Architecture of the Alpine Deformation and Geotectonic Setting of the Hellenides. A synthesis

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Introduction

The Hellenic orogen, as a branch of the broader Alpine orogenic belt in Laurasia, were resulted from the convergence and final continental collision of Europe and Apulia plates in a complicated, multiphase deformational regime, with the questions around, the existence of one or more Tethys ocean basins between Europe and Apulia continents and the origin of the old Paleozoic Crystalline fragments incorporated in the Hellenides to remain under debate until today (**Fig**. **1;** Gawlick et al. 2008, Robertson 2012, Papanikolaou 2013). The goal of this work was to present the main geological structure and architecture of the Hellenic orogenic belt, as well as the new aspects for its geotectonic evolution during the Alpine orogeny. We based on our recent studies about the deformational history of the Hellenides but also on the more modern views, published from others colleagues, concerning the Alpine geotectonic reconstruction of the Hellenides.

Architecture of Deformation

The Alpine structural evolution in Hellenides starts with the continental rifting of the Pangaea Super-continent during the Permo-Triassic and the opening of the Neotethyan Ocean. Subsequently, deformation history and metamorphism are recorded in six main tectonic events from the Middle Jurassic to present day (D1-D6; Kilias et al. 2010, 2013). The structural evolution from the Permo-Triassic to the recent is briefly described below (Kilias et al. 2010, 2013). Older Paleozoic deformational events have been strongly overprinted by the Alpine deformation. They are recognized only as rests in some places in the Paleozoic basement rocks of the Internal Hellenides.

1. **Permo-Triassic**: continental rifting, bimodal magmatism and A-type granite intrusion.
2. **Triassic-Jurassic**: passive margins extension and sedimentation.
3. **Middle Jurassic**: intraoceanic subduction, amphibolite sole, ophiolite mélanges, island arc magmatism.
4. **Mid-Late Jurassic**: ophiolite obduction, ophiolite mélanges formation at the front of the advanced ophiolites, high-pressure metamorphism, retrogression from greenschist to amphibolite facies metamorphic conditions, W-ward and E-ward sense of movement and crustal imbrication at the western (Pelagonian) and eastern (Serbo-Macedonian) marginal parts respectively of the Neotethyan realm, **D1.**

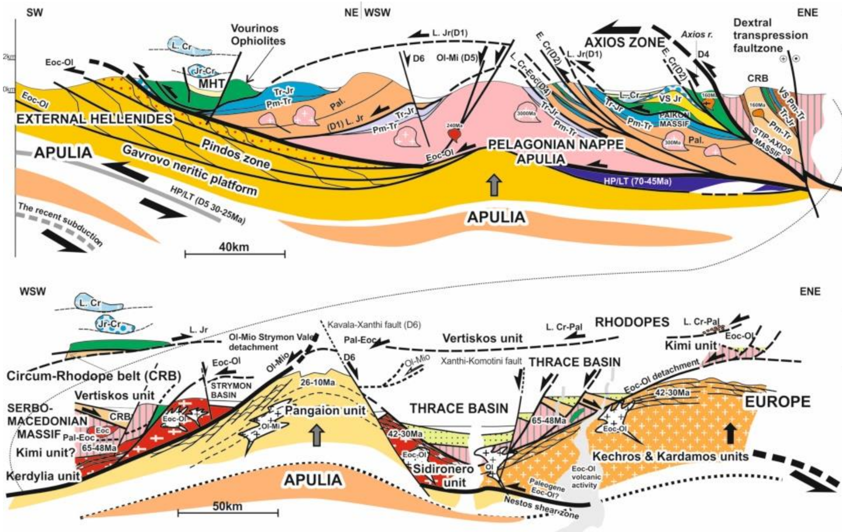
- Deposition during extension? of the **Upper Jurassic-Lower Cretaceous** sediments above or at the front of the obducted ophiolites.

