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Testing Alternative Tectono-Stratigraphic Interpretations of the Late Palaeozoic–Early Mesozoic Karakaya Complex in NW Turkey: Support for an Accretionary Origin Related to Northward Subduction of Palaeotethys

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Abstract: Lower Carboniferous–Upper Triassic rocks of the Karakaya Complex exposed E–W across Turkey are critical to reconstructions of Palaeotethys in the Eastern Mediterranean region. Despite decades of research, the origin and emplacement of the Karakaya Complex remains controversial because it is mapped either as an overall stratigraphic succession of sedimentary olistostromes or as a stack of thrust sheets and mélange. Tectonic models include a continental rift, a back-arc rift, a marginal oceanic basin, and an accretionary prism formed by subduction of a wide ocean. Subduction is seen as either northwards or southwards. To test the alternatives, the various litho-tectonic units and their contact relations were studied in nine outcrops across northwestern Turkey. Our field evidence indicates that the Karakaya Complex was assembled by regional-scale thrust faulting without evidence of stratigraphical contacts or even of deformed sedimentary contacts between the main units. The structurally lower levels of the Karakaya Complex of Triassic age (~lower Karakaya assemblage) are dominated by an imbricated, mainly volcaniclastic sequence (~Nilüfer Unit) that was metamorphosed under high pressure-low temperature conditions and rapidly exhumed. Structurally higher, lower-grade rocks (~upper Karakaya assemblage) are characterised by several coherent lithotectonic units, including the Upper Permian–Lower Triassic Çal Unit, dominated by alkaline volcanics and shelf to redeposited carbonates, a contrasting mainly Upper Permian unit including terrigenous sediments, and the Triassic Ortaoba Unit, dominated by mid-ocean ridge-type basalts, radiolarian sediments and sandstone turbidites. Two associated composite units (Hodul and Orhanlar units) are interpreted as accretionary mélanges (rather than olistostromes) that were tectonically assembled and emplaced during Late Triassic time. Pre-Karakaya-age meta-siliciclastic sedimentary rocks (~Kalabak unit) are intruded by Devonian and Lower Carboniferous granites in several areas. Arkosic cover sediments (Halılar Formation) above the Kalabak unit accumulated during Late Triassic (Norian) time prior to final emplacement of the Karakya Complex. The 'basement units' are interpreted as thrust slices that were emplaced to a high structural level during final emplacement of the Karakaya Complex in latest Triassic time. Transgression by shelf sediments followed from the Early Jurassic onwards following regional uplift and erosion.

In our proposed tectonic model, Palaeotethyan oceanic crust (~Triassic Ortaoba Unit) subducted northwards beneath the Sakarya Continent. Seamounts capped with carbonate build-ups formed near the southern margin of Palaeotethys (~Çal Unit). The Upper Permian neritic carbonates associated with terrigenous clastics (unnamed unit) probably rifted from the Tauride continent to the south. Large oceanic seamounts erupted within the Triassic ocean (~Nilüfer Unit). The seamounts and continental fragments drifted northwards until they collided with the southern, active margin of the Sakarya Continent. The accretionary prism was emplaced northwards over deltaic to deeper-marine cover sediments of the Sakarya Continent during Norian time. Collision culminated in imbrication of the Karakaya accretionary complex with the Late Palaeozoic Sakarya 'basement' and its sedimentary cover.

Key Words: Karakaya Complex, NW Turkey, Sakarya Continent, tectonics, tectonostratigraphy

KB Türkiye'deki Geç Paleozoyik–Erken Mesozoyik Yaşlı Karakaya Kompleksi İçin Önerilen Alternatif Tektono-stratigrafik Modellerin Sınanması: Paleotetisin Kuzeye Yitimi ile İlişkili Yığışım Modeline Destek

Özet: Türkiye'de D–B yönünde yayılım gösteren Karakaya Kompleksi'nin Erken Karbonifer–Geç Triyas yaşlı kayaları, Doğu Akdeniz bölgesinde Paleotetisin kurgulanmasında kritik önem taşır. Onlarca yıldır süregelen araştırmalara rağmen, Karakaya Kompleksi'nin kökeni ve yerleşmesi halen tartışmalıdır; çünkü Karakaya Kompleksi ya sedimenter olistostromlardan oluşan düzenli bir stratigrafik istif, ya da bindirme dilimleri ve melanj paketi olarak haritalanmıştır. Önerilmiş tektonik modeller kıta içi rifti, yay-ardı rifti, okyanusal kenar havza veya büyük bir okyanusun yitimi ile oluşmuş yığışım prizmasına kadar çeşitlilik sergiler. Bu modellerde yitimin yönü ya kuzeye ya da güneye doğru olarak kabul edilmiştir. Alternatif modelleri test etmek için Karakaya Kompleksi'ni oluşturan çeşitli lito-tektonik birimler ile bunların dokanak ilişkileri kuzeybatı Türkiye'de dokuz farklı alanda çalışılmıştır. Elde ettiğimiz saha verileri, Karakaya Kompleksi'nin bölgesel ölçekli bindirme fayları ile bir araya geldiğini, ana birimler arasında herhangi bir stratigrafik dokanağın hatta deforme sedimenter dokanakların dahi varlığına ilişkin herhangi bir kanıtın olmadığını göstermektedir. Triyas yaşlı Karakaya Kompleksi'nin yapısal olarak alt seviyeleri (~alt Karakaya topluluğu), yüksek basınç-düşük sıcaklık metamorfizması geçirmiş ve hızla yükselmiş olan, ekaylı, büyük bölümüyle volkaniklastik olan bir istif (Nilüfer Birimi) ile temsil edilir. Yapısal olarak daha üstte yeralan daha düşük dereceli kayalar (~üst Karakaya topluluğu), alkalen volkanikler ve şelf ila yeniden çökelmiş karbonatlardan oluşan Geç Permiyen–Erken Triyas yaşlı Çal Birimi, terijen sedimentlerden yapılı bir Üst Permiyen birimi, ve okyanus ortası sırtı tipi bazaltlar, radyolaryalı sedimentler ve türbiditik kumtaşlarını kapsayan Triyas yaşlı Ortaoba birimi gibi birkaç litotektonik birim ile temsil edilir. Bu birimler ile ilişkili iki birim (Hodul ve Orhanlar birimleri) Geç Triyas döneminde tektonik olarak bir araya gelen ve yerleşen yığışım melanjları (olistostromlardan ziyade) olarak yorumlanmışlardır. Karakaya öncesi meta-silisiklastik sedimenter kayalar (Kalabak birimi) birçok alanda Devoniyen ve Erken Karbonifer yaşlı granitler ile kesilir. Kalabak biriminin üzerindeki arkozik örtü birimleri (Halılar Formasyonu) Karakaya Kompleksi'nin son yerleşmesinden önce, Geç Triyas (Noriyen) döneminde çökelmiştir. 'Temel birimleri' Karakaya Kompleksi'nin en geç Triyas dönemindeki son yerleşmesi sırasında daha üst yapısal konuma yerleşen bindirme dilimleri olarak yorumlanmıştır. İzleyen bölgesel yükselme ve erozyonun ardından Erken Jura'dan itibaren şelf sedimanları transgresif olarak çökelmiştir.

Önerdiğimiz tektonik modelde Paleotetis okyanus kabuğu (~Triyas Ortaoba Birimi), kuzeye Sakarya Kıtası altına doğru dalmıştır. Karbonatlar ile kaplı denizaltı tepeleri Paleotetis güney kenarının yakınlarında oluştu (Çal Birimi). Terijen kırıntılılar ile ilişkili Geç Permiyen yaşlı neritik karbonatlar (adlandırılmamış birim) olasılıkla güneydeki Toros kıtasından riftleşmiştir. Büyük okyanusal denizaltı volkanları (~Nilüfer Birimi) Triyas okyanusu içinde püskürdü. Denizaltı volkanları ve kıtasal fragmanlar kuzeye doğru göç ederek Sakarya Kıtası'nın güney, aktif kenarına çarpmıştır. Yığışım prizması kuzeye doğru, Sakarya Kıtası'nın deltayik ve daha derin denizel örtü birimleri üzerine Noriyen döneminde yerleşmiştir. Çarpışma Karakaya yığışım kompleksinin Geç Paleozoyik Sakarya 'temeli' ve sedimenter örtüsü ile ekaylanmasına neden olmuştur.

Anahtar Sözcükler: Karakaya Kompleksi, KB Türkiye, Sakarya Kıtası, tektonik, tektono-straigrafi

Introduction

The kinematics and timing of closure of Palaeotethys in the Eastern Mediterranean region continue to be debated with contrasting models being advocated to explain the origin and emplacement of several regional-scale tectonic units. Here, we consider the classic Karakaya Complex (Şengör *et al.* l984) that is exposed from east to west across Turkey. In northwestern Turkey the Karakaya Complex (Figure 1) includes a wide range of mainly metamorphosed sedimentary and igneous rocks, mainly ranging in age from Early Carboniferous to latest Triassic (see Okay & Göncüoğlu 2004 for review).

The Karakaya Complex is currently interpreted in three main ways. In the first (Figure 2a) Palaeotethys subducted *southwards* beneath the northern margin of Gondwana creating a narrow back-arc basin, effectively an intra-continental rift (Göncüoğlu *et al.* 2000). A Permian–Triassic backarc rift developed on continental basement made up of Variscan granitic rocks and older mainly meta-sedimentary rocks (Göncüoğlu *et al.* 2000; Turhan *et al.* 2004). In a variant, a back-arc basin widened and was floored by oceanic crust (Şengör & Yılmaz l981; Şengör *et al*. 1984; Genç & Yılmaz l995). In the second model (Figure 2b) Palaeotethys subducted northwards to form a back-arc rift or marginal oceanic basin along the southern margin of Eurasia (Kozur l999; Stampfli 2000; Stampfli *et al.* 2001; Stampfli & Borel 2002; Moix *et al*. 2008). In the third, contrasting, model (Figure 2c) the Karakaya Complex is interpreted as an accretionary prism related to subduction of Palaeotethys (Tekeli l981). Subduction was either southwards (Okay *et al.* l996), or northwards (Robertson *et al.* 1996, 2004; Pickett & Robertson 1996, 2004; Okay & Monié 1997; Okay 2000). Various lithotectonic units of the Karakaya Complex are variously interpreted as parts of a continental rift (Bingöl *et al.* l975; Y. Yılmaz l981; Kaya *et al.* 1986, 1991; Göncüoğlu *et al.* 2000), rifted continental

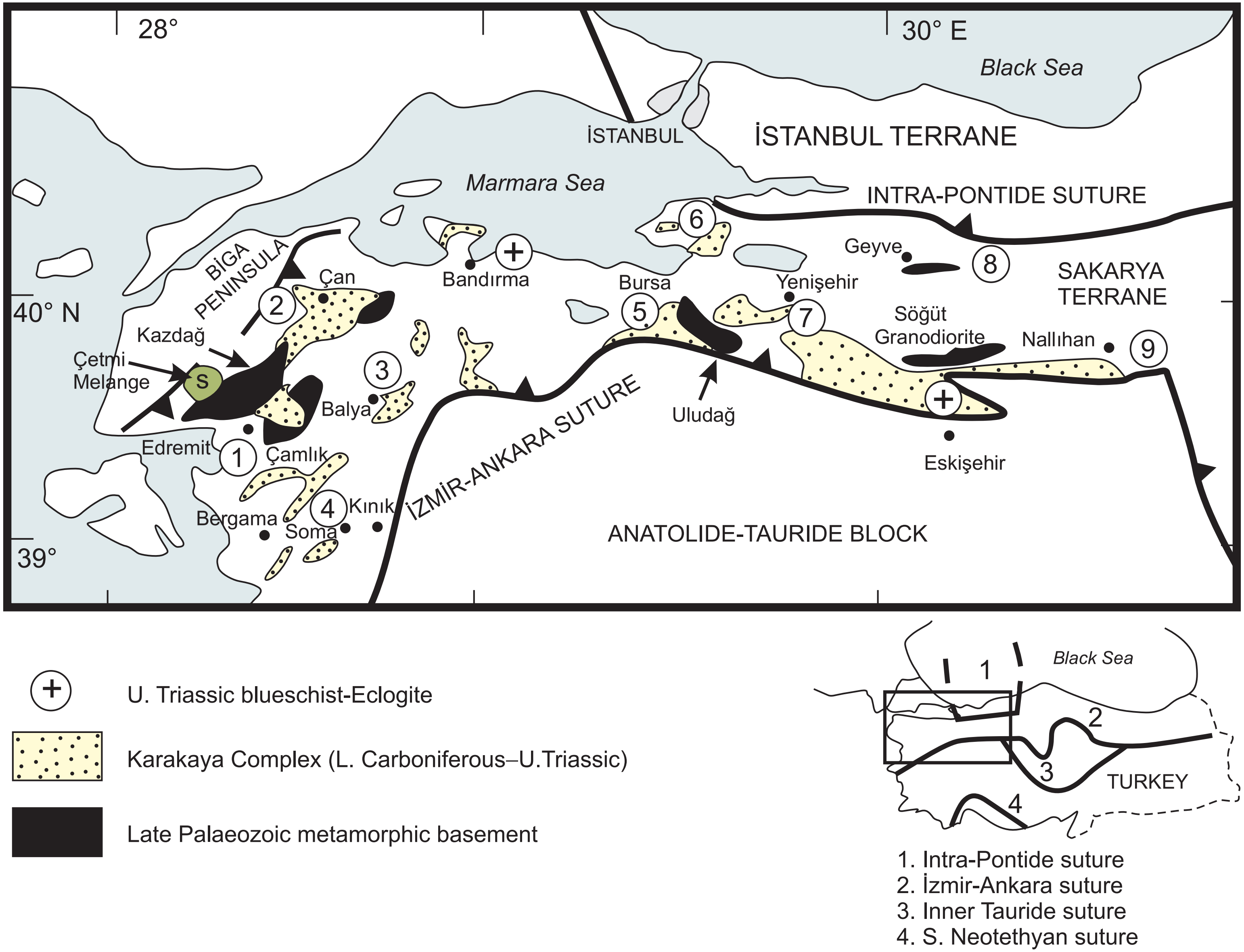

Figure 1. Outline tectonic map of NW Turkey showing the main outcrop areas of the Karakaya Complex. 1– Edremit; 2– S of Biga; 3– Around Balya; 4– N of Bergama; 5– S of Bursa; 6– N of Bursa; 7– S of Yenişehir; 8– Geyve area; 9– Nallıhan area. Inset: Main suture zones of Anatolia. The Karakaya Complex is exposed between the Intra-Pontide suture zone to the north and the İzmir-Ankara suture zone to the south (see inset sketch).

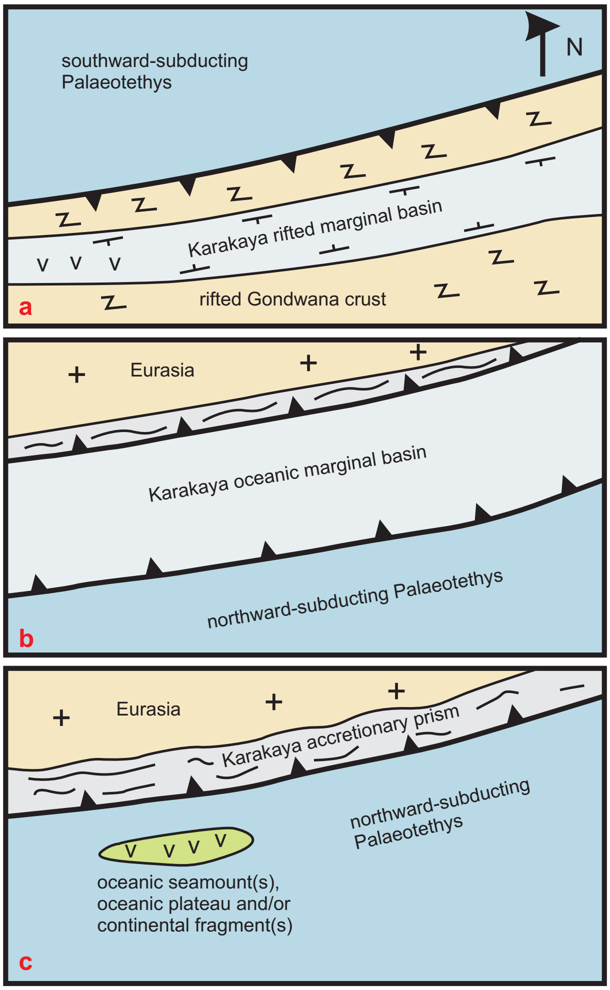

Figure 2. Alternative plate tectonic models for the area of western Turkey shown in Figure 1. **(a)** The Karakaya Complex as a back-arc basin rifted from the northern margin of the Tauride continent (Gondwana) above a southward-dipping subduction zone (Şengör & Yılmaz 1981; Genç & Yılmaz 1995; Göncüoğlu *et al.* 2000); **(b)** The Karakaya Complex as a back-arc basin rifted within the southern margin of Eurasia above a northward-dipping subduction zone (Stampfli *et al.* 2001; Stampfli & Borel 2002); **(c)** The Karakaya Complex as an accretionary prism related to northward subduction of Palaeotethys beneath Eurasia (Robertson *et al.* 1996; Ustaömer & Robertson 1997; Okay 2000; Stampfli & Kozur 2006). See text for explanation.

fragments (Pickett & Robertson 1996, 2004; Altıner *et al.* 2000), remnants of oceanic seamounts (Pickett *et al.* 1995; Pickett & Robertson 1996, 2004; Genç 2004; Sayıt & Göncüoğlu 2009), or fragments of a vast oceanic plateau (Okay 2000; Genç 2004).

In the rift-related interpretations the contacts between the main units of Permian–Triassic rocks that dominate the Karakaya Complex are interpreted as being depositional (Kaya *et al.* 1986; Kaya 1991; Göncüoğlu *et al.* 2000; Figure 3). The internally disorganised nature of the Karakaya Complex largely reflects the formation of regional-scale sedimentary olistostromes. In the subduction hypothesis the contacts between the lithotectonic units are interpreted as thrust faults and the disorganised nature reflects the emplacement of mélanges and tectonic slice complexes (Pickett & Robertson 1996, 2000; Okay 2000; Figure 4).

There is thus a debate about whether to interpret chaotic units as of sedimentary or tectonic origins or a combination of both (see e.g., Raymond 1984). Many units are made up of well-lithified clasts (e.g., limestone, basalt) set in a softer (e.g., shale) matrix. A key issue is whether these formed as sedimentary debris flows (~olistostromes) (Kaya *et al.* 1986; Kaya 1991; Göncüoğlu *et al.* 2000), or as the result of tectonic shearing to form phacoidal fabrics as in many subduction complexes (e.g., Franciscan Complex of California; Cloos & Shreve 1988 a, b).

In order to test the different hypotheses for the Karakaya Complex we have re-investigated the tectono-stratigraphy and contact relations of nine of the main outcrops in NW Turkey (Figure 1).

Tectonostratigraphy

Here, we define the Karakaya Complex as a structurally complex assemblage of Lower Carboniferous to uppermost Triassic sedimentary, igneous and metamorphic rocks that are exposed beneath a cover of less deformed, unmetamorphosed Jurassic and younger sedimentary rocks. Outcrops extend east west across Anatolia, although only those in NW Turkey are considered in detail here (Figure 1). We exclude older mainly meta-siliciclastic and meta-granitic 'basement' units from the Karakaya Complex. These older meta-sedimentary units (Devonian or older, see below) are intimately associated with the Karakaya Complex, for example in the type area in the Biga Peninsula (e.g., in Area 1, Edremit-Havran; Figures 1 & 4). In other areas (e.g., Area 9, near Nallıhan), comparable 'basement'

Figure 3. Alternative stratigraphical sub-divisions of the type area of the Karakaya Complex in the Biga Peninsula in the west of the area studied. These schemes all assume an overall stratigraphic succession from the base to the top, which has not been confirmed during this work. See text for explanation. Additional, contrasting schemes are shown in Figure 4.

units (e.g., Söğüt granite and host meta-clastic rocks; Figure 1) crop out structurally above the Karakaya Complex, separated by a north-dipping thrust of probable Eocene age. The 'basement' units are interpreted as a pre-Karakaya continental basement that in some areas was detached and emplaced as thrust sheets within the Karakaya Complex.

In its type area in the Biga Peninsula (Figure 1) the Karakya Complex has been classified either as an overall stratigraphic succession (Figure 3) or as a tectonic slice complex (Figure 4). Early workers (Blanc 1965; Bingöl *et al.* 1975; Krushensky *et al.* 1980; Kaya *et al.* 1986) assumed the existence of a coherent stratigraphy, a view retained by the Maden Tektik ve Arama Enstitüsü (MTA) during mapping of the region over several decades (e.g., Akyürek & Soysal 1983; Duru *et al.* 2007a, b, c; Pehlivan *et al.* 2007).

Recently, it was proposed that the Karakaya Complex could be broadly subdivided into lower and upper parts (Okay & Göncüoğlu 2004). These are here termed the *lower Karakaya assemblage* and the *upper Karakaya assemblage* to highlight the composite nature of both parts. The lower Karakaya assemblage is dominated by Triassic meta-volcanogenic rocks together with subordinate meta-carbonate rocks that have undergone relatively high pressure-low temperature (HP-LT) metamorphism (Monod *et al.* 1996; Monod & Okay 1999; Okay & Monié 1997; Okay *et al.* 2002). In contrast, the mainly Permian and Triassic upper Karakaya assemblage includes a variety of less metamorphosed to unmetamorphosed

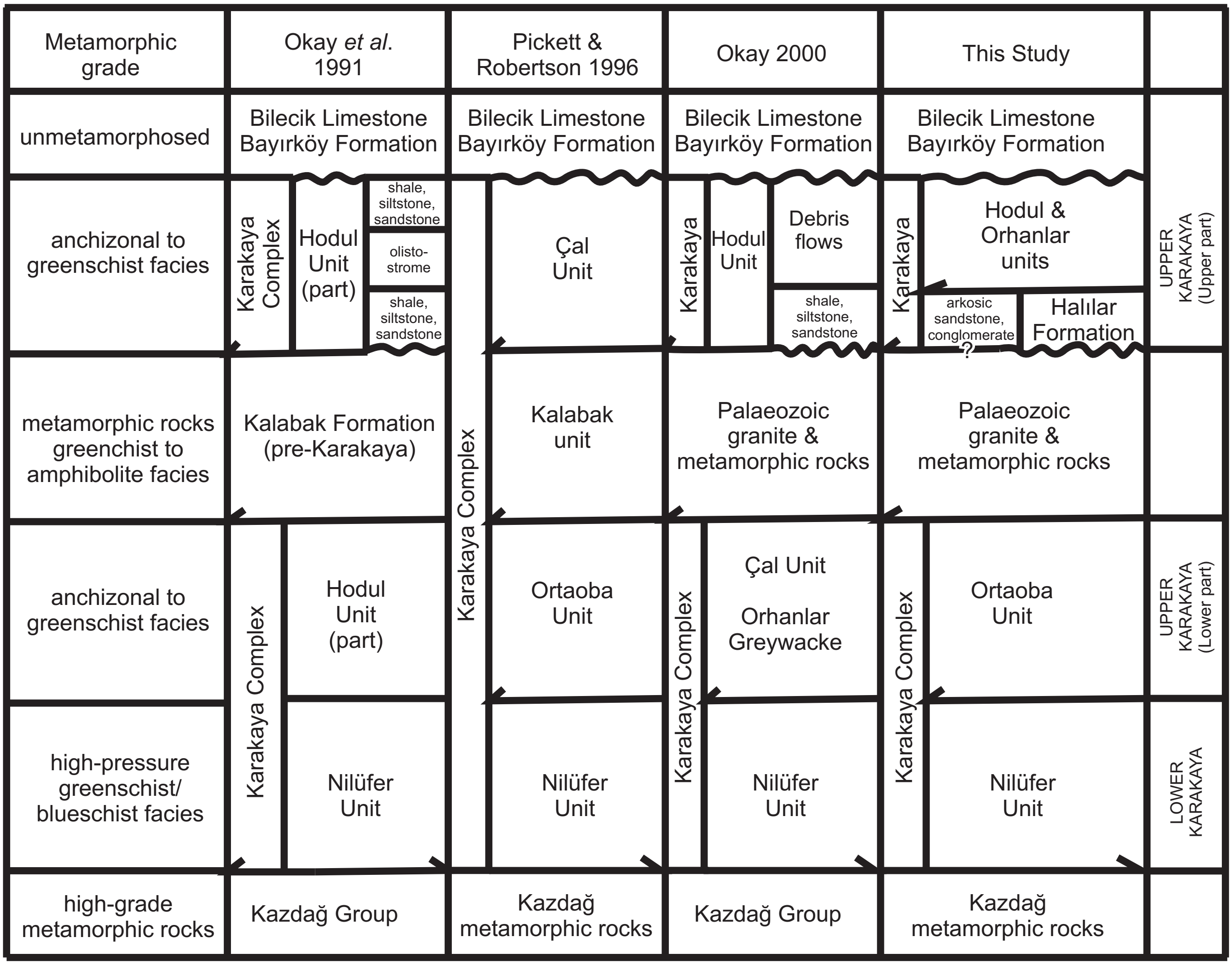

Figure 4. Additional stratigraphical subdivisions of the Karakaya Complex and related units applicable to the Biga Peninsula. These schemes assume the existence of a tectono-stratigraphy involving one or more slices of relatively high-grade 'basement' rocks interleaved with Permian–Triassic rocks of the Karakaya Complex. Our preferred tectono-stratigraphy for the type area of the Karakaya Complex in the Biga Peninsula is indicated in the far-right column. However, in some other areas metamorphic basement slices are absent and a more simple tectonostratigraphy is applicable (see Figure 5). Note: the units shown in different columns opposite each other are not all intended to show correlative units but rather the relative positions in the assumed vertical tectonostratigraphy.

igneous and sedimentary units. In different outcrops the alteration of the upper Karakaya assemblage ranges from advanced diagenesis, to very low-grade (anchimetamorphic) metamorphism, to locally greenschist facies metamorphism. Maximum pressures in the upper Karakaya assemblage remain poorly constrained (Okay *et al.* 1991; Federici *et al.* 2010).

