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Feldspar relations in Icelandic alkalic rhyolites

HARALDUR SIGURDSSON, Ph.D.
Dept. of Geology, The University of Durham[1]

SUMMARY. Alkalic rhyolites with peralkaline affinities, bearing quartz and potassic feldspar phenocrysts, are described from Iceland for the first time. Evidence from electron-probe analyses of feldspar phenocrysts indicates crystallization in or near the thermal valley of the system SiO_2–Or–Ab. Icelandic acid volcanic rocks are subdivided into alkalic rhyolites, belonging to transitional and alkalic basalt lineages, and the mildly calc-alkaline rhyolites of tholeiite lineages.

PUBLISHED chemical and mineralogical data on some acid rocks from eastern Iceland have provided good documentation of a suite of acid volcanic rocks typified by a high silica/alkalis ratio (greater than 9), an affinity with calc-alkaline acid rocks, and the presence of plagioclase phenocrysts as the salic, and often the only phenocryst phase (Carmichael, 1962, 1963). Their association with tholeiitic basalt lavas has been pointed out by Carmichael (1963) who suggested that these one-feldspar rhyolites were typical products of the fractionation of a tholeiitic magma. For some time now, these rhyolites have come to be regarded as the typical Icelandic acid magma, but the discovery of alkalic acid lavas in western and southern Iceland has shown the compositional range of Icelandic acid volcanics to be much greater than previously assumed, including types with low silica/alkalis ratio (less than 8), low in CaO, with K_2O/Na_2O ratio near unity, and showing affinities with comendites. These lavas, unlike the eastern Iceland pitchstones, frequently contain phenocrysts of quartz and alkali feldspar, ranging in composition from anorthoclase to sanidine and occasionally contain sodic plagioclase as well.

This paper is concerned with the mineralogy and chemistry of three alkalic acid rocks from the Setberg centre in western Iceland, dealing particularly with crystallization and composition trends of the feldspars, as elucidated by electron-probe analyses, but bulk chemistry is also presented. In addition to the Setberg centre, alkalic acid lavas, often showing affinities with comendites and pantellerites, have been found in the following volcanic centres: Ljósufjöll, Torfajökull, Eyjafjallajökull, and Öraefajökull. The petrology of these peralkaline acid rocks is the subject of a later publication.

Analytical methods. The mineral analyses were performed using a Geoscan electron microprobe, relating X-ray intensities of the unknowns to mineral standards of similar and known composition. Corrections were made for beam current fluctuation, dead-time, background, atomic number effects, and absorption and fluorescence, utilizing a computer program developed by Dr. J. W. Aucott. The whole-rock compositions

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[1] Present address: Seismic Research Unit, University of the West Indies, St. Augustine, Trinidad.

are based on X-ray fluorescence analyses carried out on finely crushed powders, which were pelletized and analysed with a Philips 1212 X-ray fluorescence spectrometer, using chemically analysed igneous rocks as standards. Corrections for mass absorption were made. Owing to the iterative method of calculations for both mineral and whole-rock compositions, the analyses are presented as recalculated to 100 %. FeO was determined by the metavanadate method.

Petrography

The three glassy acid rocks described here are the most siliceous volcanics of the Pleistocene phase of the Setberg centre, where they are associated with basalts transitional between alkalic and tholeiitic types. They are: an obsidian dome from Midhyrna, a glassy dyke from Lýsuskard, and a 50 m thick partly welded porphyritic glassy tuff from Grundarmön. All three samples are fresh and free of the hydration so common in acid glasses in the Icelandic Tertiary.

Grundarmön acid tuff. Modal and chemical analysis of this rock is presented in table I (no. 1). The tuff is packed with fractured but unzoned crystals of alkali feldspar and bipyramidal quartz, totalling 36 vol. %, set in a matrix of devitrified shards. No other minerals occur in this rock. The feldspar is a crypto-perthite, ranging in composition from Or_{35} to $Or_{36\cdot6}$ (table II), and an average of eight electron-probe analyses gives $Or_{35\cdot9}$. In all cases the An molecule is equal to or less than 0·2 wt. %.

