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Constraints on the onset of the Aegean back-arc extension using Oligocene NE-directed ductile shearing in the Cyclades

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Objectives

Several studies (e.g., Jolivet *et al.*, 2010) suggest that the Cyclades in central Aegean region have been affected by back-arc extension triggered by the retreat of the Hellenic subduction slab. However, the initiation time of the Aegean back-arc extension remains controversial. Specifically, post-orogenic back-arc extension in Cyclades is considered to have begun either in late Eocene/early Oligocene (Jolivet *et al.*, 2010; Laurent *et al.*, 2017) or late Oligocene/early Miocene (Avigad *et al.*, 1997) or late Miocene (Chatzaras *et al.*, 2011) or potentially in lower Pliocene (Boronkay and Doutsos, 1994). In order to shed light on this controversy, we focus on the Oligocene deformation history of the Cycladic Blueschist Unit.

Tectonic framework

The Cycladic Blueschist Unit suffered blueschist to eclogite facies metamorphism at early Eocene (Bröcker *et al.*, 2013 and references therein). Subsequent ductile-stage exhumation of the unit initiated at blueschist facies conditions and progressively continued and completed at greenschist facies conditions until early Miocene (Bröcker *et al.*, 2013). The Oligocene exhumation-related ductile deformation is mainly expressed by a penetrative foliation and an associated NE-trending stretching lineation. It is broadly accepted that top-to-the-NE shearing was dominant in west Cyclades during this deformation phase (Fig. 1: inset map) (e.g., Jolivet *et al.*, 2010).

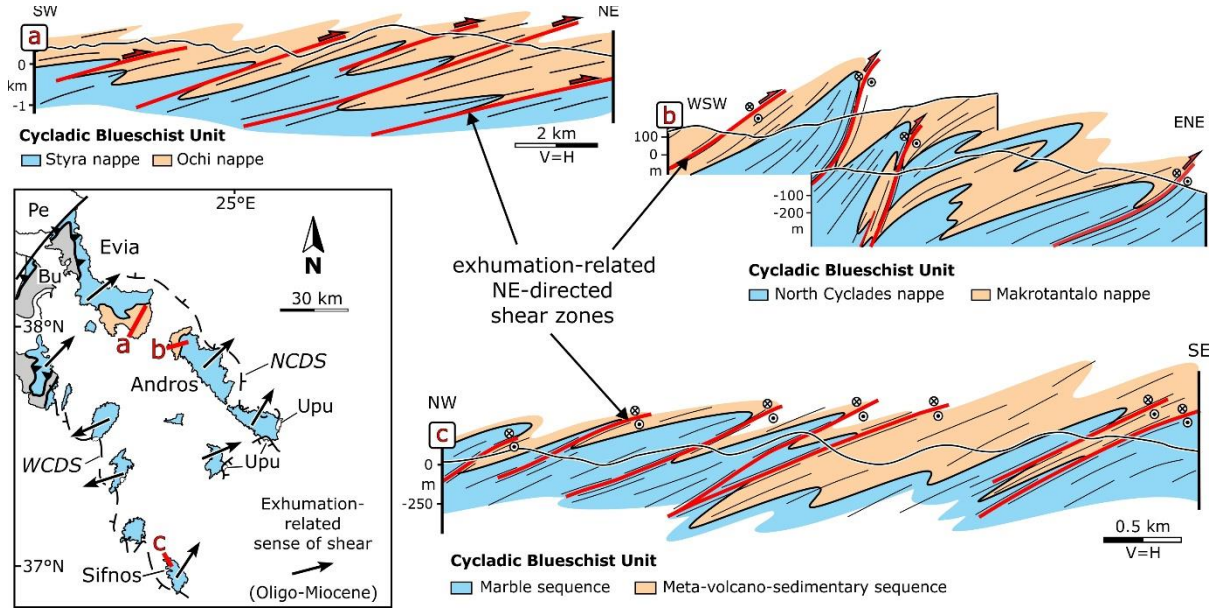

Figure 1. Cross-sections from (a) south Evia (after Xypolias *et al.*, 2012), (b) north Andros (after Gerogiannis *et al.*, 2019) and (c) north Sifnos (after Aravadinou *et al.*, 2016) illustrating the internal structural architecture of the Cycladic Blueschist Unit. Inset shows a simplified geological map of Cyclades indicating the sense of shear in the Cycladic Blueschist Unit during Oligocene-Miocene as well as the position of the cross sections (a-c). Bu, Basal unit; Pe, Pelagonian; Upu, Uppermost unit; NCDS and WCDS, North and West Cycladic Detachment System, respectively.

However, the tectonic context in which this shearing occurred remains controversial. Specifically, it has been suggested that the Oligocene NE-directed shearing has: (a) a normal-sense and reflects the motion of the upper NE-dipping detachment formed during SW-wards Oligocene extrusion/exhumation of the Cycladic Blueschist Unit under overall orogenic compression (Ring *et al.*, 2007); (b) a normal-sense and genetically linked with the formation of the North Cycladic Detachment System due to overall, back-arc related extension (Laurent *et al.*, 2017); and (c) a thrust-sense and reflects the direction of extrusion/exhumation of the Cycladic Blueschist Unit under overall orogenic compression (Xypolias *et al.*, 2012).

Key structural observations

Outcrop-scale kinematic indicators indicating top-down-to-NE and top-up-to-NE sense of shear cannot be used to discriminate between large-scale normal- and thrust-sense of shearing during exhumation. Post-orogenic doming in

Cyclades has probably masked the original orientation of the foliation formed during exhumation. Therefore, other criteria should be used to discriminate between the above assumptions.

The absence of Oligocene extensional sedimentary basins and magmatism, as well as the absence of downward increase in the metamorphic pressure, do not support the interpretation that NE-directed shearing was linked with normal-sense movements under an overall extension. Moreover, in many Cycladic islands, the NE-directed shearing is associated with the restacking of the early nappe pile of the Cycladic Blueschist Unit, which formed during the burial stage. In south Evia and north Andros, for example, we have mapped a series of NE-directed shear zones that cut up-section in their transport direction and have brought the lower North Cyclades nappe (also known as Styra nappe in Evia) over the upper Ochi-Makrotantalo nappe (Fig. 1a, b). Such a deformation pattern is to be expected in contractional belts, and therefore, it seems that the NE-directed shear zones have operated as ductile thrusts. Chemical analysis of amphiboles defining the mylonitic foliation in these shear zones has shown that thrust-sense movements started at blueschist facies conditions and progressively continued until the completion of the greenschist facies metamorphism at early Miocene. A similar situation has also been observed in northern Sifnos. There, a lower marble sequence was thrust over an upper meta-volcano-sedimentary sequence via a series of NE-directed shear zones that operated under blueschist facies to greenschist facies conditions (Fig. 1c).

Conclusions

Our structural observations show that NE-directed shearing in the Cycladic Blueschist Unit had a thrust-sense until the early Miocene when the greenschist facies metamorphism was completed. Therefore, the Oligocene NE-directed shearing within the Cycladic Blueschist Unit was associated with thrust-sense movements that occurred under overall orogenic contraction. This finding implies that the Cyclades area was affected by back-arc extension not earlier than early Miocene times.

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