Middle Miocene E-W tectonic horst structure of Crete through extensional detachment faults

D Papanikolaou[1,3] **and E Vassilakis**[2]
[1] Professor of Dynamics and Tectonics, School of Geology and Geoenvironment, Department of Dynamics, Tectonics and Applied Geology, National and Kapodestrian University of Athens, 15784, Greece
[2] Research Scientist, School of Geology and Geoenvironment, Department of Dynamics, Tectonics and Applied Geology, National and Kapodestrian University of Athens, 15784, Greece

E-mail: dpapan@geol.uoa.gr, evasilak@geol.uoa.gr

Abstract. Two east-west trending extensional detachment faults have been recognized in Crete, one with top-to-the-north motion of the hanging wall toward the Cretan Sea and one with top-to-the-south motion of the hanging wall toward the Libyan Sea. The east-west trending zone between these two detachment faults, which forms their common footwall, comprises a tectonic horst formed during Middle Miocene slip on the detachment faults. The detachment faults disrupt the overall tectono-stratigraphic succession of Crete and are localized along pre-existing thrust faults and along particular portions of the stratigraphic sequence, including the transition between the Permo-Triassic Tyros Beds and the base of the Upper Triassic-Eocene carbonate platform of the Tripolis nappe. By recognizing several different tectono-stratigraphic formations within what is generally termed the "phyllite-quartzite", it is possible to distinguish these extensional detachment faults from thrust faults and minor discontinuities in the sequence. The deformation history of units within Crete can be summarized as: (i) compressional deformation producing arc-parallel east-west trending south-directed thrust faults in Oligocene to Early Miocene time (ii) extensional deformation along arc-parallel, east-west trending detachment faults in Middle Miocene time, with hanging wall motion to the north and south; (iii) Late Miocene-Quaternary extensional deformation along high-angle normal and oblique normal faults that disrupt the older arc-parallel structures.

1. Introduction

The first detailed geological and tectonic data of Crete were presented by Papastamatiou [1, 2] during the beginning of geological mapping at scale 1:50,000. The general picture was quite similar to that of continental Greece and Peloponnesus with the Pindos unit nappe overlying the Tripolis unit and its metamorphic basement. During the 1970's several studies resulted distinguishing a more detailed tectono-sratigraphic succession for Crete by differentiating several nappes either at the base of the nappe pile (tectonic units of Ida – Plattenkalk, Trypali, Phyllites-Quartzites) or at the top (tectonic units of Arvi, Miamou, Vatos, Asteroussia) [3, 4, 5, 6, 7, 8]. Based on the distinction between the low-grade Permo-Triassic Tyros Beds at the base of the Tripolis Upper Triassic – Eocene carbonate platform and the underlying medium grade metamorphic rocks of the Arna unit in Peloponnesus [9] a

[3] To whom any correspondence should be addressed.

modified tectono-stratigraphic succession for the Phyllites-Quartzites unit of Crete was proposed by adding the new unit of Western Crete between the Autochthon basement and the Arna unit as well as including the Variscan Sitia metamorphic rocks within the Tyros Beds [10]. The tectonic contacts separating the above tectonic units were generally considered as thrusts.

During the 1990's - 2000's several papers have proposed the interpretation that some of the previous tectonic contacts are extensional detachments usually separating the non metamorphosed nappes from the underlying metamorphosed units [11, 12, 13]. However, in several cases the amount of throw and the overall extensional deformation across the proposed extensional detachments were not demonstrated. On the contrary, it was obvious that in some cases the tectonic surfaces interpreted as extensional detachments separated the Late Triassic base of the Tripolis carbonate platform from its immediate normal stratigraphic sequence to the Tyros Beds (Middle Triassic). Thus, it was important to examine the tectonic contacts and decipher which ones were either thrusts, or extensional detachments, or surfaces of minor 'decollement' type sliding due to disharmonic phenomena, or even more complex cases with opposite kinematic characteristics of primary thrusting followed by secondary extension. This latter case would be interpreted - from a kinematic point of view - as an initial slip direction to the south, compatible with the folding and thrusting geometry of the Hellenides, followed by a younger slip direction to the north (unless, the detachments were also directed to the south).

