

Review

Mineralization and Skarn Formation Associated with Alkaline Magma Chambers Emplaced in a Limestone Basement: A Review

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Abstract: The emplacement of shallow magma chambers within a carbonate basement is a typical feature of many volcanic systems around the world. The accompanying formation of exoskarns, endoskarns, cumulates, exsolved fluids and differentiated melts at the interface between the magma chamber and carbonate host-rock is well documented through mineralogical and geochemical studies of ejected skarns and cumulates and through fluid and melt inclusion studies. This review presents the current knowledge on the interaction of alkaline magma chambers with carbonate-bearing host-rocks, with a focus on the geochemical evolution and mineralization at the outer margins of the magma chamber and the accessory mineral phases at Somma-Vesuvius, Colli Albani and Merapi volcanic systems. Furthermore, we discuss how this interaction and its products, especially the CO₂ released during the thermometamorphic decarbonation of the carbonate host-rock, impacts the eruptive behavior in all three systems.

Keywords: skarn xenoliths; magma–carbonate interaction; magma chamber processes; metasomatizing fluids; CO₂ emission



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1. Introduction

Skarn formation is a common process in the peripheral zones of magma chambers that are emplaced within carbonate-bearing rocks. These calc-silicate xenoliths are found at many hazardous volcanoes around the world, including Vesuvius [1–6], Colli Albani [7–10], Merapi [11–13], Lascar [14], Popocatepetl [15], Pacaya [16] and Nisirois [17]. They provide evidence of the complex reaction processes in and around the magma chamber, which can have a profound effect on the host magma in terms of altering magma differentiation trends and the crystallization of major and accessory mineral phases [3,8,13], liberating large volumes of crustal CO₂ [5,12,18–20] and affecting eruptive dynamics and styles [21].

Profound knowledge on carbonate assimilation by magmas and skarn formation around magma chambers emplaced in limestone basements has been acquired through various approaches over the last ~30 years. Many studies focused on the petrographic and geochemical description of skarn and cumulate xenoliths and their respective mineralogy within eruptive products [1–4,6–11,13,14,22]. Studies on isotope mass balance calculations [5,23], on in-situ stable isotopes [12] and on induced changes in magmatic redox conditions and phase equilibria [24,25] shed additional light on the processes and results of skarn formation. Experimental carbonate assimilation studies have provided valuable insights into the kinetics of decarbonation and carbonate dissolution in magmas [18,26–30]. Lastly, the economic metallogenic potential of the involved metasomatizing magmatic fluids has also been researched [31,32].

Generally, two types of skarns are discriminated on the basis of their protolith: endoskarns and exoskarns. Endoskarns form due to contamination and/or metasomatism of the magma chamber's peripheral parts [33–36]. Two processes have been suggested for

their genesis: (i) reciprocal diffusion metasomatism between carbonates and magma [37,38], or (ii) limestone assimilation whereby the magma close to the contact is enriched in Ca derived from the ingested and dissolved host carbonates [39,40]. Exoskarns, on the other hand, often form within the carbonate host-rock through solid-state reactions and interaction with a metasomatizing fluid that has been exsolved from the magma during cooling and has interacted with the Ca-rich melt or the endoskarns [33–36]. As a third type, magmatic skarns form at the initial stages of magma entering the host carbonates due to high-T effects (pyrometamorphism) at the magma–carbonate contact [3]. Additionally, skarn formation is often accompanied by the formation of a solidification front within the magma consisting of mushy cumulates, syenites or fergusonites [3,8].

This review focuses on three volcanic systems with alkaline magma chambers emplaced in a limestone-bearing basement: Somma-Vesuvius, Colli Albani (both in Italy) and Merapi (Indonesia). The majority of the literature for such settings is on these three volcanic systems. Somma-Vesuvius and Colli Albani represent the ultrapotassic alkaline magma differentiation, while Merapi represents a typical volcanic arc magma type. The comparison of three distinct volcanic settings allows us to interpret the involved processes and their results in a more general light. This might be helpful to understand skarn formation processes and the associated mineralogy of these xenoliths also at other, less studied, volcanic systems.

2. Geological Background

As indicated in the introduction, we focus throughout this review on three volcanic systems: Somma-Vesuvius, Colli Albani (both in Italy) and Merapi (Indonesia). Here, we briefly introduce their respective geological setting.

2.1. Somma-Vesuvius Volcanic System

Somma-Vesuvius is an active volcanic system and one of the potentially most hazardous ones in Europe as it threatens the densely populated Neapolitan area. The volcano consists of the remnants of the older Somma edifice and the more recent Vesuvius cone that grew within the summit caldera after the AD79 Pompeii eruption [41,42]. The upper crust underlying the volcanic system has been well characterized by outcrops and the Trecase deep borehole [43,44]. It consists of the upper ~2 km of mainly older volcanic deposits, which are followed by an ~8 km thick succession of Triassic to Cretaceous limestones and dolomites [45,46]. The shallow Vesuvius magma chambers are usually emplaced at 3–8 km of depth [47,48] and hence are of the same depth as the Mesozoic carbonate platform, making limestones and dolostones the most common wall-rocks. Interactions between these carbonate wall-rocks and the Vesuvius magmas have been inferred through numerous studies [49–52].

Within this review, we summarize the findings from skarn xenoliths of four Vesuvius eruptions: (1) the 1944 eruption [1,3], (2) the 1631 eruption [6,53,54], (3) the AD 472 “Pollena” eruption [2,3,5] and (4) the AD 79 “Pompeii” eruption [3,5]. Their magmatic compositions are generally strongly silica-undersaturated with high alkali content and range from tephrite to phonolite [6,55–57].

2.2. Colli Albani Volcanic District (CAVD)

The Colli Albani Volcanic District (hereafter CAVD) belongs to the ultrapotassic Roman Magmatic Province, which stretches from southern Tuscany to central Latium (Italy) [58]. The CAVD volcanic deposits overlie a thick sedimentary succession consisting of Neogene shales, pelitic units and Mesozoic carbonate successions [59]. The carbonate layers are up to 5 km thick and located in the upper 6–8 km of the local crust, as shown by seismic data [60]. Eruptions at the CAVD are generally thought to be fed by a shallow magma chamber situated between 3 and 6 km in depth and hence within the carbonate sequence [61,62]. Magma–carbonate interactions have been inferred to take place at the CAVD through several studies [7,63–65].

Within this review, we cover skarn xenoliths that originate from two different eruptive units of the Albano Maar activity: (1) Unit-a, a breccia level belonging to the first cycle of Albano Maar activity [8,10,66]; and (2) blocks from pyroclastic density current deposits of the most recent hydrovolcanic phase of Albano Maar activity [7,9,22].

2.3. Merapi Volcano

The Merapi volcano is an active stratovolcano of the Sunda Arc in Central Java (Indonesia). It is considered one of the most dangerous Sunda Arc volcanoes, with a nearly continuous activity of dome growth and gravitational (partial) dome collapses inducing pyroclastic density currents [67]. Vulcanian to sub-Plinian eruptions, such as the 2010 eruption, occur at longer ~100-year timescales [68,69]. Merapi overlies an 8–11 km thick sedimentary succession, the Kendeng basin, which consists of Cretaceous to Cenozoic volcanoclastic sediments that are overlain by shallow marine limestones and marls, with units of up to 2 km in thickness [70,71]. The magma composition at Merapi differs from the highly silica-undersaturated alkaline magmas of Vesuvius and Colli Albani and ranges from high-K basalt to basaltic andesite [72]. The assimilation of the local limestones by Merapi-magmas has already been discussed previously in several studies [11,23,73,74].

