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RHEOLOGY AND STRAIN PATTERNS DURING THE EXHUMATION OF THE PHYLLITE-QUARTZITE NAPPE IN CENTRAL CRETE (GREECE).

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ABSTRACT

The characteristic quartz microstructure and the shape and relative position of individual grains/clasts were used to study in this paper the rheology and strain during the exhumation of the Phyllite-quartzite (PQ) nappe of central Crete. The PQ nappe has recorded a dominant and a secondary quartz microstructure, indicating that dislocation creep flow, under crystal plastic processes was the main deformation mechanism during exhumation. Pressure solution is restricted only in few phyllitic samples, and is responsible for the volume loss. Strain analysis on the other hand, revealed that the finite strain ellipsoid lye mainly in the flattening field, suggesting a significant volume loss, whereas both simple and pure shear strains developed during the deformation. With increasing strain intensity the finite strain ellipsoid tends to become more oblate, accelerating the mass transfer mechanisms. The present occurrence of the PQ nappe in boudinage form is thus the result of the crystal plastic deformation mechanism, that yielded to rock softening and to the significant volume loss.

KEY WORDS: Crete, Phyllite-Quartzite, exhumation, rheology, strain.

1. INTRODUCTION

Crete posses the central part of the Hellenic island arc, lying above the Active Hellenic subduction zone (Fig. 1a). It experiences a complex orogenic process, which started from the Eocene and is still continuing with the neotectonic activity (Fassoulas 1995). The Lower nappes of the island, composed by the Plattenkalk series, the Trypali unit and the Phyllite-quartzite nappe(Fig. 1a; Bonneau 1984, Hall et al. 1984, Papanikolaou 1988, Kilias et al. 1992, Fassoulas et al. 1994), suffered in Late Oligocene/Early Miocene (Seidel et al. 1982) a high pressure/low temperature metamorphism. A Main detachment fault (Fig. 1b) separates these lower metamorphic nappes from the non-metamorphosed at the base, Upper nappes of the island (Kilias et al. 1992, Fassoulas et al. 1994).

Recent studies in central Crete (Kilias et al. 1992; 1994, Fassoulas et al. 1993; 1994, Fassoulas 1995;1997) revealed that the Phyllite-quartzite (PQ) nappe underwent in Middle-Late Miocene, a ductile D_2 crustal extension, that was associated with detachment faulting. Extension resulted in crustal thinning and exhumation of the high pressure metamorphosed lower nappes. Tectonic unroofing was accelerated by the moderate- to low-angle detachment faults. The duration of this exhumation process is constrained by the first deposition in the tectonic basins of the Middle Miocene sediments and the formation of a later local D_3 compression, that was dated as Late Miocene (Fassoulas et al. 1994).

Schwarz and Stoeckhert (1996) studied the rheology of the Phyllite-quartzite nappe in western Crete, and argue that deformation during rapid burial and subsequent exhumation took place mainly by pressure

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Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

solution, allowing for high bulk strain. Crystal plastic processes were recognized only in a few samples of pure quartzites.

In this paper we investigate the rheology and the strain patterns during the exhumation of the PQ nappe in central Crete. Although a SEM microscope is necessary to study the slip planes, the intracrystalline dislocations, and to establish the flow lows, however, there exist enough optical characteristics, related mainly to the quartz microstructure, that can be used for the identification of the deformation mechanisms (Knipe, 1989). The quartz microstructure of pure quartzites and phyllites of the PQ nappe was used to define the deformation mechanisms that operated during the exhumation process. Furthermore, the shape of individual grains/clasts and the relative position of grains/clasts were also used to determine the finite strain ellipsoid and the strain components.

