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Crystallization of orbicular rocks exemplified by the Slättemossa occurrence, southeastern Sweden

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Abstract – The orbicular rock at Slättemossa, southeastern Sweden, has a quartz monzodioritic composition. The cores of the orbicules crystallized directly from the orbicule-forming magma; cores made up of xenoliths have not been observed. Outside the core follow first an inner mafic, a felsic and then an outer mafic shell. The orbicules occur in a matrix, which is similar to the core. They grew simultaneously and show an almost perfect parallelism in evolution. After initial 'normal' crystallization of the magma, superheating probably triggered by a sudden addition of volatiles destroyed earlier formed nuclei and also affected the already crystallized part of the rock. Cooling caused heterogeneous nucleation and rapid crystallization, which formed the inner mafic shell. This is enriched in mafic minerals, especially biotite, compared to the core. At the same time the grain size becomes significantly smaller. Depletion in mafic components, possibly intensified by a sudden change in physical conditions, destabilized biotite and amphibole crystallization, causing oversaturation in plagioclase components, forming a felsic shell having a sharp boundary with the mafic shell. Plagioclase is extremely altered. Mafic minerals were then stabilized, probably due to depletion of plagioclase components, and an outer mafic shell formed. With the return to homogeneous nucleation, matrix formation concluded the crystallization. Orbicules might have moved in the magma causing some squeezing of magma surrounding the orbicules, but major movements involved the settling of the whole package of orbicules and matrix in the surrounding non-orbicular magma.

Keywords: orbicular, monzodiorite, Proterozoic, Sweden.

1. Introduction

Orbicular rocks are conspicuous but rare textural varieties of plutonic rocks forming tiny volumes in larger plutons. They consist of a matrix of variable composition and rounded, often concentrically zoned bodies, the orbicules. They are seldom more than a few hundred square metres in areal extent and have in many cases only been found as erratic boulders. The reason for their restricted volume is doubtless that specific conditions govern their crystallization (see, e.g. Leveson, 1963; Vernon, 1985; Ort, 1992; Decitre, Gasquet & Marignac, 2002). The orbicular rocks near Deshai, Pakistan, exemplify a less common occurrence. Orbicules occur in close-packed groups, separated by the dioritic country rock containing occasional orbicules. These outcrops are found along an approximately 1500 metres long steep fault (Symes, Bevan & Qasim, 1987). In addition, Symes, Bevan & Qasim (1987) report a smaller outcrop of a more coherent orbicular rock about a kilometre from the main outcrops. They give no data on the original orientation of the orbicular rocks.

Lahti (2005) reviewed the orbicular rocks of Finland, showing that they occur in all types of compositions from carbonatite to ultramafic and granitic rocks. Finland, with 90 reported occurrences of orbicular rocks, has a large proportion of the reported localities in the world. In some rocks, the orbicules are simple spheroids, whereas in other rocks they consist of several concentric shells. Various mechanisms are offered to explain their origin; today, magmatic models are generally preferred. An orbicule encompasses much of the crystallization history of the rock in a self-contained body, which is of special interest from a magmatic point of view. The orbicular rock at Slättemossa, southern Sweden, which is discussed in this contribution, is certainly of magmatic origin (see below).

Holst & Eichstädt (1884) and Bäckström (1894) first described the orbicular rock at Slättemossa, although Erdmann (1848) had previously mentioned the occurrence of an erratic boulder, the source of which was never found. Persson (1989) mapped the area recently, but did not specifically investigate the orbicular rock.

We present a more complete petrographic and mineral chemical description of the orbicules and their matrix. From the descriptions of orbicular rocks occurring in various settings, it is clear that no single model can explain all of their different varieties. The purpose of the present contribution is primarily to understand the formation of the orbicular rock at Slättemossa. Many, but not all, of our conclusions can be generalized to other occurrences.

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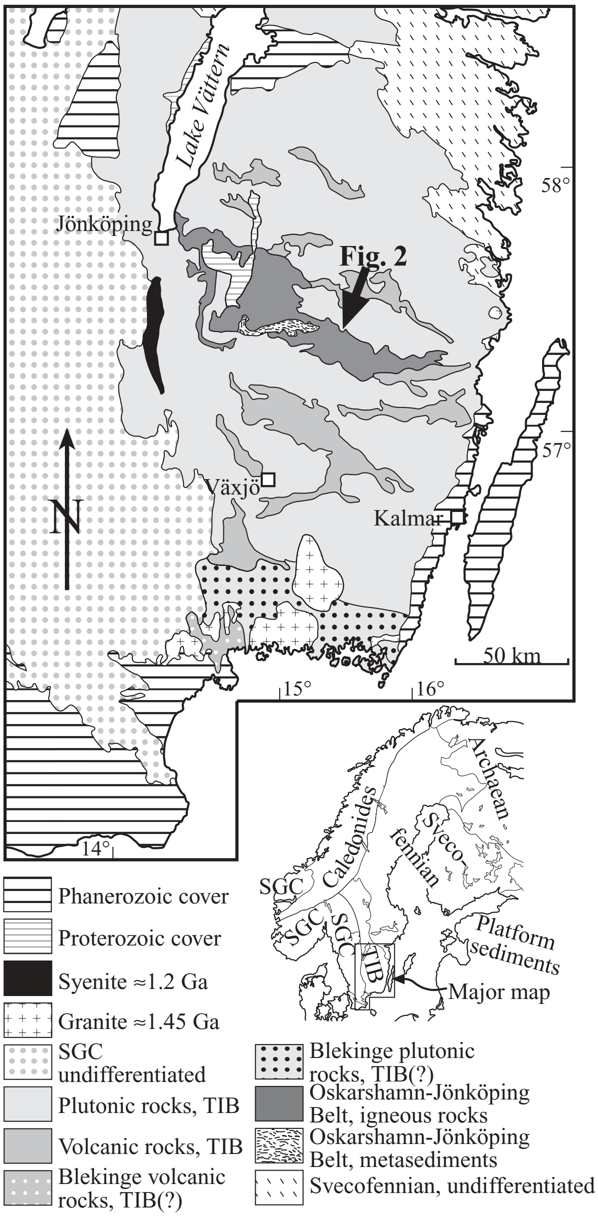

Figure 1. Geological map of southeastern Sweden showing the southern part of the Transscandinavian Igneous Belt and its northeastern boundary towards the Svecofennian, simplified from Lundqvist *et al.* (1994). The position of Figure 2 is marked. TIB – Transscandinavian Igneous Belt; SGC – Southwest Scandinavian Gneiss Complex (made up of the Western and Eastern segments).

