# PARTIAL MELTING OF THE MID-TO LOWER CRUST AND STRUCTURES IN MIGMATITES: INSIGHTS INTO TYPE OF FLOW DURING LATE-OROGENIC EXTENSIONAL COLLAPSE (E. RHODOPE, BULGARIA)

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**Abstract:** High-grade gneisses and migmatites are exposed in the core of the Kesebir dome in Eastern Rhodope. Structural analysis of migmatites indicate that partial melting in the mid-to lower crust was coeval with NE-directed shearing in the core gneisses and upper crustal ductile-brittle extension. Geometry and kinematics of shear zones and structures in migmatites define partitioned internal deformation in the footwall of the detachment between coaxial strain in the core and localized non-coaxial shear in detachment zone.

**Keywords:** partial melting, migmatites, shear zones, late-orogenic collapse, Rhodope

## Introduction

The formation of high-temperature/low-pressure migmatite-granite terranes have been attributed to the processes of crustal anatexis and migmatite production in the late stages in evolution of orogenic belts. Petrological studies have shown that the normal metamorphic consequence of crustal thickening is an increase of temperature after the maximum pressures were attained (England & Thompson, 1984), that caused thermal relaxation of overthickened crust. Thermal equilibration and subsequent partial melting of the middle to lower part of crust have been suggested as an efficient driving mechanism, operating in renewed syn-to post-thickening crustal extension in the collapse stage (Dewey, 1988).

The Kesebir dome in Eastern Rhodope displays structural section, which provide an unique opportunity to direct examination of strain pattern in metamorphic domes associated with its emplacement from deep to shallow structural levels beneath low-angle detachment fault systems, that allow assessment on the mode of ductile flow in the mid-to lower crust during late-orogenic collapse.

The present paper focuses on the type of flow and geometry of internal deformation within the footwalls of detachment faults as revealed by ductile structures and shear zones in partially molten part of the crust.

**Geological framework**

The Kesebir dome (Bonev, 2002) in Eastern Rhodope is an antiformal metamorphic culmination that lies in the hinterland of the Alpine collisional system (Fig. 1 a). The dome has subelliptical map pattern, elongated NE-SW parallel to the strike of the orogen, and extends mainly on the territory of S Bulgaria and partly in N Greece.

The lowest structural level consists of orthogneisses and migmatites exhumed during NNE-directed extensional unroofing of overlying units along low-angle detachment fault system (Fig. 1 a). Sillimanite-bearing migmatites and migmatitic gneisses are exposed in a dome-shaped metamorphic culmination outlined by major planar structural elements. Migmatites and migmatitic gneisses originated at the expense of partial melting of fertile metapsammites and metapelites that occur as foliation parallel slivers within the core orthogneisses. The main structural type migmatites are represented of stromatitic metatexites, occasionally diatexites (Menhert, 1968), delineated of alternating leucosomes of granitic composition and biotite-rich melanosome bands. Primary mineral assemblage in migmatites is represented of quartz-biotite-garnet-plagioclase-K-feldspar-sillimanite. Association of K-feldspar+sillimanite in migmatites unequivocally demonstrates temperature increase under high-temperature/low-pressure metamorphic conditions that are consistent with the presence of partially molten crustal material.

**Ductile flow and structures in migmatites**

The major fabric in the migmatites is well defined of regularly spaced leucosomes alternating with melanosomes that represent "in situ" melt segregation. The main foliation of the migmatites is syn-migmatitic layering subparallel to the foliation of enclosing orthogneisses. Migmatitic layering results from combination of melt segregation and subsequent sub-solidus flow. A mineral elongation lineation, occasionally stretching lineation in high-strain zones is consistently oriented NE-SW, parallel or oblique to the axes of tight to isoclinal folds in migmatites. Shear sense indicators in migmatites and gneisses from the core and detachment zone in both ductile and brittle domain unequivocally demonstrate a top-to the NE sense of shear (Fig. 1 a).

Numerous metric to decametric, flat-laying ductile shear zones are developed in migmatites within the core. The characteristic deflection of foliation from shear zones inner parts toward boundaries demonstrate consistent sense of shear. An important feature on the geometry of shear zones is that they are developed in conjugate sets, displaying opposite shear sense (Fig. 2 a). Individual discrete shear zones also display analogous kinematic characteristics to that of conjugate sets (Fig. 2 b, d). Sense of shear is top-to the NNE in north dipping and top-to the SSW in south dipping shear zones, respectively. Thus, the shear zones indicate component of coaxial stretching in the central part of the dome. In addition, this pattern of flow is recorded in the quartz *c*-axis preferred orientations, where fabric skeleton tend to plot on asymmetric to symmetric girdles normal to the flow plane, indicated of small-scale shear bands.

