Fluids drainage along detachments: the West Cycladic Detachment System and synkinematic skarns on Serifos Island (Cyclades, Greece)

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Introduction

The Aegean back-arc domain results from the collapse of the Hellenides, driven by an acceleration of slab retreat at 30-35 Ma (Jolivet and Faccenna, 2000). During this extensional period, exhumation of metamorphic core complexes and emplacement of syn-tectonic plutons occured below large crustal-scale shallow dipping shear zones and **detachments**, in their footwall such as **the West Cycladic Detachment System** (WCDS) (Jolivet et al., 2010; Lecomte et al., 2010 ; Iglseder et al., 2011 ; Grasemann et al., 2012).

Isotopic studies have shown that the **fluids** present in the **detachments** and their footwall contain a large proportion of **surface-derived fluids** that invade the crust along these **preferential drains** (Famin 2003). Associated with magmatic events, the drainage of fluids can cause the formations of mineralization, including **skarns**.

Skarns can form during contact metamorphism and from a variety of metasomatic processes involving fluids of magmatic, metamorphic, meteoric or marine origin. They are found adjacent to plutonic intrusions, along faults and major shear zones (Meinert, 1992).

In general, regional tectonics is often neglected of the mineralogical and metamorphic study of skarns and rare are the studies including the dynamic part of the emplacement history. Because of its exceptional outcrops, Serifos is a good example to study links between skarns, intrusions, and detachments.

I. Geological settings

- Serifos is located in the **Aegean Sea** in the western part of the Cyclades archipelago, 100km SSE of Athens
- The island of Serifos is interpreted as an **MCC** exhumed below the **WCDS** (Grasemann and Petrakakis, 2007), intruded by a **I-type granodiorite intrusion**.
- The magmatic body is hosted in three tectono-metamorphic units:

(1) the **Cycladic Continental Basement** composed of gneiss and massive mylonitic schists, less than 200 m thick, covered with calcite and dolomite mylonitic marbles.
(2) the **Cycladic Blueschists Unit** is composed of amphibolites at the base overlain by green-schist with marble intercalations.
(3) the **Upper Cycladic Unit** is composed of marble and ankeritised protocataclastic shales. In the peninsula of Kavos Kiklopas in the SW of Serifos a 10 meters thick serpentinite lense is exposed.

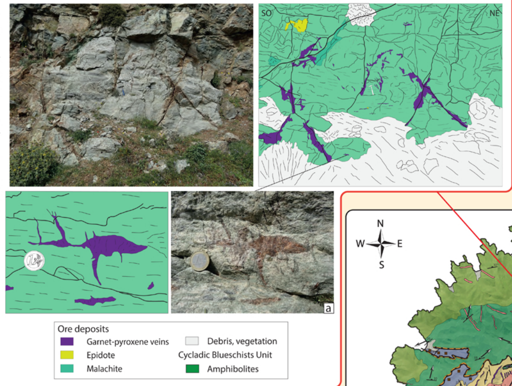
- These units are separated by **two detachments** which both show **top-to-the SSW kinematics**. The Continental Cycladic Basement Unit-Cycladic Blueschists Unit contact crops out very well around Meghàlo Livadhi Bay and Cycladic Blueschists Unit-Upper Cycladic Unit interface intersects the Kavos Kiklopas and Platy Yialos peninsulas

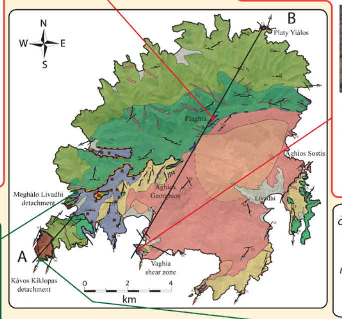
II. Petro-structural study of skarns

2) Garnet-pyroxene exoskarns at Plaghia

High temperature skarns

Fissural garnet-pyroxene skarns appear in the basement along the northern edge of the granodiorite.
It is characterized by the presence of numerous garnet-pyroxene veins in amphibolites belonging to Cycladic Blueschists Unit.
Most veins show a core of anhedral brown andradite with thin rim of bottle green hedenbergite, with a granoblastic texture.
Some horizontal veins also have vertical apophyses that cut the mylonitic foliation (a). Other veins are exclusively filled with pyroxene (b).





