DYNAMIC CONTROL ON SERPENTINE CRYSTALLIZATION IN VEINS WITHIN SOUTHERN ZAGROS SUTURE ZONE SERPENTINITES, PENJWEEN COMPLEX, NE IRAQ

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ABSTRACT

The Penjween serpentinized peridotites occupy parts of the southern Zagros Suture Zone displaying pseudomorphic and non-pseudomorphic micro-textures, in addition to different types of vein serpentine formation. Serpentinization is accompanied by abundant veining marked by generations of vein-filling serpentines with a high variety of morphologies and textures that correspond to different mechanisms and conditions of formation. The author have selected a representative set of veins from serpentinized peridotite of Penjween ophiolite from different localities and studied them in detail for their microstructures by coupling optical and scanning electron microscopy (SEM) with Back-Scattered electron (BSE) images. Four main veining episodes (V1 to V4) accompany the serpentinization of the oceanic lithosphere of the Penjween serpentinite peridotites. Serpentine microstructures and mineral composition of veins provide information on the relative rates of crack opening, vein mineral precipitation, the crystallization conditions, and the temporal evolution of alteration. The first episode represents vein generation V1 and is interpreted as tectonically controlled penetration of early seawater-dominated fluid within peridotites, enhancing thermal cracking and mesh texture formation. The second episode marks two subsequent vein types (V2 and V3) formed in a closed, diffusive system and accommodated volume expansion required to reach serpentinization of the protolith (Stage 1). The last vein episode (V4) records instead an open hydrothermal system, where brittle fracturing and advective transfer dominated and enabled the completion of serpentinization (Stage 2). These results show a complete history of alteration, with the crystallization of different types of serpentine recording different tectonic events and modes of hydrothermal alteration of the Tethys oceanic lithosphere.

السيطرة الحركية على تبلور السربنتين في العروق ضمن نطاق تلاحم زاگروس الجنوبي السربنتيني، معقد پنجوين شمال شرق العراق

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المستخلص

يشغل بريدوتايت پنجوين السربنتيني جزء من نطاق تلاحم زاگروس الجنوبي ويظهر أنسجة دقيقة ذات تحول كاذب إلى عدم تحول، بالإضافة إلى تكون أنواع متعددة من عروق السربنتين. عملية السربنتنة ترافقت بكثرة العروق بدليل تكون عروق مملوئه بالسربنتين بأشكال وأنسجة مختلفة متكونة بميكانيكيات وظروف تكوين مختلفة. اخترنا مجاميع ذات تمثيل جيد من عروق البريدوتايت السربنتيني العائد إلى أوفيولات پنجوين من مواقع مختلفة وتم دراستها بالتفصيل من ناحية أنسجتها الدقيقة بطريقة المايكروسكوب البصري والمايكروسكوب الماسح ألالكتروني (SEM) وصور التشتت الخلفي (BSE). أربعة مراحل من العروق (V1 – V4) رافقت عملية السربنتنة للقشرة المحيطية

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لبريدوتايت پنجوين السربنتيني. التراكيب الدقيقة والتركيب المعدني للعروق أعطت معلومات عن نسبة انفتاح التشققات وترسب المعادن في العروق وظروف التبلور والتطور الحراري للتغيير. المرحلة الأولى تمثلت في تكون العروق (V1) وفسر على أساس الاختراق الحركي المبكر لمياه البحر الحاوية على المحاليل المرافقة للبريدوتايت. المرحلة الثانية أشارت إلى نوعين لاحقين من العروق (V2 و V3) تكونت في نظام مغلق، منتشر ليتلائم مع التوسع الحجمي المطلوب للوصول لعملية السربنتنة لصخور المصدر(المرحلة الأولى). عروق المرحلة الأخيرة (V4) سجلت عوضاً عن ذلك نظام حراري مائي مفتوح في أماكن سيطرة التكسرات الهشة والتي ساعدت في اكتمال عملية السربنتنة (المرحلة الثانية). هذه النتائج بينت التاريخ الكامل للتغيير مع عملية التبلور للأنواع المختلفة من السربنتين مسجلة أحداث تكتونية مختلفة وأنماط من التغير المائي الحراري للقشرة القارية لمحيط التيثس.

INTRODUCTION

Deformation and hydration processes are intimately linked in the oceanic lithosphere, but the feedbacks between them are still poorly understood, especially in ultramafic rocks where serpentinization results in a decrease of rock density that implies a volume increase and/ or mass transfer (Andreani *et al*., 2007). Serpentinization is accompanied by abundant veining marked by generations of vein-filling serpentines with a high variety of morphologies and textures that correspond to different mechanisms and conditions of formation (Dilek *et al*., 1997 and Andreani *et al*., 2007). Serpentines are tri-octahedral sheet silicates [$Mg_3Si_2O_5$ (OH_4)] that include four main structural types: lizardite (planar structure), chrysotile (cylindrical structure), polygonal serpentine (tubular with a polygonized section) and antigorite (modulated structure) (Wicks and O'Hanley, 1988 and Auzende *et al*., 2003). These various microstructures reflect different wrapping modes of tetrahedral (T) and octahedral (O) sheets in response to their geometrical misfit (Wicks and whittaker, 1975 and Rinaudo and Gastaldi, 2003). Under serpentinization conditions, all serpentines can be found owing to their stability over a wide temperature domain with negligible P dependence (Fig.1). Lizardite and chrysotile form directly from olivine at temperature well below 300^o C (O'Hanely and Wicks, 1995). Antigorite is stable at higher temperature, approximately 250 – < 600° C (Evans, 2004). Recent experimental studies in static hydrothermal systems (Grauby *et al*., 1998 and Normand *et al*., 2002) show that the occurrence of different serpentine (chrysotile and lizardite) are dominantly controlled by the reaction kinetics (Fig.2) rather than by P or T conditions and deformation processes also modify physico-chemical conditions and therefore affect serpentine crystallization (Andreani *et al*., 2004). Serpentine microstructures are thus prospective tools to identify and constrict different deformation and fluid-rock processes (Andreani *et al*., 2007). The Penjween serpentinites of the southern Zagros Suture Zone display pseudomorphic and non-pseudomorphic micro-textures in addition to different types of vein serpentine formation. In the present paper a detailed study of different serpentine veins occurrences within the Penjween serpentinites are presented to constrain the role of deformation and mass transfer processes during hydration of Tethyan oceanic peridotites.