The migmatites show syn-migmatic way-up criteria (Burg, 1991), which on the basis of asymmetric distribution of less dense and less viscous leucosome material that tend to migrate upward, define way-up sequence. The criteria include cauliflower structures (Fig. 2 c) that represent incipient diapiric structures on a centimeter to meter scale, and branching fractures filled with granitic material that tend to migrate upward. The latter structures are commonly observed within or adjacent to shear zones. The melt fraction within migmatites tend to concentrate in low-pressure sites provided by dilatant zones outside shear zones boundaries. These criteria indicate right way-up sequence on the north-northwestern side of the dome, and its northwestern asymmetry on the base of outward tilting to upright foliation attitude.

Structural analysis of migmatites indicate that partial melting of the mid-to lower crust is coeval with NNE to NE-directed ductile shear deformation within the core gneisses and brittle-ductile to brittle extension in detachment zone. Therefore, partial melting and acquisition of the major fabric develop concurrently with main-phase deformation and doming.

## Discussion and concluding remarks

Physical experiments and analytical studies of crustal extension show that brittle extension in the upper crust is accomodated by ductile flow of the lower crust (Block & Royden, 1990; Brun et al., 1994 a). Strain pattern and kinematics of the ductile flow in gneiss domes associated with detachment fault systems predicts complicated picture that implies complex interaction of non-coaxial and coaxial strains at different structural levels (Brun et al., 1994 b).

The geometric and kinematic framework in the migmatites from the core of Kesebir dome is consistent with existing analogue and theoretical models and add new evidences in proof on the expected internal deformation within extensional gneiss domes.

Ductile structures and strain pattern in migmatites reveal the following points on the flow type of the mid-to lower crust in the footwalls of detachment fault systems:

- Partitioning of deformation at different structural domains within detachment footwall relates to the emplacement kinematics of metamorphic domes and strain intensity in detachment zone
- Ductile flow in the mid-to lower crust within the detachment footwalls during its uplift is achieved through non-coaxial deformation, but mainly by nearly coaxial strain, and is strongly localized non-coaxial shear in the detachment itself
- Crustal anatexis may play an important role on the mechanical weakening of crustal column and facilitate ductile flow during late-orogenic collapse while the middle crust was partially molten

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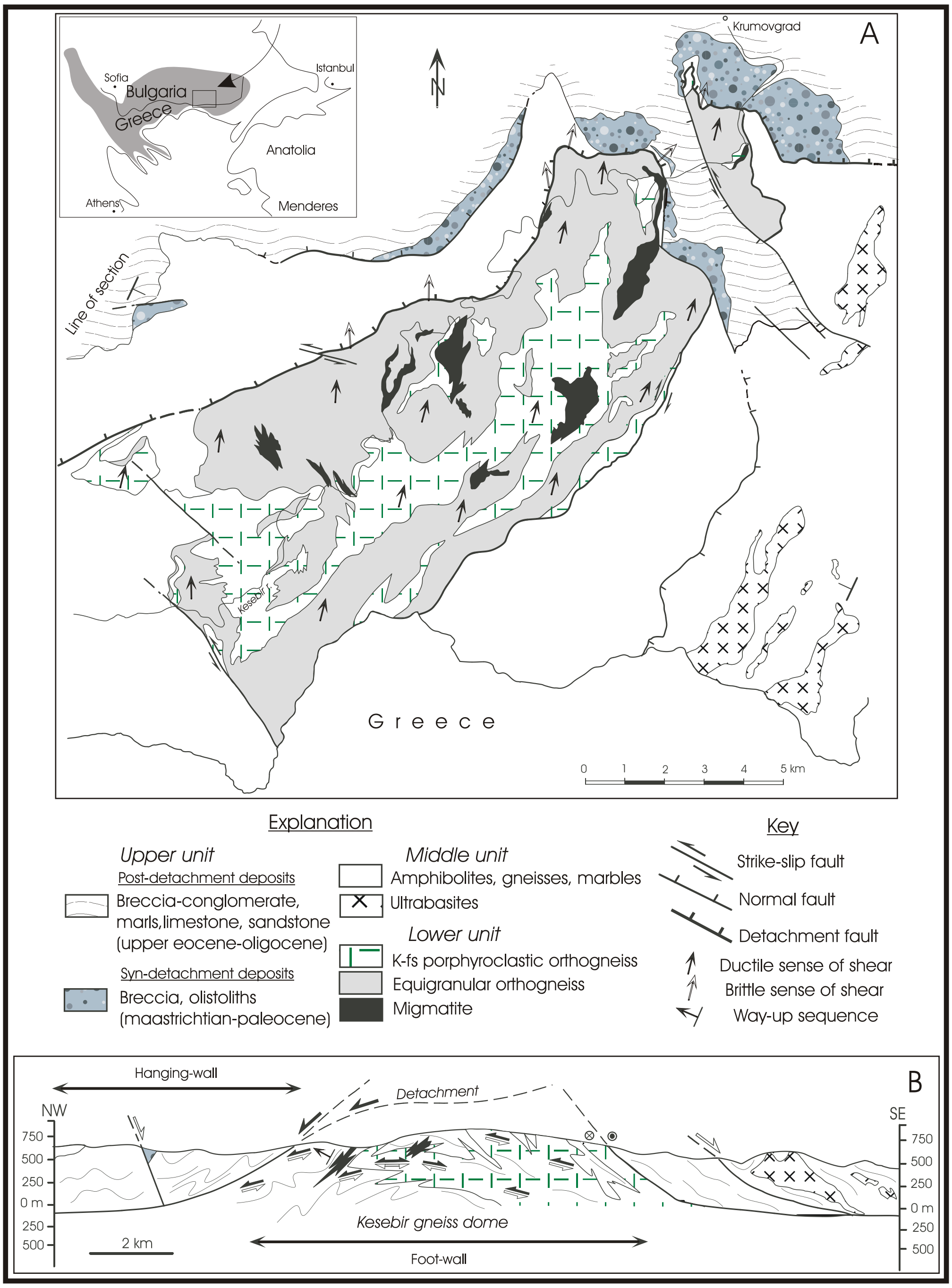
**Fig. 1.** a) Synthetic geologic-structural map of Kesebir dome showing migmatites and containing kinematic information. Inset: framed - area studied, shaded - Rhodope domain, b) Interpretative cross-section showing ductile flow in the dome crestal part inferred from strain pattern and kinematics. Line of section indicated on fig. 1 a.

