EXTENSIONAL COLLAPSE OF THE HELLENIDES: A REVIEW

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Abstract: In this paper we summarise the geometry and kinematics of late-orogenic extension and orogen collapse in the Hellenic arc-shaped orogen during the Tertiary. The Hellenic orogen shows both symmetric and asymmetric late-orogenic extension giving rise to the exhumation of deep-seated crustal rocks. Double-vergent extension took place in the cold accretionary prism (Olympos, Ossa, Pelion, and Crete) without significant crustal heating, whereas asymmetric extensional collapse occurred in the back-arc areas (Rhodopes and Cyclades), associated with significant crustal heating. Extension started in the internal Hellenides during the Eocene and extended progressively to the external Hellenides during the Miocene. Tertiary late-orogenic extension of the Hellenides occurred concomitantly behind a south-to-southwest migrating compressional front, finally forming an archetypal orogenic system. Late-orogenic extension in the Hellenides could have been driven by changes in the rate and direction of convergence between the African and Eurasian plates during the Tertiary.

Key words: Hellenide Orogen, late-orogenic extension, Tertiary exhumation, accretionary prism, Mediterranean back-arc basins.

Resumen: El Orógeno Helénide como parte del cinturón alpino mediterráneo, está estrechamente relacionado con la convergencia entre las placas africana y euroasiática durante el Mesozoico y el Cenozoico. En este contexto, durante el Terciario temprano a medio se produjo la colisión de bloques menores de estos continentes, como las placas Apulia y Pelagia, dando lugar a la formación de la mayor parte del mencionado Orógeno Helénide. Este estado se caracteriza por la formación de "pilas de mantos" producidas por cabalgamientos dirigidos fundamentalmente hacia el suroeste (respecto a la orientación actual) y el consiguiente engrosamiento de la corteza continental. Esta tectónica terciaria está asociada con la formación de dos cinturones metamórficos principales de alta P / baja T, alineados a lo largo de dos arcos concéntricos, uno interno y otro externo, que reflejan la evolución de procesos de subducción sucesivos. El cinturón interno se desarrolló durante el Paleoceno-Eoceno y está caracterizado por la zona de sutura entre Helénides Internos (placa superior) y Helénides Externos (placa inferior) que aflora en los montes Olimpo, Ossa y Pelión, en la isla de Evia y en las islas Ciclades. El cinturón externo de alta P / baja T se formó en el Oligoceno-Mioceno y está caracterizado por una zona de "collage" situada en el interior de los Helénides Externos que aflora en el Peloponeso meridional y en Creta. La tectónica extensional ha jugado un papel muy importante en la configuración final del Orógeno Helénide. En este artículo se investiga la geometría y la cinemática de la extensión tardí-orogénica y del colapso orogénico en los Helénides durante el Terciario. El estudio del Orógeno refleja la existencia de extensión tardí-orogénica, tanto de tipo simétrico como asimétrico, que dio lugar al colapso del Orógeno y al levantamiento y exhumación de rocas de niveles corticales más profundos. Por encima del prisma de acreción frío (Olimpo, Ossa, Pelión, Creta) se produce extensión divergente (simétrica) sin calentamiento cortical significativo. En el área trasera del arco (Rodopos, Ciclades) tiene lugar colapso extensional asimétrico asociado a un significativo calentamiento cortical. La extensión tardí-orogénica terciaria en los Helénides junto con la compresión en el frente de deformación de la placa litosférica estirada, constituyen un sistema orogénico dinámico que migró hacia el suroeste. La extensión comenzó en el Eoceno en los Helénides Internos y alcanzó progresivamente los Helénides Externos durante el Mioceno. La geometría y la cinemática de la extensión tardí-orogénica en los Helénides podrían ser atribuidas a cambios en la velocidad de convergencia entre las placas africana y euroasiática durante el Terciario.

Palabras clave: Orógeno Helénide, extensión tardí-orogénica, exhumación terciaria, prisma de acreción, cuencas retro-arco Mediterráneas.


During the last two decades, late-orogenic extension, that is, extension following orogenic stacking and lithosphere thickening, has been intensively investigated by many geoscientists, thus lending a new understanding to orogenic processes and the incidence of plate-convergence boundary conditions (e.g., Wernicke 1981, 1985; Platt, 1986; Dewey, 1988; Ruppel, 1995). The most influential result of this process is that horizontal extension through large-scale, low-angle extensional shear zones and normal faults leads to the uplift and exhumation of crustal rocks from deeper tectonic levels.