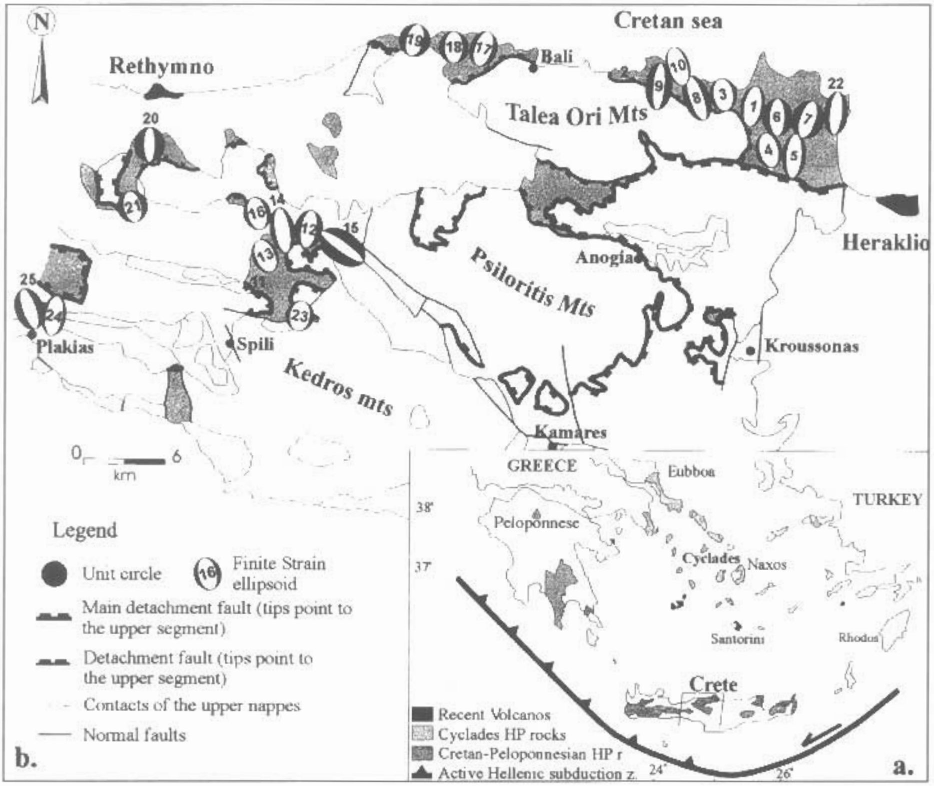

Fig. 1: a. The south Aegean region and the main geological features, in square the study area. b. Geological map of central Crete showing the occurrence of the Phyllite-quartzite nappe in central Crete and its tectonic contacts with the above and bellow nappes. The location of samples are also cited, numbers refer to Table 1.

2. GEOLOGICAL SETTING OF THE PQ NAPPE.

The Phyllite-quartzite nappe crops out all over Crete, extending northwards to the Pelopponese (Fytrolakis 1980) and Santorini Island (Kilias et al. 1997; Fig. 1). It consists mainly of phyllites, quartzites, marbles and metavolcanics, of Permian to Upper Triassic age (Krahl 1983). In Late Oligocene/Early Miocene PQ nappe suffered a high pressure/low temperature metamorphism (Seidel et al. 1982), that increases from east to west, ranging from 8 Kb and 300 °C in eastern Crete to 10 Kb and 400 °C in western (Theye et al. 1992). A retrograde, low greenschist metamorphism affected the PQ nappe during the exhumation (Theye et al. 1992, Fassoulas et al. 1994, Fassoulas 1995). Jolivet et al. (1995) argue that in western Crete parts of the PQ rocks were exhumed through a fast cooling path and parts through a slower cooling path, without evidence of retrogradation.

