High spectral resolution optical image analysis as a tool for elucidating major extensional structures in detailed geological mapping

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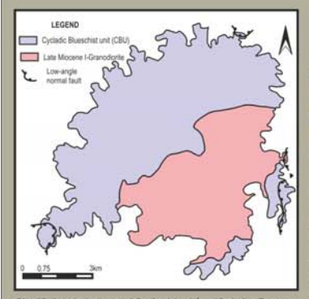
ABSTRACT

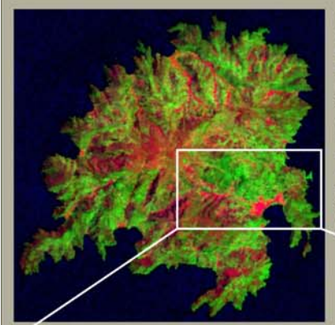
The Attic-Cycladic complex (Aegean Sea, Greece) is a natural laboratory for studying crustal-scale extensional processes and structures. The central Cycladic islands are situated in a crustal-scale extensional detachment system that has accommodated regional, N-S back-arc extension due to the collapsing Alpine orogen and rollback of the subducting African slab. A system of regional scale, low-angle normal faults has extensively reworked the Alpine nappe stack pile and resulted the exhumation of lower-plate rocks and the tectonic denudation of the upper-plate that is only sparsely exposed throughout the Aegean Sea. Extension was also accompanied by widespread plutonism and volcanic activity, which followed the southward migrating arc. In several Cycladic islands (e.g. Tinos, Mykonos, Naxos, etc) Middle to late Miocene (~15-10 Ma) syn-extensional granitic intrusions are observed below major low-angle normal faults. Mylonitic to cataclastic deformation associated with these faults resulted the formation of alteration zones, mainly chloritized micro-breccia, located at the roof of the granitic rocks, which mark the tectonic contact with the upper plate rocks. In some cases, this chloritic micro-breccia (e.g. the low-angle normal fault) is preserved while in most cases is either eroded or diffused. Optical image interpretation of remote sensing multispectral data proved to be a useful tool for the detailed mapping of these major extensional structures and the associated alteration zones. Several pseudo-chromatic images of the Cycladic islands were produced showing the alteration zones and marking the tectonic contacts between the footwalls and hanging walls of different detachment surfaces, which are exposed to the open air. Spectral signatures of the minerals, which were identified either through microscopy or during fieldwork, were used and the new false-color images fused with high-resolution panchromatic air photographs gave us the opportunity to increase the accuracy of the field mapping and consequently realize the tectonic evolution of the central part of the Aegean micro-plate.

SERIFOS



Simplified geological map of Serifos Island (modified after Tschegg and Grasemann 2009).

In Serifos Island (Cyclades, Greece), a ~9-11Ma granodiorite intruded a greenschist-facies, brittle-ductile to brittle low-angle normal fault during extension and exhumation of the Cycladic Blueschist Belt.
The brittle, low-angle fault plane juxtaposed mylonitic granodiorite, deformed under upper greenschist-facies conditions (footwall) against a weakly foliated granodiorite, deformed under lower greenschist-facies conditions (hanging wall).
The hanging wall granodiorite was completely metasomatized by infiltrating fluids, a process that led to extensive leaching of the mafic components and bleaching.



A Landsat-ETM+ satellite image of 30th of June 2000, was used for spectral interpretation. The initial purpose was to use the spectral characteristics of the rock outcrops on the island and relate them with the results of the image interpretation. We used visible, near infrared and short wave infrared bands for ratio calculations. At Serifos isl. dataset the ratios B5/B7 was used for Red, B3/B1 was used for Green and B4/B3 was used for Blue (left). The result was in agreement with the field observations but since the area where the detachment crops out is quite small, we increased the spatial resolution by merging the interpreted image with an ortho-photograph with 1-meter resolution (down). The detachment zone can be easily located on the image with acceptable resolution and assist the fieldwork in a great percentage.

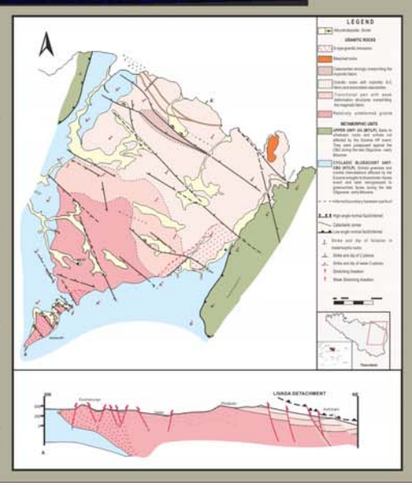
TINOS

In the interpreted Landsat ETM+ image the ratios B5/B7 was used for Red, B3/B1 was used for Green and B4/B3 was used for Blue. There is a distinct difference between the deeper non deformed to weakly deformed parts of the granitic rocks and the external part that exhibits protomylonitic to mylonitic fabric. The remote sensing techniques which led to this interpretation will be used to trim the outcrop traces, which were mapped during fieldwork (dashed lines on the image) as minor modifications are needed in order to improve the geological map.

