# Late Miocene ductile extension and detachment faulting, Mykonos, Greece

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## ABSTRACT

**The geometry and style of structural relations at map to microscopic scale on Mykonos, Cyclades, Aegean Sea, Greece, suggests ductile extension and detachment faulting during the late Miocene. This island is dominated by granitic rocks that have a well-developed, shallowly dipping mylonitic foliation and a northeast-southwest-trending mineral elongation lineation. Kinematic indicators in these rocks exhibit a top-to-the-northeast, down-dip sense of shear. Textural relations suggest that conditions during mylonitic deformation were greenschist to amphibolite facies, and published K/Ar geochronology suggests a late Miocene age for this deformation event. Mylonitic rocks lie in the footwall of a low-angle fault, and fault striae parallel to the elongation lineation suggest kinematic coordination between mylonitic deformation and movement along the fault. Translation along the fault juxtaposes younger tilted sedimentary rocks of low metamorphic grade upon the once deeper mylonitic rocks. The style and geometry of deformational fabrics and map relations on this island are strikingly similar to those observed in metamorphic core complexes of the western United States.**

## INTRODUCTION

In the Cyclades, Aegean Sea, Greece (Fig. 1), an Oligocene to Miocene Barrovian metamorphic event overprinted an Eocene blueschist facies event with widespread greenschist to amphibolite facies retrogression of blueschist facies fabrics. Following the peak of Barrovian metamorphism, there was a major intrusive event during the late Miocene. Many workers have attributed the Barrovian metamorphic and plutonic event to thrust faulting and northeast-directed subduction of the African plate below the Apulian microplate (e.g., Altherr and Seidel, 1977; Altherr et al., 1982; Blake et al., 1981; Durr et al., 1978; Jansen, 1977; Papanikolaou, 1980; Wijbrans and McDougall, 1988). More recently, however, workers have proposed that mesoscopic and map-scale structural fabrics associated with the Barrovian metamorphic and plutonic event were the result of crustal extension (Lister et al., 1984; Faure and Bonneau, 1988; Lee and Lister, 1990; Gautier et al., 1990; Faure et al., 1991). In this paper we describe the first detailed study of the geometry and style of structural and map relations from the island of Mykonos (Fig. 1). We show that the intrusive event was broadly synchronous with ductile extension, and we propose that the style and geometry of deformation are similar to those observed in metamorphic core complexes of the western United States (cf. Crittenden et al., 1980). Our interpretation differs markedly from the conclusions of Faure and Bonneau (1988) and Faure et al. (1991), who proposed, on the basis of a reconnaissance study, a gravity sliding origin for the detachment fault observed on this island.

## REGIONAL SETTING

The island of Mykonos is located in the Cycladic blueschist belt in the central Aegean (Fig. 1). Rocks of the Cycladic blueschist belt have been subdivided into two main tectonic groups and are interpreted as forming a complicated pile of nappe and thrust sheets (Altherr and Seidel, 1977; Bonneau, 1984; Papanikolaou, 1984, 1987). The lower group comprises a basement of 300–500 Ma orthogneiss and paragneiss (Andriessen et al., 1987; Henjes-Kunst and Kreuzer, 1982; van der Maar, 1980, 1981; van der Maar et al., 1981) overlain by a sequence of metamorphosed Mesozoic carbonate, pelitic, volcanic, and ophiolitic rocks (Altherr and Seidel, 1977; Jansen, 1977; Papanikolaou, 1980), which have been intruded by late Miocene granite (Altherr et al., 1982; Schliestedt et al., 1987). This sequence of rocks is overlain, in low-angle fault contact, by an upper group composed of ophiolitic rocks covered by Cretaceous limestone and Oligocene and Miocene molasse sediments (Jansen, 1977; Durr and Altherr, 1979; Papanikolaou, 1980).