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

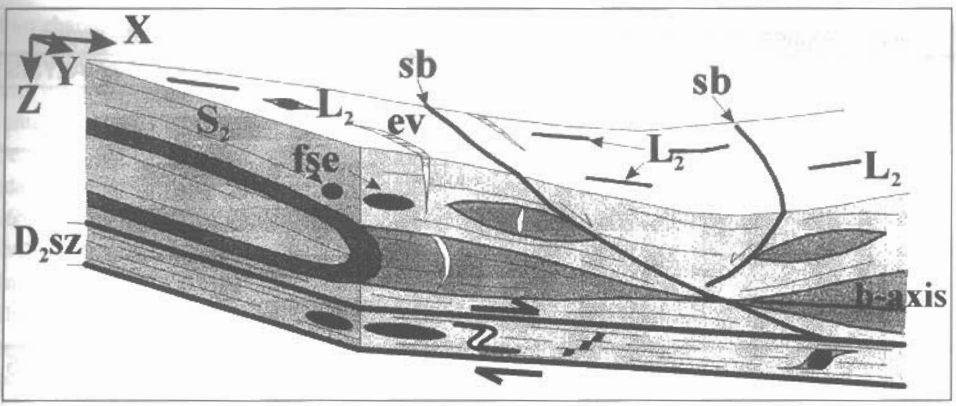

Fig. 2: Sketch illustrating the characteristic deformation of the Phyllite-quartzite nappe. L_2, S_2 the stretching lineation and foliation during the exhumation, fse, the finite strain ellipsoid, ev, extension veins, D_2sz, extensional D_2 shear zones, sb, shear bands and b-axis, the b-axis of the isoclinal folds. X,Y,Z the principal strain axes. (From Fassoulas 1995).

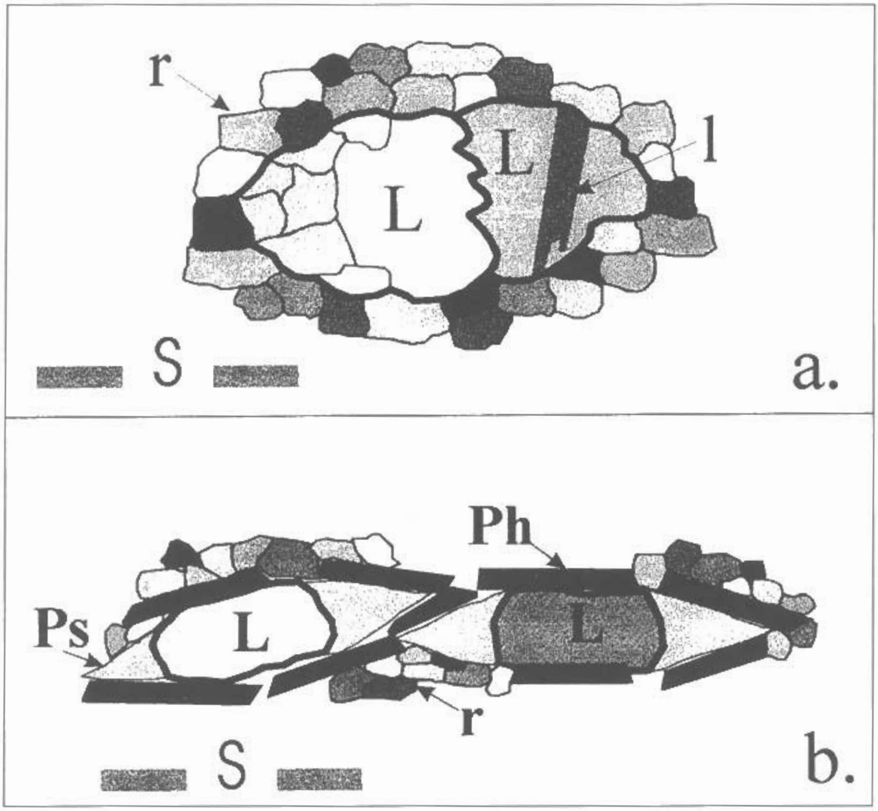

Fig. 3: The characteristic quartz microstructure. a. The microstructure occurring in the whole PQ nappe. b. The microstructure occurring in few phyllitic samples. L, large quartz grains, r, recrystallized quartz grains, Ph, phyllosilicate minerals, S, the S_2 foliation plane, l, deformation lamelae.

In cental Crete PQ crops out as isolated, boudinaged bodies between the HP metamorphosed also Plattenkalk nappe and the Upper nappes (Fig. 1b), with a thickness ranging from a few meters to hundred. This is in contrast with its occurrence in western Crete, where it is about 1.5 Km thick (Fytrolakis 1980).

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

Table 1. Optical microstructures and strain analysis of the Phyllite-quartzite nappe.