In this study, we cover skarn xenoliths of various recent eruptions, which can be summarized in two groups: (1) skarn xenoliths from the 1998 block and ash flow deposits [11], and (2) skarn xenoliths from 1994–2010 dome lavas [12,13].

3. Skarn Formation and Associated Mineralization

In this chapter, we introduce some general processes that are associated with skarn formation in volcanic environments and then summarize the present-day knowledge about skarn formation and mineralization at the peripheral parts of the alkaline magma chambers at Somma-Vesuvius, Colli Albani and Merapi.

Generally, two types of skarns are discriminated from each other on the basis of their protolith. Endoskarns or magmatic skarns crystallize from melts at the peripheral parts of the magma chamber and are often enriched in Ca (and Mg-) bearing mineral phases due to carbonate assimilation. Exoskarns form from carbonate wall-rocks often through solid-state reactions or due to alterations induced by intruding metasomatizing fluids that were released by the magma during crystallization and have interacted with the carbonate host-rock or endoskarns [33–36]. While the interaction of magmas with a Ca-rich or calcitic limestone leads to the formation of wollastonite, garnet (grossular-andradite) and Ca-rich clinopyroxene (e.g., Ca-Tschermakite), the interaction with a dolomitic limestone leads to the formation of olivine (forsterite), phlogopite, spinel and clinopyroxene [3,13]. In natural systems, mixed dolomitic and Ca-rich limestone successions are not uncommon; hence, a mixed occurrence of these mineral phases in volcanic skarn xenoliths is likely the rule rather than an exception.

In the subsequent chapters, we summarize the findings of numerous skarn-related studies for each of the three volcanic systems. We focus especially on differences and similarities in the following three points: (1) the major mineral phases that form in cumulates and skarns due to the magma–carbonate interaction; (2) how the crystallization of these mineral assemblages affects magma composition; and (3) the metasomatizing fluids released by the magmas during crystallization, the enrichment of incompatible elements within them and the associated formation of exotic accessory mineral phases within the skarns.

3.1. Skarn Formation at Somma-Vesuvius Volcanic System

For the Vesuvius system, we summarize the findings on skarn ejecta of four eruptions: the AD 79 “Pompeii” eruption, the AD 472 “Pollena” eruption, the 1631 eruption and the 1944 eruption (Table 1). The studies mainly focused on the skarn ejecta and did not discuss in detail the cumulate ejecta (clinopyroxenites to olivine-clinopyroxenites) that have been found [3] and might be related to skarn formation in the peripheral parts of the magma chamber.

Table 1. Summary of skarn research reported for various Somma-Vesuvius eruptions. Abbreviations: Cpx = clinopyroxene and n.d. = not described in the literature. Data from [1–6,31,53–57].

Eruption	Magma Composition/Magma Chamber	Solidification Front Rock	Skarn/Cumulate Type	Main Mineral Phases	Rare Mineral Phases	Accessory Mineral Phases	Metasomatizing Fluid Composition
1944 [1,3,57]	tephrite to phonotephrite/ homogeneous mafic magma chamber	Upper part: glass bearing fergusites	Magmatic Skarn: melilite-bearing skarn	fassaitic cpx + melilite + olivine + spinel	glass + plagioclase + perovskite	-	Cl-F-H ₂ O-rich fluid phase
		Lower part: Cumulates (clinopyroxenites to olivine-clinopyroxenites)	Magmatic Skarn: phlogopite-bearing skarn	fassaitic cpx + phlogopite + spinel + olivine	glass + plagioclase + periclase; cpx rarely has diopsidic/salitic cores	-	
			Exoskarn: periclase-bearing skarn thermo-metamorphic periclase-bearing marbles	fassaitic cpx + periclase + olivine + spinel + perovskite interstitial periclase in calcite + mg-rich calcite	- olivine	-	
1631 [6,53,54]	phonotephrite to phonolite / stratified magma chamber	n.d.	Pyroxenite	cpx + biotite + apatite	spinel + anorthite + amphibole + leucite	Zr- and Ti-Oxides	n.d.
			Endoskarn: phlogopite-bearing skarn	phlogopite	olivine + cpx	-	
			Zoned Skarn	(1) olivine + spinel (2) calcite	(1) perovskite + qandilite + baddeleyite (2) inclusions of olivine, spinel and Mg-Ti-/Zr-Oxides	(1) zirconolite + calzirtite -	
AD 472 “Pollena” [2,3,5,56]	phonotephrite to phonolite/stratified magma chamber	Upper Part: foid-bearing syenites	Endoskarn: melilite-bearing skarn	fassaitic cpx + melilite + phlogopite	wollastonite	-	n.d.
		Lower Part: Cumulates (clinopyroxenites to olivine-clinopyroxenites)	Magmatic Skarn: phlogopite-bearing skarn thermo-metamorphic marbles	fassaitic cpx + phlogopite + spinel	olivine + nephelin + calcite	-	

Table 1. Cont.

Eruption	Magma Composition/Magma Chamber	Solidification Front Rock	Skarn/Cumulate Type	Main Mineral Phases	Rare Mineral Phases	Accessory Mineral Phases	Metasomatizing Fluid Composition
AD 79 "Pompei"[3–5,31,55,56]	tephriphonolite and phonolite/two-folded magma chamber	Upper Part: foid-bearing syenites	Endoskarn (only 1 sample)	fassaitic cpx + olivine + spinel + calcite + garnet	phlogopite + dolomite + nepheline + anorthite + microsommite	REE- and Th-allanite + pyrrhotite + apatite + sphene + zircon + scheelite + thorite + monzanite + stibnite + Nb- and Zr-perovskite + pyrite + galena	Cl-F-H ₂ O-rich fluid phase
		Lower Part: Cumulates (clinopyroxenites to olivine-clinopyroxenites)	Magmatic Skarn: melilite-bearing skarn	fassaitic cpx + phlogopite + spinel	olivine + melilite	-	
			Magmatic Skarn: phlogopite-bearing skarn	fassaitic cpx + olivine + spinel + calcite	phlogopite + dolomite + nepheline	-	
			Exoskarn: phlogopite-bearing skarn	olivine + phlogopite + calcite + dolomite	spinel + sodalite	pyrrhotite + apatite + thorianite + baddeleyte + U-thorite	
			Exoskarn: periclase-bearing skarn	olivine + spinel + calcite	dolomite + periclase + magnesite	baddeleyte + monzanite + sphene + REE-flouride	
			Hornfels (only 1 sample)	wollastonite + fassaitic cpx + anorthite	contains rhyolitic glass with quartz + fassaitic cpx;	pyrrhotite + sphene	
			thermo-metamorphic marbles				

Overall, the major mineral phases and skarn mineral compositions do not change much in between these four eruptions. The slight differences in the AD 79, AD 472, 1631 and 1944 eruptions have mainly been attributed to different stages of maturity of the magma chamber (Figure 1) [3]. The formation of Mg-bearing mineral phases like clinopyroxene, olivine and spinel in all skarn phases at Vesuvius indicate that the host-rock is mainly a dolostone; even so, the Mg content in the assimilated wall-rocks has been higher in the deeper situated (7–8 km depth) AD 79 magma chamber and lower in the shallower (3–4 km depth) AD 472 magma chamber [5].

