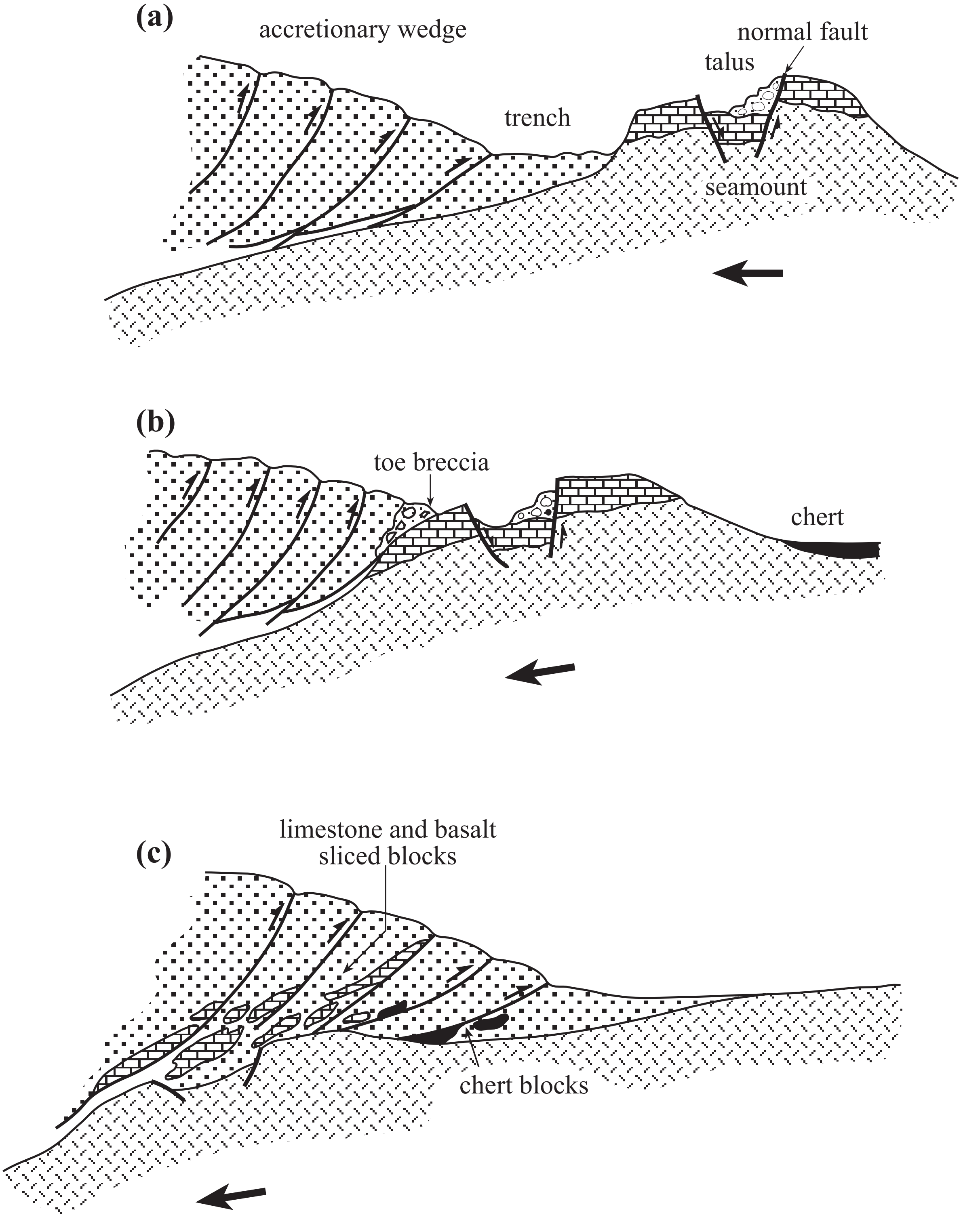


Figure 21. Model for the arrival of a seamount at a trench and its incorporation into an accretionary prism based on study of the Daiichi-Kashima Seamount in the Japan Trench (after Taira *et al.* 1989). The Nilüfer Unit was probably underplated to the fore-arc whereas the structurally overlying Ortaoba Unit with accreted at the trench toe (Pickett & Robertson 1996; see text for discussion).

previously included within the Hodul Unit by these authors. For this reason, a more concisely defined Ortaoba Unit was introduced (Pickett 1994).

The contact of the Ortaoba Unit with the underlying Nilüfer Unit is interpreted by us as a regional low-angle thrust (Pickett & Robertson 1996; Figure 9). We are unable to confirm the existence of a normal contact, even locally (cf. Akürek & Soysal 1983). Leven & Okay (1996) suggested that the Nilüfer Unit is stratigraphically overlain by arkosic clastic rocks of their Hodul Unit and Okay (2000) proposed that a sheared depositional contact may exist, although we found no evidence of this.

At the base of the Ortaoba Unit in the Edremit area, pillow lavas, associated with hyaloclastites (Figure 15c & d) plot in the MORB field on tectonic-discrimination diagrams; also, clinopyroxene phenocrysts are of non-orogenic type based on electron-probe analysis (Pickett 1994; Pickett & Robertson 1996). Overlying siliceous mudstones pass depositionally upward into recrystallised red ribbon radiolarian cherts, up to 20-m thick. Overlying feldspathic turbidites (mainly sub-arkose) are interbedded with dark shale and mudstone.

The Ortaoba Unit is strongly sheared, with ubiquitous layer-parallel extension, disruption and thrust repetition. Basalt and chert occur only rarely as discontinuous tectonic slices. Lithological associations correlated with the Ortaoba (i.e., Hodul) Unit occur throughout NW Turkey and include the "Dışkaya Formation" in the north, between Bursa and Gemlik (Wiedmann *et al.* 1992). Our reconnaissance of these areas indicates that this unit was tectonically assembled and cannot be considered as a stratigraphical formation.

Fauna found within limestone blocks of Okay's Hodul Unit (equivalent to our Ortaoba Unit) include conodonts, ostracods, cephalopods and fish remains. Calcareous blocks of the "Dışkaya Formation" in the north (also equivalent to our Ortaoba Unit) are well dated as middle Late Scythian (based on conodonts), Late Scythian (from ostracods) and middle Late Scythian (from cephalopods) (Wiedmann *et al.* 1992). Higher in the overall lithostratigraphy, blocks of calcareous sedimentary rocks yielded Middle Anisian conodonts, together with a Permian to Triassic conodont fauna; limestone blocks also contain *Halobia* of Norian age (Wiedmann *et al.* 1992). Kozur *et al.* (1996) report the presence of radiolarians of Early–Middle Scythian age. In addition, fusulinids and small foraminifera, reported by Leven & Okay (1991), indicate the presence of most of the Carboniferous and Permian stages, with Late Permian ages being the most common (Murgabian to Midian).