2. Re-interpretation of the tectonic contacts of the Cretan units: thrusts or extensional detachments?

The tectono-stratigraphic nappe pile of Crete was analyzed by the re-interpretation of the geological maps combined with new field observations. Our research resulted a new map of the tectono-stratigraphic units of Crete at the scale of 1:200,000. Special emphasis was given to the distinction of the complex term "Phyllites-Quartzites" which, in fact, has to be analyzed in several tectono-stratigaphic units. Thus, from the tectonically deeper metamorphosed carbonate rocks of the relative autochthon unit of Mani (or Metamorphosed Ionian) to the shallower carbonate rocks of the Tripolis carbonate platform there is a number of different tectono-stratigraphic formations within the schistose type formations usually named in the literature as "Phyllites-Quartzites", such as (figure 1): i) The metamorphosed flysch of the Mani unit (Oligocene age, known also as Kalavros Beds), ii) The complex unit of Western Crete, comprising a Tyros type low-grade metamorphosed volcano-sedimentary sequence of Permian to Middle Triassic age, followed by Middle to Late Triassic evaporites and Late Triassic to Early Jurassic crystalline limestones (referenced as Trypali unit), iii) Medium-grade HP/LT metamorphic rocks of the Arna unit (or Phyllites-Quartzites s.s.), with the age of this unit being presumed to be Paleozoic but its metamorphism is Late Tertiary, and iv) The Permo-Triassic volcano-sedimentary base of the Tripolis platform, consisting of phyllites, meta-sandstones, volcanic rocks and some carbonate layers, equivalent to the Tyros Beds in Peloponnesus (partly known as the Ravdoucha Beds). Some evaporites and particularly the Variscan high-grade metamorphic rocks of the Sitia unit occur within the Tyros Beds in eastern Crete. Thus, the above units belong to the External Carbonate platform of the Hellenides (Terrane H_1) [14] as Mani Autochthon represents the more external part of the platform between Paxos and Ionian units, the Western Crete nappe represents a part of Ionian unit - mainly its lower part below the pelagic Middle Jurassic – Eocene sequence [15] - and finally Arna, Tyros Beds and Tripolis platform represent the central part of the external platform as the Tyros Beds occur stratigraphically underneath the platform and Arna unit represents the pre-Alpine Paleozoic basement of this platform. The presumed unconformity between the Arna basement rocks and Tyros Beds sequence has been used as a tectonic surface of discontinuity and has localized the formation of the individual tectonic unit of the Arna nappe.

The Ethia unit (equivalent to the Pindos unit in continental Greece) is usually observed superimposed on the Tripolis unit, as several nappes with limited outcrop extent all around Crete Island that occur at the higher positions in the Cretan nappe pile (figure 2). These higher nappes are: i)

Arvi unit, comprising Late Cretaceous basalts and pelagic sediments, ii) Miamou unit, comprising a late Cretaceous wild-flysch, iii) Vatos unit, comprising a Late Paleozoic – Jurassic sedimentary sequence, iv) Asteroussia nappe, comprising high-grade metamorphic rocks and granites with a Late Cretaceous age of metamorphism, and v) the Cretan ophiolitic nappe, found at the topmost position, although sometimes ophiolite bodies are also found intercalated with the Vatos and Asteroussia nappes. The aforementioned tectonic units belong to the Pindos – Cyclades tectono-stratigraphic terrane H_2 [14], with the exception of the Asteroussia metamorphics that may represent slices of the basement rocks of the internal carbonate platform of the Pelagonian terrane (H_3).

