Bulletin of the Geological Society of Greece

Vol. 43, 2010

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https://doi.org/10.12681/bgsg.11190

Δελτίο της Ελληνικής Γεωλογικής Εταιρίας, 2010
Πρακτικά 12ου Διεθνούς Συνεδρίου
Πάτρα, Μάιος 2010

Bulletin of the Geological Society of Greece, 2010
Proceedings of the 12th International Congress
Patras, May, 2010

THE NATURE OF DUCTILE DEFORMATION IN THE PHYLLITE-QUARTZITE UNIT (EXTERNAL HELLENIDES)

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Abstract

This work describes the nature of ductile deformation in the Phyllite-Quartzite (PQ) unit in terms of structural evolution and spatial variation of finite strain and vorticity of flow. The PQ unit is affected by at least three ductile deformation ($D_{1,2,3}$) phases. However, the D_2 is the dominant phase resulting in the formation of a penetrative foliation (S_2) which is by far the most common structural feature in all scales of observation. A stretching lineation (L_2), which trends perpendicular to the structural grain of the belt, is well-developed within the S_2 plane. Numerous kinematic criteria clearly indicate west (or south)-directed transport of the PQ unit during D_2. This phase is also characterized by a systematic non-linear increase of strain ratio (Rxz) with proximity to the Basal thrust. Spatial variation of kinematic vorticity number reveals an increase of pure shear component of D_2 deformation towards the middle structural levels of the unit. These results are used to discuss the validity of various geodynamic models related to the exhumation of the PQ unit.

Key words: *Progressive deformation; finite strain; vorticity; high-pressure rocks; Greece.*

1. Introduction

The metamorphic rocks of the Phyllite-Quartzite (PQ) unit belong to the External Hellenides and constitute a Late Oligocene–Early Miocene high pressure–low temperature (HP-LT) belt, which extends over a distance of 600 km. Over the last two decades, several tectonic models for the exhumation of the PQ unit have been proposed, including underplating with symmetric syn-orogenic (Fassoulas et al. 1994) or asymmetric syn-(or post-) orogenic extension (Jolivet et al., 1996), delamination of the subducting crust followed by buoyancy-driven exhumation (Thomson et al., 1999), solid-state ductile extrusion contemporaneous with continent-continent collision (Xypolias and Doutsos, 2000; Doutsos et al., 2000) as well as gravitational collapse and erosion of a thickened crustal wedge (Zulauf et al., 2008). Each of these models predicts different structural settings and requires different deformation paths for the PQ unit rocks. For example, models of syn-orogenic extension require the creation of large extensional detachments and the formation of extensional sedimentary basins in the upper plate, the model of buoyancy-driven exhumation suggests that the bulk of the PQ unit was escaped upward as a coherent block, unaffected by any pervasive deformation. The ductile extrusion model, in turn, suggests that the exhumation was achieved by upward transport-parallel elongation of the PQ unit rocks and requires penetrative ductile deformation. Therefore, it is clear that despite numerous studies in the area, the mechanism related to the exhumation of the PQ unit is still a matter of debate. Much of the debate stems from the fact that there is also no consensus for the internal structure and tectonic evolution of the PQ unit. This work summarises the results of qualitative and quantitative structural analyses performed in the unit mainly over the last decade and uses these to discuss the applicability of various geodynamic models.

