Record of a Palaeogene syn-collisional extension in the north Aegean region: evidence from the Kemer micaschists (NW Turkey)

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Abstract – In NW Turkey, the medium-grade Kemer micaschists of the Biga Peninsula record NE-directed extension related to ductile to brittle–ductile shearing during the Palaeogene period: a lower limit for their exhumation is given by the Late Maastrichtian age of the HP–LT metamorphism of a similar nearby area (Çamlıca micaschists); an upper limit is given by the Early Eocene intrusion age of the post-kinematic Karabiga granitoid, dated as 52.7 ± 1.9 Ma using the U–Pb LA–ICP–MS method on xenotime. Correlations with the northeasterly Rhodope region and integration into the geodynamical regional frame indicate that the Kemer micaschists experienced an extensional deformation connected to a collisional context in latest Cretaceous–early Tertiary times. The Kemer micaschists therefore represent a new area (the first in Turkey), which suffered synorogenic extension in the north Aegean domain at the very beginning of Tertiary times.

Keywords: ductile shear, metamorphism, extension, north Aegean, U–Pb (LA–ICP–MS) geochronology, xenotime.

1. Introduction

Since the 1980s, much effort has been made to understand the geodynamic evolution of mountain belts, from the convergent phase to their final collapse. More specifically, many studies focused on the exhumation processes bringing deformed metamorphic rocks up to the surface. Erosion does not behave alone, and a significant part of the exhumation relates to extensional crustal-scale shear zones (Wernicke, 1981; Platt, 1986). Several studies have distinguished synorogenic extension, taking place during the build-up of the mountain belt, from post-orogenic extension, occurring once the building processes have stopped (Malavieille, 1997; Jolivet & Goffé, 2000).

The Aegean region is definitively accepted as a natural laboratory for studying extensional processes (e.g. Lister, Banga & Feenstra, 1984; Jolivet & Patriat, 1999). In this area, the exhumation-related extensional shearing took place in both syn- and post-orogenic contexts, following several cycles of subduction–collision since the Late Cretaceous epoch (Jolivet & Faccenna, 2000).

Although a few regions, such as the Rhodope Massif, Cycladic Islands and Menderes Massif, have been the focus of most of the recent studies (Dinter & Royden, 1993, Gautier & Brun, 1994; Bozkurt & Oberhansli, 2001; Ring & Collins, 2005), there are still some areas where the data are scarce, but whose investigation would significantly increase our knowledge of the exhumation processes in the Aegean region. Despite its key location in the Aegean region, east of the Rhodope Massif and north of the Menderes Massif, the Biga Peninsula of NW Turkey is one of these poorly known areas (Fig. 1). Recent studies have already demonstrated the occurrence of Oligo-Miocene exhumation processes in the southern peninsula (post-orogenic extension of the Kazdağ Core Complex: Okay & Satır, 2000a), but there were no results indicating an earlier extensional phase.

In the northern part of the Biga Peninsula, a NE–SW-trending strip of micaschists is exposed along the southern coast of the Marmara Sea (Fig. 1). These metamorphic rocks are the northern extension and counterpart of the Çamlıca metamorphics cropping out west of the peninsula (Okay, Siyako & Bürkan, 1991). There, the metamorphic rocks contain relics of an eclogitic HP–LT metamorphism, dated as 65–69 Ma (Okay & Satır, 2000b). The kinematic pattern
2. Geological setting

Noteworthy geological features of the Biga Peninsula include (a) the various units of the pre-Liassic Karakaya Complex (Okay et al. 1996; Okay & Göncüoğlu, 2004); (b) the accretion-related pre-Cenomanian Çetmi mélangé and the ophiolitic Ezine Zone (Okay, Siyako & Büarkan, 1991; Beccaletto & Jenny, 2004; Beccaletto et al. 2005), whose geodynamic evolution is related to that of the Rhodope; (c) high- to medium-grade metamorphic rock (Okay & Satır, 2000a,b), including the Kemer micaschists, systematically occurring at the base of the previously mentioned units; and (d) Tertiary plutonic and associated volcanic rocks, with collisional to extensional geochemical signatures (Yılmaz et al. 1995; Yılmaz et al. 2001).

