Exaggerated grain growth in the metamorphism of monomineralic rocks

BY

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Abstract. It is shown that porphyroblasts in dunites, dolomites, and anorthosites formed during metamorphism by exaggerated grain growth. Normal grain-growth inhibiting factors are accessory constituents, oriented structures, and annealing twins.

According to the traditional metallurgical and more recent ceramic and mineralogic usage, recrystallization is the process by which a new generation of essentially strain-free grains grow at the expense of the originally badly deformed crystals. Grain growth is the increase of grain-size during metamorphism; the driving force is the interfacial free energy. BUERGER and WASHKEN (1947) pointed out that the metamorphism of monomineralic rocks usually takes place by recrystallization and grain growth in the solid state. Dunites, anorthosites, limestones, and quartzites commonly show distinct signs of grain growth, as demonstrated by VOLL (1960). VERNON (1965) described grain growth phenomena of plagioclase in mafic gneisses. STANTON (1964) showed that metamorphic ores consisting of single-phase aggregates of either pyrite, pyrrhotite, sphalerite, or galena have grown according to the same principles. By normal grain growth, the average size of the grains increases, and the size of the individual grains is fairly uniform. If, on the other hand, a small fraction of the grains attains a large size by growing more rapidly than others, the process is called exaggerated (abnormal, discontinuous) grain growth (see e.g. HILLERT 1965). It is the purpose of the present note to draw attention to porphyroblastic structures in monomineralic rocks indicative of exaggerated grain growth.

An area of dunite at Åheim, Sunnmöre in West Norway, contains a number of nearly spherical monocrystals of olivine varying in size

Fig. 1. Exaggerated grain growth in dunite. The central large grain having thirteen sides has grown by the migration of its boundaries towards their centres of curvature. The black grains are olivine in extinction position. The composition of the small and the large olivine crystals is about Fo 12. Nicols +. × 29.

from about 1 mm up to 15–20 mm. The average grain size of the matrix is 0.5–1 mm. In stream gravel of the dunite area, similar olivine crystals, about 10 cm in diameter, have been found. The dunite contains small amounts of chlorite, diopside, tremolite, and iron ores. The fact that the angles between olivine grain boundaries are usually about 120 degrees is attributed to nearly isotropic grain boundary energy. Most boundaries are curved, the large grains always having convex boundaries when observed from the inside (Fig. 1). Olivine/olivine boundaries are commonly perpendicular to the basal plane of chlorite, demonstrating a high dihedral angle and high interfacial energy of the boundary between olivine and the 001-plane of chlorite. This may be an important factor in preventing normal grain growth during metamorphism (VOLL 1960).

Exaggerated grain growth has been obtained experimentally in annealed calcite aggregates (GRIGGS *et al.* 1960). Similar porphyroblasts are sometimes observed in the dolomites of North Norway, although the structures are not so spectacular as in the dunites. The equilibrium angles at triple junctions and the convex boundaries of the large grains indicate the nature of the porphyroblasts. The matrix, as well as the large grains, is completely unstrained, both in the dolomite and the dunite, so the growth is in no way related to strain-induced boundary migration.

The theoretical basis for the understanding of normal and exaggerated grain growth in metamorphic rocks is the result of work done in metallic and ceramic systems (BURKE and TURNBULL 1952, BURKE 1959). It has been shown that the rate of grain boundary movement during grain growth is inversely proportional to the radius of the curvature of the boundary, or, in other words, inversely proportional to the average grain size: $dD/dt = K/D$, where D is the average diameter of the grains. In principle, therefore, if time does not put an end to the growth as in many geological processes, grain growth will continue until a single-phase polycrystalline rock becomes a single giant crystal. Such rocks do not exist, because in addition to the diminishing rate of growth as time progresses — approaching zero — there is usually a limiting grain size due to the presence of other minerals (or pores) which may inhibit grain growth. Normal grain growth stops when $D = d/f$, where D again is the average diameter of the grains, d the average diameter of the inclusions, and f the volume fraction of the inclusions. Evidence of the impeding effect of mineral inclusions is offered by VOGT (1940), who demonstrated that the grain size of metamorphic pelitic rocks in the Trondheim area decreases with increasing content of carbonaceous matter. The ability of small amounts of graphite to restrict grain growth has been confirmed experimentally in hot-pressed BeO (LANGROD 1965). Other examples of grain-growth inhibiting inclusions in metamorphic rocks are given by VOLL (1960). It appears that a prerequisite for the occurrence of exaggerated grain growth in metallic and ceramic systems is the presence of inclusions or pores. Because the growth force is proportional to $N = 6$, where N is the number of sides of the grains, a large grain, which for topological reasons has more sides and more curved boundaries, may be able to grow past the impurities. This grain then consumes its smaller neighbours, the boundaries of which are locked by the inclusions. As monomineralic rocks are never strictly single-phased, but contain accessory

