

THE RHEOLOGICAL PROPERTIES OF ROCKS IN A COMPRESSIONAL DUCTILE SHEAR ZONE, PHYLLITE-QUARTZITE SERIES, PELOPONNESE

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ABSTRACT

The magnitudes of differential stress, strain rate and viscosity during the formation of an extruding crustal-scale shear zone (Phyllite-Quartzite Series, PQS) were estimated providing new insights on the mechanical behavior of the middle continental crust of the External Hellenides during compression. The differential flow stress during ductile deformation of PQS, in the Taygetos and Chelmos tectonic windows, has been analyzed using grain-size piezometer. Quartz tectonites from the Taygetos and Chelmos areas have mean grain sizes of 42 μm and 51 μm , respectively. Extrapolation of quartzite flow-laws indicates that tectonic extrusion of the PQS occurred at strain rates slightly faster than 10^{-13}s^{-1} . These estimates suggest that the extruding zone had a relatively low-viscosity of the order of 10^{19} to 10^{20} Pa-s. Finally, the combination of the obtained strain rate values with published quantitative analyses for the deformation path in the PQS implies that during the initial stage of the tectonic extrusion process the displacement rates parallel to the Taygetos-Parnon and Chelmos Thrusts, were $\sim 6\text{mm/year}$ and 3mm/year , respectively.

KEY WORDS: Quartzites; rheology; ductile shear-zones; Phyllite-Quartzite Series; Peloponnese.

1. INTRODUCTION

Although considerable progress has been made by numerous geologists toward the understanding of the geometrical evolution of intraplate thrust faults and the kinematics of the associated ductile shear zones, the magnitudes of several rheological parameters, such as differential stress and strain rate, responsible for the tectonic deformation of those process remain poorly understood (Engelder, 1993; Ranalli, 1995). In the case of tectonically active regions, the magnitude of differential stress can be estimated using geophysical data or measured directly in the uppermost part of the lithosphere (e.g. Molnar & England, 1990; Whitmarsh et al., 1991). Alternatively, the magnitude of differential stress in the exhumed orogenic belts inaccessible to direct measurement can be derived from the microstructures in ductile deformed rocks (e.g. Goetze & Kohlstedt, 1973, Twiss, 1977; Koch 1983; Gleason & Tullis, 1993). Consequently, the estimated flow stress values can be used, in conjunction with the temperature history of the rocks and experimentally flow laws, to infer the strain rate during the development of ductile shear zones (e.g. Paterson & Luan, 1990; Gleason & Tullis, 1993).

The aim of this paper is to use theoretically derived microstructural piezometry of quartz to infer the differential stress during the deformation of quartzose rocks of the Phyllite-Quartzite Series (PQS) in the Peloponnese. The strain rate and effective viscosity during the syn-compressional exhumation of these rocks are then estimated by applying quartzite flow laws at the calculated stresses and published metamorphic temperatures. For the purpose of this analysis 36 representative quartz-rich samples were selected from the PQS, which derived from the cores of two major tectonic windows (Chelmos, Taygetos, Fig. 1a).

2. TECTONIC SETTING

The Peloponnese comprises a nappe pile of different tectonic units (Fig. 1), each characteristic of a distinct paleogeographic domain in the External Hellenides. From top to bottom, and from internal to external in terms of paleogeographic configuration within the Apulian, four main tectono-stratigraphic units can be distinguished (e.g. Jacobshagen 1986): (1) The «Pindos Thrust Belt» which comprises mainly deep-water carbonates, and siliclastic and siliceous Mesozoic-Cenozoic rocks; (2) the «Tripolitza-Tyros Zone» which represents mainly a thick carbonate platform of Mesozoic-Cenozoic age; (3) the metamorphic sequence of the «Phyllite-Quartzite Series» (PQS) which is considered as an original Permo-Triassic volcanic-clastic rift sequence; and (4) the metamorphic Mesozoic-Cenozoic «Plattenkalk Series» which is either part of the Ionian or the Pre-Apulian zone.