		RHEOLOGY										STRAIN ANALYSIS			
		Pressure solution			Crystal Plasticity										
A/A	Samples	mineral differencation	extension veins	pressure shadow	lamellae	deformation zones	twinning	internal polygonization	dynamic recrystallization	CPO	dendate boundaries	X:Y:Z	K	r	Φ°
1	A1	-	-	-	+	-	-	-	+	+	-	1.58/.91/.69	2.3	2.05	36
2	AN2	-	-	+	+	-	-	-	+	+	-				
3	AN5	-	-	-	-	-	-	-	+	-	-	1.25/1.03/.78	.69	1.53	40
4	AN23											1.36/1.0/.74	1.04	1.71	4
5	AN24	-	-	+	-	-	-	-	+	+	-	1.72/.91/.63	2.01	2.3	26
6	AN25	-	-	-	+	-	-	+	+	+	+	1.44/1.15/.6	.27	2.2	2
7	AN26	-	-	+	+	-	-	+	+	+	+	1.47/1.25/.54	.13	2.49	21
8	AN29	-	-	+	+	-	-	-	+	+	-	1.82/1.0/.55	.99	2.6	18
9	AN38	-	-	-	+	-	+	-	+	-	-	1.84/1.3/.47	.19	3.2	5
10	AN50	-	-	-	+	-	-	+	+	-	-	1.54/.88/.73	3.75	1.95	52
11	PR2	+	+	+	-	-	-	-	-	-	-				
12	PR4	-	-	-	+	+	-	+	+	-	+	1.47/1.09/.62	.46	2.1	6
13	PR5	-	-	+	-	-	-	-	+	+	-	1.32/.97/.78	1.44	1.6	19
14	PR6	-	-	+	+	-	-	-	-	+	-	1.76/.93/.61	1.65	2.4	28
15	PR7	-	-	+	-	-	-	-	-	-	-	2.06/1.21/.4	.34	3.7	11
16	PR8	-	-	-	+	-	-	+	+	-	+	1.29/1.05/.74	.55	1.65	27
17	PR9	-	-	-	+	-	-	-	+	-	-	1.39/1.04/.69	.67	1.84	43
18	PR11	-	-	-	-	-	-	-	+	+	-	1.21/1.14/.73	.1	1.62	45
19	PR12	-	-	-	+	-	-	+	+	+	+	1.26/1.21/.66	.05	1.87	23
20	RE1	-	-	+	+	-	-	+	+	+	+	1.34/1.18/.44	.38	4.2	16
21	RE2	-	-	-	+	-	-	+	+	+	+	1.22/1.19/.69	.04	1.75	9
22	IR12											1.7/.9/.5	1.35	2.69	10
23	ME16	-	-	-	+	-	-	-	+	+	+	1.18/1.08/.81	.31	1.62	37
24	SE10	-	+	+	-	-	-	-	+	+	-	1.57/.93/.68	1.83	2.05	48
25	SE11	-	-	-	+	-	-	+	+	+	+	1.64/1.1/.55	.49	2.49	10

3. QUARTZ RHEOLOGY.

In central Crete the PQ was strongly affected by the intense D_2 extensional event and the associated retrograde metamorphism, that overprinted all the earlier D_1 structures (Fassoulas 1995). D_2 deformation is characterized by isoclinal folding associated with a penetrative S_2 foliation, intense stretching parallel to the L_2 lineation, boudinage and extensional vein formation, especially at the fold limbs (Fig. 2; Fassoulas 1995). Localized small and large scale, low angle shear zones indicate a normal sense of shear either to the north or to the south. The overall kinematic and structural analysis indicates deformation under bulk coaxial conditions, resulting finally to the exhumation, thinning and boudinage formation of the PQ nappe (Fassoulas et all. 1993; 1994, Kilias et al. 1994).