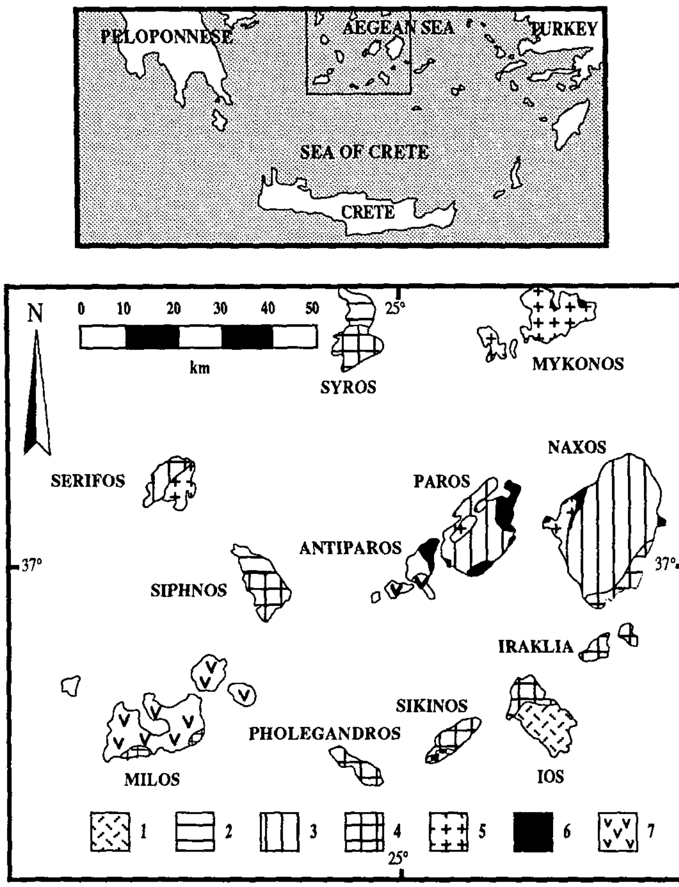


**Figure 1. Generalized geologic map of central and southern part of Cyclades islands, southern Aegean. 1—Basement gneisses; 2—Eocene high-pressure metamorphic rocks; 3—Miocene medium-pressure (Barrovian) metamorphic rocks; 4—Eocene high-pressure metamorphism overprinted by Miocene medium-pressure metamorphism; 5—Miocene granitoids; 6—Permian to Miocene sedimentary rocks; 7—Pliocene to Holocene volcanic rocks.**

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The lower group of rocks records at least two metamorphic events. The oldest event is a high-pressure–low-temperature metamorphism that is best preserved on the islands of Syros and Siphnos (Fig. 1). Numerous K/Ar, Rb/Sr, and $^{40}Ar/^{39}Ar$ analyses of phengite, paragonite, and glaucophane from blueschist facies rocks yield Eocene ages (Altherr et al., 1979; Andriessen et al., 1979; Wijbrans and McDougall, 1986; Wijbrans et al., 1990), indicating the time of cooling below ~330 °C following blueschist facies metamorphism. It has been suggested that the blueschist facies event was the result of northward subduction of the Apulian microplate beneath the Eurasian continent (Altherr et al., 1979; Blake et al., 1981; Bonneau, 1984).

Blueschist facies assemblages were pervasively overprinted by a Barrovian metamorphic event. Peak metamorphic conditions during this event were greenschist to upper amphibolite facies, locally reaching anatexis on the island of Naxos (Jansen and Schuiling, 1976; Andriessen et al., 1979; Altherr et al., 1979, 1982; Wijbrans and McDougall, 1986). K/Ar, $^{40}Ar/^{39}Ar$, and Rb/Sr geochronologic studies on micas and hornblendes suggest a late Oligocene to mid-Miocene age for this event (Altherr et al., 1982; Andriessen et al., 1979; Durr et al., 1978; Wijbrans and McDougall, 1986, 1988). During the late Miocene, subsequent to the culmination of the Barrovian metamorphic event, I- and S-type granites were emplaced, causing local contact metamorphism (Altherr et al., 1982; Wijbrans and McDougall, 1988).

## MYKONOS

The island of Mykonos is dominated by a medium- to coarse-grained hornblende + biotite monzogranite that is intruded by numerous pegmatite and aplite dikes (Fig. 2). Along the southwestern part of the island, small pendants of marble, metapelite, and amphibolite are exposed. These rocks exhibit a well-developed mylonitic fabric and are exposed beneath a shallow-dipping fault. Overlying the fault are marble, greenstones (Durr and Altherr, 1979), sandstone, and conglomerate.