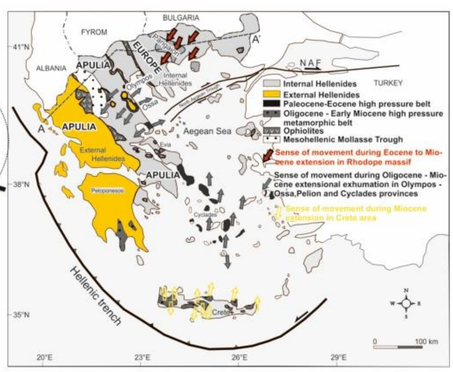
5. **Albian-Aptian (upper Early Cretaceous)**: W-ward and E-ward crustal imbrication, syn-tectonic low grade metamorphism, **D2.**
6. **Upper Cretaceous:** extension, shallow water carbonate sedimentation terminated in the Paleocene with the internal Hellenides flysch, **D3.** Starting of subduction of the Axios/Vardar ocean remnants under the European margin.
7. **Tertiary (Paleocene-Eocene)**: compression, W-ward sense of movement, HP/LT metamorphism and building of the Internal Hellenides high pressure belt of Paleocene-Eocene age (Olympos-Ossa, Cyclades), progressively emplacement during the **Eocene-Oligocene** of the Pelagonian nappe together with the *HP/LT internal metamorphic belt* on the External Hellenides, **D4**. Syn-orogenic extension associated with high-temperature metamorphism, migmatization and magmatism in the Serbo-Macedonian/Rhodope metamorphic province, **D4.**
8. **Oligocene-Miocene:** HP/LT metamorphism and building of the *External Hellenides high pressure belt* associated with compression and nappe stacking in the External Hellenides, **D5**. Syn-orogenic extension, high-temperature metamorphism and magmatism in the Internal Hellenides (**D5;** Olympos-Ossa, Kyklades and Serbo-Macedonian/Rhodope metamorphic province).
9. **Neogene-Quaternary**: active Hellenic subduction, extension and intramontagne basin formation, **D6**. Recent neo-tectonic activity.

As it is concluded by the above structural description, compression, nappe stacking and high-pressure metamorphism alternated progressively through time with extension, orogenic collapse and medium- to high-temperature metamorphism. Extension was leading to uplift and exhumation of deep crustal levels as tectonic windows and metamorphic core complexes. The deformation during the extensional stages were progressively evolving from ductile to brittle conditions. An S- to SW-ward migration of the dynamic peer compression vs extension is clearly recognized during the Tertiary in the Hellenides. In any case extension and crustal uplift follow burial, compression and nappe stacking (Kilias et al. 2010, 2013, Burg 2012). The kinematic pattern of the extension and compression tectonics appears to be complicated, but nevertheless for both stages, compressional and extensional, the recognized stretching lineation and associated movement direction are roughly perpendicular to the Hellenic arc; these are NE-SW trending in the west and N-S trending in the center, with a main movement direction, at least for the compressional tectonics, SW- and S-ward respectively (Kilias et al. 2002, 2010, Papanikolaou 2013). The sense of shear during the extensional stages of deformation and the nappes' collapse appears in many places bivergent (SW- to S-ward and NE- to N-ward), indicating an important component of bulk coaxial deformation during extension (Fig. 1; Kilias et al. 2002, 2010, 2013).

Geotectonic reconstruction- Conclusions

According to our more recent structural works (Kilias et al. 2010, 2013, Michail et al. 2016), as well as a lot of studies from others researchers, concerning the geodynamic evolution of the Hellenides (e.g. Gawlick et al. 2008, Froitzheim et al. 2014), all ophiolite belts in the Hellenides, as well as the Middle-Late Jurassic island arc magmatic products during the Neotethyan intra-oceanic subduction (Michail et al. 2016), subsequently incorporated inbetween the Axios/Vardar zone units and the Circum-Rhodope belt, were originated from a single source and this was the Neotethyan Axios /Vardar ocean basin. The latter closed finally during the Late Cretaceous-Paleocene subducted totally E-ward under the European





Geometry of kinematics (sense of shear) during the Tertiary extensional tectonics in Hellenides (Kilias et al. 2002)

Figure 1. Geological cross-section (A-A`) through the Hellenides (A-A` is indicated on the geological map of Greece, right). The geometry and kinematics of deformation is also shown (D1 to D6 events). 26-10Ma cooling ages (after Kilias et al. 2013)

