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REPLY

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Stratigraphic and metamorphic inversions in the central Menderes massif. A new structural model

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Introduction

In Okay (2001), I described the geology of the southern Ödemiş submassif, where there is evidence for metamorphic and stratigraphic inversions. Based on previous work, I suggested that the whole of the Ödemiş submassif forms an inverted sequence over an area of 85 by 70 km. In contrast, the stratigraphic and metamorphic sequences in the Çine submassif in the south are known to be upright. On the basis of a lithostratigraphic correlation between the Ödemiş and Çine submassifs, I put forward a recumbent fold model for the Menderes Massif. Gessner et al. (2001a) address four topics related to this model: (1) lithological correlations, (2) thrusting versus normal faulting, (3) the structural and geometric viability, and (4) implications for the Alpine orogeny. I discuss these points below:

Lithostratigraphic correlation

Lithostratigraphic correlation between the Çine and Ödemiş submassifs and the existence of inverted metamorphism in the Ödemiş submassif form the basis of the Menderes fold model, and, therefore, require a critical discussion. In the late 1970s and 1980s a stratigraphy of the Menderes Massif was established based on work in the Çine submassif (Fig. 1; Dürr 1975; Çağlayan et al. 1980; Konak et al. 1987). In this region, orthogneisses with Pan-African zircon (~550 Ma) and Eocene (43–38 Ma) Ar–Ar mica ages form the base of the sequence (Hetzel and Reischmann 1996; Loos and Reischmann 1999). They are overlain by the Selimiye formation of unfossiliferous garnet–mica-schists with rare quartzite and metabasite interlayers. The Selimiye formation passes up into a very characteristic marble–phyllite–quartzite series, the Göktepe formation, which have yielded Permian and Carboniferous coral, algae, brachiopods and fusulinid-type foraminifera in several localities (e.g., Phillippson 1918; Önay 1949; Dürr 1975). The Göktepe formation is overlain by emery- and metabauxite-bearing marbles, which contain Triassic and Cretaceous macro and microfossils (Dürr 1975; Özer et al. 2001). The neritic carbonate series extend up to Campanian, and are overlain by red pelagic marbles with Late Campanian–Late Maastrichtian *Globotruncana* species (Özer et al. 2001). Slightly metamorphosed flysch and wildflysch with Middle Paleocene foraminifera lie over the pelagic carbonates and mark the end of sedimentation in the Menderes Massif (Fig. 1). The Lower Tertiary flysch of the Menderes Massif is tectonically overlain by the Triassic clastic and carbonate rocks of the Lycian nappes. This well-established stratigraphy can be traced for 200 km along the southern rim of the Menderes Massif from the Bafa Lake to Babadağ (cf. Fig. 2 of Okay 2001).

I extended this well-known stratigraphy of the Çine submassif 120 km north to the Ödemiş submassif. Gessner et al. (2001a) object to this correlation on the grounds that in the Menderes Massif "mylonitisation and metamorphism, the latter of which in part reached anatectic conditions, occurred during at least two orogenies... large-scale lithological correlations in high-grade multiply metamorphosed and deformed rocks are problematic". However, as discussed below, there is evidence only for a single *Phanerozoic* orogeny including metamorphism in the Menderes Massif, and most of the Menderes Massif consists of low-grade greenschist-facies metamorphic rocks (Fig. 2).

It is not clear as which two orogenies Gessner et al (2001) refer when they discuss metamorphism in the Menderes Massif. Ashworth and Evirgen (1984), which they cite in support of their statement, write in their abstract "Local retrograde effects are noted but *no evidence is found for a polymetamorphic record* in the mineral compositions". Hetzel et al. (1998) and Ring et al.