The Ortaoba (Hodul) Unit was interpreted by Pickett & Robertson (1996) as a subduction-accretion complex, in which slivers of Triassic MORB-type basalts and depositionally overlying radiolarites were incorporated into feldspathic turbidites, also of Triassic age, in a subduction-trench setting. The feldspathic sedimentary rocks, including granite clasts, were presumably derived from granitic rocks within the Sakarya crystalline basement, assumed to lie within the fore-arc area to the north. Underplating of accretionary material or a collisional event could have resulted in uplift and erosion of the fore-arc, thereby liberating feldspathic clastic sediments from granitic intrusions. Okay (2000) suggested that granitic rocks (e.g., Çamlık Granite) were uplifted as a result of collision of a LIP, allowing the exposure and erosion of intrusions. Granitic rocks could also have been exposed to erosion within the active margin by other processes including extension (caused by trench roll-back) or strike-slip (transtension or transpression).

The limestone blocks within the Ortaoba Unit, derived from mainly neritic sequences of Triassic (Scythian), Permian and Carboniferous age, are also assumed to have been accreted from the subducting oceanic plate. These, together with the scattered blocks of Palaeozoic calcareous pelagic sedimentary rocks could be taken to indicate the presence of a Tethyan ocean dating back at least to Carboniferous times. One possibility is that these pelagic carbonates were accreted from subducting Late Palaeozoic oceanic crust, which has otherwise disappeared without trace. In keeping with this suggestion, Late Palaeozoic pelagic sediments in the central Pontides can be interpreted as having formed in a precursor to the inferred Early Mesozoic Küre marginal basin (Robertson *et al.* 2004).

Kalabak Unit: Fine-grained Clastic Sediments of Uncertain Setting

This unit (Figure 10), equivalent to the Kalabak Formation of Okay *et al.* (1991), is up to 5 km thick in the Edremit area, and comprises dark grey phyllites, quartzofeldspathic schists and scarce horizons of deformed conglomerate and recrystallised limestone. A similar sequence is exposed farther south, to the north of Bergama (Figure 4), where foliation, small asymmetrical folds, shear zones and small-scale duplex structures are developed. The age and tectonic setting of the Kalabak Unit remain questionable. Mapping northeast of Edremit has suggested that the phyllites of the Kalabak Formation are intruded by the Çamlık Metagranodiorite pluton that may be as old as Early Devonian (399 ± 13 Ma; Okay *et al.* 1996). Although exposure is inadequate to demonstrate the presence of chilled margins, the outcrop pattern suggests the existence of a granitic core (kilometre-scale) surrounded by phyllite. Also, a small (c. 15 m across) enclave of phyllite was found within the granite and this was interpreted as a large xenolith (Pickett 1994). In view of this, the Kalabak Unit is here excluded from the true Karakaya Complex. In the area NE of Havran, the Kalabak Unit and, locally the Çamlık Granite are unconformably overlain by undeformed clastic/calcareous sedimentary rocks of latest Triassic age. The implied Palaeozoic age of the Kalabak Unit suggests that this unit already formed a part of the Eurasian fore-arc when the Karakaya Complex as a whole was emplaced in Late Triassic time.

Çal Unit: Permian Neritic Carbonates

The structurally highest unit of the Karakaya Complex, the Çal Unit (0–1-km thick), is widely exposed especially in the Edremit, Çan and Balya areas (Okay *et al.* 1991, 1996; Figures 9 & 10). In these areas it comprises relatively undeformed and unmetamorphosed debris flows of variable composition (mainly limestone or basalt), subordinate basaltic lava flows and breccias of WPB-type basalt, as well as numerous detached blocks and disrupted fragments of Upper Permian neritic limestones. In the Edremit area, the Çal Unit forms a klippen of Upper Permian limestones, associated with, basalt, red mudstone and micaceous sandstone. A critical question, discussed below, is whether these sedimentary rocks are depositionally associated with the original Late Permian neritic limestone or were instead tectonically introduced later during accretion, as effectively a matrix of a mélange. The upper part of the Çal Unit in the Edremit area is dominated by debris flows with volcanic clasts and Upper Permian limestone blocks. These debris-flow deposits range from mainly limestone-derived to mainly volcaniclastic in origin. Clasts exhibit a WPB-type geochemistry (Pickett 1994; Pickett & Robertson 1996). Locally (at Çanlıbaba; Pickett 1994), foliation and S-C structures indicate top-to-the-NW movement.

Redeposited carbonates (calciturbidites and blocks) within the Çal Unit commonly contain a Late Permian fauna (Okay *et al.* 1991, 1996; Leven & Okay 1996). Also, blocks of radiolarian chert southeast of Çan yielded radiolarians that were initially dated as Early Permian (Okay & Mostler 1994), but were later reclassified as Late Permian (i.e., Dorashamian by H. Kozur). In addition, the Çal Unit locally includes Anisian limestones, up to several hundred metres thick (Okay 2000).

Elsewhere in NW Turkey (e.g., south of Manyas and on the island of Marmara), volcaniclastic rocks are reported to be depositionally overlain by carbonates, up to several hundred metres thick (Okay *et al.* 1996). Also, the Carboniferous–Permian schist and neritic carbonates of Lesbos (Katsikatsos *et al.* 1982) and the upper Middle Permian Chios Allochthon (Migiros 1992) may be of comparable origin (Robertson & Pickett 2000). Elsewhere, lithofacies similar to the Çal Unit occur widely throughout the Karakaya Complex (e.g., Ankara area).

Association of the Çal Unit with Terrigenous Sedimentary Rocks

In the Çan area, described by Okay *et al.* (1991), we observed a range of limestone-rich debris flows, volcanic-rich debris flows and mixed limestone and debris flows with no evidence of associated terrigenous sedimentary rocks. However, different facies associations were seen elsewhere.