A simple two-fold division of the Karakaya Complex is easily applicable to some areas (e.g., Areas 4 Bergama, 5 Bursa and 9 Nallıhan; see Figures 1 and 5). However, in other areas where the complex is associated with 'basement' units (e.g., Areas 1 Edremit and 7 Yenişehir; Figure 1) this subdivision is less easy to apply in the field. Even in some areas without 'basement' exposure the two-fold division is complicated by Late Mesozoic compressional deformation and neotectonic strike-slip (e.g., central Biga Peninsula).

The lower Karakaya assemblage is dominated by meta-volcanogenic rocks that were mapped as the Nilüfer Unit in the type area of the Biga Peninsula

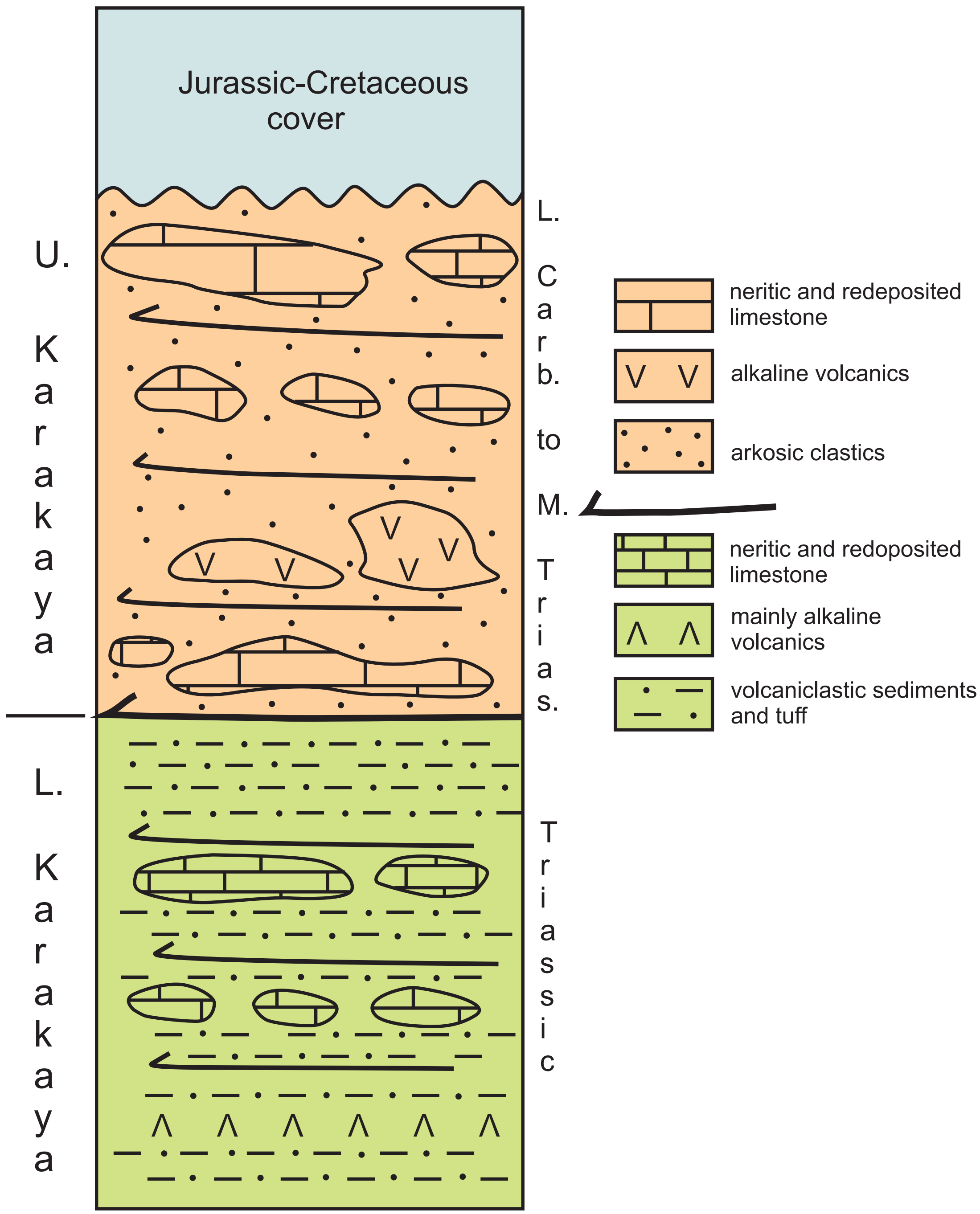

Figure 5. Simple two-fold division of the Karakaya Complex into a *lower Karakaya assemblage* and *an upper Karakaya assemblage*. The lower assemblage is dominated by Triassic volcanogenic rocks (~Nilüfer Unit), whereas the mainly Permian–Triassic upper Karakaya assemblage is more regionally variable and includes Upper Permian volcanogenic rocks (~Çal Unit), Upper Permian–Triassic(?) neritic limestones associated with terrigenous sediments. Triassic MORB and radiolarites (Ortaoba Unit), and two composite mélange units (Hodul and Orhanlar units). The two-fold division is clearly applicable in several areas (e.g., Areas 4 Bergama, 5 Bursa and 9 Nallıhan), but is complicated in other areas by the presence of 'basement' outcrops or the effects of Alpine thrusting and neotectonic strike-slip (see Figure 4, this work for our preferred tectonostratigraphy of the Biga Peninsula).

(Okay *et al.* 1991; Pickett & Robertson 1996, 2004; see Figure 4). Similar lithological assemblages were given different names in other areas (see Okay & Göncüoğlu 2004). In general, the Nilüfer Unit and its equivalents become more deformed, recrystallised and metamorphosed structurally downwards (Pickett & Robertson 1996, 2004), while the metamorphic grade also appears to increase northwards (e.g., in Bursa and Bandırma areas; Okay 2000; Okay & Monié 1997). A lens of eclogite has been reported from thrust slices of greenschist-facies rocks in the northwest of the area (E of Bandırma; Okay & Monié 1997). Several thrust slices of high-grade rocks are also known further east (N of Eskişehir) (Okay *et al.* 2002). The Nilüfer Unit has yielded Early Triassic conodonts in marble and meta-volcanic rocks south of Bursa (Kozur *et al.* 2000) and Mid-Triassic conodonts from the Kozak Mountains north of Bergama (Kaya & Mostler 1992). Ar-Ar isotopic dating of phengite and amphibolite from the eclogite lens (Okay & Monié 1997) and from blueschist and HP greenschist facies metabasalts north of Eskişehir (Okay *et al.* 2002) yielded similar Late Triassic (205–215 Ma) ages.

The upper Karakaya assemblage is here subdivided into several well-defined lithotectonic units (Figures 4 & 5). The structurally lowest unit, the Ortaoba Unit is currently recognised only in the Biga Peninsula. It is mainly mid-ocean-ridge (MOR)-type basaltic rocks overlain by radiolarites, passing upwards into quartzo-feldspathic sandstones (Pickett 1994; Pickett & Robertson 1996). Generally above this is the Çal Unit (Blanc l965; Okay *et al.* 1991), a mainly Upper Permian succession of volcanic breccias, volcaniclastic sediments, alkaline lava flows, calciturbidites and neritic limestones, plus rarely dated Permian chert (Okay *et al.* 1991). We infer a structurally high position for the Çal Unit rather than locating it beneath Palaeozoic 'basement rocks' (see Figure 4). Equivalents of the Çal Unit are exposed in many areas (Okay & Göncüoğlu 2004; see below).

In several areas large blocks and dismembered thrust slices of mainly Upper Permian limestones (Area 4 Bergama; Figure 1) are depositionally intercalated with terrigenous sandstones and mudrocks without interbedded volcanic rocks. These features differ from the typically volcanogenic Çal Unit (Pickett & Robertson 1996, 2000) and are therefore considered separately. One other unit, the Triassic Camialan Limestone (Okay *et al.* 1991) is of debateable origin, as discussed below.

In addition, Okay *et al.* (1991) mapped a widespread unit of 'olistostromes' in the Biga Peninsula as the Hodul Unit after a type area southeast of Biga town. This includes blocks ranging from Early Carboniferous to Late Permian in age set a matrix of Upper Triassic arkosic sandstone and shale. This unit is equivalent to the Dışkaya Formation, as particularly described from the Bursa region (Area 6; Figure 1) (Kaya *et al.* 1986, 1989). Pickett (l994) recognised that Okay *et al.*'s (1991) Hodul Unit is a composite unit. Parts of this unit were accordingly assigned to more specific lithotectonic units, notably the Çal Unit, the Ortaoba Unit, an un-named unit of Upper Permian limestones with terrigenous interbeds and also uppermost Triassic arkosic sequences associated with Palaeozoic 'basement' (e.g., Halılar Formation, Figures 4). After taking account of these specific lithotectonic units large outcrops across the Biga Peninsula and elsewhere remain mainly unclassified. These are dominated by sandstone turbidites associated with blocks of Lower Carboniferous–Lower Triassic limestone, Upper Permian volcanogenic rocks, pelagic limestone and radiolarian chert which are only rarely well dated. These composite exposures are here termed the Hodul unit (used in a more restricted sense than Okay *et al.* 1991) and the more local Orhanlar Unit (Okay *et al.* 1991) (Figure 4).

During this work we also considered the relation of the Karakaya Complex to older 'basement' rocks, as exposed in the Biga Peninsula and elsewhere. Meta-sedimentary rocks of greenschist to amphibolite facies grade are locally intruded by Devonian meta-granitic rocks (e.g., Çamlık; Figure 1) of at least greenschist-facies grade (Okay *et al.* 1991, 2006; Pickett & Robertson 1996; Duru *et al.* 2007a, b, c; Aysal *et al.* 2011). In some places, the metamorphic 'basement' is unconformably overlain by Upper Triassic clastic sedimentary rocks (e.g., Area 1; Figure 1). Further northeast the metamorphic basement of the Uludağ is terminated upwards by a major tectonic contact related to neotectonic extension or strike-slip (Okay *et al.* 2008; Figure 1). In the northeast of the region (Area 8, near Geyve; Figure 1) Palaeozoic meta-granitic and meta-sedimentary country rocks are reported to be depositionally overlain by Upper Permian shallow-water limestones (Turhan *et al.* 2004), which, if correct, has important implications for tectonic models of the Karakaya Complex.

Any tectonic interpretation needs to take account of structural data. Pickett (l994) collected kinematic data especially small-scale folds in the Nilüfer Unit and the associated Kalabak unit in the Biga Peninsula (i.e. Area 1 Edremit). The data showed a wide scatter although with a slight predominance of northerly and northwesterly directions (Pickett & Robertson 1996). Northerly-directed movement was most clearly observed in the Kalabak unit (e.g., Area 1 Edremit and Area 4 near Kınık; Figure 1). Any inferred emplacement directions need to take account of Alpine thrusting, neotectonic strike-slip and any palaeo-rotation affecting the area, especially the Biga Peninsula.

During this work we collected several types of structural kinematic data; i.e. trend and plunge of asymmetrical folds, outcrop-scale duplexes, small-scale C/S fabrics, fault offsets and the trend, plunge and sense of movement of slickensides on fault planes. We highlight kinematic vergence from several areas where we were able to collect coherent data sets that we relate to the Triassic emplacement of the Karakaya Complex (i.e. lacking evidence of polyphase deformation).

Field Evidence for the Lower Karakaya Assemblage

Lower Karakaya Internal Contact Relations

In the Biga Peninsula MTA mapped Palaeozoic meta-granitic rocks and meta-clastic country rocks as a regional basement to the Karakaya Complex (Duru *et al.* 2007 a, b, c; Figure 3). For Areas 1 (Edremit-Havran) and 2 (S of Biga), MTA further subdivided 'higher-grade' Karakaya rocks into two different stratigraphical formations. These are rarely in direct contact with each other although a thrust contact was mapped in the Biga area (Duru *et al.* 2007b). The lower of the two units was mapped as the Sazak Formation, made up schistose rocks of inferred (but undated) Palaeozoic age. This formation was mapped as being overlain by the Mehmetalan Formation, which is locally dated as Triassic and comprises less metamorphosed volcanics and marble (Figure 3). In other studies both of these formations were mapped together as the Nilüfer Unit (Okay *et al.* 1991; Pickett & Robertson 1996, 2004; see Figures 3 & 4).

During this work we examined the contact between the Sazak and Mehmetalan formations north of Edremit (Area 1; Figure 1), especially in a well-exposed road section just south of Pınarbaşı village (Figure 6). In this area we could not confirm the existence of any systematic differences in lithology or metamorphism that would support a subdivision into two formations. We instead observed similar meta-basaltic rocks, volcaniclastic sedimentary rocks and marble forming detached blocks and clastic intercalations above and below the inferred contact. MTA mapped additional outcrops of the Sazak Formation elsewhere (e.g., south of Biga; Area 2) but these lithologies are very similar to the Nilüfer Unit in the Edremit area. The Sazak Formation in the type area (near Sazak; Figure 7) is dominated by silvery grey volcanogenic phyllite, which contrasts with typically more greenish volcanogenic phyllites mapped as the same formation elsewhere (e.g., Edremit area). However, such differences can be accounted for by local facies variation, for example, the relative amount of pale meta-siliceous tuff versus darker basalt-derived volcaniclastic sedimentary rocks. In summary, we consider the Sazak and Mehmetalan Formations as being equivalent to the Nilüfer Unit.

Lower Karakaya Internal Composition and Structure

The internal fabric of the lower Karakaya assemblage (~Nilüfer Unit) was examined in Areas 1 (N of Edremit), 2 (S of Biga), 3 (around Balya), 5 (S of Bursa) and 9 (Nallıhan). Previously, this mainly volcanogenic unit was treated as a sedimentary olistostrome (Kaya *et al.* 1989; Göncüoğlu *et al.* 2000), a coherent stratigraphical succession (Duru *et al.* 2007a, b, c), or a volcanogenic succession duplicated by thrusting (Pickett & Robertson 1996, 2004).

In some previous studies the Nilüfer Unit was described as mainly mafic lavas (e.g., Duru 2007a, b, c; Genç 2004). However, even where most

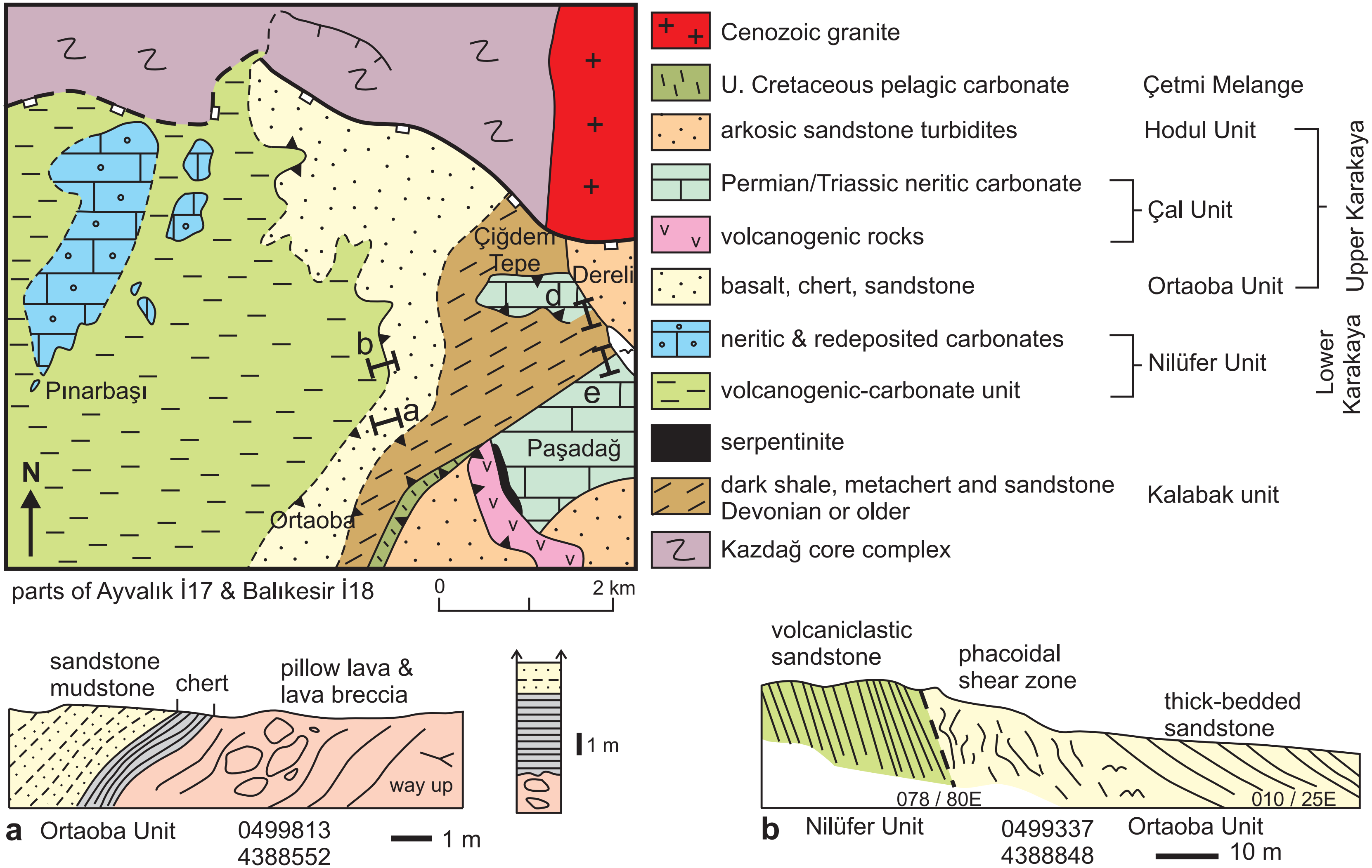

Figure 6. Outline geological map of the Edremit area (Area 1; Figure 1). Based on Pickett (1994), Pickett & Robertson (1996), Duru *et al.* (2007a, b) and this work; **(a)** Ortaoba Unit. Pillow lava is locally covered by radiolarian chert passing upwards into arkosic sandstone turbidites; **(b)** Kalabak 'basement' unit structurally overlain by the volcanogenic Çal Unit.

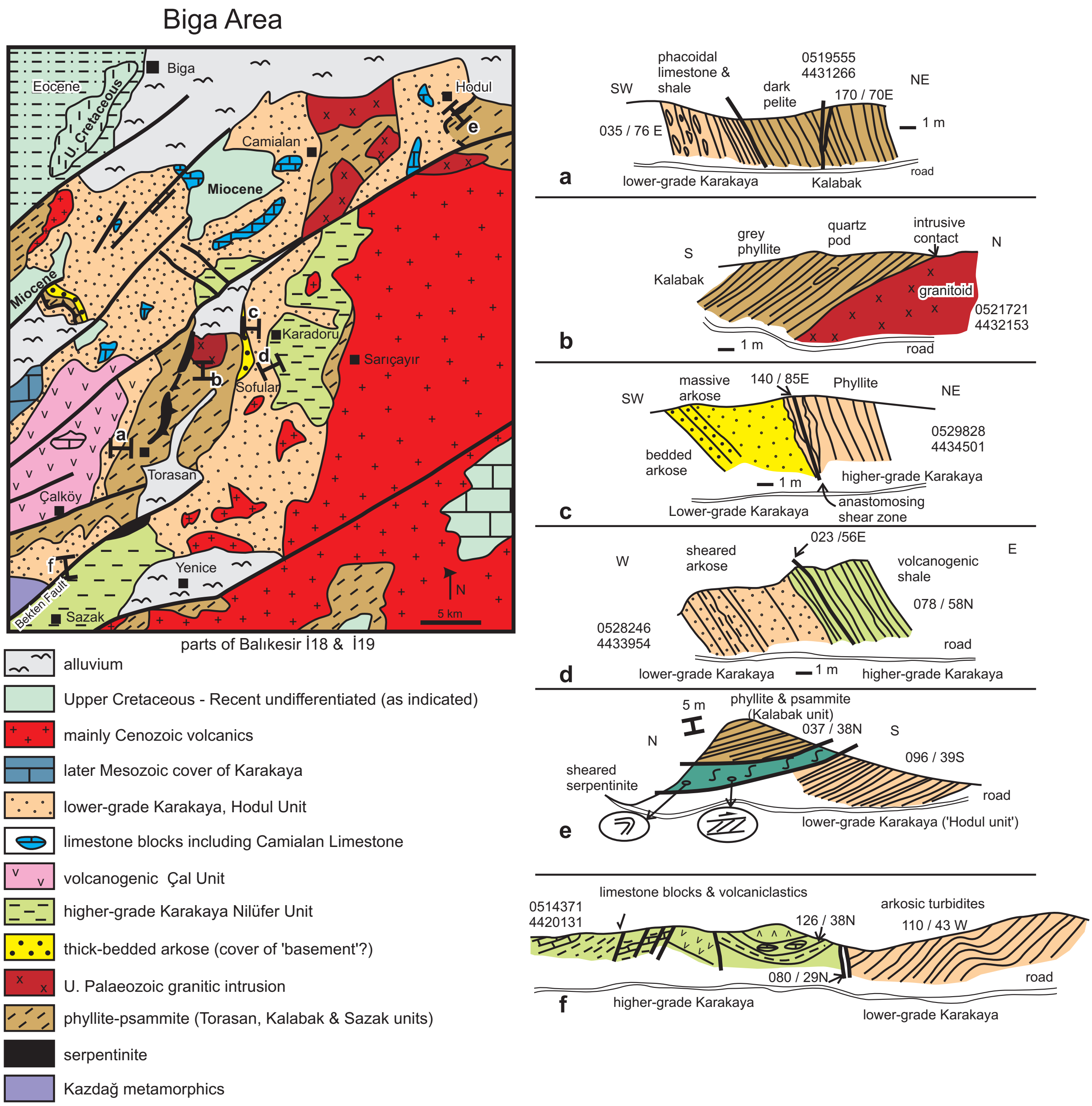

Figure 7. Outline geological map of the area south of Biga (Area 2; Figure 1). Based on Duru *et al.* (2007c) with modifications based on Okay *et al.* (1991); Pickett & Robertson (1996) and this work. In this area the simple two-fold lower vs. upper division of the Karakaya is not easily applicable mainly owing to the effects of neotectonics. Sections on right. **(a)** Tectonic contact between lower-grade Karakaya (Hodul Unit) and 'basement' (Torasan ~Kalabak); **(b)** Granitic intrusion into pre-Karakaya Torasan (~Kalabak) unit; **(c)** Low-angle tectonic contact between bedded arkose and the Hodul unit. The arkose is inferred to have accumulated above a local granitic basement that is not exposed; **(d)** Low-angle tectonic contact between lower-grade Karakaya (Hodul Unit) and higher-grade Karakaya (~Nilufer Unit); **(e)** Slice of serpentinised harzburgite between Torasan (~Kalabak) above and Hodul Unit below, possibly the result of Alpine re-thrusting; **(f)** Zone of high-angle fault contacts between higher-grade Karakaya (~Nilüfer Unit) and lower-grade Karakaya (~Hodul Unit and Çal Unit). See text for explanation.

deformed and metamorphosed near the structural base of the unit, the protoliths can be identified as dominantly fragmental volcanic rocks (see Figure 8a) and detrital carbonate rocks (see Figure 8b, c), together with subordinate amounts of pillowed and massive lava flows. The fragmental material (>80%