Taking into account the geometry and kinematics of these extensional shear zones, two end-member modes of exhumation of deep crustal rocks have been proposed (e.g., McKenzie, 1978; Wernicke, 1985; Lister et al., 1986; Hamilton, 1987; Davis and Lister, 1988; Malavieille, 1993): (1) The asymmetric type, which is characterised by simple-shear or non-coaxial deformation, and (2) the symmetric type, which is related to coaxial or pure-shear deformation. The first type is characterised by the development of a master low-angle extensional system, with listric normal faults in the upper crust, coalescing within a deeper ductile shear zone. Extension along the basal detachment fault drives upward doming and uplift of the underlying crust. The second type is characterised by the development of two conjugate sets of low-angle extensional shear zones with opposite sense-of-shear on the two sides of the exhumed dome.

This paper summarises the geometry and kinematics of the late-orogenic extension evidenced by Tertiary, large-scale, low-angle detachment systems recognised in different parts of the Hellenic orogen. This summary provides a thorough overview of the evolution of this extension during the Tertiary and a better understanding of the mechanisms for the Hellenic orogen collapse during the Alpine orogeny.

The nappe pile of the Hellenic orogen

The Hellenic orogen (Fig. 1), as a part of the Alpine orogen in Eurasia, is closely related to the convergence between the African and Eurasian plates during the Mesozoic and Tertiary and the closure of the Tethyan ocean basin or basins (Aubouin et al., 1963; Godfriaux, 1968; Jacobshagen et al., 1978; Seidel et al., 1982; Robertson and Dixon, 1984; Vergely 1984; Mountrakis, 1986; Schermer et al., 1989; Doutos et al., 1993; Dinter, 1998).

A complex nappe-pile structure dominates the Hellenides. In the Hellenic mainland and the island of Crete, the structural sequence comprises (Figs. 1 and 2), from top to bottom:

1) The Mesozoic ophiolite unit (oph) of the Axios (Ax) and Subpelagonian (Sp) zones over lain by transgressive Cretaceous limestones terminating in an upper Cretaceous-Palaeocene flysch.

2) The Pelagonian nappe (Pl), consisting of a pre-

Alpine Pelagonian continental basement, is formed of gneisses and schists intruded by upper Palaeozoic granitoids. These nappe are overlain by an upper Palaeozoic-Triassic, volcano-sedimentary sequence and Triassic-Jurassic, platform carbonate rocks.

3) The internal blueschist unit with high P-low T blueschist facies metamorphism of uncertain age.

4) The weakly-to non-metamorphosed sedimentary sequences of the External Hellenides constitute the bottom of the Hellenic nappe-pile edifice. The External Hellenides are composed of tectonic sheets with neritic and pelagic limestones and flysch deposits of Triassic to Miocene age, and were deposited along the Apulian continental margin. The Parnassos (Pa), Pindos (Pm), Gavrovo-Tripoli (G), Ionian (I) and Paxos (P) zones belong to the External Hellenides.

5) The external blueschist unit of the External Hellenides.

The Serbomacedonian (Sm) and Rhodope (Rh) massifs in the NE Hellenides have been considered as the relative hinterland of the Hellenic orogenic belt. They comprise a structurally complex domain of tectonically intercalated high- and low-grade pre- and syn-Alpine metamorphosed rocks, intruded by syn- and post-kinematic Mesozoic and Tertiary igneous rocks/bodies. Recent studies have distinguished in the Rhodope massif a Tertiary metamorphic core complex (Dinter and Royden, 1993; Dinter, 1998; Kilius et al., 1999). The Serbomacedonian massif, together with the Circum Rhodope Belt (CRB), with a volcano sedimentary series of Triassic-Jurassic age, overthrust the Axios zone towards the SW (Tranos et al., 1999). The Serbomacedonian and Rhodope massifs, the Circum Rhodope Belt, the internal blueschist unit and the Pelagonian nappe constitute the main part of the Internal Hellenides. Furthermore, the Attico-Cycladic massif (AC) in the Cyclades and Evia islands and the Attica peninsula is mainly composed of high-pressure rocks of the internal HP belt, overlying a carbonate metamorphic sequence and underlying thinned Hercynian or older crystalline basement rocks. Remnants of ophiolitic rocks overlain by transgressive Cretaceous limestones occupy the tectonic top of the Cycladic structural sequence. Thus, in the Cyclades a nappe-stack order is exposed that is similar to that described for the Hellenic mainland. Some parts of the Attico-Cycladic massif have been interpreted as Tertiary metamorphic core complexes (Lister et al., 1984; Gautier and Brun, 1994).

