GLASS AND AMYGDULES IN PRECAMBRIAN DIABASES FROM ORIVESI, SOUTHERN FINLAND

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Glassy apophyses of a Precambrian diabase dyke appear at Orivesi, southern Finland. In chemical composition the glass is a subalkaline tholeiite. The glass content of the apophyses is 90 %, the only crystals found being two generations of plagioclase and some sporadic olivine. The intrusion temperature is 1150°—1160°C and the mineral assemblage indicates low pressure. Although the water content of the glass is high, only weak signs of devitrification are present. The preservation of the glass proves that no temperature rise has taken place in the area during the last 1600 Ma.

Diabase in another dyke of the same set shows amygdaloidal structure. The amygdules that appear at the upper contact are spheroidal and consist of calcite and euhedral quartz. Since the formation of amygdules is a phenomenon of shallow depths, the present erosion level is close to the 1600-Ma-old Precambrian one.

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Introduction

Nearly all known volcanic glasses are Miocene or younger. The only indications nowadays of the glassy origin of many Precambrian rocks are the outlines of perlitic cracks and the presence of spherulites (Marshall 1961). In the olivine diabase dyke set of Häme, Finland, described by Laitakari (1969) and Mäkipää (1979), undevitrified Precambrian glass was found. It appears in diabase apophyses some ten metres long and about ten centimetres wide. The wider parts of the apophyses seem to be almost holocrystalline, but the tails, which are less than 1—2 cm wide, are more or less glassy. This paper is a description of a typical glassy tail. The parent diabase dyke is 2.70 m wide, vertical and with a strike of N10W. The glass is found about 25 m from the dyke in an apophysis striking N15E and dipping 60NE in a road cut near Aihtianjärvi, Orivesi (map sheet 2142, coordinates x = 6840.10 and y = 514.90).

The diabase dykes in the Häme area, of which there have been more than one hundred observed, cut sharply the Svecokarelidic bedrock. The regional metamorphism of this bedrock took place some 1800—1900 Ma ago (Kouvo and Tilton 1966). According to U-Pb and Rb-Sr radiometric age determinations on whole rocks and minerals, the age of the dyke set is about 1650 Ma (Laitakari 1969; Otto van Breemen and Olavi Kouvo, pers. comm.).

A diabase amygdaloid was found in association with the same set of dykes. The amygdules appear in an 8-metre wide subophitic olivine diabase dyke that strikes N85W and dips 70N at Leväslahti, Orivesi (map sheet 2142, coordinates x = 6835.23 and y = 531.37).

Although some glassy diabases from Finland have been mentioned in the literature, only one has been described in detail (Pehrman 1933). The glassy amygdaloidal diabase from Kirjala described by Pehrman (op.cit.) is however wholly opaque as a result of devitrification.

The diabase glass

General

The fresh broken surface of the glass is lustrous black, but in thin section it is brown. Where, owing to secondary alteration, the granitic host rock is red (cf. Smith 1974 pp. 614—630), the glass is greenish blue and slightly birefringent. In unaltered grey granite the glass is black (Fig. 1). The apophysis studied is cut by several tiny cracks. Traces of incipient devitrification can be seen along these cracks and at the contacts between the glass and the granitic host rock. The contacts between the host rock and the apophysis are sharp and almost no melting effects were observed. The glass content of the apophysis is 90 %. The only crystals found are two generations of plagioclase and some sporadic olivine. The older plagioclase phenocrysts are large (∅ ∼ 1 mm) equidimensional euhedrons; the younger ones are laths about 0.3 mm long (Fig. 2). These laths show flow orientation, a common feature of primary crystallites (Marshall 1961). Similar oriented laths appear in the Kirjala diabase glass (Pehrmann 1933). The larger phenocrysts show well-developed lamellar albite twinning. Besides lamellar twinning, the smaller laths exhibit simple twinning according to the Carlsbad law. The phenocrysts, and some of the laths, show very diffuse zonality. The lack of sector zoning indicates slow growth (Bryan 1972). The central parts of the crystals are weakly sericitized. The composition of the large phenocrysts and the smaller laths was optically determined as An 55—60. Many of the laths are broken by the above-mentioned cracks.

