



Characteristics of low-angle normal faulting in Serifos (Western Cyclades, Greece)

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Abstract: On the island of Serifos SSW-directed low-angle faults accommodated crustal thinning during Miocene extension. Cross-cutting relationships suggest that the low-angle faults interacted with WNW-ESE striking conjugate high-angle normal faults in both the hanging and the footwall. Although high- and low-angle faults were likely synkinematic, the deformation mechanism differs significantly in both systems. The low-angle faults are characterized by several meters of low-grade, ultra-fine grained marble mylonites below several decimetres of ultracataclases. The high-angle faults represent mainly brittle deformation resulting in slickensides, cataclases and pseudotachylites. The Ar/Ar mica geochronology yields uniform ages across the low-angle faults suggesting a nearly horizontal detachment at temperatures coincident with the brittle-ductile transition zone.

Keywords: low-angle faults, crustal extension, metamorphic core complex, brittle-ductile transition, Aegean.

Low-angle normal faults (fault dip <math><30^\circ</math>) are a major class of faults that occur in much of the geologic record in both extensional and contractional continental settings (Wernicke, 1981; Burchfiel *et al.*, 1992; Axen *et al.*, 1999) and at slow spreading mid-ocean ridges (MacLeod *et al.*, 2002; Garcés and Gee, 2007). The origin of continental low-angle normal faults remains controversial because fault mechanical theory predicts the formation of extensional faults in the brittle upper crust at dip angles steeper than $\sim 60^\circ$ (Anderson, 1951). Whereas some of the reported continental low-angle normal faults rotated either actively or passively from steep to shallow dips (Buck, 1988; Koyi and Skelton, 2001), others are thought to have origin at low-angles, which requires low apparent fault friction probably due to high fluid pressure or weak fault-zone materials (Manatschal, 1999; Mehl *et al.*, 2005; Niemeijer and Spiers, 2007; Numelin *et al.*, 2007). In this work, we report the synkinematic existence of high- and low-angle normal faults during the exhumation of the Serifos metamorphic core complex.

Field observations

Serifos is located in the Aegean Sea, 100 km SE of Athens and belongs to the Cycladic Islands. In the northern part of the island, the main foliation defines an open dome shape consisting mainly of schists and marbles. The central and southeast portions of the island are largely dominated by a Late Miocene (around 10 Ma) shallow-level I-type granodiorite pluton and associated numerous dykes of roughly the same age (Altherr *et al.*, 1988; Iglseder *et al.*, 2005). Recently, Serifos has been described as a metamorphic core complex (Grasemann *et al.*, 2004), which experienced mid-crustal cooling and final exhumation during the Late Miocene (Vogel *et al.*, 2007).

Spectacular SSW-directed low-angle normal faults have been described from the NNE and SSW headlands of Serifos (Grasemann and Petrakakis, 2007). These normal faults have the following characteristics in common: i) deformation is localized along a knife-

sharp plane. Below the fault-plane, several meters of ultramylonitic, ultra-fine grained marbles experienced ductile SSW-directed shear, ii) in schists within layers of marbles at structurally lower levels, ductile deformation is generally weaker, more distributed and localised in meter-scale shear bands indicating WSW-directed kinematics, iii) structurally above the fault plane that is marked by polished slickensides, the marble ultramylonites are overlain by several generations of decimeter-thick ultracataclasites. Scaly fabrics in clay-rich layers indicate SSW-directed shear, iv) the rocks structurally above the zones of ultramylonitic and ultracataclastic deformation are characterized by ankeritized protocataclasites, v) WSW- to SSW-directed progressive ductile to brittle deformation is associated with WNW-ESE oriented shortening forming upright folds with fold axes parallel to the shearing direction, and vi) low-angle normal faults cut high-angle faults but are also offset by high-angle faults suggesting that high-angle faults were active before and after low-angle faulting.

More specifically, the low-angle faults kinematically interact with high-angle faults, which accommodate NNE-SSW extension along conjugate steeply dipping brittle fault planes in both the hanging wall and the footwall. The high-angle faults are associated with cataclastic deformation and record offset of marker horizons along slickensides from several centimetres up to several tens of meters. Frequently these faults are associated with the formation of pseudotachylites. At an outcrop scale, the high-angle fault sets occur either in the hanging wall and/or in the footwall of the low-angle fault. Cross-cutting relationship suggest that space problems associated with horst-and-graben type extensional deformation in the footwall is accommodated with ductile flow within the ultramylonitic marble horizon of the low-angle fault zone.

Discussion and conclusions

Cross-cutting relationships of high- and low-angle normal faulting clearly demonstrates that both fault systems were active during the final ductile to brittle/ductile stage of exhumation of the Serifos metamorphic core complex. Brittle conjugate high-angle normal faults occur in the footwall and the hanging wall of the low-grade ductile marble mylonites of the low-angle normal fault. Ductile deformation in the marble mylonites resolves space problems associated with high-angle brittle horst-and-graben type exten-

sion suggesting that both fault systems were synchronously active and genetically related. Whereas frequent observations of pseudotachylites in the high-angle faults suggest rapid fault movement probably associated with seismicity, no pseudotachylites have been found along the low-angle faults. Microstructures in ultracataclasites of the low-angle faults show marked similarities with structureless cataclastic microstructures generated by rotary shear experiments demonstrating unusually strong velocity weakening (Niemeijer and Spiers, 2007), probably suggesting that at least during brittle deformation the low-angle faults were weak.

The dykes associated with the intrusion of the granodiorite strictly follow the conjugate high-angle brittle fault system. Because some of the dykes and the upper structural levels of the granodiorite are overprinted by the ductile low-angle fault system, this last stage of extensional exhumation of the Serifos metamorphic core complex was active around 9 Ma. Mass-balance and volume-change estimates correlating undeformed granodiorites with intensively overprinted ultramylonites within low-angle shear zones indicate insignificant whole-rock mass as well as volume changes. Observed fractionation of LREE relative to HREE and gain of incompatible LIL elements in the ultramylonite are interpreted to be unrelated to the kind of deformation but a result of fluid compositions and P-T conditions during the deformation process.

The ductile/brittle fault system arches over the whole island and can be structurally traced in a NNE-SSW section over 10 km. Interestingly, Ar/Ar geochronology of white micas from the schists is surprisingly uniform and no offset of the cooling age pattern is observed across the low-angle normal faults. This observation constrains a very narrow temperature range (roughly between 300-350 °C) within which the ductile movement of low-angle normal faulting occurred. Considering the exposed length of the fault system and assuming that the palaeoisotherms were approximately horizontal, the low-angle fault system was at that stage also subhorizontal.

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