In the Kozak Massif in the Bergama region (Figures 2 & 5) Permian limestone crops out at the top of a ridge (Ada Tepe) NE of the village of Adaköy (Figure 8). Permian limestones are thrust over debris flows and feldspathic sandstones. The base of the sandstone is marked by a 5-m-thick breccia which contains angular limestone fragments (80–90%), sandstone, quartz and chert clasts in a quartz-rich sandy matrix. The sandstone matrix contains carbonate debris including small carbonate clasts and isolated, well-preserved fusulinids. The clasts range in size from 1–5 cm. These terrigenous sedimentary rocks appear to be part of the original basement of the Permian neritic limestone succession.

Elsewhere, similar relations are seen associated with a disrupted Permian platform stretching NE from İvrindi through Balya, east of the Biga Peninsula (Figures 2 & 4). Exposures are fragmentary and contacts with other units of the Karakaya Complex are not exposed. Interbedded limestone, terrigenous sandstone and shale are exposed along the road from İvrindi to Balya, just outside Balya. The sandstone intercalations consist mainly of quartz and feldspar with traces of cross-bedding. In addition, NE of Balya on the Ilıca-Şamlı road, the base of a limestone block contains an intraformational conglomerate with angular limestone clasts, some of which are quartz rich. The matrix comprises quartz grains and alkali feldspar (including microcline and perthite).

Elsewhere, in the vicinity of Çalköy village a good reference section for the lower levels of the Çal Unit is exposed along the road, which connects the villages of Aşağıkaraaşık and Yukarıkaraaşık. Limestone breccias and volcanic flows with red mudstones are underlain by a succession of interbedded sandstone and shale. The sandstone is grey, medium- to coarse-grained and rich in mica and feldspar. At this locality, the contact with the overlying volcanogenic succession is faulted.

In the Edremit area, the Upper Permian Çal Unit is well exposed around the east flanks of Çiğdem Tepe (Figure 11). An intact limestone succession there is underlain by relatively undeformed red-brown mudstone, including silt-grade fragments of mica. The mudstone contains small blocks of fine- to medium-grained dark green sandstone. The sandstone consists mainly of angular quartz and feldspar grains in a muddy clay and mica-rich matrix, together with plagioclase, opaque minerals, lithic clasts and secondary chlorite and rare rutile. The quartz ranges from showing undulose extinction to very recrystallised. Rock fragments include foliated mica schist, shale, basalt, myrmekitic quartz-feldspar and chert or devitrified basic volcanic rock. The matrix is a mixture of quartz, clays, opaque minerals and chlorite.

Two samples of red-brown siltstone and one of fine-grained sandstone from the Çiğdem Tepe area were analysed by XRF (Table 3) and the results were normalised to NASC (North American Shale Composite). These three samples show typical terrigenous signatures, with a slight enrichment of Cr and Ni (Figure 22), which points to an enhanced mafic igneous component.

Interpretation of the Çal Unit as an Accreted Continental Fragment

Pickett & Robertson (1996) interpreted the Çal Unit as related to subduction/accretion processes. Pickett *et al.* (1995) initially interpreted the Çal Unit as relating to the accretion of one, or several, oceanic seamounts, influenced by exposures in the Çan area. However, subsequent detailed fieldwork elsewhere showed that, in most areas, the lower part of the Çal Unit contains abundant terrigenous shales and sandstones. More locally, the Upper Permian limestones blocks include primary interbeds of shale or sandstones. Exceptionally, terrigenous sedimentary rocks can be seen to pass depositionally upward into relatively intact Upper Permian carbonate successions.

If the sandstones were, in effect, trench-type turbidites introduced during tectonic accretion of the Çal Unit, they would be expected to be compositionally similar to the sandstones of the structurally underlying Ortaoba Unit. However, there are marked colour and compositional differences. The Çal sandstones are relatively dark, unaltered and include abundant quartz, feldspar, mica and varied lithic fragments (i.e., largely lithic sandstones and subgreywackes), whereas the Ortaoba sandstones are paler, and more altered with abundant quartz, feldspar and abundant devitrified felsic-volcanic debris resulting in arkosic compositions. In addition, chemical analysis of the related shales clearly indicates a terrigenous origin (Figure 22). The Çal sandstones record a mainly recycled orogenic origin, whereas the Ortaoba sandstones are indicative of a mainly magmatic arc origin.

In summary, we infer that the Upper Permian limestones of the Çal Unit originally accumulated on a substratum of terrigenous sediments. These sediments, in turn, presumably overlie a continental basement that is no longer preserved. When the Çal Unit was tectonically accreted relatively incompetent terrigenous clastic sediments were sheared and entrained with the disrupted Upper Permian limestones, only rarely leaving primary depositional relationships intact. A similar terrigenous sedimentary base was reported for counterparts of the Çal Unit (i.e., Aktaş Formation) in the central Pontides (Ustaömer & Robertson 1997).

To explain the setting (i.e., terrigenous basement) of the Çal Unit, we infer that the Late Permian platform

Table 3. Major and trace element analyses of sedimentary rocks from the Çal and Orhanlar units

	Çal Unit near Edremit			Orhanlar
	siltstone	siltstone	sandstone	greywacke
wt %	78B/90	78C/90	79B/90	ORH3
SiO_2	72.75	59.06	59.20	69.43
Al_2O_3	11.19	18.08	17.97	10.20
Fe_2O_3	3.97	8.54	7.63	5.66
MgO	1.91	2.63	3.64	2.95
CaO	2.09	0.40	0.43	2.92
Na_2O	2.15	1.45	1.44	1.59
K_2O	1.408	4.096	3.598	1.341
TiO_2	0.559	0.850	0.796	0.668
MnO	0.059	0.188	0.087	0.149
P_2O_5	0.145	0.101	0.134	0.148
LOI	3.87	4.09	4.70	4.69
Total	100.10	99.49	99.61	99.75
ppm				
Nb	12.3	19.1	13.1	10.3
Zr	162.4	195.4	146.0	159.3
Y	19.9	28.6	24.9	17.4
Sr	99.7	39.0	64.3	64.2
Rb	54.6	165.7	145.5	51.0
Th	10.9	19.2	11.2	6.3
Pb	13.0	36.7	19.6	15.8
Zn	68.5	131.2	98.6	76.7
Cu	14.3	66.0	41.7	24.8
Ni	72.5	101.8	105.3	93.1
Cr	160.0	139.7	209.8	202.3
Ce	69.5	96.8	90.8	38.6
Nd	28.0	29.2	31.8	14.0
La	37.7	37.4	32.4	9.4
V	82.4	193.9	192.3	119.6
Ba	172.7	346.2	424.7	235.2
Sc	8.7	21.1	30.0	13.8

carbonates were initially deposited on a continental, rather than an oceanic basement. This was associated with rift-related, extensional faulting, mass wasting and WPB-type volcanism. Such a setting could help explain the local presence of two phases of conglomerate formation (i.e., lithified conglomerate within a younger rudaceous rock).