Midhyrna obsidian. The peralkaline affinities of this obsidian are clear from the chemical analyses (table I, no. 2), but, while having a peralkalinity ratio of only 0·91 (mol % $(Na_2O+K_2O)/Al_2O_3$), the rock is strictly speaking not peralkaline in the sense of having acmite or sodium metasilicate in the norm, but approaches closely a comendite composition. This rock is almost entirely glassy, with small phenocrysts totalling only 0·6 vol. %. Phenocrysts of alkali feldspar, clinopyroxene, and iron oxides occur in roughly equal proportions. The euhedral alkali feldspar phenocrysts range from Or_{35} to Or_{41} and contain less than 1 % of the An molecule. Very small and rare feldspar crystals of a more sodic composition occur in the glass, with the composition Or_{25} to Or_{31} and an An content up to 2 %. Preliminary electron-probe analyses of the greenish clinopyroxenes indicate a rather sodic composition.

Glassy acid dyke. This rock from Lýsuskard is a comenditic obsidian (no. 3), with a peralkalinity ratio of 1·3 (mol % $(Na_2O+K_2O)/Al_2O_3$) and thus has the distinction of being the first peralkaline acid rock described from Iceland.[1]

The glass contains 1·4 vol. % of sanidine phenocrysts, subhedral and 1–2 mm in diameter, ranging in composition from Or_{47} to Or_{41}. Quartz forms larger, often slightly embayed grains, constituting 0·8 vol. % of the rock. Elongated crystals of a faintly translucent, deep red or brown mineral, up to 1 mm in length, form rare phenocrysts and are probably of aenigmatite, but this awaits electron-probe confirmation.

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[1] Recently Dr. D. K. Bailey has drawn the author's attention to an analysis of an acmite-normative obsidian from Öraefajökull, southern Iceland, published without comment by Carmichael (1967, table 5).

TABLE I. *Chemical composition of Icelandic alkalic acid volcanic rocks, with comparisons*

	1	2	3	4	5	6	7
SiO_2	74·2	75·0	73·0	73·7	75·0	73·10	73·5
Al_2O_3	14·0	13·5	10·3	12·8	12·7	13·09	13·3
Fe_2O_3	2·3	1·0	2·9	2·0	1·3	1·19	1·44
FeO	0·1	1·0	3·2	1·7	1·1	1·43	1·81
MgO	tr	tr	tr	0·1	0·1	0·43	0·33
CaO	0·04	0·2	0·12	0·3	0·6	0·87	1·64
Na_2O	3·93	4·70	5·68	4·59	4·16	4·03	4·46
K_2O	4·84	4·40	4·28	4·41	4·76	4·92	3·03
TiO_2	0·29	0·08	0·24	0·25	0·17	0·39	0·31
P_2O_5	tr	tr	tr	tr	0·07	0·11	0·11
MnO	0·19	0·07	0·23	0·13	0·05	—	0·08

Normative mineralogy (wt %):

	1	2	3	4	5	6	7
Q	32·8	29·9	28·1	31·3	31·1	28·4	34·0
or	28·6	26·0	25·3	24·6	27·8	28·9	16·7
ab	33·3	39·8	29·4	38·9	35·1	34·1	37·9
an	0·05	1·0	—	1·3	2·0	3·1	6·8
ac	—	—	8·4	—	—	—	—
ms	—	—	2·2	—	—	—	—
di	—	—	0·5	—	—	0·5	—
hy	0·02	1·1	5·7	1·6	0·9	1·8	2·7
mt	0·2	1·4	—	1·7	1·9	1·9	1·2
il	0·6	1·2	0·5	0·5	0·3	0·8	0·5
ap	—	—	—	—	0·2	0·3	0·3
hm	2·2	—	—	—	—	—	—

Normative composition in three-component system quartz–orthoclase–albite:

	1	2	3	4	5	6	7
Q	34·7	31·2	33·9	33·0	33·1	31·1	38·4
Or	30·1	27·2	30·6	25·8	29·7	31·7	18·8
Ab	35·2	41·6	35·5	41·2	37·2	37·2	42·8

1. Porphyritic acid tuff, Grundarmön, Setberg centre, western Iceland (311). Modal composition: 22·5 % feldspar, 14 % quartz, 63·5 % glass.
2. Obsidian dome from Midhyrna, Setberg volcanic centre, western Iceland (295). Modal composition: 0·3 % feldspar, 0·1 % pyroxene, 0·2 % iron oxides, 99½ % glass.
3. Glassy acid dyke, Lýsuskard, Setberg centre, western Iceland (331). Modal composition: feldspar 1·4 %, quartz 0·8 %, glass 97·8 %.
4. Average composition of alkalic rhyolites from western and southern Iceland (8 chemical analyses).
5. Nockolds (1954) average of 21 analyses of alkalic rhyolite and rhyolite–obsidian, recalculated to 100 % water-free.
6. Alkalic rhyolite from Tweed shield volcano, Australia (Richards, 1916, analysis 6, table 1).
7. Walker's (1966) average of 58 Icelandic acid rocks, recalculated to 100 % water-free.