2. Geological setting

The Baltic Shield comprises a number of terrains (cf. Fig. 1). Archaean rocks are restricted to the eastern and northern parts of the Shield. The Palaeoproterozoic Svecofennian Orogen (1.9 to 1.8 Ga) forms the central part of the Shield, fringed in the west and southwest by the Transscandinavian Igneous Belt. To the west a slightly younger terrain occurs, the Southwest Scandinavian Gneiss Complex, which was metamorphosed during Sveconorwegian–Grenvillian (*c.* 1 Ga) times. The Transscandinavian Igneous Belt consists of dominating granites tending towards monzonite and syenite and roughly coeval, dominantly felsic volcanic rocks. The rocks are bimodal with rather abundant small gabbroic and dioritic bodies scattered among the felsic rocks. Except for localized shear zones, the rocks are either undeformed or merely weakly deformed. Volcanic rocks have escaped erosion where down-faulted into graben-like structures. In many cases, volcanic textures are well preserved. According to Åhäll & Larson's (2000) compilation, the Transscandinavian Igneous Belt rocks intruded during a rather long time span. The main part of the Transscandinavian Igneous Belt granitoids intruded between 1.81 and 1.77 Ga. A younger, principally western, extension gives ages between 1.72 and 1.66 Ga. Some authors (Åhäll & Larson, 2000; Åhäll, Connelly & Brewer, 2002) wish to exclude a few older intrusions (≈ 1.85 Ga) from the Transscandinavian Igneous Belt magmatism; others (Andersson & Wikström, 2001) prefer to include them.

In the Transscandinavian Igneous Belt, a belt of slightly older rocks, the Oskarshamn–Jönköping Belt, occurs (Fig. 1). It consists of metasedimentary, granitoid and volcanic rocks including pillow lavas. Mansfeld (1996) reports two age determinations on zircons from rocks occurring in this area. A foliated tonalite gives 1834 ± 3 Ma, whereas a rhyolite resting on this tonalite gives an age typical for Transscandinavian Igneous Belt volcanics, 1800 ± 8 Ma. Åhäll, Connelly & Brewer (2002) obtained 1823 ± 2 Ma for another tonalite from the same area.

The area around Slättemossa is heavily forested and covered with thin glacial drift, but small outcrops are common. Figure 2 is a simplified geological map (Persson, 1989) showing the area around Slättemossa and a more detailed sketch of one of two outcrops of the orbicular rock. Two small outcrops of a biotite-rich, foliated, rather mafic rock are found close to the orbicular rock. No contacts with the former rock are exposed. According to fieldwork for the present contribution, the size of this mafic body is appreciably smaller than indicated on the original map (Persson, 1989). The very small magnetic anomaly associated with this mafic rock compared to those associated with other mafic bodies (Persson, 1989) confirms our interpretation.

3. Petrographic description of the orbicular rock

The Slättemossa orbicular rock is included within the Transscandinavian Igneous Belt rocks, but only about 600–700 metres from the contact with the Oskarshamn–Jönköping Belt. It is exposed in two outcrops of between 15 and 20 m^2, approximately 50 metres apart, along a line striking at 65°. It is not known whether the two outcrops belong to one single body of orbicular rock or to two different bodies. The latter interpretation is most probably correct. The rock is essentially matrix supported, but normally the

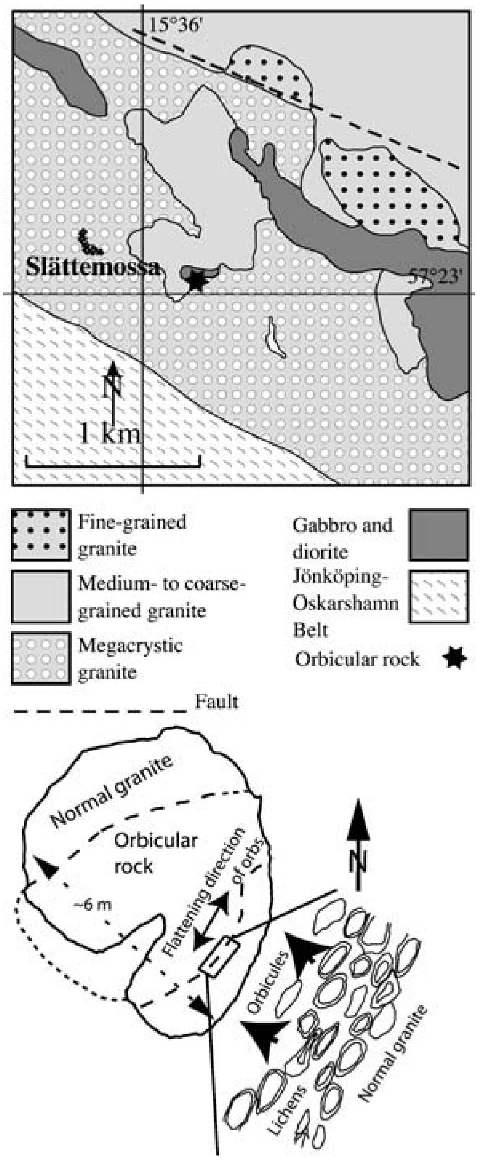

Figure 2. Map showing the surroundings of the orbicular rock at Slättemossa, simplified and revised after Persson (1989). The present revision concerns the mafic rock occurring to the northwest of the orbicular rock, which according to the original map should be a larger body. Due to poor exposures its size might be overestimated. The hamlet of Slättemossa is shown with hatch marks. Outcrop sketch: The dashed line shows the contact with the normal granite. The western boundary (dotted line) is uncertain. The flattening direction coincides in both outcrops; traced from a photo.