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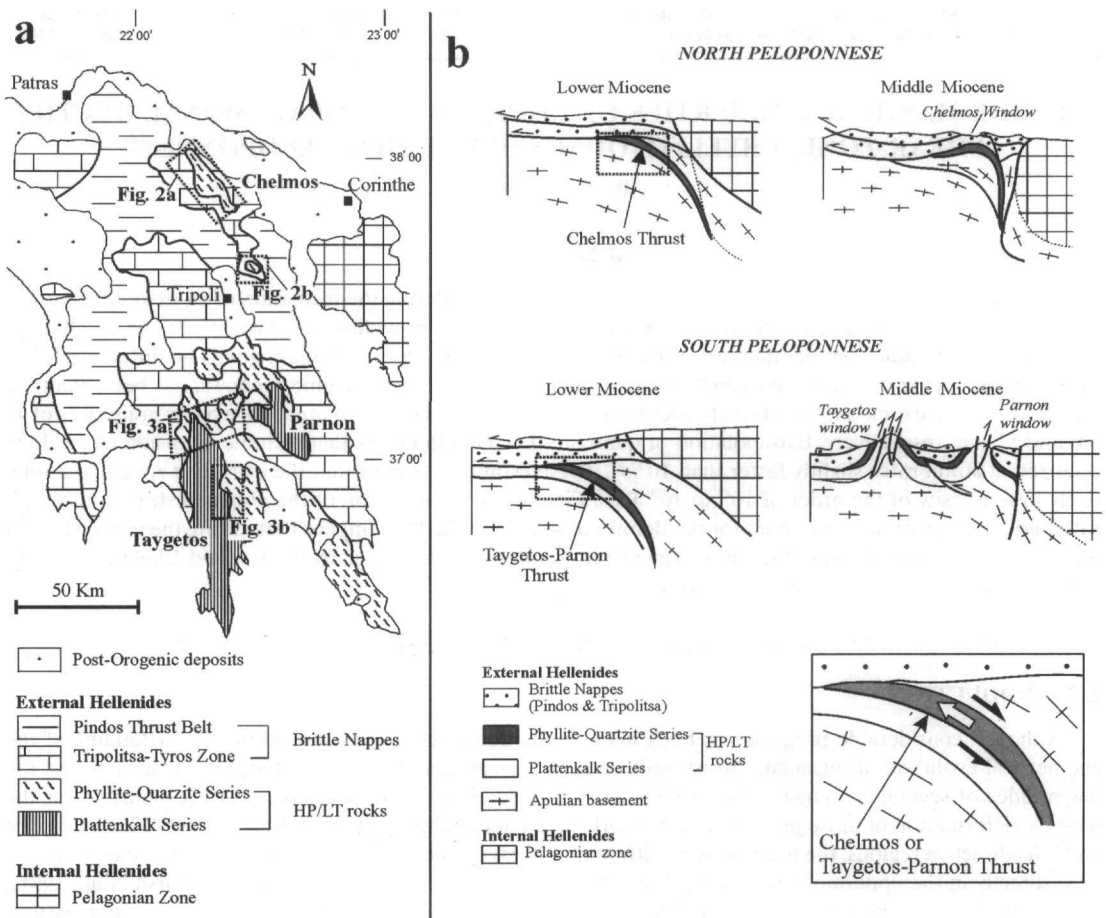


Figure 1. (a) General tectonic map of the Peloponnese, showing principal structural units and the location of the Chelmos and Taygetos windows. The locations of the maps in Figures 2a, 2b, 3a and 3c are indicated by boxes. (b) Evolutionary models of the development of the north (by Xypolias & Doutsos, 2000) and south Peloponnese (by Doutsos et al., 2000) along east-west geological cross-sections. Inset shows in detail the solid-state extrusion of the Phyllite-Quartzite Series.