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

Two characteristic types of quartz microstructure has been recorded to the phyllitic and quartzitic rocks of the PQ nappe during the D_2 deformation (Figs. 3, 6). The first occurring both in quartzites and phyllites is characterized by large quartz grains floating in a mass of smaller recrystallized grains (Fig. 6a) that usually expose a well crystallographic preferred orientation (CPO) of the optical c-axis (Fig. 4, Table 1). Dentate grain boundaries, as well as polygonization in smaller quartz grains with low angle grain boundaries, deformation lamellae, and deformation band and occurring within the large quartz crystals (Fig. 6b), suggest dislocation creep processes (Knipe 1989). The thermally activated dislocation creep flow involves accumulation of strain by intracrystalline processes under crystal plasticity deformation mechanisms (Barber 1985).

The second type of microstructure occurs mainly in phyllitic rocks. It is characterized by large flattened quartz grains surrounded by phyllosilicate minerals (white mica, chlorite) and characteristic pressure shadows filled with fine-grained recrystallized quartz (Figs. 3b, 6c). Extension veins occur also in micro- and meso-scale (Fig.2). These structures indicate transfer of material away from zones of high intergranural normal stress to interfaces with low normal stresses, attributing to pressure solution processes under diffusional mass transfer mechanism (Etheridge et al. 1984). However, new recrystallized grains, with high angle boundaries, exposing in few samples a well-defined crystallographic preferred orientation (Table 1, Fig. 4), and in some cases, deformation lamellae within the large grains, point also to crystal-plastic mechanisms.

Diffusional mass transfer, especially pressure solution, was favoured in the phyllitic rocks, where phyllosilicate minerals could support mass transfer on a fluid film, through grain boundaries. However, such mechanisms could have established during the earlier D_1 deformation, as has been observed in western Crete (Schwartz and Stoeckhert 1996).

4. STRAIN ANALYSIS.

In order to define the finite strain ellipsoid and the strain components during the exhumation process of the PQ nappe, the shape dependent Rf/theta (Peach and Lisle 1979, Lisle 1984) and the center to center Fry (Hanna and Fry 1979) techniques were applied. Special care was given during the measurements and special tests were made (Fassoulas 1995) to avoid errors implied by rock inhomogenities and the measurement process.

More than twenty samples were studied in cross sections cut parallel to the principal planes of the finite strain ellipsoid (i.e. XZ and YZ sections). After processing these data with the SPAR program, the principal extensions $(1+e_1)$ of the finite strain ellipsoid, the Flinn value (**K**, Flinn 1978), the angle **Φ°** of the X-axis of the finite strain ellipsoid with the shear zone boudary and the strain intensity, **r** (Watterson 1968) were derived and are presented in Table 1. The orientation and the shape of the finite strain ellipsoids are depicted as ellipses in Fig. 1, representing the black the finite strain ellipsoid in the XY section and the white in the XZ section.

Plotting data in a modified Ln Flinn diagramm (Kliegfield et al. 1981; Fig. 5a) it appears that the finite strain ellipsoids lye mainly in the apparent flattening field and few in the plane strain line and the apparent constrictional field. Both pure and simple shear strains have been recorded in these samples, as can be seen by comparing this diagram with the Φ°-Rs diagram (Fig. 5b). This diagram illustrates for each sample, the angle Φ° of the X-axis of the finite strain ellipsoid against the magnitude of strain,Rs, in the XZ section (Kliegfield et al. 1981). According to Ramsey and Huber (1983), the samples lying in the constrictional field indicate usually simple shear strain under constant volume, while those lying in the apparent flattening field indicate pure shear and volume loss.

However, as we can obtain from the Ln Flinn and the Strain partitioning plots (Fig. 5a,b), most of the analyzed samples indicate volume loss, that can reach in few of them 50% of total volume, achieved during a combination of simple and pure shear strains. Additionally, it is characteristic that the samples with the lower K-value (K<<1, Table 1) come from rocks outcropping near to the large detachment zones (Fig. 1b).

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

In order to examine existing relations between the strain intensity with the shape of the finite strain ellipsoid, and subsequently with volume loss, the K-value were plot (Fig. 5c) against the strain intensity r (where $r = \frac{X}{Y} + \frac{Y}{Z} - 1$, X,Y,Z the principal axes of the finite strain ellipsoid,Watterson 1968).

