Neogene brittle detachment faulting on Kos (E Greece): implications for a southern break-away fault of the Menderes metamorphic core complex (western Turkey)

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Abstract: The southern limit of the Menderes metamorphic core complex has recently been proposed to be formed by an Oligocene–early Miocene top-to-the-north breakaway detachment fault, the Daçta–Kahle fault running across the Lycian nappes in southwestern Turkey. Proving a breakaway detachment fault as opposed to a ‘simple’ local high-angle normal fault is generally hampered by absence of a metamorphic contrast between hanging wall and footwall. The island of Kos lies close to the inferred southern breakaway fault. It exposes Permo- Carboniferous anehalite-metamorphic rocks, intruded and contact-metamorphosed at upper crustal levels by a 12 Ma old monzonte during or close to peak-burial conditions. Here, we show that exhumation of these rocks occurred along a top-to-the-north brittle extensional detachment fault underneath upper Mesozoic and Palaeogene non-metamorphic carbonates after 12 Ma, and that any (undocumented) earlier extension did not lead to significant exhumation of the Permo-Carboniferous rocks. Kos should thus be placed within the Cyclades–Menderes extensional province since 12 Ma. The age of exhumation is younger than the proposed activity of the breakaway fault, the existence of which we cannot corroborate. We conclude that the brittle detachment of Kos cannot be straightforwardly correlated to any ductile-to-brittle detachments of the Menderes or eastern Cycladic metamorphic core complexes further to the north and may represent a relatively isolated structure.

Metamorphic core complexes have since long been recognized to form due to exhumation along low-angle extensional detachment faults that juxtapose high-grade metamorphic rocks in the footwall against upper crustal rocks in the hanging wall (Crittenden et al. 1980; Wernicke 1981, 1995; Davis 1993, Lister et al. 1984; Lister & Davis 1989; Fig. 1). Recent modelling of formation of metamorphic core complexes suggests that core complexes form in two stages: in the first stage, symmetric boudinage of the crust leads to a graben at the surface and lower crustal flow into the extending region, followed by a second stage where a mid-crustal shearzone at depth links with one of the brittle graben-bounding faults in the upper crust to form a sigmoidal extensional detachment along which a metamorphic dome is exhumed and eventually the detachment will lack a ductile history, juxtaposing only upper crustal, low-grade metamorphic rocks in footwall and hanging wall in an area between the exhumed metamorphic rocks and a break-away fault (Fig. 1). This breakaway fault can be considered to be the boundary of the metamorphic core complex (Dorsey & Becker 1995; Otton 1995; van Hinsbergen & Meulenkamp 2006).

The Menderes core complex in western Turkey (Fig. 2) is one of the largest in the world and formed as a result of c. North–South extension in the Aegean backarc since the late Oligocene (Bozkurt & Park 1994; Hetzel et al. 1995a, b; Bozkurt & Satir 2000; Bozkurt & Oberhansli 2001; Gessner et al. 2001). Multiple extensional detachment faults with both top-to-the-north and top-to-the-south sense of shear have been recognized in the Menderes massif, and a clear structural asymmetry on the scale of the whole massif is not evident (Hetzel et al. 1995a; Gessner et al. 2001). Recently, however, Seyitoğlu et al. (2004) postulated that an Oligocene–lower Miocene ‘Kahle–Daçta fault zone’ in the central part of the Lycian nappes of southwestern Turkey (Fig. 2) formed a break-away fault of the Menderes metamorphic core complex, thus suggesting that in the early...
stages of exhumation, top-to-the-north unroofing was the dominant process of exhumation. Proving that the Kahle–Datca fault zone is indeed a break-away brittle detachment fault, as opposed to a relatively small-displacement normal fault is difficult, since the most obvious criterion for an extensional detachment fault – a metamorphic contrast between hanging wall and footwall – is absent.