Mylonitic fabric in rocks of the footwall consists of a well-developed, generally shallowly northeast-dipping foliation (S-plane) and a mineral elongation lineation that trends east-northeast–west-southwest (Fig. 2). Mylonitic foliation in the granite is defined by medium- to coarse-grained flattened and elongate quartz grains and feldspars, and aligned biotite flakes. In the metasedimentary rocks, the foliation is defined by compositional banding, flattened and elongate quartz grains, and aligned mica flakes. The mineral elongation lineation is primarily defined by stretched quartz grains, smeared-out biotite, and recrystallized tails on feldspar porphyroclasts. As marked by the development of mylonitic fabric, strain increases from southwest to northeast across the island, although locally it is heterogeneous, a function of the variable relative percentage of large megacrysts of potassium feldspar.

Crystal-plastic processes dominate at the microscopic scale. Quartz grains exhibit undulatory extinction, recrystallization into fine new grains and small subgrains at old grain boundaries, dynamic recrystallization, and grain-boundary migration. Feldspars also exhibit recrystallization into small new grains and subgrains at grain boundaries. Biotite forms medium-sized grains and, along with quartz and feldspar, is commonly recrystallized into fine new grains. These fine grains are smeared-out, defining C-planes that lie at a small angle to the mylonitic foliation. Potassium feldspar porphyroclasts and hornblendes exhibit brittle micro-normal faults that dip to the northeast and southwest at moderate to high angles to the mylonitic foliation, although the southwest-dipping microfaults are more common. These microfaults are commonly pulled apart with growth of new quartz and biotite between pulled-apart feldspar and hornblende grains, respectively. The new quartz and biotite grains in these microfaults are typically sheared, exhibiting a normal sense of movement. Feldspars also exhibit variable degrees of cataclasis.

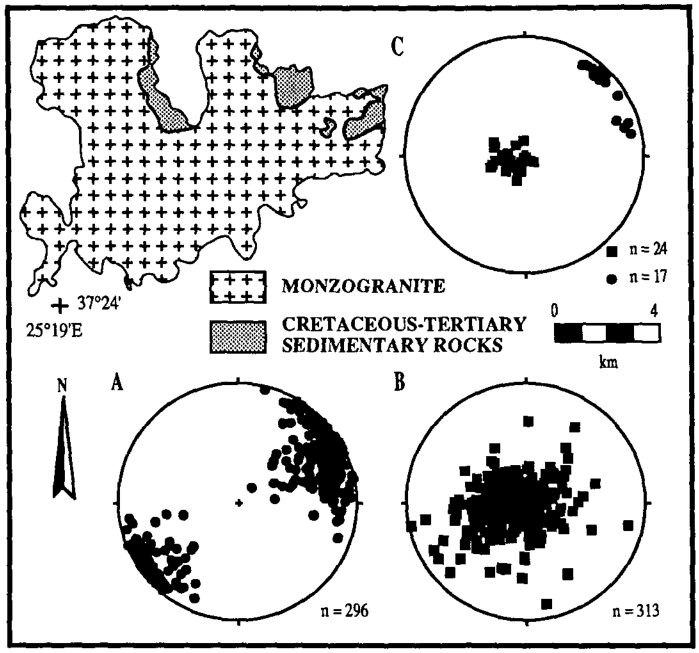


**Figure 2. Simplified geologic map of Mykonos (from J. Lee, unpublished mapping) and lower-hemisphere stereonets of structural data. A: Trend and plunge of mineral elongation lineation. B: Poles to mylonitic foliation. C: Poles to low-angle fault plane (squares) and trend and plunge of fault striae (circles).**

Microscopic and mesoscopic kinematic indicators are ubiquitous throughout these rocks. At the microscopic scale, S-C fabrics, oblique quartz grain shape foliations, asymmetric biotite "fish," asymmetric pressure shadows on feldspar porphyroclasts, and rolled feldspar porphyroclasts are observed. Shear bands, at the mesoscopic and microscopic scale, dip as much as 30° more steeply to the northeast than the mesoscopic mylonitic foliation. These structures indicate a consistent top-to-the-northeast sense of shear, which is down-dip relative to the present orientation of the mylonitic foliation.