We envisage the Çal Unit as originating as a continental fragment that rifted from the Anatolide margin to the south and drifted across Tethys to be later accreted at the Eurasian active margin to the north (Robertson *et al.* 2004). During accretion, the Çal Unit was detached from its inferred continental basement and emplaced as the highest unit in the thrust stack, prior to latest Triassic–Early Jurassic transgression. The Çal Unit was never deeply buried and metamorphosed as a result of this detachment and emplacement. The missing continental substratum possibly was already strongly

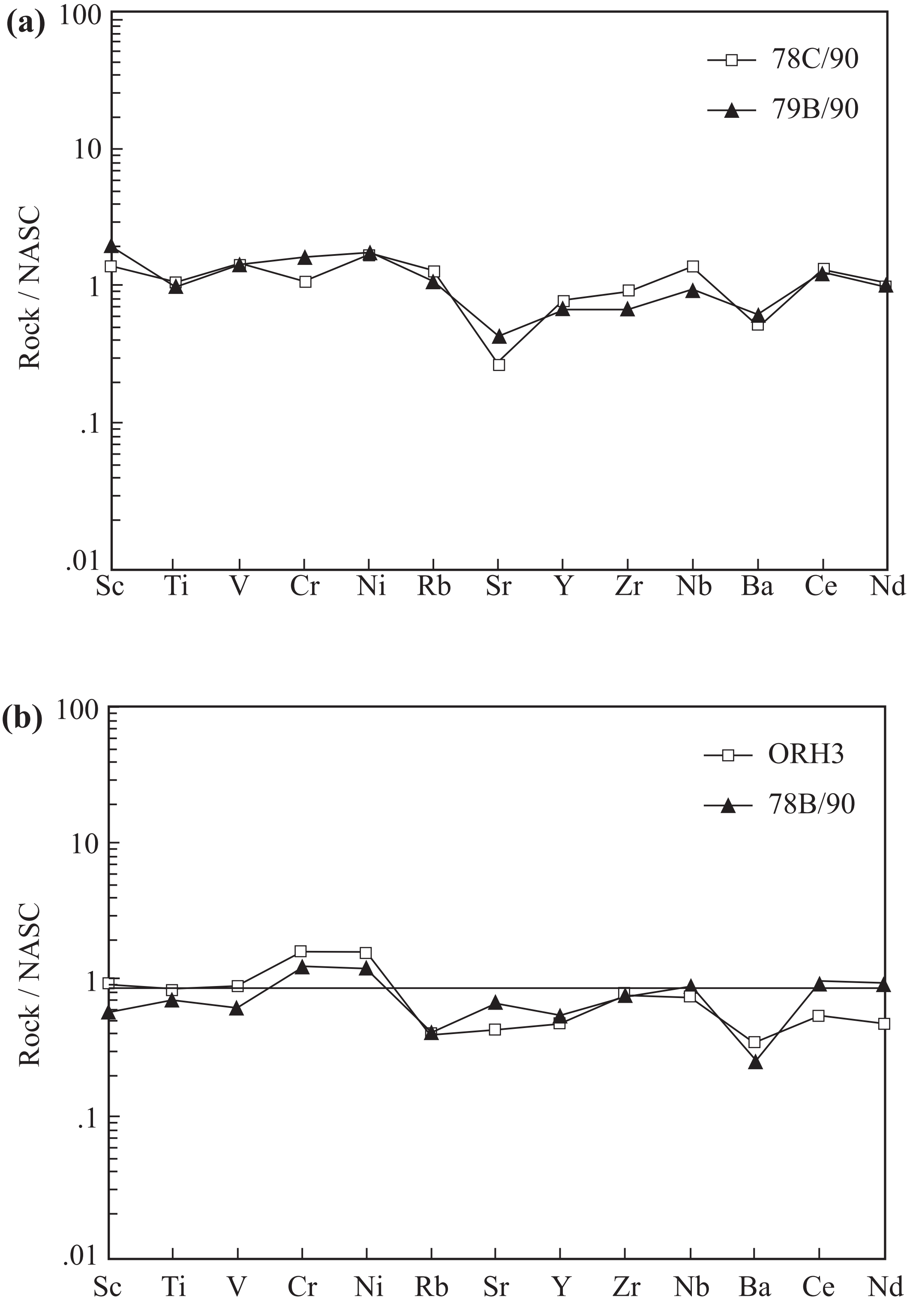


Figure 22. Siltstones and sandstones chemically analysed by XRF from the Çal Unit, normalised against average North Atlantic Shale composition (NASC; Gromet *et al.* 1984). Data shown in full in Table 3.

thinned during much earlier rifting and was thus readily underthrust/subducted without being preserved within the Karakaya Complex.

Orhanlar Greywacke: Siliciclastic Turbidites

This distinctive clastic unit occurs in isolated exposures (e.g., north of Balya, outside our study area; Figure 4) and thus its structural relationship to the other units of the Karakaya Complex is unclear. In different areas it appears to tectonically overlie either the Nilüfer Unit or the Ortaoba (Hodul) Unit (Okay *et al.* 1991). This unit shows strong layer-parallel extension that has destroyed much of the original bedding. These sandstones are mainly greywacke, with quartz, plagioclase, opaque minerals, black metachert (lydite), red radiolarian chert, basalt and phyllite clasts set in an argillaceous matrix (Okay 2000). This siliciclastic composition contrasts with the more arkosic sandstones of the Ortaoba Unit and with the basic volcaniclastic nature of the Nilüfer Unit. A terrigenous composition is also indicated by chemical analysis (Figure 22; Table 3). There are occasional small blocks of Middle Carboniferous limestone, rich in corals, brachiopods and foraminifera (Okay *et al.* 1991, 1996), as observed in the type locality north of Balya (Figure 4). Southwest of Bursa (Figure 4), rare limestone blocks are assigned to an ill-defined Late Permian age. Locally (south of Mustafakemalpaşa), the size (up to several hundred metres across) and relative number of blocks increases rapidly. The Orhanlar Greywacke is not directly dated, but is assumed to be Triassic in age from the presence of Late Permian limestone blocks and a Liassic unconformable cover (Leven & Okay 1996).