distance between adjacent orbicules does not exceed 1 cm; in most cases only a few millimetres separate the orbicules at their closest points (Fig. 3a, b). Zones of slightly flattened orbicules occur, with a flattening direction that is similar in both outcrops (cf. Fig. 2), and that is subparallel to the contact with the rocks of the Oskarshamn–Jönköping Belt. Most orbicules have a diameter of approximately 7 cm; a few are smaller. In many cases, this might be due to cutting effects. A few orbicules reach about 10 cm in diameter. In the southern outcrop, a few larger orbicules (up to 20 cm) occur, with cores that are larger than normal, but outer shells are comparable with the majority of the other orbicules.

At the southern outcrop, a few metres of the contact between the orbicular rock and the country rock granite are exposed. The orbicules are slightly flattened almost parallel to the contact (Fig. 2). They start to occur along an approximately straight line without any definable contact between country rock granite and the matrix of the orbicular rock. Compared to the normal Småland granite, the granite occurring close to the orbicular rock is poor in quartz.

In the Slättemossa occurrence, all orbicules share similar features (cf. Fig. 3a, b). They consist of a core, with a diameter of 2–5 cm. The cores are invariably made up of an intermediate igneous rock (cf. Fig. 4) of approximately monzodioritic composition. The cores are too small to allow an accurate determination of their compositions using point counting; occasional megacrysts may lead to erroneous plots in a Streckeisen diagram. Cores consisting of xenoliths or large megacrysts have not been observed. The content of mafic minerals in the core increases over a distance of approximately 5 mm, giving rise to an inner mafic shell of 3 to 8 mm in width (Fig. 4). The inner boundary with the core is often irregular, whereas the outer one with a felsic shell (Fig. 4) is macroscopically sharp and smooth. The felsic shell varies in width between 3 and 10 mm. One or two extremely thin (< 0.2 mm) discontinuous mafic shells may occur in the felsic shell. The boundary with an outer mafic shell is rather indistinct (Fig. 4). The amount of mafic crystals increases from zero to that typical for the mafic shell ($\approx$ 35–50 %) over a distance of a millimetre. This outer mafic shell is between 3 and 8 mm thick. The boundary against the matrix is sharp, even if undulating. The orbicular rock is grey to dark grey; in places the matrix has a reddish shade.

The core is medium grained and dominated by feldspars; plagioclase dominates strongly over K-feldspar. K-feldspar usually occurs as small microcline-twinned interstitial crystals. Quartz is subordinate, less than 10 % of the core, but the amount varies from core to core. It generally occurs as clusters of several small grains. Most of the plagioclase is strongly sericitized, and unaltered crystals of plagioclase occur sparsely. Plagioclase crystals are subhedral, normally approximately between 4 and 5 mm in length and between 2 and 3 mm in width; occasional larger crystals are found. The amount of mafic minerals varies between 10 and 20 %. Irregular crystals of amphibole with strongly sutured outlines dominate. They are often poikiloblastic with inclusions of quartz and feldspars. The amphibole is pleochroic from dark bluish green to pale green. Biotite occurs but is subordinate to amphibole. It is often strongly altered to penninite. It may be bent, and similarly to the amphibole, it appears to have

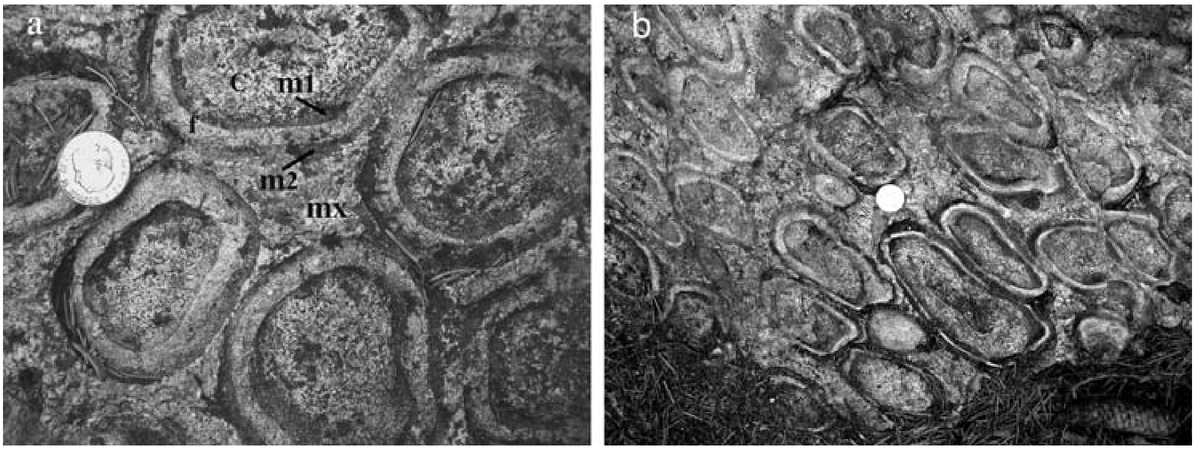

Figure 3. Weathered surface of the orbicular rock having (a) approximately spherical and (b) flattened orbicules. The mafic shells weather strongly. Normally, thin veneers of matrix material are found between neighbouring orbicules. c – core; m1 – inner mafic shell; m2 – outer mafic shell, mx – matrix, f – felsic shell. The mafic shells do not show up clearly due to weathering. Diameter of coin is 24 mm.