MATERIALS AND METHODS

The serpentinized peridotites samples of the present study which croup out within the Southern part of Zagros Suture Zone were collected in Penjween area near Kani-Mngah, Milakawa and Rawgan villages, NE Iraq. Characterization of different serpentine vein types, their textures, and micro-structures were determined by coupling Optical Microscopy, Scanning Electron Microscopy (SEM) and Electron Probe Micro-analyses (EPMA). SEM images were preformed on a Quanta 400 FP2013/12 Scanning Electron Microscope at Department of Geology, University of Sulaimani under 30 kV acceleration voltages. Micro-analyses of relict minerals, serpentine veins polymorphs were carried out with a JEOL-840A

(WDS-EDS) Scanning Electron Microscope, equipped with an Oxford energy-dispersive detector (EDX) analytical system (Link ISIS series L2001-S) at Osaka Prefcture University. The analyses were performed under 15 kV accelerating voltage and 0.5 nA current beam. Suitable natural and synthetic silicate oxides were used as standards for calibration. The ZAF method was employed for corrections.

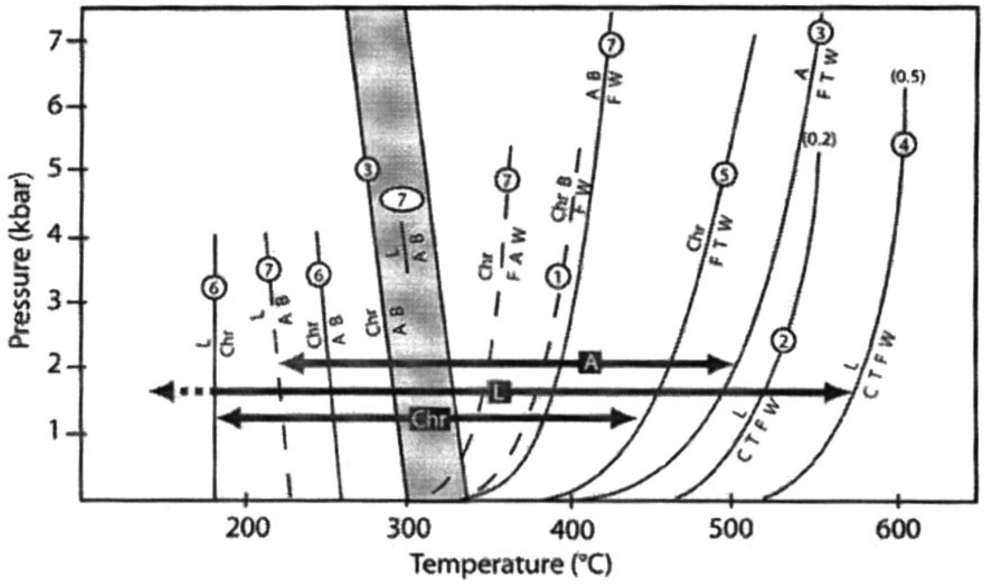

Fig.1: Phase diagram in the MSH system for the three main types of serpentine realized with compiled available data from experimental, theoretical, and natural studies of

1) Johannes (1968), **2)** Chernosky (1973), **3)** Evans *et al*. (1976), **4)** Caruso and Chernosky (1979), **5)** Chernosky *et al*. (1988), **6)** O'Hanley and Wicks (1995), and **7)** Evans (2004). Complementary curves from the MASH system are added (Andreani *et al*., 2007) to represent the enlarged stability field of Lizardite as a function of its Al content, given in X_{Al} by the number in brackets (X_{Al} = 0.2 is equivalent to Al_2O_3 = 3.7 wt% and X_{Al} = 0.5 is equivalent to Al_2O_3 = 9.2 wt%). A, Antigorite; B, brucite; C, chlorite; Chr, chrysotile; L, lizardite; F, foresterite; T, talc; W, H_2O)

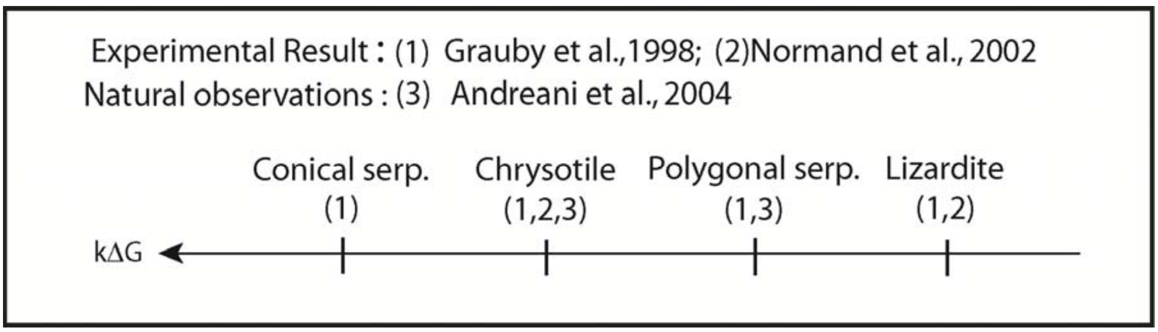

Fig.2: Role of kinetic effects on microstructure crystallization in serpentine synthesis (Grauby *et al*., 1998) and olivine dissolution (Normand *et al*., 2002) experiments compared to available natural observations (Andeani *et al*., 2004)

GEOLOGICAL SETTING

The Zagros Suture Zone (ZSZ) which was formed as a result of two distinct phases of subduction and collision, during the Late Cretaceous and Mio-Pliocene respectively between the Arabian passive margin and the Iranian microcontinent active margin formed a 5 – 70 Km wide belt along the Iraqi-Iranian borders (Jassim and Buday, 2006). This Zone is characterized by tectonic units of thrust sheets. The tectonic units (Zones) comprise from the outer part of the Suture Zone inwards: Qulqula – Khwakurk, Penjween – Walash, and Shalair (Aswad, 1999 and Jassim *et al*., 2006). The Southern part of this zone (Penjween area) is characterized by occurrence of two distinguishable serpentinized peridotites (Fig.3). The first type, which is associated with ophiolites, includes serpentinite broken formation (massive blocks of metabastite enclosed in a matrix of serpentinite schist) of 80 – 110 Ma (Aziz *et al*., 2011). The second type has drastically different petrogenesis, age and regional field relationships, consists of exotic blocks of mixed age (150 and 200 Ma) (Aziz *et al*., 2011). The presence of two groups of distally-separated serpentinites with different emplacement-age and fore arc tectonic affinity could indicate that the closure of Tethys culminated in two fortuitous subduction processes (Aswad *et al*., 2011).

