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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 the locus of a crustal-scale extensional detachment system that has accommodated regional back-arc extension due to the collapse of the Alpine orogen and rollback of the subducting African slab. Regional scale, low-angle normal faults dismembered the Alpine nappe pile and caused the exhumation of lower-plate rocks. In several Cycladic islands (e.g. Tinos, Mykonos, Naxos, etc) middle to late Miocene syn-extensional granitic intrusions are observed at the footwall of these major low-angle normal faults. Mylonitic to cataclastic deformation and fluid infiltration associated with these faults resulted in the formation of composite deformation+alteration zones that are located at the roof of the granitic intrusions and mark the tectonic contact with the upper plate. 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 detachments, which are today exposed to the surface. Spectral signatures of specific minerals identified either through microscopy or during fieldwork, were used and the new false-color images fused with high-resolution panchromatic air photographs revealed components that are intangible by classical techniques and increased the accuracy of the field mapping.

INTRODUCTION

The Attic-Cycladic complex (central Aegean Sea, Greece, Fig 1) was formed in Miocene times when the thick Alpine orogenic nappe pile that was formed during late Cretaceous to Cenozoic subduction and subsequent accretion of Gondwana derived blocks was destroyed by several crustal-scale extensional detachment faults as a result of slab rollback and gravitational collapse (1,2).

The development of the Cycladic metamorphic core complexes along asymmetric low-angle extensional detachments resulted in the exhumation of the lower-plate metamorphic rocks and the tectonic denudation of the upper-plate (3,4,5 and references therein). On Tinos Island (north Cyclades, Greece), the tectono-stratigraphic column includes three low-angle normal faults with top to NE sense of shear that are all part of the North Cycladic Detachment System (4,6). At the northeastern part of the island a ~15-14 Ma I-type granodiorite and a few smaller ~14 Ma S-type intrusions pierced through the ~21-20 Ma, ductile, Tinos Detachment and intruded along the middle Miocene (~13-15Ma), greenschist-facies, brittle-ductile to brittle, Livada Detachment, which is now eroded (6).

Naxos Island was the first place in the Cyclades where a metamorphic core complex was identified and studied (7). The late Miocene Naxos-Paros extensional Detachment System juxtaposes supra-detachment Neogene sediments against the Mesozoic Cycladic Blueschist Unit rocks (CBU) and a

~12Ma I-type granodiorite that's intruded into the CBU and along this detachment during the last stages of exhumation (8,9).

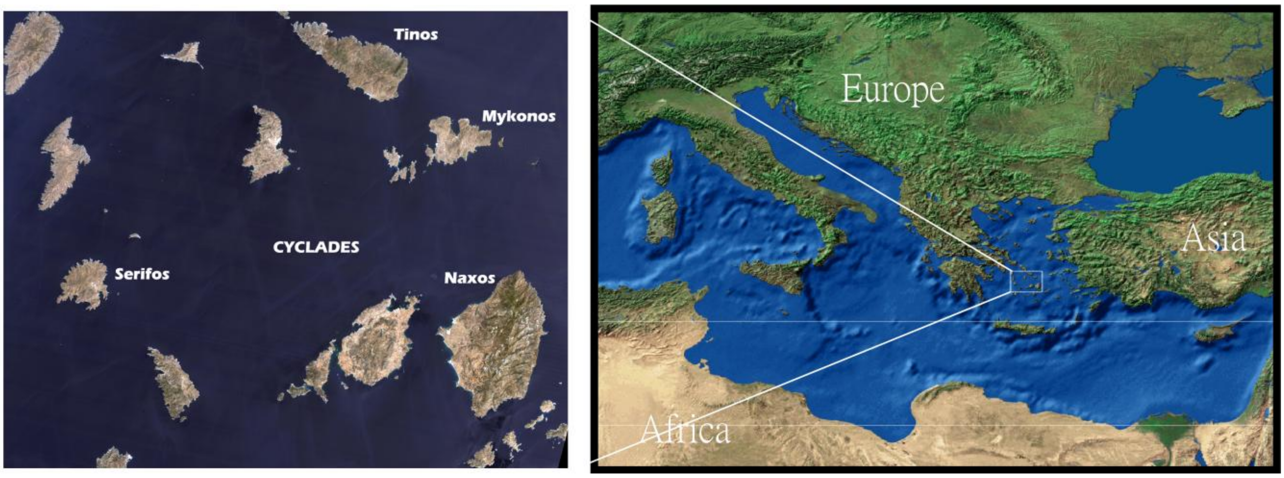

Figure 1: Location of the Cycladic islands of the Aegean Sea (right) mentioned in this paper, in a true color Landsat7-TM dataset (182/34, capture date June 30th 2000).