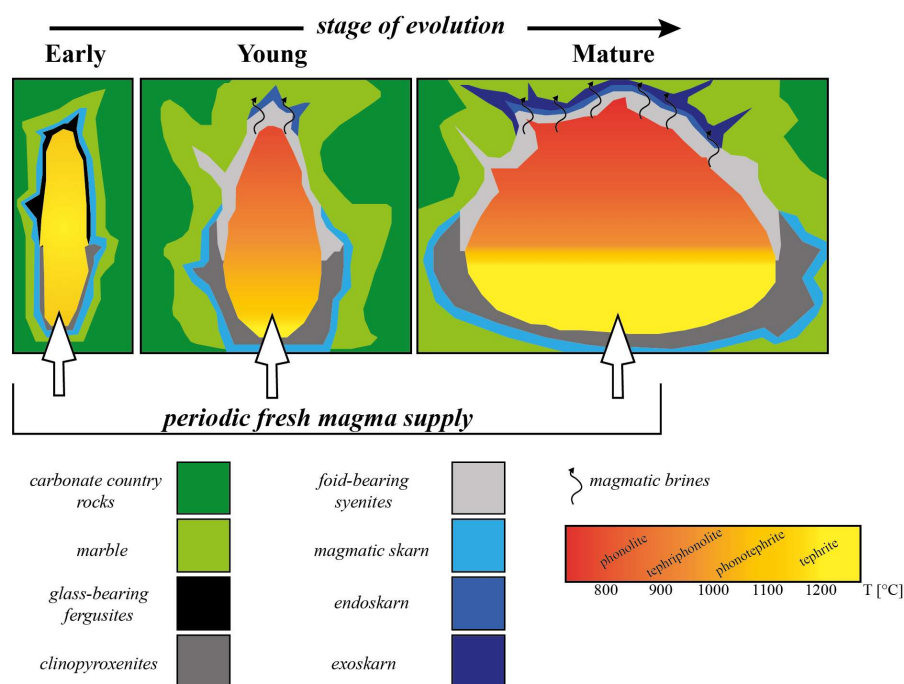


Figure 1. Sketch of magma–host-rock interaction as function of magma chamber maturity at Somma-Vesuvius. Figure is not to scale. Image taken from [3].

The occurrence of magmatic xenoliths like cumulates, glass-bearing fergusonites and foid-bearing syenites suggests the presence of a solidification front. In theory, this solidification front would propagate inward and thicken over time [75], which, at Vesuvius, is reduced or prevented by the refilling of the magma chamber with tephritic magma [76]. Between this solidification front and the wall-rocks, the different skarn phases' outward sequence can be idealized as follows: solidification front–melilite-bearing endoskarns–phlogopite-bearing endoskarns–periclase-bearing exoskarns–thermometamorphic marbles–carbonate wall-rocks.

The melilite-bearing endoskarns need high temperatures of formation, since melilite is only stable above 950 °C (at 100 MPa; [77]) and hence are the result of the direct interaction of carbonate wall-rock with high-temperature silicate melt [3]. They consist mainly of fassaitic clinopyroxene, melilite, olivine (with high forsterite content), spinel and interstitial glass. Depending on the maturity of the magma chamber (and hence T-gradient within the magma chamber), the melilite-bearing endoskarns would form only in the lower and hotter parts of the magma chamber for the 1631 eruption, AD 472 eruption and the AD 79 eruption, while, during the 1944 eruption, it could form throughout the magma chamber [3].

In the upper parts of the more evolved magma chambers, phlogopite-bearing endoskarns mainly form. They commonly contain fluid inclusions, indicating magmatic hypersaline fluid phase circulation, which is also preserved in the solidification front rocks (foid-bearing syenites) in the upper parts of these magma chambers [3]. In the AD 472 endoskarns, complex carbonate-bearing melt inclusions have been found [2]. The composition of this fluid can be summarized as a Na-K-Ca-carbonate-chloride-rich hydrosaline melt.

These melt inclusions are thought to result from the interaction of a magmatic hyper-saline fluid with carbonate wall-rocks, which then metasomatizes the crust, generating the phlogopite-bearing endoskarns [2]. The phlogopite-bearing skarns consist mainly of fassaitic clinopyroxene, phlogopite, spinel and olivine. In some samples, minor interstitial glass, plagioclase and periclase can be found [1].

The occurrence of the periclase-bearing exoskarns is strongly related to the infiltration of magmatic fluids into the carbonate wall-rocks. This type of skarn is often formed within veins in xenolith marbles and hence needs to be interpreted as the result of infiltration metasomatism [3]. This type of exoskarns typically consists of fassaitic clinopyroxene, periclase, olivine and spinel, with perovskite, dolomite and calcite being found in some samples [3]. Since the exsolution and infiltration into the carbonate protolith take a lot of time, this type of skarn is mostly found around more evolved magma chambers and has a very reduced extension around the 1944 magma chamber [3].

The most differing eruption regarding skarn formation at Vesuvius is the 1631 eruption. While the overall mineralogy is very similar to the other three mentioned eruptions (i.e., occurrence of pyroxenites and phlogopite-bearing skarns in the 1631 ejecta [53]), the occurrence of a zoned or banded skarn stands out (Figure 2).

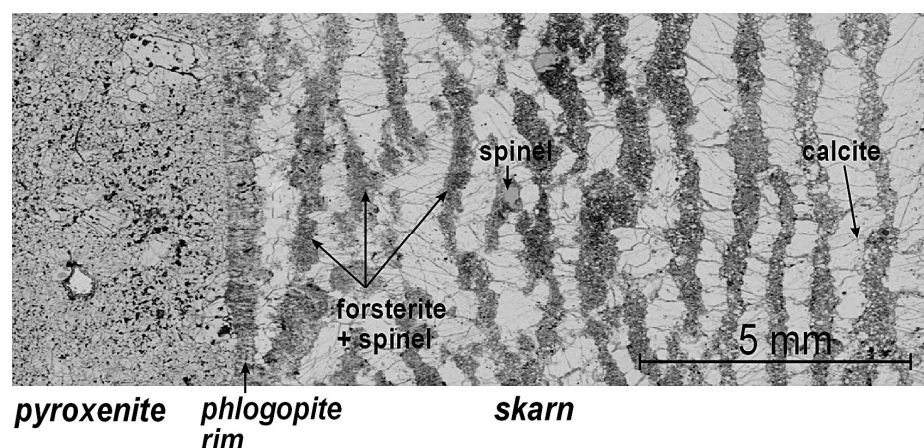


Figure 2. Thin-section photograph of banded skarn (forsterite + spinel layers and calcite layers) in contact with pyroxenite. At the direct contact, a phlogopite layer has formed. Image modified after [54].

These banded skarns have a phlogopite layer at the contact to the magma or pyroxenite and consist of two distinct mineral assemblages: (1) layers of forsterite and spinel, with minor amounts of oxides like perovskite, qandilite (Mg-Ti-oxide) and baddeleyite (Zr-oxide) and accessory mineral phases zirconolite and calzirtite; and (2) layers of calcite with occasional inclusions of forsterite, spinel and the aforementioned oxides [53,54]. It was argued that the skarn's metasomatic development took place at the pyroxenite's expense, through leaching of Na, K, Si and Fe [53]. The leaching process is related to the circulation of fluids, which are equilibrated with the carbonate host-rocks, and hence is responsible for forming the banded forsterite + spinel and calcite skarns [53].