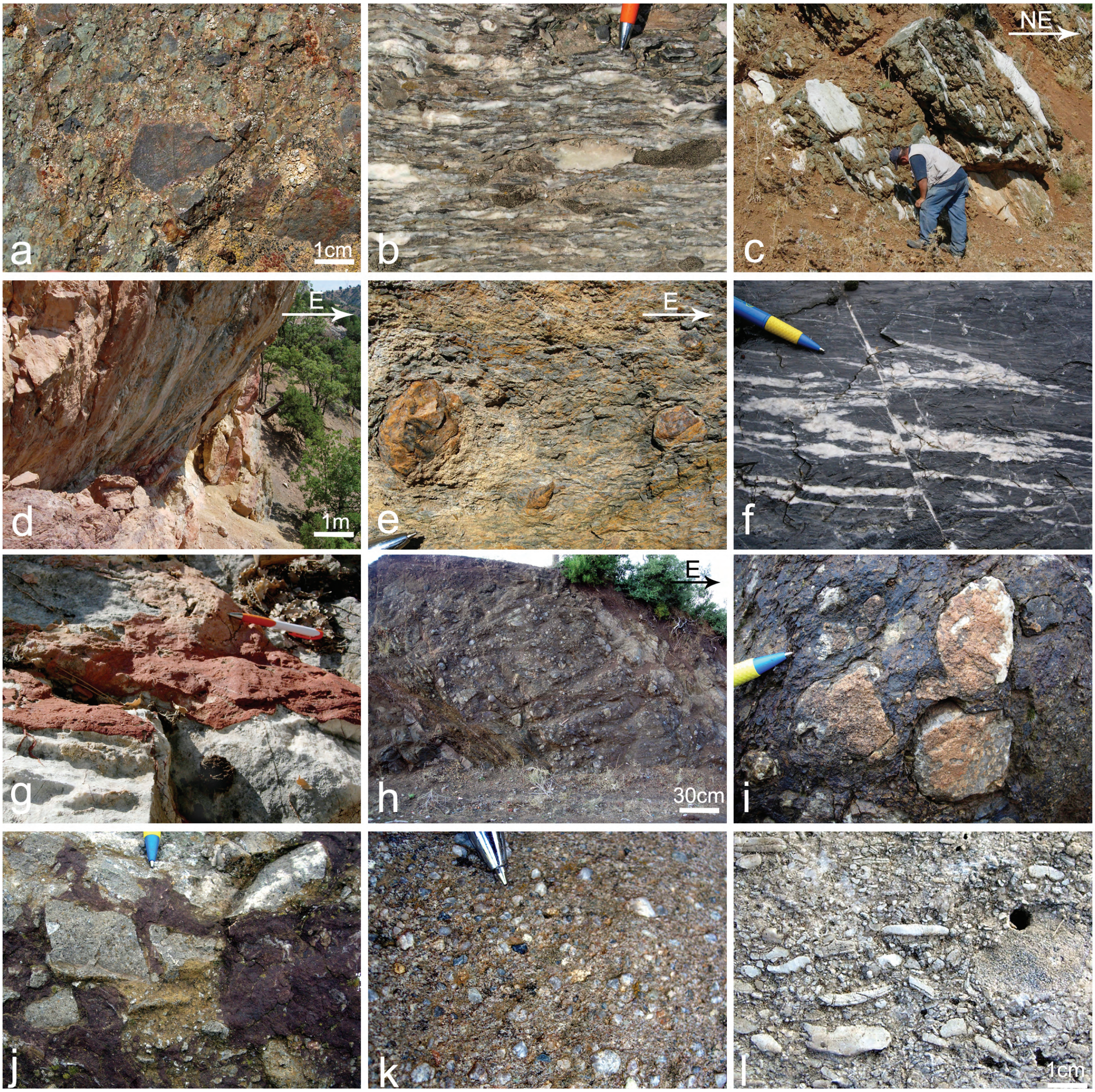

Figure 8. Field photographs of the Karakaya Complex. **(a)** Volcaniclastic breccia from the higher-grade Karakaya Complex (~Nilüfer Unit); Area 4 (NW of Halılağlar; 1:100,000 map sheet Balıkesir-F4; GPS near 0525022 4355538; see Figure 11); **(b)** Flattened marble and volcanic clasts in a sequence of interbedded debris flows and shale; Area 9, road section just N of Tepeköy village; 1:100,000 map sheet Adapazarı-H 26; GPS 0345922, 4430075; **(c)** Debris flow of flattened marble clasts in a recrystallised volcaniclastic matrix; Higher-grade Karakaya; Area 4 (N of Bergama); road section NW of Halılağlar 1:100,000 map sheet Balıkesir-F4, GPS 0525022 4355538; see Figure 11); **(d)** Regional-scale thrust fault separating lower and upper Karakaya assemblages. Volcaniclastic sediments of the higher-grade lower Karakaya are overthrust by volcanogenic sediments and neritic limestones of the lower-grade upper Karakaya (Çal-type unit); near Ortaçal Tepe, SW of Nallıhan (Area 9) (GPS 0353909 4444750; see Figure 12c); **(e)** Sub-rounded carbonate clasts in a matrix of sheared shale; formed by tectonic break-up of thin-bedded limestone/shale (not a sedimentary debris flow); same locality as a;

by volume) ranges from lava breccia, to hyaloclastite, to volcaniclastic sediment, to tuff. The meta-volcaniclastic sedimentary rocks were previously interpreted to range from low-energy volcanogenic mudrocks, to turbidites, to high-energy mass-flow deposits (Pickett & Robertson 1996, 2004). Intact sequences lack evidence of terrigenous quartz. However, terrigenous meta-sedimentary rocks are present as thin units (< 10 m thick) intersheared with more coherent volcanogenic sequences (Pickett & Robertson 2004).

Several lines of evidence indicate that the lower Karakaya assemblage (~Nilüfer Unit and equivalents) is tectonically assembled: (1) Intact sequences, commonly tens to hundreds of metres thick, are separated by bedding-parallel shear zones interpreted as thrust faults; (2) local intercalations of harzburgite and dunite (e.g., Area 4, north of Bergama, near Uruçlar; Akyürek & Soysal 1983) are interpreted as emplaced oceanic lithosphere (Pickett & Robertson 2004; this work); (3) similarly, the Lower Karakaya assemblage (Yenişehir metamorphic association) in Area 7 includes a thrust sheet of dismembered ophiolitic serpentinite and gabbro (Genç & Yılmaz 1995; Genç 2004); (4) as noted above volcanogenic sequences are occasionally interrupted by thin (< 10 m) units of thrust-bounded quartzo-feldspathic meta-sandstones and meta-mudrocks (Pickett & Robertson 1996, 2004).

Preferred kinematic vergence of folds and other kinematic indicators is rare in the Nilüfer Unit and equivalents perhaps because of the predominance of semi-ductile flattening strain (Figures 8f; 9c). However, southward vergence (Figures 9b; 10B) was observed in Area 5 (S of Bursa) along the west bank of the Nilüfer Çay (see Kaya *et al.* l989).

Lower and Upper Karakaya Contact Relations

The contact between the lower and upper Karakaya assemblages has been interpreted as a regional stratigraphic contact (Kaya 1991; Kaya *et al.* 1986, 1989), as partly tectonic and partly a sheared stratigraphical contact (Akyürek & Soysal 1983; Duru *et al.* 2007a, b, c; Okay 2000; Okay & Göncuoğlu 2004), or as a regional thrust contact (Picket & Robertson 1996, 2000).

Contact relations were studied in Areas 1 (Edremit), 2 (S of Biga), 4 (N of Bergama), 5 (S of Bursa) and 9 (Nallıhan) (Figure 1). Particular attention was paid to the structure, metamorphism and lithology in the vicinity of contacts. Reported occurrences of conglomerates near the base of the upper Karakaya assemblage are critical, for example in Area 4 north of Balya (Akyürek & Soysal 1983) and in Area 9 north of Nallıhan (Göncuöğlu *et al.* 2000; Timur & Aksay 2002).

In the Erdemit area (Figure 6) the Nilüfer Unit (lower Karakaya assemblage) maps out as structurally underlying the Ortaoba Unit (Upper Karakaya assemblage) (Okay *et al.* 1991; Pickett & Robertson 1996; Duru *et al.* 2007a; this work). A marked angular discordance exists between steep-dipping, bedding-parallel foliation in higher metamorphic grade rocks of the Nilüfer Unit below and sedimentary bedding in the shallower-dipping, lower-grade Ortaoba Unit above (Figure 6). The two units are separated by ~25 m of strongly sheared, phacoidal sandstone and shale. In other areas, a thrust contact, generally of a low-angle nature, was observed between the lower and upper Karakaya assemblages.

In some places, primary thrust contacts have been re-imbricated to produce steep-dipping contacts. For

Figure 8. Continued.

(f) Ductile isoclinal folds in dark micritic limestone; from a block of meta-carbonate in higher-grade Karakaya (~Nilüfer Unit); near Sazak road; 100,000 map sheet Balıkesir-İ18; see Figure 7); **(g)** Red radiolarian chert covering neritic limestone of the lower-grade Çal-type unit. Radiolarite also infills neptunian fissures. Area 9, S of Ortaçal Tepe, near Nallıhan (1:100,000 map sheet Adapazarı-H26; GPS near GPS 0354098 4444617; Figure 12); **(h)** Well-bedded volcanogenic debris flow; Çal Unit; road to Aşağikaraşik; 100,000 map sheet Balıkesir-İ18; GPS 0516234 4428066; **(i)** Recrystallised limestone clasts in a matrix of dark volcanogenic shale; debris flow in Çal Unit; Area 2, Yenice-Derenti road S of Çal; 1:100,000 map sheet Balıkesir-İ18; GPS near 0512729 4424605; see Figure 7; **(j)** Altered greenish basaltic clasts in a matrix of reddish-brown volcanogenic mudstone; Area 2, near Çalköy, 100,000 map sheet Balıkesir-İ18; GPS near 0513324 4424992; see Figure 7; **(k)** Quartz-rich pebblestone interbedded with higher part of exposed Upper Permian limestone sequence; Area 8 (near Geyve), near stream section north of Kadirler; Map sheet H24; see Figure 18; **(l)** Upper Permian bioclastic limestone for near top of an exposed sequence rich in shell fragments and large foraminifera; Area 8 (near Geyve), Map sheet H24, near GPS 0270371 4479397; see Figure 18a.

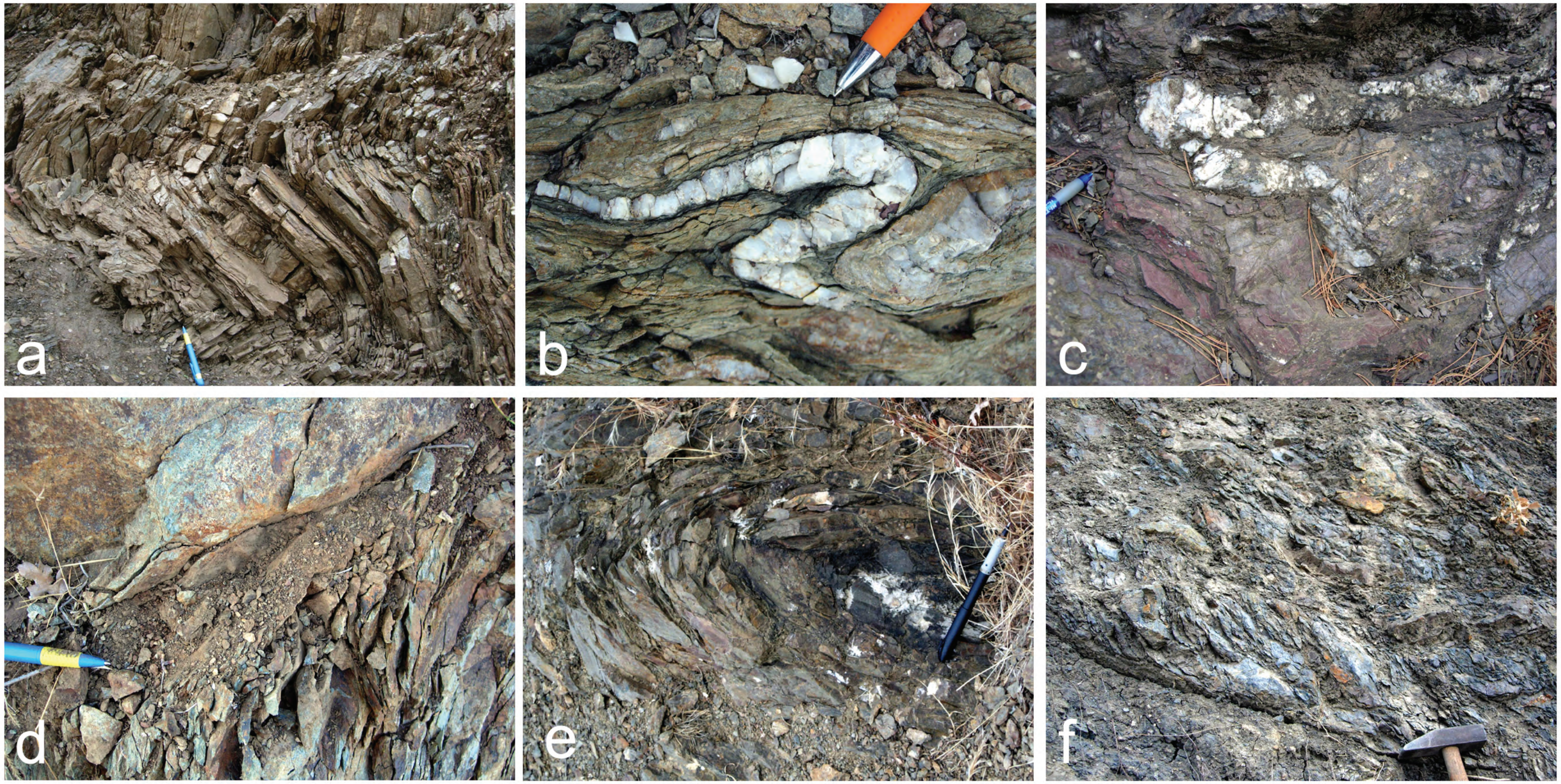

Figure 9. Field photographs of representative kinematic features; **(a)** Asymmetrical kink bands in Palaeozoic psammite and phyllite (Torasan unit); from Area 2, near Hodul, SE of Biga; 1:100,000 map sheet Bandırma-H18, GPS, near 0539472 4449546; **(b)** Ductile folding of volcaniclastic shale cut by quartz vein; Higher-grade-type Karakaya (~Nilüfer Unit); 100,000 map sheet Adapazarı-H26; **(c)** Semi-ductile folded quartz veining in chert-rich volcanogenic shale; Nilüfer River; S of Bursa; Map sheet H21; GPS near 0672055 4436965; **(d)** Duplex shear plane with competent sandstone, above and incompetent shale, below; Area 9, near Alanköy; GPS near 0347275 4441544; **(e)** Asymmetrical fold formed by folding of competent thin-bedded sandstone with interbedded relatively incompetent shale; Aydancık to Kızaklı road section; 1:100,000 map sheet H22; near GPS 0684761, 4461968; **(f)** C-S fabric developed in silty shale; d-f from Area 6, N of Bursa (same locality as e).

example, Duru *et al.* (2007a) mapped a sliver of the Late Mesozoic Çetmi Mélange within the Karakaya Complex in Area 1 (Edremit; Figure 6). The Çetmi Mélange was emplaced related to the Alpine thrusting that affected the Biga Peninsula (Okay *et al.* 1991; Pickett l994; Beccaletto & Jenny 2004). This resulted in the re-activation of some Karakaya-aged thrust faults. In addition, in Area 1 (Edremit) some thrust faults are offset by neotectonic high-angle normal faults related to rifting in Edremit Bay (Duru *et al.* 2004; Cavazza *et al.* 2009).

In the area south of Biga (Area 2; e.g., near Sazak; Figure 7) the contact between the lower Karakaya assemblage (mapped by Duru *et al.* 2007c

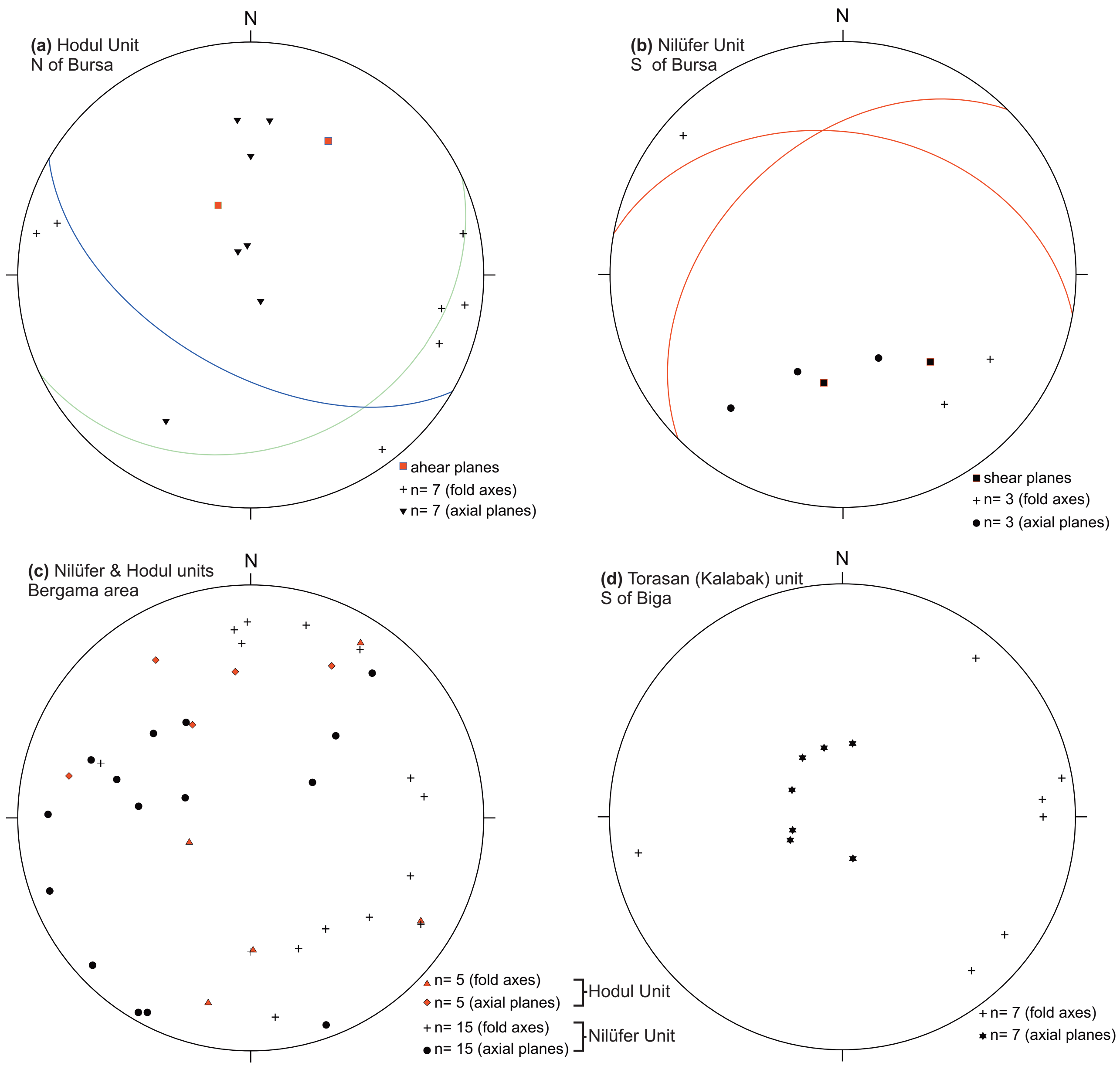

Figure 10. Stereo plots (polar projections) of structural data from selected areas; **(a)** Hodul (~Dışkaya unit), north of Bursa; **(b)** Nilüfer Unit south of Bursa; **(c)** Nilüfer and Hodul units in the Bergama area; **(d)** Torasan (~Kalabak) unit south of Biga. See text for explanation. Only data where coherent data sets related to initial emplacement of the Karakaya Complex are shown.

as undifferentiated Karakaya Formation) and the upper Karakaya assemblage (mapped as Sazak metamorphics or Sazak Formation), is shown as a NE–SW-trending high-angle neotectonic fault (Bekten Fault; Duru *et al.* 2007c). During this work the existence of major high-angle shear zones was confirmed (Figure 7). The adjacent, lower Karakaya assemblage (~Nilüfer Unit) is cut by numerous sub-parallel, moderately to steeply inclined shear planes and small normal faults (Figure 7f). Steep, sheared contacts are exposed elsewhere in the area sub-parallel to the mapped neotectonic strike-slip faults (e.g., Figure 7c). Primary thrust contacts in this area were reactivated related to strike-slip on several splays of the North Anatolian Transform Fault that transect the Biga Peninsula.

In the area north of Bergama (Area 4; Figure 11) the contact between the lower and upper Karakaya assemblages is well exposed over >10 km laterally. There is a sharp upward lithological change from foliated greenish volcanogenic rocks with local clastic carbonate interbeds or blocks (~Nilüfer Unit) to less deformed paler, yellowish-orange bedded sandstones and mudrocks (~Çal Unit). At three localities (Figure 11a–c) a major thrust fault is orientated subparallel to the foliation in the higher-grade rocks beneath and also to the bedding in the lower-grade rocks above.

In the area south of Bursa (Area 5) the contact between the lower Karakaya assemblage (~Nilüfer Unit) and the Upper Karakaya assemblage (~Hodul Unit or Dışkaya Formation) was located to within several metres in a road section, although the precise contact is covered by colluvium (GPS: Bursa H22 d4 0671593 4437340). Basalt and grey pelagic limestone of the higher metamorphic grade Nilüfer Unit pass into sheared volcanogenic lithologies, followed by phacoidally deformed, pale, thick-bedded arkosic sandstone and shale of the less metamorphosed upper Karakaya assemblage (~Hodul Unit). There are no signs of a sedimentary transition between the two units (cf. Kaya *et al.* 1989).

The easternmost area studied (Area 9 Nallıhan) includes an E–W-trending, elongate outcrop (~100 km long) of lower Karakaya assemblage rocks mapped as the Tepeköy metamorphics by Göncüoğlu *et al.* (2000), or the Gökcekaya metamorphics by MTA (Timur & Aksay 2002). Göncüoğlu *et al.* (2000) interpret this outcrop as a forearc-trench complex of pre-Permian(?) age. This is unconformably covered by an assemblage of upper Karakaya lithologies (Soğukkuyu metamorphics) beginning with a locally derived basal conglomerate. Alternatively, the entire Karakaya outcrop in this area was mapped by MTA as a stratigraphical succession of chlorite-sericite schist, phyllite, calc-schist and metabasic phyllite (Gökçekaya metamorphics), passing upwards into lenticular, recrystallised limestone and marble (Eğr change to "scattered" Aksay 2002).

T e lower and the upper Karakaya assemblage is well exposed at one key locality, Ortaçal Tepe (Figure 12). We observed that this is a major zone of thrusting (Figure 8d) marked by a ~5 m of intense shearing. A sequence of mainly meta-volcanogenic shales, turbiditic volcaniclastic sandstones and black phyllites with scatted blocks of marble and meta-lava is well exposed beneath the thrust (~Nilüfer Unit; Figure 12a). Above the shear zone, volcanogenic rocks including basalt pass depositionally upwards into limestones interbedded with shale, and then into massive shallow-water limestone (Ortaçal limestone; Figures 12 & 13a). This limestone is capped with a veneer of red radiolarian chert that has filtered down into neptunian fissures (Figure 8g). The limestone maps out as a tectonic lens that passes laterally into tectonic blocks (Figure 12a). The neritic limestone is structurally overlain by a thrust sheet of pillow lava, lava breccia, hyaloclastite, volcaniclastic turbidites, volcanogenic debris flows, calciturbidites and chert-rich pelagic carbonates, comparable with the Çal Unit in the Biga Peninsula. The neritic limestone (Ortaçal limestone) is interpreted as a part of a carbonate build-up on a volcanic basement that subsided and was covered by radiolarite before being emplaced, together with the upper Karakaya assemblage (see Discussion section).