The External Hellenides in the Peloponnese developed during Tertiary time, following the closure of Pindos Ocean and the consequent continent - continent collision between the Apulian and Pelagonian. In the course of this tectonism, the protolith of the PQS, which was underthrust beneath the Tripolitsa basement (e.g. Thiebault & Triboulet, 1984), underwent metamorphism resulting in the formation of greenschist to blueschist metamorphic assemblages (e.g. Katagas, 1980). This middle to high-pressure event is geochronologically dated at ca 23 Ma (Seidel et al. 1982). In the South Peloponnese, peak metamorphic conditions for the PQS have been estimated at $400 \pm 50^\circ\text{C}$ and 11-13 kbar by Theye (1988) or $450^\circ \pm 30^\circ\text{C}$ and 17 ± 4 kbar by Theye & Seidel (1991). According to Bassias & Triboulet (1993), in the Taygetos area the maximum conditions of this metamorphism reached temperatures of 400°C and pressures of 10 kbar. P-T conditions during metamorphism of the rocks exposed in the Chelmos window (PQS) are estimated at $375^\circ \pm 25^\circ\text{C}$ and 5 kbar (e.g. Katagas et al., 1991). The exhumation history of the PQS began at the Oligocene-Miocene boundary. At this time, the PQS acted as a ductile shear zone and started to extrude westwards between the «Taygetos-Parnon Thrust», or the «Chelmos Thrust» (see Fig. 1b), and the basement of Tripolitsa-Tyros Zone (Xypolias & Doutsos, 2000; Doutsos et al., 2000). The final effect of this extrusion process was to place the metamorphosed rocks of the PQS in contact with the overlying unmetamorphosed cover nappes along a normal fault (Fig. 1b), but in a tectonic setting without any net extension of the overall system.

3. MICROSTRUCTURES IN THE PQS

Ductile deformation within the PQS produced a penetrative foliation and a well-developed ENE-WSW trending mineral-stretching lineation (Figs. 2, 3) which is defined by streaks of white mica, actinolite and elongated quartz aggregates. Quartz-rich tectonites have undergone extensive dynamic recrystallization and formed well-developed lattice and grain shape preferred orientation patterns, indicating dislocation creep as the dominant mechanism. Shear sense indicators, such as microstructures (oblique grain shape in recrystallized quartzites, mica-fish) and quartz c-axis fabrics, indicate that crystal-plastic deformation within the PQS was associated with top-to-the W-SW sense of shearing (Xypolias & Doutsos, 2000; Doutsos et al. 2000). Samples analysed for this study, from both the Chelmos and Taygetos areas (Figs 1, 2, 3), are composed of quartz as the main constituent with phyllosilicates (white mica and/or chlorite) varying from 5 to 30 modal percent. Microscopic analysis in these samples showed that the dynamic recrystallization of quartz aggregates is controlled by a combination of both progressive subgrain-rotation (SR) and grain-boundary-migration (GBM) recrystallization. Microstructures indicative of SR-recrystallization, such as core-and-mantle structures (White, 1976); and microstructures indicative of GBM-recrystallization, such as grain-boundary-bulging (White, 1976), castellate microstructures, window and dragging microstructures (Jessel, 1987), are observed in the analysed samples, either individually or in combination with the same sample. Summarising, microstructures indicating a coupling of progressive SR- and GBM- recrystallization, specimens having extensive dynamic recrystallization and the present of oblique grain shape in quartzite rocks (see above) may be interpreted as a result of deformation in the dislocation creep regime III or in a transitional dislocation creep regime II and III (Hirth & Tullis, 1992).