The presence in the Orhanlar Unit of basalt, lydite and red chert is suggestive of derivation from an oceanic assemblage, whereas the quartz and alkali feldspar points to an additional continental margin source. Okay (2000) interpreted the Orhanlar Unit as part of the accretionary wedge, but it is unclear why the siliciclastic composition should differ so markedly from the arkosic sandstones of the Ortaoba Unit, discussed above. It is possible that the Orhanlar Greywacke was partly derived from erosion of deep-sea sedimentary rocks and basalt that were previously accreted to the Eurasian margin, together with continental basement material (i.e., Sakarya basement). If correct, this points to an earlier history of Late Palaeozoic history of northward subduction beneath the Eurasian margin in this area, consistent with the presence of Late Palaeozoic pelagic material within the Karakaya Complex (Kozur & Kaya 1994). It is indeed likely that the active margin to the north was laterally variable with silicic or granitic basement, cover sediments, or previously accreted oceanic material exposed in different areas.

Latest Triassic–Early Jurassic Cover

The Karakaya Complex as a whole is unconformably overlain by clastic sedimentary rocks, locally up to 1000-m thick (Halılar Formation of Krushensky *et al.* 1980; Figure 9). In some parts of the Edremit-Havran area (e.g., Kocaçal Tepe; Figure 9) low-grade shales and siltstones were included by Okay *et al.* (1991) in their Hodul Unit. However, these rocks are much less deformed and unmetamorphosed. Shallow-water trace fossils (e.g., *Thalassinoides* and *Skolithus*) appear near the top of this clastic succession suggesting relatively shallow-water deposition. There is a gradational passage upward into pink, nodular, pelagic limestone of lowermost Jurassic (Sinemurian) age (Bilecik Limestone). The presence of brachiopods, ammonites and foraminifera also establishes a Sinemurian age for the transgressive limestones (Bayırköy Formation) in areas where the basal clastic sediments (Halılar Formation) are thin or absent (Altıner *et al.* 1991).

Pickett & Robertson (1996) interpreted the lowermost clastic sedimentary rocks of the cover sequence as accumulating in perched basins during the latest stages of Late Triassic subduction-accretion. Okay (2000) favoured a post-tectonic origin. Our present view is that the final emplacement of the Karakaya Complex onto the leading edge of Eurasian margin produced a highly irregular, tectonically active topography, which was progressively infilled with mainly fine-grained siliciclastic sediment. The margin was then stabilised facilitating a transition to shelf-carbonate deposition (Bilecik Limestone) in Sinemurian time. This marked the onset of a prolonged phase of passive margin accumulation on a drowned shelf.

Tectonic Models for Genesis of the Karakaya Complex

In this final section, we utilise the information and interpretations of the Nilüfer Unit and the related units to test alternative regional plate tectonic models for the Karakaya Complex. Previous tectonic models assumed that the complex was tectonically associated with contemporaneous “Palaeotethyan” ophiolites, the Denizgören and Lesbos ophiolites in the region (Figure 2). These were assumed to be of pre-Liassic age, mainly as they tectonically overlie Upper Permian shallow-water carbonates without intervening younger units (Okay *et al.* 1991; Pickett & Robertson 1996). K–Ar dating of the metamorphic sole of the Lesbos ophiolite yielded Late Jurassic ages (Hatzipanagiotou & Pe-Piper 1995). Ar-Ar dating of the sole of the Denizgören Ophiolite gave a Early Cretaceous age (Okay *et al.* 1996). These ophiolites are now re-interpreted as emplaced younger “Neotethyan” oceanic lithosphere (Okay *et al.* 1996) and thus are excluded from the discussion below.

There are currently four main alternative tectonic models that assume an accretionary origin for the Nilüfer Unit, but which differ on the questions of subduction polarity and whether the Karakaya Complex represents a back-arc basin above a subduction zone or the remains of a wide ocean basin.

Marginal Basin Related to Southward Subduction

The Triassic Tethys, rooted along the present Eurasian margin in the Pontides, was subducted southward in the Triassic to form a narrow back-arc marginal basin adjacent to the future Anatolide-Tauride platform; Figure 20a). This basin closed by latest Triassic time during the “Cimmerian” orogeny (Şengör & Yılmaz 1981; Şengör *et al.* 1984; Yılmaz *et al.* 1997). Several arguments oppose this hypothesis: (1) lack of preserved proximal-distal relationships within a former rift; (2) absence of terrigenous sedimentary rocks within the Nilüfer Unit; (3) the Nilüfer Unit shows evidence of build up to, or above, sea level rather than a typical rift/passive-margin subsidence, with shallow-water sedimentary rocks deepening upward; (4) the Triassic volcanic rocks (Nilüfer and Çal units) lack a geochemical subduction component, unlike modern rifted back-arc basins (e.g., Lau and Mariana back-arc basins, SW Pacific; Hawkins 1995; Parson *et al.* 1990, 1994).

Arc-Forearc Complex Related to Southward Subduction

This interpretation is similar to that above except that the Karakaya Complex is interpreted as the remnants of the “main Palaeotethys”. A volcanic arc was located in the north and rifted marginal basin in the south (Figure 20c). Subduction culminated in continental collision and northward emplacement of the Karakaya Complex. The main problems here are: (1) inferred arc volcanics related to possible southward subduction (Okay *et al.* 1996) were found to be within-plate basalts of the Nilüfer Unit and no separate Triassic arc unit has yet been discovered within the Karakaya Complex; (2) there is no evidence of a subduction backstop along the Anatolide-Tauride platform margin to the south. Triassic successions (e.g., of Chios or Karaburun) instead record rifting and passive margin subsidence (Robertson & Pickett 2000; Robertson *et al.* 2004); 3. There is no evidence of collision-related folding, crustal thickening, or HT/LP-type deep-burial metamorphism of the Karakaya Complex as a whole as would be expected if continental collision had taken place. Also, the Anatolide-Tauride margin to the south retains an overall passive margin history from Early Triassic onwards.