To the southeast, the Kemer micaschists are tectonically bounded by the Çetmi mélangé (Fig. 1), which passively suffered the deformations described in this study. In the west, both are intruded by the post-kinematic Karabiga granitoid. These three units are hidden under the Marmara Sea further to the north. The oldest rocks unconformably overlying the Kemer micaschists are the fluvio-deltaic sediments of pre-Upper Eocene age of the Fıcıtepe Formation, and volcanics with inferred Palaeocene to Eocene ages (Siyako, Bürkan & Okay, 1989).

3. The Kemer micaschists

3.a. Ductile deformation and shear fabrics

The medium-grade metasedimentary sequence of the Kemer micaschists consists predominantly of garnet-bearing quartz-white micaschists intercalated with...
quartz-chlorite schists, and subordinate quartz-chlorite-albite schists, phyllites, calc-schists and rare quartzites and metabasites. The metamorphic mineral assemblage of the metapelites includes $\text{Qtz} + \text{Ms} + \text{Chl} + \text{Ab} \pm \text{Grt} \pm \text{Bt} \pm \text{Spn} \pm \text{Ap}$.

The main regionally penetrative deformation in the Kemer micaschists results from a major shearing event that produced pervasive ductile fabrics characterized by (Figs 1, 2): (a) a flat-lying to moderately south-dipping regional foliation, representing a ubiquitous schistosity and/or metamorphic layering, parallel to the lithological contacts; (b) a strong NE–SW-trending stretching lineation, with shallow plunges in both opposite directions, although predominantly south (Fig. 2). Small-scale inclined or intrafolial folds are tight to isoclinal with a NE vergence. Their hinges vary in attitude from orthogonal to mostly parallel to the stretching lineation (Fig. 2); (c) various shear criteria, indicating a regionally consistent top-to-the-NE tectonic transport in present coordinates, parallel to the lineation. Note that traces of any earlier deformation(s) are obliterated by the strong shearing related to the main deformation.

Shallow NE-dipping, up to decametre-scale, asymmetric extensional shear bands represent prominent mylonitic fabrics, depicting intense non-coaxial deformation (Fig. 3). Metamorphic layering/foliation progressively becomes mylonitic close to the shear bands, producing an asymmetric foliation boudinage in between. Other asymmetric macro- and micro-structures used as kinematic indicators are abundant (porphyroclast systems, drag folds, small-scale shears, flanking structures). Calcite-filled tension gashes account for the transition from ductile to ductile–brittle shear deformation. Relationships between metamorphic mineral assemblages and deformational structures indicate that ductile shear fabrics were coeval with the upper greenschist-facies metamorphism, as demonstrated by crystallization of syntectonic albite and sphene porphyroblasts, and pressure fringes on garnets that parallel and define the stretching lineation.

Locally, a late non-penetrative deformational fabric is characterized by a discontinuous crenulation cleavage, axial planar to folds with E–W-oriented axes, and tracing an intersection lineation. This later deformation, spatially linked to a small granodiorite body in the southwest, is characterized by the development of retrogressive chlorite after white micas and calcite. The last deformation is a predominant set of NE-dipping high-angle normal faults indicating a relatively pronounced brittle deformation at a shallow structural level.

3b. Extension-related deformation and shearing

The pre-extension, possibly contractional contact between the Kemer micaschists and the Çetmi mélange is reworked as late, recent strike-slip faults, most likely connected with the activity of the nearby Plio-Quaternary North Anatolian Fault (Armijo, Meyer & Hubert, 1999; Şengör et al., 2005). The dominant shear structures in the metamorphic rocks are extensional asymmetric shear bands that have attenuated the metamorphic layering, parallel to the stretching lineation, equated with the kinematic direction. They contributed to the ductile stretching and thinning of the metamorphic pile. Shear fabrics and the strain gradient in quartz-mica mylonites are consistent with a top-to-the-NE shear zone, whose uppermost levels, however, are hidden in the Marmara Sea. Moreover, the shear structures are never associated, at any scale, with compressional structures, such as folds or thrusts. Therefore, the character of shear structures and the kinematic continuity during progressive deformation from ductile
to ductile–brittle shear, followed by brittle faulting, are consistent with NE–SW-oriented extension and exhumation of the metamorphic pile. Interestingly, this NE–SW kinematic direction of extension parallels the trend of the extension known in the southerly Menderes massif and Lycian nappes of western Turkey (e.g. Walcott & White, 1998).