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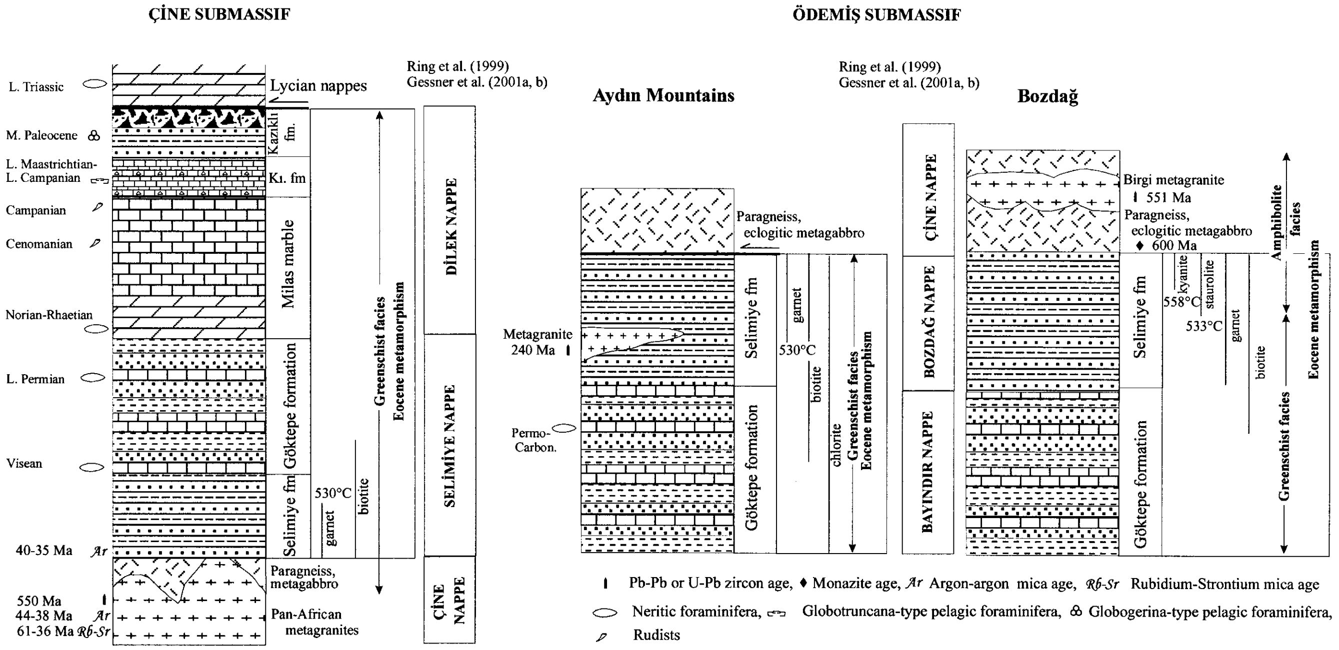

Fig. 1 Stratigraphic, metamorphic and isotopic data from the Çine and Ödemiş submassifs (stratigraphy: Dürr 1975; Çağlayan et al. 1980; Okay 2001; Özer et al. 2001; metamorphism: İzdar 1971; Evirgen and Ataman 1982; Ashworth and Evirgen 1984, 1985; Evirgen and Ashworth 1984; Okay 2001; isotopic data: Satır and Friedrichsen 1986; Hetzel and Reischmann 1996; Hetzel et al. 1998; Loos and Reischmann 1999; Koralay et al. 2001). The "nappe" terminology of Ring et al (1999) and Gessner et al. (2001a, 2001b) is shown for comparison. Note that in the Çine submassif these "nappes" emplace younger rocks over older rocks, and the stratigraphic range of each "nappe" is mutually exclusive, unlike any known nappe pile. *L.* Late; *M.* middle