Northward Subduction with the Karakaya Complex as a Back-arc Marginal Basin

In this option, the subduction zone was located to the south of the Karakaya Complex (Stampfli 2000; Stampfli *et al.* 2001). The position of such a southerly subduction zone is questionable. It does not lie to the south of the Tauride platform as it is well known that the southern Neotethys was undergoing rifting and continental break-up in Mid–Late Triassic time (Marcoux 1995; Poisson 1984; Robertson & Woodcock 1984; Robertson 1993). A northward-dipping subduction zone located north of the Anatolide-Tauride platform is also unlikely, as arc volcanics are not recorded between the inferred position of the subduction zone and the supposed Karakaya back-arc basin to the north. Recently, Stampfli & Borel (2002) have inferred that a northward-dipping "Paleotethyan" subduction zone was located between the Tauride unit and the Anatolide unit. This is, however, opposed by the long-held view that the Tauride-Anatolide platform represents a single tectonic unit from Late Palaeozoic time onward (Şengör & Yılmaz 1981; Altıner *et al.* 2000). Also, as noted above, the Karakaya volcanics show no evidence of a subduction-related chemical influence. In addition, there is little evidence of voluminous acidic airfall tuffs and redeposited arc-derived sedimentary rocks, such as those of the SW Pacific marginal basins

(Woodlark Basin; Taylor *et al.* 1999; Robertson *et al.* 2001).

Northward Subduction of a Wide Triassic Tethys

A wide Triassic ocean was subducted northwards, constructing the Karakaya accretionary wedge along the Eurasian margin (Figure 20b). The Nilüfer Unit represents seamounts that were later accreted to the Eurasian margin. Continental fragments rifted from the Anatolide-Tauride margin in Late Permian–Early Triassic time (Robertson & Pickett 2000) and drifted northward, opening a new Triassic ocean behind them until they, too, collided with the Eurasian margin and were accreted (Figure 20d). Following the collision of seamounts and continental fragments in latest Triassic time, the accretionary wedge was covered by shallow-water clastic/carbonate sedimentary rocks recording the beginning of a passive-margin phase that lasted into Cretaceous time. This last mechanism best fits the available evidence (Robertson *et al.* 2004).

This hypothesis is compatible with most of the evidence given in this paper and below is developed further.

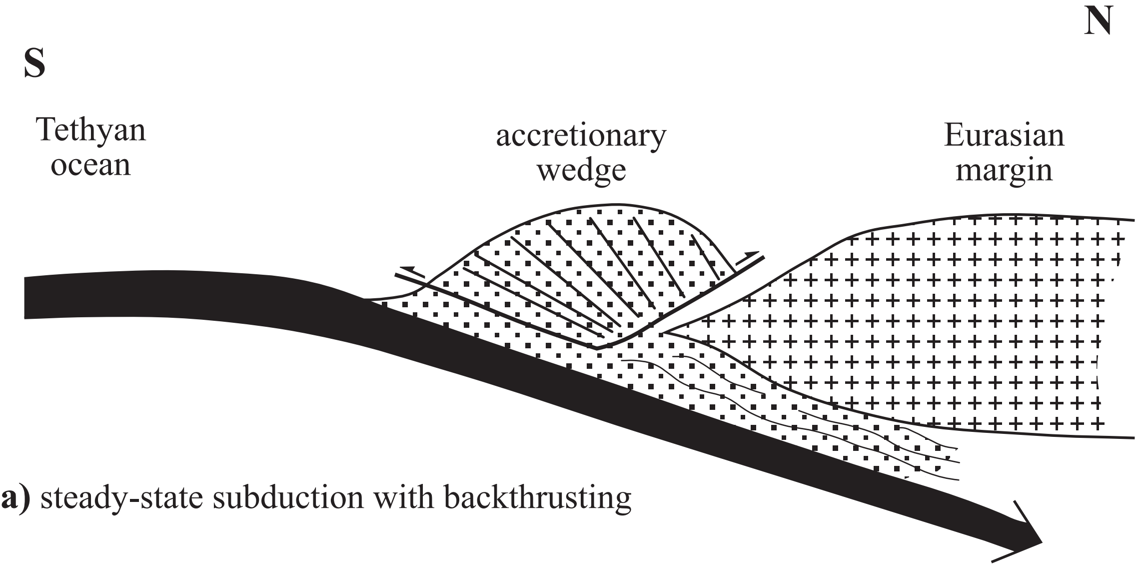
Alternative Mechanism for Final Emplacement of the Karakaya Complex

Most interpretations assume that the Karakaya Complex was finally emplaced northward over the leading edge of the Eurasian margin prior to earliest Jurassic time (Bingöl *et al.* 1975; Okay *et al.* 1991, 1996; Pickett & Robertson 1996). However, Okay (2000) suggested that the Karakaya Complex was imbricated with the Eurasian active continental margin on a large scale as a result of collision with a LIP (Figure 20c). The main evidence is that the Palaeozoic granodiorites are locally reported to structurally overlie the Nilüfer Unit (e.g., the Söğüt granodiorite in the east; Figure 1; Okay 2000). In the Biga Peninsula the Karakaya Complex overlies the Kazdağ Massif (Figure 9) but interpretation must take into account the evidence that the underlying Sakarya basement was extensionally exhumed as a core complexes in Neogene time (Pickett 1994; Okay & Satır 2000), disturbing the previous tectono-stratigraphy. If the Karakaya Complex was regionally thrust beneath the Eurasian arc, it should, however, be preserved as a regionally over-riding crustal-scale thrust sheet (e.g., resulting in burial metamorphism of the Late Permian Çal Unit), whereas the Karakaya Complex regionally forms the highest structural level of the Permo–Triassic tectono-stratigraphy in NW Turkey and was transgressed by Early Jurassic shelf carbonates soon after its final emplacement. It, therefore, seems inescapable that the Karakaya Complex was thrust > 50 km northward over the Eurasian continental margin (Figure 1).

