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Quantitative kinematics of a frictional viscous low-angle normal fault on Kea (Western Cyclades, Greece)

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Abstract: Lithospheric extension during the Miocene is well documented in the Aegean. Within the Central and Western Cyclades extension has been documented in detail by the formation of Metamorphic Core Complexes and movement along low-angle normal faults (LANFs). Focusing on a hitherto unrecognised main low-angled fault geometry outcropping on northern Kea, this work presents pervasive evidence of top-to-south kinematics.

Keywords: Aegean, Cyclades, Kea, low-angle normal faults, detachment, kinematics, fault zone, crustal extension, exhumation.

Within the overall context of the extensional regime in the Cyclades, recent studies give evidence to support bi-directional movement. Compared to the top-to-NNE-NE directed kinematics which characterise the Eastern Cyclades, our new results place Kea, along with Kythnos and Serifos (Grasemann and Petrakakis 2007; Müller *et al.*, 2007; Schneider *et al.*, 2007; Iglseder *et al.*, 2008; Lenauer *et al.*, 2008; Mörtl *et al.*, 2008; Voit, 2008), in a row of islands having top-to-SW-SSW shearing in the Western Cyclades (Fig. 1).

As part of Project ACCEL (Aegean Core Complexes along an Extending Lithosphere), new 1:50 000 and better scale mapping on Kea has identified a tectonostratigraphy: footwall and fault-zone. No unambiguously hanging wall rocks have been identified yet. In this work we examine NW Kea with a focus on a large scale frictional-viscous low angle normal fault.

Based on Quickbird imaging, high-precision GPS, structural, lithological and tectonostratigraphic data, a detailed geological/structural map of NW Kea has been compiled (Fig. 2A).

Previous work

Kea has been geologically the subject of only relatively few published articles so far. There was some lineation data published in a thesis and a publication by Walcott (1998) and Walcott and White (1998) but the main information source hitherto has been the 1:50 000 geological map of Kea (Davis, 1972, 1982). During her studies, Davis petrographically characterised the main lithologies, describing non-metamorphic limestone klippen on top of greenschist-facies metamorphosed lithologies.

During remapping, the ‘klippen’ turned out to be discordant 10 m thick ultramylonitic marble as well as dolomitic breccia, both of which form part of a viscous-frictional shear zone.

Geology of Kea

The island comprises a domed, low-angle normal fault system (Müller *et al.*, 2007) formed during greenschist-facies metamorphic conditions.

Indicated by a pervasive subhorizontal foliation and fold axial-surfaces, a low-angle fault geometry as well