As a consequence of the extensional regime, a delimited sedimentary basin of pre-Upper Eocene age developed, filling up the available empty space above the Kemer micaschists (Karaağaç and Fıçıtepe formations: Siyako, Bürkan & Okay, 1989). As expected, the regressive, shallowing-up sedimentary sequence (turbiditic, then deltaic, then fluviatile facies) contains pebbles derived from both the Kemer micaschists and the Çetmi mélange.

4. The Karabiga granitoid: pinning of the shear fabrics

The Karabiga granitoid occurs as an intrusive body into the Kemer metamorphics and the Çetmi mélange. Petrographically, it ranges from granodiorite and quartz-monzonite to granite. Its geochemical signature indicates mature arc or collision affinities, related to a volcanic arc and/or a collisional tectonic setting (Delaloye & Bingöl, 2000; Güçtekin, Köprübaş & Aldanmaz, 2004). The pluton displays a characteristic equigranular texture, and does not contain any foliation, even close to the contacts with the Kemer micaschists. Moreover, numerous veins cross-cut the main foliation of the metamorphics (Fig. 4). All these features lead to interpretation of the Karabiga granitoid as a post-kinematic pluton, post-dating the extensional ductile shearing of the Kemer micaschists.

Delaloye & Bingöl (2000) obtained an individual age of $45.3 \pm 0.9$ Ma from a biotite using the K/Ar method. We interpret it as the cooling age of the plutonic body below the relevant closure temperature of the biotite with respect to the K/Ar system (about $300\, ^\circ C$). Depending on the cooling rate, this age could be significantly younger than the real intrusion age of the granitoid body.

In order to settle this question, we performed U–Pb laser ablation ICP-MS analyses on xenotime. We selected xenotime and not zircon because of the poor quality of the recovered zircon grains (fractures, inclusions) and potential complexity of the U–Th–Pb systems of these minerals in granitoids (inheritance, Pb loss). Details of the analytical procedure can be found in Appendix 1. Although there are relatively few data available on the U–Pb systems in xenotime (YPO₄), this mineral is thought to behave like monazite (e.g. Aleinikoff & Grauch, 1990; Hawkins & Bowring, 1997), and a similar high closure temperature for Pb ($725 \pm 25\, ^\circ C$ after Copeland, Parrish & Harrison, 1988) is assumed. Thus, the U–Pb xenotime age is expected to yield a crystallization age close to the real intrusion age of the Karabiga pluton. Crystals separated from the studied sample occur as yellow to orange, euhedral, dipyramidal grains, with no evidence of complex internal structure (core or inclusions) under binocular examination. Nine spot analyses have been performed on seven grains (Table 1) and all data points cluster close to concordia with consistent apparent ages (Fig. 5). Analyses can be combined to provide a $^{206}\text{Pb}^{238}\text{U}$ weighted mean of $52.7 \pm 1.9\, ^\text{Ma} (2\sigma)$ interpreted as dating crystallization of the xenotime in the magma. This Eocene age is thus interpreted as dating the intrusion of the Karabiga granitoid into the Kemer micaschists and constitutes a lower limit for the extensional ductile shearing observed in the micaschists. In addition, it is c. 7 Ma older than the K–Ar biotite age of Delaloye & Bingöl (2000) and suggests a high cooling rate of around $57\, ^\circ C\, \text{Ma}^{-1}$ following intrusion of the Karabiga granitoid.

5. Discussion and implications

5.a. Timing of the exhumation of the Kemer micaschists

The U–Pb age indicates that the extensional deformation was terminated by Early Eocene times. The
metamorphic rocks then reached the surface before the Late Eocene, as shown by the first sedimentary rocks overlying the metamorphic rocks.