Intrusion and exhumation of granodioritic rocks in the footwall of large detachment systems is associated with cataclastic deformation fluid infiltration and alteration processes that produce different types of fault rocks with distinct features and special composition.

Remote sensing is considered to be a useful tool for assisting field mapping and in the past, remote sensing methods have been mostly used in order to identify regional scale structures and not so much in detailed mapping (10).

In this paper we use sophisticated remote sensing techniques in order to integrate the results of classic field mapping and structural analysis methods in the islands of Tinos and Naxos. The resulting high-spectral resolution images exhibit impressively good relation with the geological maps thus proving useful in identifying major extensional structures such as the trace of low-angle normal faults and distinguishing footwall from hanging wall. Also, it is demonstrated that in some cases e.g. Tinos Island the satellite image interpretation can be used to fine tune existing detailed maps.

METHODS

The acquired remote sensing data (downloaded from USGS earth-explorer) proved to be very useful especially after digital interpretation in different levels. Various images were produced especially by using several spectral band combinations as well as spectral ratios aiming to a clear and precise outcrop imaging. The ability of using the panchromatic band of Landsat7-ETM+ with increased spatial resolution (15m) allowed the merging procedure with the multispectral bands, by using the Brovey Transform algorithm, to a single fused dataset was very significant as this gave the opportunity to work in larger scales (11). The band ratio images that were used were focused on mineral composition related to fluid infiltration and rock alteration in extensional detachment zones and the absence of vegetation at the studied areas revealed the exact location of tectonic structures. The data were ortho-rectified to the Hellenic Geodetic Reference System 1987 by using a 25 meter Digital Elevation Model derived by topographic maps with 20 meter contours.

In order to test the degree of applicability and the validity of results obtained by remote sensing techniques we chose two well-studied cases in the Attic-Cycladic complex e.g. Tinos and Naxos islands, which were already mapped in detail by the authors.

Detailed mapping of the granitic intrusions of NE Tinos island and the enveloping rocks (Fig 2) and study of the magmatic and deformation structures in all scales revealed that the internal part of the pluton was more or less not deformed or only weakly deformed, in contrast with the roof of the pluton that has developed a protomylonitic to mylonitic fabric overprinted by subsequent cataclastic deformation and later on by high-angle normal faults.