Yellow patches with sharp borders appear in the brown glass. These patches show weak anisotropy, but X-ray studies proved them to be amorphous. Although to a certain extent they resemble the spherulites often described in glasses (e.g. Lofgren 1971), the phenomenon observed is probably caused by immiscibility between two silicate liquids (cf. Philpotts 1979). Microprobe analysis of these two glasses showed a marked decrease in the silica, sodium and lime content in the yellow glass but an increase in the magnesium and especially the iron content. The yellow glass is regarded as a differentiation product of the parent liquid. In fact euhedral, partly serpentinized olivine has been found in some of these patches (Fig. 3). The crystals closely resemble the euhedral olivine in the glassy olivine tholeiite from Taiwan described by Liou (1974). This indicates that the yellow patches refer to a differentiation stage in the crystallization process of olivine.

According to the curves of Peck et al. (1966) the glass content of 90 % corresponds to an intrusion temperature of about 1100 °C. The curves of Murase and McBirney (1973) and Wright and Peck (1978) indicate an intrusion temperature of 1150°—1160 °C. These values are in good agreement with the intrusion temperature 1140°—1170 °C determined by Mäkipää (1979) using phase-equilibria. From approximation of the curve given by Peck et al. (1966), the cooling rate corresponding to a glass content of 90 % is as high as about 1200 °/h.

Chemical composition

The chemical composition of the diabase glass and the parent diabase dyke was de-

Fig. 1. Glassy apophysis in granitic host. Observe the correlation between the devitrified bluish glass and the disturbed red granite.

termined by X-ray fluorescence methods (Table 1). Water was determined with the Penfield tube method. Because the iron content was determined as total Fe_2O_3, the FeO/Fe_2O_3 ratio was calculated using the regression equation for volcanic rocks given by Le Maitre (1976).

Except for the great differences in the water content, the chemical composition of the glass is much like that of the Kirjala diabase glass described by Pehrman (1933). Water concentrations as high as in the Orivesi diabase glass have been reported from glass in Mull pitchstone (Drysdale 1979). In the Mull pitchstone only some of the water is primary magmatic, most of it being secondary as a result of hydration (ibid.); at Orivesi, however, the water is thought to be

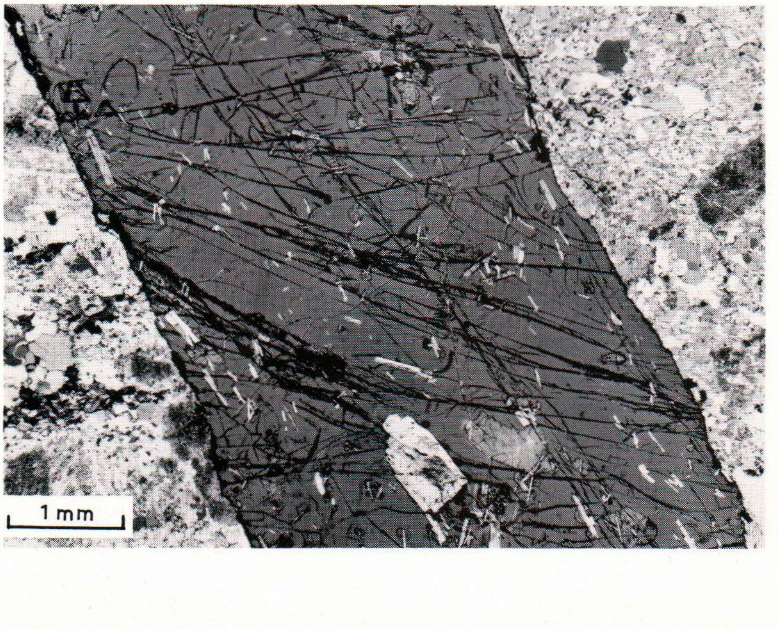

Fig. 2. Photomicrograph of diabase glass in granitic host. Nicols partly crossed.