Components of both the underlying lower Karakaya assemblage (schistose volcanogenic rocks) and the overlying upper Karakaya lithologies (less deformed and less metamorphosed volcanogenic and carbonate rocks) are entrained within an interval of shearing separating the two Karakaya assemblages. Within this interval volcanogenic rocks, mudrocks and thin-bedded limestones have undergone extreme layer-parallel extension to form

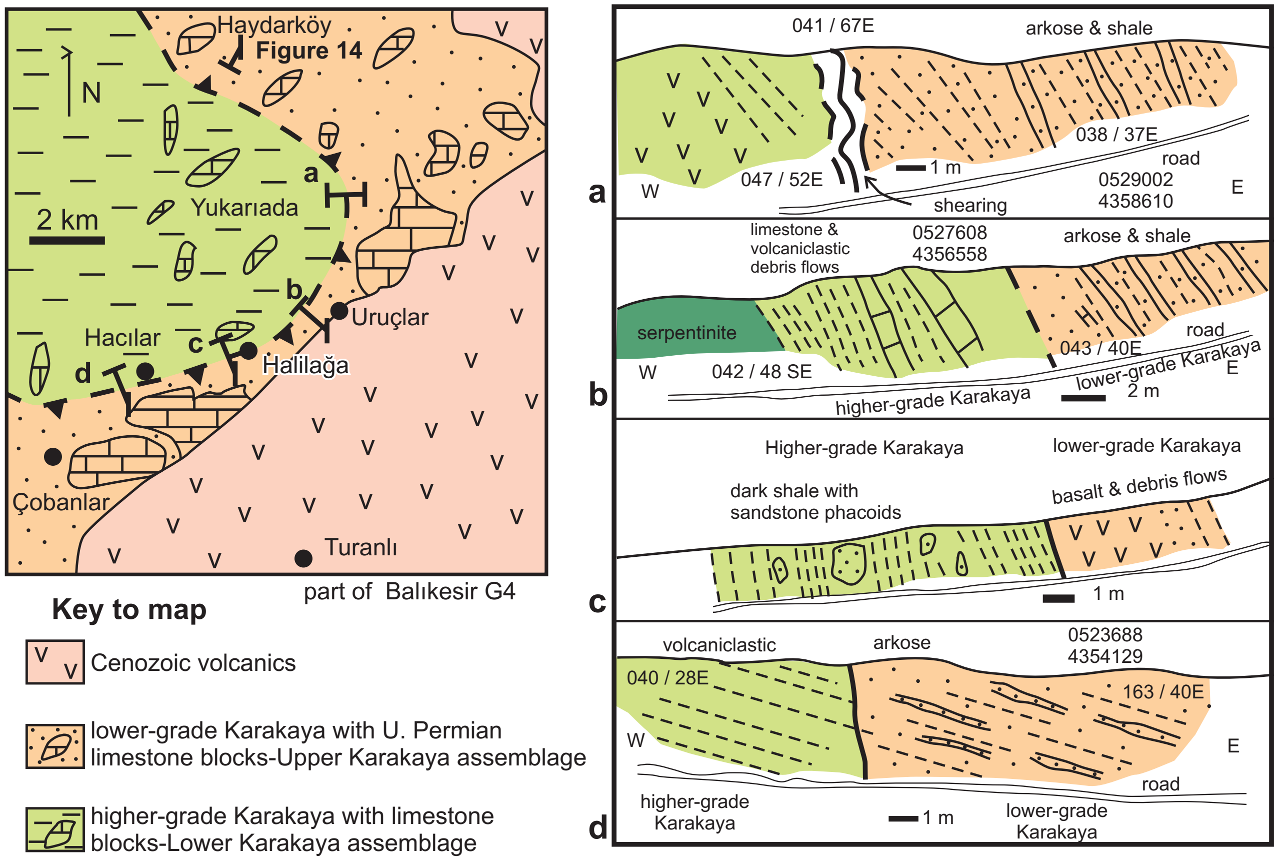

Figure 11. Outline geological map of the area north of Bergama (Area 4, Figure 1). Based on Akyürek & Soysal (1983), with modifications based on Pickett & Robertson (1996) and this work. (a–d) Local sections showing key contact relations. Sections on left: **(a)** Higher-grade Karakaya (~Nilüfer Unit) structurally overlain by lower-grade Karakaya (~Hodul Unit); **(b)** Slice of serpentinite close to the thrust contact between the higher-grade Karakaya (~Nilüfer Unit) and the lower-grade Karakaya (~Hodul Unit), above; **(c)** Higher-grade Karakaya (~Nilüfer Unit) overthrust by lower-grade Karakaya (~Hodul Unit with Çal Unit-type volcanics). See text for discussion.

elongate phacoids (Figure 12 a, b). Some of these are tectonically abraded, rounded and polished in a sheared incompetent matrix (Figure 8e). These rounded features are tectonic in origin and should not be interpreted as sedimentary matrix-supported conglomerates.

Upper Karakaya Internal Composition and Structure

The greenschist facies rocks of the Ortaoba Unit (Figure 4) are well exposed as thrust slices and blocks in Area 1 (N of Edremit; Figure 6a) and in Area 2 (S of Biga). The protoliths are MORB overlain by radiolarian cherts and mudstones, grading upwards into feldspathic turbidites (Pickett & Robertson 1996). These rocks form dismembered thrust sheets and blocks within outcrops of arkosic sandstones and exotic blocks, especially marble. The structural thickness of the mapped Ortaoba Unit as a whole was estimated as >5 km, but was probably ~1 km before structural repetition (Pickett 1994). The Ortaoba Unit is dated as Triassic by the directly overlying radiolarites (H. Kozur, personal communication 2009).

The Çal Unit is dominated by volcanogenic rocks and neritic to redeposited carbonates. It is locally dated as Late Permian–Early Triassic based on dating of radiolarian chert and pelagic limestone in several areas (Kozur & Kaya 1994; Kozur 1997; Kozur *et al.* 2000). Upper Permian and Triassic (Scythian,

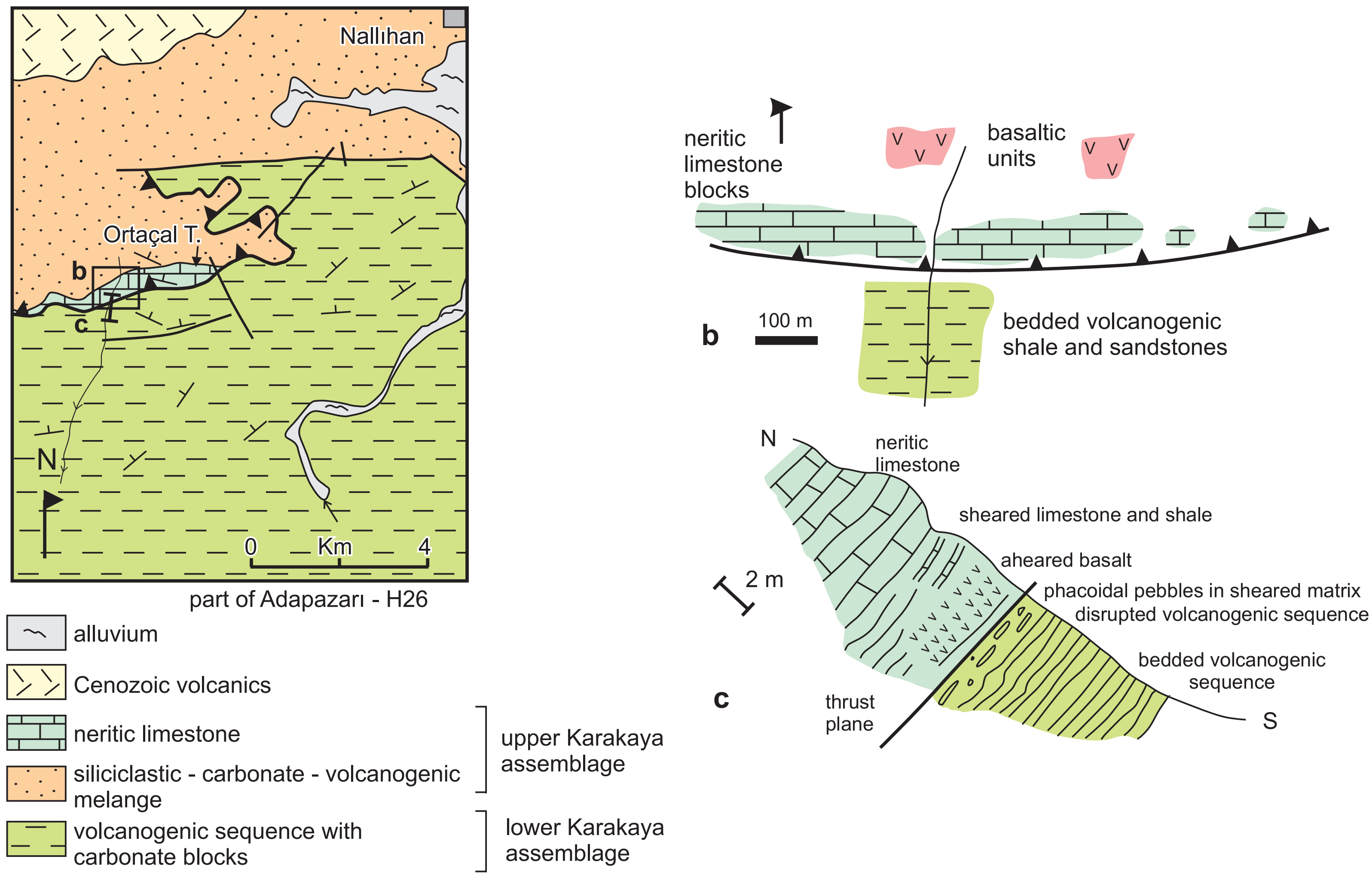

Figure 12. **(a)** Outline geological map of the area near Nallıhan (Area 9, Figure 1). Based on Timur & Aksay (2002) and this work. **(a, b)** Local map and cross-section showing key contact relations. The simple twofold lower and upper Karakaya subdivision is applicable to this area. See text for discussion.

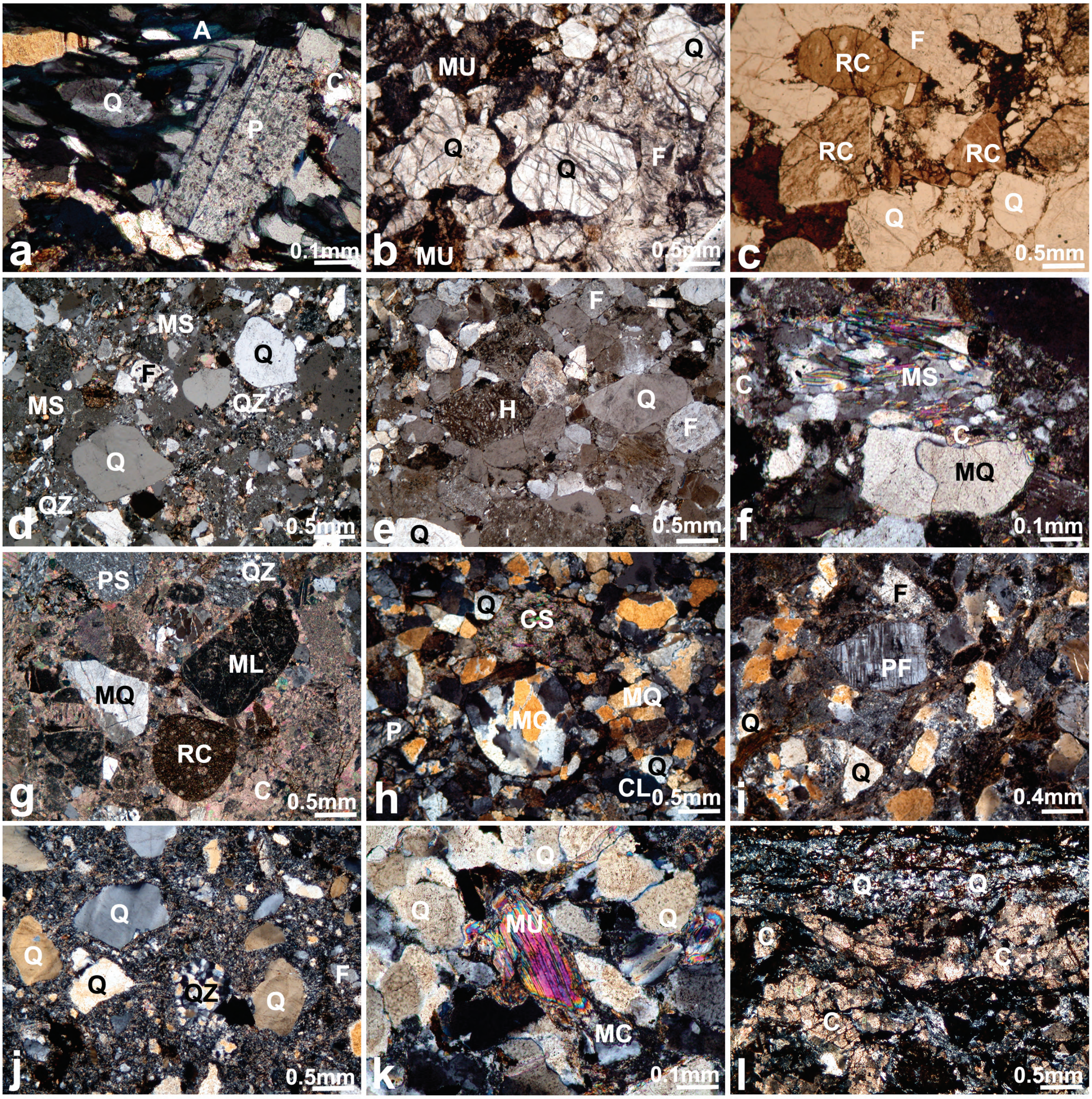

Figure 13. Photomicrographs. **(a)** Volcaniclastic sandstone with large plagioclase crystal, set in a fine-grained, schistose matrix, recrystallised to quartz (Q), plagioclase (P), amphibole (A) and calcite (C) (Q). Note the strain shadows suggesting relatively ductile deformation. Crossed nicols; uppermost part of the lower Karakaya assemblage SW of Ortaçal Tepe; SW of Nallıhan, GPS: near 0353975 4444989; **(b)** Well-rounded, brittle-fractured quartz (Q) grains together with minor smaller altered feldspar (F) and mudrock (MU) grains in a sparse muddy matrix, with secondary calcite spar cement; Plane-polarised light; Çobanlar Unit; Area 4 (N of Bergama); road section between Haydarköy and İkizce; GPS 0528474 4363206); **(c)** Sandstone with common well-rounded grains of radiolarian chert (RC), together with mainly angular to sub-rounded quartz (Q) and some feldspar (F) grains in a sparse muddy matrix. Plane-polarised light; Orhanlar Unit, Area 3, N of Danishment, GPS 0552092 4416819; **(d)** Typical sandstone forming the mélange matrix of the upper Karakaya assemblage (~Hodul Unit); angular to rounded grains of quartz, with smaller grains of quartzite (QZ), micaschist (MS) and feldspar (F) (e.g.,

→

Anisian and Ladinian) ages were also determined from limestone exotics, especially in Area 6 (N of Bursa; Kaya *et al.* 1986; Wiedmann *et al.* 1992), although these may be correlated with the Hodul unit (see below).

The Çal Unit generally occurs at a high structural level in the upper Karakaya assemblage, for example in the type area near Çalköy (Area 2; Figure 7). The little metamorphosed Çal Unit crops out as locally intact stratigraphical sequences, variably interrupted by thrust faulting. The lavas are alkaline, within plate-type basalt (WPB), basalt breccia, hyaloclastite, volcaniclastic turbidites and volcaniclastic debris flows. These are intercalated with calciturbidites, carbonate debris flows and detached blocks of neritic to redeposited limestone (Okay *et al.* 1991; Pickett 1994; Pickett & Robertson 1996; Figure 8 h–j). Such sequences are well exposed in Area 2 forming a ~NE–SW-trending outcrop south of Biga (Figure 7) and in Area 1 (near Paşadağ N of Edremit; Figure 6). In places, volcanic rocks are stratigraphically overlain by neritic limestones, as seen in Area 1 (near Paşadağ; Figure 6) and in Area 9 (near Nallıhan; Figure 12). In some areas lithologies equivalent to the Çal Unit occur as dismembered thrust sheets or blocks in an arkosic sandstone matrix (e.g., south of Biga, Figure 7); these are included within the Hodul Unit (see below).

Pickett (1994) and Pickett & Robertson (1996, 2004) reported the presence of shallow-water limestones that include quartz-bearing, terrigenous sandstones and terrigenous mudstones within well-bedded Upper Permian limestones (e.g., in Area 4, Kozak Massif; Area 1, Ciğdem Tepe; Area 2, near Çalköy). In contrast to the Upper Permian limestones of the Çal Unit these limestones lack evidence of a volcanic basement or interbedded volcanogenic rocks. We focused on road sections in Area 4, north of Yukarıada (i.e. ~1 km from Haydarköy near the turnoff to İkizce; Map sheet Balıkesir J18; GPS 0527988, 4363202; Figure 11). Interbeds of terrigenous shale and thin lenses of fine- to medium-grained sandstone are present at the base of (Figure 14 log 1) and within (Figure 14 log 3) an intact sequence of shallow-water limestones mapped as Late Permian–Triassic(?) according to mapping by MTA (Akyürek & Soysal 1983; Kaya & Mostler 1992). Thin sections of the coarsest sandstones revealed well-rounded grains, mainly quartz in a sparse micritic matrix (Figure 13b). Chemical analysis previously

Figure 13. Continued.
perthite) and minor components, with a sparse calcite spar cement; half-polarised light; from near the base of the mélange near Akçal Mah., near Patlak (Area 3, around Balya), GPS: 0553464 4398665; **(e)** Sandstone forming the mélange matrix; includes angular- to rounded grains of quartz (Q), altered feldspar (F), altered hyaloclastite (H), plus minor constituents; well-bedded sandstone turbidite sequence beneath mélange; Plane-polarised light; Upper Karakaya (~Hodul Unit), near Çamlıca, Area 3; GPS 0565644 442621; **(f)** Detrital grains of muscovite schist (MS) and metamorphic quartzite (MQ) with lithic sandstone; minor calcite cement (C); Kalabak unit; Crossed nicols; Area 1, N of Edremit; GPS near 0500445 4388882; **(g)** Carbonate-siliciclastic sandstone; angular to rounded grains of metamorphic quartz (MQ), quartzite (QZ), bioclastic micritic limestone (ML), radiolarian chert (RC), psammite (PS) and minor constituents, with a calcite spar cement; Plane-polarised light; from Norian sequence; Area 3 (around Balya); near Patlak, GPS 0551506 4400923; **(h)** Sandstone overlying basement of the Çamlık Metagranodiorite; mainly well-rounded grains of metamorphic quartz (quartzite) (MQ), angular to subangular quartz (Q), calc-schist (CS), plagioclase (P) and chlorite (CL); crossed nicols; Area 1, near Havran; GPS 0515883 4384365; **(i)** Half-polarised light view of sandstone unconformably overlying Variscan basement (Kenderli Formation). Rounded grain of perthitic feldspar (PF), together with other, mainly angular grains of quartz (Q), feldspar (F) and shale in a sparse muddy matrix; crossed nicols; Area 8, GPS 0740941 4447060; **(j)** Typical sandstone of the 'Variscan basement' (intruded by granitic rocks) from beneath Upper Permian limestone in the Geyve area. Note the angular grains of mainly quartz (strained) (Q) and quartzite (QZ), with minor micaschist (MS) and feldspar (F) set in a matrix of microcrystalline quartz and ferruginous mud; crossed nicols; Area 8, stream section near Kadirler, GPS near 0274538 4478501; **(k)** Typical sandstone between the 'Variscan' basement below and Upper Permian limestone above. Note the angular to sub-rounded grains of muscovite (MU), quartz (Q) and minor metamorphic quartz (MQ) (mostly fused by pressure solution); crossed nicols; Area 8, stream section near Kadirler, GPS near 0274538 4478501; **(l)** Bedding sub-parallel shear zone within sandstone-mudstone alternations, directly beneath a sedimentary transition to Upper Permian limestone. Sandstone with a muddy matrix is recrystallised to calcite (C) and quartz (Q) with remnants of ferruginous mudstone (dark); crossed nicols; Area 8, road section east of Kadirler, GPS 0270993 4479961.

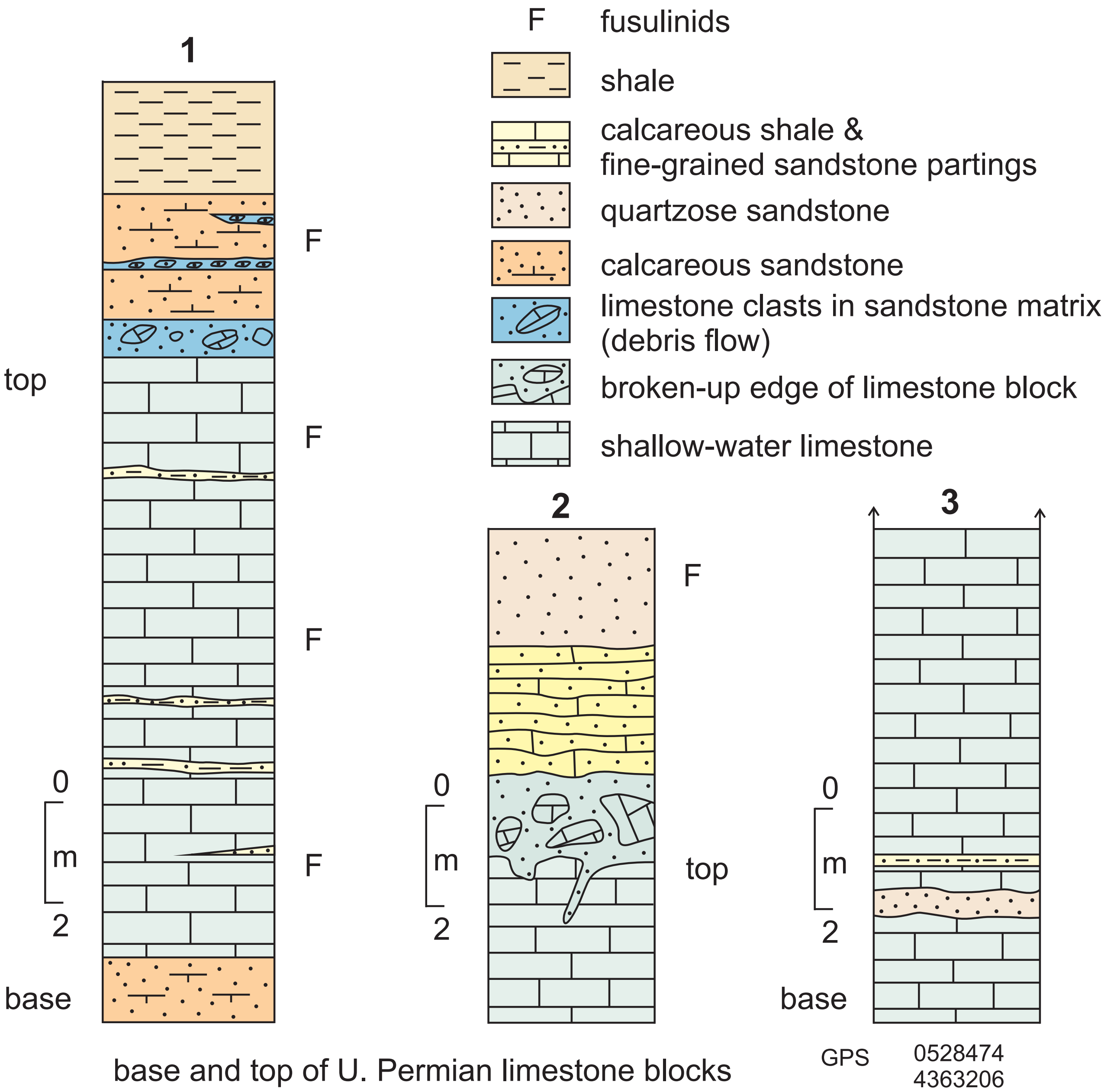

Figure 14. Measured sedimentary logs showing the relationship of Upper Permian neritic limestone blocks to associated terrigenous clastic sediments in Area 4 (N of Bergama). 1– Calcareous sandstone passing conformably upwards into neritic limestone, overlain by limestone-derived debris flows, calcareous sandstone and shale. The lower contact is a with siliciclastic sediments, while the upper contact locally reflects the break-up of an intact carbonate sequence to form a limestone block; 2– Detail of the upper surface of a limestone block showing break-up to form limestone talus related to tectonic emplacement; 3– Terrigenous sandstone and shale interbedded with neritic limestone, near the base of a detached block of limestone. The base of this limestone is not exposed, but similar blocks are enveloped by terrigenous sandstone elsewhere. Logs measured between Haydarköy and İkizce (see Figure 11); 1 & 2 modified from Pickett (1994); 3, this study.

showed that interbedded shales are compositionally similar to average continentally derived mudrock (Pickett 1994). In addition, some of the blocks are partially mantled by carbonate-derived talus and debris-flows (Figure 14, log 2) that relate to tectonic emplacement (see Discussion section). The blocks and dismembered thrust sheets are enveloped in terrigenous-derived mudrocks, quartzo-feldspathic sandstones and pebbly conglomerates (Figure 14, log 1; upper levels; Figure 17f) that are correlated with the Hodul unit (see below).