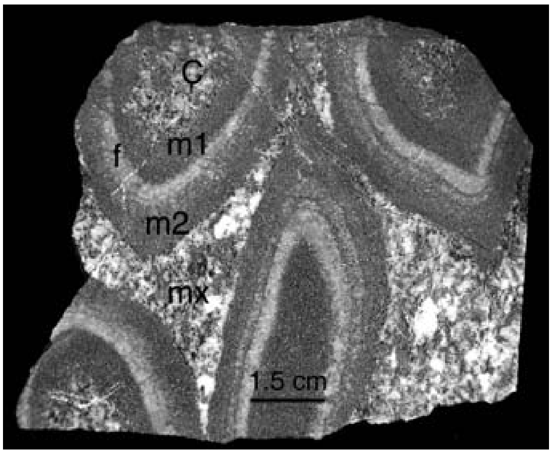

Figure 4. Sawn face of the orbicular rock. The apparent lack of a core in the large orbicule in the middle is an effect of cutting. Note the rather irregular outline of the core and the textural similarities between core and matrix. c – core; m1 – inner mafic shell; m2 – outer mafic shell; f – felsic shell; mx – matrix.

been partly dissolved. Epidote occurs as small rounded grains often associated with amphibole. Probably, epidote is a primary phase (cf. Owen, 1991), but this is not certain for all crystals.

The amount of felsic minerals, the grain size and the degree of plagioclase alteration all decrease towards the inner mafic shell. It is not always possible to define an exact boundary in micro-scale (cf., however, Fig. 5a). In the mafic shell, about a third of the minerals are either amphibole or biotite. The ratio of amphibole to biotite is markedly lower than in the core. In some orbicules, almost no amphibole persists; in others the ratio approaches 0.5. Biotite crystals close to the core often tend to a radial arrangement, while in the outer part they have a tendency to be tangentially oriented (cf. Fig. 6). Alteration to chlorite varies from modest to almost complete. The degree of sericitization of the plagioclase is still high but markedly lower than in the core and even almost fresh crystals occur. Sparse crystals of quartz are found with the feldspar. Epidote occurs as an accessory mineral.

The boundary with the felsic shell is always sharp (Fig. 5b), though some crystals from the inner mafic shell may protrude into the felsic shell. The felsic shell is almost exclusively made up of sericitized feldspar; almost no unaltered feldspar remains (cf. Fig. 7). Small amounts of mafic and opaque minerals occur. Biotite is altered to chlorite; epidote occurs associated with amphibole. Minute opaque minerals occur as irregular, scattered crystals, but also with a concentration into extremely thin (< 0.1 mm), discontinuous shells of tangentially ordered crystals.

The outer mafic shell is similar to the inner one, with a boundary that is not very well defined at the micro-scale (Fig. 5c). Feldspar alteration is ubiquitous but not as strong as in the core or the inner shells. Small amounts of quartz occur together with plagioclase. Amphibole makes up between 30 and 35 % of the shell. It is associated with biotite and with sparse, small crystals of epidote. The ratio between amphibole and biotite varies among the orbicules. Epidote appears to be a primary magmatic phase (cf. Owen, 1991). In some orbicules, biotite is strongly tangentially oriented, in others orientation is only weakly developed. In some cases, the degree of chloritization is strong, which may obliterate the boundary between shells.

Typical for both the core and the shells are irregular crystal forms suggestive of dissolution. This is conspicuous for biotite and amphibole crystals but less so in the strongly altered feldspar crystals. In the felsic shell, alteration obliterates grain boundaries giving the whole area the appearance of a light-coloured homogeneous mass.

