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Growth mechanism of snowball garnets from the Lukmanier Pass area (Central Alps, Switzerland): a combined μCT/EPMA/EBSD study

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ABSTRACT

For two decades, considerable efforts have been made to explain the formation of snowball garnets by either the rotational or non-rotational models. On the basis of morphological, chemical and crystallographic evidence, this paper presents new data on snowball garnets showing that the formation of these microstructures can be explained by the combination of the two previously proposed mechanisms operating consecutively during garnet growth. The crystallization sequence of garnet revealed by Mn contouring and the distribution of crystallographic orientations within the spiral indicate that the final stages of garnet growth are controlled by post-kinematic crystallization. However, some microstructural arguments plead for a rotational contribution during the first stages of growth. In this view, the overall spiral geometry is thought to overestimate the true amount of rotation experienced by the garnets. Results also reveal the existence of complex snowball garnets consisting of several grains formed from distinct nucleation sites.

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Introduction

Snowball garnets, also referred to as spiral-shaped garnets, are characterized by the presence of sigmoidal inclusion trails with a relative rotation angle exceeding 90° (Williams and Jiang, 1999). The formation of snowball garnets is explained by two controversial models: one argues for porphyroblast growth with rotation in respect to the foliation in a single tectonic phase of non-coaxial flow (e.g. Schoneveld, 1977; Passchier *et al.*, 1992), whereas the other argues for porphyroblast growth without rotation, involving overgrowth of successive generations of near orthogonal foliations (e.g. Bell *et al.*, 1992). So far, most efforts to assess these two models have focused on geometrical proofs. However, this approach has failed to resolve the issue completely as most geometries observed in snowball garnets can be explained by both the rotational and the non-rotational models (e.g. Johnson, 1993; Stallard, 2003).

An alternative way of deciphering the development of snowball garnet porphyroblasts consists of combining chemical zoning and crystallographic orientation analysis with geometrical arguments. In a recent paper, Ikeda *et al.* (2002) used a combined approach to account for the formation of snowball garnets. Based on the chemical zoning and the monocrystalline nature of the investigated garnets, they concluded that growth and rotation of garnet occur simultaneously during a single metamorphic event. In light of new evidence provided by micro-computed X-ray tomography (μCT), electron probe microanalysis (EPMA) and electron backscattered diffraction (EBSD) techniques, we present an alternative model to account for the growth of snowball garnets.

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Geological setting

The samples were collected in the Lukmanier Pass area, Central Alps, Switzerland (Fig. 1). This region comprises two major tectonic units: the Gotthard Massif to the north, partly overlain by a Mesozoic sedimentary cover, and the Lukmanier Massif to the south. Previous investigations (e.g. Chadwick, 1968) show that the Lukmanier area has a complex tectonic history involving three main phases of deformation. All of them are related to southwards and upwards tectonic movements resulting from the Tertiary continent–continent collision between the Eurasian and Apulian plates.

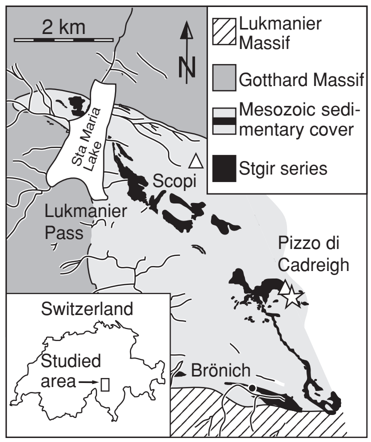

Fig. 1 Simplified geological map of the Lukmanier Pass area. The sampling location (708.163/156.045, Swiss national grid coordinates) is indicated by a star.