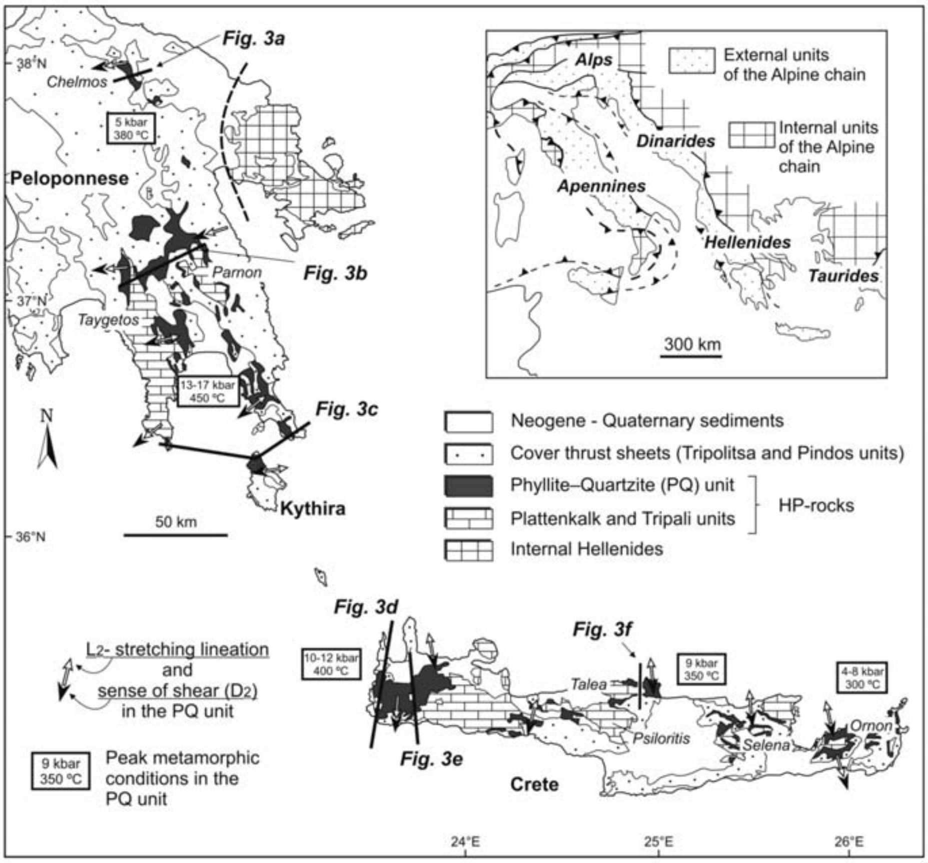

Fig. 1: Simplified geological map of the southwest External Hellenides. L_2 stretching lineation, sense of shear (D_2) and peak metamorphic conditions in the PQ unit are also shown. Metamorphic data after Katagas et al. (1991), Theye et al. (1992), Blumör (1998). Inset: generalized map of the Alpine chain in southeastern Europe (modified after Xypolias et al. 2007).

2. Geological setting

The External Hellenides are part of the Alpine Orogenic belt (Fig. 1a, inset) and form an orocline connecting the Dinarides to the NW with the Taurides to the SE. They mainly consist of Mesozoic and Cenozoic sedimentary rocks that were deposited on the rifted northern margin of the Apulia microcontinent. The present disposition of the External Hellenides is largely the result of progressive southward (in palaeo-coordinates) stacking of nappes/units (Fig. 1). Nappe stacking took place from Eocene to Early Miocene times, following the closure of the Pindos Ocean and the subsequent northward subduction and collision of the Apulia beneath the Pelagonian microcontinent (e.g. Doutsos et al., 1993, Xypolias and Doutsos, 2000).

The PQ unit is considered to be a metamorphosed Late Carboniferouse–Upper Triassic rift sequence consisting of phyllites, quartzites, metaconglomerates and marble intercalations (Robertson, 2006 and references therein). The thickness of the PQ unit is ca. 2 km in the central parts of the HP-belt (Kythira, westernmost Crete; Fig. 1) and decreases systematically towards its lateral tips (north Peloponnese, east Crete; Fig. 1) where it approaches ca. 1 km (Xypolias et al., 2007). Metamorphic conditions in the PQ unit (Fig. 1) decrease systematically in map-view from the central parts to the lateral tips of the belt (e.g. Theye et al., 1992). Peak P-T conditions have been constrained at 450 ± 30 °C and 13–17 kbar (Theye et al. 1992, Blumör 1998) while the age of the metamorphic peak is constrained at 19–24 Ma (K-Ar and ^{39}Ar-^{40}Ar on white mica; e.g. Panagos et al., 1979, Seidel et al. ,1982). The PQ unit is tectonically emplaced on the Plattenkalk unit by a major ductile thrust (Greiling, 1982; Doutsos et al., 2000; Zulauf et al., 2002; Xypolias and Kokkalas, 2006), the "*Basal thrust*".