4. RECRYSTALLIZED GRAIN SIZE PIEZOMETRY

The differential flow stress in dislocation creep is related to certain microstructural parameters such as recrystallized grain size, sub-grain size and dislocation density. This raises the possibility that the palaeostress of rocks can be estimated from these parameters. In this work, theoretically derived and experimentally calibrated grain-size piezometry of quartz was used to infer the differential flow stress of deforming aggregates assuming steady state dislocation creep. The recrystallized grain size from the 36 selected quartz-rich samples (19 from the Chelmos area and 17 from the Taygetos area, Figs. 2,3) was determined using the Heyn method of linear intercept analysis (see DeHoff & Rheins, 1968). About 500-800 grains were measured in each thin section and the grain size was calculated from the relationship $1.5(abc)^{1/3}$, where a, b and c are the number of grains per unit length on three different traverses across the thin section. Three traverses were chosen parallel, perpendicular and at 45° to the microscopic foliation. Only pure quartz layers were measured, because impurities (e.g. mica) hinder grain-boundary migration and generally produce a smaller stable grain size (Christie and Ord, 1980). To evaluate flow stress, the recrystallized grain size piezometer derived by Twiss (1977) was used, as it is a piezometer most closely matching the newly established laws for quartz aggregates (Gleason and Tullis, 1993). It follows the form:

$$\sigma = A \cdot D^m$$

where σ is the differential stress ($\sigma_1 - \sigma_3$), D is the grain size in mm, and A (=603 MPa) and m (=0.68) are constants (Twiss, 1977).

4.1. RESULTS

The results of recrystallized quartz grain size measurements from 36 samples are given in Figure 4a. Recrystallized grain sizes of all 19 samples from the Chelmos area span the range 30-109 mm (Fig. 4a). However, the values of the grain size obtained can be separated into two major groups. As displayed schematically in Figure 4b, the grain sizes (D) from 13 samples (Group A) are tightly clustered between 30 and 52 mm while in the rest 6 samples (Group B) the values of parameters D appears to be higher and lie in the range of 77-109 mm. Furthermore, it is significant to say that the 13 samples of group A were selected within the lower, more intensely recrystallized levels of the PQS. In contrast, the six samples (FN1, FN2, FN4, FN16, AG1, AG10) of the group B are restricted within a narrow zone close to the contact between the PQS with the Tyros Beds and/or Tripolitza Zone (see Fig. 2). This observation suggests that the samples of group A are more representative and describe more effectively the distribution of the grain size in the PQS than the samples of the group B. The average grain size for group A is of the order of 42 mm. The 17 samples collected from the Taygetos area contain recrystallized quartz grains with a more restricted range of size from 32 to 67 mm; twelve out of 17 are within the range 41-59 mm (Fig. 4c). The average grain size for the Taygetos area's samples is of the order of 51 mm.

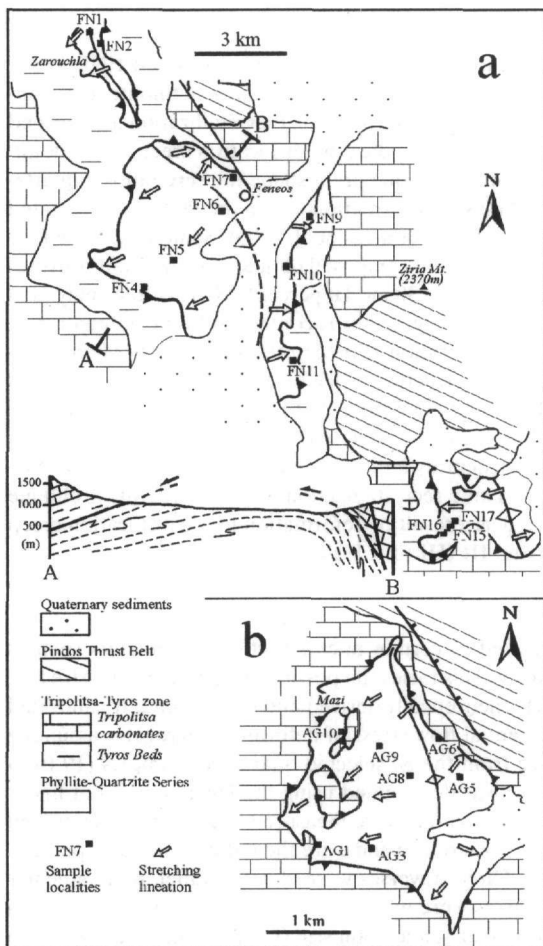


Figure 2. Structural and sample maps for the northern (a) and southern (b) part of the Chelmos window. For the location of the maps see Figure 1.