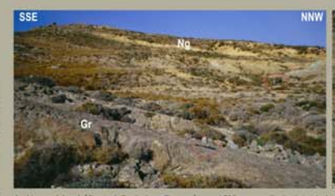
In Tinos Island (north Cyclades Greece), a ~15-14 Ma granodiorite pierced through the ~21-20 Ma, ductile, Tinos Detachment and intruded along the middle Miocene, greenschist-facies, brittle-ductile to brittle, Livada Detachment.
The internal part of the pluton was more or less not deformed or only weakly deformed whereas the roof of the pluton has developed a protomylonitic to mylonitic fabric overprinted by subsequent cataclastic deformation and later on by high-angle normal faults.

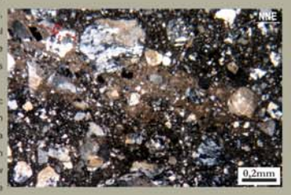
A deformation gradient can be observed from the centre of the Island (Exombourgo) towards the coastline (Skliros Ormos Bay - Avlomani - Livada Bay).
The core of the pluton, exposed in Volax and Exombourgo area (possible feeder zone), exhibits a magmatic to sub-magmatic foliation (Sm) formed by aligned euhedral to subhedral feldspar and quartz grains and/or schlieren layering. Weak deformation structures start to develop and gradually increase in intensity towards the NE.

The roof of the pluton, exposed along the coastline (from Skliros Ormos bay to Livada Bay), exhibits a protomylonitic to mylonitic S-C fabric with domino and book-shelf sliding in feldspar, subgrain formation and ribbon quartz, σ- and δ-clasts and biotite fish.

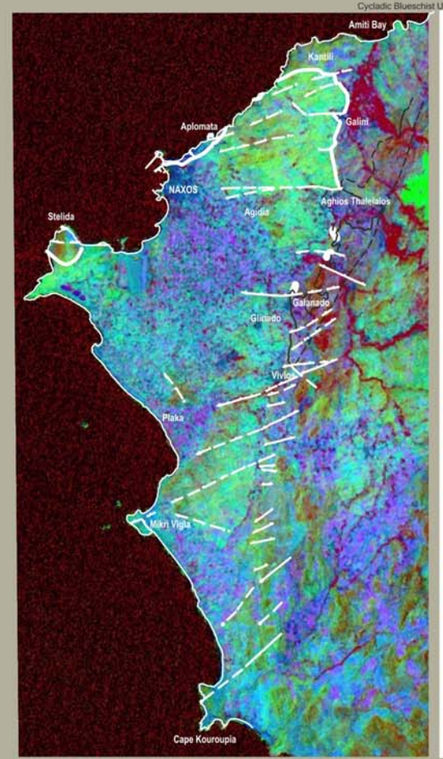


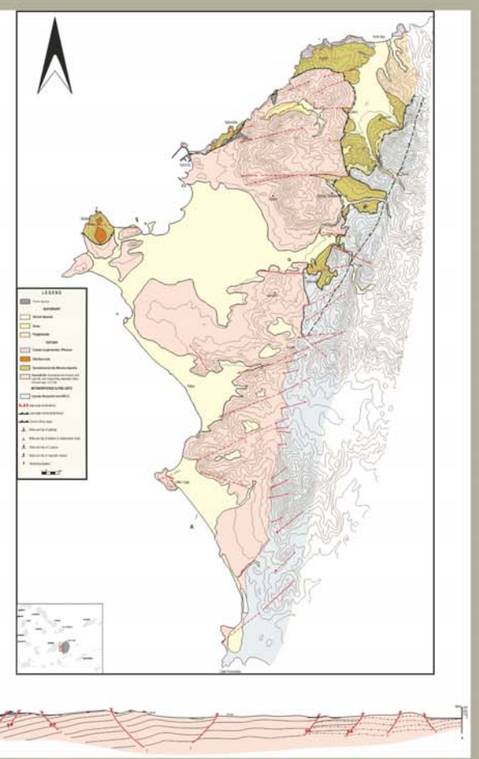
NAXOS





In Naxos Island (Central Cyclades, Greece), a ~12Ma granodiorite intruded along the late Miocene, brittle-ductile to brittle Naxos Detachment. A brittle, low-angle fault plane separates the strongly deformed syn-extensional Neogene deposits of the supra-detachment basin (Ng - hanging wall) from the footwall granodiorite (Gr), deformed under lower greenschists - facies conditions.
At the northern part, in the carapace of the pluton the early-stage mylonitic fabric was extensively reworked by late-stage cataclastic deformation synchronous to massive fluid infiltration, which led to the formation of a cohesive cataclasite to ultracataclasite exhibiting chloritization ankeritization and sericitization. The southern part of the granite is undeformed and a few hundred meters thick metamorphic aureole is observed in the host rocks of the Cycladic Blueschist Unit.





A different kind of image interpretation was applied at this subset of the Landsat ETM+ image. Ratios B3/B1 was used for Red, B5/B4 was used for Green and B5/B7 was used for Blue. The resulted image is in good relation with the fieldwork mapping as certain colors can be attributed to different geologic structures. The most impressive identification is the distinction of the hanging wall from the foot wall of the extensional detachment fault. It seems that the mineral composition of the detachment surface is very much differentiated from the surrounding outcrops, in terms of its spectral reflectance. Other structures, either important or not, were also identified on this part of the island, revealing the significance of satellite image interpretation techniques as an additional tool for accurate and detailed geological mapping.

Index map of the Cycladic complex and the individual islands mentioned in this work

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