



Characteristics of low-angle normal fault formation on Kea (Western Cyclades, Greece)

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Abstract: The geology of Kea Island shows further evidence for low-angle normal fault (LANF) formation in the Western Cyclades. Structural investigations have demonstrated the existence of a hitherto unrecognised ductile-brittle shear zone with strikingly consistent top-to-SSW extensional kinematics together with a WNW-ESE oriented shortening component. The tectonostratigraphy comprises a >380 m thick, shallowly-dipping schist-calcite marble unit, overlain by ca. 150 m thick fault rocks consisting of cohesive cataclasites, ultramylonitic calcite marbles, brecciated dolostones and protomylonitic calcite marbles. The presence of blueschist-facies lenses and ⁴⁰Ar/³⁹Ar geochronology point to a significant role of LANFs in exhumation processes and greenschist-facies overprint during Miocene crustal evolution.

Keywords: low-angle normal faults, extension, fault-rocks, exhumation processes, Kea, Aegean.

For more than three decades the evolution of LANFs has inspired the interest of earth scientists globally. These structures represent a class of faults with dip angles of <30° that occur in both transtensional and transpressional geodynamic regimes. Controversy exists about the origin of LANFs because they do not conform to current theories of fault-mechanics (Axen, 2004, 2007 and references therein), that predict steep (~60°) normal fault orientations in the brittle crust (Anderson, 1942) and frictional lock-up of existing normal faults at dips of ~30° or less (Collettini and Sibson, 2001).

In the Cycladic region of the eastern Mediterranean, exhumation of deep-seated rocks and metamorphic core complex formation is due to widespread exten-

sion, probably related to the southwards retreat of the Hellenic subduction zone (Royden, 1993) and rotation of back-arc crustal blocks (Walcott and White, 1998). Regional extension has generated a network of crustal-scale LANF systems and significant lithospheric thinning (Lister *et al.*, 1984).

The work presented here is a result of project ACCEL (Aegean Core Complexes along an Extended Lithosphere), which focuses on investigating the petrology, geochronology, structural geology and geodynamic interpretation of the Western Cyclades. In this contribution, we describe the formation of a major fault-rock zone in the island of Kea from ductile to brittle conditions and the preservation of HP metamorphic rocks along a LANF zone.

Geological setting and field observations

The island of Kea is located 60 km SE of Athens in the Aegean Sea. The first geological study was carried out by Davis (1972), who mapped the island and petrographically characterized the main lithologies. The litho- and tectonostratigraphic columns are dominated by the >380 m thick Intermediate Unit of the Attic-Cycladic Crystalline. This comprises a sequence of greenschist-facies metabasitic, felsic and carbonate schists intercalated with pure and impure calcite marbles and quartzites (Voit, 2008). Typical mineral assemblages for these schists involve Ab + Chl + Ms + Qtz + Ep/Zo + Act + Bt ± Kfs ± Tur ± Ap (after Kretz, 1983) with varying amounts of Cal. Locally relictic Gln and Grt are preserved. A well-developed mylonitic foliation is often overgrown by syn- to post-tectonic Ep/Zo- and Ab-blastesis. The schists are interbedded with fine-grained, occasionally statically recrystallized, blue-grey calcite marble-mylonites and rare quartzites. Notably, the marbles have been highly strained with a consistent NNE/NE-SSW/SW stretching lineation and an intense isoclinal folding with fold-axis frequently (sub)-parallel to the main stretching direction. Numerous shear sense indicators, for example SC-SCC'-fabrics and monocline clast-geometries show top-to-SSW-directed kinematics (Müller *et al.*, 2007; Voit, 2008). White mica $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronometry, performed on different structural levels within the Intermediate Unit, yielded consistent early Miocene (15-20 Ma) ages (Schneider *et al.*, 2007) and constrain the timing of exhumation and cooling of the crustal section.

The Intermediate Unit is overlain by an ~150 m thick fault-rock zone consisting of up to 5 m of cohesive cataclasites, ~30 m ultramylonitic calcite marbles and ~100 m of brecciated dolostones and protomylonitic calcite marbles. These units preserve identical structures and kinematic development as described for the Intermediate Unit. The fault-rock lithologies occur as isolated within outcrops in the NNW and SSE parts of the island and form an open structural dome gently arched over the whole island (Müller *et al.*, 2007). The presence of blueschist-facies lenses in contact with the main shear zone points to a significant role of LANFs in exhumation processes and greenschist-facies overprint during Miocene crustal evolution. In addition, the island-wide LANF can be bounded over a distance of 19.5 km.

Recorded within all lithologies is a consistent NW/WNW-SE/ESE-striking conjugated brittle, brittle-ductile high-angle fault pattern perpendicular to

the main stretching direction. The varying dip-angles and fault-modes point to a progressive development and interaction between contemporaneous movements on high-angle and low-angle normal faults. Additionally, leaching during retrograde metamorphism and/or hydrothermal activity resulted in a locally intense ankeritisation of carbonate units and mineralisation and ore formation along the high-angle faults.

Conclusions and discussion

Based on field observations and microstructural investigations we can show the development of a major crustal shear zone with different stages of LANF-evolution and -formation from ductile to brittle conditions. Cross-cutting relationships of high- and low-angle normal faults impressively demonstrate the co-genetic architecture and activity of both fault systems during formation of the extensional metamorphic dome on Kea. Microstructures in ultramylonitic marbles with dolostone intercalations show an evolution of the LANF under viscous-frictional conditions (Voit, 2008). Field and microstructural observations in cataclasites and overlying dolostones with stylolites indicate the principal stress direction and require low apparent fault friction probably due to high fluid pressure and/or weak fault-zone materials (Niemeijer and Spiers, 2007).

Ar/Ar-data along the LANF zone on Kea point in respect to the Western Cyclades Serifos metamorphic core complex LANFs (Grasemann and Petrakakis, 2007; Iglseder *et al.*, 2008) to an earlier Miocene evolution and show a similar cooling history observed at Tinos Island (Jolivet *et al.*, 2004).

In addition we postulate, with respect to observations in Lavrion on the Greek mainland (Skarpelis *et al.*, 2008), the existence of a tectonic boundary between the Intermediate Unit and the fault rock zone, likely bounded by a LANF. Nonetheless the consistent top-to-SW/SSW kinematics of LANFs on Kea, Kythnos, and Serifos demonstrates the importance of the Western Cyclades in the overall tectono-metamorphic evolution and geodynamics of the Aegean region.

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