(1999) refer to Pan-African, Cimmerian and Alpide deformation and metamorphism in the Menderes Massif. The existence of a Pan-African regional metamorphism and deformation, reaching granulite and eclogite facies conditions, followed by the intrusion of 550 Ma granites is accepted by all workers in the Menderes Massif (e.g., Dora et al. 2001; Candan et al. 2001). Paleozoic to Lower Tertiary sediments were laid down on this Pan-African basement followed by the Alpide deformation and metamorphism during the Eocene. The only data for a Triassic orogeny are small Lower Triassic metagranitic intrusives in the Ödemiş submassif (Fig. 1; Koralay et al. 2001). Garnet–mica-schists of the Selimiye formation lying immediately above the Pan-African metagranites in the Çine submassif have yielded muscovite Ar–Ar ages of 40–35 Ma with no indication of a Triassic heating event (Fig. 1; Hetzel and Reischmann 1996) or polymetamorphism (Ashworth and Evirgen 1984). The isotopic data, absence of polymetamorphism in the Phanerozoic sequence of the Menderes Massif, stratigraphic continuity between the Permo-Carboniferous and Triassic series leaves little room for a Permo-Triassic metamorphism and deformation, as speculated by Akkök (1983) and Ring et al. (1999). The stratigraphic sequences in the Tauride nappes, which have shared the same paleogeographic realm as the Menderes Massif, extend from Cambrian to Late Cretaceous/Eocene with no evidence of a Permo-Triassic metamorphism or orogeny (e.g., Gutnic et al. 1979). Stratigraphic, isotopic and petrological data indicate that the post-550 Ma sequence of the Menderes Massif has been affected by a single contractional metamorphic and deformational event during the Eocene.

Although I agree that "large-scale lithological correlations in high-grade multiply metamorphosed and deformed rocks are problematic", the major part of the Ödemiş and Çine submassifs is neither high-grade nor multiply metamorphosed (Figs. 1 and 2). Most of the region shows only greenschist-facies metamorphism with the exception of a small area north of Ödemiş. Primary structures, such as bedding, are readily recognizable in the field in the Ödemiş and Çine submassifs. The marble–phyllite–quartzite series in the Ödemiş submassif (in both Bozdağ and Aydın Dağları), which I correlated with the Göktepe formation, is in lower greenschist-facies. Typical metamorphic minerals in metapelites in this series is quartz + plagioclase + muscovite + chlorite ± biotite ± chloritoid (İzdar 1971; Evirgen and Ataman 1982; Okay 2001). The overlying Selimiye formation is in greenschist-facies in the southern Ödemiş submassif (Okay 2001) and in greenschist to amphibolite facies in the northern Ödemiş submassif (Evirgen and Ataman 1982). Furthermore, petrological studies have shown that a single Barrovian-type metamorphism has affected the Selimiye and Göktepe formations in the Ödemiş and Çine submassifs (Ashworth and Evirgen 1984, 1985; Okay 2001). Contrary to the statement of Gessner et al. (2001), metabasites intercalated with the mica-schists in the Selimiye formation in the Ödemiş submassif (the Bozdağ "nappe" of Ring et al. 1999) do not contain any evidence for any early eclogite-facies metamorphism (Okay 2001; Hetzel et al. 1998).