Nappe stacking started in the middle-upper Jurassic with the obduction of the ophiolitic unit onto the Pelagonian carbonate cover from one or more Tethyan ocean basins (Jacobshagen et al., 1978; Vergely, 1984; Mountrakis, 1986). At the same time, syn-metamorphic deformation and basement-involved thrusting in greenschist to amphibolite facies conditions affected the internal parts of Hellenides (Yarwood and Dixon, 1977; Jacobshagen et al., 1978; Vergely, 1984). Deformation progressed episodically throughout the
Cretaceous and Tertiary. During the late Eocene, the Pelagonian nappe and the internal blueschist unit were transported SW-wards onto the External Hellenides, thus ending the last stage of the Tertiary collision (Godfriaux, 1968; Schermer et al., 1989; Schermer 1990; Kilias et al., 1991). However, in contrast, some researchers suggest a NE-ward emplacement of the Pelagonian nappe (Barton, 1976; Doutsos et al., 1993; Lips et al., 1998).

The initial Tertiary tectonics were characterised by extensive nappe stacking, mostly directed towards the SW (with respect to the present-day orientation), and continental crustal thickening. Nappe stacking occurred throughout the Tertiary, with a migration of the deformation and compressional front towards the SW (Aubouin et al., 1963; Schermer et al., 1989; Robertson et al., 1996). Nowadays, active compression is recognised along the Hellenic subduction trench, south of Crete, in relation with the subduction of the African plate beneath the Hellenides (Figs. 1 and 3) (Le Pichon and Angelier, 1979; Spakman et al., 1988; Meulenkamp et al., 1988).

Tertiary collisional tectonics and crustal thickening is associated with the formation of the two main high-pressure (HP) metamorphic belts shaping two concentric arcs, the internal and the external one, reflecting the evolution of successive subduction processes (Figs. 3 and 4a):

1. The internal HP belt, which consists of metasediments and meta-volcanic rocks deriving from a continental margin, reached peak pressures during the Palaeocene-Eocene (Godfriaux, 1968; Wijbrans and McDougall, 1988; Schermer et al., 1989; Schermer, 1990; Lips et al., 1998). This HP belt represents the suture zone between the Pelagonian nappe (upper plate) and the External Hellenides (lower plate); this suture zone is exposed in the Olympos, Ossa, and Pelion mountains as well as in the Evia and Cyclades islands (Godfriaux, 1968; Schliestedt et al., 1987; Schermer, 1990; Kilias et al., 1991). HP metamorphism reached blueschist and eclogite facies. Estimated peak PT conditions for this event are ca. 15 kbar and 450-500°C in the Cyclades (Fig. 4b) (Altherr et al., 1972; Schliestedt et al., 1987). However, in the Olympos, Ossa, Pelion and Evia areas, P-T conditions are ca. 5-8 kbar and 300-350°C (Fig. 4c) (Schermer et al., 1989; Kilias et al., 1991).

2. The external HP belt lies within the External Hellenides and reached peak PT conditions during the Oligocene to Miocene (Seidel et al., 1982). It crops out in southern Peloponnesos and Crete; the Phyllite-Quartzite and Plattenkalk units comprise the external HP belt in the latter area (Seidel et al., 1982). Maximum P-T conditions of ca. 10 kbar and 450°C have been estimated for these rocks (Fig. 4d) (Thomson et al., 1998).

Another HP metamorphic event has recently been reported in the internal-most part of the Hellenic orogen, in the Rhodope crystalline massif (Liatí, 1986). However, the age of this metamorphism is still under discussion; some authors considering this early subduction event to have taken place during the Cretaceous (Wawrzienitz and Mposkos, 1997), while others date it as Eocene (Liatí and Gebauer, 1999).

Tertiary late-orogenic extension

Extensional tectonics played a significant role in the Tertiary-to-Recent tectonic evolution and the final configuration of the Hellenic orogen. Late-orogenic extension occurred both in the internal Hellenides and in the two HP belts, causing orogenic collapse and crustal thinning. Extensional exhumation of the deeper tectonic units occurred at the same time, thus giving rise to a series of tectonic windows and metamorphic core complexes (Lister et al., 1984; Schermer et al., 1989; Kilias et al., 1991, 1994, 1995; Dinter and Royden, 1993).