The two initial phases of deformation (D_1 and D_2) correspond to a crustal thickening event related to top-to-the-N directed movements which most probably reflect the southward underthrusting of the Mesozoic sedimentary cover beneath the frontal part of the Apulian plate. Whereas the first deformation (D_1) was responsible for isoclinal folding and imbricate stacking of basement and sedimentary cover units, the D_2 phase generated the axial planar surface of the large isoclinal folds observed in the Lukmanier Pass area. Intensive

SE-directed back-folding and back-thrusting (D_3) subsequently caused the upward movements of crustal material and the exhumation of the Lukmanier metamorphic rocks.

The occurrence of snowball garnets is restricted to specific levels of the Liassic Stgir series (cover of the Gotthard Massif) (Chadwick, 1968; Fox, 1975), which are characterized by thin alternations of quartz and mica-rich layers. The main structural element in those garnet-bearing levels consists of a N-dipping penetrative crenulation cleavage (S_2) (Fig. 2a), associated with a monotonous N–S mineral lineation. Shear indicators clearly show a top-to-the-N directed sense of shear for S_2. The relationship between crystallization and deformation indicates that the main stage of garnet growth occurred contemporaneously with the S_2 formation, i.e. during the D_2 phase. The overprinting of S_2 over the earlier schistosity (S_1) resulted in the formation of closely spaced microlithons displaying a subhorizontal E–W crenulation lineation parallel to the rotation axis of the snowball garnets. Both S_1 and S_2 foliations were subsequently folded to form asymmetric, centimetre to kilometre-scale folds (F_3) verging to the SW. A slightly NE-dipping crenulation cleavage (S_3) is locally visible in the hinges of the F_3 folds, but no penetrative schistosity is reported. Occasionally, D_3 produced shear bands (SB_3) with top-to-the-S directed movements (Fig. 2b).

The studied samples contain the mineral assemblage garnet + muscovite + biotite + quartz + plagioclase with minor epidote, chlorite and ilmenite. Although the garnet-forming reaction has not yet been fully established, the systematic occurrence of garnet crystals along mica-rich layers strongly suggests mica as reactant. Regional mapping of the mineral distribution throughout the Lukmanier Pass indicates a metamorphic field gradient characterized by peak conditions increasing gradually from the chloritoid zone to the north of the Santa Maria Lake, to the staurolite–kyanite zone in the Brönich area to the south (Fox, 1975). Thermobarometric analysis of metapelites indicates peak conditions evolving from 410 °C for the chloritoid zone (Rahn *et al.*, 2002) to 550 °C/5.5 kbar for the staurolite–kyanite zone (Engi *et al.*, 1995).

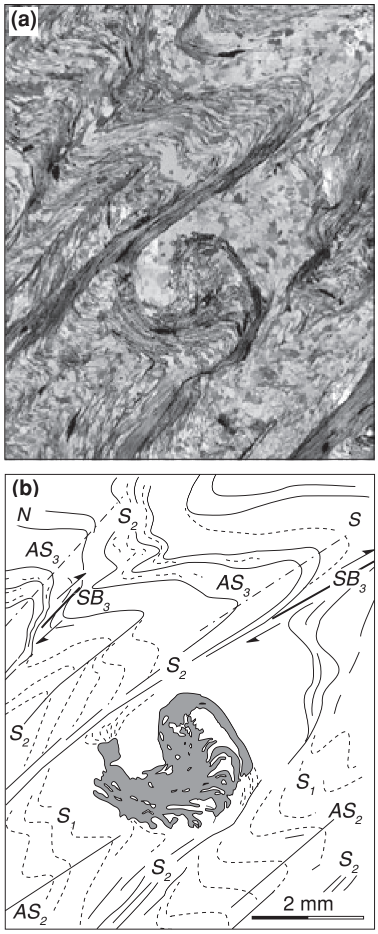

Fig. 2 Photomicrograph (a) and sketch (b) of the same area illustrating the relationship between the snowball garnets and the foliations S_1, S_2 and S_3. AS, axial surface; SB, shear bands.