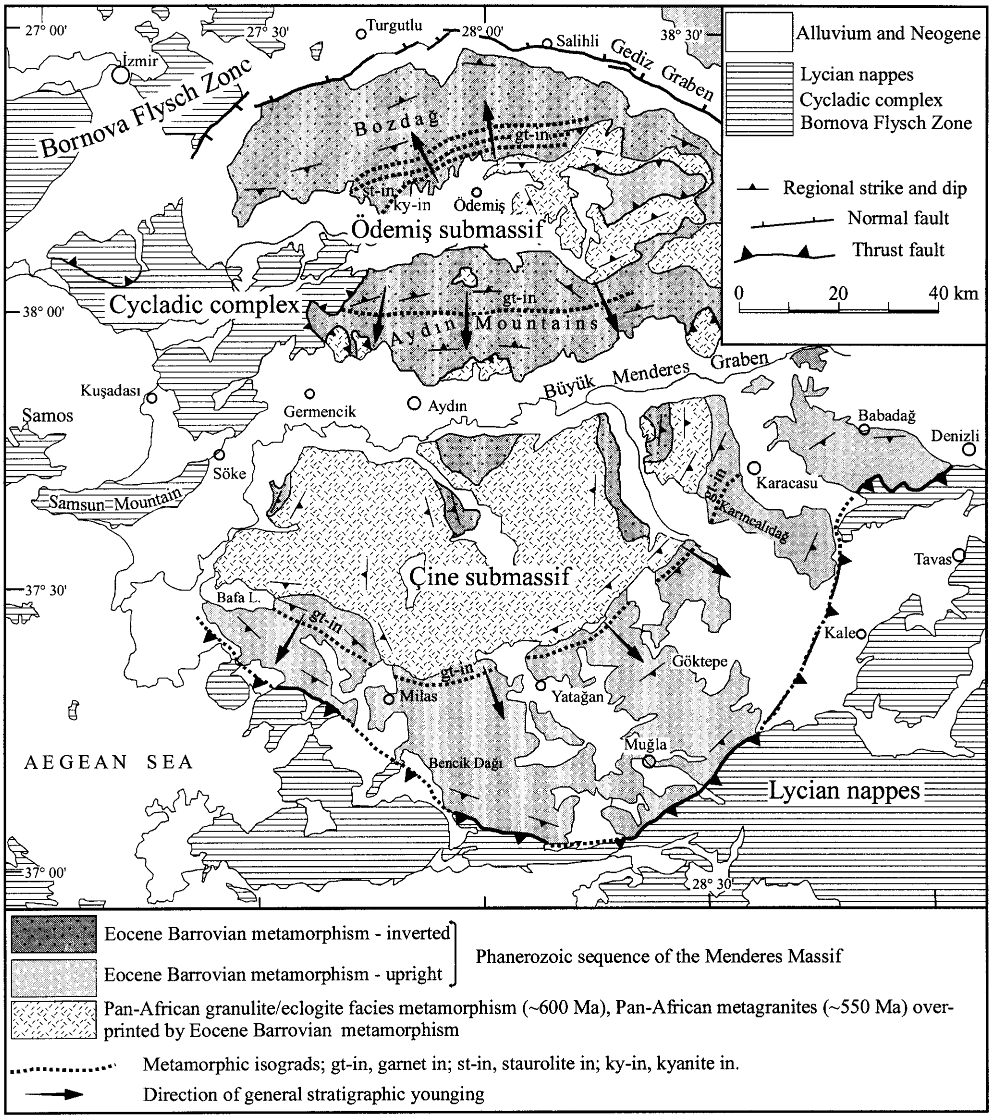

Fig. 2 Metamorphic map of the Menderes Massif showing the isograds of the Eocene Barrovian regional metamorphism (Evirgen and Ataman 1982; Ashworth and Evirgen 1984; Evirgen and Ashworth 1984; Okay 2001). *Black arrows* indicate the general stratigraphic younging direction in the Phanerozoic sequence of the Menderes Massif. For a more detailed geological map of the Menderes Massif see Fig. 2 of Okay (2001)

A second important point is that the correlation of the Göktepe and Selimiye formations between the Çine and Ödemiş submassifs is not lithological, but lithostratigraphic. Therefore, the statement that "metapelite, which appears similar in the field (to the Göktepe formation) occurs as xenoliths in 550 Ma orthogneiss" is not very relevant. In the Çine submassif, the Göktepe formation lies stratigraphically over monotonous garnet–mica-schists of the Selimiye formation (Fig. 1). In the Ödemiş submassif, the sequence is inverted and monotonous garnet–mica-schists overlie a lower-grade marble–phyllite–quartzite sequence, which I correlated with the Göktepe formation. Citing unpublished work, Gessner et al. (2001a) suggest that the boundaries in the Ödemiş submassif are in fact greenschist-facies shear zones. In a deformed metamorphic area such as the Menderes Massif, shearing and thrusting will be expected to concentrate along major lithological boundaries. In the Aydın Mountains part of the contact between the Selimiye formation and the underlying Göktepe formation is a thrust (Okay 2001). However, these shear zones of unconstrained offsets are not evidence against the Menderes fold model.