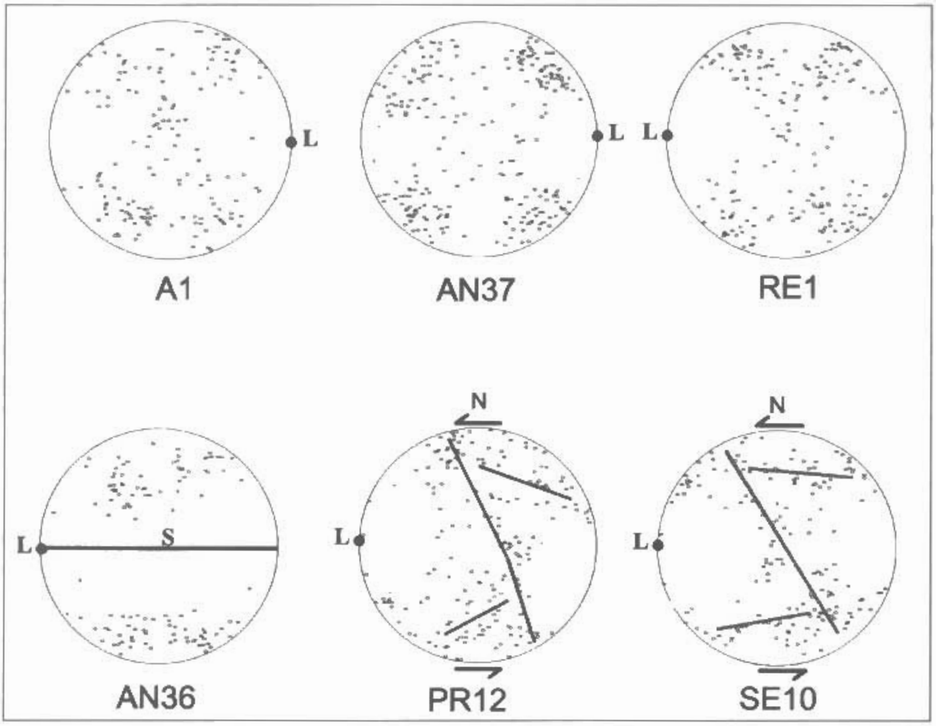

Fig. 4: Crystallographic preferred orientations of the optical quartz c-axis. L, indicates the L2 stretching lineation. The sense of shear is shown in PR12 and SE10 samples.

According to this plot, at moderate intensities (approximately 2) both prolate (constrictional) and oblate (flattening) ellipsoids occurred. However, with increasing strain intensity the ellipsoids tend to become more oblate, and thus volume loss to become higher. This is in agreement with the observation that volume loss is higher at intensely sheared rocks. We should mention here that strain intensity reflects the total strain suffered by a rock mass, and it is independent of the different strain rates that may have taken place locally.

As has been asserted by Mohanty and Ramsay (1994), although volume loss is independent on shear strain rate, it can reach high amounts in shear zones (80-90%). This is due to chemical and mineralogical changes, and is attributed to grain-size reduction at the early stages of deformation, that can increase the porosity of the whole rock and support mass transfer.

5. STATE OF DEFORMATION DURING THE EXHUMATION PROCESS - CONCLUSIONS.

The Miocene exhumation process that affected the PQ nappe in central Crete is characterised by, intense subhorizontal stretching and vertical thinning, reflected by the boudinage formation, the conjugate normal detachment zones and extension vein systems (Kilias et al. 1992, Fassoulas et al. 1993; 1994, Fassoulas 1995). This complex deformation resulted in characteristic structures that are visible both in macro- and micro scale. Instead of its appearance in western Crete, the PQ nappe in the central part of the island occurs in isolated, boudinaged intensely strained bodies. Especially in the Psiloritis Mountains, the nappe has been totally disappeared between the carbonate masses of the underlying Plattenkalk and the overlain Upper nappes (Fig. 1b).