The extensional shear zones and extensional detachments which accommodated the collapse of the Hellenic orogen have a diverse geometry and kinematics, as detailed below (Figs. 3, 4a and 5):

1. In the crystalline Rhodope massif of the internal Hellenides (Kiliás and Mountrakis, 1990; Dinter and Royden, 1993) and in the Cyclades area (Gautier and Brun, 1994), the collapse took place along low-angle extensional systems and associated extensional shear zones. The main sense of shear of these systems is top to the SW in the Rhodope massif, and top to the NNE in the Cyclades area (Figs. 6c and 6d). The upwarping of the normal shear zone surfaces caused by tectonic denudation can lead to the exhumation of lower plate rocks which usually crop out in the core of domal structures.

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(2) In the Olympos, Ossa, and Pelion areas (Fig. 5) (Kiliás, 1991; Kiliás et al., 1991, 1995), as well as on the island of Crete (Kiliás et al., 1994; Fassoulas et al., 1994), a double-vergent extensional regime has been documented. In this area orogenic collapse took place throughout two different systems of low-angle extensional shear zones, showing opposite sense-of-shear in the flanks of the lower-plate dome (Figs. 6a and 6b). These anthetic extensional shear zones developed either coevally, suggesting bulk coaxial deformation, or almost coevally in time, the result being a double-vergent extensional regime and symmetrical domes. The dominant sense of displacement of these extensional shear zones is both top-to-the-SW and to-the-NE in the Olympos, Ossa, and Pelion mountains, and both top-to-the-N and to-the-S in Crete.

In the areas of Rhodope and Cyclades, extensional exhumation occurred associated with significant heating under low P conditions, leading to greenschist and amphibolite facies metamorphism (HT metamorphism) and granite intrusions (Liatí, 1986; Wijbrans and McDougall, 1988), so that the HP mineral assemblages have been preserved only as relics (Fig. 4b; Liatí, 1986; Altherr et al., 1982). Granite intrusions followed the HT event in these areas (Liatí, 1986; Schliestedt et al., 1987; Dinter, 1998; Kiliás and Mountrakis, 1998). In contrast, in the Olympos, Ossa, Pelion, and Crete regions, extensional exhumation took place under isothermal decompression conditions in a relatively cold environment (Figs. 4b, c). As a result, and in association with the rapid orogenic exhumation, the initial HP mineral assemblages have been preserved in these regions (Schermer et al., 1989; Kiliás et al., 1991, 1995; Thomson et al., 1998).

Extensional collapse in the Rhodope and Cyclades areas took place behind the orogenic arc in the back-arc area, whereas in Olympos, Ossa, Pelion, and Crete, extensional collapse took place immediately above the cold accretionary prism of the Hellenic orogen (Fig. 4a) (Kiliás, 1991; Jolivet et al., 1994; Kiliás et al., 1994; Fassoulas et al., 1994).

Footwall rocks from the crystalline Rhodope massif have progressively cooled from the Oecene/Oligocene up to the Miocene. Cooling to near-surface temperatures becomes progressively younger towards the SW, that is, parallel to the sense of displacement of the detachment. (Liatí, 1986; Dinter and Royden, 1993; Wawrzienitz, 1997; Dinter, 1998). Kiliás et al. (1999) related the gradual uplift of the Rhodope massif to extensional collapse of the orogen. Moreover, in Cyclades the extension began during the Oligocene-Miocene, as indicated by the age of the syn-extensional metamorphism (Altherr et al., 1982; Lister et al., 1984). In Olympos, Ossa, and Pelion, extensional collapse started during the Oligocene-Miocene (Schermer et al., 1989; Sfikos et al., 1991; Kiliás et al., 1991).
Figure 4: (a) Schematic cross-sections illustrating the geometry and kinematics of the late-orogenic extension and associated compression in the Hellenides and for different ages, (b), (c), (d) indicate the representative P-T paths of the HP metamorphic belts in the Cyclades (taken from Wijbrans and McDougall, 1988), Olympos-Ossa (Schermer, 1990) and Crete (Thomson et al., 1998) areas respectively, (e) the SSW-wards propagation of the subduction processes and the associated compression in the Hellenides.

Figure 5.- Geological cross-sections illustrating the double-vergent sense of movement of the orogenic collapse of the Hellenides at the Olympos, Ossa and Pelion areas (from Kilias, 2001).

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al., 1995), whereas in Crete it initiated during the middle Miocene (Kilias et al., 1994; Fassoulas et al., 1994; Thomson et al., 1998).