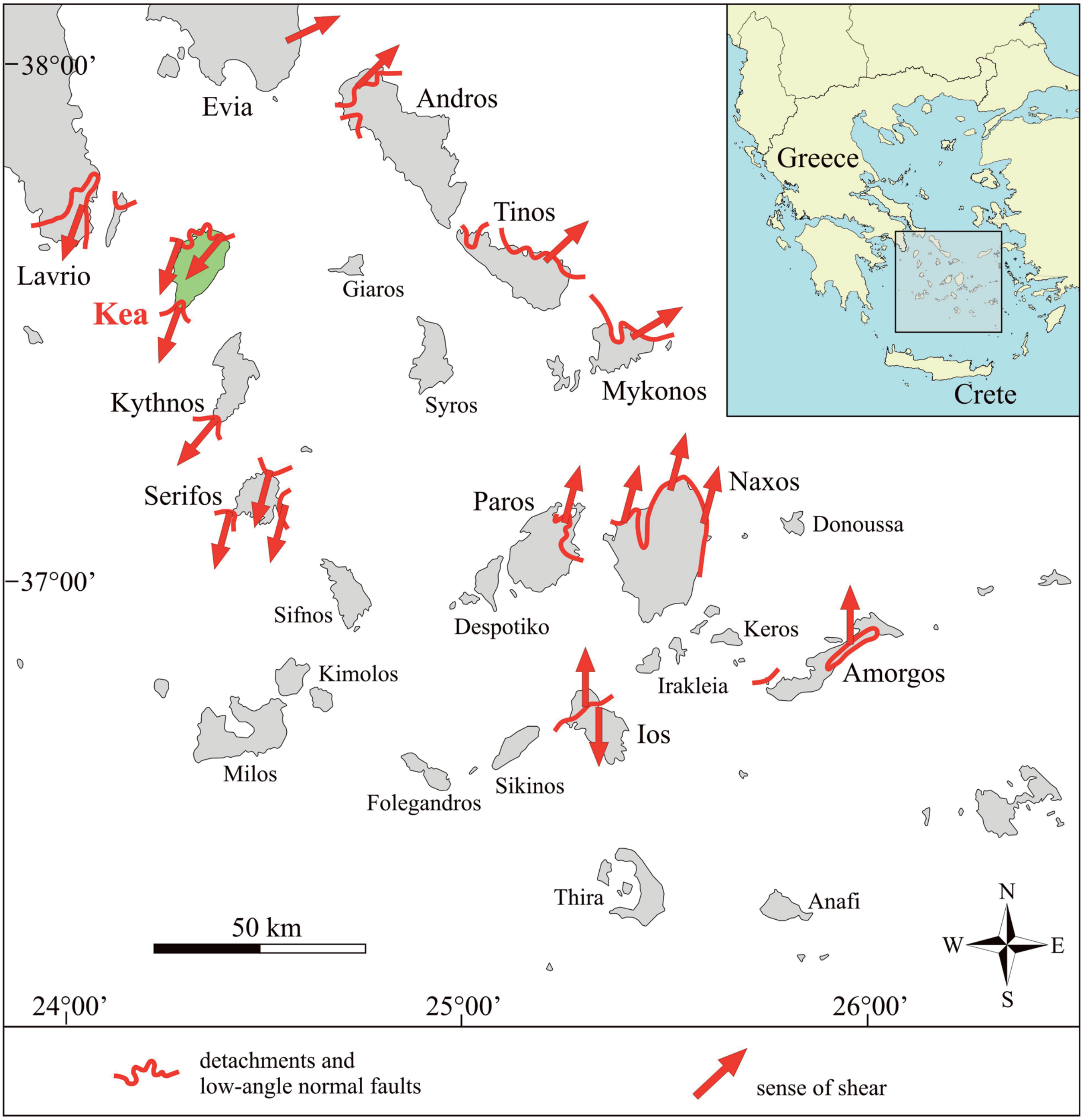

Figure 1. Geotectonic overview of the Cyclades Islands, with the geographical location of Kea in the western Cyclades, showing main detachments with sense of shear (modified of Forster and Lister, 1999; Iglseder *et al.*, 2008). The Otzias Bay Detachment is localised on the northwestern part of the Island of Kea.

as extensional movement was identified. We therefore divided Kea structurally into footwall rocks and fault-zone rocks.

The lithologies of the footwall are mainly built up and dominated by rocks added to the Intermediate Unit of the Attic-Cycladic Crystalline. In general, these comprise a sequence of greenschist-facies metabasitic and felsic as well as carbonate schists which are represented by a typical mineral assemblage of Ab + Chl + Ms + Qtz + Ep/Zo + Act + Bt ± Kfs ± Tur ± Ap (after Kretz, 1983) with varying amounts of Cal. Lithological variations are lensoid. These schists are interbedded with pure and also impure blue-grey to locally white calcitic marble and with thin, folded quartz layers; boudinaged in some areas and often (ultra-) mylonitic, as well as rare quartzites. The blue-grey calcitic marbles of the footwall have a pro-