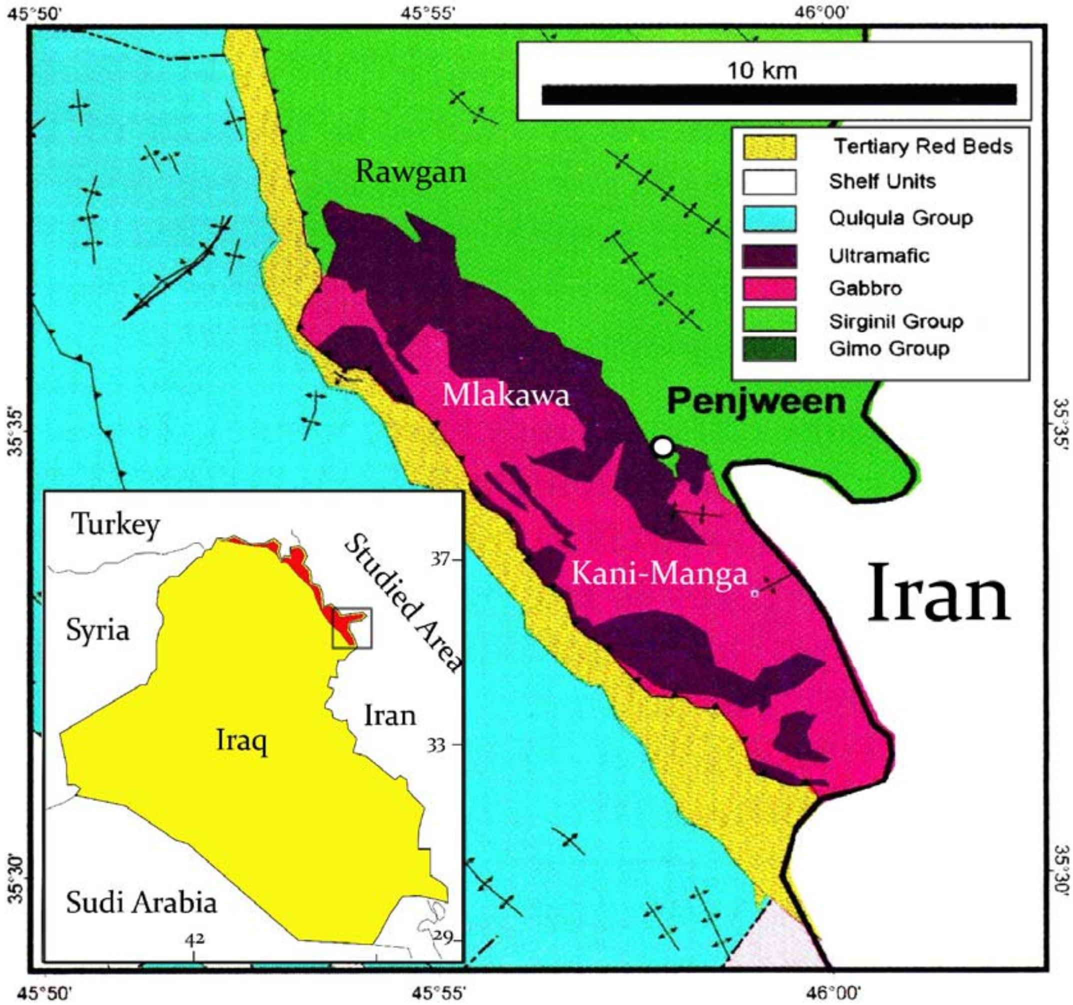

Fig.3: Geological map of Penjween igneous complex showing the location of the studied area (after Buday and Goff, 2006)

MINERALOGY

The mineral assemblages of serpentines and the vein-serpentine polymorphs in the Penjween serpentinites were determined by petrography, XRD and scanning electron microscope techniques. The serpentinites reveal relict olivine, pyroxene, and spinel with metamorphic assemblage amphibole, chlorite, carbonate and talc, as well as variable proportions of a predominantly serpentine polymorph (lizardite, chrysotile, and antigorite). The serpentine group minerals in the massive serpentinites consist of lizardite-chrysotile association. Lizardite itself may be replaced by chrysotile in massive serpentinite occurrences and by antigorite in the shared type serpentinite forming serpentinite schist (antigorite schist) of Penjween. Chrysotile is found in a cross-fiber veins representing a two-stage process of cross-fiber formation marked by clinochrysotile formation along the wall of the vein (Fig.4A), followed by clinochrysotile-lizardite intergrowth that occupies the entire width of the vein (Fig.4B). Most sheared serpentinites are composed of platy antigorites with shape-preferred orientation indicative of antigorite schist (Fig.4C). Relict olivine occurs as porphyroblasts in partly serpentinized samples (Fig.4D), while in mylonitized serpentinite of Penjween area, it occurs as elongate grains. Orthopyroxenes retain their original shape, relict orthopyroxene grains occur as elongate porphyroclast (Fig.4E) or as aggregates of deformed crystals and they retain the altered exsolution lamellae. Clinopyroxene grains usually occur as porphyroclasts or as subhedral crystals in serpentinites whose protolith is lherzolite. Generally, the serpentinization of Penjween serpentinite is accompanied by the formation of magnetite heterogeneously distributed within the mesh textures. Magnetite in serpentine is predominantly secondary and is a by-product of either formation from chromite alteration or from alteration of olivine and orthopyroxene, which form discontinuous veinlets of magnetite (Aziz, 2008 and Mohammad, 2009) and conjunction with BSE imaging, from core to rim, three spinel stages have been recognized: the residual mantle stage, a Cr-rich stage and a third stage showing a very narrow magnetite rim (Fig.4F). These three stages are represented by primary Cr-spinel, pre-serpentinization- metamorphosed spinel and syn- or post-serpentinization spinel, respectively (Aswad *et al*., 2011). Chlorite either encircles the chromain spinel or present as inclusions within the ferritchromite (Figure 4G). Calcite occurs as a vein mineral, surrounded by brecciated serpentine grains and as replacement (Fig.4H). The association of calcite and serpentine is referred to as ophicalcite (Lemoine, 1980 and Lemoine *et al*., 1987). These mineralogical assemblages indicate that the original ultramafic protoliths are harzburgite, dunite and to a lesser extent lherzolite which was serpentinized under green schist to amphibolite facies (Aziz, 2008).