continental margin, including the Serbo-Macedonian and Strandja/Sredna Gora massifs (Fig. 1). In this content, the ophiolite nappes (e.g. the Vourinos ophiolite complex etc.) and the island arc magmatic products (e.g. Fanos granite, Chortiatis magmatic series etc.) should be considered as far-travelled nappes on the Hellenides continental parts (Pelagonian nappe and Serbo-Macedonian massif, Fig. 1; Gawlick et al. 2008, Kilias et al. 2010). Furthermore, the deposition of the Upper Jurassic sedimentary carbonate series (Gawlick et al. 2008, Robertson 2012) on the top of the obducted ophiolite nappe clearly determine the upper limit of the ophiolite emplacement in the ?Kimmeridgian/Tithonian (Fig. 1). In this scenario we assume that the Vardar/Axios ophiolites are also allochthones and the Axios/Vardar suture zone should be traced in-between the Rhodopes nappes, more eastern (Fig. 1; Froitzheim et al. 2014). Additionally, regarding this structural architecture and evolution the lower-most Pangaion Rhodope unit, today exhumed as an Oligocene-Miocene metamorphic core complex, should be the marginal part of the Apulia plate (Pelagonia?), which was unterthrusted below the Serbo-Macedonian massif and the Rhodope nappes stack during the Cretaceous-Tertiary, subsequently following the Upper Cretaceous subduction of the Neotethyan Axios/Vardar ocean (Fig. 1; Froitzheim et al. 2014). The Apulia carbonate platform is also exhumed in the Olympos-Ossa window and the Attico-Cycladic massif below the Paleocene-Eocene high pressure belt and the Pelagonian nappe (Jolivet et al. 2004, Kilias et al. 2010). Additionally, in the Cyclades area is also exhumed the Paleozoic basement of the Apulia plate as a metamorphic core complex under the carbonate platform and the overlain Internal Hellenides nappe stack. Cretaceous-Tertiary nappe stacking and crustal thickening in the Internal Hellenides were followed by syn-to late-orogenic extension, crustal thinning and exhumation of the deeper structural units as tectonic windows or metamorphic core complexes (Fig. 1; Burg 2012, Kilias et al. 2013, Froitzheim et al. 2014). High-temperature metamorphism, partly migmatization and intense magmatism associated the Tertiary extensional tectonic regime (Burg 2012, Kilias et al. 2013). Extension occurred simultaneously with compression and W-ward verging nappes' stacking in the External Hellenides (Jolivet et al. 2004, Kilias et al. 2010, Froitzheim et al. 2014). A retreating subduction zone and roll back of the subducted lithospheric slab under the Hellenides nappes stack and collapse of an overthickened crust or mantel delamination (Burg 2012, Froitzheim et al. 2014) could well explain the Tertiary extensional tectonics in the Internal Hellenides taken place simultaneously with compression in the External Hellenides and the Hellenic foreland.

References

Burg, J.P., 2012. Rhodope: From Mesozoic convergence to Cenozoic extension. Review of petro-structural data in the geochronological frame. J. Virtual Explorer. 42.

Froitzheim, N., Jahn-Awe, S., Frei, D., Wainwright, A.N., Maas, R., Georgiev, N., Nagel, T.J., Pleuger, J., 2014. Age and composition of meta-ophiolite from the Rhodope Middle Allochthon (Satovcha, Bulgaria): A test for the maximum-allochthony hypothesis of the Hellenides. Tectonics 33, 1477–1500.

Gawlick, H.J., Frisch, W., Hoxha, L., Dumitrica, P., Krystyn, L., Lein, R., Missoni, S., Schlagintweit, F., 2008. Mirdita Zone ophiolites and associated sediments in Albania reveal Neotethys Ocean origin. Int. J. Earth Sci. 97, 865–881.

Jolivet, L., Rimmele, G., Oberhansli, R., Goffe, B., Candan, O., 2004. Correlation of syn-orogenic tectonic and metamorphic events in the Cyclades, the Lycian nappes and the Menderes massif. Geodynamic implications. Bull. Soc. Geol. Fr. 175, 217–238.

Kilias, A., Tranos, M.D., Orozco, M., Alonso-Chaves, F.M., Soto, J.I., 2002. Extensional collapse of the Hellenides: A review. Rev. la Soc. Geol. Espana 15, 129–139.

Kilias, A., Frisch, W., Avgerinas, A., Dunkl, I., Falalakis, G., Gawlick, H.-J., 2010. Alpine architecture and kinematics of deformation of the northern Pelagonian nappe pile in the Hellenides. Austrian J. Earth Sci. 103, 4–28.

Kilias, A., Falalakis, G., Sfeikos, A., Papadimitriou, E., Vamvaka, A., Gkarlaouni, C., 2013. The Thrace basin in the Rhodope province of NE Greece - A tertiary supradetachment basin and its geodynamic implications. Tectonophysics 595–596, 90–105.

Michail, M., Pipera, K., Koroneos, A., Kilias, A., Ntaflos, T., 2016. New perspectives on the origin and emplacement of the Late Jurassic Fanos granite, associated with an intra-oceanic subduction within the Neotethyan Axios-Vardar Ocean. Int. J. Earth Sci. 105, 1965–1983.

Papanikolaou, D., 2013. Tectonostratigraphic models of the Alpine terranes and subduction history of the Hellenides. Tectonophysics 595–596,

Robertson, A.H.F., 2012. Late Palaeozoic–Cenozoic tectonic development of Greece and Albania in the context of alternative reconstructions of Tethys in the Eastern Mediterranean region. Int. Geol. Rev. 54, 373–454.