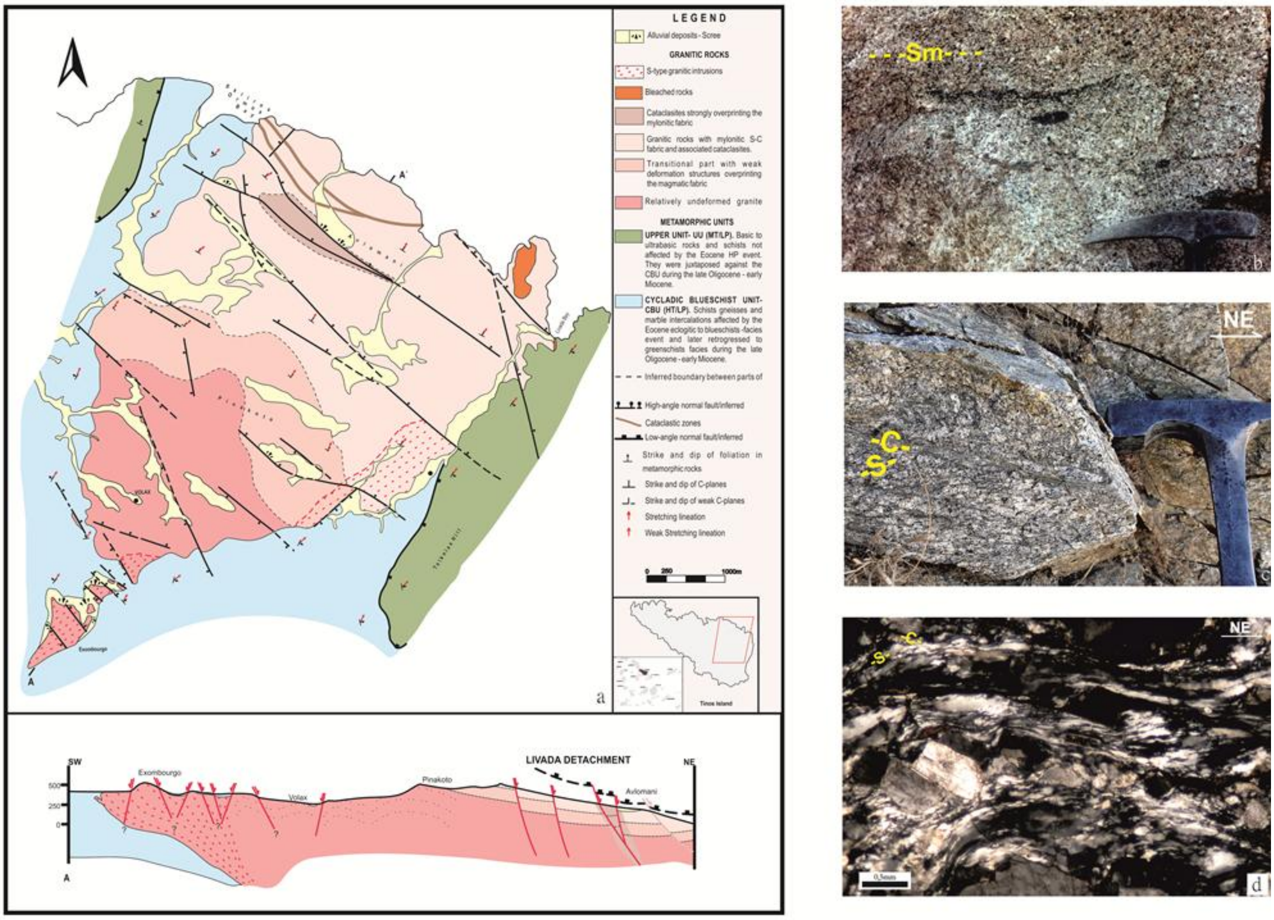

Figure 2: a) Geological map of northeast Tinos. b) Magmatic structures from the almost undeformed internal part of the pluton c) Mesoscopic scale S-C fabric from the rim of the granodiorite. d) Microphotograph showing the protomylonitic to mylonitic fabric of the granodiorite.

A deformation gradient can be observed from the centre of the Island (Exombourgo - Volax) towards the coastline (Skliros Ormos Bay - Avlomani - Livada Bay). The core of the pluton, exposed in Volax and Exombourgo area, which represents the 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 e.g the external part of the intrusion. The roof of the pluton is exposed along the coastline (from Skliros Ormos bay to Livada Bay), and exhibits a subhorizontal protomylonitic to mylonitc S-C fabric. Meosocopic and microscopic scale structures such as domino and book-shelf sliding in feldspar, subgrain formation and ribbon quartz, σ- and δ-clasts and biotite fish indicate that deformation took place in P-T conditions corresponding to lower greenschist facies e.g. along the brittle - ductile transition. The mylonitic fabric is variably overprinted by generations of gradually steeper cataclastic C_c-surfaces associated with proto- to ultracataclasites that are often accompanied by pseudotachylitic veins. Relatively small patches of bleached granodioritic rocks can be observed in several places and especially at or near Livada Bay.

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 (Fig 3). 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 were 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.

