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

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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 occurred 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; Jlglseder et al., 2011; Grasemann et al., 2012).

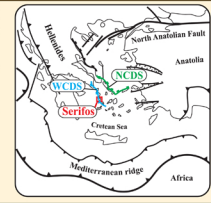
Isotopic studies have shown that the **fluids** present in the **detachments** and their footwall contain a large proportion of **surface-derived fluids** that invade the crust along these **preferential drains** (Famin 2003). Associated with magmatic events, the drainage of fluids can cause the formations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

Endoskarn 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 alteration 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 Meghalo Livadhí Bay

The brecciated pyroxene +/- ilvaite skarn outcrops at the hanging wall of Meghalo Livadhí detachment at the Cycladic Blueschists 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.

4) Brecciated skarn at Cape Kavos Kiklopas Medium temperature skarns

The skarn morphology present on Cape Kavos Kiklopas is similar to that of brecciated pyroxene +/- ilvaite skarn observed near Meghalo Livadhí. 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 Kavos Kiklopas detachment and is limited to the north by a steep normal fault.

4) Brecciated skarn at Cape Kavos Kiklopas Medium temperature skarns

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

Skarn has the morphology of a cokaide breccia, with concentric corrae around large clasts sometimes pluriometric and around geodes and cavities. The main prograde paragenesis includes hedenbergite, ilvaite, epidote, calcite and quartz.

Lithologies

Ore deposits	Quaternary	Cycladic Blueschists Unit	Main structures
Garnet-pyroxene veins	Alluvial sediments	Ultramylonitic marbles	Detachment
Episote	Greenishot, marble layers	Amphibolites with gneiss intercalations	Extensional shear zone
Malachite	Granodiorite (border facies)	Dolomite-calcite marble	Field foliation
	Ankeritized schists	Gneiss with metabasite intercalations	Field location with sense of shear
			Field location with sense of shear

Ore deposits

- Garnet-pyroxene veins
- Episote
- Malachite
- Debris, vegetation
- Cycladic Blueschists Unit
- Amphibolites

Upper Cycladic Unit

- Granodiorite (border facies)
- Ankeritized schists
- Gneiss with metabasite intercalations

Cycladic Continental Basement Unit

- Ultramylonitic marbles
- Greenishot, marble layers
- Amphibolites with gneiss intercalations
- Dolomite-calcite marble
- Gneiss with metabasite intercalations

Main structures

- Detachment
- Extensional shear zone
- Field foliation
- Field location with sense of shear
- Field location with sense of shear

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 Kiklopas 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. Calcshists 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 Livadhí bay

The brecciated pyroxene +/- ilvaite skarn shows no deformation after its formation. Within the cokaide breccia, blocks and clasts show a strong disparity in the foliation attitude implying that they were 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 Meghalo Livadhí detachment.

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 Meghalo Livadhí detachment and the uppermost Kavos Kiklopas detachment). Importantly, this cross section shows that the Serifos pluton has intruded the MCC, up to piercing the brittle-ductile Meghalo Livadhí detachment. And this cross section show structural position of Serifos skarns. (Modified after Rabillard et al. in prep)

3) Model of skarn formation

Vaghia endoskarn

Establishment of the prograde "bubble" and "ribbon" endoskarn

Retgression phase of "ribbon" endoskarn

Endoskarn is boudinaged and stretched parallel together with the host marbles with a top-to-the South kinematics of shearing

Regional level of brecciated pyroxene +/- ilvaite skarn

Formation of a cataclaste invaded by fluids. Whether this cataclaste is purely a tectonic cataclaste invaded by fluids or partly an hydraulic breccia assisted by overpressured fluids is debatable.

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

Ilvaite and hedenbergite then crystallize around clasts forming veins with centripetal growth

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.

Vertical Zonation of the Brecciated Skarn

Top

Bottom

Ore deposits

- Brecciated pyroxene +/- ilvaite skarn
- Fe-Ilvaite Mineralizations
- Cycladic Blueschists Unit
- Metapelite
- Amphibolites

Cycladic Continental Basement Unit

- Grey marbles
- Intrusive rocks
- Granodioritic dikes and sills
- Detachment

Upper Cycladic Unit

- Ankeritized schists
- Cycladic Blueschists Unit
- Calcshists

Ore deposit

- Cataclaste brecciated pyroxene skarn
- Brecciated pyroxene skarn
- Detachment
- Normal faults

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