An isolated outcrop further east, near Kaşal (south of İvrindi) includes several blocks (100–500 m across) of Norian to Rhaetian (latest Triassic) neritic limestone (Kaşal Limestone Member; up to 80 m thick) (Okay & Altıner 2004). Terrigenous mudstone and siltstone are interbedded with the base of these limestones. Compositionally similar sandstones form the enveloping clastic sediment matrix. These limestones have been interpreted as a latest Triassic succession of reefal carbonates that developed on a substratum of terrigenous clastic sediments (Okay & Altıner 2004). The succession was later tectonically disrupted to form detached blocks in a larger-scale mélange (~Hodul Unit) dominated by Upper Permian limestone blocks.

An additional unit is the Camialan Limestone, which is mainly exposed in Area 2 (S of Biga, Figure 7; Okay *et al.* 1991). This limestone was initially assigned an Anisian age (Bingöl *et al.* 1973). A comparable limestone (Paşadağ Limestone) in the Edremit area yielded Mid-Late Triassic fossils (Gözler *et al.* l984), although this was later mapped as part of the Çal Unit (Okay *et al.* 1991; Pickett & Robertson l996). Mid-Triassic fossils were reported elsewhere (around Hoşköy) (Gözler *et al.* 1984). In addition, Okay *et al.* (1991) assigned an Anisian age to the Camialan Limestone, whereas Duru *et al.* (2007a, b, c) infer a Middle–Late Triassic age.

Pickett (1994) observed that the succession in the type area (Camialan; Figure 7) begins with green volcanogenic shale, followed by pelagic limestone with chert and then appeared to pass upwards into massive limestone. In agreement, southwest of Sofular (Figure 7), we observed that greenish volcanogenic rocks (undated) pass upwards into black phyllite and then into thick-bedded to massive pale micritic carbonate rocks typical of the Camialan Limestone. The black phyllites are suggestive of an oxygen-poor depositional setting in contrast to the typically reddish, well-oxidised pelagic sediments and radiolarites of the Çal Unit. The Camialan Limestone could represent the sedimentary cover of a volcanogenic unit (seamount?) that shallowed and was covered by neritic carbonate during Early–Middle Triassic time.

Upper Karakaya Composite Units

The upper Karakaya assemblage additionally contains two composite mélange units that are characterised by blocks of several different ages in a clastic sedimentary matrix of variable composition.

The first of the composite units is our redefined Hodul Unit, a mélange with an arkosic sandstone matrix together with subordinate lithoclastic matrix-supported conglomerates. The Hodul unit (~Dışkaya Formation) is widely exposed, especially in the central and northern Biga Peninsula, including Area 3 (near Balya; Figure 15), Area 4 (N of Bergama; Figure 11) and Area 6 (N of Bursa). Carbonate blocks have been dated as Middle Visean (lower Carboniferous), Late Permian and Ladinian (Middle Triassic) in different areas (Leven & Okay 1996; Altıner *et al.* 2000). The matrix of the mélange contains Late Triassic *Halobia* sp. in Area 6 (N of Bursa; Kaya 1991). A rare block of chert and pelagic limestone within arkosic sandstones northeast of Balya has been dated as Carboniferous (Okay & Mostler 1994). Norian-aged dark shale is also reported from a small outcrop south of İvrindi (Okay & Altıner 2004), as noted above. Blocks of Devonian radiolarite have recently been reported locally (Okay *et al.* 2011). In most areas the available kinematic evidence does not indicate any preferred direction of emplacement of the Hodul Unit. However, northward vergence was widely observed as folds, CS fabrics and small-scale duplexes north of Bursa (Figures 9d–f & 10a).

In some areas the Hodul unit appears to be chaotic, dominated by limestone blocks in an arkosic sandstone and mudstone matrix (e.g., Area 6, N of Bursa). However, in some areas discrete slices of volcanic rocks and associated neritic limestones (~Çal Unit) alternate with arkosic sandstone turbidites, shales and less abundant matrix-supported conglomerates (Figures 16.1, 2 & 17j–l). Good examples are exposed in the northern part of Area 2 (near Hodul; Figure 7) and north of Balya (near Deliktaş; Figure 15). The contacts between the thrust slices and blocks (volcanics and limestone) and the clastic matrix, where exposed are marked by intervals of sheared, phacoidal sandstone and shale up to several metres thick (e.g., E of Batlak, Figure 15b; S of Danişment, Figure 15c).

The matrix-supported conglomerates exhibit extreme layer-parallel extension to form phacoids in a matrix of sheared mudrock. A shear fabric within incompetent mudrocks is typically displaced

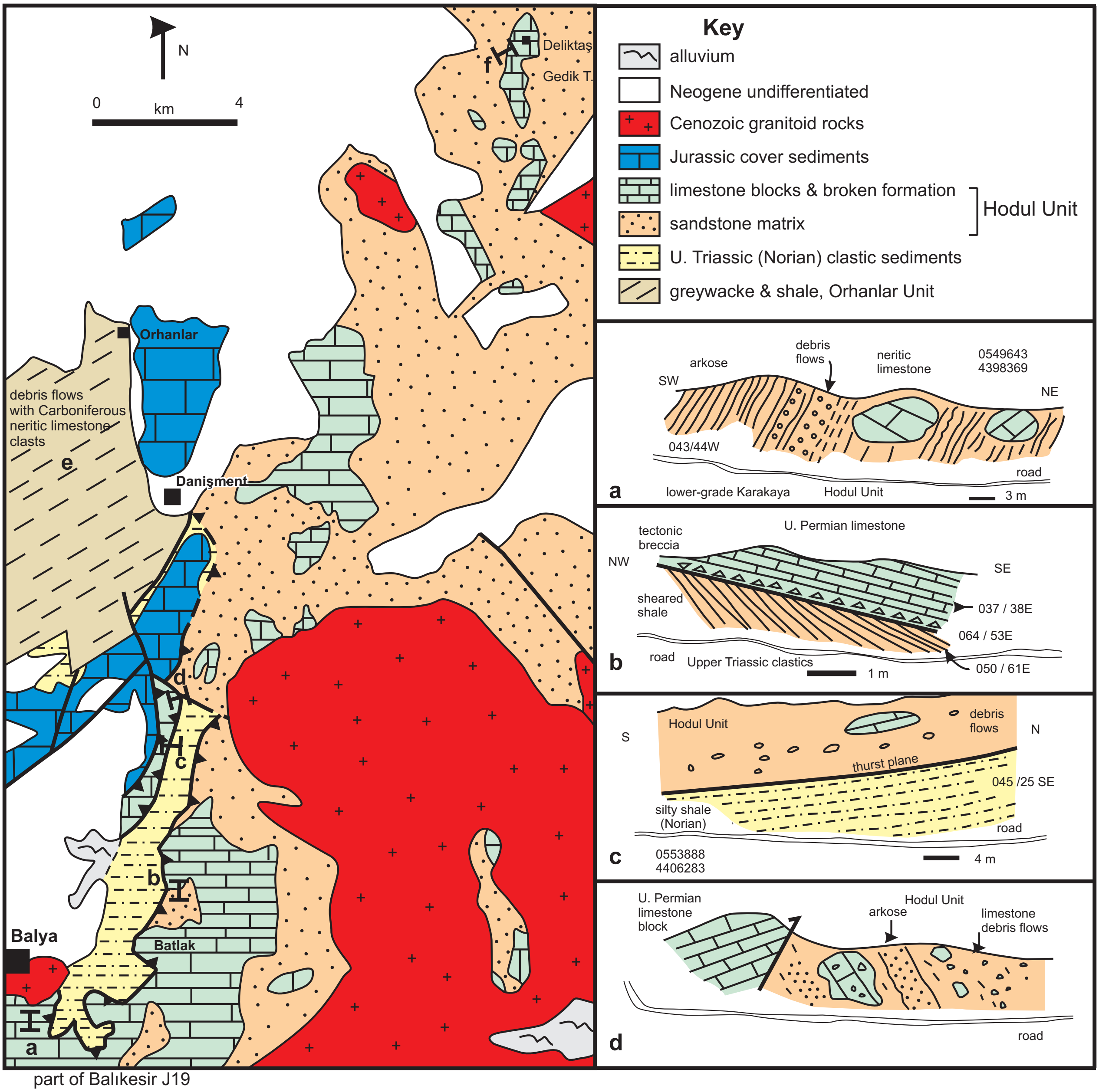

Figure 15. Outline geological map of the area around Balya (Area 3; Figure 1). Based on Pehlivan *et al.* (2007), with modifications from Okay *et al.* (1991), Pickett & Robertson (1996) and this work. (a–d) Local sections showing key contact relations. **(a)** Sedimentary mélange (olistostrome) interpreted as lower levels of the U. Triassic Hodul unit; **(b)** Upper Triassic arkosic sediments overthrust by a large dismembered thrust sheet (broken formation) of Upper Permian limestone (~Hodul Unit); **(c)** Norian bedded silty shales overthrust by debris flows (olistostromes) (~Hodul Unit). The Norian sequence is interpreted as part of the cover of the Variscan basement although no contact is exposed; **(d)** Debris flows (olistostromes) in high-angle fault contact with a large block of Upper Permian limestone; both ~Hodul Unit (both thrust over the coherent Norian shale sequence in c). See text for discussion.

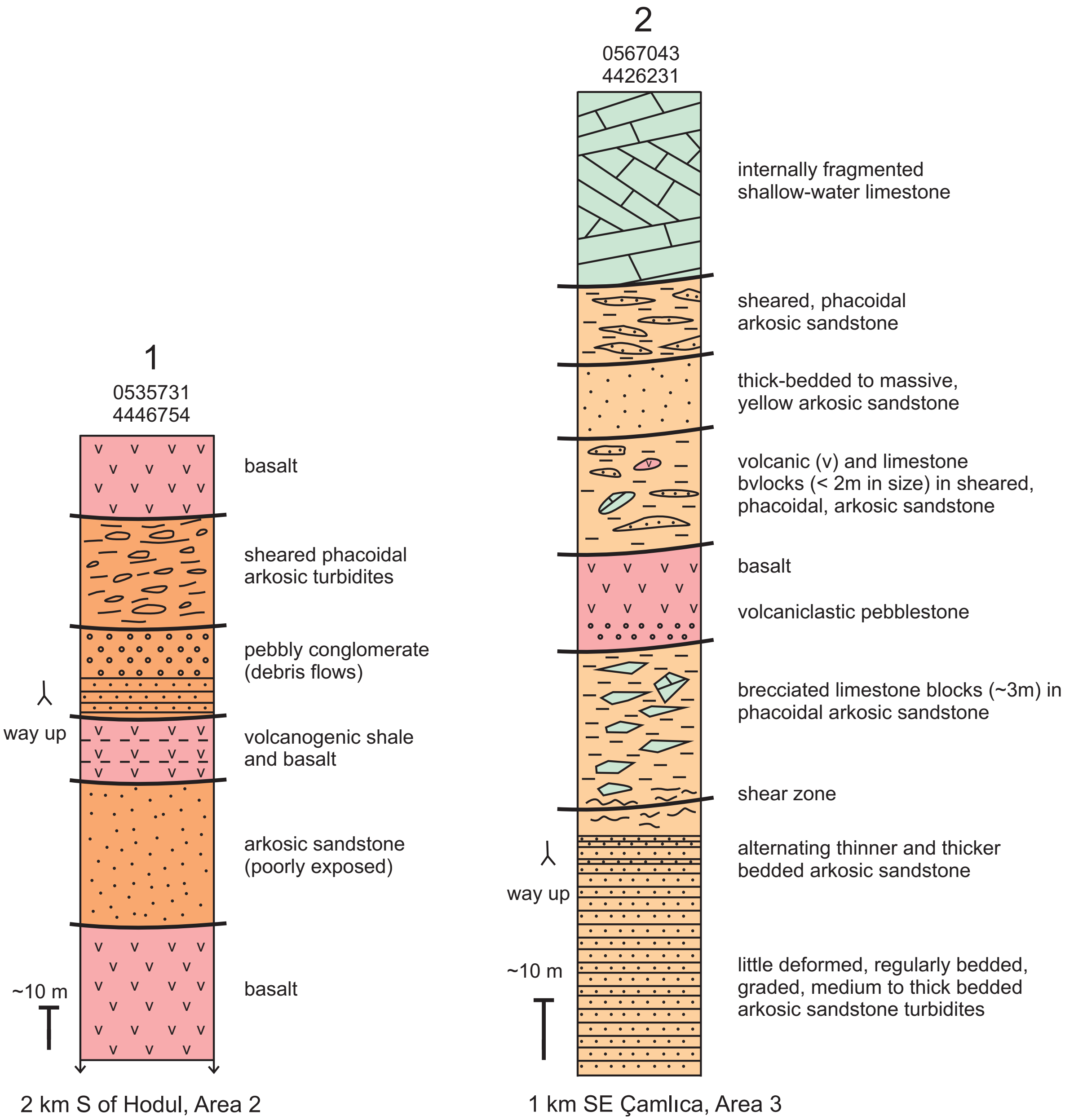

Figure 16. Measured sedimentary logs showing internal relationships in the Lower-grade Karakaya mélange (~Hodul Unit of Okay *et al.* 1991). 1– Interslicing of volcanogenic rocks comparable (~Çal Unit) with terrigenous sandstones and debris flows (U. Triassic) of the mélange matrix (~Hodul Unit); Area 2, south of Hodul; 2– Volcanogenic rocks and Permian neritic limestone (~Çal Unit) intersliced with U. Triassic sheared terrigenous turbidites of the mélange matrix (~Hodul Unit); SE of Çamlica. These relationships show that the mélange is mainly an Upper Triassic tectonic slice complex rather than an 'olistostrome' in its entirety.

around tectonic lenses of well-cemented, competent sandstones. In general, medium-thickness beds are dismembered to form sandstone phacoids set in a shaly matrix. The thick beds have broken up to form isolated sub-rounded to elongate blocks (phacoids; Figure 17c) admixed with mudrock, whereas the thin beds are completely disaggregated to form pebbly mudstones in a sheared mudrock matrix (e.g., Area 6, N of Bursa).

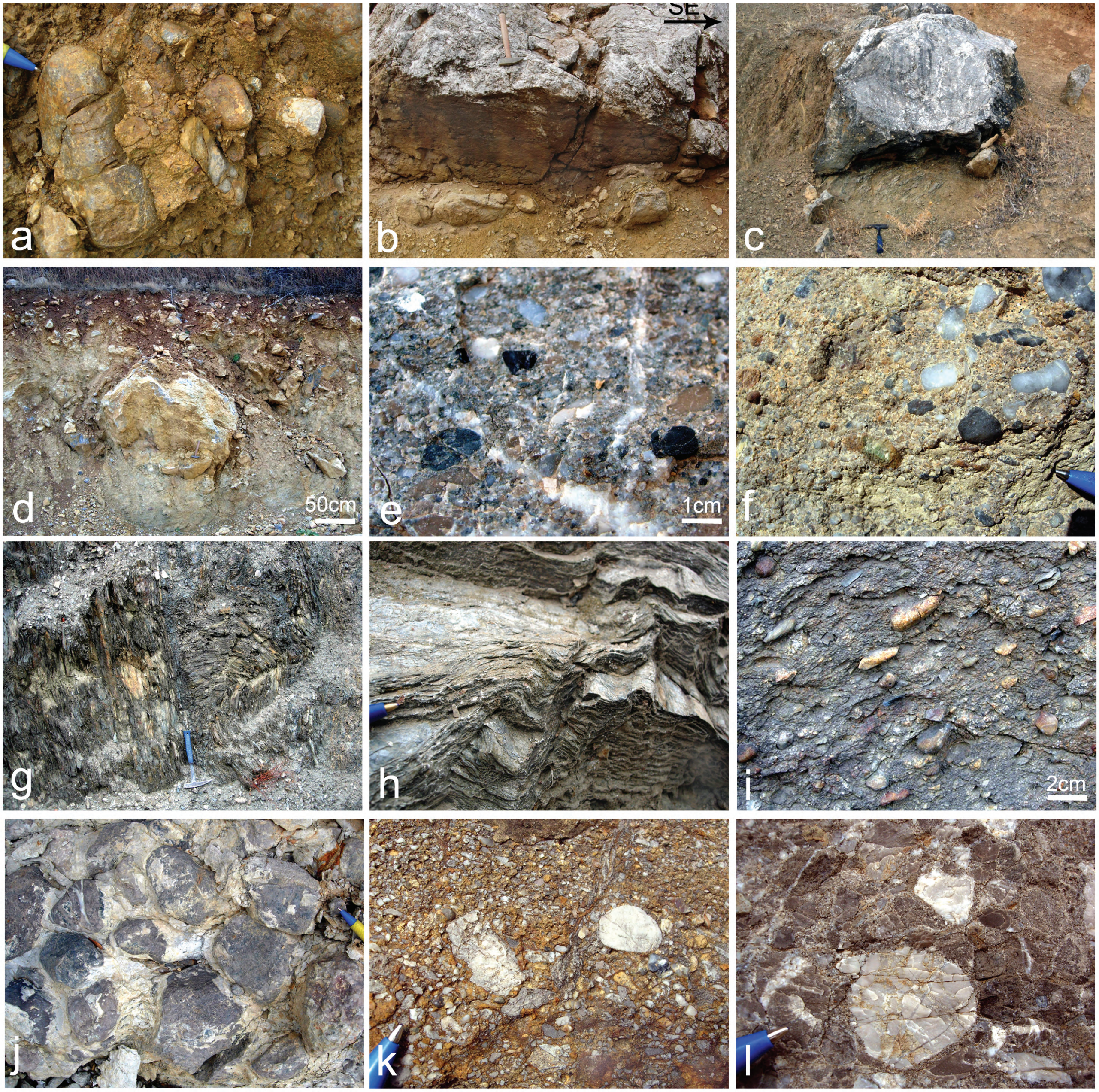

Figure 17. Field photographs of the Karakaya Complex and 'basement'. **(a)** Pebbly debris-flow with rounded clasts including limestone, quartz and granite near the base of the mélange; Area 3 (north of Balya; 1:100,000 map sheet Balıkesir-119; near GPS 0553346 4398689; see Figure 15; **(b)** Thrust contact between Upper Permian limestone and underlying arkosic sandstone and shale. The fault plane is slickensided and brecciated; same area as 'a'; **(c)** Typical phacoid of recrystallised marble in a matrix of sheared terrigenous shale. Such phacoids typically formed by layer-parallel extension of thick limestone beds and should not be confused with a sedimentary block in a debris flow; Area 6, N of Bursa; near Aydancık, 1:100,000 map sheet H22; near GPS 0684066 4464276; **(d)** Block of Upper Permian limestone in matrix of deformed calcareous shale and thin-bedded limestone; road section south of Balya; interpreted as part of a debris-flow unit underlying an emplaced, dismembered Upper Permian carbonate platform unit (Çal Unit). 1:100,000 map sheet Balıkesir-119; 0549676 4399189); 100,000 map sheet Balıkesir-İ 19; see Figure 15; **(e)** Pebbly debris-flow with well-rounded, redeposited clasts of limestone, quartz and black chert. From beneath the emplaced Upper Permian dismembered carbonate platform; Area 3, road section

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In all of the areas studied the sandstones of the Hodul Unit are compositionally similar, with predominate metamorphic quartz, plagioclase and alkali feldspar, together with minor muscovite, mica schist, calc-schist, perthite, micrite and heavy minerals (e.g., zircon; opaque minerals) (Figure 13j). These sediments were mainly derived from granitic and siliceous metamorphic basement rocks. Many of the larger grains are moderately to well rounded and mixed with more angular grains. Sandstones rarely contain silicic or mafic volcanic grains, for example in Area 2 (e.g., near Çalköy).

In some areas the Hodul unit as a whole is directly underlain by a sequence of true sedimentary debris flows, typically characterised by variably orientated sedimentary blocks (‘olistoliths’) of Upper Permian shallow-water limestone (<10 m in size). These are set in a matrix of mudrock and matrix-supported limestone conglomerates (e.g., S of Balya; Figure 17a, d), commonly with well-rounded clasts (Figure 17e). Thin sections revealed mixtures of mainly quartz, plagioclase and alkali feldspar, together with variably recrystallised neritic carbonate rocks (e.g., echinoderm spines; benthic foraminifera) and less common grains of biotite schist, perthite, red radiolarian chert and both silicic and basic extrusive igneous rocks. Larger detrital grains are typically well rounded. The sands were derived from granitic and siliceous basement rocks plus oceanic lithologies.

Comparable mélange is exposed in Area 8, south of Geyve (part of the Yenişehir-Geyve Ridge). This was described as a broken formation together with olistostromes including limestone blocks in a matrix of arkosic sandstone Upper Permian radiolarian sediments (Göncüoğlu *et al.* 2004; Figure 18). If correctly interpreted this would imply the existence of a Permian chaotic unit with important tectonic implications.

Where well exposed on forest roads we observed that several contrasting mélange units are structurally intercalated. One such unit (between Yukarıyayla and Pazarkaya Tepe) includes debris flows with Lower and Upper Permian limestone clasts and a block of recrystallised limestone, while a second includes basaltic lava, micritic carbonate and reddish coloured mudstones; a third unit, exposed on the forest road (towards Çinetaşı Forest Tower, SW of Pazartepe (GPS: Adapazarı h24 b1; 72326/80059), comprises arkosic sandstones with occasional debris flows. This third unit is critical as it includes rare blocks of recrystallised limestone, volcanogenic rocks and also pale green radiolarian cherts (5–9 cm thick) of Late Permian age (Göncüoğlu *et al.* 2004). Crucially, the chert is described as being interbedded with arkosic sandstone and siltstone. The Late Permian age of this chert was used to date the entire outcrop in this area (Göncüoğlu *et al.* 2004). Unfortunately, the Lower Permian chert was not found to exist at the quoted location perhaps owing to re-grading of the road. In any case, the reported chert and enveloping terrigenous clastic sediment could alternatively be explained as part of an Upper Permian exotic block within mélange that we correlate with the Triassic-formed Hodul Unit.

Another outcrop of mélange in Area 8 (near Geyve) was described as being overlain by a large thrust sheet dominated by Upper Permian neritic limestone (Derbent Limestone) and basaltic

Figure 17. Continued.
N of Balya; see Figure 15; **(f)** Quartzose pebblestone; part of matrix of mélange of U. Permian limestone, near Haydarköy; seen in unconformable sedimentary contact with limestone block; 1:00,000 map sheet Balıkesir-İ19, near GPS 0527988 4363202; see Figure 15; **(g)** Dark, schistose phyllite deformed by thrust faulting; Kalabak unit; Area 1; N of Havran, near Kalabak; 1:100,000 map sheet Balıkesir-İ18; near 0510142 4383716; see Figure 20; **(h)** Folded pelitic schist; type area of the Kalabak Formation, near Kalabak, location as ‘g’; **(i)** Lenticular debris flow with rounded redeposited clasts, including granite and schist; Triassic Halılar Formation; N of Havran; 1:100,000 map sheet Balikesir-İ18; near GPS 0510142 4383716; see Figure 20; **(j)** Sub-rounded limestone clasts in a lenticular, matrix-supported debris flow; Norian succession; Area 3; W of Batlak; 100,000 map sheet Balıkesir-İ19; near GPS 0551506 4400923; see Figure 15; **(k)** Lenticular pebbly debris flow in clastic matrix, Norian sequence, below dismembered, emplaced Permian carbonate platform; Norian succession; Area 3; W of Batlak; 100,000 map sheet Balıkesir-İ19; near GPS near 0551506 4400923; see Figure 15; **(l)** Channelised limestone conglomerate made up of redeposited limestone pebbles and cobbles (some rounded) deposited by mass flow. Norian succession; Area 3; W of Batlak; 100,000 map sheet Balıkesir-İ19; near GPS near 0551506 4400923; see Figure 15.