Analytical procedures

Three-dimensional imaging was obtained by μCT using a high-resolution Skyscan-1072 system (SKYSCAN, Kontich, Belgium) with a conical 100 kV X-ray source. A Cameca SX 50 electron microprobe (CAMECA, Gennevilliers Cedex, France) (beam current of 150 nA at 25 kV) was used for the mapping of chemical elements through wavelength dispersive X-ray spectroscopy (WDS). Crystallographic orientations were collected by EBSD using a Philips FEI XL30 SFEG Sirion scanning electron microscope (Philips, Eindhoven, Netherlands) (probe current of 20 nA for an acceleration voltage of 30 kV).

Three-dimensional geometry

Micro-computed X-ray tomography images reveal that the geometry of most garnets is characterized by a core region, around which two spiral arms are wound over more than 300°. Because of their very elongated shape parallel to the apparent rotation axis, the studied garnets look more like rolled cylinders than snowballs. The core region and the base of the spirals are commonly connected with the adjacent arms by short, curved garnet bridges (Fig. 3a). According to Schoneveld (1977), bridges are created by thin mica-rich layers progressively captured from the surrounding matrix

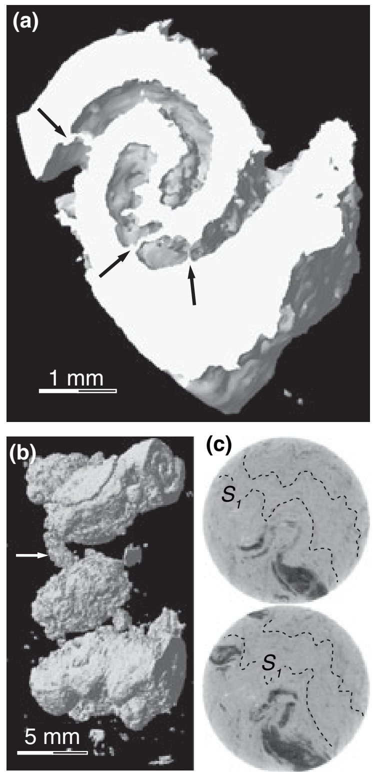

Fig. 3 (a) μCT image of sample Luk_02_5 illustrating the typical spiral morphology of snowball garnets. The core region of the spiral is connected to the arms by thin curved bridges (black arrows). (b) μCT view of three vertically aligned garnets. The two porphyroblasts on top are connected to each other by a thick garnet appendage (white arrow). (c) Selected two-dimensional sections (normal to the cylinder axis) based on μCT data showing trails of garnet grains (in black) mimicking the foliation Se (dashed line) of the host rock.

and dragged towards the centre as the spiral forms. Replacement of mica by garnet is commonly believed to freeze the bridge geometry.

Neighbouring spiral garnets are occasionally linked to each other by appendages (Fig. 3b), consisting of small aligned garnet grains. Selected two-dimensional sections of tomographic images reveal that the trails left by these grains mimic the S_1 foliation (Fig. 3c). Optical microscopy observations indicate that most of these grains occur within mica-rich layers. The correspondence in geometry between the tortuous and crenulated external foliation (S_1) and the alignment of garnet grains replacing mica suggests that the nucleation and growth of garnet continued after D_2 had stopped.