The structurally lower Plattenkalk unit is composed of Carboniferous–Eocene carbonate rocks overlain by an Oligocene limy metaflysch with metaconglomerate horizons (e.g. Kowalczyk et al., 1977). Metamorphic index minerals in the Plattenkalk unit have only been found in central Crete at the Talea Window and indicate P-T conditions of 7–10 kbar and ca. 350 °C (Theye et al., 1992). Exceptionally in west Crete, an Upper Triassic–Lower Jurassic carbonate sequence, the Tripali unit, lies tectonically between the Plattenkalk and the PQ units.

The PQ unit is, in turn, overlain by the Tripolitsa and Pindos units representing the cover thrust sheets (Fig. 1). The Pindos and Tripolitsa units are mainly composed of Triassic to Eocene carbonate rocks and an upper Eocene flysch. The Pindos unit tectonically rests on the Tripolitsa unit and both units have a combined structural thickness no greater than 6 km. At the base of Tripolitsa carbonate rocks, a thin Permo-Triassic sequence, referred to as the Tyros Beds, which is in tectonic contact with the underlying PQ unit, has suffered very low-grade metamorphism (200–350 °C, 3–6 kbar; e.g. Thieboult and Triboulet, 1984).

Unconformably above the Cretan nappe pile lies a Neogene sedimentary succession. Data from Crete indicate that sedimentation started with terrigenous deposits of Middle Miocene age, followed by Upper Miocene–Pleistocene fluviolacustrine and open-marine sediments (e.g. Kokkalas et al., 2006).

3. Phases of ductile deformation

Based primarily on overprinting criteria observed in map to outcrop scales as well as on microstructural data, three principal ductile deformation phases (D_1–D_3) have been distinguished to constrain the structural evolution of the PQ unit (Greiling, 1982; Doutsos et al., 2000; Fassoulas et al., 1994; Zulauf et al., 2002; Kokkalas and Doutsos, 2004; Chatzaras et al., 2006; Xypolias et al., 2008). Deformation/metamorphism relationships described below in combination with the proposed P-T-t paths (Fig. 2) imply that these successive phases were coeval with progressive burial and exhumation of the PQ unit rocks.

3.1 D_1 deformation

The older recognized structures (D_1) in the PQ Unit are tight to isoclinal folds with wavelengths ranging from a few mm to about 10 cm. These structures are poorly preserved throughout the area due to intense D_2 ductile deformation and recrystallization. On outcrop scale, the S_1 fabric can be locally recognized mainly within thin competent quartzite layers (Fig. 2a), where it wraps around F_2 fold closures while folded S_1 within the phyllites is mainly visible on the microscale.

3.2 D_2 deformation

Structures and fabrics generated during D_2 deformation are pervasively developed throughout the PQ unit, and are by far the most common structural features observed in the field. This deformation phase is accompanied by a penetrative foliation (S_2) defined by the shape-preferred orientation of glaucophane and chloritoid needles as well as the alignment of micaceous films and elongated quartz aggregates (Fig. 2a). A mineral stretching and clast-elongation lineation (L_2) is well-developed within