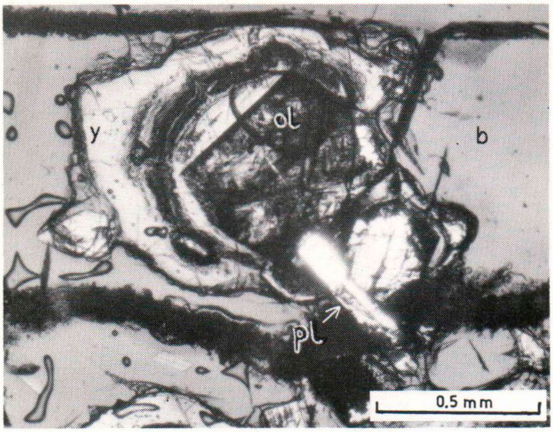

Fig. 3. Photomicrograph of partly serpentinized euhedral olivine in yellow glass. ol = olivine, pl = plagioclase, y = yellow glass, b = brown glass. Nicols parallel.

of magmatic origin. A high concentration of volatiles, in this case water since no carbon dioxide has been found, is consistent with the vesiculation of the diabase in the amygdaloid to be described later. Signs of hydration in the black glass have not been observed. The high water content in the magma decreases the viscosity and enables the magma to move at high velocity (cf. Khitarov and Lebedev 1978). Such conditions are needed for the formation of a glass apophysis. A high water content in the parent magma is possible without fractionation of olivine if the magma originates from very shallow depths (Nicholls and Ringwood 1973). Fractionation of olivine at greater depths and at earlier stages is conceivable.

The CIPW norm minerals were calculated for the purpose of nomenclature and the differentiation index (cf. Wedepohl 1969 p. 228, Irvine and Baragar 1971). The norm minerals calculated from unprepared data are given in Table 1; calculated from prepared data according to Irvine and Baragar (op.cit.) they are given in Table 2. If the glass is regarded as residual, the differentiation index (Table 2) of the glass and parent dyke compared with the silica content shows the opposite trend to that postulated by Thornton and Tuttle (1960).

According to the diagrams of Irvine and Baragar (1971), both the glass and the crystallized diabase represent subalkaline tholeiites, although the crystallized diabase is close to the alkaline field and could be regarded as an alkaline basalt.

The contents of trace elements, determined by OES and XRF methods, are given in Table 3. The trace element concentrations, chiefly V, Cr, Ni, Cu and Rb, indicate that the glass represents a differentiated magma compared with the crystallized diabase (cf. Wedepohl, Handbook of Geochemistry, Vol. II/2, II/3 and II/4). Like the residual glass of Kap Daussy tholeiite dyke (Vincent 1950), the Orivesi magma appears to have followed a rather unusual course of differentiation. This is shown by the very low concentration of alkalies and the relatively low concentration of silica compared with the crystallized parent dyke. Glassy rocks generally represent a high silica fractionation (Marshall 1961). Experimental studies by Thornton and Tuttle (1960) show that fractional crystallization of complex magmas produces liquids that move towards the petrogeny's residua system, SiO_2-

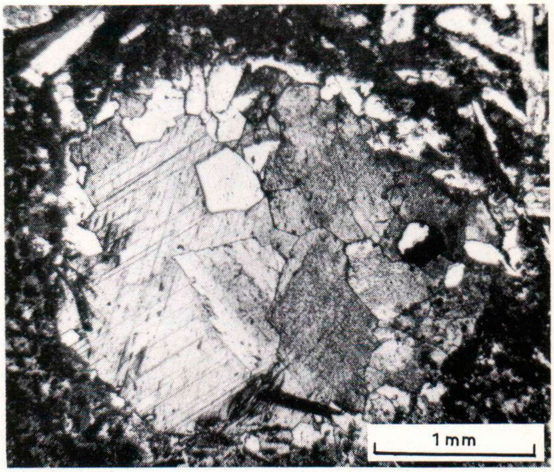

Fig. 4. Photomicrograph of amygdule in olivine diabase. The amygdule consists of calcite and euhedral quartz. Nicols partly crossed.

Table 1. Chemical composition of the diabase glass and parent diabase dyke (analyst V. Hoffrén) together with the calculated CIPW norm minerals (%).

		Diabase glass		Parent diabase dyke
SiO_2		46.46		49.21
TiO_2		2.79		2.74
Al_2O_3		14.34		15.54
Tot. Fe as Fe_2O_3		14.99		15.74
FeO		10.40		9.68
Fe_2O_3		3.43		4.98
MnO		0.18		0.18
MgO		4.20		4.44
CaO		7.08		7.28
Na_2O		0.89		3.01
K_2O		0.99		1.91
P_2O_5		0.73		0.74
H_2O		8.80		—
		100.29		99.71
CIPW norm minerals				
Salic:				
Quartz		12.7		1.7
Corundum		0.7		—
Orthoclase		5.8		11.3
Albite		7.5		25.5
Anorthite		30.3		23.2
Plagioclase	An80	37.9	An48	48.7
Femic:				
Diopside		—		6.6
Hypersthene		22.4		17.3
Magnetite		5.0		7.2
Ilmenite		5.3		5.2
Apatite		1.7		1.7

$NaAlSiO_4$-$KAlSiO_4$. The unusual composition of the glass may be due to the fact that apohyses do not grow from the contacts of the parent dyke but from the central part (see Fig. 14 in Laitakari 1969). In this case, the glass represents a residual liquid in situ after the crystallization of plagioclase.