The island of Kos (Fig. 2), however, may provide a case to test the existence of a brittle extensional detachment between the Kahle–Datca fault and the metamorphic complex of the Menderes. Kos is located only about 15 kilometres NW of the Datça fault, and c.15 km SW of the Bodrum peninsula, where the southernmost metamorphic rocks flanking the Menderes massif were found (Rimmelé et al. 2003). The Dikeos Window in southeastern

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**Fig. 1.** Schematized cross-section of a metamorphic core complex, indicating the relationship between the break-away fault and the position of the metamorphic core (modified after Lister & Davis (1989)).

**Fig. 2.** Geological map of Greece and western Turkey, modified after Jolivet et al. (2004) with the position of the Datça–Kahle fault, postulated by Seyitoğlu et al. (2004) to form the Oligocene–lower Miocene break-away fault of the Menderes metamorphic core complex.
Kos exposes Permo-Carboniferous sedimentary rocks which were intruded and metamorphosed at shallow crustal levels by the Kos monzonite around 12 Ma (Altherr et al. 1976; Kalt et al. 1998). A brittle fault zone separates these rocks from isolated occurrences of upper Mesozoic and lower Cenozoic carbonate units and Palaeogene flysch with olistoliths (Desio 1931; Altherr et al. 1976, 1982; Gralla 1982; Henjes-Kunst et al. 1988; Kalt et al. 1998; Papanikolaou & Nomikou 1998; Fig. 3). In this paper we present new information concerning the nature of the contact between the Kos monzonite and surrounding contact-metamorphosed Permo-Carboniferous series, and the overlying upper Mesozoic to Palaeogene carbonates with Palaeogene flysch and discuss these results in light of the kinematic evolution of the Menderes metamorphic core complex and the postulated existence of a southern breakaway fault.

Geological setting

Menderes metamorphic core complex

The Menderes region of western Turkey (Fig. 2) exposes a large-scale complex of Pan-African basement and Palaeozoic to Cenozoic metasedimentary and igneous rocks (Schuiling 1962; Bozkurt & Park 1994, 1999; Hetzel et al. 1998; Bozkurt & Oberhänsli 2001; Gldony & Hetzel 2007). It exposes metamorphosed parts of the northern Tauride–Anatolide block that underthrusted below the Izmir–Ankara suture zone during Palaeogene–Eurasian convergence (Şengör & Yılmaz 1981; Jolivet et al. 2004). The protolith of the Menderes basement terrain formed lateral palinspastic units to those of the neighboring Cyclades in central Greece, which share a history of late Palaeozoic to Palaeogene sedimentation and Palaeogene underthrusting and metamorphism (Ring et al. 1999a; Bozkurt & Oberhänsli 2001; Jolivet et al. 2004). To the south, the Menderes Massif is overlain by the Lycian nappes, the northern part of which underwent a HP/LT metamorphic history (Rimmele et al. 2003, 2005). The Lycian nappes consist of thrust sheets of Permo-Triassic clastic sediments and Mesozoic to Palaeogene carbonates and flysch, overthrust by an ophiolitic mélangé and serpentinised peridotites (Bernoulli et al. 1974; Okay 1989; Collins & Robertson 1997). Within the Menderes metamorphic core complex, Neogene postorogenic extension was accommodated along several extensional detachments both with top-to-the-north (Hetzel et al. 1995a; Ring et al. 1999a; Bozkurt & Sözbilir 2004; Isik et al. 2004) and top-to-the-south sense of shear (Bozkurt & Park 1994; Hetzel et al. 1995b; Bozkurt 2001, 2004, 2007; Gessner et al. 2001; Lips et al. 2001), which led Hetzel et al. (1995a) and Gessner et al. (2001) to propose bivergent extension of equal importance in the exhumation history of the Menderes region. Low-temperature geochronology has shown that cooling of the
metamorphic rocks, attributed to exhumation along
the extensional detachments, continued until
approximately 8–5 Ma (Gessner et al. 2001; Ring
et al. 2003).
A top-to-the-north break-away fault to the
Menderes-Lycian nappes detachment system
formed by the Datça–Kahle fault, such as that pos-
tulated by Seyitoğlu et al. (2004) would however
imply that the early Neogene stages of exhumation
for the Menderes-Lycian nappes system were
accommodated along a dominantly top-to-the-north
extensional detachment system.