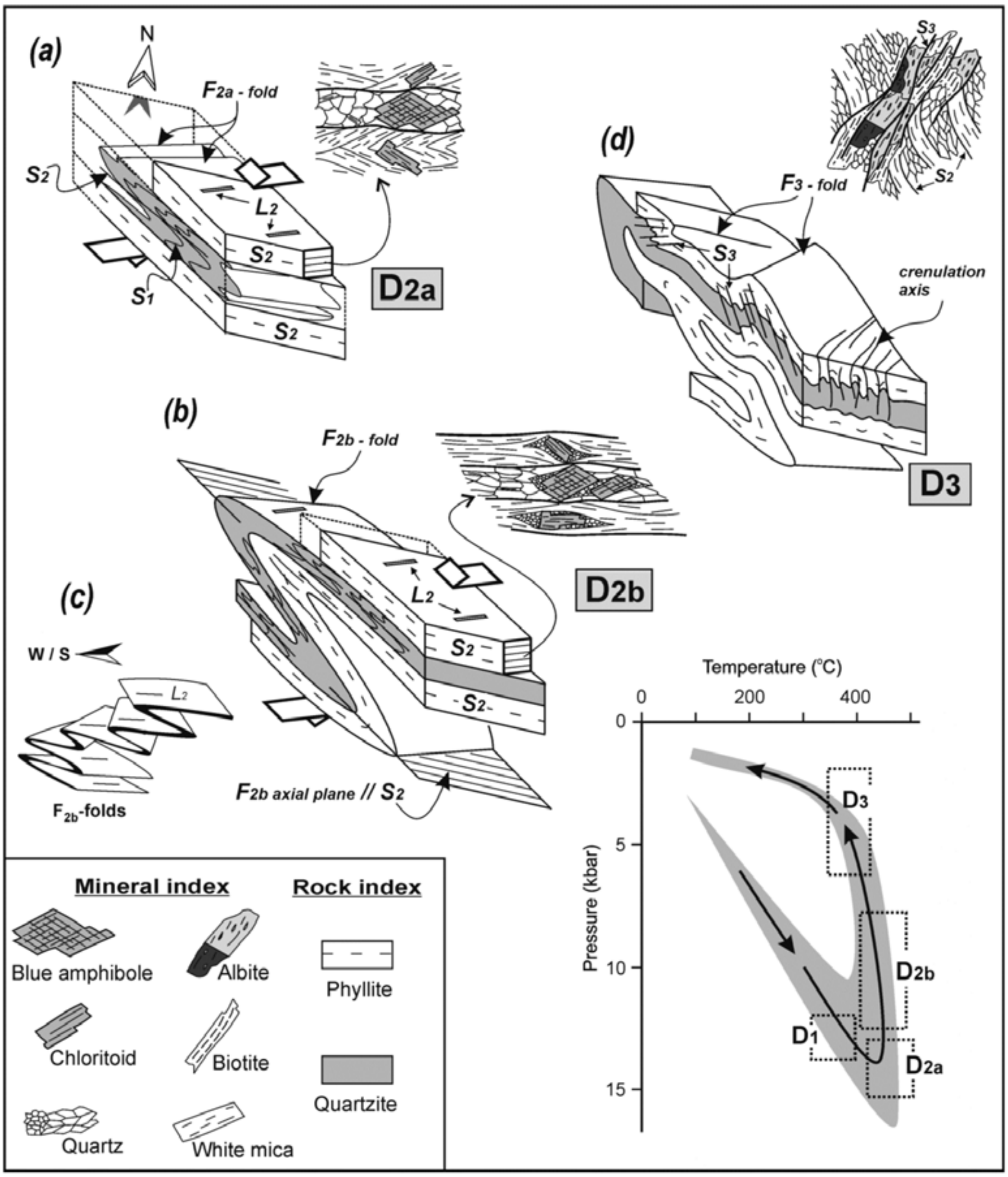

Fig. 2: Deformation/metamorphism relationships and progressive deformation of the PQ unit rocks. Block diagrams showing progressive deformation and associated structures during D_{2a} (a), D_{2b} (b) and D_3 (d) deformation subphases/phases, respectively. Line drawings summarize crystallization-deformation relationships. (c) Block sketch showing the rotation and tightening of F2b folds towards the lower structural levels of the PQ unit. The pressure-temperature path was constructed combining paths proposed by Blumör (1998) and Thomson et al. (1998) for the southern Peloponnese and western Crete, respectively. (Modified after Xypolias et al. 2008).

the plane of S_2 (Fig. 2a). Throughout southwest Hellenides, L_2 systematically trends perpendicular to the structural grain of the belt (Fig. 1).