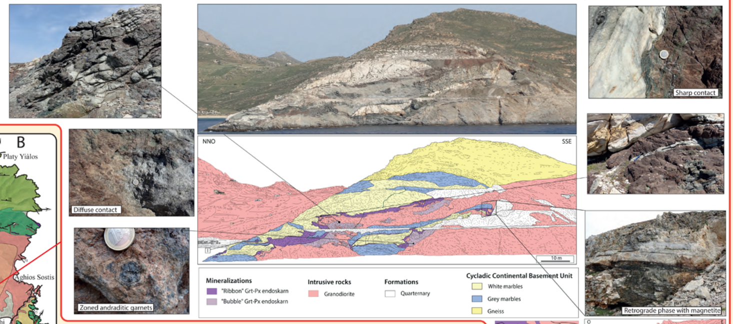
3) Garnet-pyroxene endoskarns at Vaghia Bay

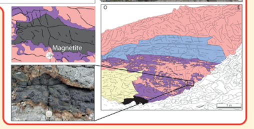
High temperature skarns

Endoskarns is represented which mainly consists of garnet- and pyroxene, specifically isotropic andradite and hedenbergitic clinopyroxene, where the granodiorite intrudes the Cycladic Continental Basement Unit marbles and gneiss. It mainly consists of garnet- and pyroxene, specifically isotropic andradite and hedenbergitic clinopyroxene. The Vaghia outcrop is characterized by the presence of a ten-meters thick granodiorite sill intruding an alternation of relatively pure gray and white marbles. The Vaghia endoskarns occurs in two facies :

1) The «bubbles» endoskarn

2) The «ribbon» endoskarn



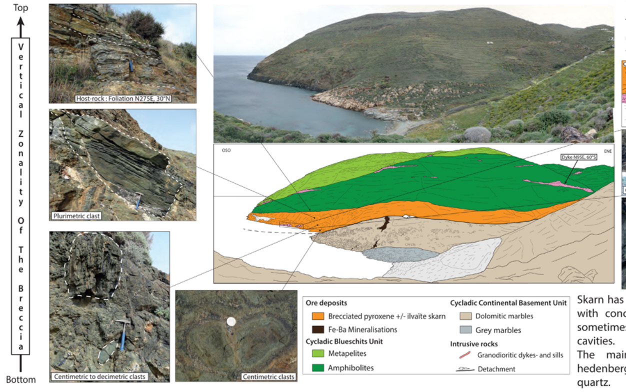


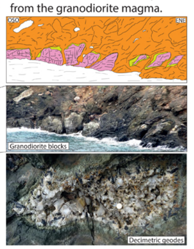
4) Regional level of brecciated pyroxene +/- ilvaite skarn in Meghàlo Livhàdi Bay

The brecciated pyroxene +/- ilvaite skarn outcrops at the hanging wall of Meghàlo Livadhi detachment at the Cycladic Blueschits Unit amphibolites - Cycladic Continental Basement Unit marbles interface. It has the characteristics of a breccia with blocks of various sizes, up to several meters, and reaches a thickness of up to 30 m.

Medium temperature skarns

The formation of this regional level of brecciated skarn is inseparable from the granodiorite magma.



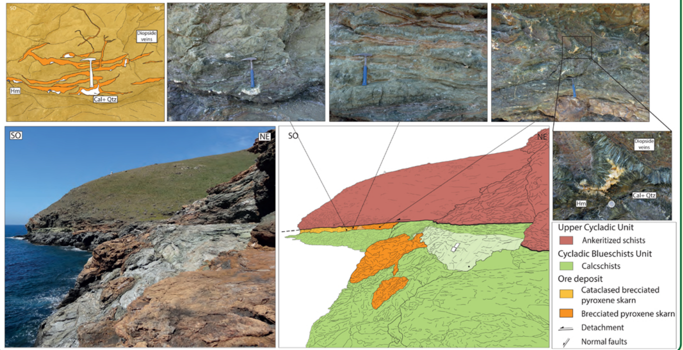


Skarn has the morphology of a cokade breccia, with concentric coronae around large clasts sometimes plurimetric and around geodes and cavities.
The main prograde paragenesis includes hedenbergite, ilvaïte, epidote, calcite and quartz.

4) Brecciated skarn at Cape Kavos Kiklopas

Medium temperature skarns

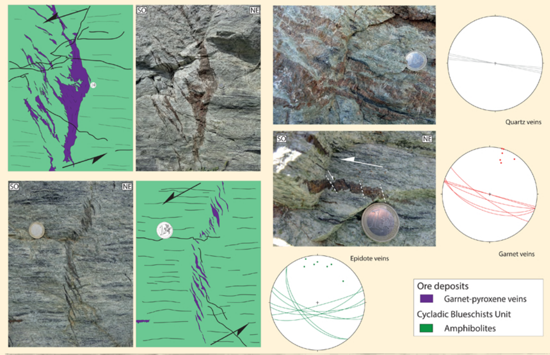
The skarns morphology present on Cape Kavos Kiklopas is similar to that of brecciated pyroxene +/- ilvaite skarn observed near Meghàlo Livadhi. However, the extension of this skarn is much more limited, only a hundred meters wide and 3-5 meters thick. This skarn, which is structurally the highest, is at the footwall of the Kávos Kiklopas detachment and is limited to the north by a steep normal fault.