The Kemer micaschists are lithologically and structurally comparable to the Çamlıca micaschists, cropping out southwestward. Both units, representing a continuous metamorphic belt in the Biga Peninsula, are separated by 40 km of volcanics and sedimentary rocks of various Tertiary ages (Siyako, Bürkan & Okay, 1989). The only difference concerns the metamorphic conditions reached before their exhumation. While the Kemer micaschists show only medium-grade conditions reached before their exhumation, the Çamlıca micaschists locally contain metre-scale amphibolite boudins with preserved HP–LT eclogitic parageneses, implying that they have been buried more deeply than the Kemer micaschists. The eclogite-facies metamorphism occurred at the end of the Maastrichtian (65–69 Ma; Okay & Satır, 2000b). The latter age gives a lower limit for the exhumation of the Çamlıca micaschists, and hence, considering the similarity between both occurrences of metamorphics, for the exhumation of the Kemer micaschists.

As the extensional processes occurred after the peak metamorphism (late Maastrichtian) and before the intrusion of the Karabiga granite (Early Eocene), the ductile extensional shear deformation related to the exhumation of the Kemer micaschists must be Palaeocene–earliest Eocene in age.

5.b. Correlations of the Kemer micaschists

The regional tectonic framework suggests that the metamorphic terrains suitable for correlation are situated in the eastern Rhodope Massif of Greece and Bulgaria. There, the tectonic pattern is dominated by late Alpine metamorphic culminations, namely the Kesebir–Kardamos and the Byala reka–Iechkros domes (Bonev, 2006; Bonev, Burg & Ivanov, 2006; Bonev, Marchev & Singer, 2006). From the base to the top, both large-scale structures expose a pre-Alpine and Alpine basement consisting of lower and upper high-grade tectonic units, and an overlying low-grade Jurassic–Early Cretaceous subduction–accretion unit. Basement units are respectively bounded by contractional, symmetamorphic thrust contacts related to pre-latest Cretaceous crustal thickening, and low-angle extensional detachments related to Tertiary extension (Krohe & Mposkos, 2002; Bonev, Burg & Ivanov, 2006; Bonev, Marchev & Singer, 2006). U–Pb zircon ages of 71.5 ± 3.5 Ma and 73.5 ± 2.5 Ma for eclogite-facies metamorphism, followed by a greenschist-facies stage at 61.5 ± 2.5 Ma (Liati, Gebauer & Wysoczanski, 2002; Liati, 2005), c. 69–53 Ma late-post-tectonic granitoids (Ovtcharova et al. 2003; Marchev et al. 2004) and Maastrichtian/Palaeocene–early Eocene sedimentary filling (Boyanov & Goranov, 2001), constrain the exhumation processes of the upper high-grade unit in the hangingwall of detachments between the latest Cretaceous and Early Tertiary. In addition, recent tectonic studies have shown that NE-directed extension in the eastern Rhodope started in pre-Eocene times, followed by Middle Eocene exhumation of the lower high-grade unit in the footwall of detachments (Bonev, Burg & Ivanov, 2006; Bonev, Marchev & Singer, 2006).

Therefore, similar kinematics and overlapping temporal constraints on metamorphic ages, regional stratigraphy and intrusive activity collectively imply a direct geodynamic link between the eastern Rhodope and the Biga Peninsula. The correlation of the pre-Tertiary Çetmi mélange and Ezine Zone of the Biga Peninsula with Rhodopian units, plus their common geodynamic
evolution, fully support the proposed correlation (Beccaletto, 2004; Beccaletto & Jenny, 2004).

5.6. Geodynamic frame
The tectono-metamorphic pattern exposed in eastern Rhodope and Biga Peninsula (burial then exhumation) further indicates that both regions likely experienced deformation connected to a collisional context in latest Cretaceous–early Tertiary times. Indeed, at the regional scale, the extensional deformation described above is contemporaneous with the closure of the Vardar Ocean and the subsequent collision between the Pelagonian terrane and the Rhodope margin (e.g. Stampfli & Borel, 2004). Moreover, in the same collisional geodynamic context, Bonev et al. (2006) have recently demonstrated in eastern Rhodope the occurrence of early Tertiary syn-collisional extensional features and the exhumation of related units.