The D_2 deformation can be subdivided in two successive increments (D_{2a}, D_{2b}) of ductile deformation. The earlier D_{2a} structures appear to be coeval with the main growth of HP-minerals (Fig. 2a) and can be locally recognized in the form of minor isoclinal folds (F_{2a}), which typically trend parallel to the regional L_2 orientation. The second increment of D_2 deformation is accompanied by outcrop-scale F_{2b} folds. As F_{2b} fold axes are sub-parallel or at a small angle to the L_2 lineation and fold axial planes are parallel to the regional S_2 foliation (Fig. 2b), a genetic link between S_2/L_2 and fold development is suggested.

Throughout the PQ unit, it has been recorded a systematic relation between the orientation and style of folds with respect to the structural level in the unit. Specifically, at lower structural levels, the F_{2b} folds are isoclinal with their axes oblique to sub-parallel to the L_2 while at progressively upper structural levels there is an increase in both the apical angle of the folds and the range of divergence between the fold axis and the L_2 orientation (Fig. 2c; e.g. Xypolias and Doutsos, 2000; Chatzaras et al., 2006). This finding is indicative of a progressive rotation of fold axes into the X-axis of finite strain (e.g. Alsop, 1992), resulting from an overall increase in strain magnitude as the contact between the PQ and the Plattenkalk units is approached.

Numerous kinematic indicators such as quartz c-axis fabrics, oblique grain shape fabrics, asymmetric boudins, sigma-shaped porphyroclasts, bookshelf tiling of HP-related minerals, S/C fabrics and single sets C'-type shear bands indicate a clear top-to-the-west (Peloponnese and Kythira) top-to-the-south (Crete) shear sense (Xypolias and Koukouvelas, 2001; Zulauf et al., 2002; Chatzaras et al., 2006). Evidence for top-to-the-east (or north) shearing (backward motion) has been mainly found at the upper structural levels of the PQ unit. Petrofabric data from central Peloponnese also reveals that west-directed ductile shearing in the PQ unit possibly occurred at deformation temperatures of 400–450 °C, while the east-directed movements occurred at lower temperatures (ca. 350 °C). These data imply that backward shearing occurred during the late stages of ductile deformation.

It is semantic to note that throughout the PQ unit quartzites show evidence of dynamic recrystallization accommodated by both subgrain rotation and low-temperature grain-boundary migration. This, in addition to the presence of strong quartz c-axes preferred orientation patterns recorded in Peloponnese and Kythira suggest that dislocation creep was the dominant deformation mechanism during D_2 shearing (Xypolias and Kokkalas, 2006). Evidence for deformation by dissolution precipitation creep is mainly restricted to metasiltstones, where quartz clasts are embedded in a phyllosilicate-rich matrix and occasionally show pressure shadows on both sides of grains (Schwarz and Stockhert, 1996).

3.3 D_3 deformation

The third deformation phase (D_3), is less widely developed than D_2 and is mainly represented by centimetre- to metre scale folds (F_3) and crenulations deforming S_2. The mesoscopic F_3 folds are predominantly open with a gently inclined axial plane cleavage. Microstructural observations from Kythira have shown that discrete S_3 cleavage domains serve as the site for growth of both biotite and albite. Corrosion of quartz and mica along this steeply dipping cleavage has also been recognized indicating that dissolution-mass transfer processes played an important role in their formation. Based on the above mentioned observations, it seems that D_3 deformation commenced under ductile conditions and became progressively more brittle with time.