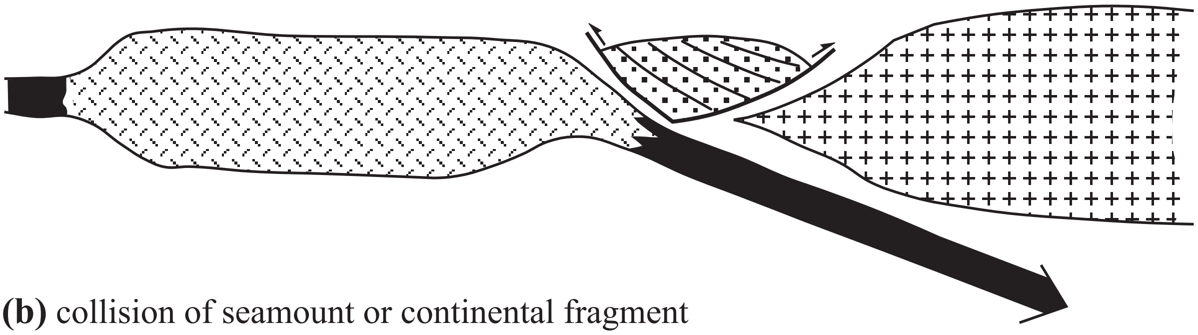
There are three possible mechanisms for this inferred northward final emplacement. (1) The accretionary wedge could have grown so large so that to maintain its critical taper (equilibrium shape) it underwent gravity spreading northward (Figure 23a). Such backthrusting is, for example, observed in the Barbados accretionary prism (Brown & Westbrook 1987). The main problem is the lack of preserved steep dips within the Karakaya Complex as a whole that would be expected within an over-thickened accretionary wedge. Also, we have not observed large-scale re-imbrication and interslicing of the individual units of the Karakaya Complex, as is typical of back-thrust accretionary wedges. Indeed, the overall tectono-stratigraphy is maintained regionally even where individual units (e.g., Ortaoba [Hodul] Unit) are quite thin (< 100 m). (2) Collision of a continental fragment or oceanic seamount resulted in the previously assembled accretionary wedge being detached and bulldozed over the fore-arc to the north (Figure 23b). The main problem here is the absence of evidence of large-scale re-imbrication, as in option 1. (3) Northward subduction culminated in jamming of the trench by a seamount (e.g., Nilüfer-type units), or continental fragments (e.g., Çal-type units) (Figure 23c). Such a collision then triggered a reversal of subduction polarity allowing the Karakaya Complex to be rapidly assembled above a localised southward-dipping zone of underthrusting/subduction (Pickett & Robertson 1996; Figure 20c). In this model, the Late Permian platform was emplaced at a high structural level without being subducted, explaining its unmetamorphosed nature. The main difficulty here is the absence of definitive structural evidence, a deficiency that needs to be addressed in future studies.

Conclusions

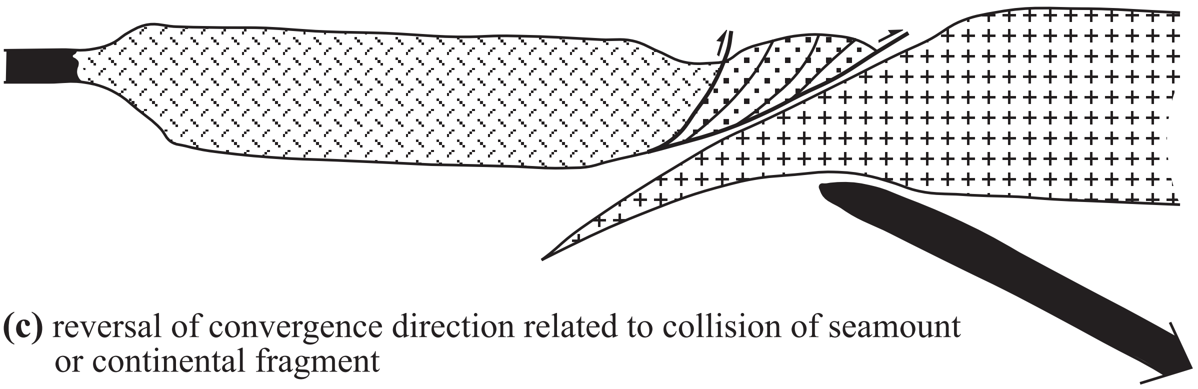
1. Dismembered units of Triassic volcanics, volcanogenic sedimentary rocks and detached limestone blocks, termed the Nilüfer Unit, form an



(a) steady-state subduction with backthrusting



(b) collision of seamount or continental fragment



(c) reversal of convergence direction related to collision of seamount or continental fragment

Figure 23. Alternative mechanisms of emplacement of Karakaya Complex northwards over the leading edge of the Eurasian continental margin (Sakarya basement). (a) Backthrusting as a consequence of steady-state subduction as the critical taper is exceeded; (b) emplacement as a result of collision of a subducting seamount/LIP or continental fragment; (c) emplacement as a result of reversal of the subduction/convergence direction caused by collision of a subducting seamount/LIP or continental fragment. Option c appears most appropriate as shown in Figure 20d (Pickett & Robertson 1996).

important structural component (up to at least 7-km thick) of the Karakaya Complex in NW Turkey. The Nilüfer Unit is the lowest of a stack of gently inclined, low-angle thrust sheets that mainly comprise Permian and Triassic lithologies.

2. The Nilüfer Unit is restored as one, or more, oceanic seamounts made up of basaltic lavas, basic pyroclastic sediment (tuff, hyaloclastite, flow-front breccia), debris flows, calciturbidites and hemipelagic sedimentary rocks that largely accumulated in slope, to base-of-slope settings. The Nilüfer volcanogenic sections were locally topped by Triassic neritic limestone. Terrigenous sediment is absent, except within thin tectonic intercalations that include limestone debris flows with pebbles of quartz, felsic volcanics and granite. The seamounts were constructed on oceanic crust that was subducted leaving little trace after accretion.
3. Whole-rock geochemistry (by XRF) and clinopyroxene analysis (by electron microprobe) show that basalts in each of the Nilüfer exposure areas studied are of within-plate (non-orogenic) type, with no detectable subduction influence.
4. Alternative origins of the Nilüfer Unit as a Triassic continental rift, or large oceanic plateau (Large Igneous Province) are problematic for reasons of field relations or chemical composition, respectively. Instead, an origin as one, or several, oceanic seamounts is preferred, related to hot-spot (plume) activity within the Triassic Tethys. The seamount(s) approached, or breached sea-level, generating basic pyroclastic material. Neritic carbonates locally capped the seamount(s) and reworking of volcaniclastic and carbonate material occured on the flanks.
5. Thin tectonic intercalations of limestone debris flow deposits contain exotic clasts, including granite, felsic volcanics and quartz. These mass flow deposits are seen as margin-derived sediments that were tectonically interleaved with the seamounts when they disintegrated in a subduction-trench setting.
6. The Nilüfer Unit was largely subducted and underplated beneath the Eurasian fore-arc (Sakarya basement), where it underwent HP/LT (locally eclogitic) high-pressure metamorphism. Underplated high-pressure rocks were exhumed to the toe of the subduction zone prior to earliest Jurassic time. In addition, some fragments, particularly Triassic limestone build-ups, were accreted at the toe of the subduction complex and escaped subduction.
7. The overall tectono-stratigraphy of the region, with crystalline rocks at the base, combined with field structural evidence suggests that the Karakaya Complex was regionally thrust northward over the southern edge of the Eurasian (Sakarya) fore-arc prior to earliest Jurassic time. It was then overlain by carbonate sediments on a submerged shelf forming part of the Eurasian (Pontide) continental margin.
8. A working hypothesis is proposed that involves steady-state northward subduction and accretion of various units at different stages. The Ortaoba (Hodul) Unit records steady-state subduction including Triassic oceanic crust and overlying radiolarian sediments (Figure 24a). The Nilüfer Unit records subduction, accretion and underplating of large Triassic volcanic piles, probably one or more oceanic seamounts (Figure 24b). The Çal Unit is interpreted as a continental fragment (Figure 24c), rifted from the southern (Anatolide-Tauride) margin, which drifted across Tethys and was eventually accreted to the Eurasian margin. The resulting collision may have resulted in regional subduction reversal and final northward emplacement of the Karakaya accretionary wedge over the leading edge of the Eurasian margin.