The age of the monzogranite is uncertain. U/Pb analyses of zircons from this intrusion yield discordant ages of ~11 Ma, the result of an inherited older, premagmatic crustal component and Pb loss (Henjes-Kunst et al., 1988). K/Ar geochronology on igneous hornblendes and biotites yields cooling ages of between 10 and 12 Ma (Durr et al., 1978; Altherr et al., 1982); hornblendes from the amphibolites yield slightly older K/Ar ages of up to 14.2 Ma (Altherr et al., 1982), probably the result of incorporation of excess Ar. Fission-track thermochronology on apatites yields ages of 10.0 and 9.5 Ma (Altherr et al., 1982).

The low-angle planar fault dips $<30°$ to the northeast (Fig. 2) and is subparallel to the underlying mylonitic foliation. The fault is well exposed on the northeast side of the island and contains well-developed east-northeast–west-southwest–trending fault striae, which parallel the trend of the mineral elongation lineation in footwall rocks (Fig. 2). Within the upper 1 m of the footwall beneath the fault, mylonitic rocks have been brecciated and fractured, forming cataclastic and ultracataclastic rocks, and they contain retrograde chlorite.

Tilted Cretaceous-Tertiary marble, greenstones, sandstone, and conglomerate lie in the hanging wall of the low-angle fault. Bedding in the sedimentary strata strikes northwest-southeast and dips ~30° to the southwest. These rocks are cut by moderately northeast to east-dipping normal faults that merge with or are cut by the underlying low-angle fault.

## DISCUSSION AND CONCLUSIONS

The geometry and style of structural and map relations described here indicate an extensional origin for the mylonitic foliation and mineral elongation lineation in footwall mylonitic rocks and the overlying low-angle fault exposed on Mykonos, and they are similar to those observed in the metamorphic core complexes of the western United States. In addition, microscopic textural relations and published K/Ar geochronologic data constrain the temperature conditions and timing of mylonitic deformation.

Figure 3 schematically shows several lines of evidence that demonstrate an extensional origin for the mylonitic fabrics and the low-angle fault on Mykonos: (1) kinematic indicators in footwall mylonitic rocks exhibit a northeast-directed down-dip, or normal, sense of shear relative to the present orientation of the mylonitic foliation and the overlying low-angle fault; (2) parallelism between the footwall mylonitic elongation lineation and fault striae suggests kinematic coordination between formation of the mylonitic rocks and slip on the fault; (3) footwall rocks exhibit a progression of ductile structures overprinted by brittle structures at both the microscopic and mesoscopic scale; and (4) the fault juxtaposes unmetamorphosed or weakly metamorphosed shallow crustal rocks in the hanging wall upon higher metamorphic grade midcrustal rocks and plutonic rocks in the footwall. These relations suggest that mylonitic rocks originated in a normal-sense shear zone at midcrustal depths where crystal-plastic processes were operative. Uplift of mylonitic rocks in the shear zone translated these rocks to shallower crustal levels and into the footwall of a brittle normal fault, where brittle processes overprinted mylonitic fabrics. Translation along the fault juxtaposed the midcrustal footwall mylonitic rocks against shallow crustal, unmetamorphosed or weakly metamorphosed rocks, resulting in stratigraphic omission, not duplication. These data unambiguously indicate normal slip along the fault in an extensional tectonic setting.

Crystal-plastic behavior of feldspar and quartz, as well as new growth of biotite in pressure shadows and between fractured and pulled-apart hornblende grains, indicates metamorphic conditions of amphibolite to greenschist facies during mylonitic deformation. K/Ar geochronologic studies on hornblende and biotites from this island yield ages between 10 and 12 Ma. These ages represent the time of closure to Ar at temperatures of about 530 and 280 °C (Harrison and McDougall, 1980; Harrison et al., 1985), which bracket the range over which the described crystal-plastic textures will form. The textures described above and the limited geochronologic data suggest that intrusion was broadly synchronous with mylonitic deformation; thus, the 10–12 Ma ages represent the time of mylonitic deformation. Apatite fission track ages of 10.0 and 9.5 Ma indicate cooling below 150 °C (Green et al., 1989), well below the temperature range over which the described crystal-plastic textures will form. The apatite fission-track ages suggest that by 9.5 Ma ductile deformation had ceased and mylonitic rocks had been uplifted to shallow levels of the crust in the footwall of the normal fault.