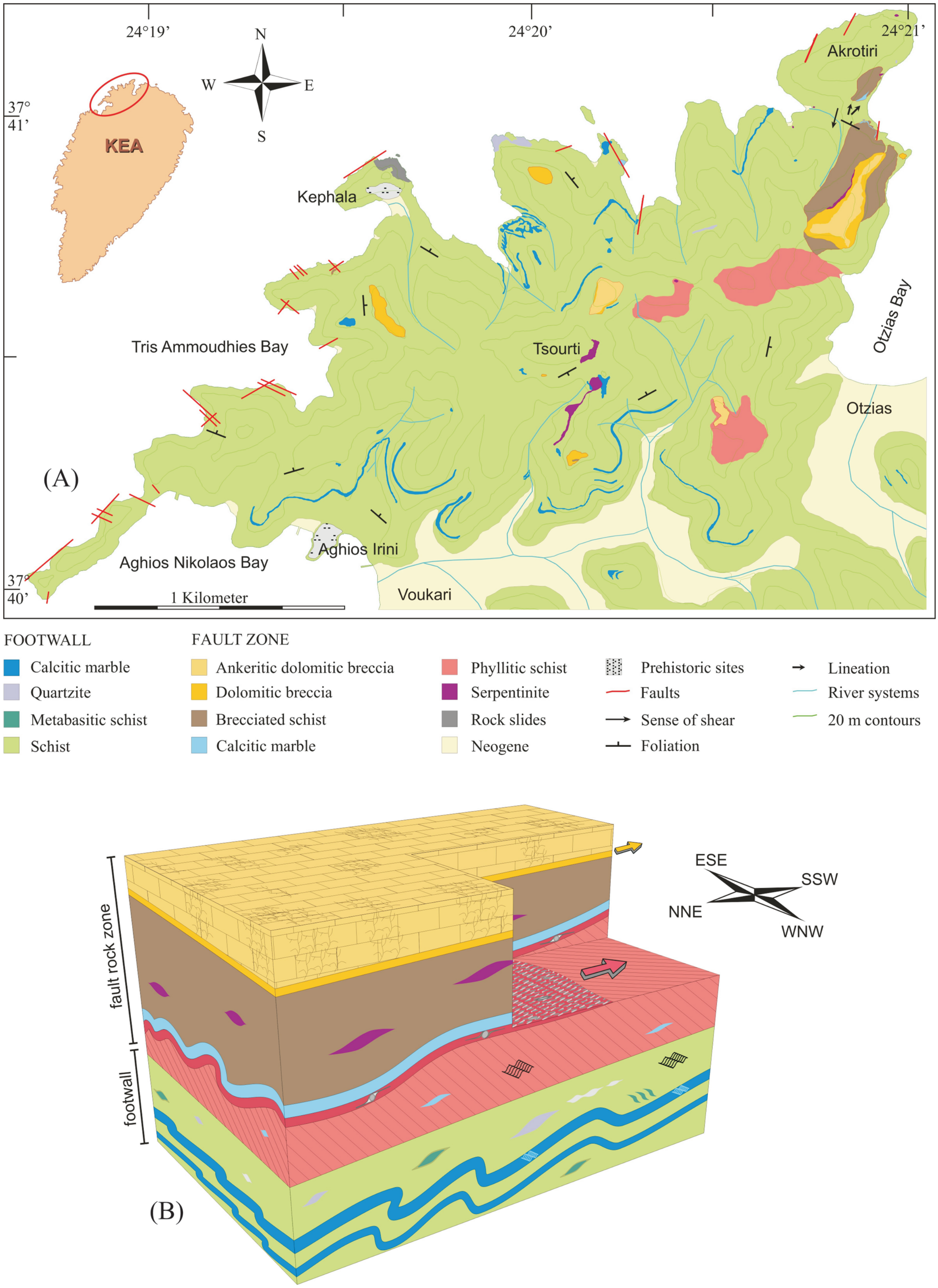

Figure 2. (A) Detailed geological map of NW Kea. Location of prehistoric sites with metalworking modified after Gale (1998), (B) schematic synoptic diagram of the footwall and fault zone at the Otzias Bay Detachment.

nounced stretching lineation which has a strikingly consistent SSW-NNE orientation. Shear criteria show that it formed during top-to-south sense movement.