The effect of skarn formation on magma composition at Vesuvius has repeatedly been subject to debates, starting as early as 1933 with the inaugural proposition that the peculiar melt composition of Vesuvius might result from carbonate assimilation [78]. The description of the presence of skarn and cumulate ejecta in products of every major Somma-Vesuvius eruption [45], and the documentation of exotic, silica-poor, alkali- and Ca-rich melt inclusions in mafic crystals of some recent eruptions [2], indicate the pervasive nature of magma–carbonate interactions during magma residence and crystallization in shallow reservoirs. Magma compositions in Vesuvius magma chambers have generally been inferred to evolve from a tephritic primitive melt up to phonolitic compositions [6,55–57]. Nevertheless, the true extent of the magma–carbonate interaction is still debated. Initially,

it was argued that the presence of the skarns and a solidification front would virtually isolate the residing magma and hence limit the effect of skarn formation on the residing magmas [2,3,49], while more recent studies relate the extent of carbonate assimilation to the maturity of the magma chamber (more effective in young and frequently refilled magma chambers) [52,79]. However, crystals in the eruptive products of Somma-Vesuvius generally show enriched $\delta^{18}\text{O}$ -values ($\sim 7\text{--}11\text{‰}$; [5]) compared to the mantle source (5.7‰ ; [80,81]), indicating the assimilation of carbonate wall-rocks with high $\delta^{18}\text{O}$ -values ($\sim 28\text{--}33\text{‰}$; [5]). This indicates either extensive carbonate assimilation, which affects large parts of the magmas stored in the magma chamber, or a very effective magma mixing of a relatively small amount of highly affected magmas (formed at the margins of the magma chamber) with the residual magma.

Another process that may lead to elevated carbonate assimilation (and hence to a more silica-undersaturated and Ca-Mg-richer melt) is the so-called “skarn-recycling” [5], which describes the detachment and subsequent ingestion into the residing magma of skarn pieces from the contact aureole (Figure 3). This leads to the assimilation of the detached piece and may also create a fresh contact surface between magma and host-rock [5].

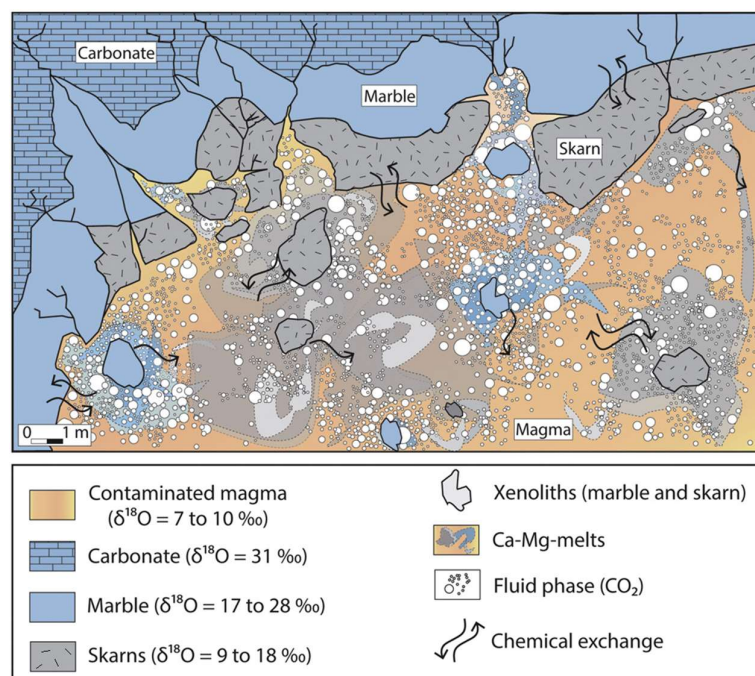


Figure 3. Schematic sketch of the skarn-recycling process. Ca-Mg-melts are Si-melts that are enriched in Ca and Mg due to assimilation of skarn or carbonate host-rock. Sketch is not to scale. Image taken from [5].

The detachment of the skarn pieces might be induced through volcanic unrest, earthquakes, tremors, magma migration, thermal cracking and diking [82]. Very recently, a similar process, called magmatic stoping (i.e., the formation and transport of host-rock pieces into a magmatic body; [83]), during caldera collapse of the Pomici di Base eruption has been proposed to lead to rapid carbonate assimilation and CO_2 -rich fluids, which may enhance eruption explosivity.

The accessory mineral phases (often as inclusions) at Vesuvius have mainly been studied for the AD 79 eruption. The occurrence of these mineral phases is strongly related to the composition of the metasomatizing fluids. The presence of stibnite and scheelite reflects the influx of W, Sb and Pb, which are usually complexed by chloride (Sb, Pb) and hydroxy (W) ions [84,85] and hence confirm the Cl-rich nature of the magmatic brine. REE-, Zr-, Nb-, Ti-, Th- and U-bearing accessory phases are present in all skarn types and reflect more generally the accumulation of incompatible elements in magmatic brines [4].

The occurrence of REE-fluoride minerals confirms the presence of F within the magmatic brine [4], while pyrrhotite indicates the presence of a sulfide phase within the brine. It was shown that the magmatic fluids in AD 79 skarns were particularly enriched in Zn, Mo, W, Sb, Bi, Tl and Pb [31]. These metals show two positive correlations, (1) Pb-Zn-Tl-Bi and (2) Mo-W, which probably reflect different complexing agents (chloride for the first group, hydroxy for the second) [31]. Besides having a very complex composition with different complexing agents (chloride, fluoride, sulfide, sulfate, hydroxy), it can be concluded that a chloride-H₂O-fluoride phase dominates the Vesuvius magmatic brine. This might also be the result of variable initial compositions of fluids leaving the crystallizing magma, as reported, for example, for granite-derived magmatic hydrothermal fluids [86].

3.2. Skarn Formation at CAVD

The Colli Albani skarn xenoliths that have previously been analyzed and are objects of this summary originate from two different units of the Albano Maar activity (a breccia-level of Unit-a [8] and a pyroclastic density current deposit of the most recent hydrovolcanic activity [9]). Even so, further occurrences of skarn xenoliths are documented; for example, in the Pozzolane Rosse and Villa Senni ignimbrites [62] and the Prata Porci Maar eruption [87], the Albano Maar skarn xenoliths and cumulates remain the only ones with a detailed petrographic and geochemical description (Table 2). The lithic clasts ejected during the latest hydrovolcanic activity of the Albano Maar analyzed might consist not only of skarn and cumulate samples [7,9,22]. Only Group 1 and Group 2 samples resemble typical cumulate and skarn xenoliths formed from the direct magma interaction with carbonate wall-rocks [9]. The origin of Group 3 and Group 4 lithic clasts is unclear, as their dominant mineral phase is K-feldspar and their whole rock composition is plotted in the field of phonolite, which is absent from the melt composition in the history of eruptive products of the CAVD [9]. However, the presence of phonolitic and K-feldspar-bearing magmas within the CAVD plumbing system was suggested at depth [9]. Their absence in the eruptive products of the CAVD was explained by extensive compositional modification, for example, due to reactions with carbonate wall-rocks at depth. Due to the unclear origin and genesis of the Group 3 and Group 4 lithic clasts, we focus only on the first two groups in this review. The skarn and cumulate samples from a breccia level of Unit-a of the Albano Maar succession were petrographically and geochemically described and subdivided into three types each (Table 2) [8,10].

The primitive olivine clinopyroxene cumulate (OCCp) consists, as the name already says, of mainly olivine and clinopyroxene and some rare Cr-spinel enclosed by olivine. The differentiated olivine clinopyroxene cumulate (OCCd) consists also of mainly olivine and clinopyroxene and some intracumulus glass. Calcite rarely occurs as an inclusion in clinopyroxene. The difference between OCCp and OCCd is the lower forsterite content in the olivine (Fo₉₀ in OCCp to Fo₈₈ in OCCd) and the presence of calcite in OCCd [8,10]. The phlogopite-bearing orthocumulate mainly consists of olivine, clinopyroxene and phlogopite. The rarely present spinel is always enclosed by olivine. The lithic clasts summarized as Group 1 ejected during the most recent hydrovolcanic activity [9] most closely relate to these olivine clinopyroxene cumulates.

Table 2. Summary of skarn research reported for the Albano Maar skarn xenoliths. Abbreviations: Cpx = clinopyroxene, K-fsp = alkali feldspar and n.d. = not described in the literature. Data from [7–10].