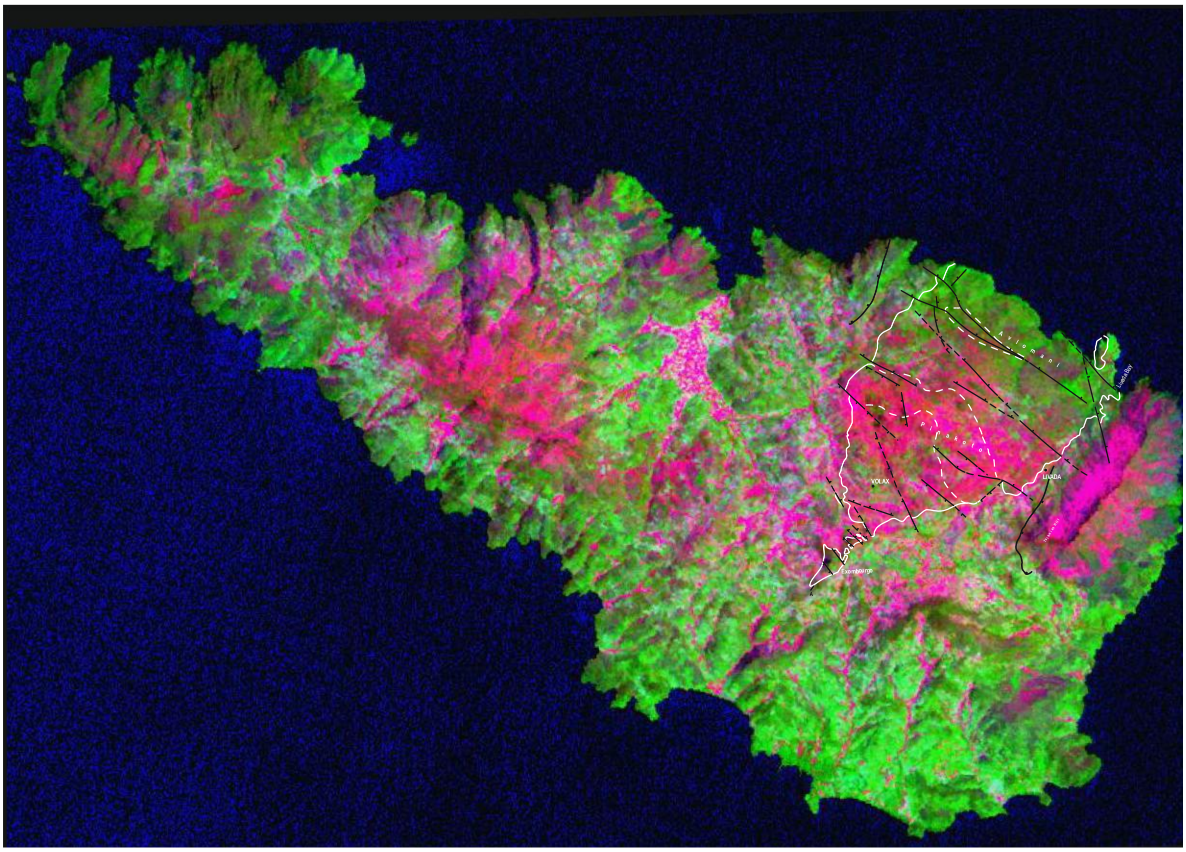

Figure 3: Pseudo-chromatic image of Tinos Island with Landsat ETM+ band ratios B5/B7, B3/B1, B4/B3 (R,G,B). The different lines show the outcrops mapped during fieldwork which are in agreement with the colours of the interpreted image.

The western part of Naxos In the western part of Naxos Island (Central Cyclades, Greece), a ~12Ma N-S oblong granodiorite intruded along the late Miocene, brittle-ductile to brittle top to the N sense of shear Naxos Detachment (Fig. 4). The detachment is marked by a low-angle fault plane that separates the strongly deformed syn-extensional Neogene deposits of the supra-detachment basin in the hanging wall from the footwall granodiorite. Similar to Tinos Island numerous meso- to microscopic scale structures (domino and book-shelf sliding in feldspar, subgrain formation and ribbon quartz, σ- and δ-clasts and biotite fish) also reveal that the granodiorite was deformed under lower greenschists - facies conditions.

At the northern part, along the in the carapace of the pluton the early-stage mylonitic fabric was extensively reworked by late-stage cataclastic deformation synchronous to extensive fluid infiltration, which led to the formation of a cohesive cataclasite to ultracataclasite that was also accompanied by alteration processes such as chloritization, limonitization, ankeritization and sericitization. The southern part of the granite is relatively undeformed and a few hundred meters thick metamorphic aureole is observed in the host rocks of the Cycladic Blueschist Unit.