Phyllitic schists are mainly observed at the base of the fault zone and around marble (mega-) boudins, representing higher strain zones within the greenschist unit footwall rocks.

The fault-zone rocks consist of dark brown to rusty red ankeritised dolomitic breccia, pale brown to faintly reddish cohesive dolomitic cataclasites, and of ochre to rusty red-stained brecciated (ultra-) cataclastic schist (dolostones) derived from the footwall and often ultramylonitic calcite marbles with occasional boudins of dolomitic marble.

The Otzias Bay Detachment

Within the overall fault system of Kea, the Otzias Bay Detachment (OBD) is part of a higher strain shear-zone (see Figs. 1, 2A and 2B).

In the northwestern part of the island the fault zone crops out nicely, giving a view of brecciated dolomite (locally strongly ankeritised), serpentinite lenses associated with talc schists and a cataclastic schistous zone bounded by the LANF.

In detail, the detachment comprises a several metre-thick cataclastic fault zone, with large calcitic breccia fragments with a broad grain-size distribution, interlayered with a few fine-grained gouge layers, several cm thick. A gently folded but knife-sharp fault surface is distinct and characterises the area of the OBD. It separates brittle cohesive cataclasite from brittle/ductile to ductile marbles and schists (Fig. 2B).

Ductily folded calcitic (ultra-) mylonitic marbles with thin quartz layers and carbonate-derived cataclasite, greenschist facies chloritic and quartzitic schists make up the footwall. The detachment dips at low angles towards the NNW.

Gentle folding of the OBD and the structurally upper cataclastic zones about NNE-SSW orientated axes suggest that a WNW-ESE shortening component accompanied deformation from ductile, through brittle/ductile to brittle conditions.

Due to high-strain shearing in an extensional regime accompanied by perpendicular shortening and upright folding, axes of non-cylindrical folds in the mylonites have rotated into the finite stretching direction, generating and preserving various stages within the evolution of ductile refolds.

The varying orientations of veins and faults indicate different generations and multiple reactivation periods. A superimposing of ductilely deformed footwall rocks by various stages of late brittle overprint, such as mode 2 cracks (Irwin, 1957) alternately being refilled by ore rich fluids, quartz and calcite, can be observed throughout the area.

In some places, minor faults bearing angular-breccia of host rock are filled with travertine and calcite. These faults cross-cut older sets of veins and joints and continue into the cataclastic fault zone. Suspended nature ("frozen-in" status) and restorable geometry of broken fragments puts dynamic rupture accompanied by high fluid pressure into debate.

A very late stage of brittle overprint is represented by steep major cross-cutting faults.

At the detachment an older ductile NE-SW lineation is overprinted by a younger NNE-SSW finite stretching direction, indicating britte-ductile to brittle conditions.

Shear sense criteria

Within both the footwall greenschists and in the overlying fault rocks, ductile shear-sense criteria consistently show a top-to-SSW movement. Indicators recorded include delta and sigma clasts, flanking structures, asymmetric boudinage, stable porphyroclasts with monoclinic symmetry, as well as rotated and boudinaged veins. Brittle shear-sense indicators, in particular scaly fabrics and Riedel geometries of secondary fractures, are consistent with this shearing direction.

Some examples in the OBD-cataclasite that indicate the co-existence of fabrics generated under frictional as well as creep conditions are fabrics showing a range of creep-type fabrics, mm to metre scale breccia tails, smeared out matrix layers and discrete slip planes that define geometries of S-C planes, flanking structures and asymmetric porphyroclasts all indicating a top-to-south sense of shear.

Discussion and conclusion

Based upon detailed geological and structural mapping we describe various stages and conditions of low-angle normal fault formation along a major shear zone in the northwestern part of the island of Kea.

Multiple, low-angle cataclastic fault zones formed within, and (sub-) parallel to, a regional mylonitic ductile foliation, and a widespread system of minor and major sets of (sub-) steep vertical cross-cutting faults act as indicators for co-genetic architecture and activity of both fault systems during the evolution of the crustal-scale low-angle frictional-viscous normal fault system on Kea.