Eruption	Magma Composition	Solidification Front Rock	Skarn / Cumulate Type	Main Mineral Phases	Rare Mineral Phases	Accessory Mineral Phases	Metasomatizing Fluid Composition
Albano Maar (Unit a) [8,10]	Trachybasalt (primitive) to Phonotephrite (differentiated)	OCCp (primitive olivine-bearing orthocumulate)	Endoskarn: CaTs-rich	cpx + spinel	olivine + calcite inclusions in cpx and spinel + interstitial glass	-	n.d.
		OCCd (differentiated olivine-bearing orthocumulate)	Endoskarn: CaTs-rich with two mingled domains	(1) calcite bearing + cpx + olivine + spinel + phlogopite + glass (2) calcite free + cpx + olivine + vesiculated glass	(1) calcite inclusions in spinel (2) phlogopite	- -	
		POC (phlogopite-bearing orthocumulate)	Exoskarn: layered skarn	(1) carbonate layers: calcite + olivine + cpx (2) silicate layer: cpx (90%) + calcite	- (2) phlogopite, olivine, spinel	- -	
Albano Maar (late-stage hydro-volcanic activity) [7,9]	leucite-tephrite - leucite to phonotephrite	n.d.	Group 1	cpx + foids + phlogopite + K-Fsp + garnet	-	amphibole + Fe-Ti-oxides + fluorite + zircon + sphene + cuspidine + Ca-Th-REE-rich Si-phosphates	F-rich fluid phase
			Group 2	(1) olivine + spinel (2) phlogopite + olivine + cpx + spinel	- (2) interstitial glass	- -	
			Group 3	K-fsp + phlogopite	leucite + sodalite group minerals + garnet + cpx + phlogopite + nephelin <u>reaction rim</u> : polygonal microlites of acicular leucite; <u>matrix</u> : wollastonite + garnet + leucite + sodalite-group minerals + nephelin + phlogopite	apatite + magnetite + pyrrhotite + Ca-Th-REE-rich Si-phosphates	
			Group 4	K-fsp + phlogopite		matrix: wollastonite + garnet + cpx + leucite as phenocrysts	

The three types of skarns are Ca-Tschermak-rich endoskarn, hybrid Ca-Tschermak-rich endoskarns and exoskarns. The Ca-Tschermak-rich endoskarn is characterized by the presence of abundant clinopyroxene (average ~54 vol.%), green spinel (average ~14 vol.%) and olivine (up to 43 vol.%), closely packed but with some pore space (<7 vol.%), resembling overall a hypidiomorphic igneous texture. Phlogopite crystals are present as inclusions in olivine, and calcite crystals (up to ~10 vol.%) are present as inclusions in clinopyroxene and spinel. The presence of interstitial glass (<1 vol.%) confirms the formation in magma and hence the classification as endoskarn [33]. The hybrid Ca-Tschermak-rich endoskarns are characterized by two mingled domains: (1) calcite-bearing domain with clinopyroxene, olivine spinel (with calcite inclusions) and phlogopite; and (2) calcite-free domain with brown vesiculated glass, clinopyroxene and embayed olivine, which is sometimes surrounded by marginal phlogopite. The calcite-free domain texturally resembles the cumulates [10]. The exoskarn samples consist of two foliation domains: (1) a carbonate layer with abundant calcite (up to 80 vol.%) and minor olivine and clinopyroxene, and (2) a silicate layer with abundant clinopyroxene (up to 90 vol.%) and minor calcite. Olivine, spinel and phlogopite rarely occur in the silicate layer [8,10]. All skarn samples have an ultramafic to mafic whole-rock composition [10]. Also, the Group 2 rocks of the latest hydrovolcanic activity are ultramafic, and the present mineral phases like olivine, spinel, clinopyroxene and phlogopite, as well as the presence of interstitial glass [9], make the classification as endoskarns reasonable.

A time-dependent schematic overview of how and under which conditions cumulate and skarn phases form at Colli Albani was designed and is illustrated in Figure 4 [8,10].

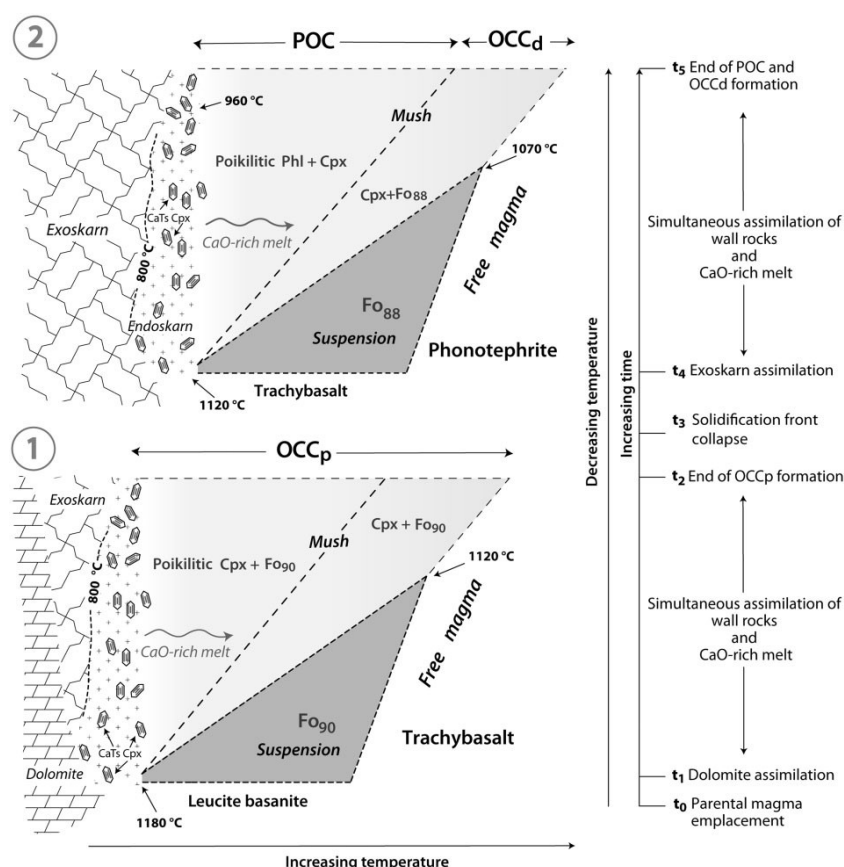


Figure 4. Schematic diagram of temporal and spatial evolution of skarns and cumulates at Colli Albani in a two-step model. ①: OCCp – formation, ②: OCCd- and POC-formation. Abbreviations: Fo = Forsterite; Cpx = Clinopyroxene; CaTs Cpx = Ca-Tschermakitic Clinopyroxene; Phl = Phlogopite; OCCp = primitive Olivine-bearing Clinopyroxene Cumulate; OCCd = differentiated Olivine-bearing Clinopyroxene Cumulate; POC = Phlogopite-bearing orthocumulate. Image taken from [10].

In this model, the parental magma is of a leucitite-basanite composition, interacting with a dolostone host-rock. In the first step, this interaction will lead to the formation of a primitive olivine clinopyroxene cumulate (OCCp) and an endoskarn-phase dominated by CaTs-rich clinopyroxene within the magma and an exoskarn-phase within the host-rock. The formation of this olivine and clinopyroxene-bearing solidification front induces magma differentiation, which is controlled through the dolomite wall-rock and CaO-rich melt assimilation, toward a trachybasaltic composition. When this solidification front collapses [88], the trachybasaltic melt interacts with the wall-rocks, initiating the second step, during which the differentiated olivine clinopyroxene cumulates (OCCs) and, closer to the host rock and hence at lower T , the phlogopite-bearing orthocumulates (POCs) form. The occurrence of a trachybasaltic melt, which is absent in other eruptive products at CAVD, has been confirmed by melt inclusions in the olivine of the OCCp [10].