Geology of Kos
The eastern Greek island of Kos is located only
about 15 km NW of the Datça fault (Fig. 2), and
15 km SW of the Bodrum peninsula, where the
southernmost HP/LT metamorphic parageneses
are found in the Lycian nappes (Rimmelé et al.
2003; Fig. 2). It has thus a position in the region
where a brittle detachment fault has been postulated
by Seyitoğlu et al. (2004). In southeastern Kos, the
Dikeos window exposes Permo-Carboniferous
anachimetamorphic sediments which were folded
and then intruded and contact-metamorphosed by
the Kos monzonite around 12 Ma (Altherr et al.
1976; Gralla 1982; Kalt et al. 1998). These are sep-
arated by a brittle fault zone from upper Mesozoic
and lower Cenozoic carbonate units and Palaeogene
wildflysch with olistoliths (Desio 1931; Altherr
et al. 1976, 1982; Gralla 1982; Henjes-Kunst et al.
1988; Kalt et al. 1998; Papanikolaou & Nomikou
1998; Fig. 3). The age of folding of the Permo-
Carboniferous rocks of Kos cannot be constrained
better than between their deposition and the intru-
sion of the Kos Monzonite, but is likely related to
the Alpine folding and thrusting history. Upper
Mesozoic recrystallized limestones also occur on
the Kefalos peninsula of western Kos (Papanikolaou
& Nomikou 1998). The age and lithology of the
Kefalos limestones suggest they are correlatable
with the limestones overlying the Dikeos window,
although the recrystallized nature of the Kefalos
limestones led Papanikolaou & Nomikou (1998) to
suggest that they may share a burial history with
the Dikeos Permo-Carboniferous rocks. Kalt et al.
(1998) provided Palaeobarometry estimates for the
Kos Monzonite and surrounding contact-
metamorphosed Permo-Carboniferous sediments.
Al-in-hornblende barometry yielded pressures of
3.1–5.1 kbar, but Kalt et al. (1998) indicated that
this is likely an overestimation and render pressure
estimates obtained from mineral parageneses in
the contact metamorphic aureole of 1.5–2.5 kbar
more reliable. The very low metamorphic grade of
the Permo-Carboniferous sediments outside the
contact metamorphic aureole (Altherr et al. 1976;
Gralla 1982; Kalt et al. 1998) indicate that the Kos
monzonite intruded close to or during peak-burial
conditions of the Permo-Carboniferous metapelites,
corresponding to c. 1.5–2.5 kbar, or c. 5–7.5 km of
depth. The anachimetamorphic sediments consist of
carbonate, shale and sandstone with sedimentary
ages ranging from Ordovician to Permian (Desio
1931; Altherr et al. 1976). The clear contact meta-
amorphic aureole in the Permo-Carboniferous rocks
is absent in the overlying carbonate succession
(Altherr et al. 1976; Kalt et al. 1998). Altherr
et al. (1976) therefore suggested that the contact
between the Kos monzonite and the upper Mesozoic
and Palaeogene carbonates postdates intrusion and
cooling of the monzonite and these authors inter-
preted this contact as a thrust fault. Fission track
cooling ages suggest cooling of the monzonite
below c. 100 °C around 7 Ma (Altherr et al. 1982).
To date, no structural information has been avail-
able for this contact fault zone.

The Neogene sedimentary cover of Kos consists of
lower Miocene molassic sediments on western
Kos unconformably overlying the Mesozoic carbon-
ates (Papanikolaou & Nomikou 1998), and north of
the Dikeos window ranges from middle Miocene to
Pleistocene shallow marine to terrestrial deposits
(Böger et al. 1974; Altherr et al. 1976; Willmann
1983). It dips southward as a result of north-dipping
normal faults that separate the sediments from the
pre-Neogene basement (Böger et al. 1974; Fig. 3).