During the early stages of the Tertiary late-orogenic extension, pervasive shallow-dipping main schistosity ($S_2$) associated with stretching lineation ($L_2$) formed in the stretched deeper crustal parts and the HP metamorphic belts. Simultaneously with the $D_2$ ductile fabric, normal faults with the same kinematic symmetry formed in the higher crustal levels, leading to the development of extended basins. According to our above description, both $S_2$ fabric and $L_2$ stretching lineation indicate a different age and P-T metamorphic conditions as well as orientation at the several deformed parts of Hellenides.

The $S_2$ schistosity partly or totally overprints a previous fabric that formed during the HP deformational stage ($S_1$ schistosity). Usually, due to intense transposition of the pre-existing schistosity along the $S_2$ planes, both the $S_1$ and $S_2$ schistostities trace almost parallel, whereas in other cases very distinct crenulation occurs. Occasionally, isoclinal folded elongate quartz lenses and/or white micas are included as intrafolial rootless fold within the $S_2$ microlithons.

In the Rhodope and Cyclades back-arc areas, ductile $D_2$ shear zones indicate a thickness of at least 1-2 km. They occurred simultaneously with or outlasted the thermal peak of the HT metamorphism and continued to be active as the temperature decreased (Lister et al., 1984; Schliestedt et al., 1987; Kilias et al., 1999). In the Olympus - Ossa accretionary prism area, ductile extensional shear zones reveal a thickness of some hundred metres associated with intense mylonitization and very low-grade retrogression of the HP mineral assemblages (Schermer et al., 1989; Kilias et al., 1991; Sfeikos et al., 1991). Finally, in the Crete accretionary prism area, extensional deformation is localised at its early stages in ductile thinner shear zones also associated with very low-grade retrogression of the HP mineral assemblages (Fassoulas et al., 1995; Thomson et al., 1998).

Discrete brittle-ductile to brittle low-angle extensional fault zones ($S_3$) have progressively formed under lower P-T conditions, thus indicating the progressive uplift of the orogen. Extensional processes still continue to the present, forming high-angle extensional faults with analogous geometry and kinematics.

**Discussion and Conclusions**

Taking into account the aforementioned description of the characteristic elements and timing of the Tertiary late-orogenic extension in the Hellenides, it can be established that it started in the more internal parts of the orogen and progressively proceeded towards the SSW to the more
external ones: (1) In the crystalline Rhodope massif, the onset of extension and collapse took place during the Eocene / Oligocene; (2) more externally, along the internal HP metamorphic belt (Olympos, Ossa, Pelion, and Cyclades), extensional collapse started during the Oligocene to Miocene transition, and (3) in the outermost parts, along the external HP metamorphic belt (in Crete) extension initiated during the middle Miocene.

Late-orogenic extension evolved in a continuing plate-convergence regime, wherein compression and crustal thickening at the outermost parts of the orogen took places simultaneously with extension at the core of the orogen (Fig. 4) (e.g., Schermer et al., 1989; Kilias et al., 1999). On the other hand, the late-orogenic extension occurred always after the compression and lithospheric thickening associated with HP metamorphism and subduction processes, considerably affecting HP metamorphic belts.

Consequently, we can conclude that during the Tertiary and under a constant plate-convergence regime, extension and compression in the Hellenic orogen constituted a dynamic system migrating progressively to the SSW (Figs. 4 and 7). As a result, the deep crustal levels were exhumed during extensional tectonics simultaneously with the underplating of lithospheric material and nappe stacking in the deformational front of the orogen (Figs. 3 and 4) (Kilias et al., 1999).

When late-orogenic extensional tectonics took place in the back-arc area (i.e. crystalline Rhodope massif and Cyclades), orogenic collapse evolved asymmetrically; whereas extensional collapse above

Figure 7.- SSW progressive migration of the extension in the Hellenides during the Tertiary. The ages correspond to the onset of extension (Kilias et al., 1999).
the cold accretionary prism (i.e. Olympos, Ossa, Pelion, and Crete areas) seems to fit the symmetric mode of deformation (Figs. 3, 4 and 5).

The differences in geometry and kinematics of the extensional deformation along the collapsed orogen could be ascribed to changes in the convergence rate between the African and Eurasian plates during the Tertiary in combination with a retreat of the subduction zone towards the S (Dercourt et al., 1986; Royden, 1993). We suggest that the continuing subduction of Africa counteracted the high potential energy of the overthickened Hellenic accretionary prism so that asymmetrical collapse was favoured in the back-arc area. Extensional collapse above the cold accretionary prism, on the other hand, developed symmetrically, possibly due to an increase in the buoyant stresses resulting from the subducted African slab in combination with the dynamic instabilities of the thick accretionary prism.

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