SERPENTINE MICROTEXTURES: PSEUDOMORPHS AND VEINS

▪ Mesh (or Hourglass) and Bastite Textures

The main hydration textures in the Penjween serpentinites are pseudomorphic Mesh (or hourglass) and Bastite textures after olivine and pyroxene, respectively, and represent the bulk of lithosphere alteration in volume (Andreani, 2007 and Azer and Khalil, 2005). These textures are characteristics of oceanic hydration under static conditions (Wicks and whittaker, 1977 and Dungan, 1979). The Mesh texture shows dark isotropic (magnetite) cores, sometimes the mesh center (cores) consist of relict olivine surrounded by a rim (cords) consisting of lizardite (Fig.5A). No brucite was clearly identified in these serpentinites, thus the major serpentinization of olivine to produce serpentines and magnetite is:

1) $6(Mg, Fe)_2 SiO_4 + 7H_2O = 3(Mg, Fe)_3 Si_2O_5(OH)_4 + Fe_3O_4 + H_2$

Olivine + water = serpentine (mesh) + magnetite + hydrogen

H- Calcite occurs as a vein mineral (200 μm)

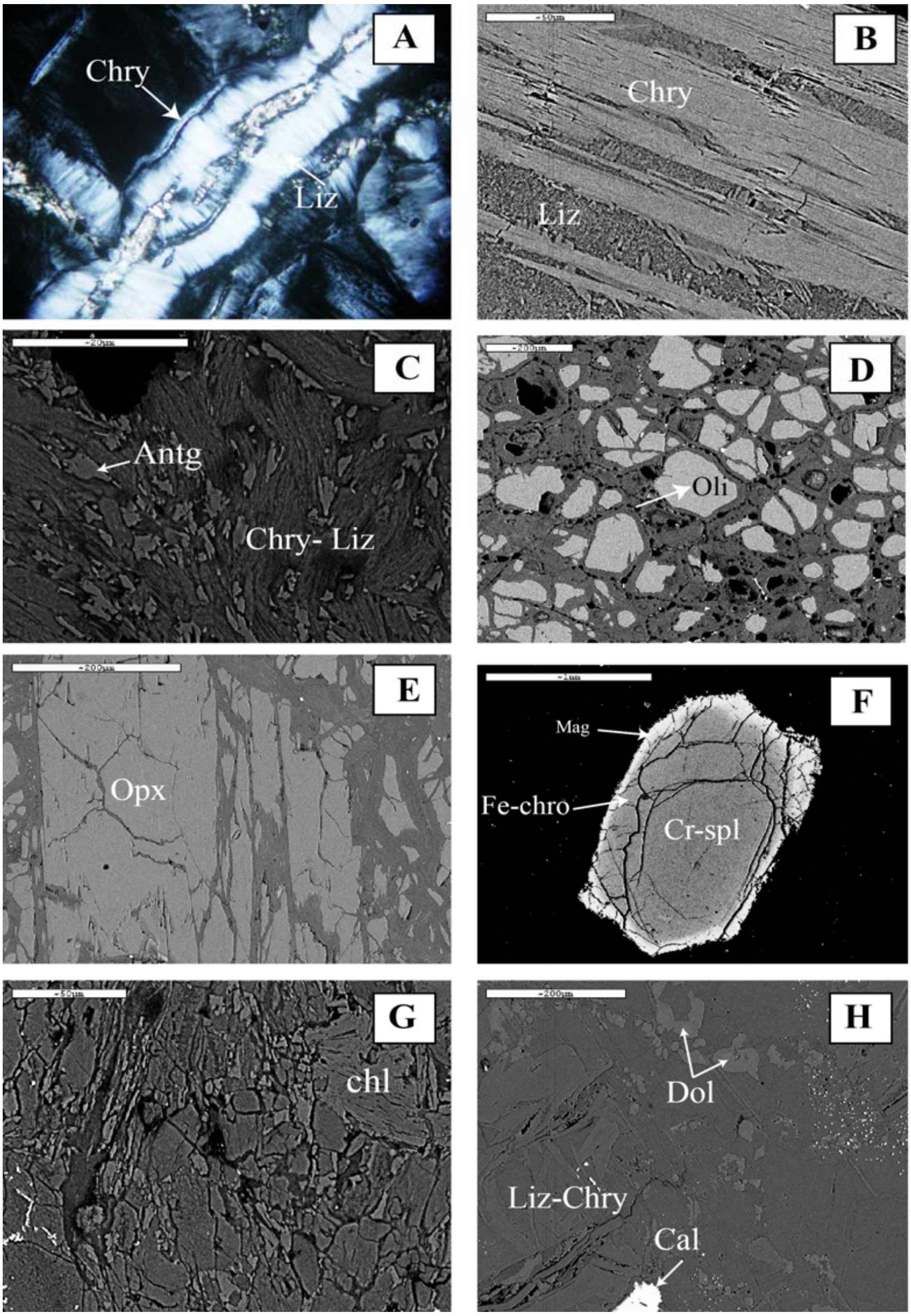

Fig.4: Penjween vein serpentine (mineral abbreviation from Kertz, 1983)

A- Photomicrograph of Clinochrysotile formation along the wall of the vein (40X)
B- Photomicrograph of Clinochrysotile-lizardite intergrowth (50 µm)
C- Photomicrograph of planner antigorite and fibrous chrysotile (20 µm)
D- Back-scattered electron image of porphyroblasts of relict olivine (200 µm)
E- Back-scattered electron image of orthopyroxene (200 µm)
F- Cr-spinel grain (1 mm)
G- Chlorite as inclusions within the ferritchromite (50 µm)

Hourglass textures are restricted to pyroxene rich serpentinites. This type of texture is related to the fracture in the mineral grains rather than grain boundaries; Hourglass texture is similar to mesh texture, but a distinction between mesh rim and mesh center is not possible, it consists only of mesh rim that extends to the center of the cell (Fig.5B). Bastite textures usually take up the shape of the replaced mineral (serpentine), however, sometimes, they show an irregular shape, which may be the result of later deformation (Li *et al*., 2004). Hydration of pyroxene produces silica and should favor the formation of talc and/ or tremolite (Allen and Seyfried, 2003). Some orthopyroxenes (bastites) are composed of small sheets of fine serpentine. In agreement with bulk rock data, the limited occurrence of clinopyroxene relics and bastites in thin sections of the serpentinite confirms an olivine-rich harzburgitic rather than a lherzolitic protolith. The exclusive formation of serpentine from orthpyroxene is:

2) $3(Mg, Fe)\,SiO_3 + 2H_2O = (Mg, Fe)_3\,SiO_5(OH)_4 + SiO_2$
Orthpyroxene + water = serpentine (bastite) + Si released in the fluid phase

Magnetite is ubiquitous in all serpentine products. The majority of magnetite occurrences in the studied samples are predominantly secondary formed by two processes during serpentinization. First is syn-serpentinization magnetite grains formed as a product of alteration of olivine, in which the iron content of olivine mineral is frequently replaced by magnetite which occurs as fine dusty material, stringers, small discontinuous veinlet along mesh lines (Fig.5C), and train of grains outlining olivine pseudomorphs, and also occurs as dense aggregates within mesh cores; the second is pre-serpentinization magnetite produce a very narrow rim occupying the outermost of rimmed primary Cr-spinel (Fig.5D).

- **Non-pseudomorphic Microstructures**

Non-pseudomorphic (interpenetrating and interlocking) textures are very common in the Penjween serpentinites. Interpenetrating textures consist of elongated interpenetrating blades of serpentine across previous serpentine generations and textures (Wicks and O'Hanley, 1988, and O'Hanley and Wicks, 1995) and mostly appear in extensively serpentinized rocks in which elongate, interpenetrating blades of serpentine replace pseudomorphic serpentine (Fig.5E), while sheared type of serpentinite is characterized by interpenetrating (tiger-skin) texture. An increasing degree of recrystallization during serpentinization processes correlates with more and increasingly heterogeneous distribution of magnetite, serpentinites which exhibit completely recrystallized interpenetrating textures suggest a stage to be the result of complete annealing during late stages of the metamorphic evolution (Li *et al*., 2004).

Interlocking textures consist of more equigranular grains of serpentine and may consist of a combination of lizardite, chrysotile and antigorite (Wicks and O'Hanley, 1988 and O'Hanley and Wicks, 1995). Most Penjween serpentinites show interlocking textures, in which more or less equant serpentine grains and/ or serrate serpentine veins (chrysotile) replace pseudomorphic serpentine (Fig.5F).

- **Veins**

In addition to the typical and well-studied pseudomorphic (Mesh, Horglass and Bastite) and Non-pseudomorphic (Interpenetrating and interlocking) textures, four main type of serpentine veins were identified based on textural and morphological criteria under optical microscope with crossed polarized light. The identification of serpentine polymorphs and their associations in veins was accomplished by electron microscopy imaging. The SEM images of vein filling show the irregular thicknesses of bands ranging from 10 µm to > 50 µm (fig.6A).

─ **V1 Vein Type:** V1 veining occurs in almost all samples independent of the overall degree of serpentinization, V1 veins show an regular shape, with width between a few to 100 of micrometers (fig.6A). In the extensive serpentinized samples, Lizardite [SEM images show the planar structure (Fig.6B)] are replaced by chrysotile. The V1 veins are cross-cut by the other vein types, V2 through V4. The main feature of V1 veins is a high magnetite concentration in clusters along the vein wall (Fig.7A). Magnetite is also abundant as isolated micrometric grains within the vein centers (Fig.7B). SEM images reveal that V1 veins are mainly filled by a homogenous, microgranular material in which spherical areas of several micrometers in diameter develop locally (Fig.6C). The homogeneous material is made of conical chrysotile up to 50 µm in diameter.

─ **V2 Vein Type:** V2 veins are lens-shaped and occur both as interconnected and isolated features. They reach to several cm in length and a few mm in width (Fig.7C). V2 veins are mainly observed within the olivine pseudomorphs where they tend to follow ancient olivine outlines (Fig.7D). They also cross-cut pyroxene crystals when properly oriented or they bypass the pyroxenes when crystals are not properly oriented. Iron oxide alignments are generally observed along one of the vein walls, with elongated oxide grains parallel to the fibers locally incorporated within the vein. SEM images of V2-type show that the V2 type veins are filled by nanotubes of chrysotile with a diameter > 50 µm, that are continuous and span the vein wall (Fig.6D).

─ **V3 Vein Type:** The V3 veins are lens-shaped and not necessarily interconnected, in contrast with the V2-type veins. Their length is variable; they can be a few mm to few cm long. They show silcken-fibres recording a shear component of deformation during this veining event. Under crossed-polarized light, V3 veins are characterized by a banding parallel to vein edges (Fig.7E). The bands correspond to the discrete infill of a protoserpentine + chrysotile + polygonal serpentine assemblage; displaying an overall preferred orientation perpendicular to the local vein wall.

─ **V4 Vein Type:** The last vein generation V4, is distinguished from the earlier ones by being smooth with irregular walls and non-fibrous, their width is irregular, ranging between tens of µm to tens of mm. sometime they appear as isolated veins locally cutting the cross the thin section. Matrix fragments are locally trapped within the vein by crystallization sealing. V4 veins are filled with carbonates, which represent late stage alteration (Fig.7F).

DISCUSSION

▪ Serpentine Crystallization During Vein Formation

The formation of a vein requires three successive stages: (1) a space opening at a rate that is linked to the stress/ strain regime; (2) a transfer of elements to the vein in the presence of a fluid; and (3) a vein-filling episode of mineral crystallization (Andreani *et al*., 2007). The first stage of veining (V1) in Penjween serpentinite peridotite is characterized by an iron-rich fluid, as indicated by the formation of iron oxide along theses veins (formed within the mesh textures) and is mainly associated with the hydration of olivine to form serpentine as in reaction (1). In mesh rims, lizardite mimics olivine outlines in all space directions, suggesting that the alteration process involved very low water/ rock reaction (e.g., Viti and Mellini, 1998 and Baronnet and Boudier, 2001). The second phase of veining (V2), is characterized by homogeneous diameter and the continuity of cylindrical chrysotile fibers, suggesting a single