Accessory mineral phases have only been studied in the cumulate and skarn xenoliths of the most recent hydrovolcanic activity at Albano Maar [7,9]. The mineral phases found in their Group 1 and Group 2 rocks are amphibole, Fe-Ti-oxides, fluorite, zircon, sphene, cuspidine and Ca-Th-REE-rich Si-phosphates. The presence of fluorite and cuspidine indicates that the metasomatizing fluid within the CAVD-system is dominated by a fluoride phase. For the cumulates and skarn xenoliths of the Unit-a breccia-level, only an enrichment in incompatible trace elements from cumulates to endoskarns—with endoskarns, for example, having the highest REE-concentrations—was described [8,10].

3.3. Skarn Formation at Merapi Volcano

The samples for the skarn studies on Merapi are mostly derived from a very broad range of eruptions either described as 1994–2010 dome lavas [12] or 1994–2010 eruptions [13], besides the samples from the 1998 block and ash flow [11]. A summary of all three works is given in Table 3.

For the 1994–2010 eruptions, 33 calc-silicate xenolith samples were divided into endoskarns (or magmatic skarns), exoskarns and buchites based on the dominant mineralogy, modal zonation and the presence of glass [13]. Overall, the endoskarn samples mainly consist of clinopyroxene, wollastonite, plagioclase (anorthite), garnet and interstitial glass. This mineralogy for the endoskarns is consistent with the previous endoskarn descriptions at Merapi [11,12]. The single endoskarn samples, however, exhibit a large mineralogical variety, which is why they were subdivided into a series of idealized mineralogical/textural zones [13]. These zones reflect different reaction zones and the skarn core and are ordered as follows: magma – R1 – R2 – R3 – R4 – skarn core (Figure 5).

In this idealized scheme, reaction zone R1 mainly consists of clinopyroxene and magnetite, which originates from the magma. R2 mainly consists of plagioclase and clinopyroxene, with some interstitial glass and rare amounts of amphibole. R3 is a thin layer of clinopyroxene, separating R2 from R4, which consists of vesiculated glass, clinopyroxene and microlites of plagioclase and wollastonite. In some samples, larger quartz crystals are also present in R4. In some samples, the glassy R4-zone is missing, and the R3-zone consists of Ca-Tschermak-rich clinopyroxene and garnet [13]. The exoskarns have been subdivided into two groups based on their respective mineralogy: Group A) wollastonite, garnet and plagioclase as the major mineral phases with minor amounts of Ca-Tschermak-rich clinopyroxene, quartz and calcite; and Group B) gehlenite, garnet (grossular), Ca-Tschermak-rich clinopyroxene, spinel, wollastonite and plagioclase [13]. The occurrence of wollastonite, garnets and Ca-rich clinopyroxene, and the absence of Mg-rich skarn minerals like olivine or periclase indicate that the assimilated wall-rock was Ca-rich limestone. In Figure 6, a schematic overview of the involved process of skarn formation at Merapi is given.

Table 3. Summary of skarn research conducted at Merapi volcano. Abbreviations: cpx = clinopyroxene; CaTs-cpx = Ca-Tschermakitic clinopyroxene; n.d. = not described in the literature. Data from [11–13,72].

Eruption	Magma Composition	Solidification Front Rock	Skarn/Cumulate Type	Main Mineral Phases	Rare Mineral Phases	Accessory Mineral Phases	Metasomatizing Fluid Composition
1998 block and ash flow [11,72]	basaltic andesite	n.d.	Skarn (not specified)	wollastonite + diopsidic cpx	Ca-plagioclase (anorthite) + quartz + Ca-amphibole (tremolite) + garnet	-	n.d.
1994–2010 dome lavas [12,72]	high-K basalt to basaltic andesite	n.d.	Endoskarn	wollastonite + cpx + plagioclase + glass	calcite + quartz + garnet	wadalite-like phase + gehlenite + cuspidine + flourite	n.d.
			Exoskarn	fassaitic cpx + wollastonite + plagioclase + garnet	calcite	cuspidine + spurrite + flourite	
1994–2010 eruptions [13,72]	high-K basalt to basaltic andesite	n.d.	Endoskarn (magma-R1-R2-R3-R4-skarn core)	R1: cpx + magnetite	-	R1–4 and Core: calcite + titanite + chromite + gehlenite + wadalite-like phase + Ca-Zr-Ti-O mineral + cotunnite + anhydrite + baryte + pyrrhotite + cubanite	F-Cl-S-rich fluid phase
				R2: plagioclase + cpx	R2: glass + amphibole		
				R3: cpx			
				R4: vesicular glass + cpx	R4: plagioclase + wollastonite + quartz		
			Exoskarn (2 distinct mineral assemblages)	Core: wollastonite	Core: cpx + garnet	(1) cuspidine + ellestadite + anhydrite + pyrrhotite	
				(1) wollastonite + garnet + plagioclase	(1) CaTs-cpx + quartz + calcite		
				(2) gehlenite + garnet + CaTs-cpx + spinel + wollastonite + plagioclase	-	(2) ellestadite	

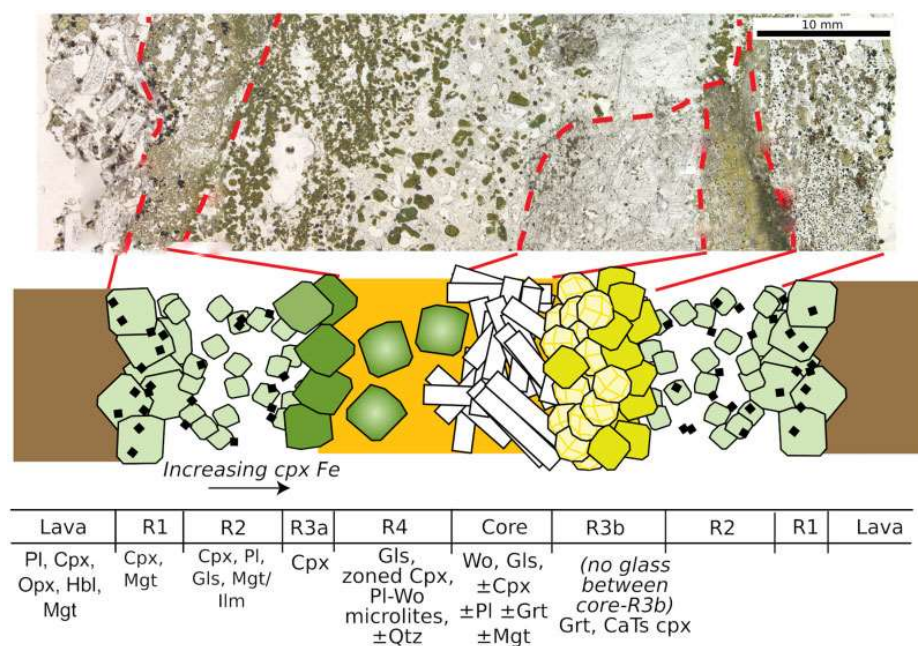


Figure 5. Idealized scheme of zoning patterns in endoskarn samples at Merapi volcano. Abbreviations: Pl = plagioclase; Cpx = clinopyroxene; Opx = orthopyroxene; Hbl = hornblende; Mgt = magnetite; Ilm = Ilmenite; Gls = Ca-enriched interstitial glass; Wo = wollastonite; Qtz = Quartz; Grt = garnet; CaTs cpx = Ca-Tschermakitic clinopyroxene. Image modified after [13].