Minerals and crystallization

Plagioclase appears as large equidimensional polyhedral crystals and as smaller laths. The chemical composition of the phenocrysts and the laths is presented in Table 4. The composition of plagioclase in the granitic host is given for the purpose of comparison. The lower alkali concentration in the laths that crystallized later is believed to reflect crystallization in the alkali-poor differentiated magma.

In shape, the plagioclase laths resemble the skeletal or hollow plagioclase described by Lofgren (1974). The difference in size and texture shows that plagioclase crystallized in two different stages: the earlier one within a supercooling of below 30 °C, the later one at a supercooling of about 30 °C (cf. op.cit.). With progressively higher cooling rates, a

Table 2. CIPW norm minerals and differentiation index of diabase glass and parent diabase dyke calculated from prepared data according to Irvine and Baragar (1971) (%).

		Diabase glass		Parent diabase dyke
Salic:				
Quartz		13.9		0.8
Corundum		0.7		—
Orthoclase		6.4		11.3
Albite		8.2		25.5
Anorthite		33.2		23.3
Plagioclase	An80	41.4	An48	48.9
Femic:				
Diopside		—		6.7
Hypersthene		24.5		19.1
Magnetite		5.4		6.2
Ilmenite		5.8		5.2
Apatite		1.9		1.7
Differentiation index		28		37

Table 3. Trace element concentrations in diabase glass and parent diabase dyke (analyst V. Hoffrén) (ppm).

	Diabase glass	Parent diabase dyke
V	130	230
Cr	46	82
Ni	45	64
Cu	46	70
Ga	43	45
Rb	80	40
Sr	440	400
Zr	230	230
Ba	650	750

Table 4. Microprobe analysis of plagioclase phenocrysts (average of 6 analyses) and plagioclase laths (average of 6 analyses) together with plagioclase in granitic host (average of 2 analyses) (analyst R. Törnroos) (%).

	Large phenocrysts	Laths	Granitic
SiO_2	50.16	49.63	60.93
TiO_2	0.45	0.74	—
Al_2O_3	30.49	30.75	22.01
FeO	0.33	0.46	1.28
MnO	0.03	0.01	—
MgO	0.12	0.14	—
CaO	12.68	13.22	4.53
Na_2O	4.32	4.25	10.15
K_2O	0.63	0.51	0.22
	99.21	99.71	99.12
Number of ions on the basis of 32 oxygens			
Si	9.248	9.130	11.036
Ti	0.062	0.102	0.000
Al	6.626	6.667	4.698
Fe^{2+}	0.051	0.071	0.194
Mn	0.005	0.002	0.000
Mg	0.033	0.038	0.000
Ca	2.505	2.606	0.879
Na	1.544	1.516	3.564
K	0.148	0.120	0.051
Mol.%	Ab 36.8 An 59.7 Or 3.5	Ab 35.7 An 61.4 Or 2.8	Ab 79.3 An 19.6 Or 1.1

given phase will elongate parallel to directions of easy growth (Fleet 1975). Large crystals of equal size crystallize only at low cooling rates at temperatures slightly below the liquidus (Marshall 1961).

In the same way, euhedral olivine crystallizes where the cooling rate and the undercooling are lowest (Kirkpatrick 1975, Donaldson 1976). The observed euhedral olivine indicates growth in a magma with a cooling rate of less than 10 °/h (cf. Donaldson 1976) at or just below the liquidus (Bryan 1972). The low cooling rate and the low degree of undercooling explains the delay in olivine crystallization. In cooling magmas (cooling rate usually less than 25 °/h), a sudden slight decrease in temperature will cause nucleation far sooner than steady cooling (Donaldson 1979).