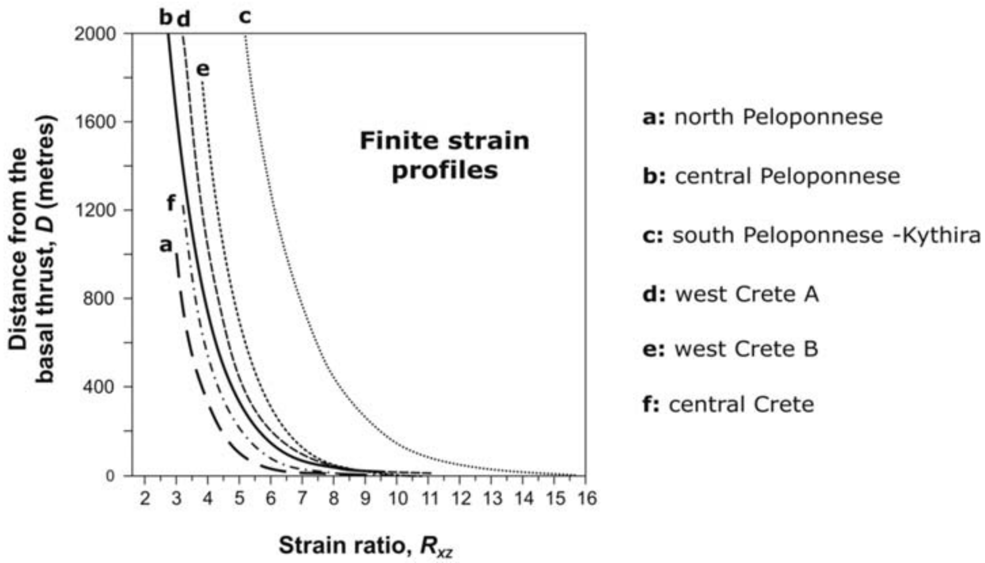

Fig. 3: The best fit curves describing the spatial variation of strain ratio along six traverses in the PQ unit. The location of these traverses is illustrated in Figure 1. (Modified after Xypolias et al. 2007)

4. Finite strain

Systematic analysis of the spatial variation of finite strain associated with D_2 deformation in the PQ unit rocks has been carried out along six traverses (Xypolias et al., 2007 and references therein). The location of these traverses is illustrated in Figure 1. The analysis is based on a total of 200 oriented samples collected from different structural levels above the basal thrust. Finite-strain ratio R_{XZ} was estimated using graphical and algebraic Rf/φ methods (Lisle, 1994). Plastically deformed quartz grains and clasts in fine-grained metaconglomerates, metapsammites, metasiltstones and quartzites were used as strain markers. It is emphasized that strain analysis was not carried out in pure quartzites showing extensive dynamic recrystallization because the shape of the most deformed grains may have restored to more equant form. However, analysis was performed in a few quartzites that include slightly recrystallized quartz ribbons embedded in a fine grained matrix. The majority of analysed samples are characterized by the presence of mica aggregates that anastomose around plastically elongated quartz grains or clasts showing evidence of undulose extinction.

Data of the strain ratio (Rxz) were plotted against distance (D) from the basal thrust to examine the variation of R_{XZ} values along the six traverses. The best fit curves describing the spatial variation of strain ratio in the PQ unit are illustrated in Figure 3. As a whole, the profiles show a systematic strain increase with proximity to the basal thrust. However, strain gradient is not constant from the top to the bottom of the shear zone. Specifically, the downward increase in strain ratio is slight at the upper and middle levels of the unit and becomes abrupt at a projected distance of 300 m above the basal thrust (Fig. 3). This progressive non-linear strain increase towards the basal thrust obeys a specific logarithmic function (see Xypolias et al., 2007 for details).

So far, less systematic analytical work about the shape of finite strain ellipsoid has been done. In Crete, the shape of strain ellipsoid varies from flattening via plane to prolate (Fassoulas et al., 1994; Zulauf et al., 2002). 3D strain data from north Peloponnese show slightly constrictional to plane strain conditions, with k being approximately 1.4 (Xypolias and Doutsos, 2000).