Contact between the Dikeos
Permo-Carboniferous and
Cretaceous rocks
The contact between the footwall (contact-
metamorphosed Permo-Carboniferous clastic sedi-
ments and the Kos monzonite) and the hanging
wall (non-metamorphosed upper Mesozoic and
Palaeogene carbonates and Palaeogene flysch) is
exposed in three areas along the northern side of the
Dikeos window (Fig. 3): In the west (location I),
upper Mesozoic and Palaeogene carbonates overlies the Kos monzonite, in the east (location II)
the Permo-Carboniferous is overlain by the Mesozoic and Palaeogene carbonates and Palaeogene flysch) is
exposed in three areas along the northern side of the
Dikeos window (Fig. 3): In the west (location I),
upper Mesozoic and Palaeogene carbonates overlies the Kos monzonite, in the east (location II)
the Permo-Carboniferous is overlain by the Palaeo-
gene flysch and in the central part (location III) the
carbonates overlie the Permo-Carboniferous series.
In all three cases, the contact is of tectonic origin.
The footwall is dome-shaped, and the contact fault
zone is dipping northwesterly in the west, and north-
easterly in the east (Fig. 3). Upper Mesozoic and
Palaeogene carbonates are not laterally continuous,
and appear as isolated klippen on the top of the Permo-
Carboniferous series and the Kos monzonite
(Fig. 3). They are heavily brecciated but do not
contain clear individual shear zones.
Fig. 4. (a–d) Photographs and interpretative sketch of locality II, showing kinematic indicators that give evidence for a top-to-the-north motion along the Kos brittle detachment fault zone. For location, see Figures 3a and b. Even though the amount of data is limited, this view orthogonal to the strike of the fault zone indicates an important component of top-to-the-north motion of this fault zone. We argue that this fault zone represents a brittle, top-to-the-north extensional detachment fault that exhumed the Permo-Carboniferous succession and the Kos monzonite from underneath upper Mesozoic and Palaeogene successions and overlying middle Miocene and younger basin sediments since 12 Ma (see text for further details).
**Location I**

The contact between the Kos monzonite and the upper Mesozoic and Palaeogene carbonates at location I is a brittle fault zone of typically 10–100 m wide, which is developed as north to northeast dipping gouge zones in the monzonite. Lack of a fabric and absence of correlation markers in the monzonite hampers determination of the sense of shear along this fault zone. The deformation zone is several tens of metres thick, below which the monzonite is undeformed.

**Location II**

The contact in the east at location II, between the flysch and the Permo-Carboniferous series (Fig. 4) is a mélangé of brittlely deformed rocks of hundreds of meters thick, dipping at approximately 40° to the NE. The chaotic character of hanging wall and footwall prevails determining a conclusive sense of shear. The flysch is much more deformed than the underlying Permo-Carboniferous unit, although part of this deformation may be the result of a nappe stacking episode and soft-sediment deformation.

**Location III**

In contrast, at location III the contact between the upper Mesozoic and Palaeogene carbonates and the Permo-Carboniferous rocks is characterized by a brittle fault zone with an asymmetric tectonic fabric formed by beds that are dragged along north-dipping faults. The fabric between the north-dipping faults indicates a clear top-to-the-north component of shear (Fig. 4). We did not observe a clear lineation on the fault planes and we can hence not exclude a component of strike-slip. The fault zone consists of an anastomosing set of up to 20 cm wide fault gouges and fault breccias. The total exposed thickness of the fault zone is at least 100 m.

Despite the scarce amount of kinematic data that we obtained from the few outcrops available in the fault system between the Permo-Carboniferous series and the monzonite, and the overlying isolated occurrences of upper Mesozoic and Palaeogene successions is scarce, the asymmetric fabric in the cross-section orthogonal to the strike of the fault zone suggests that the emplacement of the hanging wall over the footwall was associated with a strong component of top-to-the-north shear. In the next section, we will combine this with the available information on the metamorphical, geochronological and stratigraphical information to determine the extensional or contractual origin of this fault zone.