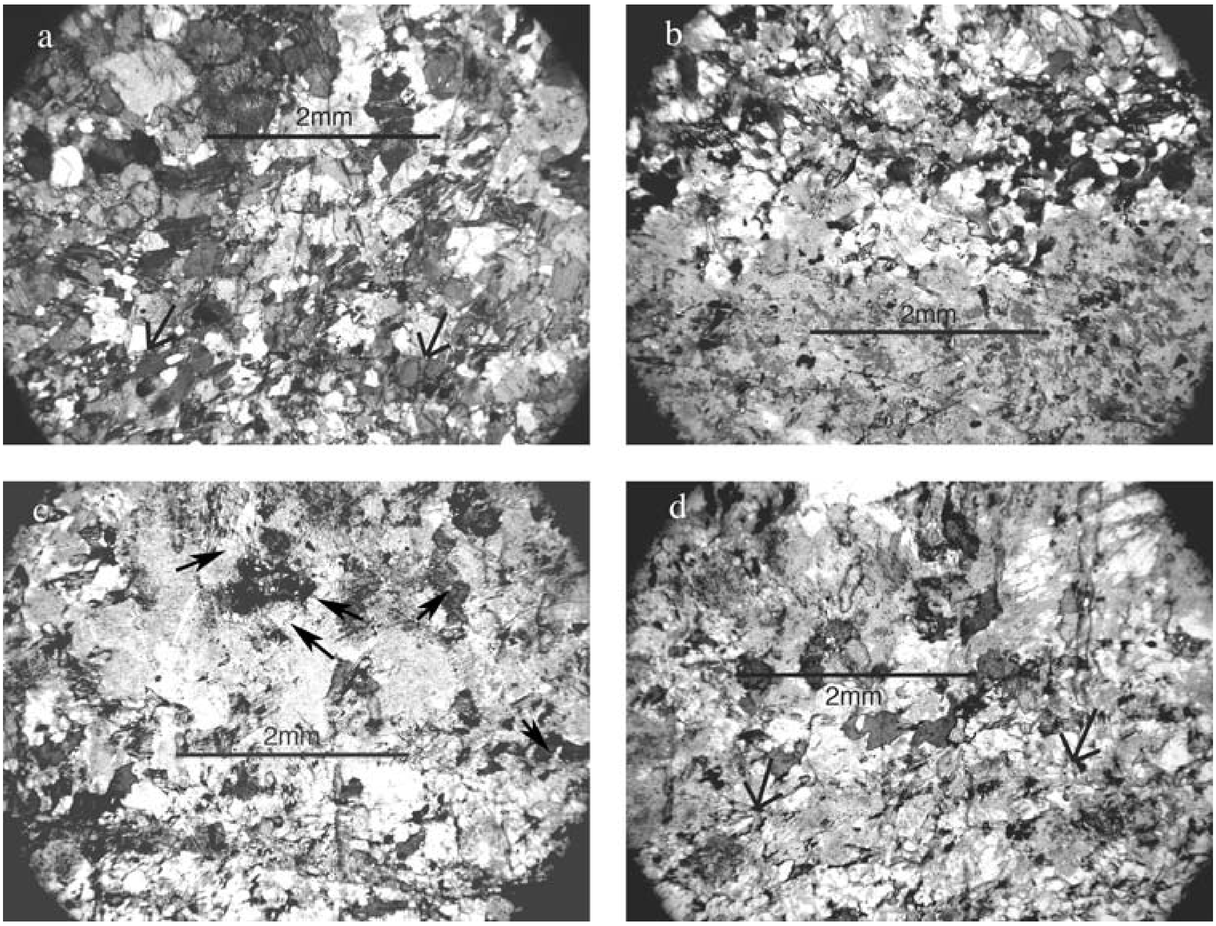

Figure 5. Micro-photos of the orbicules. (a) Boundary between the core and inner mafic shell; in this case the boundary is fairly well defined. The boundary is marked with two black arrows. Note difference in grain size (crossed polars). (b) Boundary between inner mafic and felsic shells; the grey colour of the felsic shell is due to strong alteration of plagioclase (parallel light). (c) The boundary between the felsic and the outer mafic shells is less well defined with an increasing amount of mafic minerals in the felsic shell. The grain size decrease is rather abrupt (parallel light). (d) The boundary between the outer mafic shell and the matrix is most easily seen as an increase in grain size (arrows, parallel light).

Macroscopically, the boundary between the outer mafic shell and the matrix is sharp (cf. Figs 3, 4); at the microscopic scale, however, it is most often gradual. The grain size in the matrix is comparable to that in the core, with a majority of the grains around two millimetres but with occasional megacrysts. Feldspar dominates over mafic minerals. Most of the plagioclase is strongly altered. In some sections, fresh plagioclase occurs as isolated islands in a strongly sericitized matrix crystal. Microcline and quartz occur in higher amounts than in the orbicules. The quartz content exceeds 10 % in some sections, and may occur as myrmekitic intergrowths. Amphibole and biotite make up about 20 % of the matrix. The ratio between these two mafic minerals varies strongly. Chloritization varies from modest to almost complete. An apparent correlation between strong sericitization and chloritization is noted. In addition, small amounts of epidote, titanite, apatite and zircon occur. Sporadic zircon crystals reach up to a millimetre in length. The mineral composition suggests a monzodioritic rock composition.

4. Mineral chemistry

Mineral compositions were determined with a Link eXL EDS system equipped with a Ge-detector mounted on a JEOL JSM-6400 scanning electron microscope. The applied acceleration voltage was 18 kV, analytical time 100 seconds (live) with a dead time of about 25 %. Natural and synthetic mineral standards were used. The instrument was calibrated using a Co-metal standard.

Amphiboles from the core, the inner and outer mafic shells and the matrix were analysed. We have no analyses for hydrogen and halogens, thus all analyses are based on 23 oxygens (46 negative charges in the silica-oxygen framework). Small amounts of chlorine do, however, show up in many X-ray spectra. Cations cannot be allotted to the various positions in an amphibole without knowledge of the Fe^{3+}/Fe^{2+} ratio.

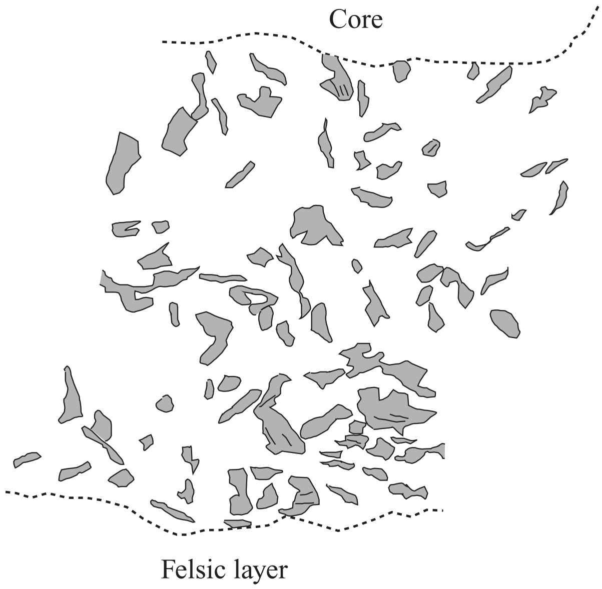

Figure 6. Outlines of biotite and chlorite crystals in the inner mafic shell. At the core boundary, biotite has a tendency to be oriented at high angles to the boundary, but close to the felsic shell it tends to low-angle orientations. The inner mafic shell is approximately 5 mm wide. Traced after three micro-photos.

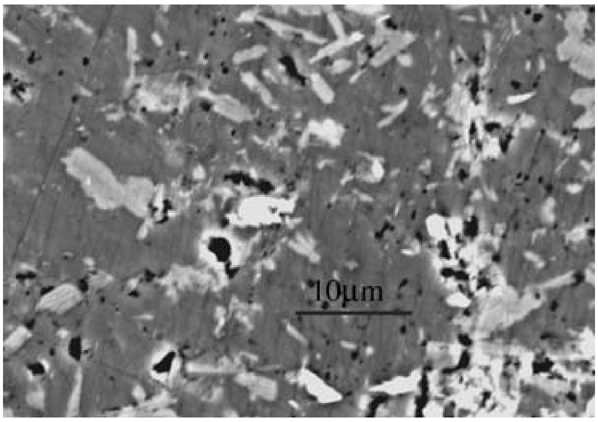

Figure 7. Backscatter image of felsic layer. Dark grey is albite-rich plagioclase (approx. an_{15}); lighter grey is phyllosilicates of various compositions (paragonite, muscovite and margarite components). Very light areas contain some Fe and are probably composed of trioctahedral phyllosilicates and possibly epidote-group minerals. The phases are too small to be analysed. X-ray and backscatter images do not allow a sufficient high resolution in silicate material.