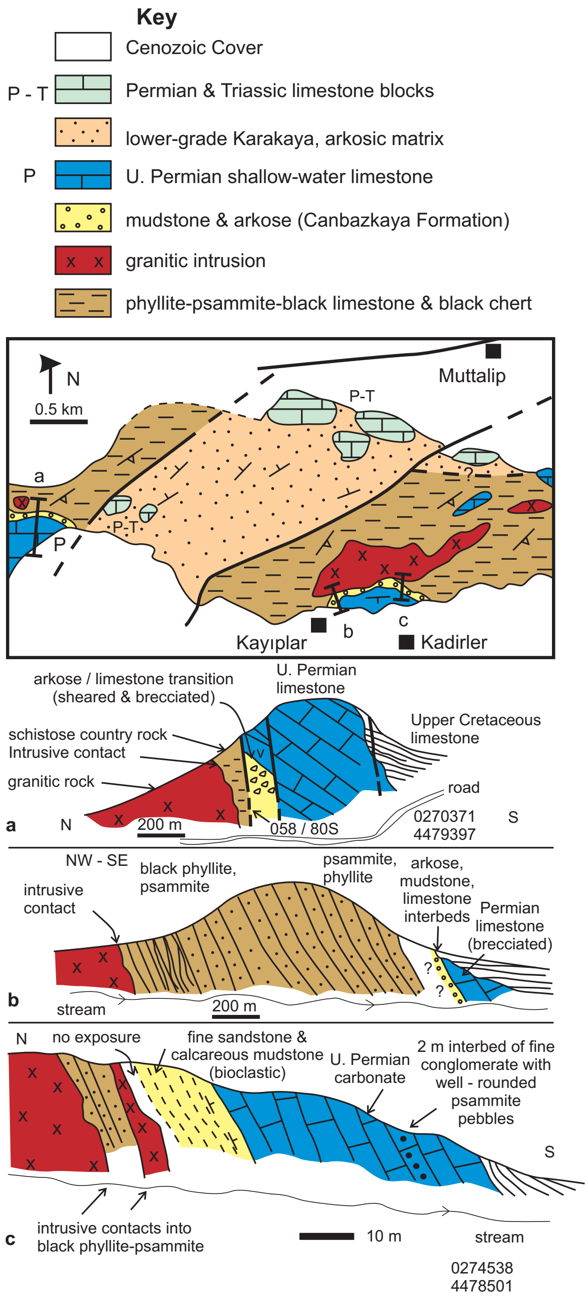

Figure 18. Outline geological map of the area near Geyve (Area 8; Figure 1). Based on Turhan *et al.* (2004) and this work. (a–c) Local sections showing key contact relations. **(a)** Basement meta-sedimentary rocks (~Kalabak unit) intruded by granitic rock, followed by a zone of high-angle faults (?related to neotectonic strike slip); **(b)** Basement meta-sedimentary rocks again intruded by granitic rocks; no exposure beneath Permian limestone, followed by U. Cretaceous limestone cover; **(c)** 'Basement' followed by Upper Permian limestones but with no exposed contact. See text for discussion.

volcanic rocks (pillow-basalt-limestone association) (Göncüoğlu *et al.* 2004; Figure 18). However, this unit maps out as detached blocks within a matrix of arkosic sandstones and shale (e.g., on Pazarkaya Tepe). Associated exposures of massive bioclastic limestone debris flows, thick-bedded bioclastic limestone debris flows (with angular detrital quartz grains), calciturbidites, nodular pelagic limestone (reddish-purple) and associated vesicular pillow basalt and basaltic breccia can all be correlated with the Hodul Unit.

Further west along the elongate Yenişehir-Geyve outcrop Saner (1977, l978) reported a metamorphic basement (e.g., mica schist) that was depositionally overlain by clastic meta-sedimentary rocks, including thick-bedded sandstones grading into Upper Permian (Murghabian–Midian) recrystallised micritic limestones (Derbent Limestones). On the other hand, Altıner *et al.* (2000) reported a Late Triassic olistostrome unconformably overlying meta-granitic rocks (Bozüyük Granitoid) in the Derbent (İznik) area of Bursa region. These outcrops are additional candidates for tectonically emplaced Triassic mélange (~Hodul Unit).

The second of the composite units is the much more locally developed Orhanlar Unit, known mainly from the central Biga Peninsula (Okay *et al.* 1991). This is largely made up of little metamorphosed fine- to medium-grained, medium- to thick-bedded grey or dark brown sandstone turbidites and shales. Blocks of lower Carboniferous neritic limestone are locally present (Okay *et al.* 1991). The Orhanlar unit in Area 3 (near Danişment; Figure 15) has been mapped as entirely bounded by faults or younger units (Pehlivan *et al.* 2007). However in places, the unit is mapped as being overlain by Lower Jurassic sedimentary rocks (Bayırköy Formation; Pehlivan *et al.* 2007) suggesting that it is located at a high structural level within the upper Karakaya assemblage. Comparable facies elsewhere (e.g., Bursa-Mustafakemalpaşa area) additionally contain rare blocks of Permian neritic limestone (Leven & Okay 1996).

West of Danişment (Figure 15), we observed that the Orhanlar Unit is dominated by thin- to medium- and thick-bedded, dark-coloured sandstone turbidites and shales. The sandstones include occasional lenses (<2 m thick) of poorly consolidated pebblestones with well-rounded pebbles of black chert, up to 3 cm in size (GPS Balıkesir J19 0551328 4412679). The pebblestones contain radiolarian chert, quartz (monocrystalline and polycrystalline), plagioclase, alkali feldspar, perthite and biotite, together with locally abundant grains of basalt, blue chlorite and siliceous extrusive rock. The provenance of the sandstones is similar to the Upper Karakaya sandstones elsewhere (e.g., Hodul Unit; see below), with the addition of basic and siliceous extrusive rocks and chert (Figure 13c). Similar volcanic rock and chert grains are also occasionally present in the Ortaoba Unit (Pickett & Robertson 1996) and in the sandstone matrix of the Hodul Unit (e.g., in Area 3, near Çamlıca; see below). Exotic blocks occur locally as well-rounded boulders and cobbles of grey or pinkish micritic limestone (< 3 m in size). Associated lenticular debris flows contain small limestone clasts (<0.5 m thick) strewn through a poorly consolidated sandstone matrix. The limestone clasts contain a rich lower Carboniferous assemblage including crinoids, benthic foraminifera (e.g., *Miliolina* sp.) and microbial carbonate, set in a largely unrecrystallised micritic matrix (Okay *et al.* 1991; Leven & Okay 1996).

Late Palaeozoic Granite and Metamorphic 'Basement'

Are the 'basement' rocks to be considered as a true basement of the Karakaya Complex or as thrust sheets within it?

'Basement' gneiss and schist are intruded by granitic rocks of early Carboniferous age (Ustaömer *et al.* 2010) in the east of the area (e.g., Söğüt Granodiorite), from around Söğüt to Nallıhan, to the north of the Karakaya outcrops (Yılmaz 1979; Kadıoğlu *et al.* 1994; Kibici *et al.* 2010; Figure 1). Further west, 'basement rocks' are structurally underlain by the Karakaya Complex (Sarıcakaya-Söğüt area). Further west again (Figure 19) a thin slice of 'basement' (mainly psammite and phyllite) is mapped as thrust over a lower Karakaya assemblage (Area 7, south of Yenişehir; Genç & Yılmaz 1995).

In the Biga Peninsula, 'basement' and Karakaya Complex are in direct structural contact in several areas. 'Basement' rocks are mapped as the Kalabak or Torasan formations (or units) in different areas (Krushensky *et al.* 1980; Okay *et al.* 1991; Pickett & Robertson 1996; Duru *et al.* 2007a, b, c; Figures 3 & 9a). These rocks are mainly psammites and pelites with small amounts of black meta-chert (lydite), small marble blocks (< 5 m), meta-basic volcanics and meta-serpentinite. In Area 1 (Havran) the Çamlık meta-granodiorite yielded mean single zircon Pb/Pb ages of 399±13 Ma and 397±1.4 Ma; i.e. Early-Mid Devonian (Okay *et al.* 1996, 2006). The granitic rocks were initially thought to intrude Triassic sediments (Altıner *et al.* 1991). However, according to later MTA mapping (Duru *et al.* 2007a, b, c) Palaeozoic meta-granitic rocks including the Çamlık meta-granodiorite cut schistose metamorphic 'basement' (Kalabak or Torasan units). Recent Shrimp and LA-ICP-MS U-Pb zircon dating of several other plutons that intrude the Kalabak unit in the Biga Peninsula also yielded Early to Mid-Devonian ages (Aysal *et al.* 2011).

The presence of basement-type lithologies at a high structural level in the Karakaya Complex was explained by Alpine(?) or neotectonic(?) faulting by Duru *et al.* (2007a, b, c). In contrast, Okay *et al.* (1991) and Pickett (1994) mapped the Kalabak unit in the Edremit-Havran area as a large thrust slice of pre-Karakaya 'basement' that was emplaced to a high structural level interleaved with the Karakaya Complex. During this work, the foliation in the Kalabak unit was observed to be sub-parallel to the bedding in the underlying Karakaya Complex (Ortaoba Unit) in the Edremit-Havran area although the actual contact between the two units is rarely exposed. This is in keeping with the low-angle thrust contact mapped by Okay *et al.* (1991) and Pickett & Robertson (1996). We observed that the upper contact of the Kalabak unit with the Çal Unit (above) is another low-angle thrust, associated with sheared serpentinite, as exposed from Paşadağ to Çiğdem Tepe (Figure 6). Further southeast, the contact with the [illegible] by MTA (Duru *et al.* 2007[illegible] associated with a sliver the Mesozoic Çetmi Mélange (Figure 6).

The eastward extension of the Kalabak unit was again mapped as a high-angle contact on the adjacent 1:100,000-scale map sheet (Balıkesir-İ 18) (Duru *et al.* 2007b). This contact was examined at two palaces

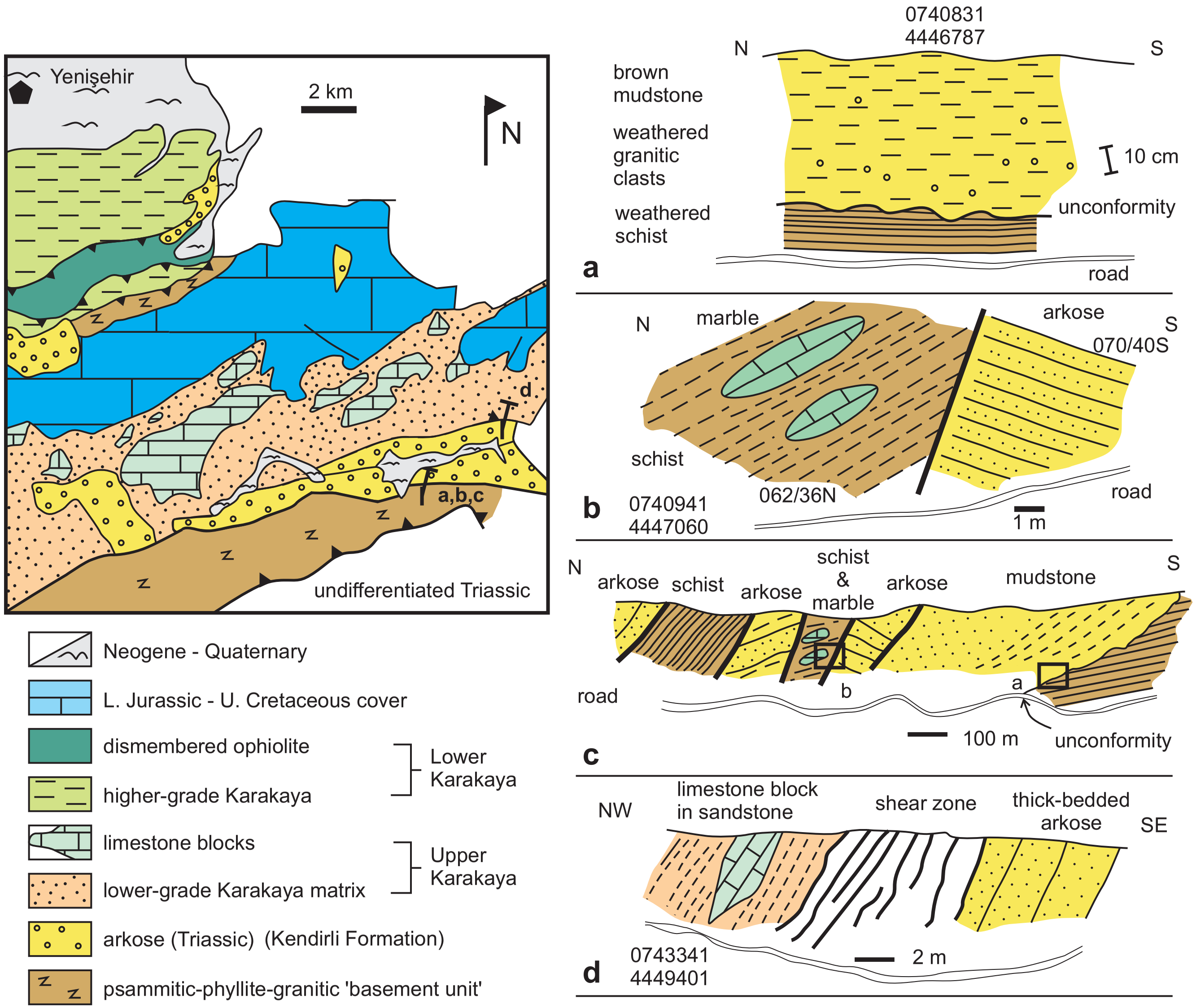

Figure 19. Outline geological map of the area south of Yenişehir (Area 7; Figure 1). Based on Genç & Yılmaz (1995), (a–c) Local sections showing key contact relations. **(a)** Details of locally exposed unconformity between 'basement' schist and cover sediments (Kenderli Formation); **(b)** Arkosic sandstones (Kenderli Formation) in this area in high-angle (strike-slip(?) fault contact with 'basement' schists containing marble lenses; **(c)** Composite section including a & b (above), showing how metamorphic basement rocks (schists) are unconformably overlain by arkosic sediments, but also intercalated with slivers of other 'basement' rocks (schist and marble). See text for discussion.

First, on Çiğdem Tepe (Figure 6), gently dipping pelitic schists of the Kalabak unit (116/32SW) are in high-angle fault contact with more steeply dipping micritic limestones of the Çal Unit. Further east, near Dereli (0502387 4389106) pelitic schists of the Kalabak unit are separated from neritic limestones of the Çal Unit by a high-angle fault (Figure 6). The eastward extension of the southeasterly contact of the Çal Unit (south of Dereli) is also inferred to be a high-angle fault. The Kalabak unit dips southwards, whereas limestones of the Çal Unit dip steeply westwards, separated by a high-angle spaced shear
change "Erdemit" to "Edremit" nother fault-bounded outcrop
apped further south (Duru *et al.* 2007b).

In summary, in the area north of Edremit the lower and upper contacts between the Kalabak unit and the Ortaoba and Çal units respectively, are interpreted as primary thrust contacts. These contacts were commonly reactivated, first by southward-directed thrust emplacement of the Upper Cretaceous Çetmi Mélange and then by NE–SW- trending high-angle faulting parallel to the Neotectonic Erdemit graben (Duru *et al.* 2007c). Additional, relationships exposed further north, in the Biga area (Figure 7) between the Kalabak (~Torasan) Unit and the Karakaya Complex (Ortaoba, Çal and Hodul units)
change "lower" to "upper" –f. These field relations indicate
rops (~Kalabak and Torasan units) are mainly in high-angle fault contact with the Karakaya Complex in this area. However, the Kalabak unit and related granitic intrusions appear to be sandwiched between the lower Karakaya assemblage (~Nilüfer Unit or Sazak Formation; e.g., near Sazak; Figure 7) and the lower Karakaya assemblage (~Çal Unit). The 'basement' lithologies are, therefore, interpreted as one or several large thrust slices within the Karakaya Complex as a whole.

'Basement' Meta-sedimentary Rocks

The Kalabak unit is predominantly psammitic and pelitic (Figure 17g, h). In Area 1, north of Edremit (Figure 6), the Kalabak unit consists of alternating dark grey to black, pelites with subordinate psammites and occasional pods of marble (up 1 m thick); these could be either sheared interbeds or flattened blocks. Meta-sandstones are uniformly fine to medium grained in this area. Thicker-bedded psammites predominate in some other areas, for example in Area 1, north of Havran (Figure 20) and in Area 2, east of Hodul (Figure 7). Comparable lithologies are exposed in many other areas, for example, in Area 8 (S of Geyve; Figure 18), where dark pelites, pelitic schists and psammites dominate, together with rare pods of dark recrystallised biogenic chert, black marble and siliceous tuff (Turhan *et al.* 2004).

The typical bed thicknesses of the psammites (up to several metres), lateral persistence of individual beds and the ubiquitous presence of pelitic interbeds are suggestive of an origin as relatively proximal turbidites (although few sedimentary structures have survived). In Area 8 (near Geyve; Figure 18) psammites and pelites are intercalated with black ribbon cherts forming lenses and blocks, up to several metres in size. In area 2 (S of Biga; near Torasan; Figure 7) typical meta-sedimentary rocks are locally intercalated with lenses of meta-harzburgite up to several hundred metres wide by > l km long (Duru *et al.* 2007c), indicating tectonic assembly. Northward vergence is clearly documented southeast of Biga (Figures 9a & 10d).

Thin section study indicates that the Kalabak unit is compositionally similar in all of the areas studied (Figure 13f). Litharenites and quartzarenites predominate, mainly made up of angular quartz, quartz (unstrained and polycrystalline), plagioclase, subordinate alkali feldspar and perthite, minor muscovite and common sandstone or siltstone rip-up clasts. The matrix is typically silty claystone. The sediments were sourced from granitic and silicic metamorphic rocks, similar to the Triassic siliciclastic sandstones of the upper Karakaya assemblage (e.g., Çal Unit). However, the Kalabak unit meta-sandstones tend to be more matrix-rich and the grains more angular. In many case the sandstones do not appear to be significantly more metamorphosed than the Triassic sandstones of the Upper Karakaya assemblage (i.e. greenschist facies). However, locally near shear zones (e.g., Area 1, near Havran) the metasediments are schistose or phyllitic and near the granite they exhibit contact metamorphism (e.g., Area 1 near Çamlık meta-granodiorite; Area 8, near granites in the Geyve area).

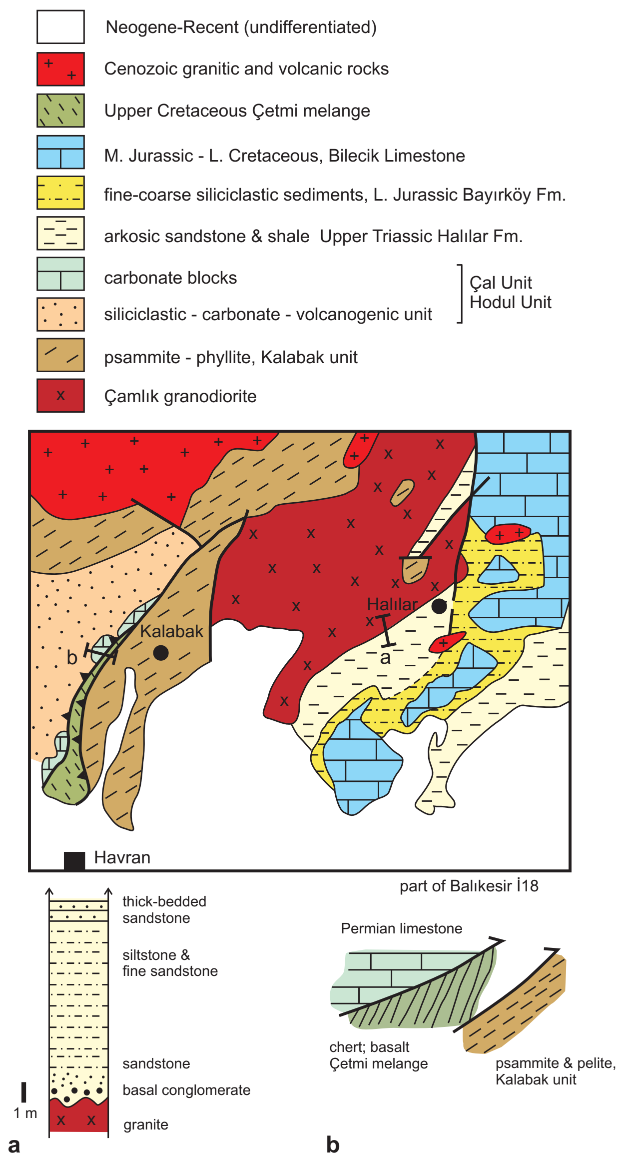

Figure 20. Geology of the area near Havran (Area 1; Figure 1). **(a)** Outline geological map of the area; based on Duru *et al.* (2007c) with modifications from Okay *et al.* (1991), Pickett & Robertson (1996) and this work; **(a)** Local log showing the base of the unconformable sedimentary cover of the Çamlık Meta-granodiorite, near Havran; **(b)** Local cross-section showing a slice of the Late Mesozoic Çetmi Mélange. See text for explanation.

Sedimentary Cover

In the Biga Peninsula, near Havran (Figure 20), the Devonian Çamlık meta-granodiorite is unconformably overlain by unmetamorphosed Triassic clastic sedimentary rocks (Altıner *et al.* 1991; Okay *et al.* 1991; Pickett & Robertson 1996). An unconformity at the base of the Triassic succession has long been known regionally (Gümüş 1964). For example the basal conglomerate near Çamlık includes large granitic boulders, up to 8 cm in size (Pickett 1994). Where studied by us west of Halılar (Figure 20, locality a), the meta-granodiorite is overlain, first by thin granite-derived conglomerates and then by white or pale grey arkosic sandstones. An irregular surface of the granodiorite is overlain by a thin basal conglomerate (0.4 m thick), passing upwards into pebbly sandstone with well-rounded quartz pebbles and angular clasts of dark siliceous phyllite and recrystallised chert (Figure 17i).

The basal sandstones are mainly made up of monocrystalline quartz, polycrystalline quartz (quartzite), altered plagioclase, alkali feldspar, muscovite, biotite, mica-schist, calc-schist and micrite, derived from granitic and silicic units (Figure 13h). Despite directly overlying the Devonian Çamlık meta-granodiorite much of the basal material was derived from an unexposed area of terrigenous metamorphic rocks, presumably the Kalabak unit. However, arkosic sandstones derived from granitic rocks become relatively more abundant higher in the succession.

The overlying siliciclastic succession (Halılar Formation; Krushensky *et al.* 1980) grades upward up into finer-grained, thinner bedded silty and argillaceous sediments, in total up to 1000 m thick (e.g., in Pınar Dere; Pickett 1994). The lower part of the succession (Figure 21, log 1, lower unit) contains scattered Upper Triassic bivalves and brachiopods and common plant material and can be interpreted as a restricted non-marine deltaic, to shallow-marine setting adjacent to a low-lying landmass. Above this, dark mudstone and siltstone with sandstone and conglomerate interbeds contain Norian shelly fossils including the pelagic bivalve *Boitra buchii* (Gümüş 1964; Aslaner 1965; Altıner *et al.* 1991; Pickett 1994). Bouma-type sedimentary structures suggest palaeoflow mainly towards the south and southeast (Pickett 1994). Rapid subsidence accommodated the accumulation of siliciclastic sediments rich in organic matter in an open-marine setting (see Discussion section). These sediments were derived from mixed granitic and metamorphic source areas but without

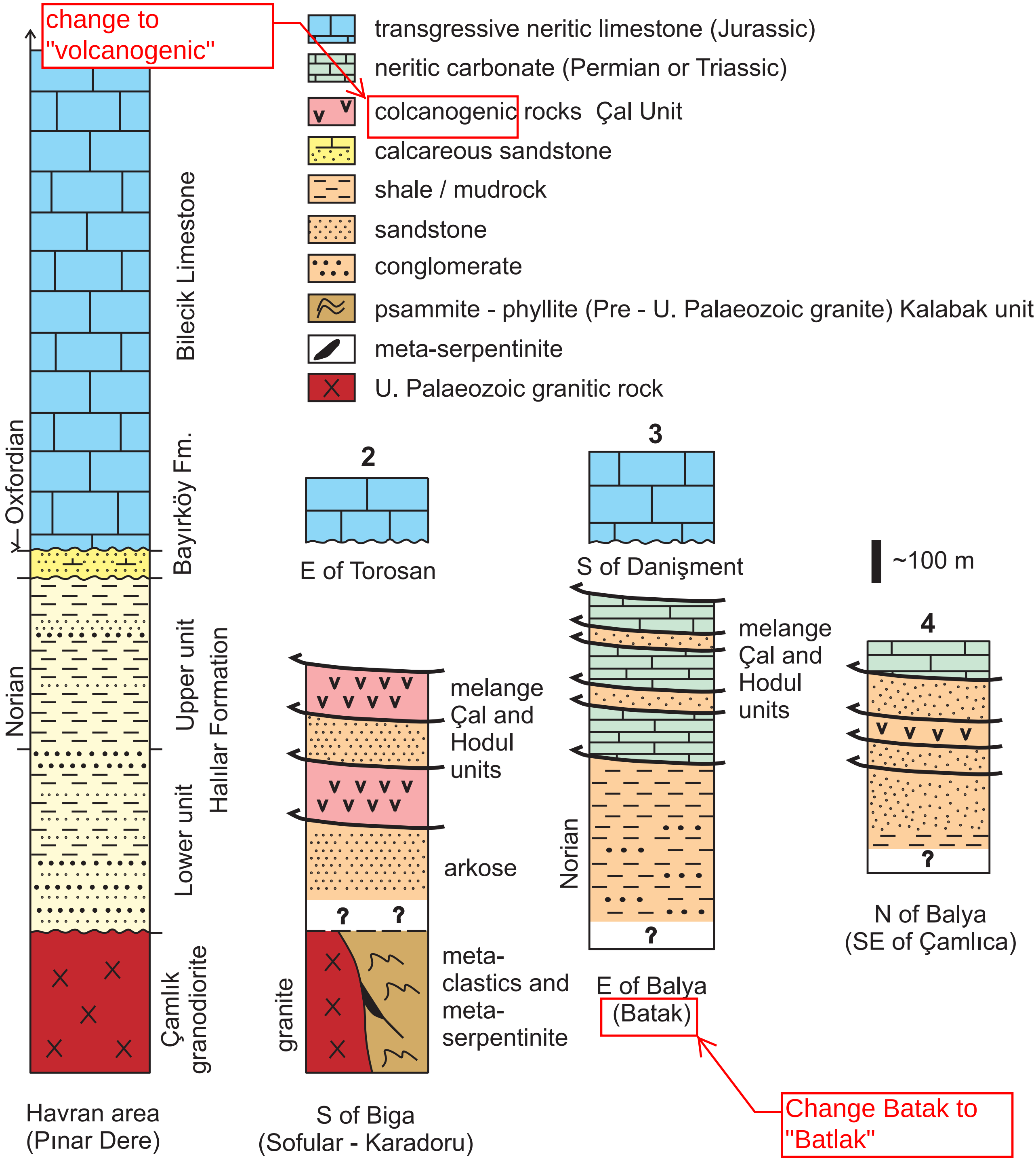

Figure 21. Sedimentary logs of latest Triassic (or inferred latest Triassic) successions in relation to Palaeozoic basement units and arkosic cover, Permian–Triassic Karakaya lithologies and Jurassic cover. Data sources: 1– Okay *et al.* (1991); Pickett (1994); this work; 2– Duru *et al.* (2007b); this work; 3,4– Pehlivan *et al.* (2007) and this work.

an identifiable contribution from the Karakaya Complex (Pickett 1994; Pickett & Robertson 1996; this study).