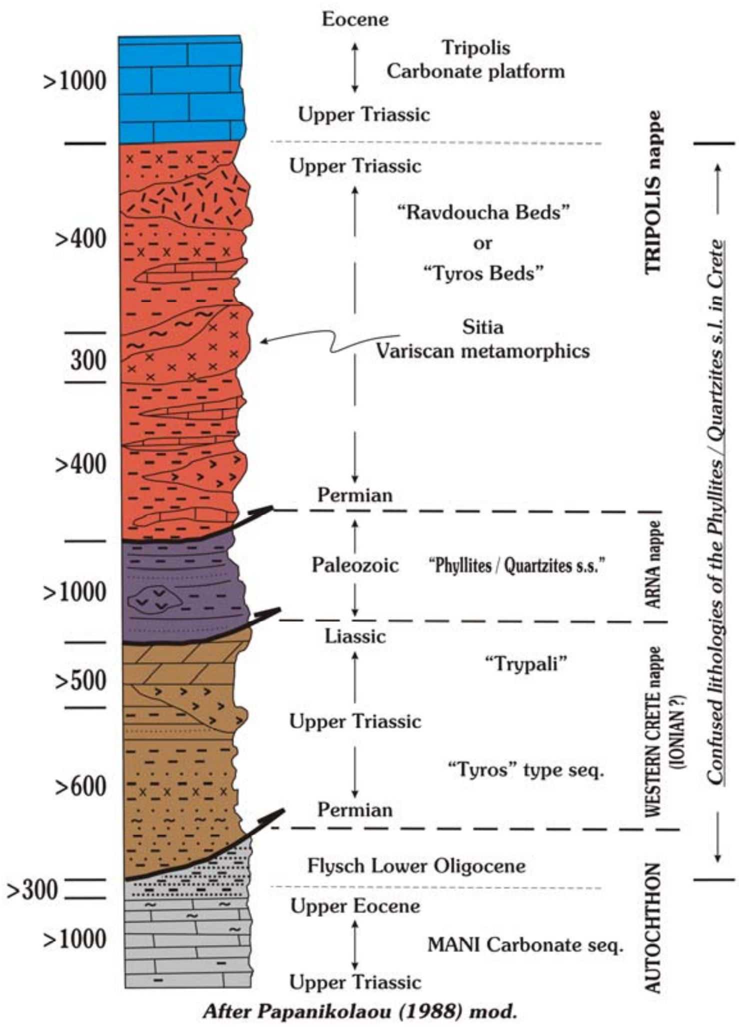

Figure 1. The most significant part of the Cretan tectono-stratigraphy which is quite often misinterpreted as Phyllites-Quartzites unit in Crete, consists of several members of four different tectonic units.

The primary tectonic contacts of the above tectonic units are thrusts, which can be observed in numerous outcrops shown on our tectonic map of Crete. The tectonic transport is from north to south, with spectacular isoclinal folds (of kilometer scale) observed in the Autochthon marbles. The overall tectonic asymmetry is comparable to that in continental Greece, where the tectonic transport is from east-northeast to west-southwest. The age of thrusting, as indicated by the syn-tectonic flysch formations of the nappes, ranges between Late Eocene in the higher nappes to Early Miocene in the lower nappes.

3. Middle Miocene Tectonic Horst Structure of Crete

Secondary tectonic contacts representing extensional detachments occur in several places but they generally form two zones of extensional detachments that strike east–west and dip 10^{o}-30^{o} northwards under the Cretan Sea and southwards under the Libyan sea respectively (figure 2). These two east-west trending low-angle normal faults have controlled the east-west orientation of Crete and have produced its general tectonic horst structure. However, they do not follow a particular tectonic contact but several planes of anisotropy representing both primary thrusts and stratigraphic boundaries. The structural omission across these detachments varies, in some cases the whole tectono-stratigraphic column of Crete is missing, such as in the area of the southern slopes of Psiloritis Mt, where ophiolites of the uppermost unit are resting on the lowest unit of the autochthon marbles [16]. This structure is similar to the Parnon detachment in the Peloponnesus regime [17]. In some other places, significant parts of the Cretan nappe pile are missing, like in the area east of Viannos, where the upper nappes of Arvi and Pindos occur at the hanging wall next to the Tripolis carbonates which are located at the footwall. The Psiloritis and Viannos detachments belong to the southern detachment of Crete together with the detachment observed along the southwestern coastline of Crete in Cape Cryos, Paleochora and Sougia. Here, relics of Tripolis and overlying Pindos nappe dip northwards against the detachment whereas the Western Crete unit forms the footwall. The northern detachment of Crete can be observed in the area of Platanos, Sfinari and Topolia in northwestern Crete, where the Pindos and Tripolis nappes occur in the hanging wall whereas Arna unit forms the footwall. Another fault belonging to the northern detachment occurs in the area of Spili and Vatos in central Crete where the Vatos unit imbricated with the ophiolites occurs in the hanging wall whereas the Arna and Tripolis units form the footwall.

The age of the extensional detachments is Middle Miocene as dated by syn-tectonic sediments of breccia-conglomerates (e.g. the Topolia formation) [18]. Some impressive sub-horizontal contacts observed between the Tripolis carbonates and the Tyros Beds (as in the area of Sitia) are minor structures without any important structural omission. The sharp contact observed in several outcrops is due to disharmonic phenomena developed during the compressive primary and/or the extensional secondary deformation.