III. Deformation of Serifos skarns

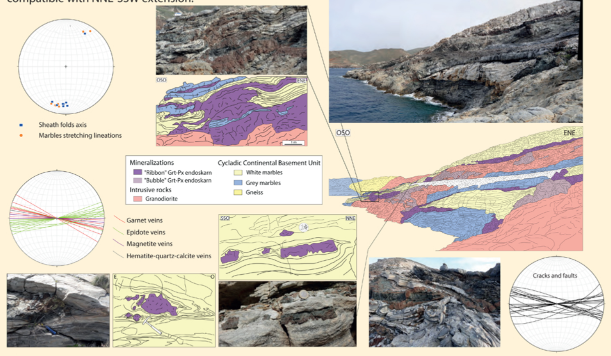
1) Plaghia, north of the granodiorite

Some veins show a systematic en-echelon pattern, antithetic shearing and vertical cracks compatible with NNE-SSW extension.



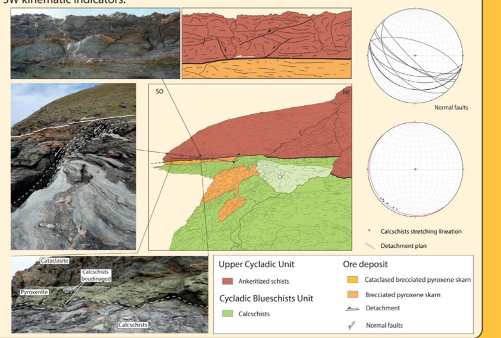
2) Cape Vaghia

The Vaghia outcrop characterized the presence of the endoskarn is one of the most deformed outcrops on the island, compatible with NNE-SSW extension.



3) Kavos Kiklopás cape

The detachment is marked by deformation evolving from ductile-brittle to brittle. It is characterized by a low dip of 5° to the SW. Calcschists and ultramylonitic marbles present just below the detachment exhibit an intense stretching lineation trending NE-SW, with top-to-the SW kinematic indicators.

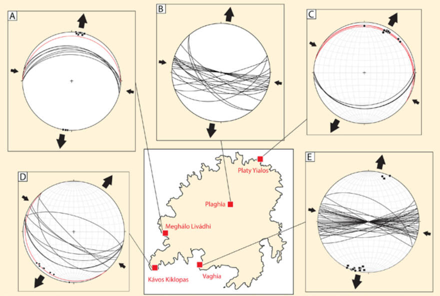


4) Meghalo Livádhi bay

The brecciated pyroxene +/- ilvaite skarn shows no deformation after its formation. Within the cokade breccia, blocks and clasts show a strong disparity in the foliation attitude implying that they have freely rotated within the breccia during the formation of skarn.

5) Synthesis of finite strain

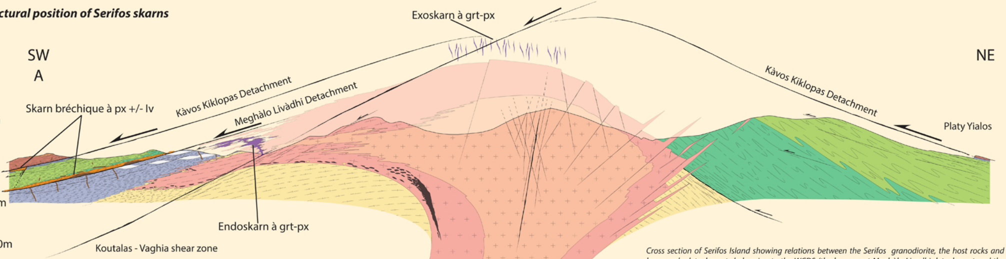
A slight difference in the orientation of the finite strain axes is observed between the two detachments. The Vaghia and Plaghia outcrops suggest a shearing direction with a kinematic top to the SSW, as for Meghálo Livádhi detachment.



Synthesis of all structural data and determining the orientation of axes of the finite strain for the two detachments and principal outcrops of skarn.