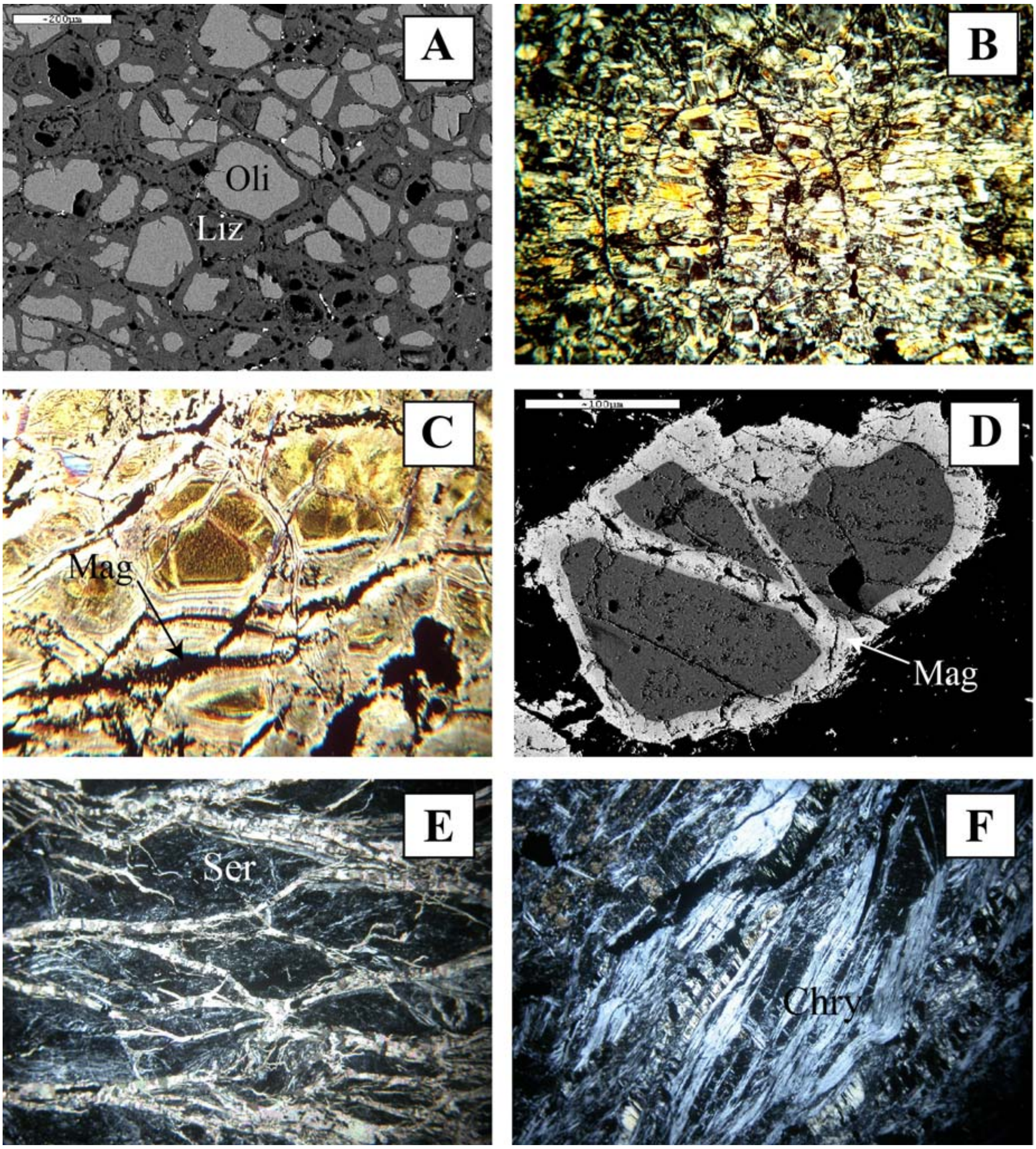

Fig.5:

A- Back-Scattered Electron Image of mesh texture (200 μm)
B- Photomicrograph of hourglass texture (40X)
C- Photomicrograph of discontinuous veinlet of magnetite along mesh lines (40X)
D- Cr-spinel grain surrounded by a rim of magnetite (100 μm)
E- Photomicrograph of tiger-skin texture of sheared serpentinite (40X)
F- Chrysotile replaces pseudomorphic serpentine in vein (40X)