The crystallized mineral assemblage plagioclase-olivine indicates a crystallization pressure of between 1—9 kb, probably closer to 1 kb (cf. Green and Ringwood 1967). At this pressure the olivine liquidus is about 1300 °C. Plagioclase begins to crystallize at about 1250 °C (op. cit.). A temperature of 1290 °C and a pressure of 13 kb equal a depth of 42 km; 1100 °C and 5 kb are equal to only 16 km (Evans and Nash 1979).

Plagioclase was the first mineral to crystallize in the glassy diabase of Kirjala (Pehrman 1933). As Pehrman (op.cit.) postulated, this contradicts the evolution series of Bowen. The same crystallization course found at Orivesi is ascribed to delay in the nucleation of olivine.

Physical properties

The specific gravity of the glass (excluding phenocrysts) was determined with a Berman balance. The average of three determinations was 2.676. The refractive index determined by the immersion method was 1.586 (λ = 589 nm).

According to the diagram of George (1924), the observed specific gravity is slightly too low compared with the refractive index. This is explained by the plagioclase laths. Tilley (1922) established that feldspar crystallites in basalt glasses lower the specific gravity from the true one.

A microprobe analysis of the brown glass together with the composition corresponding to the observed refractive index according to George (1924) is presented in Table 5.

The diabase amygdaloid

The amygdules in the olivine diabase at Orivesi are spheroidal, about 2 mm in size and consist of calcite and euhedral quartz (Fig. 4). Similar amygdules appear in the glassy diabase of Kirjala, although these are

Table 5. Microprobe analysis of brown diabase glass (analyst R. Törnroos) together with the corresponding data based on the refractive index according to George (1924) (%).

	Microprobe analysis	$n = 1.586$
SiO_2	51.9	49
TiO_2	1.0	
Al_2O_3	14.0	
FeO	12.8	13.5
MnO	0.1	
MgO	5.4	5
CaO	8.2	8.5
Na_2O	0.6	
K_2O	1.4	2
P_2O_5	—	
SO_3	0.1	
NiO	—	
	95.5	

smaller and consist of quartz, calcite, chlorite, biotite and pyrrhotite (Pehrman 1933). Amygdules are not visible at the contacts of the dyke, the first being visible about 40 cm from the upper contact. This is consistent with the Kirjala glassy diabase (op.cit.). In amygdaloidal diabase boulders from Latvia described by Eskola (1934a), the amygdules consist of prehnite, and the plagioclase phenocrysts as well as the groundmass plagioclase have changed to prehnite. Some of the amygdules are calcite (Eskola 1934b). According to Eskola (1934a, b), the amygdaloidal structure of the boulders indicates that they derived from a submarine rock.

The amygdules in Alae Lava Lake change markedly in size and shape at a depth of 6 m. Below this depth, almost all the amygdules are about 1 mm in size and angular; above it, they are larger and spheroidal (Peck et al. 1966, Peck 1978). This shows that vesiculation, and particularly the formation of spheroidal amygdules, is a phenomenon limited to the upper parts of a cooling magma.

Consequently the upper parts of the diabase dyke are exposed, indicating that the present erosion level is close to that of 1600 Ma ago.

Conclusions

The chemical composition shows that diabase glass from Orivesi represents an at least partly differentiated magma. The differentiation course differs from the usual one and, instead of producing a granitic magma has resulted in low alkali concentration. The glass represents a residual liquid after the crystallization of plagioclase.

The crystallization of plagioclase as the primary mineral indicates crystallization at a low cooling rate close to liquidus. In this case the nucleation of olivine is delayed. The existence of two different plagioclase types is believed to reflect crystallization in the parent magma and in the partly differentiated magma.

The amygdaloidal structure in another olivine diabase dyke in the same area indicates crystallization at shallow depth. The exposure of this diabase amygdaloid indicates that the present erosion level is close to the 1600 Ma old Precambrian one.

The high water content in the diabase glass is considered mainly of primary origin. Devitrification of a glass in the presence of water takes place rapidly at temperatures no higher than 300 °C (Marshall 1961). The ubiquity of water limits the existence of volcanic glasses and accounts for the absence of glass from old formations (ibid.). Consequently no thermal activity has taken place in the area in question during the last 1600 Ma.

Although Snyder and Hedge (1978) postulated that Precambrian porphyry dykes and small ultramafic intrusions never contain glass, glassy apophyses have been found at Orivesi, southern Finland.

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