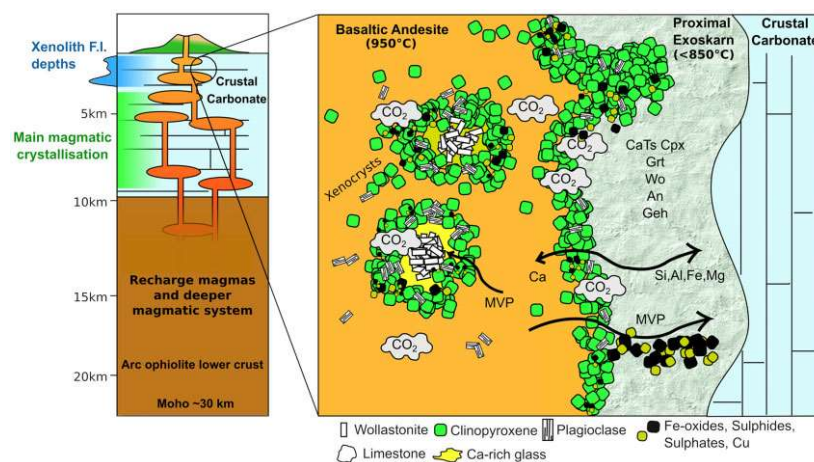


Figure 6. Schematic summary of skarn forming processes at Merapi volcano. Abbreviations: CaTs cpx = Ca-Tschermakitic clinopyroxene; Grt = garnet; Wo = wollastonite; An = anorthite; Geh = gehlenite; MVP = magmatic volatile phase. Image taken from [13].

The melt composition commonly found in recent eruptive products of Merapi is a high-K basalt to a basaltic andesite (~50–68 wt.% SiO_2 ; [72]) and hence not silica-undersaturated like at Vesuvius or Colli Albani. Melt inclusions within these eruptive products and xenolith glasses formed at the magma–carbonate interface even record compositions with 60–75 wt.% SiO_2 [13]. Hence, the crystallization of clinopyroxene and plagioclase does not drive these melts toward silica-undersaturation, but rather to the typical arc magma plagioclase and clinopyroxene differentiation assemblage [89], and the overall effect of carbonate assimilation on the magma composition might be limited to slightly elevated Ca contents [13]. In addition, the generally lower temperature and higher SiO_2 content in the Merapi magmas have a lower capacity of carbonate assimilation [5,8,24,90], and instead favor the formation of skarn minerals (e.g., wollastonite) that cause only small apparent changes to melt compositions [17,29]. Nevertheless, several isotope systems record high

levels of interaction [11,23,73,91], which might result from the generally higher mobilities of isotopes of trace elements (e.g., Sr, B). This decoupling of the limited whole-rock evidence for carbonate assimilation and the recorded high levels of assimilation in isotope systems has previously been observed in experimental studies [18,28,92].

Accessory mineral phases have been studied extensively and they provide insights into a very complex magmatically derived volatile phase [13]. Numerous F-Cl-S mineral phases (see Table 1 in [13]) have been identified and prove the presence of this volatile phase and its interaction with the skarn xenoliths. For example, the occurrence of fluorite and cuspidine indicates the presence of F within the magmatic volatile phase; the presence of cotunnite and a wadalite-like mineral hints at Cl being part of the magmatic volatile phase; and lastly, the two sulfide minerals pyrrhotite and cubanite, as well as the two sulfate-minerals ellestadite and anhydrite, indicate the presence of S in the magmatic volatile phase. These accessory mineral phases are generally found in both endo- and exoskarns, but not all endoskarn samples [13]. Notable at Merapi is also the presence of Cu in minerals like cubanite and as a minor constituent in pyrrhotite. Both occur mainly in endoskarn samples of the R2 reaction zone and are generally surrounded by anhydrite [13], documenting an interaction of a Cu-S-enriched fluid with a carbonate phase. It is well known that the disproportionation of SO₂ into sulfide and sulfate is a potential mineralization process in carbonate and calcium-bearing rocks, which may occur on the timescale of hours [93]. This might explain the co-existing pyrrhotite, cubanite and anhydrite assemblage in the R2-endoskarns. Cu-rich sulfide melts have been previously recorded at Merapi [94] and sulfur-bearing magmas as sources of Cu have been noted along the Sunda arc [94,95]. Hence, we conclude that all three phases (F, Cl and S) are equally important in the Merapi system.

4. Discussion

In this chapter, we discuss the similarities and differences of the three skarn-forming systems. We focus on the following three points: (1) the major mineral assemblage, (2) the effect of skarn formation on magma composition, and (3) the involved fluid phase(s) and how they control the accessory mineral assemblage. However, it must be noted that even as a high number of skarn samples have been studied for all three volcanoes, neither dataset guarantees completeness.

In general, skarn formation is a very common process at magma chambers emplaced in carbonate-bearing host-rocks independent of the magma composition. The overall results of the interaction in the peripheral parts of the magma chamber (i.e., in contact with the carbonate host-rock) include the formation of mushy solidification front rocks (e.g., syenites, fergusonites) or cumulates (clinopyroxenites), endoskarns, exoskarns and thermometamorphically altered host carbonates [3,10,13]. The extent of these zones depends very much on interaction time (or maturity of the magma chamber) and magma chamber stability [3].

The main skarn mineral assemblage is similar in Somma-Vesuvius and Colli Albani skarns. They mainly consist of clinopyroxene, olivine, spinel and phlogopite, with less abundant melilite, calcite, dolomite, periclase and foids (leucite and nepheline). Endoskarns often contain various amounts of interstitial glass. Clinopyroxene is described to be of fassaitic (Ca(Mg,Fe,Al,Ti)(Si,Al)₂O₆) or Ca-Tschermakitic (CaAl₂SiO₆) composition and hence is generally Ca-rich. Olivine instead shows high abundances of a forsteritic (Mg₂SiO₄) phase, generally in the range of Fo₈₀-Fo₉₉, and hence is like the occurrence of spinel and phlogopite, an indicator of the presence of Mg. This mineral assemblage reflects the interaction of magma with a Ca- and Mg-rich source and is hence a dolomitic limestone. In both volcanic systems, the presence of dolomites below the volcanic edifice has been demonstrated [43,44,59,60]. On the other hand, the main skarn mineral assemblage at Merapi consists of wollastonite, plagioclase, clinopyroxene and garnet, and less abundantly gehlenite, calcite and quartz. Clinopyroxenes at Merapi have been described to be diopsidic (CaMgSi₂O₆; [11]) or fassaitic [12,13] and hence are generally more Ca-rich pyroxenes. Plagioclases show highly anorthitic compositions and garnets exhibit a large grossular

component, both being the respective Ca-rich phases. The general crystallization of Ca-rich phases and the absence of Mg-rich phases like olivine and spinel indicate a Ca-rich limestone as the host-rock at Merapi, which is compositionally in agreement with the locally exposed limestone [70,71]. Recent experimental studies have found that the reactions between carbonate host-rock and magma increase the stability fields of clinopyroxene and, in more evolved melts, plagioclase [20,25,64]. The main source of the carbonate components (Ca, Mg) contaminating the magmas have been inferred to be skarn-derived Ca-rich melts [8,13,24]. Some xenolith cores at Merapi have even preserved the rare instance of an actual calcite carbonate melt [12]. We conclude that the main mineral assemblages of the respective skarn phases are highly dependent on the kind of wall-rock that becomes assimilated (dolomites vs. Ca-rich limestones).