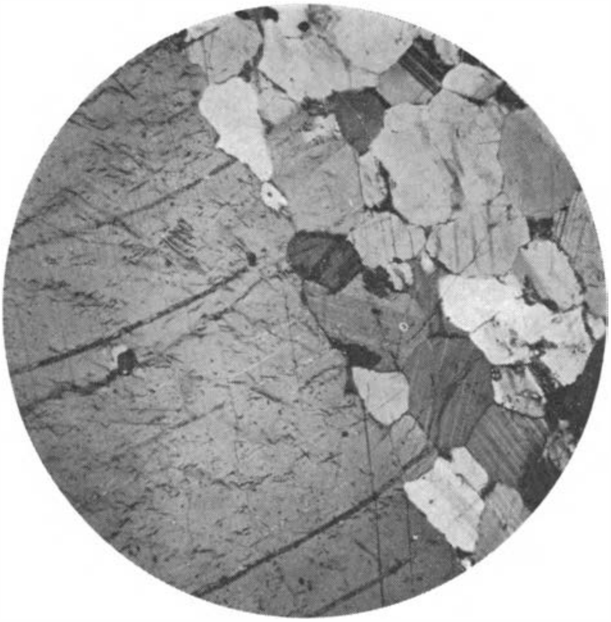

Fig. 2. Porphyroblast of plagioclase in anorthosite. The composition of the small grains is similar to the large one and about An 43. The twins are probably annealing twins, that is to say they originated by grain growth. Some potash feldspar commonly occurs along grain boundaries, especially at triple junctions. Nicols +. × 22.

constituents of various kinds, the above explanation may also apply to natural rocks. An additional factor may be the effect of an oriented metamorphic structure. The Åheim dunite is slightly foliated and contains lattice-oriented olivine grains (PHILLIPS 1938). This implies the presence of low-energy boundaries of low mobility and a grain which is differently oriented from the majority will grow more easily. Similarly, an inhomogeneous distribution of accessories which assume the role of grain-growth inhibitors may explain some cases of grain growth, especially in the absence of engulfed accessories in the interior of the large grains.

As expected from the grain boundary energy model, the shape of the porphyroblasts formed by exaggerated grain growth is more or less spherical (Fig. 1). Porphyroblasts of plagioclase in the anorthosite of the Egersund region, which in all likelihood are formed by exaggerated grain growth, commonly appear to have an idiomorphic outline. The boundaries, however, are not perfectly straight, but form grooves at the intersections with the boundaries of the smaller grains (Fig. 2) showing adjustment to equilibrium angles. Twinning according to the albite law is very common. Following an argument proposed by FULLMAN and FISCHER (1951) that 'annealing twins may form during grain growth when the free energy of the boundaries between a grain's neighbours and its twin would be less than that of the boundaries between the neighbours and the grain itself', it may be suggested that this reduction in the total interfacial free energy (the driving force for grain growth) might be an important restriction to grain growth in anorthosites. Euhedral porphyroblasts of gypsum in fine-grained gypsum are frequently observed (GRIGOR'EV 1965). Straight boundaries over large distances may, theoretically at least, be explained in terms of anisotropic grain boundary energy. A more likely solution to the problem, explaining euhedral exaggerated grain growth in some ceramic systems, may according to KOOY (1962) lie in the presence of a fluid phase having a small dihedral angle. Grain growth may then take place by a solution and precipitation process, and the grains will display the euhedral shape characteristic of minerals solidified from the melt.

It is probable that exaggerated grain growth frequently occasions porphyroblastesis in metamorphic monomineralic rocks. Is not the porphyroblastic structure observed in metamorphic evaporites sometimes the result of such processes? However, there is a definite need for experimental studies to find out what controls grain growth phenomena in natural rocks.

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A note on the interpenetration of detrital quartz grains during the formation of sedimentary quartzites

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Abstract. It is suggested that contrasting degrees of quartz interpenetration in a small sample of sediment are due to non-uniform wetting of the grains by pore water.

Compaction of sand grains because of increasing pressure occasioned by burial results in a volume reduction of the sediments. Slight burial tends to rearrange the sand grains to give higher packing density and lower pore volume resulting in a permeable sandstone in which the quartz grains have mutual, tangential contacts. This is achieved by the grains sliding over one another. With increasing depth of burial,