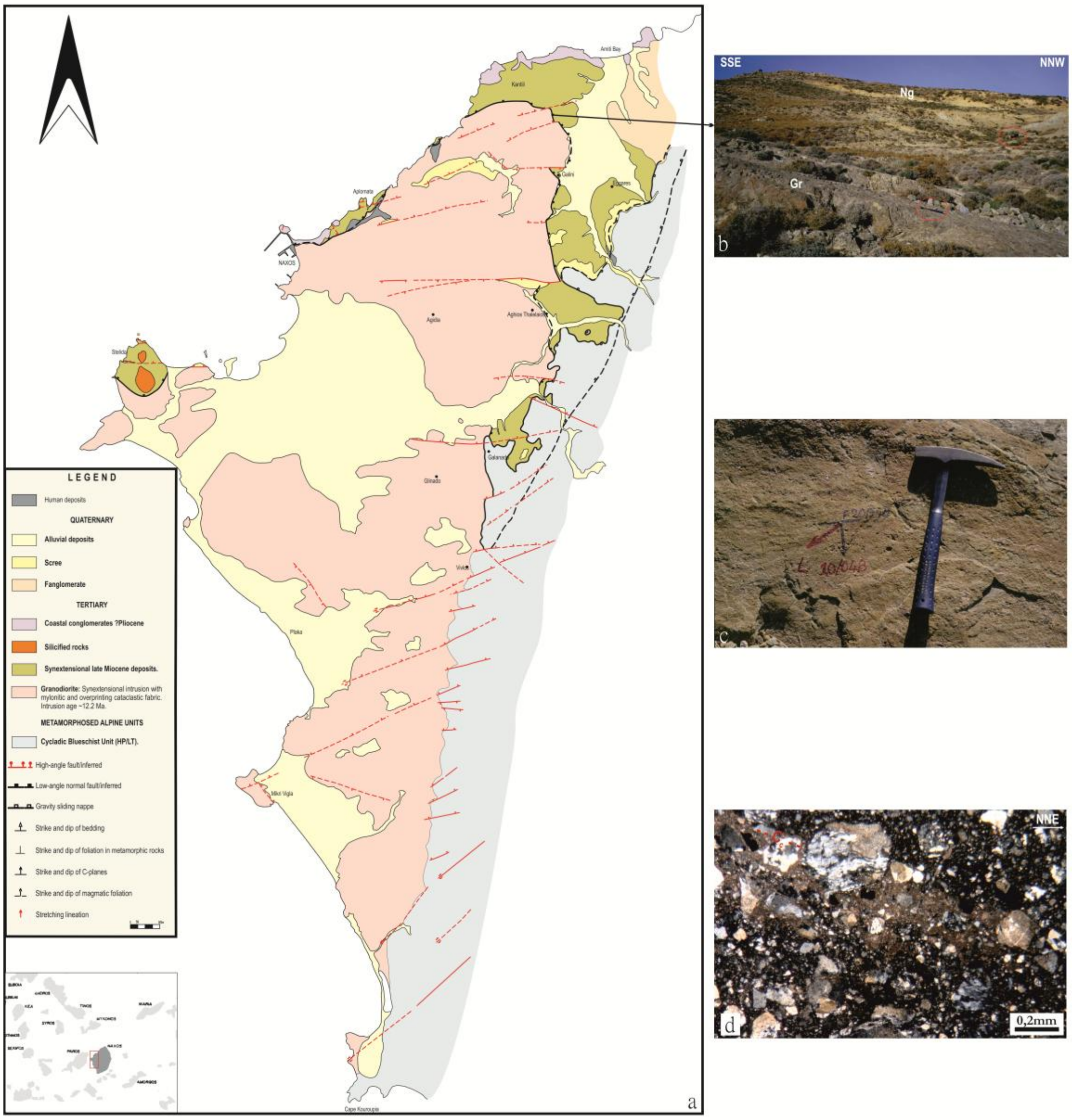

Figure 4: a) Geological map of east Naxos. b) View of the low-angle normal fault that juxtaposed the granodiorite (Gr) against the Neogene sediments (Ng). c) Close view of the cataclastic limonitic-rich fault surface. d) Microphotograph of the fluid infiltrated cataclasite.

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 (Fig 5). The resulted image is in good relation with the fieldwork mapping as certain colours can be attributed to different geologic and tectonic 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.