Skarn formation and the crystallization of skarn and cumulate minerals from the magma do not affect the magma composition much if the parental magma is not already silica-undersaturated. At Merapi, for example, where the parental magma is thought to be high-K basalt to basaltic andesite (SiO₂ of ~50 to 68 wt.%; [72]) and some melt inclusions show compositions with even higher SiO₂ content (up to ~75 wt.%; [13]), the effect of carbonate assimilation on the major element melt composition is negligible, since the generally colder and higher SiO₂ content favor the crystallization of skarn minerals (like wollastonite) that cause only small apparent changes to magma composition [17,29]. Instead, it shows the normal arc magma differentiation trend with plagioclase and pyroxene crystallization [89]. In these magmas, carbonate assimilation can nevertheless be identified via the slightly higher Ca contents and the isotope systems (like $\delta^{18}\text{O}$ -values or Sr-ratios; see [5,11,23,73,91] for details). Instead, if the parental magmas are already silica-undersaturated like the implied parental magmas of Vesuvius (Tephrite; [57]) and Colli Albani (Leucitite-Tephrite; [9]), the crystallization of Si-rich phases like clinopyroxene and olivine during skarn and cumulate formation drives the magma composition further toward silica undersaturation [5,10]. Carbonate assimilation in these melts will result in the highly Ca-enriched phonotephritic to phonolitic magmas [3] and sometimes even more silica-undersaturated foiditic compositions [5,8].

The accessory mineral phases in skarn systems are generally strongly affected by the presence of a magmatic fluid that interacted with carbonate host-rocks or with the skarns and is enriched in incompatible (trace) elements [3,9,13,31]. While, at Vesuvius, chlorine, fluorine and H₂O are the predominant complexing volatile species in the magmatic brine, they are fluorine at Colli Albani and a broad mixture of fluorine, chlorine and sulfur at Merapi. In skarn environments with alkaline magmas, the presence of fluorine in the magmatic brine might be indicated by the presence of accessory minerals like fluorite and cuspidine [9,13]; chlorine is implied by the presence of cotunnite, wadalite, stibnite and scheelite [3,13,31]; and pyrrhotite, cubanite, ellestadite and anhydrite point to the presence of sulfur [13]. From summarizing these three volcanic systems, this seems to be a general trend, independent of magma composition. Additionally, we observe this magmatic fluid rich in F/Cl/S in all three volcanic systems to be accumulating rare REE-, Zr-, Nb-, Ti-, Th- and U-bearing accessory phases [4,13] and metals like Cu, Zn, Mo, W, Sb, Bi, Tl and Pb, and hence, skarn environments might play an important role in metal or ore deposition [13,31]. For example, the extreme Th, U and LREE enrichments (Th 400 to 800 ppm; U 100 to 220 ppm; La 590 ppm) measured in melt inclusions [8] cannot be related to any known magma evolution process and support transport and enrichment by fluid phases. It needs to be noted, though, that the origin of fluorine, chlorine or sulfur is the magmatic source in the mantle [9,31,58] and that they do not derive from the interaction with the carbonate host-rock. This magmatic fluid will only react with the carbonate host-rock or Ca(-Mg)-rich mineral phases in the skarns to form Ca(-Mg)-rich fluorite, chlorite, sulfide or sulfate minerals.

The decarbonation of the carbonate host-rocks is the most important process during skarn formation regarding magma ascent and eruptive dynamics, since it adds CO₂ to the volcanic volatile budget [12,19,25,65,96]. This process can be measured by a varied

$\delta^{13}\text{C}$ -concentration in volcanic gases, which are closer to the values of the local limestone source [96,97]. Experimentally, the CO_2 -liberation has been shown to be a very fast process, adding large quantities of CO_2 to the magmatic mixture before and during the respective volcanic eruptions [18,20], even if these interactions should occur very shallowly [30]. For Plinian-type eruptions (like at Somma-Vesuvius), it has been shown through numerical modeling how the excess CO_2 (from an external source, like limestone host-rocks) increases the driving pressure of an eruption and hence the mass eruption rate [21], most likely implemented by a prolonged eruption duration like those suggested for the Plinian phases of the Pomici di Avellino and Pomici di Base eruptions of Somma-Vesuvius [98,99]. In spite of their very silica-undersaturated compositions, the eruptions at CAVD appear anomalously explosive. Experimental studies have shown how the crystallization of clinopyroxene and leucite in these hydrous Ca-enriched ultrapotassic melts during ascent drive the melt composition toward K-foiditic compositions [26], while increasing the overall viscosity of the magmatic mixture (melt + crystals + free volatile phases) by two orders of magnitude [65]. For the Pozzolane Rosse eruption, for example, it was hypothesized that the withdrawal of magma due to effusive eruption caused a depressurization of the remaining magma, causing extensive leucite crystallization [65]. Furthermore, magma decompression may have caused bubble expansion of the pervasive free CO_2 in the magma reservoir (due to skarn formation and limestone assimilation) and increasing tensile stress in the magma, ultimately leading to fragmentation and the highly explosive subplinian scoria fallout of the Pozzolane Rosse eruption [65]. At dome-forming volcanoes (like Merapi), the formation of skarn and the assimilation of the carbonate host-rocks is likely controlling the rate of dome extrusion as, for example, during the 2006 eruption [18,100]. The increase in a free CO_2 -rich volatile phase originates from a higher amount of decarbonation (hence larger affected surface or volume) of the carbonate host-rocks and skarns. This might be triggered by the arrival of a new and hotter batch of magma from depth (thus increasing decarbonation distance into the host-rock) as for the 2010 eruption [101,102] or by earthquakes, tremors or wall-rock instabilities (thus creating fresh magma–carbonate interaction surfaces), like during the 2006 eruption [18,19,100].

5. Conclusions

The emplacement of magma chambers within carbonate-bearing host-rocks is not an uncommon process on Earth. Several volcanic systems, including Colli Albani, Lascar, Merapi, Nisiro, Pacaya, Popocatepetl and Somma-Vesuvius, are situated above a carbonate basement and calc-silicate or skarn xenoliths have been found in their eruptive products [1–17].

However, the major mineral assemblages of these xenoliths do not reflect changes in magma composition, but instead seem to depend on the host rock and the availability to assimilate calcium (Ca-rich limestone) or calcium and magnesium (dolomite). While the assimilation of Ca-rich limestones in the peripheral parts of alkaline magma chambers leads to the formation of a mineral assemblage that is mainly constituted of wollastonite, plagioclase and clinopyroxene, the assimilation of a dolomite host-rock would lead to the formation of clinopyroxene, olivine and spinel.

Skarn formation may affect magma differentiation, especially in already silica-undersaturated systems. In such a system (here: Colli Albani and Somma-Vesuvius), the crystallization of silica-rich mineral phases like clinopyroxene and olivine would drive the magma composition further toward silica-undersaturation and the assimilation of the host-rocks would instead enrich the magma composition in Ca (and/or Mg). On the other hand, if the parental magma has higher SiO_2 contents (here: Merapi), the crystallization of clinopyroxene and wollastonite would not affect the major element magma composition. The extent of carbonate assimilation in these systems might only be recognized in isotope systems like $\delta^{18}\text{O}$ and Sr-ratio.

The accessory mineral phases result from the accumulation of incompatible elements in magmatic brines during magma cooling. Which minerals crystallize is heavily dependent on which volatile phase is dominant: fluorite and apatite indicate a F-rich volatile phase;

cotunnite, stibnite and scheelite hint at a Cl-rich fluid and pyrrhotite; and anhydrite and ellestadite are minerals that form in S-rich magmatic brine.

Lastly, skarn formation liberates large quantities of CO₂ through decarbonation of the assimilated carbonate wall-rock. This additional externally derived volatile phase in the gas budget of the magma may lead to a larger mass eruption rate and prolonged eruptions. Therefore, the identification that a volcanic system is an active skarn-forming system might bear consequences for the volcanic hazard around these volcanoes and this review might help in recognizing skarn xenoliths in volcanic systems elsewhere.

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