Second, critical evidence for the Menderes fold model is the large-scale metamorphic inversion in the Ödemiş submassif. İzdar (1971), who is credited by Gessner et al (2001a) with the initial description of the metamorphic inversion, does not mention or even imply an inversion of metamorphic isograds in the Bozdağ, where he worked. Hetzel et al. (1998) described a metamorphic inversion from the northern Ödemiş submassif, which they related to the "numerous north-directed thrusts", although evidence for these thrusts was not provided. It is also difficult to envisage numerous thrusts creating a regular inverted metamorphic sequence over a vertical thickness in excess of seven kilometers (Evirgen and Ataman 1982). In the southern Ödemiş submassif the metamorphic inversion with the garnet zone overlying the biotite zone is well exposed in the rugged topography (Okay 2001).

Lithostratigraphic correlation between the Çine and Ödemiş submassifs involves greenschist-facies Phanerozoic cover units of the Menderes Massif, namely the Göktepe and Selimiye formations. These formations have undergone only a single period of orogeny and regional metamorphism, and retain many of their sedimentary features. There is little ambiguity in correlating these distinctive lithostratigraphic units across a distance of 120 km.

Thrusting versus normal faulting

In orogenic belts, such as Western Alps, Himalaya or Appalachians, low-angle faults that emplace older sequences on younger sequences are generally thrusts, and those that emplace younger units over older units are normal faults or extensional shear zones. Disregard of this simple rule have led to the thrust interpretation of the extensional detachments in the Basin and Range province in USA or in the Cyclades in the Aegean. Naturally there are exceptions to this rule, but these have to be demonstrated as such.

In the southern Ödemiş submassif, flat-lying sheets of Pan-African augen-gneiss lie tectonically over lower-grade metamorphic rocks (fault 1 of Gessner et al. 2001a). There is no spatial or temporal relation between these flat-lying gneiss klippen distributed throughout the southern Ödemiş submassif, and the southward-dipping, much steeper Neogene to active normal faults of the Büyük Menderes Graben. Therefore, I interpreted the gneiss klippen as part of a major thrust sheet, which possibly also includes the high-grade schists and gneisses of the Kiraz region. An extensional detachment interpretation of the fault zone under the gneiss klippen, as favored by Emre and Sözbilir (1997) and Gessner et al. (2001a), poses more problems, and there is no data to prefer this complex interpretation. In fact, Lips et al. (2001) dated schists directly below the gneiss klippen in the Aydın Mountains and obtained an Ar–Ar muscovite age of 36 Ma. This isotopic datum indicates that the emplacement of the gneiss thrust sheet is related to the Eocene contractional tectonics rather than to the Early Miocene extension.

The gneiss klippen described by Hetzel et al. (1995) from the northern margin of the Ödemiş submassif are two small bodies, caught up in the normal fault system of the Gediz graben. In contrast to the much larger gneiss klippen in the Aydın Mountains, the small gneiss klippen in the northern Bozdağ are strongly affected by the Neogene to recent extensional tectonics. The Neogene structures in these gneisses have no relevance to the Eocene contractional history of the Menderes Massif.

Structural and geometric viability

Gessner et al (2001a) argue that no structural evidence is presented for the two folding events (D_A and D_B) in Okay (2001). The apparent antiformal axis (D_B) along the Büyük Menderes and Gediz grabens are largely caused by the Neogene to Recent shoulder uplift along the grabens, and are not related to a contractional folding episode. However, the gentle east–west trending synformal anticline along the Küçük Menderes valley must be related to a late folding event, possibly represented by the open folds, and late stage kink bands with east–west trending axis described in the southern Ödemiş submassif (Okay 2001).