In the area studied (Figure 21.1) the overlying Bayırköy Formation (Altınlı 1973) is likely to be of Bajocian age locally (Altıner *et al.* 1991), implying a time gap between emplacement of the Karakaya Complex and the onset of cover deposition. However, further east the Bayırköy Formation extends down to Sinemurian–Pliensbachian, mainly based on dating of Ammonitico Rosso (Alkaya 1981; Altıner *et al.* 1991). The Bayırköy Formation is predominantly calcareous sandstones and mudstones rich in shelly fossils (e.g., brachiopods and echinoderms) with shallow-water trace fossils (e.g., *Thalassinoides*; *Chondrites*), together indicative of deposition in a relatively high-energy shallow-marine setting (Altıner *et al.* 1991; Pickett 1994). The succession passes into shallow-marine shelf carbonates of Bajocian-Bathonian age (Bilecik Group; Altıner *et al.* 1991).

The contact between the Halılar and Bayırköy formations is not exposed in the section studied (Figure 20.1). Elsewhere, this contact is interpreted either as a sedimentary transition (Altıner *et al.* 1991), or as a parallel unconformity (Okay *et al.* 1991). The latter is likely in view of the apparently abrupt change from relatively deep-water muddy sediments to shallow-marine, mixed carbonate-siliciclastic sediments and the probable time gap between the final emplacement of the Karakaya Complex and transgression.

One key question is why the latest Triassic clastic sediments in the Havran area (Halılar Formation) lack evidence of overthrusting by the Upper Karakaya assemblage in contrast to comparable facies to the north and south. Possibly Karakaya rocks were emplaced over the Hallılar Formation, but later eroded, represented by the poorly exposed disconformity and time gap at the base of the Lower Jurassic Bayırköy Formation. Alternatively, the 'basement' and its cover in the Havran area were uplifted in response to collision, isolating this area from the emplacement of the [illegible]. In either case, the topography of t[illegible]cks was smoothed by subaerial erosion during Early Jurassic time, followed by regional marine transgression.

Elsewhere, facies mapped as the Bayırköy Formation are dated as Toarcian–Aalenian, for example near Çan, based on the occurrence of *Posidonia sp.*; Okay *et al.* 1991). Jurassic sediments unconformably overlie different units of the upper Karakaya Complex in several areas (e.g., Çal Unit in Area 2; Orhanlar unit in Area 3). In Area 3 (near Çalköy; Figure 7), a basal conglomerate contains well-rounded clasts overlain by sandy limestones, siltstones and s[illegible] Late Liassic shallow-marine bivalve *Bostrica bronni* (Okay *et al.* 1991).

In Area 2 (S of Biga; Figure 7), the 'basement' is fault-bounded and unconformably overlying sediments have not been recognised. However, nearby sediments to the east take the form of thick-bedded, relatively coarse, pebbly arkoses that are likely to have formed part of the sedimentary cover of the granitic (e.g., near Sofular (Figure 21, log 2). In thin section these sandstones are dominated by well-rounded grains of monocrystalline quartz, plagioclase, alkali feldspar, perthite, micaschist and also polycrystalline quartz (quartzite), consistent with a mainly granitic source.

In Area 3, north of Balya (Figure 15), an intact Norian (Upper Triassic) succession (Balya Formation of Pehlivan *et al.* 2007) is dated by the presence of *Halobia neumayri* (Aygen 1956; Okay *et al.* 1991; [illegible]996). The lower part of this succession is mainly dark, finely laminated mudstone-siltstone with thin-shelled bivalve fragments (Altıner *et al.* 2000) and then passes upwards into lenticular polymict debris flows with clasts of neritic limestone, minor chert, granitic rocks and sandstone conglomerates (Figures 13g, 17j, k, l & 21, log 3 Admixed clasts of micritic or recrystallised neritic carbonate rocks (up to 30 cm in size) of Late Permian age are very similar to lithologies in the overlying mélange (~Hodul unit; Figure 17d). Some of the interbedded sandstones show the mixed granitic/siliceous metamorphic provenance typical of the upper Karakaya assemblage generally (i.e. Orhanlar, Hodul and un-named Permian–Triassic? unit; Figure 13d). Similar Norian-aged sediments have been reported from the Bursa region, near İğdir (Erk 1942). A further intact succession of thick-bedded to massive and pebbly sandstones of probable Late Triassic age is exposed further north (SE of Çamlıca; Figure 21, log 4), where it is overthrust by upper Karakaya assemblage rocks (~Hodul Unit). These sandstones contain basalt and hyaloclastite in addition to granite and silicic metamorphic sources (Figure 13e). Previously the Norian sequences (and similar but undated facies) in the central and northern Biga Peninsula were mapped as part of the Karakaya Complex (Okay *et al.* 1991). However, they can instead be interpreted as part of the cover of the regional 'basement'. The Norian sequence could either be *in situ* with respect to an unexposed basement, or relatively transported.

Further east, in Area 7 (south of Yenişehir; Figure 19) basement-type rocks are in contact with massive to thick-bedded, relatively coarse-grained arkosic sandstones (Kendirli Formation). The contact between the basement and the cover is mapped as either faulted or a normal contact in different areas (Genç & Yılmaz 1995). The arkosic sandstones in this area are overthrust by the upper Karakaya assemblage (~Çal Unit; Figure 19d). We observed that the contact between the schistose 'basement' meta-sediments and the arkosic sandstones (Kendirli Formation) is typically a series of E–W strike-slip faults (Figure 19b, c) that can be related to the North Anatolian Fault (Herece 1990; Şengör *et al.* 2005). However, very locally we identified an unconformity, as shown in Figure 19a. A thin section of the basal sandstone revealed mainly quartz, plagioclase, alkali feldspar and muscovite, mainly derived from granitic rocks. Overlying less altered medium- to coarse-grained sandstone with well-rounded grains is dominated by quartz, plagioclase and alkali feldspar derived from granitic rocks, with the addition of minor amounts of metamorphic quartz (quartzite) from a silicic metamorphic basement (Figure 13i).

Basement-cover Relations in the North

In Area 8, near Geyve (Figure 18), Turhan *et al.* (2004) have reported meta-granitic rocks and schistose meta-sedimentary rocks of inferred Variscan age (Figure 13j) to be unconformably overlain by Upper Permian cover sediments. Turhan *et al.* (2004) reported the existence of a lenticular, pebbly basal conglomerate composed of material derived from locally underlying lithologies. These clastic sediments (Canbazkaya Formation) were inferred to pass gradationally into Upper Permian (Midian) shallow-water carbonates. If correct, this would suggest that the limestone accumulated on the Sakarya Continent along the northern margin of Palaeotethys. Alternatively, the Upper Permian units might be exotic, related to the Upper Triassic mélange (~Hodul Unit).

We studied three sections across the 'basement' into Upper Permian carbonate sediments A section in the vicinity of a dirt road in the west (Figure 18a) begins with little-deformed, granitic rock that intrudes meta-sedimentary psammites and pelites. There is then a break in exposure within which pebbly sandstones and shales are highly sheared with well-developed C-S fabrics before Upper Permian limestones begin (Figure 13f). This interval is cut by high-angle faults in the adjacent forest. Where the road section recommences we observed highly sheared, thick-bedded arkosic sandstones and pebblestones with well-rounded quartzitic and granitic clasts (Figure 13l). Overlying grey marls (several metres thick) grade transitionally upwards into Upper Permian neritic limestones (Figure 18a).

In a previously undescribed stream section (Figure 18b) we observed thin- to medium-bedded black pelitic rocks intruded by a granitic pluton with chilled margins. Mainly pelitic and psammitic rock dip southwards at moderate angles and pass into psammites in beds up to several metres thick, alternating with thinner-bedded psammites and pelites. The sandstones are recrystallised so that no clear sedimentary structures have survived. The lithologies are similar to the Kalabak unit in the Biga Peninsula. South of a landslipped zone, in the streambed there is an appearance of brecciated, dark fossiliferous Upper Permian limestones that are in turn unconformably overlain by Upper Cretaceous pink hemipelagic limestones.

In an adjacent stream section (Figure 18c), described by Turhan *et al.* (2004), we observed little deformed granitic rocks intruding medium-bedded recrystallised psammites and dark pelites (~Kalabak unit). The contact between the 'basement' and the Upper Permian limestones is concealed by thick brushy vegetation, a soil cover and alluvial infill. Close to the inferred contact (within <1 m) we observed unmetamorphosed, highly fossiliferous mudstones and fine-grained arkosic sandstones (Figure 13k), followed after short a break in outcrop by Upper Permian neritic limestone. The higher levels of the exposed Upper Permian sequence include an intercalation (~2 m thick) of conglomerate, mainly composed of well-rounded quartzitic pebbles (up to several centimetres in size; Figure 8k).

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We were unable to observe an unconformity and basal conglomerate in any of the three sections studied. This, therefore, leaves open the possibility that the Permian limestones were tectonically emplaced over the 'basement'. However, these sediments must originally have accumulated on a continental basement to explain the transition from marl with terrigenous grains to neritic limestone locally with intercalated quartzitic pebbles. In this regard they are similar to the Upper Permian limestones with intercalated terrigenous sediments within the upper Karakaya assemblage generally (e.g., Bergama area; Figure 14). Additional outcrops where depositional contacts between 'basement' and Permian or Triassic 'cover' have been reported (e.g., Saner 1977, 1978) still need to be restudied. However, at this stage we find no convincing evidence that the Permian limestones are other than allochthonous slices as elsewhere in the upper part of the Karakaya Complex (i.e. related to the Hodul Unit).

Discussion

Rift-related Model

In different versions of the rift model (Figure 2a, b) the rifting either occurred by break up of a continental area (Bingöl 1973; Kaya *et al.* 1986; Kaya 1991), or by extension above a subduction zone (Göncüoğlu *et al.* 2000). The extension began prior to or during Late Permian time, as suggested by the reported occurrence in Area 8 (Geyve) of Upper Permian radiolarites (Göncüoğlu *et al.* 2004). Shallow-water limestones accumulated during Late Permian time on both the southerly and northerly margins of the inferred supra-subduction rift (Göncüoğlu *et al.* 2000; Turhan *et al.* 2004). Alkaline volcanics erupted in proximal rift areas represented by the Çal Unit (Genç & Yılmaz 1995) and in more distal areas represented by the Nilüfer Unit (Sayıt & Göncüoğlu 2009). On one variant, the rift widened sufficiently for oceanic crust to form, now represented by rare ophiolitic slices (e.g., in Area 8; Genç & Yılmaz 1995; Sayıt & Göncüoğlu 2009). The rift basin closed during latest Triassic time related to further southward subduction, culminating in northward emplacement of the Karakaya Complex (Genç & Yılmaz 1995; Sayıt & Göncüoğlu 2009).

The main problems with the rift interpretation are: (1) The inferred margins and floor of the rift represented by Variscan 'basement' show no obvious evidenceofPermiancrustalextension(e.g.,coevaldyke intrusion); (2) Both the predominantly volcaniclastic Nilüfer Unit (and equivalents) and the volcanogenic Çal Unit (and equivalents) lacks terrigenous detritus suggesting that volcanism occurred away from a continent (Pickett & Robertson 1996, 2004); (3) The Early Carboniferous (Visean) age of the oldest known neritic limestone blocks in the mélange makes a northerly derivation of these carbonates unlikely because this area was still experiencing Variscan magmatism and metamorphism (Altıner *et al.* 2000; Okay *et al.* 2006); (4) The Upper Permian limestones show Eurasian faunal affinities according to Leven & Okay (1996), whereas a Gondwanan affinity would be expected if the Karakaya Complex formed by rifting of Gondwana above a southward-dipping subduction zone (Göncüoğlu *et al.* 2000). On the other hand the fauna are inferred to be Gondwanan by Altıner *et al.* (2000); (5) The Upper Permian limestones of the supposed northern margin of the rift in Area 8 (Geyve; Figure 18) might instead be a thrust-emplaced part of the Triassic mélange (~Hodul unit); (6) The Upper Permian alkaline volcanics of the Çal Unit show no evidence of the subduction influence expected in the proximal part of a back-arc rift basin (Pickett & Robertson 1996). The Triassic volcanics of the Nilüfer Unit (e.g., in the type area) similarly lack a subduction chemical influence; (7) The rift model does not explain the occurrence of blueschists and eclogites (Monod *et al.* 1996; Monod & Okay 1999; Okay & Monié 1997; Okay *et al.* 2002) unless the marginal basin widened sufficiently for oceanic crust to be subducted during Late Triassic time; (8) If a wide backarc oceanic basin did exist then there is little or no evidence of any other Palaeotethyan ocean in the region; (9) The typical tectonostratigraphy of a rifted continental margin is absent, in contrast to many other Tethyan examples, for example the Arabian continental margin in Oman or the Pindos continental margin in Greece (e.g., see Robertson 2006).

Subduction-accretion Model

The Karakaya Complex formed by subduction and accretion of oceanic crust, volcanic build-ups from within Palaeotethys, in principle related to either southward subduction (Okay *et al.* 1991; Kozur *et al.* 2000), or northward subduction (Pickett & Robertson 1996; Ustaömer & Robertson 1997; Kozur l997; Okay 2000; Okay *et al.* 2006; Figure 2c). However, subduction is generally inferred to have been northwards beneath Eurasia, consistent with the limited available structural data. Southward subduction is also unlikely because there is no evidence of a backstop to an accretionary prism in the south. This area instead shows evidence of rifting and continental break-up during Late Permian–Early Jurassic time (Robertson *et al.* 2004; Okay *et al.* 2006; Mackintosh & Robertson 2009).

The Upper Permian volcanogenic Çal Unit restores as one or more volcanic build-ups (Pickett & Robertson 1996, 2004) that probably originated in a southerly part of Palaeotethys. The Upper Permian–Triassic(?) neritic limestones, floored by terrigenous sediments can be interpreted as rifted continental fragments. The fauna in the Upper Permian exotic limestone blocks (Çal Unit and Geyve limestones) are similar to the northern facies belt of the Taurides (Altıner *et al.* 2000), which as noted above can be interpreted as part of the southern margin of Palaeotethys (~northerly Tauride continental margin) (Robertson *et al.* 2004; Okay *et al.* 2006). The Triassic Nilüfer Unit (and equivalents) represents the accreted flank facies of large intra-oceanic volcanic build-ups (Pickett & Robertson 1996, 2004).

There are several apparent objections to the subduction-accretion hypothesis. First, pre-Late Permian deep-sea sediments are rare or absent in the Karakaya Complex which could be taken to indicate that no ocean basin existed prior to this time (Kozur *et al.* 2000). However, earlier Palaeotethyan oceanic crust is likely to have subducted during the Variscan orogeny, generating the Upper Palaeozoic granitic intrusives within the Palaeozoic basement. The oceanic crust that subducted to form the Karakaya Complex is likely to have formed by rifting of the northern margin of the Tauride microcontinent (Robertson *et al.* 2004; Okay *et al.* 2006). Initial rifting of Gondwana to form Palaeotethys is likely to have taken place during Early Palaeozoic time (Stampfli & Borel 2002). However, rifting of one or more fragments is inferred to have taken place also during Permian time giving rise to the dismembered sheets and blocks of neritic carbonates interbedded with terrigenous sediments in the Karakaya Complex (Robertson *et al.* 2004; Okay *et al.* 2006). Secondly, emplaced Permian or Triassic oceanic crust is minimal. Where present, MOR-type basalts of the Ortaoba Unit are overlain by only very thin Triassic radiolarites (<10 m) followed by sandstone turbidites. Perhaps little oceanic crust ever existed within the Karakaya basin (Kozur *et al.* 2000). However, it is more likely that Permian–Triassic MORB and its deep-sea pelagic cover were simply subducted. The Ortaoba Unit is likely to represent the preferential accretion of an oceanic high together with a veneer of siliceous pelagic sediments.

Thirdly, there is no evidence of Triassic arc magmatism associated with the Palaeozoic basement units, contrary to what would be expected for a northern active margin of Palaeotethys. Triassic subduction-influenced magmatism on the other hand is locally known in Tauride-related southerly units, notably in the Karaburun Peninsula (Robertson & Picket 2000; Tatar-Erkül *et al.* 2008). However, this magmatism appears to relate to Triassic continental rifting rather than subduction (Robertson & Pickett 2000; Okay *et al.* 2006; Robertson & Ustaömer 2009). Where present, the subduction signature in these volcanic rocks could have been inherited from sub-continental mantle lithosphere rather than being related to contemporaneous Permian or Triassic subduction (Robertson & Ustaömer 2009). Possible explanations for the lack of subduction related magmatism along the Eurasian margin include: (1) By Permian–Triassic time Palaeotethys was already relatively narrow in this region, owing to subduction and closure of Palaeotethys in the Balkan area to the west (Okay *et al.* 2006; Robertson & Ustaömer 2009a, b); (2) Subduction was short-lived, possibly contemporaneous with the Triassic break-up of Gondwana to form the Southern Neotethys (e.g., Antalya ocean basin); (3) Subduction was oblique suppressing arc magmatism; (4) Subduction was of too low an angle (<30°) to promote arc volcanism.

In summary, most of the objections to the accretionary interpretation have reasonable explanations.

Setting of Oceanic Magmatism

Assuming an accretionary origin, the Triassic Nilüfer Unit is interpreted to represent the volcaniclastic apron of several seamounts that were otherwise subducted (Pickett & Robertson 1996, 2004.) Given the regional extent of the outcrops across Anatolia the existence of a number of seamounts is inferred. The flank facies of these seamounts was preferentially accreted whereas the volcanic cores subducted. Some of the volcanic material is commonly moderately to highly vesicular (vesicles <2 mm in size) suggesting eruption in relatively shallow water (less than several hundred metres deep). However, some of the volcaniclastic turbidites and laminated meta-carbonates probably accumulated in deep water.

Alternatively, Okay (2000) proposed that the Nilüfer Unit originated as a single oceanic plateau related to a Triassic Large Igneous Province (Coffin & Eldholm 1994; Ernst *et al.* 2004). In agreement, insert "then" lar to the Nilüfer Unit (Genç 2004) are also dated as Late Triassic, for example from north and south of Uludağ metamorphic massif (G. Topuz personal communication 2010) and from the Ağvanis metamorphic massif in the Eastern Pontides (Topuz *et al.* 2010).

Genç (2004) compiled the available geochemical data for Nilüfer-like rocks in the Karakaya Complex of northwestern Turkey and noted that the chemistry varies from relatively rare enriched MORB (E-MORB) (in Areas 1 Edremit and 4 Bergama), to typically enriched (OIB-type) lavas (in Areas 5, 7 & 8) (Pickett 1994; Pickett & Robertson 1996, 2004). The near-MORB-type lavas erupted to form an oceanic plateau that was later capped by small seamounts erupting typical ocean island basalts in Genç's (2004) interpretation.

There are several problems with the oceanic plateau model. First, emplaced oceanic plateaux should be represented by thick units (kilometres thick) of massive basalt (submarine flood basalts) with minimal volcaniclastic material or interbedded sediments, similar for example to the Ontong-Java and Kerguelen large igneous provinces exposed on land (Coffin & Eldholm 1994; Ernst *et al.* 2004). However, such rocks have not been reported from the Nilüfer Unit. Secondly, subaqueous flood basalts cover vast areas of the ocean floor without forming steep-sided build-ups that could given rise to the large volumes of volcaniclastic sediments (e.g., debris flows) observed in the Nilüfer Unit and equivalents. Thirdly, known modern and ancient oceanic plateaus range in chemical composition from near-MORB, to E-MORB, to low Ti-basalts and high-magnesian basalts (Coffin & Eldholm 1994; Ernst *et al.* 2004) and so differ from the ocean island-type volcanics that predominate in the Nilüfer Unit. For example, the Ontong-Java Plateau basalts are low-K tholeiites with a small range of major element, trace element and Nd-Pb-Sr-Hf isotopic variation (Fitton & Goddard 2004).

In the modified large igneous province model of Genç (2004) the main oceanic plateau model is assumed to have subducted more or less without trace whereas perched late-stage seamounts were preferentially accreted to form the Nilüfer Unit. Such seamounts are indeed associated with the Ontong-Java and Kerguelen large igneous provinces amongst other (Coffin & Eldholm 1994; Frey *et al.* 2000; Coffin *et al.* 2002; Ingle *et al.* 2002; Ernst *et al.* 2004). However, this interpretation is problematic for several reasons. First, where present (e.g., in the Edremit area) the E-MORB is interbedded with volcaniclastic sediments showing that this did not form part of a pre-existing oceanic plateau. Secondly, where present, the E-MORB plots on a fractionation trend with more evolved WPB from the same area (e.g., Edremit 'green lava suite'; Pickett 1994). Thirdly, MORB lavas are rare in the Karakaya Complex (Pickett & Robertson 1996, 2004; Genç 2004) and are not candidates for a missing oceanic plateau. Fourthly, it is not clear why an oceanic plateau on the scale of Turkey should have entirely subducted without trace. This contrasts, for example with the Ontong-Java Plateau, which was sufficiently large to influence regional subduction polarity leading to land exposure (Coffin & Eldholm 1994; Petterson *et al.* 1998; Taylor 2006). Also, within the circum-Caribbean region the collision of an oceanic plateau with an active margin resulted in tectonic emplacement of large bodies of chemically depleted basaltic rocks (Kerr *et al.* 1997, 1998; Hauff *et al.* 2000).

The main objection to the alternative origin as several seamounts (Pickett & Robertson 1996, 2000) is one of scale: the Nilüfer-type rocks extend for

>1000 km east- west across Turkey, far larger than any single modern oceanic seamount (Okay 2000). However, it is not known if all of the Nilüfer-like units in different areas formed at the same time even if they were all metamorphosed during the Late Triassic (Topuz *et al.* 2010). Also there is growing evidence that some Nilüfer-like volcanogenic rocks erupted in a contrasting subduction-related setting, for example in the Ankara Mélange (Sayıt & Göncüoğlu 2009) and on the Marmara Island (unpublished data). Several seamounts with fringing carbonate banks could instead have existed, each with its own volcaniclastic apron, similar to the Hawaiian Islands and Emperor Seamounts hot-spot chain. Several large seamounts could have collided with a trench, downfaulting and subducted one-by-one by processes similar to the Daiichi-Kashima Seamount in the Japan trench (Kobayashi *et al.* 1987). In this interpretation the associated fringing carbonates and volcaniclastic aprons where preferentially underplated beneath the 'fore-arc' to form the higher-grade Karakaya rocks (~Nilüfer Unit) while the seamount cores were subducted. If the seamounts were orientated generally E–W then, following northward subduction, they could have been emplaced within a relatively short time interval during Late Triassic time.

Model of Genesis and Emplacement

Any accretionary model needs to explain the tectono-stratigraphy of the Karakaya Complex, as in the Biga Peninsula (Figure 22). The restored setting of formation and emplacement of each of the lithotectonic units is shown in Figure 23.