**Fig. 2.** Structures and way-up criteria in migmatites. a) conjugate sets of shear zones with opposing movement directions, b) NE-directed discrete shear zone in migmatites, c) Cauliflower structure in layered migmatites. Note upper irregular surface of leucosome indicating way-up, d) SW-directed discrete shear zone in migmatites.



A
Krumovgrad
Sofia
Bulgaria
Greece
Istanbul
Anatolia
Athens
Menderes
N
Line of section
Kesebir
Greece
0 1 2 3 4 5 km
Explanation
Upper unit
Post-detachment deposits
Breccia-conglomerate, marls,limestone, sandstone (upper eocene-oligocene)
Syn-detachment deposits
Breccia, olistoliths (maastrichtian-paleocene)
Middle unit
Amphibolites, gneisses, marbles
Ultrabasites
Lower unit
K-fs porphyroclastic orthogneiss
Equigranular orthogneiss
Migmatite
Key
Strike-slip fault
Normal fault
Detachment fault
Ductile sense of shear
Brittle sense of shear
Way-up sequence
B
Hanging-wall
Detachment
NW
SE
750
500
250
0 m
250
500
2 km
Kesebir gneiss dome
Foot-wall


Fig. 1

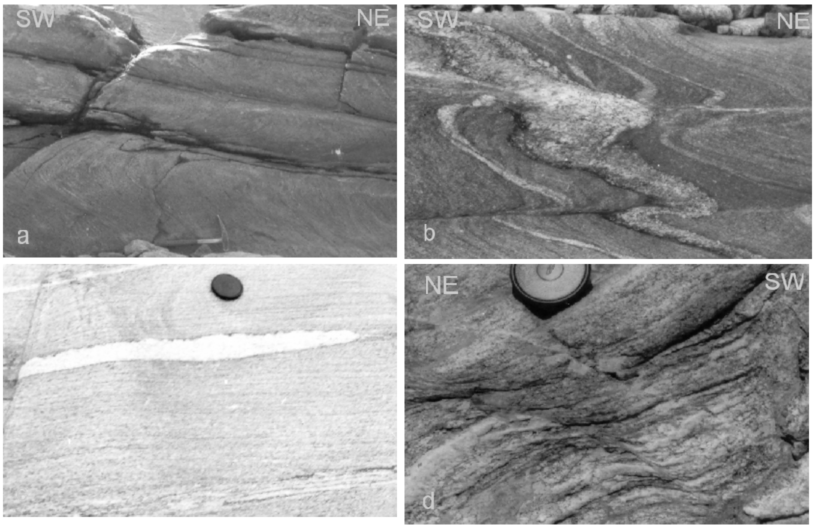



Fig. 2