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References

DAVIS, E. N. (1972): Geological structure of Kea Island. *B. Geol. Soc. Greece*, 9, 2: 252-265.

DAVIS, E. N. (1982): *Geological map of Kea, 1:50 000. Map of Greece in scale 1:50 000*. Geological Survey of Greece, Athens.

FORSTER, M. A. and LISTER, G. S. (1999): Detachment faults in the Aegean core complex of Ios, Cyclades, Greece. In: U. RING, M. T. BRANDON, G. S. LISTER and S. D. WILLET (eds): *Exhumation processes: normal faulting, ductile flow and erosion, Geol. Soc. London Spec. Publ.*, 154: 305-323.

GALE, N. H. (1998): The role of Kea in metal production and trade in the Late Bronze Age. In: L. G. MENDONI and A. MAZARAKIS (eds): *Kea-Kytnos: History and Archeology, Proceedings of an International Symposium, Kea-Kythnos*. Meaethmata, De Boccard, Paris, 27: 737-758.

GRASEMANN, B. and PETRAKAKIS, K. (2007): Evolution of the Serifos Metamorphic Core Complex. In: G. LISTER, M. FORSTER and U. RING (eds): *Inside the Aegean Metamorphic Core Complexes, J. Virtual Explorer*, 27, 2: 5-16.

IGLSEDER, C., GRASEMANN, B., SCHNEIDER, D. A., PETRAKAKIS, K., MILLER, C., KLÖTZLI, U. S., THÖNI, M., ZÁMOLYI, A. and RAMBOUSEK, C. (2008): I and S-type Plutonism on Serifos (W-Cyclades, Greece). *Tectonophysics*, doi: 10.1016/j.tecto.2008.09.021.

IRWIN, G. R. (1957): Analysis of stresses and strains near the end of a crack traversing a plate. *J. Appl. Mech.*, 24: 361-364.

KRETZ, R. (1983): Symbols for rock-forming minerals. *Am. Mineral.*, 68: 277-279

LENAUER, I., MÖRTL, G., IGLSEDER, C., GRASEMANN, B. and EDWARDS, M. A. (2008): Field evidence for a major normal fault on Kythnos Island (Western Cyclades, Greece). *Geophys. Res. Abstr.*, 10: 03218.

MÖRTL, G., GRASEMANN, B., LENAUER, I., EDWARDS. M. A., IGLSEDER, C., THÖNI, M. and MADER, D. (2008): Fluid-rock interaction in a low-angle-normal fault (Kythnos, Western Cyclades, Greece). *Geophys. Res. Abstr.*, 10: 04585.

MÜLLER, M., GRASEMANN, B., EDWARDS, M. A. and TEAM ACCEL (2007): New evidence of bidirectional extension in the Cyclades: SSW-directed low-angle normal faulting on the island of Kea, W. Aegean. *Geophys. Res. Abstr.*, 9, 7967.

SCHNEIDER, D. A., GRASEMANN, B., HEIZLER, M., VOGEL, H., IGLSEDER, C. and TEAM ACCEL (2007): Temporal patterns of detachment faulting along Cycladic extensional metamorphic domes, Aegean region. *Eos Trans., Am. Geophys. Union Abstr.*, 88: T21D-05.

VOIT, K. (2008): *Structural Geology and Geomorphology of Northern Kea - A crustal scale Viscous-frictional Shear Zone (Western Cyclades, Greece)*. Unpublished Diploma Thesis, University of Vienna, Austria, 179 pp.

WALCOTT, C. R. (1998): *The Alpine evolution of Thessaly (NW Greece) and Late Tertiary Aegean kinematics*. PhD Thesis, Utrecht University, Netherlands, 175 pp.

WALCOTT, C. R. and WHITE, S. H. (1998): Constraints on the kinematics of post-orogenic extension imposed by stretching lineations in the Aegean region. *Tectonophysics*, 298: 155-175.