The Variscan sedimentary basement (~Kalabak unit) is interpreted as tectonically assembled terrigenous turbidites, together with minor ultramafic ophiolitic rocks, black chert and volcanic basic-silicic rocks, and possibly represents a Devonian or older subduction complex. This was followed by the intrusion of Late Palaeozoic granitic rocks of I- and S-type chemical affinities that are interpreted as arc and/or post-collisional magmatism (Lower-Mid Devonian: Aysal *et al.* 2011; Early Carboniferous: Kibici *et al.* 2010) (Figure 24a). The Variscan basement is interpreted as part of the northern active margin of the Sakarya Continent during Permian–Triassic time. However, it is not known if subduction continued from Late Palaeozoic to Early Mesozoic without a break.

Northward subduction is assumed to have been active during the Late Permian, coupled with rift-related magmatism and splitting of one or more continental fragments from Gondwana (Figure 24b). The Upper Permian shelf carbonates with terrigenous intercalations are interpreted to have rifted from the southern margin, taking with them fragments of an older carbonate platform (preserved as sparse Lower Carboniferous exotics in the Orhanlar Unit). The Upper Permian Çal Unit in the Biga Peninsula is interpreted as a large seamount capped by carbonate build-ups within the Permian ocean (Figure 24b). One alternative is that the Çal volcanogenic unit and the un-named terrigenous related Upper Permian limestones represent separate oceanic seamount and continental margin units. Another is that both of these units restore as proximal to distal parts of a rifted continental margin. The inferred rifted fragments (un-named unit) and the volcanics (~Çal Unit), drifted northwards until they collided with the Sakarya active continental margin and accreted, while their basements subducted (Figures 24c & 25a). During accretion, the Upper Permian carbonate platform initially faulted giving rise to limestone talus and then dissected into blocks that became admixed with Triassic arkosic turbidites derived from the Sakarya Continent. One seamount accreted as a relatively intact body (Çal Unit), while comparable volcanics and associated sediments were incorporated as blocks and slices mainly within the accretionary Hodul Unit. Some already accreted neritic carbonate, radiolarian chert and basalt were reworked in a high-energy shallow-marine (or non-marine) setting and later reworked into a deep-sea trench setting together with less texturally mature sediment. This was followed by re-accretion within trench-type turbidites (Orhanlar Unit). Triassic oceanic crust is inferred to have formed in the wake of the migrating seamount(s) and continental fragment(s). MORB and overlying radiolarian sediments (~Ortaoba Unit) also migrated into the trench where they were covered by feldspathic turbidites and then accreted (Figure 24c).

Several large oceanic seamounts erupted in the midst of the Triassic ocean, capped by reefal build-ups

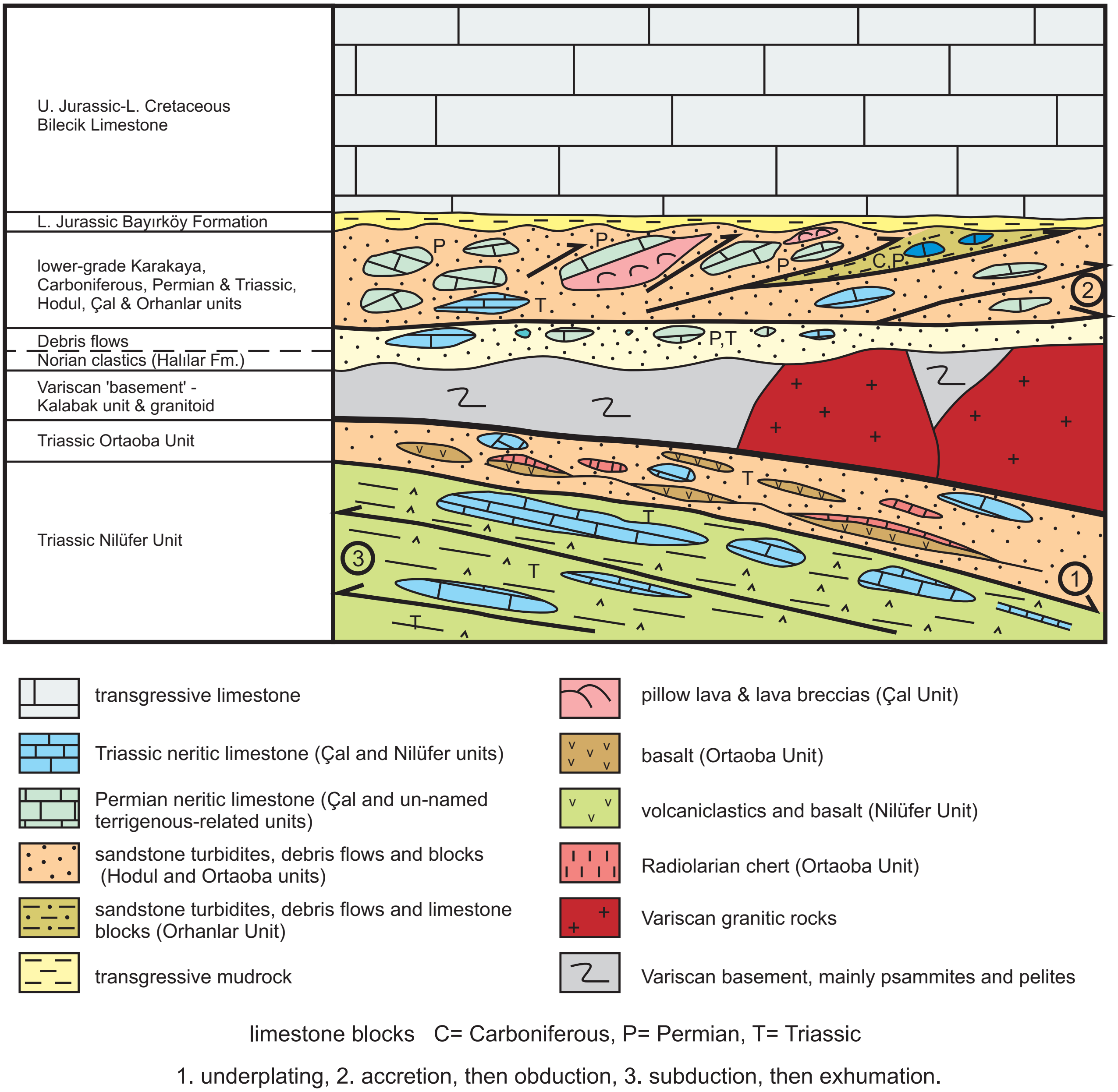

Figure 22. Rock-relations diagram summarising the tectono-stratigraphy of the Karakaya Complex and related 'basement' in the type area of the Biga Peninsula, NW Turkey. The lower Karakaya assemblage (~Triassic volcanogenic-carbonate Nilüfer Unit) and part of the upper Karakaya assemblage (i.e. Triassic basalt-chert-turbiditic sandstone ~Ortaoba Unit) are overlain by a slice of Variscan 'basement' (~Kalabak unit) including Devonian granitic rocks. The 'basement' is unconformably overlain by Upper Triassic (Norian) deltaic to shallow-marine clastic sediments. In some areas arkosic sandstones pass gradationally upwards into heterogeneous debris flows. Above comes a mélange (~Hodul Unit) dominated by slices and blocks of Permian neritic limestones and volcanogenic rocks (~Çal Unit). The mélange is unconformably overlain by Lower Jurassic, argillaceous sediments that grade upwards into Upper Jurassic–Lower Cretaceous platform carbonates. Note that the structurally underlying high-grade basement Kazdağ, a Cenozoic core complex, is omitted.

and fringed by volcaniclastic slope aprons (~Nilüfer Unit; Figure 24c). These drifted northwards until they collided with the Sakarya active margin during Late Triassic. Carbonate build-ups were occasionally decapitated and emplaced into the accretionary prism above (e.g., Camialan Limestone). In contrast, deep-

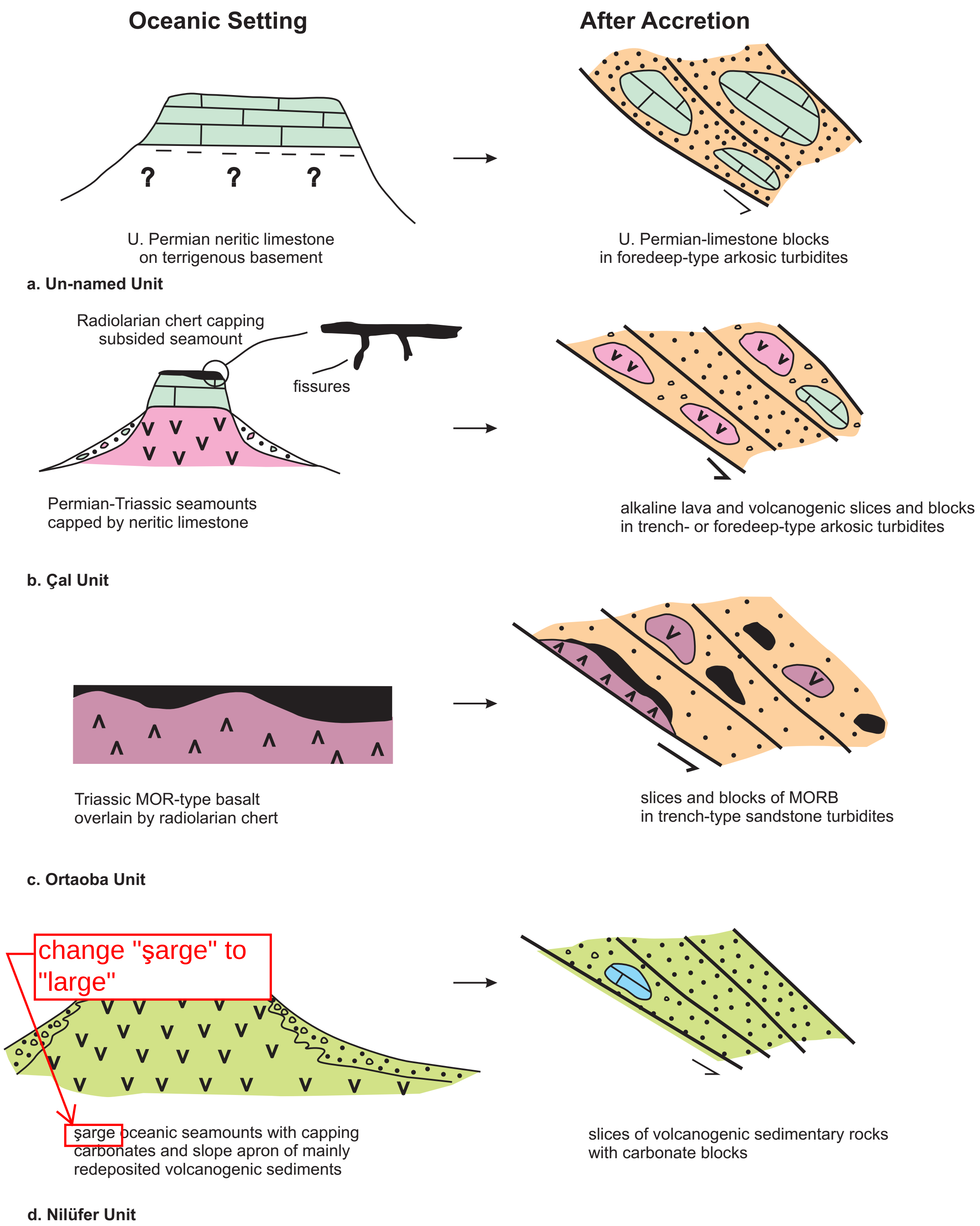

Figure 23. Inferred setting of genesis and accretion of four contrasting units of the Karakaya Complex. **(a)** Upper Permian–Triassic(?) neritic limestones interbedded near the base and underlain by terrigenous, continent-derived clastic sediments (un-named unit); **(b)** Çal Unit. Upper Permian volcanogenic rocks and related limestones and cherts; **(c)** Ortaoba Unit. Triassic oceanic crust overlain by red ribbon radiolarite, passing into feldspathic sandstones; **(d)** Nilüfer Unit. Triassic slope apron of large intraoceanic seamount(s). See text for discussion.

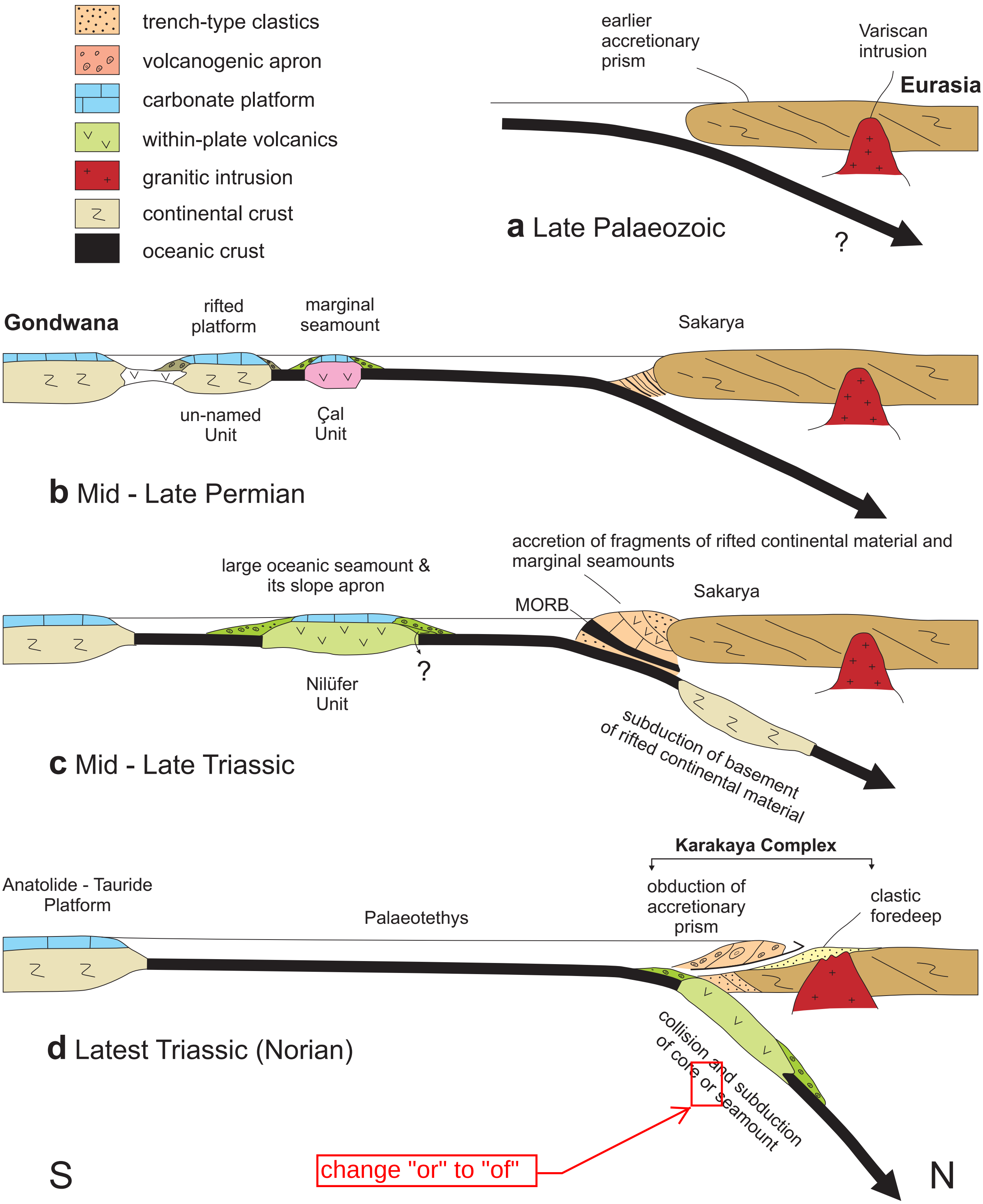

Figure 24. Tectonic model for the origin and emplacement of units making up the Karakaya Complex in northern Turkey. See text for discussion.

water slope aprons were sliced, intercalated with terrigenous sediment and underplated to the Sakarya continental basement where HP/LT metamorphism took place. Rapid exhumation during latest Triassic time was possibly facilitated by slab rollback, resulting in occasional interslicing with eclogitised oceanic lithosphere.

The attempted subduction of large Triassic seamounts (~Nilüfer Unit) caused the accretionary wedge to be emplaced northwards (Figure 25b). A likely process is uplift and gravity spreading to maintain a critical taper. This resulted in isostatic loading of the leading edge of the overriding plate (~Variscan basement) and the creation of a rapidly subsiding foreland basin. Up to 1000 m of clastic sediments accumulated during Norian time, derived from the Variscan hinterland. The basement cover was then overridden by the previously formed accretionary wedge to the form mélange that is regionally extensive (~ Hodul and Orhanlar units; Figure 25c). The distance of thrusting is estimated to be at least tens of kilometres. Debris flows dominated by detached limestone blocks were shed from the advancing allochthon and then overridden (Figures 25c). Final emplacement took place during latest Triassic–earliest Jurassic (?) (~210–202 Ma). Following uplift and erosion, the emplaced accretionary complex was transgressed by shelf sediments dating from Lower Jurassic (Sinemurian–Pliensbachian) time.

Conclusions

1. This study of the various units of the Karakaya Complex in nine outcrop areas across northwestern Turkey shows that the contacts between the major contrasting litho-tectonic units originated as primary thrust faults. No evidence was found of stratigraphical contacts or even of sheared stratigraphical contacts.
2. Basement units associated with the Karakaya Complex are interpreted as a Devonian (or older) subduction complex that includes terrigenous sediments (probably turbidites), black chert, small carbonate blocks, basic volcanic blocks or lenses and local meta-serpentinite. The assemblage is cut by Variscan subduction-related plutons in several areas. The basement is locally overlain by deltaic to deeper-marine arkosic sandstones, mudrocks and debris flows of latest Triassic (Norian) age.
3. The higher-grade rocks of the lower Karakaya assemblage (Triassic Nilüfer Unit) are mainly oceanic volcaniclastic sediments and associated neritic limestone blocks, repeated by thrusting.
4. The lower-grade rocks of the upper Karakaya assemblage include two distinct Upper Permian lithotectonic units (Çal Unit and an unnamed terrigenous-associated limestone unit). These are regionally associated with two Triassic mélange units, the regional-scale Hodul Unit and the more local Orhanlar Unit.
5. Some of the blocks of Upper Permian shallow-water limestones are depositionally underlain, and locally interbedded with, siliciclastic sediments showing that they formed adjacent to a continental area.
6. The Triassic mélanges of the upper Karakaya assemblage (~Çal & Orhanlar units) comprise slices and blocks of mainly limestones and volcanics admixed with sandstone turbidites and subordinate mass-flow deposits. These units are tectonic slice complexes rather than sedimentary olistostromes;
7. The Upper Palaeozoic basement subsided rapidly during the Late Triassic accommodating up to ~1000 m of non-marine, to shallow-marine mainly deltaic sediments. The erosional d[illegible]ifting Late Palaeozoic g[illegible]r host siliciclastic rocks (~Kalabak unit).
8. The Karakaya Complex was emplaced northwards onto the southern continental margin of the Sakarya micrcontinent during latest Triassic (Norian)–earliest Jurassic (?). This was followed by subaerial erosion and transgression by contrasting shallow-marine sediments from Early Jurassic time onwards.
9. Our preferred tectonic model for the formation and emplacement of the Karakaya Complex involves northward subduction of Palaeotethyan oceanic crust, resulting in the accretion of Upper Permian–Lower Triassic shallow-water

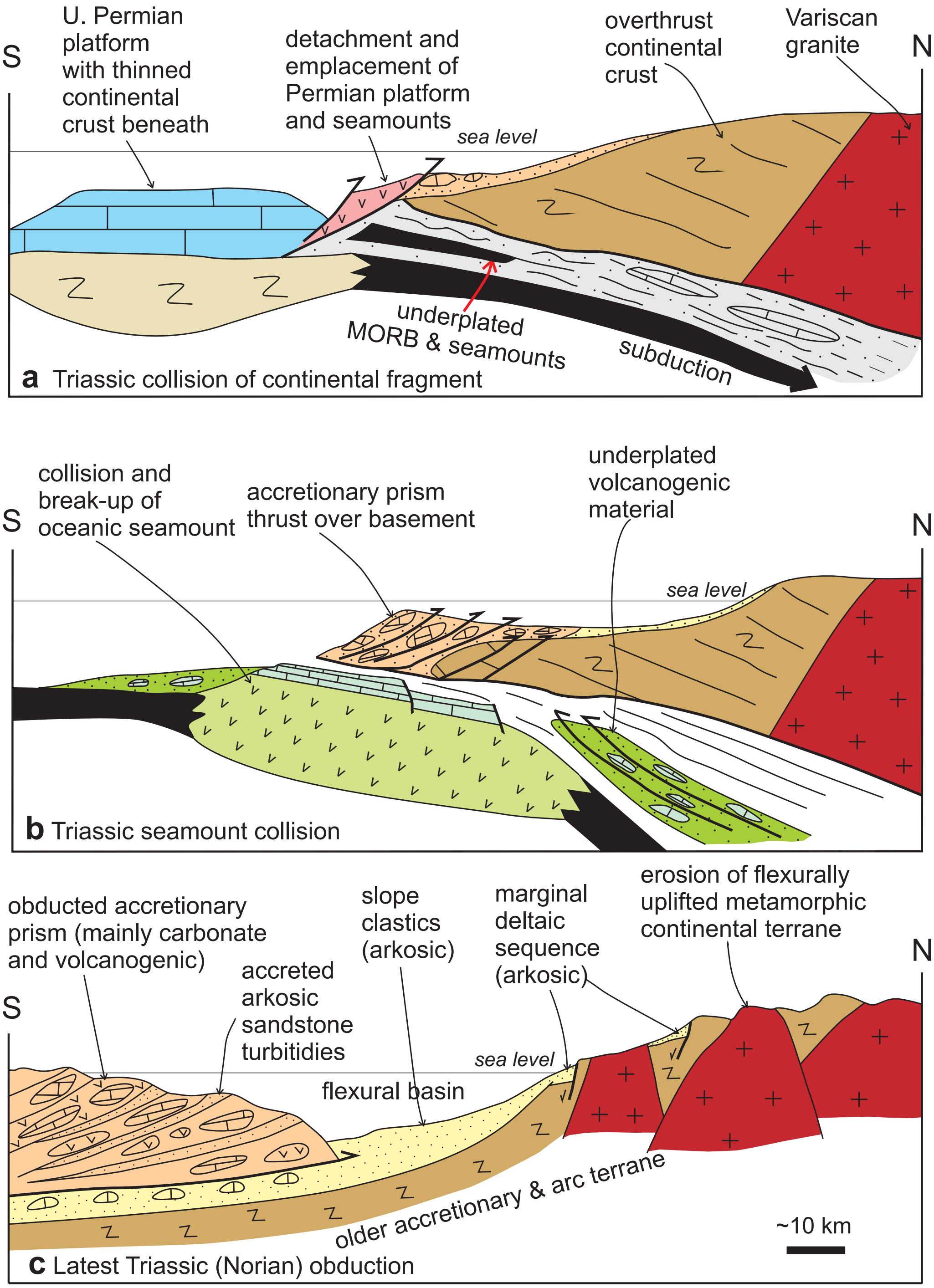

Figure 25. Inferred setting of emplacement of the Karakaya Complex; **(a)** Early-stage (Mid-Late Triassic) collision of a Upper Permian carbonate platform with a subduction trench causing delamination from underlying continental basement and initial obduction of thrust sheets and mélange dominated by Permian neritic limestone Çobanlar Unit) together with volcanogenic material (Çal Unit) in a matrix of trench-type arkosic sediments (~Hodul unit); **(b)** Later-stage (Late Triassic–Norian) collision of one, or several, large oceanic seamounts with the same active margin. The seamounts where underplated at depth beneath the active continental margin where they experienced HP/LT metamorphism (Nilüfer Unit); **(c)** The initial emplacement of the accretionary wedge led to formation of a sediment-filled flexural foredeep during Norian time and this was then over-ridden by the mélange.

carbonates, Upper Permian alkaline volcanics and large Triassic oceanic seamounts along the southern, active margin of the Sakarya Continent. The accreted material was emplaced northwards over the Sakarya Continent in response to the inferred collision of the Triassic seamounts with the subduction trench. Basaltic seamount cores were subducted while former volcaniclastic aprons underplated to the Sakarya active margin. They were then metamorphosed under high pressure-low temperature conditions, exhumed, locally intercalated with eclogitised oceanic crust and regionally emplaced.

10. Especially in the Biga Peninsula, the Karakaya Complex was further deformed related to Late Mesozoic–Early Cenozoic collisional deformation, Cenozoic extension related to southward rollback of the South Aegean arc-trench system and neotectonic strike-slip/ transpression during the tectonic escape of Anatolia along the North Anatolian Fault.

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