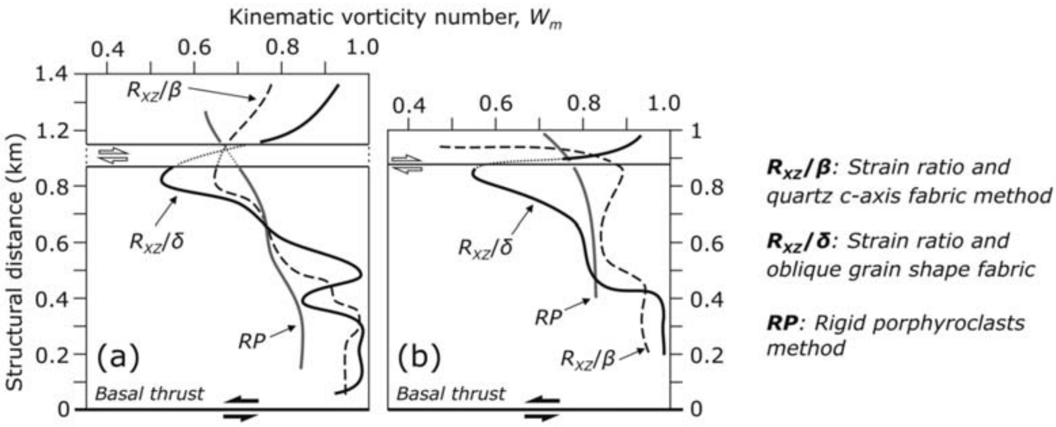

Fig. 4: Graphs (vorticity profiles) illustrating the vertical spatial variation in Wm values within the Phyllite–Quartzite unit in Taygetos (a) and Chelmos (a) areas. (Modified after Xypolias and Koukouvelas 2001; Xypolias 2009).

5. Vorticity and ductile thinning

Quantification of flow vorticity is also critically important for understanding the kinematics of rock flow in deformation zones. Mean kinematic vorticity number (Wm) is the most commonly used numerical measure to specify the shear-induced vorticity caused by the non-coaxial component of deformation. Wm is considered as a non-linear relation between the pure shear and simple shear components of deformation, with Wm = 1 implying simple shear and Wm = 0 implying pure shear flow (Passchier, 1987). Vorticity analyses have been performed in the PQ unit rocks exposed in windows of Peloponnese (Chelmos, Taygetos, Parnon) using a variety of analytical methods such as (a) the rigid porphyroclast method (Passchier, 1987), (b) the finite strain / quartz c-axis fabric method (e.g. Wallis, 1995), (c) the quartz c-axis fabric / oblique grain shape fabric method (Wallis, 1995) and (d) the finite strain / oblique grain shape fabric method (Xypolias, 2009).

Figure 4 illustrates the spatial variation of Wm within the PQ unit in Taygetos and Chelmos areas (Xypolias and Koukouvelas, 2001; Xypolias, 2009). In both vorticity profiles, the general trend observed by 'averaging' the results of these methods is that the Wm value approaches 1 close to the basal thrust and decreases upwards reaching a value less than 0.71 (equal contribution of pure and simple shear) at the middle of the unit, below a zone of backward shearing. Above this zone, the Wm values generally increase.

Deviation from ideal simple shear deformation implies ductile thinning perpendicular to the boundaries of the PQ unit and resultant dip-parallel elongation. For isochoric plane strain deformation, the stretch magnitude both normal and parallel to the flow plane can be calculated, combining strain and vorticity data (e.g. Wallis, 1995). Such calculations in Taygetos area indicate that the average transport-parallel elongation appears to be higher in the middle structural levels of the PQ unit, ranging between 60 and 90%, and lower in the deeper parts of the zone, ranging from 40% to 60%. Less significant variation in ductile thinning normal to the zone has been recorded; it is on the order of 30–45%.