Because of (a) the correlation of the extensional Kemer micaschists with similar units in eastern Rhodope, and (b) the overall collisional context in latest Cretaceous–Early Tertiary times in the north Aegean region, the Palaeogene record of ductile to ductile–brittle extensional shearing in the Kemer micaschists of NW Turkey may similarly indicate an early NE-directed extension, accommodating exhumation in an orogenic wedge during the closure of the Vardar Ocean (synorogenic extension).

6. Conclusions
The Kemer micaschists of NW Turkey show a continuous ductile to ductile–brittle extensional shearing, related to a NE–SW-oriented extensional regime. The lower limit for the shear activity is late Maastrichtian, as suggested by comparison with the similar nearby Çamlıca micaschists. Early Eocene is the upper limit, as found by dating the crystallization age of the Karabiga post-kimnematic granite. This extensional deformation occurred in the regional collisional setting of the closure of the Vardar domain.

The Kemer micaschists therefore represent a new area which suffered synorogenic extension in the Aegean domain at the very beginning of Tertiary times. This result gives the first opportunity to fill the spatial data gap between the Rhodope and the Menderes/Cycladic Massif. It also provides the chance to question further the temporal/geoodynamic relationships between syn- and post-orogenic extension in the Aegean region.

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References
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Appendix 1. Analytical techniques and LA–ICP–MS isotopic data for xenotime grains from the Karabiga granitoid (NW Turkey)

For laser ablation (LA–ICP–MS) analyses, xenotime grains were enclosed in epoxy resin with chips of the 554 Ma old Manangotry monazite crystal (Poitrasson, Chenery & Shepherd, 2000) and polished to about half of their thickness. The mount was then cleaned in ultra-pure MQ water and dried before its introduction into the ablation cell. Data were acquired at the University of Montpellier II using a 1991 vintage VG Plasmaquad II turbo ICP–MS coupled with a Geolas (Microlas) automated platform housing a 193 nm Compex 102 laser from LambdaPhysik. Experiments were conducted in a He atmosphere which enhances sensitivity and reduces inter-element fractionation (Gunther & Heinrich, 1999). Data were acquired in the peak jumping mode (1 point per peak) similarly to the procedure described in Bruguier et al. (2001). The laser was fired using an energy density of 15 J cm\(^{-2}\) at a frequency of 2 Hz and a laser spot size of 26 \(\mu\)m. This resulted in a sensitivity of around 200 cps/ppm for Pb based on measurements on the NIST 610 certified reference material. The drilling rate was measured on this material to be around 0.15 \(\mu\)m per pulse, which, under the analytical conditions used in this study, resulted in crater depths of about 18 \(\mu\)m and a removed volume of around 9550 \(\mu\)m\(^3\). This resulted in a total consumed monazite weight of approximately 48 ng by spot. The Pb/Pb and U/Pb isotopic ratios of unknowns were calibrated against the Manangotry monazite crystal as an external standard, which was measured four times for each five of unknowns using the bracketing technique. Data were reduced using a calculation spreadsheet, which allows correction for instrumental mass bias and inter-element fractionation. Accurate common lead correction during laser ablation analyses is difficult to achieve, mainly because of the isobaric interference of \(^{204}\)Hg on \(^{204}\)Pb. The contribution of \(^{204}\)Hg on \(^{204}\)Pb was estimated by measuring the \(^{202}\)Hg and assuming a \(^{202}\)Hg/\(^{204}\)Hg natural isotopic composition of 0.2298. This allows monitoring of the common lead content of the analysed grain, but corrections often resulted in spurious ages. Analyses yielding \(^{204}\)Pb close to or above the limit of detection were thus rejected. For instrumental mass bias, all measured standards were averaged to give a mean mass bias factor. This mass bias factor and its associated error were then propagated with the measured analytical errors of each individual unknown analysis. Inter-element fractionations for Pb and U are much more sensitive to analytical conditions and a bias factor was thus calculated using the four standard measurements bracketing each of the five unknowns. These four measurements were then averaged to calculate a U–Pb bias factor and its associated error which were added in quadrature to the individual error measured on each \(^{206}\)Pb/\(^{238}\)U unknown. The age quoted in this study was calculated using the Isoplot program of Ludwig (2000).