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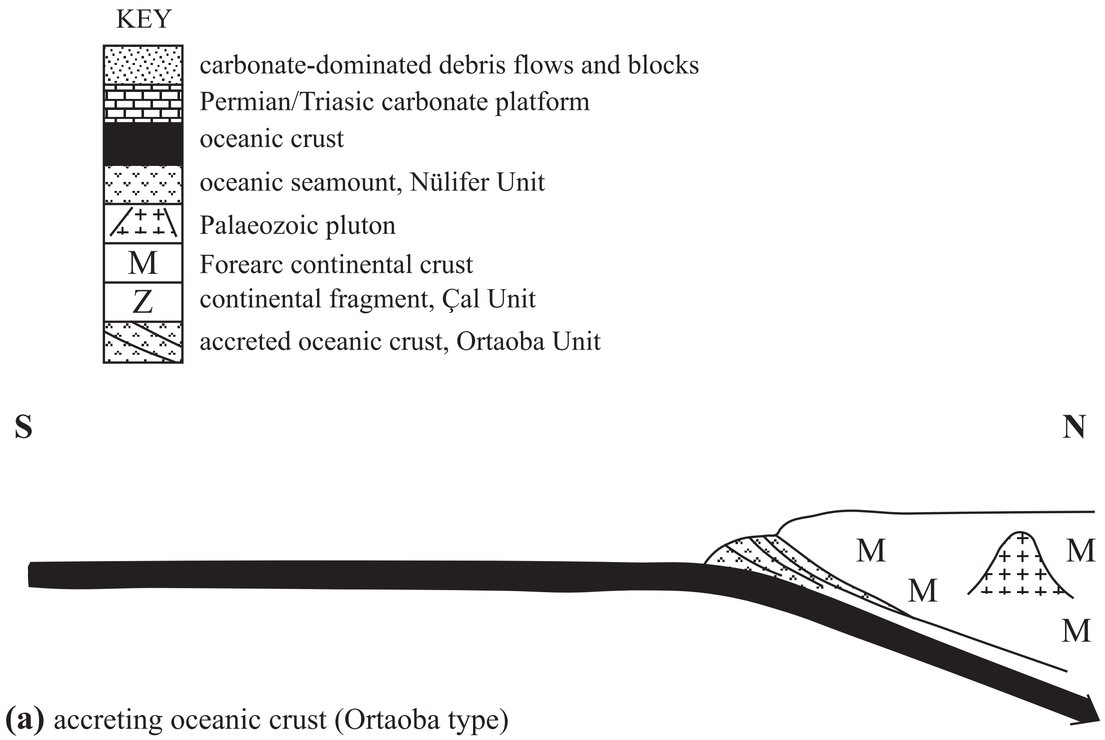
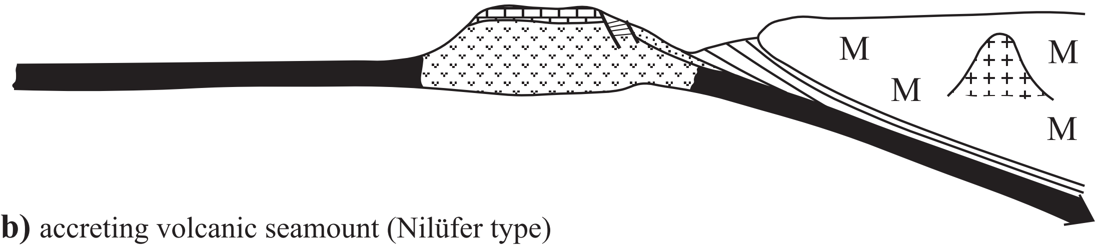
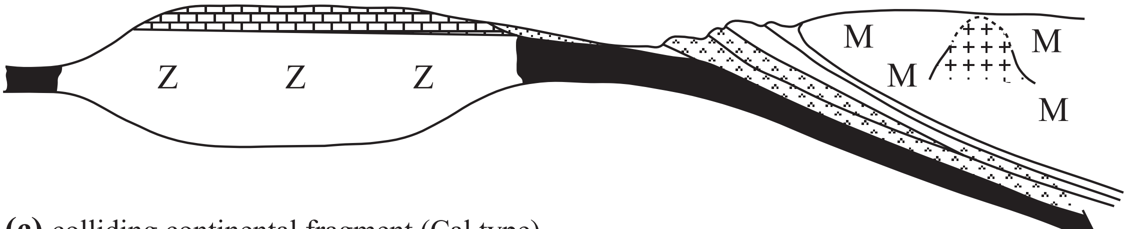


(a) accreting oceanic crust (Ortaoba type)



(b) accreting volcanic seamount (Nilüfer type)



(c) colliding continental fragment (Çal type)

Figure 24. Possible modes of emplacement of the Karakaya Complex. (a) Steady-state subduction. The Ortaoba (Hodul) Unit is interpreted as the result of subduction of oceanic crust and overlying radiolarian chert; (b) accretion of an oceanic volcanic edifice, probably a seamount (Nilüfer Unit); (c) accretion/collision of a continental fragment (Çal type). See text for discussion.

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