**Discussion**

Six issues are essential in determining the extensional or contractual nature of the fault zone.
between the non-metamorphosed upper Mesozoic
and Palaeogene carbonates and the Kos monzonite
and surrounding contact-metamorphosed Permo-
Carboniferous series: (1) The hanging wall of the
fault zone juxtaposes younger over older; and (2)
non-metamorphosed over metamorphosed rocks.
Whereas this does not exclude thrust emplacement
postdating the exhumation of the footwall, both
facts are in line with an extensional nature of
the fault zone. (3) The contact in its present-day
orientation indicates a strong component of
normal fault motion, with a comparable shear
sense and strike as the basin faults that bound and
deform the Neogene stratigraphy (Böger et al.
1974). Moreover, (4) The middle Miocene to Plio-
cene stratigraphy on Kos was deposited during and
after intrusion, exhumation and cooling of the Kos
monzonite between 12 and 7 Ma (Böger et al.
1974; Altherr et al. 1976; Willmann 1983). This,
in combination (5) with the pressure conditions of
1.5 to 2.5 kbar during the intrusion of the Kos mon-
zonite (Kalt et al. 1998) shows that approximately 5
to 7.5 km of exhumation of the Dikeos window with
respect to the sedimentary basins occurred since
12 Ma. These facts also favour an extensional
history of the contact fault zone. Finally, (6), thrust-
ing of the upper Mesozoic carbonates would require
that they formed a coherent block during emplace-
ment, unlike their present-day fragmented nature.
It would be difficult to fragment the hanging wall
during sediment acquisition on top of it in the
Neogene basin. More likely, these isolated blocks
form extensional klippen comparable to those
observed in the middle to upper Miocene Cretan
supradetachment basin (van Hinsbergen & Meulen-
kamp 2006). This combination of facts strongly sup-
ports an extensional nature for the fault zone.
We therefore argue that this fault zone represents
a brittle extensional detachment fault that accom-
modated c. 5–7.5 km of exhumation since 12 Ma.
Moreover, since the crystallization depth of the
Kos monzonite likely corresponds to the
maximum burial depth of the surrounding anch-
metamorphic Permo-Carboniferous rocks (Kalt
et al. 1998), any pre-12 Ma extension and basin for-
mation that may have affected Kos (Böger et al.
1974; Papanikolaou & Nomikou 1998) did not
lead to significant exhumation of the footwall to
the Kos detachment.
Placing this interpretation into the regional
geological context requires correlation of the pre-
Alpine rocks of the Dikeos window to those of
the Kefalos peninsula, and the pre-Alpine rocks
of Kos to the nappes of Greece and western
Turkey, which is not straightforward. The 11
recrystallized limestones of upper Cretaceous age
on the Kefalos peninsula are unconformably over-
lain by lower Miocene molassic sediments with
olistoliths (Papanikolaou & Nomikou 1998). The
recrystallized nature of the limestones led
Papanikolaou & Nomikou (1998) to suggest that they
may share a burial history with the Dikeos
Permo-Carboniferous rocks.
However, the lower Miocene unconformable
cover of the Kefalos carbonates shows that the
Kefalos Cretaceous carbonates have been near
the surface throughout the intrusion and exhumation
history of the Kos monzonite, and it supports corre-
lation to the Mesozoic rocks in the hanging wall of the
Kos detachment. Two models can be postulated
to place the pre-Alpine rocks of Kos in their regional
tectonostratigraphic context. The main difficulty in
correlation is the old age of the Kos Permo-
Carboniferous rocks, which is not known from else-
where in the Aegean or western Anatolian region
(Papanikolaou & Nomikou 1998).
Based on lithology, age and tectonostratigraphic
context, they may correspond to either the tectono-
stratigraphically lowest central Aegean nappe
formed by the Tripolitza unit, the Basal Unit and the
Phyllite Quartzite, or to the structurally highest
Lycian nappes. Blondeau et al. (1975) and Papani-
kolou & Nomikou (1998) correlated the Mesozoic
to Palaeogene carbonates of Kos to the Tripolitza
and Pindos nappes of western Greece based on age
and sedimentary facies. If this suggestion is
correct, the Permo-Carboniferous of Kos could cor-
relate to the HP/LT metamorphic Phyllite Quartzite
unit exposed on Crete. Alternatively, the pre-
Neogene rocks of Kos may belong to the Lycian
nappes, which on nearby Turkish peninsulas
expose Permo-Triassic clastic sediments and Mesozoi-
–Palaeogene carbonates and flysch (Bermoulli
et al. 1974; Collins & Robertson, 1997). We advo-
cate the latter correlation based on their non-
to anchimetamorphic character and their position
amidst rocks belonging to the Lycian nappes with
comparable age and facies exposed on the Turkish
peninsulas north and south of Kos.
The intrusion of the Kos monzonite and associ-
ated contact metamorphism provide a unique oppor-
tunity to show that in the south of the metamorphic
rocks of the Menderes metamorphic core complex,
top-to-the-north extensional detachment faulting
has been active. This suggests that Kos has been
a focused deformation site within the Cyclades–Menderes extendional province since 12 Ma. The
top-to-the-north component of shear of the brittle
Kos detachment is in line with the scenario of
Seyitöglu et al. (2004), which postulates that the
Datça fault south of Kos is the Oligocene–Lower
Miocene break-away fault of the core complex.
However, the thermodynamic reconstruction of
Kalt et al. (1998) suggests that the Kos monzonite
intruded the Permo-Carboniferous series close to
peak burial conditions, indicating that no significant
exhumation occurred on Kos prior to 12 Ma. Seyitog˘lu et al. (2004) suggested that the Datc ¸a breakaway fault was active during Oligocene to early Miocene times. This can only be valid if the rocks on Kos belong to the hanging wall of the Oligocene–early Miocene detachment system inferred by Seyitog˘lu et al. (2004). We cannot corroborate the existence of a Oligocene–early Miocene brittle detachment on Kos and this makes the scenario of Seyitog˘lu et al. (2004) unlikely. Moreover, seismic profiles of Kurt et al. (1999) and Ulug et al. (2005) cannot corroborate any on-land continuation of this fault zone and these authors instead suggested a much younger, late Miocene or Pliocene age of the Datc ¸a Fault. The existence of a brittle detachment on Kos does show that brittle detachment faulting exhumed upper crustal rocks from mid upper crustal depths south of the Menderes and eastern Cycladic metamorphic core complexes.