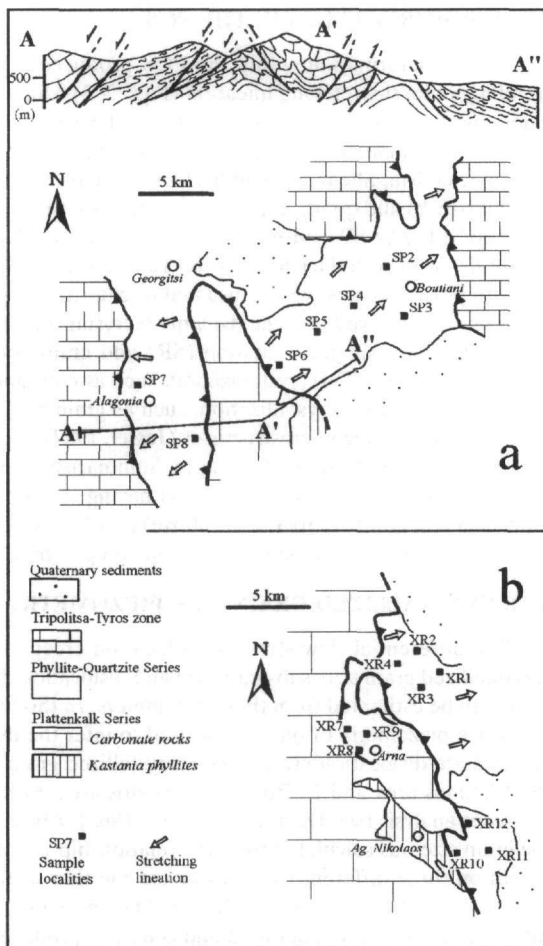


Figure 3. Structural and sample maps for the northern (a) and southern (b) part of the Taygetos window. For the location of the maps see Figure 1.

Based on Twiss calibration, the differential flow stresses implied for the average recrystallized grain sizes 42 mm from the Chelmos area and the 51 mm from the Taygetos area are of the order of 47 MPa and 41 MPa, respectively.

5. ESTIMATE OF STRAIN RATE

Differential flow stresses estimations can be combined with metamorphic temperature estimates to calculate the strain rate during deformation, by using published flow-laws. Flow-laws are derived from laboratory experiments and in some cases it may be justified to extrapolate them to geological conditions. In this work, the flow law for dislocation creep of quartz derived by Paterson and Luan (1990) for low to moderate grade rocks was applied. It has the form:

$$\dot{\epsilon} = A\sigma^n \exp(-Q/RT),$$

with A (pre-exponential factor) = $6.5 \times 10^{-8} \text{ MPa}^{-n} \text{ s}^{-1}$, Q (activation energy) = 135 kJmol^{-1} , R (gas constant) = $8.314 \text{ JK}^{-1} \text{ mol}^{-1}$ and n (stress exponent) = 3.1 ; $\dot{\epsilon}$ denote the strain rate, σ the differential stress and T the absolute temperature. As it has been noted in previous sections, the peak metamorphic temperatures for the PQS in the Chelmos window have been estimated at $375 \pm 25^\circ \text{C}$ (Katagas et al., 1991) while for the same rock unit in the Taygetos window at 400°C (Bassias & Triboulet, 1993). Finally, using the above flow-law, for temperatures