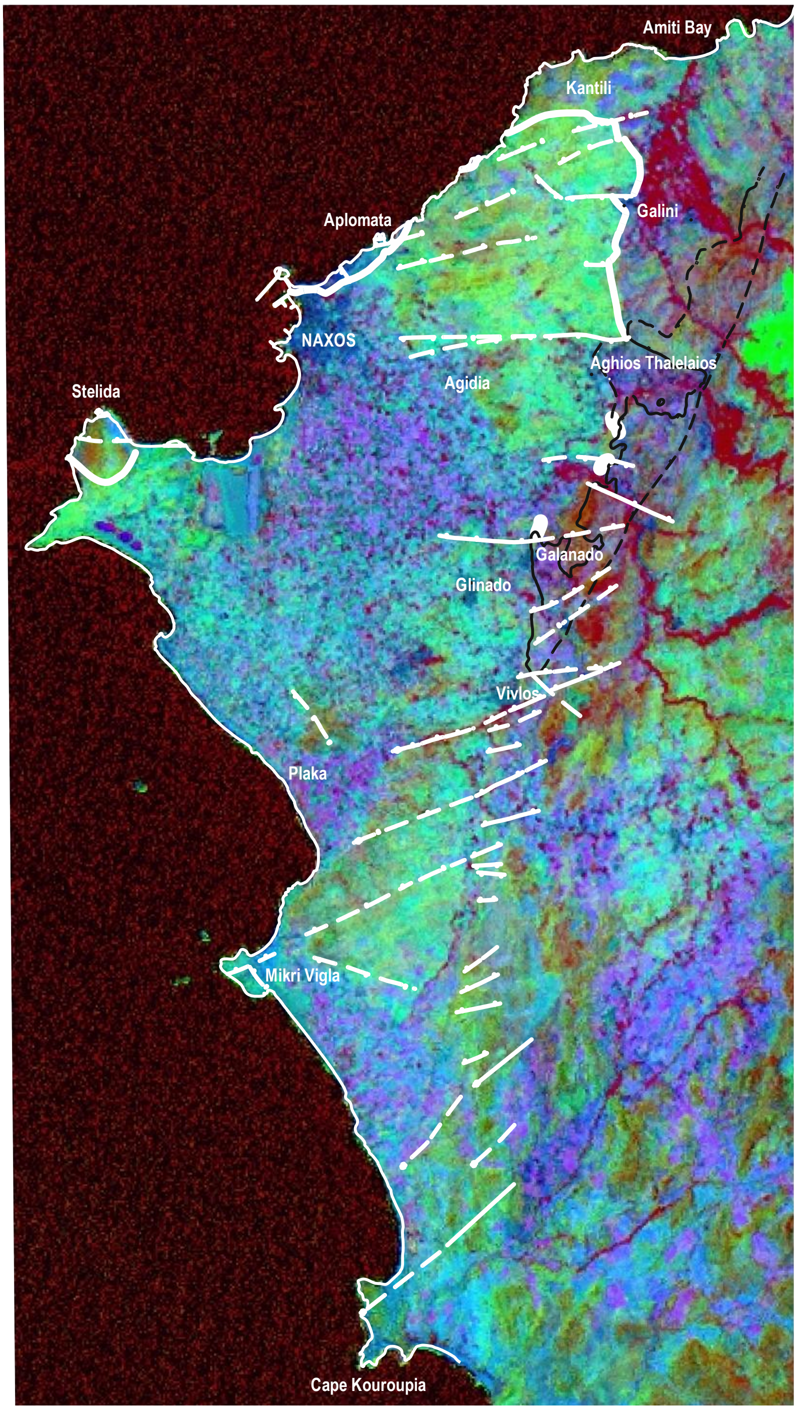

Figure 5: Pseudo-chromatic image of NE Naxos Island with Landsat ETM+ band ratios B3/B1, B5/B4, B5/B7 (R,G,B). The lines show the tectonic structures related to exhumation which are in impressive agreement with the colours of the interpreted image.

CONCLUSIONS

This paper highlights the important role that analysis of multispectral satellite data can play in the identification of surface structures related to major tectonic events and natural processes, especially at areas adjacent to extensional detachment fault zones where the mineral composition due to fluid infiltration and rock alteration is ideal and additionally no extensive vegetation cover has been developed. In most cases high spectral resolution satellite images provide significant reflection data in several spectrum parts and mathematic operations between those data increase the interpretation abilities.

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