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

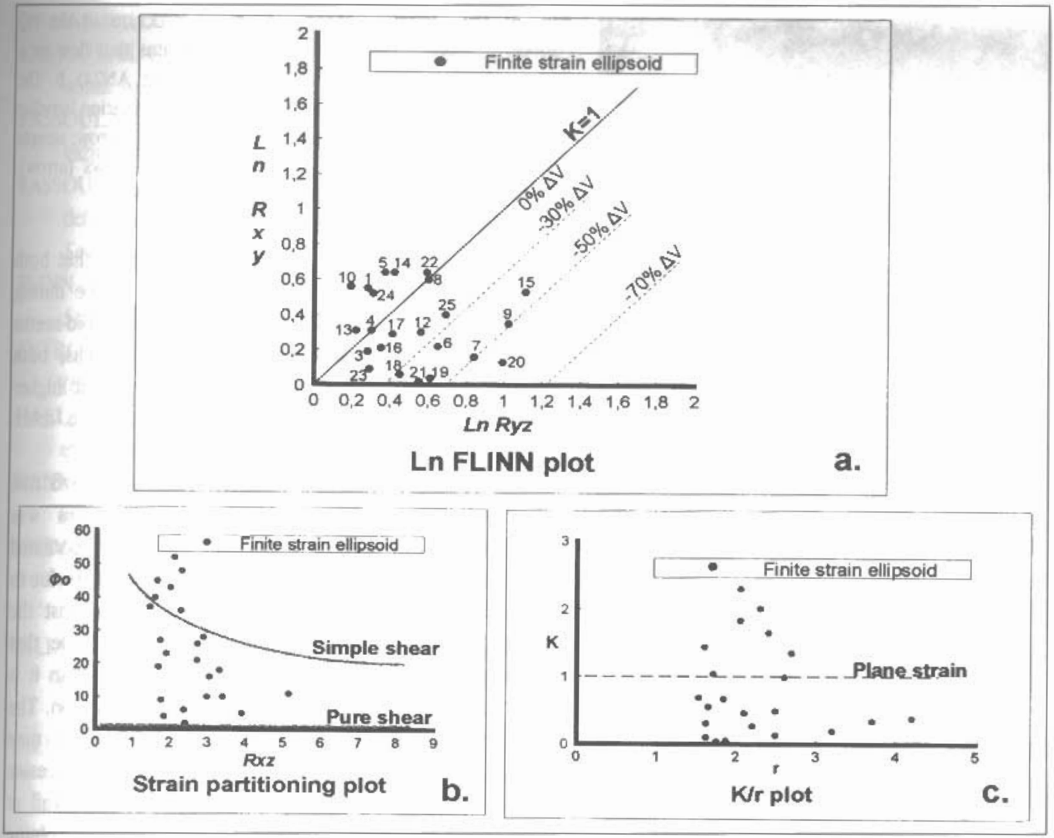

Fig. 5: The strain analysis plots. a. The modified by Kliegfield et al. (1981) Ln Flinn diagram (numbers refer to Table 1), b. The strain partitioning diagram, and c. the K-r diagram (explanations in text).

In micro scale, the characteristic quartz microstructures offer information about the rheology of the PQ rocks and subsequently, about the way and the conditions under which such a deformation developed. The microstructures occurring in pure quartzites and phyllites indicate that during the exhumation process the major deformation mechanism was crystal plasticity, and especially dislocation creep flow. Indicators for diffusion mass transfer (pressure solution) derived from phyllites, however crystal plastic processes seems to have operated also in these samples.

According to Knipe (1989), the dislocation creep flow is thermally activated at temperatures exceeding the 0.5 melting temperature of rocks consisting only by one mineral. Together with dynamic recrystallization, dislocation creep flow help to reduce the rock hardening processes and increases the ductility of the material (White et al. 1980, Schmid 1982).