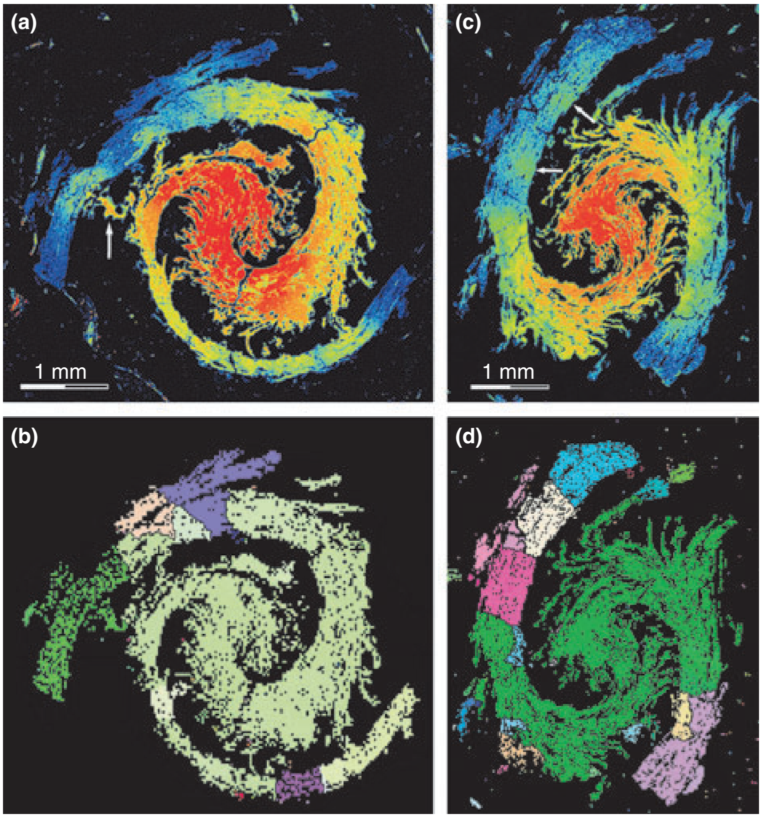

Fig. 4 WDS X-ray maps of Mn (top, concentration decreasing from red to blue) and EBSD crystallographic orientation maps (bottom) for samples Luk_02_1 (a and b) and Luk_02_7 (c and d). Secondary Mn maxima (arrows) are centred in grains with crystallographic orientations different from the one of the core region. In sample Luk_02_1, the primary core orientation is maintained in two segments of the spiral arms connected to the centre by garnet bridges (b, light green), along which a smooth decrease in Mn concentration is observed (a).

Chemical zoning

Compositional zoning is a recurrent characteristic of garnet porphyroblasts, commonly interpreted as a primary growth feature (e.g. Spear, 1993). Because of its very limited partitioning with the other phases present in pelitic schists, Mn is generally considered as the element best reflecting the successive steps of garnet growth. Assuming a local chemical equilibrium along the garnet–matrix boundary and no post-growth intracrystalline diffusion, the gradual decrease in Mn concentration from core to rim is frequently used as a proxy of time reflecting garnet growth history (e.g. Kretz, 1973; Carlson, 1989, 1991; Spear and Daniel, 1998).

X-ray compositional maps show a broadly concentric zoning of most major elements, characterized by a gradual decrease of Mn (Fig. 4a and c) and Ca from core to rim, counterbalanced by a simultaneous increase of Fe and Mg. The strong correlation in the zoning of Mn, Ca, Fe and Mg suggests that these elements achieved local equilibrium during garnet growth, thus justifying the use of Mn as a time marker. Although the variation in Mn concentration shows a roughly concentric pattern, secondary Mn maxima do exist, e.g. in the left spiral end in sample Luk_02_1 (Fig. 4a), as well as, to some extent, in the upwards-oriented spiral termination in sample Luk_02_7 (Fig. 4c).

The gradients on contoured Mn maps of sample Luk_02_1 (Fig. 5) indicate not only a decrease in Mn concentration from core to rim in the centre and along the spiral curvature, but also across two bridges connecting the core to the arms. The patterns observed after considering Mn concentration levels as time lines suggest that the areas of the arms located in the continuation of the bridges crystallized early in the microstructure development, before being reached by the crystallization front advancing along the spiral curvature. In this growth scheme, the bridges served as shortcuts, making the crystallization path from the core to the arms significantly faster. Subsequent growth, either from the bridges or the secondary nucleation sites, led to the formation of the final garnet microstructure.