We estimated the content of ferric iron from crystal chemical constraints following the scheme suggested by Leake *et al.* (1997): Al is assumed to occupy tetrahedral positions not occupied by Si. There is always an excess of Al, so no ferric iron has been considered for this position. Fe^{2+}, Fe^{3+}, Mg, Mn, Ti and remaining Al fill the M1- to M3-positions. Ca is restricted to the two M4-positions; M4-positions not occupied by Ca are filled with Mn or Fe^{2+}. The only restriction on the A-occupancy is that it is less than or equal to one. Errors in the ferric estimate are large, since

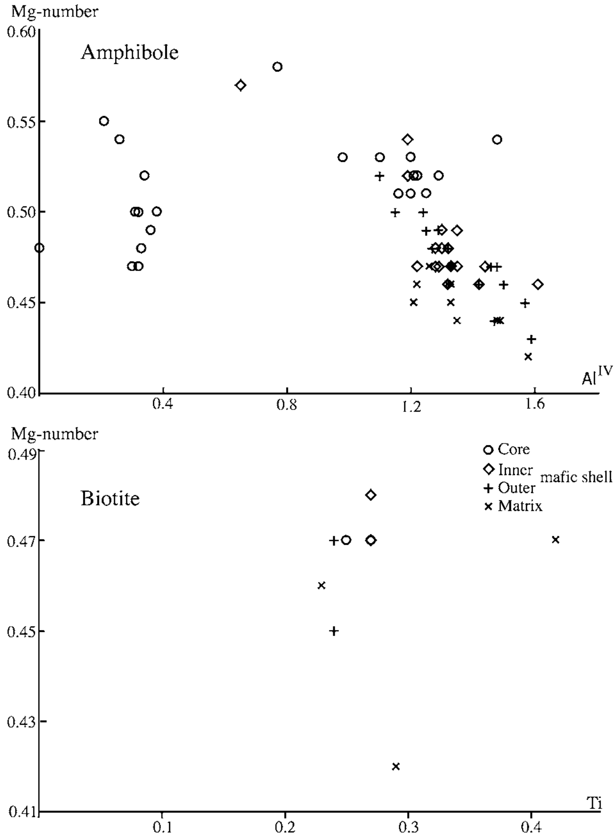

Figure 8. Plots of Mg-number (molecular Mg/(Mg + Fe)) v. number of tetrahedral Al (based on 23 oxygens) in Ca amphibole. A few analyses of biotite (Mg-number v. the number of Ti ions based on 22 oxygens) show a less well-defined trend.

most analytical errors accumulate in this estimate. In the core, amphibole compositions straddle the boundaries between magnesiohornblende, edenite and ferroedenite. In the two mafic shells and the matrix, there is almost no magnesiohornblende; ferroedenite is the dominating amphibole together with some ferrohornblende and tschermakite.

Table 1 displays a few typical analyses. Mg-numbers versus tetrahedral Al of amphibole are plotted in Figure 8. From the figure it is apparent that two populations of amphiboles, with high and low contents of tetrahedral aluminium, occur in the core. The reason for this is not known. This difference has not been observed under the optical microscope. The Mg-number decreases from the core towards the matrix (Fig. 8) even if Mg-numbers overlap in neighbouring shells. The regular decrease of the Mg-number and the similarities among different orbicules suggest that original compositions were Mg-richer in the cores than in the outer parts of the rock. We cannot exclude the possibility that some exchange of ions may have taken place, which, however, should tend to reduce rather than to amplify existing differences.

Biotite is almost always chloritized; it is thus difficult to obtain good analyses. The composition of restite

Table 1. Typical amphibole compositions

	Core		IMS		OMS		Matrix		Enclave	
SiO_2	46.09	45.97	45.85	45.23	43.45	43.98	43.89	44.68	44.00	43.77
TiO_2	0.66	0.48	0.74	0.67	0.56	0.62	1.69	0.92	3.26	3.19
Al_2O_3	8.58	8.95	9.45	9.61	9.90	10.36	8.62	8.57	9.92	9.65
FeO	19.67	19.29	20.05	20.54	21.12	21.98	21.47	21.26	15.42	14.39
MnO	0.50	0.59	0.68	0.59	0.67	0.65	0.72	0.61	0.39	0.38
MgO	10.10	9.95	9.37	9.30	8.62	8.40	8.09	8.47	12.28	12.70
CaO	12.16	12.42	12.63	12.58	12.41	12.47	11.9	12.22	11.37	11.58
Na_2O	1.09	1.01	1.09	1.10	1.12	1.12	1.03	0.93	2.09	2.05
K_2O	1.01	1.03	1.15	1.14	1.22	1.28	1.34	1.22	1.05	1.01
Total	99.86	99.69	101.01	100.76	99.07	100.86	98.9	99.13	99.78	98.73
Cations per 23 oxygen atoms										
Si	6.80	6.78	6.72	6.65	6.52	6.50	6.67	6.74	6.45	6.46
Al^{IV}	1.20	1.22	1.28	1.35	1.48	1.50	1.33	1.26	1.55	1.54
Al^{VI}	0.29	0.34	0.35	0.31	0.28	0.31	0.21	0.26	0.17	0.14
Ti	0.07	0.05	0.08	0.07	0.06	0.07	0.19	0.10	0.36	0.35
Mg	2.22	2.19	2.05	2.04	1.93	1.85	1.83	1.90	2.68	2.80
$Fe^{M1\text{-}M3}$	2.15	2.10	2.21	2.16	2.13	2.22	2.56	2.38	1.79	1.71
$Mn^{M1\text{-}M3}$	–	0.03	0.06	0.05	0.08	0.06	0.03	0.06	–	–
Fe^{3+}	0.26	0.29	0.25	0.37	0.52	0.49	0.17	0.29	–	–
Fe^{M4}	0.02	–	–	–	–	–	–	–	0.10	0.07
Mn^{M4}	0.06	0.04	0.02	0.02	–	0.02	0.06	0.02	0.05	0.05
Ca^{M4}	1.92	1.96	1.98	1.98	2.00	1.98	1.94	1.97	1.79	1.83
Na^{M4}	–	–	–	–	–	–	–	–	0.06	0.05
Ca^{A}	–	–	–	–	–	–	–	–	–	–
Na^{A}	0.31	0.29	0.31	0.31	0.32	0.32	0.30	0.27	0.53	0.54
K^{A}	0.19	0.19	0.21	0.21	0.23	0.24	0.26	0.23	0.20	0.19