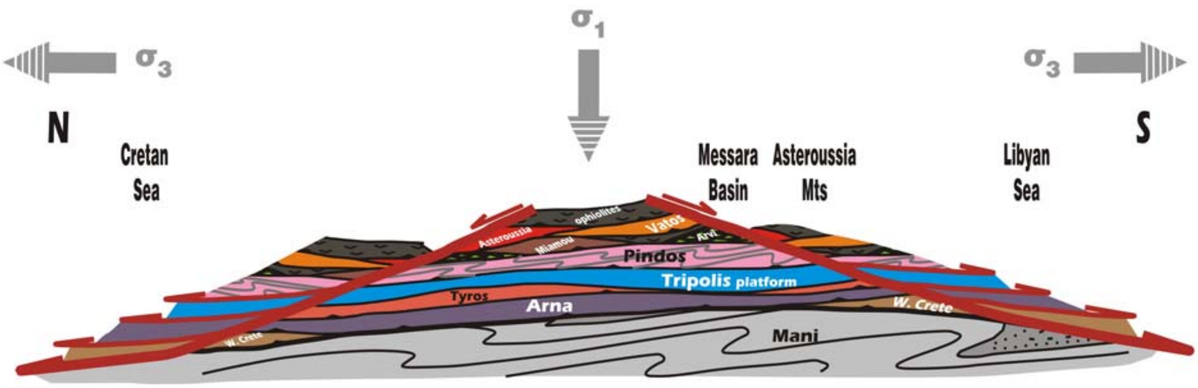

Figure 2. The Cretan nappe pile which was the result of the compressional phase later modified by arc-parallel extensional detachments dipping either northwards or southwards causing significant structural omission. The opening of the Cretan basin is related to the northern detachment and the Messara basin above the Asteroussia mountain is related to the southern detachment.

The above east-west trending extensional detachments of Crete represent arc-parallel extensional structures following the previous arc-parallel compressional thrusts and folds. The tectonic horst structure of Crete is related to the opening of the Cretan basin in the north whose southern margin is controlled by the northern detachment of Crete and western margin by the East Peloponessus detachment [17]. An opposite facing detachment has been described in Anafi Island along the northern margin of the Cretan basin with a similar succession of deformational phases [19]. The southern detachment of Crete is related to the opening of the Messara basin between Psiloritis mountain and Asteroussia mountain and its westward prolongation between southwestern Crete and Gavdos [16]. It is characteristic that all over the hanging wall of this southern detachment in Asteroussia and Gavdos the Alpine formations beneath the Middle Miocene - Quaternary sediments belong to the higher nappes (from Pindos to Asteroussia and the ophiolites).

High-angle normal and strike-slip faults dissect and disrupt the previous structure of thrusts and extensional detachments and form the tectonic margins of the Late Tortonian – Quaternary basins. The majority of such faults are seismically active structures overprinting the previous tectonic fabric. Nevertheless, some segments of the former detachments are still active today. The outcrops of the Late Miocene – Pliocene marine sediments show the blocks that subsided during this period. The general uplift of Crete during Quaternary time marks the present-day deformation with half of the island being a recently emerged area from the previously submerged neotectonic grabens.

4. Conclusions

Two east-west trending extensional detachments have been recognized in Crete with a northward slip below the Cretan Sea and a southward slip below the Libyan Sea. These two detachments bound a general east-west trending tectonic horst structure of Crete which was created during Middle Miocene time. These detachments disrupt the overall tectono-stratigraphic succession of Crete and use as sliding surfaces either the pre-existing thrusts or some stratigraphic boundaries representing strong anisotropies, such as the transition from the Permo-Triassic Tyros Beds to the base of the Late Triassic – Eocene carbonate platform of the Tripolis nappe. The distinguishing of the different tectono-stratigraphic formations occurring in what has been usually mentioned as "Phyllites-Quartzites" unit helps to decipher the real detachments from the thrusts or the minor discontinuities. Thus, the tectonic contacts developed between the Tyros Beds and the base of the Tripolis carbonate platform are not major extensional structures. In contrast, the detachment occurring along the southern slopes of Psiloritis Mt has omitted the entire Cretan tectono-stratigraphic succession (a thickness of about 10-12 km with a southward tectonic displacement of about 30-35 km). The deformational history of Crete can be summarized in three stages: (i) a first arc-parallel compressional phase with east-west trending thrusts with a southward tectonic transport during Oligocene – Early Miocene time, (ii) a second arc-parallel extensional phase of east-west trending detachments with transport both to the north and to the south during Middle Miocene time, and (iii) a third extensional phase of higher angle normal and oblique normal faults which disrupt the previous arc-parallel structures during Late Miocene – Quaternary time.

Acknowledgements

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