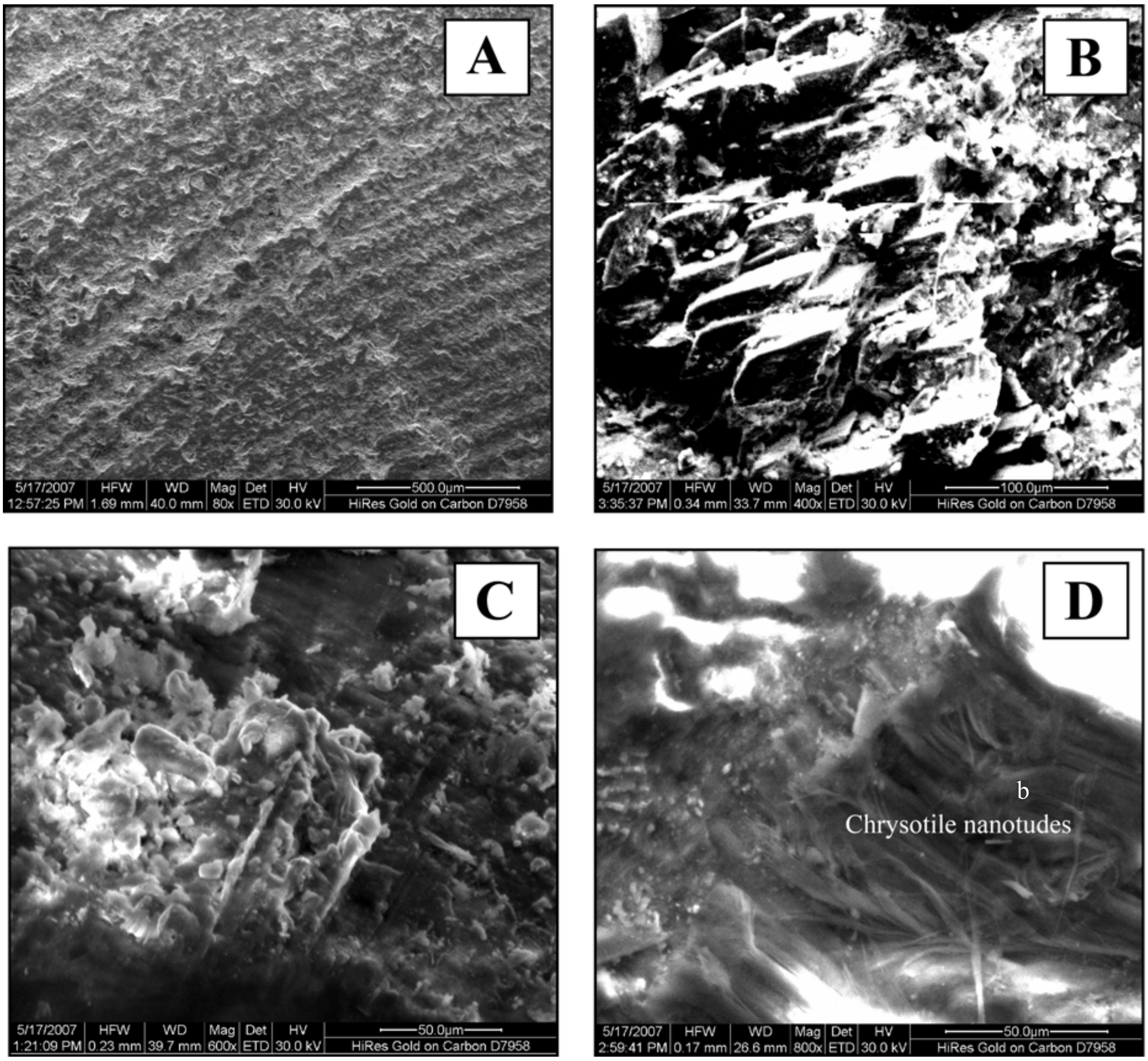

Fig.6: SEM images of the Penjween serpentine veins

A- Low magnification SEM image of vein filling
B- Lizardite planar structure
C- The inner structure of V1 veins
D- V2 type veins filled by nanotubes of chrysotile

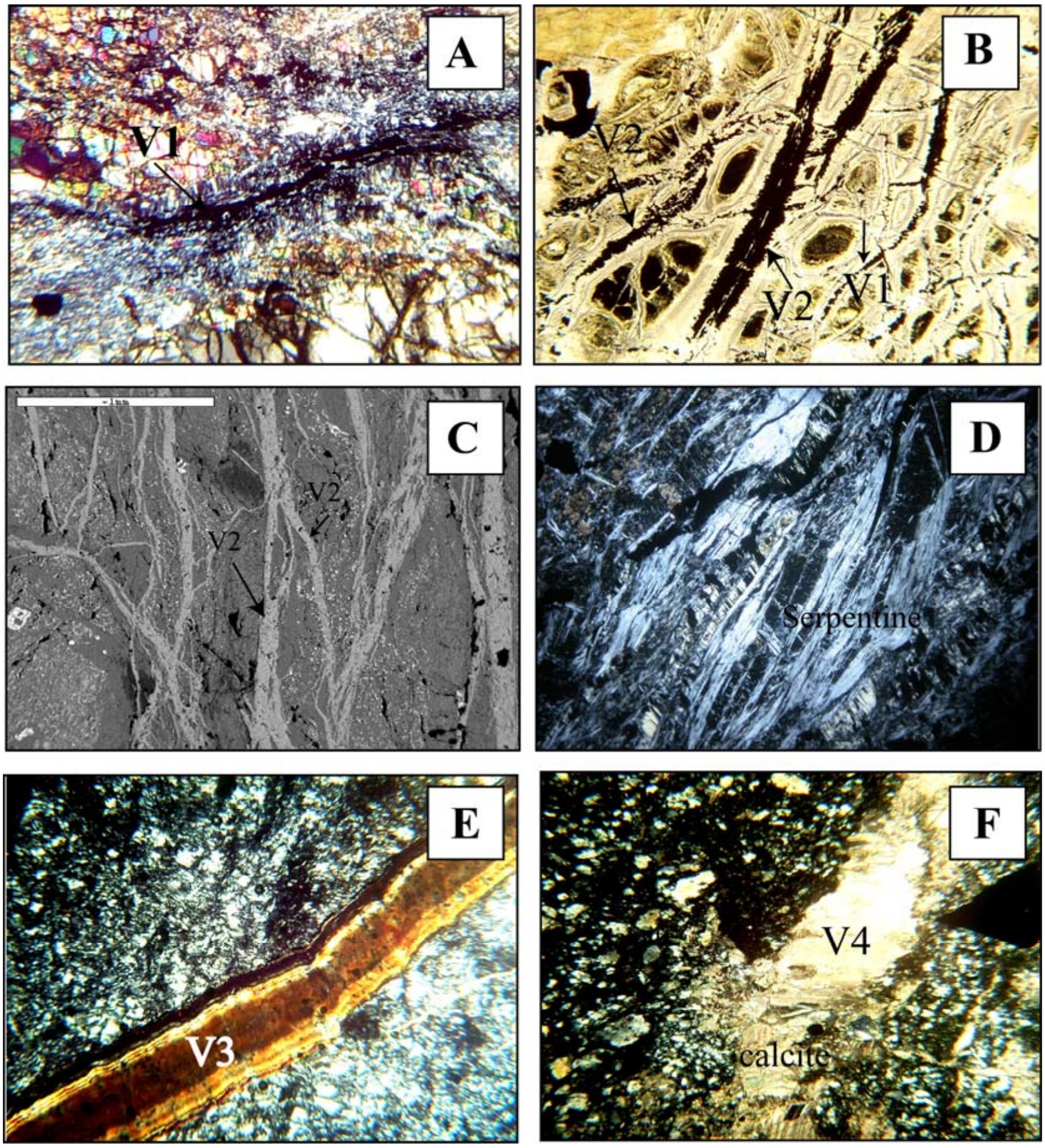

Fig.7:

A- Photomicrograph of V1 veins with high magnetite concentration in clusters along the vein wall

B- Photomicrograph of isolated micrometric grains of magnetite in the vein centers

C- Back-scattered image of V2 veins lens-shaped

D- Photomicrograph of V2 veins observed within the olivine pseudomorphs where they tend to follow ancient olivine outline

E- Photomicrograph of V3 veins

F- Photomicrograph of V4 vein type

episode of nucleation followed by a continuous growth in length occurring under a constant supersaturation (Andreani *et al*., 2007). These microstructures require a constant vein opening velocity equal or slower than the process responsible for both the supply of vein infill material and fiber growth (Hilgers *et al*., 2000 and Koehn *et al*., 2000). The banding observed in V3 veins indicates a series of discrete incremental opening, instead of a continuous one. Each micro-interstice opening is marked by a new nucleation stage of a poorly crystallized phase (Andreani *et al*., 2004). The V4 veining episode appears to corresponded to a different fluid circulation and alteration regime, named Stage 2, V4 formation requires a change in ambient conditions to produce a first stage of serpentine wall dissolution (undersaturated fluid) and a second stage favoring serpentine crystallization in veins (supersaturated fluid).