Conclusions

The Menderes metamorphic core complex western Turkey is clearly defined in the north by extensional detachments along which a sharp metamorphic contrast exists between hanging wall and footwall. The southern limit of the core complex is less well defined. An Oligocene–early Miocene breakaway fault has previously been postulated in the Lycian nappes in southwestern Turkey. Showing the existence of a breakaway detachment fault is difficult due to absence of a metamorphic contrast along the fault for those parts where only upper crustal rocks are exhumed. The island of Kos, just north of the inferred breakaway fault, exposes Permo-Carboniferous anchestimetamorphic rocks, intruded and contact-metamorphosed by a 12 Ma old monzinite. Here, we show that exhumation of these rocks was accommodated along a top-to-the-north brittle extensional detachment emplacing them underneath non-metamorphosed upper Mesozoic to Palaeogene carbonates and Neogene basin sediments.

Previously published petrological constraints on the burial history of the Permo-Carboniferous series of Kos has shown that the Kos monzonite intruded close to peak-burial conditions, showing that any pre-12 Ma extension and basin formation on Kos has not led to any detectable exhumation of the Permo-Carboniferous series. We conclude that the island of Kos should be placed within the Cyclades–Menderes extensional province. However, the age of exhumation is younger than the proposed activity of the breakaway fault, the existence of one can thus only be confirmed for the period starting sometime between 12 and 7 Ma. We conclude that the brittle detachment of Kos cannot be straightforwardly correlated to any ductile-to-brittle detachments of the Menderes or eastern Cycladic metamorphic core complexes further to the north and may represent a relatively isolated structure.

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