The strikingly similar geometry and style of structural relations at map to microscopic scale on Mykonos to those found in the metamorphic core complexes of the western United States (cf. Crittenden et al., 1980) suggest a similar tectonic origin. The structure and map relations described above, as well as the absence of features diagnostic of gravity sliding, such as pervasively shattered rocks and undulatory relief on the order of tens of metres along the basal contact (Yarnold and Lombard, 1989), preclude a gravity-slide origin for the detachment fault as proposed by Faure and Bonneau (1988) and Faure et al. (1991). This island is characterized by a low-angle normal fault or detachment fault that separates a footwall of metamorphic and intrusive rocks that have been ductilely deformed from a hanging wall of unmetamorphosed or weakly metamorphosed rocks that have been tilted and displaced along normal faults. Because of the lack of suitable offset markers across the detachment fault, the origin, movement history, and amount of translation along the low-angle detachment fault in the Mykonos metamorphic core complex are as difficult to interpret as in the metamorphic core complexes of the western United States. The 30° southwest tilt of the sedimentary strata in the hanging wall of the low-angle fault on Mykonos suggests rotation of the low-angle fault from moderate to steep angles to its present shallow orientation. Tilted hanging-wall strata can be produced by dominolike rotation of normal fault blocks, movement along listric normal faults, or bowing of the low-angle fault due to footwall uplift (e.g., Buck, 1988). Detailed cooling history (uplift) studies of the mylonitic rocks on this island are in progress to address this problem.

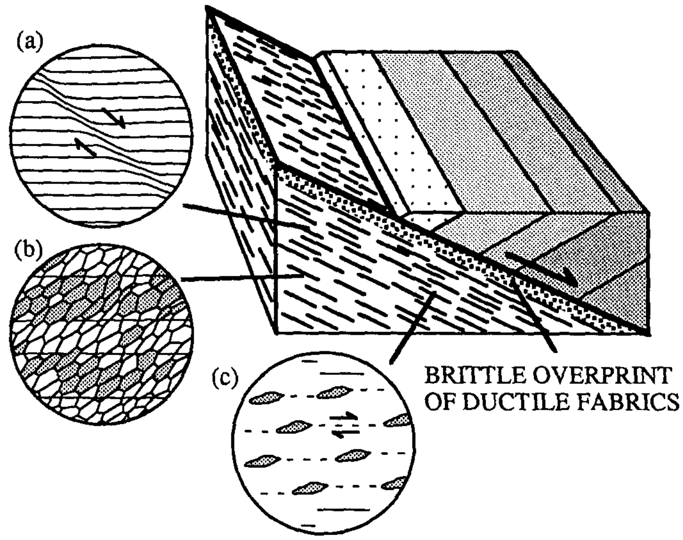


**Figure 3. Schematic three-dimensional diagram illustrating geometry of structural and map relations on Mykonos. Asymmetric kinematic indicators, such as shear bands (a) oblique quartz-grain-shape foliations (b), and mica fish (c) exhibit top-to-the-northeast normal-sense shear.**

Low-angle detachment or normal faults and ductile extensional fabrics in footwall rocks have also been recognized on Naxos, Ios (Lister et al., 1984; Buick, 1991), Tinos (Avigad and Garfunkel, 1989), Paros, Kos, and Ikaria (Lee and Lister, 1990; Gautier et al., 1990). The presence of late Miocene intrusive rocks and the late Miocene K/Ar geochronologic ages from these islands (Altherr et al., 1982) indicate that the low-angle normal faults and ductile extension are associated with the Miocene intrusive event. These relations suggest that the Miocene intrusive event was a regional extensional event behind the Hellenic trench.

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