- **Problem of Volume Expansion**

Serpentinization of peridotite decreases their density. The average density of a peridotite is 3.3 g/cm^3 whereas the average density of a serpentinite is 2.6 g/cm^3 (Deer *et al*., 1966). On the basis of these average densities, it can be estimated that, under a mass-conservative system, 100% serpentinization results in approximately 27% volume increase. Alternatively, serpentinization may occur under a volume-conservative system, in which case some element has to be removed to decrease the rock density. Whether serpentinization occurs at constant mass or constant volume has been largely debated in the literature (e.g., Thayer, 1966; Hostetler *et al*., 1966 and O'Hanley, 1992). In highly altered rocks, it is difficult to reconstruct the mode and composition of the initial peridotite. Moreover, the composition of the reacting fluid phase is essentially unknown. As consequence, the volume problem is generally ignored and the serpentinization reactions are written assuming mass conservation (Andreani *et al*., 2004). In the case of the Penjween serpentinites, the microstructures in serpentine veins record two main stages of alteration: Stage 1 occurs in a closed-diffusive system with pervasive arrival and limited convection (V1 to V3); Stage 2 occurs in an open system characterized by fluid convection in localized pathways (V4). The absence of grain-scale strain related to volume expansion during serpentine growth in the studied Penjween serpentinites suggests that serpentinization is isovolumic during both stages. This agrees with pervious microstructural observations in the Oman ophiolite and elsewhere (Baronnet and Boudier, 2001 and O'Hanley, 1992).

- **Model of serpentine vein formation**

A summary of microstructural observations within the Penjween serpentinized peridotites and their interpretation in terms of deformation style and mass transfer process along with the veining chronology is proposed in Figure (8). In veins, crystallization kinetics are affected by the deformation rate, which controls the opening rate, the water-to-rock ratio, and mass transfer processes. The different variety of serpentine observed in the Penjween serpentine veins clearly underlines the role of deformation and system of dynamics on the local departure from equilibrium and consequently on the relative occurrence of serpentine types. Two stages of alteration and veins formations were recognized within the Penjween serpentinite. Stage 1 is characterized by the formation of V1 to V3 vein that generate new volume and may acts as a sink for excess elements in which the transfer distance is limited and serpentinization may therefore be mass conservative at the scale of outcrops. During stage 2 (formation of V4), the excess matter can be removed by fluid convection in an open system and serpentinization can be completed. In stage 2, elements may be transported over larger distances and even leave the system.

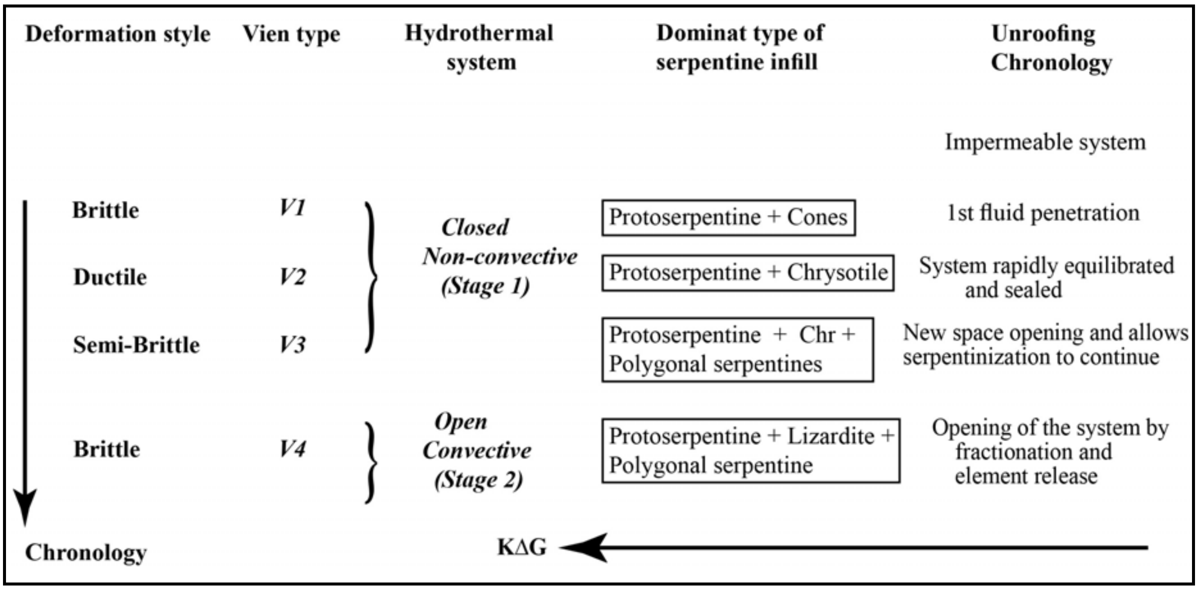

Fig.8: Summary of the structure and mineralogy and proposed model of serpentine vein formation

CONCLUSIONS

- The variability of serpentine microstructures in veins under electron microscope reflects their textural variability. This variability suggests different mechanisms of vein formation that should follow different stages of fluid/rock interaction in peridotites.
- Four veining phases associated with the serpentinization of the oceanic lithosphere at the Penjween serpentinite peridotites were identified. Serpentine microstructures and the mineral composition of theses veins provide information on the relative rates of crack opening, vein mineral precipitation, the crystallization conditions, and the temporal evolution of alteration.
- The fist three vein phases (V1 – V3) are associated with the serpentinization by accommodating the volume expansion required within a closed system, where local mass transfer and diffusion processes dominate (Stage 1).
- The last vein episode (V4) records instead an open system of hydrothermal circulation that enables transport of an excess of elements from hydration reactions and permits full serpentinization (Stage 2).
- Further identification and quantification of theses processes are required to fully understanding the evolution of the alteration of the oceanic lithosphere in Penjween Ophiolite complex and the associated changes in chemical and physical properties.

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