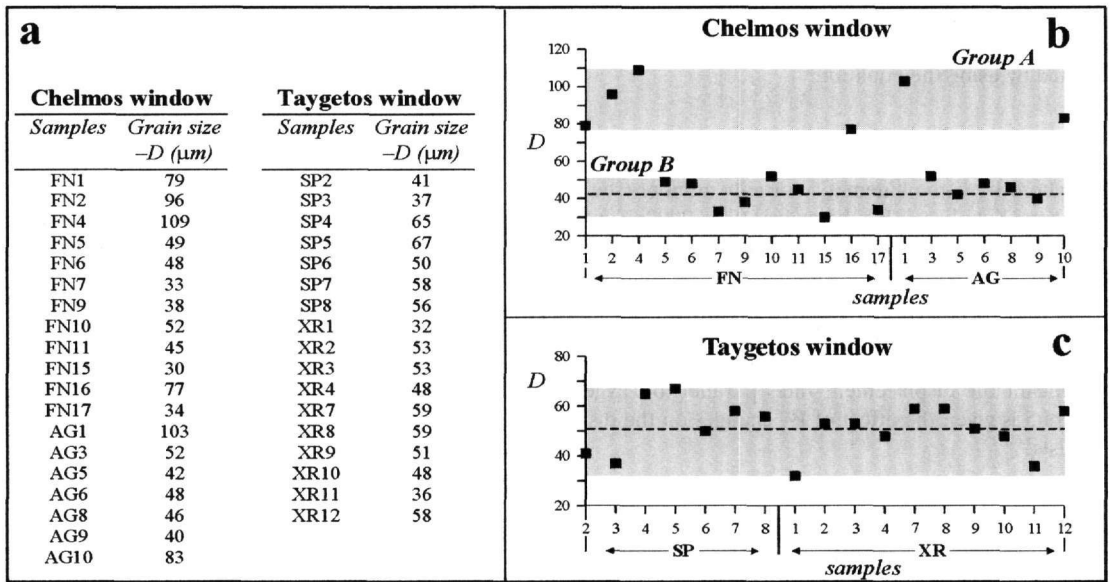


Figure 4. (a) The recrystallized quartz grain size from 36 samples. For sample localities see Figures 2 and 3. (b) Plot illustrating the variations of grain size (D) values vs. samples from the Chelmos window. The shaded areas show the value's ranges for two major groups and the dashed line indicates the average grain size. (c) Plot illustrating the variations of grain size (D) values vs. samples from the Taygetos window. The shaded area shows the value's range and the dashed line indicate the average grain size.

375°C and differential stress 47 MPa, a strain rate of 10^{-13}s^{-1} (or 3.15Ma^{-1}) is calculated for the samples from the Chelmos area. At temperatures 400°C and differential stress 41 MPa, the predicted strain rate for the rocks from the Taygetos area is of the order of $2.1 \times 10^{-13}\text{s}^{-1}$ (or 6.61Ma^{-1}). It should be noted that the observed strain rate values from both areas, lie in the limit of the conventional strain rates range (10^{-13}s^{-1} - 10^{-15}s^{-1}) suggested by Pfiffner & Ramsay (1982). According to the above authors, strain rates faster than 10^{-13}s^{-1} have been expected in mylonite zones.

6. ESTIMATE OF EFFECTIVE VISCOSITY

Estimations of the effective viscosity (η) during ductile deformation of the PQS can be made combining flow stress and strain rate data according to the following relation:

$$\eta = \sigma / 3(d\epsilon/dt)$$

(e.g. Carter & Tsenn, 1987). From the formula it is obvious that derivation of a good estimate of viscosity can be made only if deformation is homogeneous and continuous in time (t). Therefore, a conservative estimation can be given assuming constant strain rate and continuous deformation over a time span of 1 Ma. Consequently, using the observed differential stresses and strain rates values, an effective bulk viscosity for the rocks of the PQS in both windows in the range 10^{20} to $10^{19}\text{Pa} \cdot \text{s}$ is inferred.