Crystallographic orientation

Electron backscattered diffraction is used to identify possible changes in crystallographic orientation within the garnet spirals. By assuming a continuous incorporation of atoms onto the pre-existing garnet structure, a single crystallographic orientation would be expected for the whole spiral, as was observed by Ikeda *et al.* (2002) in their X-ray-based texture analysis of snowball garnets of different origins. Our EBSD maps, however, reveal that the snowball garnets from the Lukmanier Pass are composed of several grains with different, distinct crystallographic orientations. The core region and the base of the spiral arms are generally formed by one single, large grain, whereas the arm terminations

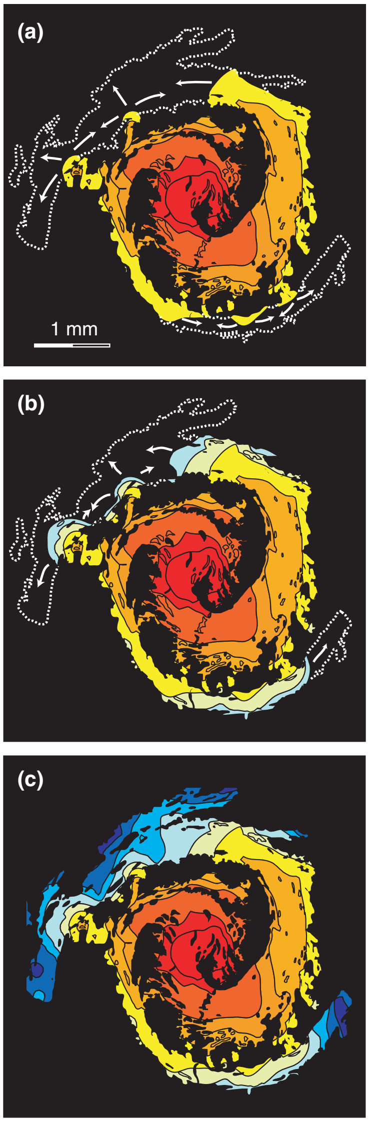

Fig. 5 Contoured Mn maps retracing the growth history of sample Luk_02_1. Arrows indicate the direction of growth.

are made of smaller and often box-shaped crystals separated by straight grain boundaries (Fig. 4b and d). The angular misorientation between those grains is typically a few tens of degrees, indicating that they are not subgrains formed by deformation of the arms. Some of the box-shaped grains contain secondary Mn maxima. Both the difference in crystallographic orientation and the occurrence of additional Mn maxima point to growth from new nucleation sites. Among the end grains, however, some of them do not show any anomalous zoning. This may be explained by the fact that the thin sections used for chemical mapping crosscut these grains at some distance from their nucleation centre.

Garnet grains with different lattice orientations totally fill the spiral terminations in sample Luk_02_7 (Fig. 4d). In sample Luk_02_1 (Fig. 4b), however, the primary core orientation is maintained in an interstitial segment of the upper arm and in the final segment of the lower arm. Both portions are connected to the core by a thin, curved garnet bridge. As previously discussed, based on chemical Mn zoning patterns, these bridges were interpreted as preferential crystallization paths between the core and the arms, suggesting an earlier crystallization of garnet across the bridges. The correspondence in crystallographic orientation between two regions of the spiral separated by grains with different lattice orientations further supports the role of crystallization shortcuts played by mica bridges. For such a crystallization path to occur, the position and final curvature of the spiral arms had to be already acquired before garnet crystallized. Therefore, we suggest that significant parts of the overall geometry were completed relatively early in the microstructure development and that the replacement of mica by garnet in the last portions of the spiral arms was mostly post-deformational.

Discussion and conclusions

Combined chemical and crystallographic analyses provide several pieces of evidence showing that the spiral-shaped overall geometry was already achieved prior to the last stages of garnet crystallization. This strongly supports a final post-kinematic growth of garnet, mainly by replacement of mica.