IMS – inner mafic shell; OMS – outer mafic shell.

biotite in composite biotite–chlorite intergrowths has probably changed from that of the original biotite due to ion redistribution between biotite and newly formed chlorite. Nevertheless, the outer parts of the orbicules appear to be poorer in magnesium than the cores.

Plagioclase is strongly altered. Analytical results suggest muscovite ($KAl_2AlSi_3O_{10}(OH)_2$), margarite ($CaAl_2Al_2Si_2O_{10}(OH)_2$) and/or paragonite ($NaAl_2AlSi_3O_{10}(OH)_2$) components to be present in the sericite (cf. Fig. 7). In addition, clinozoisite occurs. Pyrophyllite might also have formed, which could explain excess Al found in the analyses.

5. Discussion

The rather simple sequence of shells and the extreme alteration of feldspars are typical of the Slättemossa occurrence. Simonen (1941) describes orbicular rocks from Kemijärvi and Espoo (Finland) and two boulders (Simonen, 1950) from other parts of Finland, which have a much more complex shell structure than the Slättemossa rock. However, the shell sequence at Slättemossa is more complicated than the one at, for example, Ploumanac'h (Decitre, Gasquet & Marignac, 2002) or in a newly found orbicular rock in Stockholm (Persson, Persson & Sträng, 2002). Lahti (2005) describes many orbicular rocks, some of which have a more and some a less complicated structure than the Slättemossa rock. The extreme feldspar alteration found at Slättemossa is certainly not typical for orbicular rocks, but cloritization of biotite appears to be common (e.g. Lahti, 2005).

Most authors prefer a magmatic origin for orbicular rocks (cf. Hoefs & Epstein, 1969; Perttunen, 1983; Vernon, 1985). The regular change of the Mg-number of amphibole from core to shells to matrix (Fig. 8) in the Slättemossa occurrence is consistent with a model of progressive crystallization. The strong alteration of plagioclase prevents similar conclusions for this mineral. The high-temperature minerals found in all parts of the rock likewise suggest a magmatic model. Finally, the matrix around the orbicules is a typical magmatic rock. The alteration found in the rock is considered to have taken place in close connection with or immediately after crystallization, and not as a result of a later metamorphic event, since the minerals of the country rocks are not altered in the same way as described here for the orbicular rock. Indeed, the rocks of the Transscandinavian Igneous Belt are not regionally metamorphosed.

5.a. Formation of cores

The one feature common to orbicular rocks is the presence of a core. This core might be a megacryst (e.g. Ploumanac'h: Decitre, Gasquet & Marignac, 2002) or a xenolith (e.g. compilation by Elliston, 1984) or an early-crystallized part of the orbicule-forming magma. In many orbicular rocks, more than one type of core exists (Elliston, 1984; e.g. Decitre, Gasquet & Marignac, 2002; Lahti, 2005).

Orbicule formation presumably involves a mechanism whereby 'normal' homogeneous nucleation is prevented, and instead nucleation takes place around pre-existing cores. One popular model suggests that the cores may have been suspended in a superheated magma, which effectively prevents homogeneous nucleation. Unlike many occurrences of orbicular rocks, the cores of the orbicules at Slättemossa appear to be similar in composition to the matrix. They are therefore interpreted as the products of early crystallization. On cooling, these cores serve as nuclei for the successive crystallization. The mechanism, by which this early, 'normal' crystallization was interrupted to be replaced by crystallization of successive shells around the cores formed, is unknown, but presumably involved a sudden change of the conditions in the magma chamber.

Our observations suggest that the Slättemossa magma started to crystallize before orbicule formation. Thus, crystal nuclei must have existed in the magma. Since the subsequent crystallization to form the orbicules only took place around discrete cores, all other pre-existing nuclei must have been removed. Superheating is the simplest mechanism to achieve this. Two possibilities exist to create a superheated magma and remove previous nuclei: (1) to heat the magma above its liquidus, or (2) to lower the liquidus below the actual temperature of the magma. The rock having the highest liquidus temperature seems to be the orbicular rock itself, together with mafic schlieren and small amounts of a biotite-rich rock. The latter rock is marked as gabbro in Figure 2 but it is far too biotite rich. Its significance and age are uncertain, and to suggest it as a heat source would be very speculative. Thus, we cannot identify any source to heat the magma above its liquidus temperature.