The thermal overprint during the exhumation process, confirmed by the retrograde low grade metamorphism of the PQ nappe (Fassoulas et al. 1994, Fassoulas 1995), supported dislocation creep flow against the diffusion mass transfer processes. Pressure solution was thus constricted only in phyllitic rocks where the small grain size, the high porosity and the occurrence of phyllosilicate minerals permitted the mass transfer within the grain boundaries. This process could probably represent earlier stages of deformation (D_1 event?). The development of dislocation creep flow during the exhumation process resulted in rock softening and increased ductility within shear zones, accelerating the stretching and thinning of the whole PQ unit. Dynamic recrystallization, reduction of the grain size, internal deformed large grains and well defined crystallographic preferred orientation, occurring within the ductile shear zones, evidence the increase in ductility both in pure quartzites and phyllites.

Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

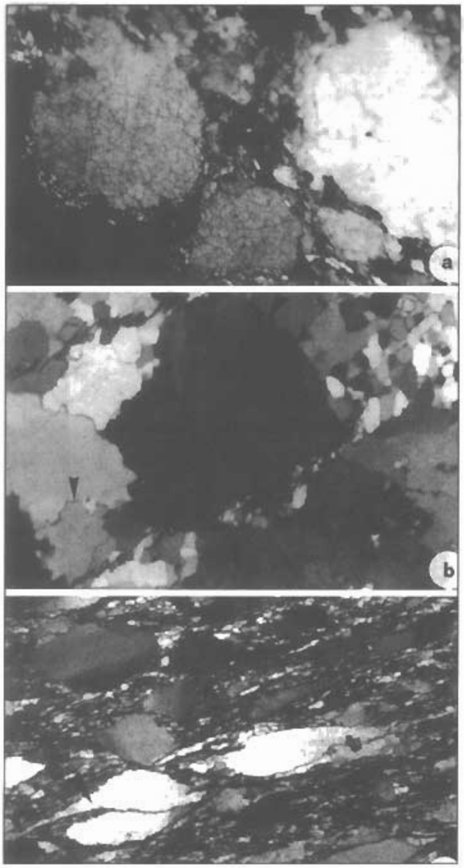

Fig. 6: The characteristic quartz micro-structure of the PQ nappe. a. Polygonization of large quartz grains that flow on a matrix of smaller recrystallized grains (sample AN24). b. The internal deformation of the large grains, i.e. deformation lamellae (large arrow) and dentate grain boundaries (small arrow; sample PR4). c. Large flatten grains with pressure shadows (arrow), surrounded by new recrystallized grains (sample RE1).

On the other hand strain analysis revealed that both simple shear and pure shear strains took place during deformation. The shape of the finite strain ellipsoid seems to be independent to the strain intensity. Thus, both prolate and oblate ellipsoids occur, whereas at higher intensity strains the ellipsoid tends to become more oblate.

The modified Ln Flinn diagram (Fig. 5a) shows that volume loss as a mass reducing mechanism was significant, although was kept relatively low, confined only in intensely sheared samples. That is probably due to the predominance of the crystal plasticity against the pressure solution. We can not however exclude that pressure solution may have contributed more than it is now appeared, at the earlier stages of deformation. The strain intensity (2-3) achieved during deformation may have accelerated also these crystal plastic processes against the pressure solution, that seems to prevail at higher strain intensities giving the higher values of volume loss (Table 1, Fig. 5).

The comparison of the presented optical characteristics of the quartz microstructure and the strain paterns of the individual grains/clasts with the structural and metamorphic characteristics of the PQ nappe, clearly demonstrates the deformation process during its exhumation. The metamorphic and strain conditions that took place during the exhumation process, accelerated the predominance of the crystal plastic mechanisms against the pressure solution, that was restricted in a few phyllitic samples. The simple shear and pure shear strains revealed by the strain analysis were induced by the tectonic escape of the upper nappes and the high differentiate stress that was superimposed by the thickened overlying crust. Thus the boudinage occurrence, the thinning and the exhumation of the whole PQ nappe was achieved mainly as a result of the predominance of crystal plastic processes that enabled rock softening and accumulation of high shear strain in the shear zones, and also by the significant volume loss during deformation.

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Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.

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Ψηφιακή Βιβλιοθήκη "Θεόφραστος" - Τμήμα Γεωλογίας. Α.Π.Θ.