6. Discussion and conclusions

It is clear, from both qualitative and quantitative analyses, that the PQ unit throughout the belt was affected by penetrative deformation during the ductile stage of exhumation. This finding is in constrast to models proposing exhumation of Cretan HP-rocks as a coherent block unaffected by any pervasive deformation (e.g. Thomson et al., 1999). They also propose that during buoyancy-driven exhumation, deformation was restricted to the vicinity of the upper bounding extensional detachment fault. Finite strain profiles, in turn, indicate a systematic non-linear increase of finite strain with proximity to the Basal thrust and do not support strain localization along the upper boundary of the unit. These findings also imply that accumulation of ductile strain was coeval with the emplacement of the PQ on the Plattenkalk units during west (or south)-directed thrusting.

Penetrative ductile deformation in the PQ unit was also associated with ductile thinning and transport-parallel elongation of the material. However, the mechanism by which the ductile thinning and transport-parallel elongation contribute in exhumation of HP-nappes is not unique (e.g. Xypolias et al., 2010). Generally, two major alternative mechanisms have been proposed up to now. According to the first (e.g. Platt, 1993) a component of ductile extensional flow along a shallow dipping mid-crustal deformation zone requires the same component of deformation to be present in the surrounding rocks at the higher structural units. Under this mechanism the exhumation of HP-rocks is achieved by unroofing along the footwalls of low-angle normal faults (syn-orogenic extension). The most reliable indicators of this mechanism are the downward increase in the metamorphic pressure as well as the formation of extensional sedimentary basins in the upper plate (Platt, 1993). Alternatively, the transport-parallel elongation can contribute to the upward ductile extrusion of the HP-rocks (Escher and Beaumont, 1997; Xypolias and Koukouvelas, 2001; Law et al., 2004). In this case, the extruding/exhuming rock unit is modelled to represent a tectonic slice bounded by a basal subduction-related thrust fault and a roof stretching fault. The roof stretching fault may display normal or thrust sense, depending on the motion of the crust above the extruding material (e.g. Godin et al., 2006).

The mechanism of syn-orogenic (asymmetric or symmetric) extension has been adopted by many authors (e.g. Fassoulas et al., 1994; Jolivet et al., 1996) to explain the removal of overburden from above the PQ unit. However, the applicability of this mechanism remains highly questionable since either Oligocene-Early Miocene extensional related basins or normal-sense metamorphic breaks within the PQ unit have been not reported so far. Moreover, it is unclear if a thinning on the order of 30–45% in the upper plate is capable to denudate tectonically the PQ unit rocks. In contrast, several studies have shown that extension lagged behind a significant part of the exhumation process, and is superposed on an orogenic wedge that contains HP-rocks at relatively shallow crustal levels. According to these studies, middle Miocene–Pleistocene extension controlled both the exhumation of HP-rocks from ~10 km to the surface and the initiation of basin formation (Papanikolaou and Vassilakis 2010 and references therein). However, these models seem to underestimate the importance of contraction-related structures deforming Middle Miocene–Early Pleistocene sediments of Crete (Kokkalas and Doutsos, 2001; Kokkalas et al., 2006; Chatzaras et al., 2006; Klein et al., 2008; Tortorici et al., 2010), suggesting that the role of extension is overestimated.

Consequently, solid-state ductile extrusion of PQ unit under continuous compression provides a reasonable explanation for the exhumation of these rocks. According to this mechanism, after peak metamorphism, the PQ unit was detached from its basement and extruded upward to the west (or south) between the basal thrust and the Tripolitsa basement at the top. The effect of this extrusion process was the emplacement of the PQ unit over the Plattenkalk unit bringing it into contact with the overlying cover thrust sheets along a roof stretching fault. The subduction-related basal thrust and roof stretching fault operated contemporaneously in a tectonic setting without any net extension of the overall system. However, as mentioned above the roof stretching fault may display normal (e.g. Crete) or thrust (e.g. Kythira) sense depending on the crust motion above this fault.

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