An effective way to radically lower the liquidus temperature is to add water (cf. Vernon, 1985) to a volatile-undersaturated magma. Besides destroying crystal nuclei, influx of water also affects already crystallized parts of the rock leading to dissolution of parts of the rock and to alteration of minerals escaping dissolution. The source of the volatiles is open to speculation, but the simplest source is a deeper part of the magma body. The poor degree of exposure does not permit observations of how the orbicular rock is located in relation to possible contacts. Influx of volatiles would lead to an essentially nucleus-free magma with dispersed fragments of altered rock serving as cores in the following orbicule-forming process. Plagioclase in the Slättemossa rock is extremely altered; irregular grain boundaries suggest dissolution of mafic minerals, and the rounded and concave forms of the cores could be a result of dissolution of the early-crystallized rock. The model of water addition is difficult to prove, but it is the easiest way to explain the destruction of nuclei, and it is consistent with the disequilibrium forms of many crystals and with the altered nature of the rock. Alteration is strongest in the felsic shell; it does not seem very probable that the surrounding country-rock and the other parts of the orbicular rock, including the matrix, should have been less altered if all of the alteration had occurred at subsolidus conditions unrelated to the formation of the orbicular rock.

5.b. Formation of shells

Superheating both stops crystallization and leads to destruction of already formed nuclei. Subsequent formation of the shells requires the physical conditions again to change rapidly; shell formation requires rapid cooling (cf. Vernon, 1985; Ort, 1992) to promote nucleation and crystallization on the remaining cores. A possibility is volcanic eruption, which would readily release water from the magma resulting in an increased solidus temperature, thus enhancing mineral growth on the existing rock fragments. Observations suggest that growth proceeded radially outwards, which in turn suggests that the growth rate exceeds the rate of heat transport from and/or element transport to the site, where growth takes place. Browne & Hunt (2004) modelled growth in an alloy. They found that columnar growth starts already at low degrees of undercooling from the mould wall, which in this case corresponds to the core of the future orbicule. In their model, they distinguished an early stage of columnar growth at high undercooling, similar to the radial growth here (cf. for K-feldspar: Decitre, Gasquet & Marignac, 2002), from a later stage of equiaxed growth corresponding to the more tangentially ordered crystals. According to the growth model, a crystal mush forms in between the dendritic or columnar crystals. In this mush, the temperature is between the solidus and liquidus. It solidifies together with the outwards-growing crystals, forming the mafic shell made up of biotite, amphibole and plagioclase. During this stage, the mafic minerals grow faster than plagioclase, exhausting the local melt in mafic components. Simultaneously the water content in the still-liquid/gaseous part of the system increases due to an increased amount of crystalline phases.

Crystallization proceeded to approximately the same stage in all orbicules, when the felsic shell started to form. This judgement is based on the similarity of the Mg-numbers in not only the inner but also in the outer mafic shells of the studied orbicules, and their similar shell widths. The boundary between the inner mafic and the felsic shell is sharp. This suggests a sudden change in physical conditions, causing an extreme change in the ratio between feldspar and mafic mineral nucleation and crystallization rates. This might be combined with an exhaustion of mafic constituents in the neighbourhood of the growing orbicule.

Crystallization continued until the saturation of plagioclase components had decreased sufficiently to allow other phases to crystallize. This is primarily due to local exhaustion of plagioclase components but might also be strengthened by factors such as increasing water contents caused by the crystallization of water-free minerals, leading to a gradual restoration of 'normal' conditions. In the rock, this is evident as a gradual but rapid increase in mafic minerals; the outer mafic shell forms. Finally, there is a return to normal conditions forming the matrix at a higher growth/nucleation rate; the grain size increases. The major difference in crystallization is found in the type of nucleation: dominantly homogeneous for core and matrix crystallization, dominantly heterogeneous for shell crystallization. The matrix makes up between 10 and 15 % of the rock.

5.c. Flattening of orbicules

At Slättemossa, orbicules only seldom impinge on each other; in most cases, a thin rim of matrix material is found between them. Nevertheless, most orbicules are oval in cross-section. The oval form suggests either deformation or directed growth of the orbicules. At the contact with the country granite, orbicules are flattened approximately parallel to the contact (cf. Fig. 2). This suggests that during orbicule growth, some deformation took place; whether this occurred during the initial or final stage of crystallization is impossible to say. Nevertheless, some of the matrix magma probably was squeezed out during this process, concentrating the orbicules into a smaller volume. It is important that the matrix obviously crystallized in continuity with the orbicules, thus no large movements of the orbicules could have taken place in relation to the magma in their immediate surroundings.

Every orbicule makes up a self-contained archive of most of the crystallization history. During crystallization of the orbicules, no mechanical transport of crystals out of the system can be proved. If no matrix had been 'squeezed' out, this should correspond to approximately 85 % of the total crystallization history of the rock. However, some flattening and squeezing have probably occurred. This stopped before the orbicules came into physical contact with each other. According to our views, this is consistent with a rather limited settling of orbicules during crystallization in relation to their immediately surrounding magma.

During orbicule crystallization, crystal settling cannot have been important. If it had, orbicules would have started to impinge on each other, which would have prevented symmetrical orbicule formation.

6. Conclusions

(1) The Slättemossa orbicular rock has a quartz monzodioritic composition.

(2) Similarly to most orbicular rocks it formed through magmatic processes.

(3) The proposed model for its formation involves:
   (a) Normal crystallization forming cores followed by influx of volatiles, which lowers the liquidus, arrests crystallization and destroys all previously formed nuclei.
   (b) On lowering of the temperature, heterogeneous nucleation leads to crystallization of an inner mafic shell at an elevated rate.
   (c) Probably a sudden change in physical conditions, combined with exhaustion of mafic components, results in the formation of a felsic shell.
   (d) Plagioclase components become locally exhausted, which leads to the next mafic shell following a thin transition zone.
   (e) The matrix is formed in direct continuity with the formation of the orbicules. During matrix formation, nucleation again becomes homogeneous.

(4) Only small movements of the orbicules relative to the magma, from which they have crystallized, have taken place. Some squeezing of interstitial magma is probable. The rock has moved as an entity to hit already-crystallized granitic rock.

(5) The results suggest that crystallization of granitoid rocks occurs as a reasonably closed process.

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