The outcrop pattern of the Menderes Massif and the orientation of foliation in the Menderes Massif (Fig. 2 of Okay 2001) indicate that the Menderes fold has the shape of a north–south-elongated sheath fold with the hinge line folded around a north–south axis. The ubiquitous north–south mineral stretching lineations in the Menderes Massif, often ascribed to extensional tectonics, is most probably related to the D_A folding event. In strongly deformed areas minor fold axis are known to rotate towards the extension direction, which explains the parallelism of the minor fold axis and the stretching lineation in the Menderes Massif. As only the upper limb of the Menderes fold is exposed in the Çine submassif (cf. Fig. 8 of Okay 2001), no change of vergence of minor folds are to be expected along this transect.

Implications for the Alpine orogeny of the Menderes Massif

Gessner et al. (2001a) calculate that the Menderes fold model implies a large amount of shortening and, therefore, they question its validity. This argument is difficult to understand because if the Menderes fold model is correct, then a large amount of shortening must have occurred in western Anatolia, which is what is expected in an orogenic belt. The pile of cover nappes in the Taurides also suggest a large shortening of the upper crust (Gutnic et al. 1979). The lower crust was possibly removed by continental subduction, a phenomenon that is recognized in several orogenic belts.

Western Anatolia is part of the Alpide orogenic belt formed during the Late Cretaceous and Tertiary through subduction of the Tethys ocean and subsequent continental collision of Gondwana and Laurasia, as well as smaller continental fragments in between (Şengör and Yılmaz 1981; Okay and Tüysüz 1999). The amount of north–south shortening since the Late Cretaceous between stable Africa and Europe along the western Anatolia transect, based on the Atlantic ocean floor data, exceeds 2,500 km, and is far greater than that along the Western Alps (Patriat et al. 1982; Livermore and Smith 1984). North–south shortening along the western Anatolian transect since the Middle Eocene, when most of the Tethyan oceans were completely subducted, is about 800 km. A significant amount of this shortening must have been taken up by the continental crust of the western Anatolia, including the Menderes Massif.

Recent studies in the Menderes Massif place undue attention on the shear zones in the metamorphic rocks, which often give different shear senses (e.g., Hetzel et al. 1998; Bozkurt 2001; Gessner et al. 2001b; Lips et al. 2001). In these studies cumulative offsets in the shear zones are not constrained. In almost all cases there is no noticeable change of metamorphic grade across the shear zones, and many shear zones occur within a single lithostratigraphic unit, all indicating that the cumulative offsets across the shear zones are minor. It is unlikely that these shear zones accommodate much of the shortening as suggested by the ocean floor data or much of the extension. In the nappe model of Ring et al. (1999) younger sequences are emplaced over older sequences in the Çine submassif and each nappe has a mutually exclusive sequence age (Fig. 1), unlike any known nappe pile in orogenic belts. Therefore, the problem in the Menderes Massif is not the excess of shortening, but rather the lack of it.

Conclusions

The stratigraphy as well as isotopic and petrological data from the Menderes Massif indicate a single period of Phanerozoic contractional deformation and metamorphism during the Eocene. At the present exposure level, most of the Menderes Massif consists of greenschist-facies metamorphic rocks. Lithostratigraphic correlation in low-grade metamorphic terrains affected by a single orogeny is a valid method. As discussed above, available data do not contradict the Menderes fold model, which is based on a lithostratigraphic correlation between the Çine and Ödemiş submassifs and on the metamorphic inversion in the Ödemiş submassif. Further work to verify the stratigraphic inversion in the Ödemiş submassif, and establish the depositional and metamorphic age of the phyllite–quartzite–marble series in the Bozdağ, which I ascribed to the Permo-Carboniferous Göktepe formation, will be critical tests for the Menderes fold hypothesis.

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