7. IMPLICATION FOR THE DISPLACEMENT RATE

Calculations of the displacement rates parallel (V_p) to the Taygetos-Parnon and Chelmos Thrust (Fig. 1), during the tectonic extrusion of the PQS, appears to be possibly if the thickness (h) of the ductile shear zone and shear strain rate (e_s) are known:

$$V_p = e_s \cdot h$$

(e.g. Jiang 1994). Field observations and published geological cross-section from the Peloponnese (e.g. A-

A-A'' in Fig. 3a) and Crete (Kokkalas & Doutsos, 2000) indicate that the PQS has a relatively fixed structural thickness approximately 1000m. According to Weijermars (1998) calculations of shear strain rate can be performed by using the equation:

$$e_s = e \cdot W_k,$$

where W_k is the kinematic vorticity number (see Means, 1994 for review). Considering, recent quantitative analyses (Xypolias & Koukouvelas, 1999, 2000; Xypolias & Doutsos, 2000) showed that ductile deformation of the rocks in the PQS has started with an initially high W_k ($W_k \approx 0.9$) which reduced as deformation proceeded ($0.6 < W_k < 0.4$). Finally, for e of 6.61 Ma^{-1} , W_k of 0.9 and h of 1000m, a displacement rate 5.9 mm/year (or 5.9 km/Ma) parallel to the Taygetos-Parnon Thrust, during the initial stages of extrusion process, is obtained. For e of 3.14 Ma^{-1} , W_k of 0.9 and h of 1000m the displacement rate parallel to the Chelmos Thrust is 2.8 mm/year (or 2.8 km/Ma). However, it is obvious that the progressive decrease of W_k during ductile deformation was affected significant the displacement rates parallel to Taygetos-Parnon and Chelmos Thrusts. In the diagram of the Figure 5 is given the effect of W_k changes on the displacement rates parallel to Taygetos-Parnon and Chelmos Thrusts.

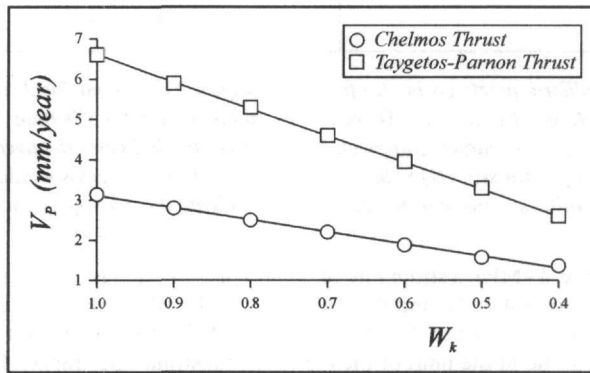


Figure 5. Diagram showing the effect of W_k (kinematic vorticity number) changes on the displacement rates (V_p) parallel to Chelmos and Taygetos - Parnon Thrusts. The ductile extrusion of the Phyllite - Quartzite Series probably starts with an initially high W_k value which reduces as deformation proceeds.

8. CONCLUDING REMARKS

Quartzites from the Phyllite-Quartzite Series (PQS) in the Chelmos and Taygetos tectonic windows (Peloponnese) have average recrystallized grain sizes of 42 mm and 51 mm, respectively. Twiss's (1977) quartz grain-size piezometer suggests that the ductile deformation occurred at differential stresses approximately 40-50 MPa. Extrapolation of quartzite flow-laws indicates that the ductile deformation in the PQS occurred at strain rates slightly faster than 10^{-13} s^{-1} . These stress and strain rate estimates suggest that during tectonic extrusion of the PQS, rocks had a relatively low-viscosity in the range 10^{20} to $10^{19} \text{ Pa}\cdot\text{s}$. Combination of the obtained strain rate values with published quantitative analyses of the rotational and stretch components of deformation indicates that during the initial stage of the tectonic extrusion process, the displacement rates parallel to the Taygetos-Parnon and Chelmos Thrusts were $\sim 6 \text{ mm/year}$ and 3 mm/year , respectively.

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