The mechanism responsible for the first stages of snowball garnet formation is more difficult to assess; however, assumptions can be made on the basis of microstructural observations. During the crustal thickening event (D_2), garnets grew on the overturned limbs of microlithons (Fig. 6) and are aligned in a direction corresponding to the crenulation lineation. This indicates that the first step of garnet crystallization post-dated the beginning of the microlithon formation and occurred when the D_2 deformation was still in progress. The growth of snowball garnets on the overturned limb of microlithons during a single deformation phase is best explained through a single and continuous rotation of garnet grains rather than through an incremental superimposition of foliations resulting from numerous changes in the stress field. Our model suggests that a rotation of 180° may be sufficient to produce a spiral-shaped geometry mimicking an amount of rotation of approximately 300° (Fig. 7). This implies that the final geometry of snowball garnets greatly overestimates the actual extent of rotation. This assumption does not dispute the shear sense in the foliation plane as it is determined by the sense of rotation of the garnet during its initial growth stage.

Our data support the idea that the growth of the snowball garnets from the Lukmanier area cannot be explained by either of the two classical models considered separately. In contrast, this study illustrates that

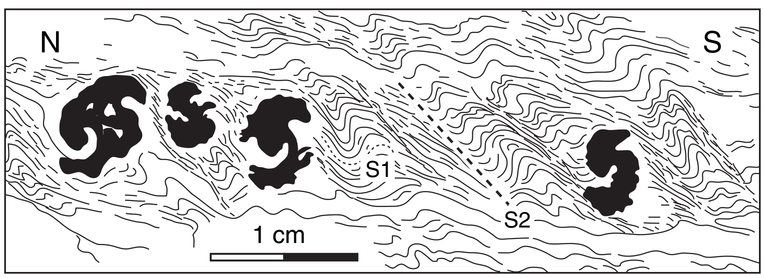

Fig. 6 Sketch cross-section perpendicular to the crenulation axis showing the distribution of snowball garnets relative to S_1 and S_2. Garnet grains are located preferentially on the inverse limbs of microlithons.

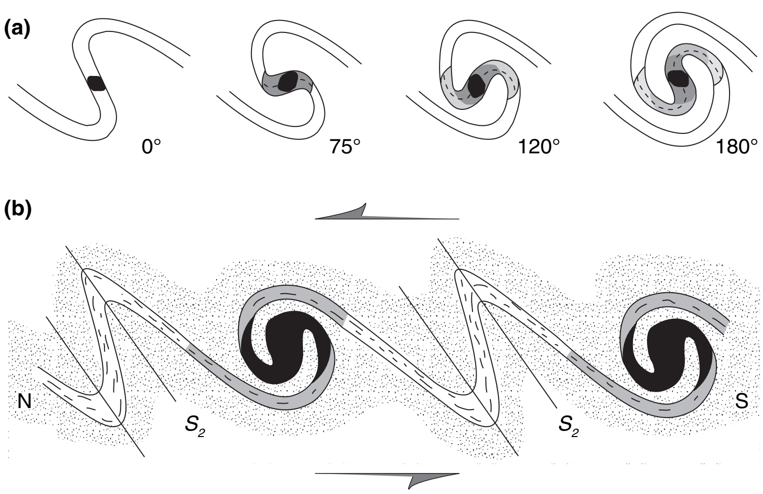

Fig. 7 (a) Growth model proposed for the studied snowball garnets. Starting from a nucleus on the inverse limb of the microlithon, a 180° rotation is sufficient to account for an apparent rotation of about 300°. (b) Idealized sketch showing the alignment of garnet grains in a crenulated rock. Syn-rotational growth is shown in black, post-deformation growth in grey.

snowball garnets may undergo a complex growth history in which both end-member mechanisms can operate consecutively. Additional chemical, structural and crystallographic analyses on a larger sample population are required to better understand the mechanism of snowball garnet formation, and to determine if our observations are valid on a larger scale.

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