IV. Discussion and Interpretations

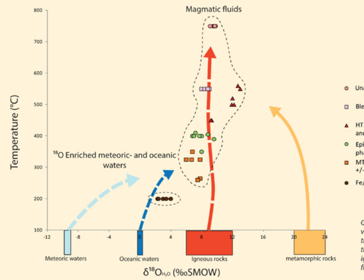
1) Structural position of Serifos skarns



Cross section of Serifos Island showing relations between the Serifos granodiorite, the host rocks and large-scale detachments belonging to the WCDS (the lowermost Meghàlo Livadhi detachment and the uppermost Kàvos Kiklopas detachment). Importantly, this cross section shows that the Serifos pluton has intruded the MCC, up to piercing the brittle/ductile Meghàlo Livadhi detachment. And this cross section show structural position of Serifos skarns. (Modified after Rabillard et al. in prep)

2) Source of fluids

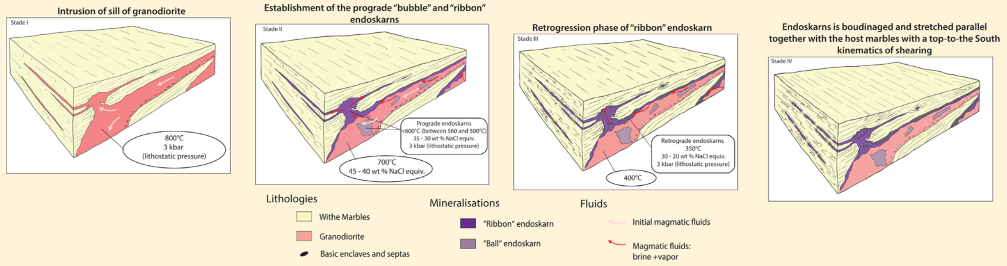
$\delta^{18}O$ values of all skarns match those of the granodiorite, indicating that metasomatic fluids originated from the pluton. The high-temperature endoskarns and skarns could possibly be furthermore enriched in metamorphic water from the host-rocks. $\delta^{18}O_{H2O}$ values of the regional level of brecciated hedenbergite +/- ilvaite skarn suggest a slight contribution by meteoric or oceanic water.
In addition, we know that this level of brecciated pyroxene +/- ilvaite skarn was formed along the Meghàlo Livádhi detachment. According to Famin (2003) detachments are major structures responsible for the deep infiltration of surface water. Fluid may then percolate along the detachment and normal faults connected to it. Thus the formation of brecciated pyroxene +/- ilvaite skarns is probably due to a mixture of magmatic and meteoric or ocean fluids enriched with δ18O at its depth migration.



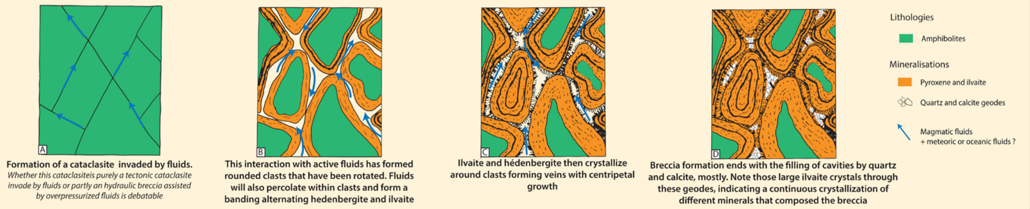
Graphic of formation temperature versus $\delta^{18}OH_2O$ data. Data come from thesis of Salemink 1985. Its indicating the fluid origin of skarns. Data fields of igneous and metamorphic rocks come from Taylor 1986.

3) Model of skarn formation

Vaghia endoskarn



Regional level of brecciated pyroxene +/- ilvaite skarn



A: **Formation of a cataclasite invaded by fluids.** *Whether this cataclasiteis purely a tectonic cataclasite invade by fluids or partly an hydraulic breccia assisted by overpressurized fluids is debatable*

B: **This interaction with active fluids has formed rounded clasts that have been rotated. Fluids will also percolate within clasts and form a banding alternating hedenbergite and ilvaite**

C: **Ilvaite and hédenbergite then crystallize around clasts forming veins with centripetal growth**

D: **Breccia formation ends with the filling of cavities by quartz and calcite, mostly. Note those large ilvaite crystals through these geodes, indicating a continuous crystallization of different minerals that composed the breccia**

Conclusion

- Skarns of Serifos are synchronous with the extensional deformation that persists after their formation.
- The entire skarn formation process is coeval with the activity of the two detachments and shearing of the pluton with a continuum of top-to-the SW kinematics.
- Detachments play a significant role in providing and drainage of surface fluid.
- The formation of skarns originates from magmatic fluids, with a slight contamination of the host-rock metamorphic fluids, or in the case of regional brecciated skarn, probably a mix of magmatic and meteoric or marine waters.
- Skarns of Serifos is an good example of structurally controlled skarn.

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