TABLE II. *Electron-probe analyses of feldspars in Icelandic alkalic acid rocks*

	1a	1b	1c	2a	2b	2c	3a	3b	3c
SiO_2	66·5	67·1	66·8	66·1	65·6	65·8	66·2	66·0	66·2
Al_2O_3	19·4	18·9	19·1	19·8	19·2	19·9	18·8	18·5	18·8
Fe_2O_3	0·7	0·7	0·7	0·2	0·2	0·2	0·8	0·8	1·1
CaO	0·03	0·03	0·01	0·19	0·14	0·25	0·04	0·03	0·04
Na_2O	7·59	7·26	7·46	7·51	7·45	8·50	6·83	7·34	6·24
K_2O	5·83	5·98	5·98	6·23	7·47	5·43	7·37	7·29	7·68
Formulae of feldspars on the basis of 32 oxygens									
Si	11·881	11·975	11·926	11·821	11·827	11·772	11·915	11·902	11·908
Al	4·081	3·983	4·023	4·180	4·007	4·188	3·981	3·940	3·996
Fe	0·090	0·091	0·093	0·023	0·029	0·022	0·105	0·108	0·144
Ca	0·006	0·006	0·002	0·037	0·028	0·048	0·008	0·006	0·008
Na	2·629	2·512	2·585	2·606	2·606	2·949	2·383	2·566	2·178
K	1·329	1·326	1·364	1·422	1·720	1·240	1·692	1·677	1·764
Z	16·000	16·000	16·000	16·000	15·932	15·982	15·999	15·949	16·000
XY	4·015	3·927	3·991	4·091	4·353	4·236	4·083	4·249	3·996
Composition, recalculated to 100 wt %									
Or	35·0	36·6	35·9	36·4	41·0	30·6	43·0	41·0	46·2
Ab	64·8	63·3	64·0	62·7	58·4	68·2	56·8	58·8	53·6
An	0·2	0·2	0·1	0·9	0·6	1·2	0·2	0·2	0·2

1a. Sanidine phenocryst in Grundarmön acid tuff (311). Most albitic analysis.
1b. Sanidine phenocryst as 1a, but most potassic analysis.
1c. Average composition of eight analyses of sanidine from the Grundarmön acid tuff.
2a. Sanidine phenocryst in obsidian from Midhyrna dome (295).
2b. Sanidine phenocryst, as 2a, most potassic analysis.
2c. Anorthoclase in Midhyrna obsidian.
3a. Sanidine phenocryst in glassy obsidian dyke from Lýsuskard (331), average of seven analyses.
3b. Sanidine phenocryst, as 3a; most albitic analysis.
3c. Sanidine from Lýsuskard dyke; most potassic analysis.

Discussion

Rock chemistry and crystal-liquid relations in the feldspar system. The compositions of the three acid rocks and their feldspars are shown in terms of normative weight % SiO_2–Ab–Or in fig. 1. The bulk composition of the Grundarmön acid tuff plots on the cotectic boundary curve separating the silica and feldspar fields in the system SiO_2–Ab–Or–H_2O at 2000 kg/cm^2. This composition is not, however, that of the acid liquid in equilibrium with feldspar and quartz, and by subtracting the appropriate amount of solid phases (22 % sanidine and 14 % quartz) from this bulk composition, we approach the true composition of the liquid ($Qz_{37}Ab_{32}Or_{31}$), which plots very close to the experimentally determined minimum on the boundary curve for the system at 1000 kg/cm^2 (fig. 1). The abundance of quartz and feldspar crystal phases in this tuff speaks clearly for our contention that the liquid had reached such a boundary curve before eruption, suggesting an immediate derivation for this acid magma from a depth of 3 to 4 km. The lack of zoning of the feldspars and the large percentage of phenocrysts indicates a period of quiet, stable crystallization at depth, before the violent transfer of the acid magma to the surface, but the latter event was too rapid for any evidence of the ascent of the magma to be recorded in the mineralogy as seen today, in the form of zoning or corrosion of phenocrysts due to decreasing pressure. The feldspar and quartz phenocrysts and the calculated acid liquid of the Grundarmön tuff form a three-phase triangle in the system SiO_2–Ab–Or, with the liquid forming the apex, positioned on the boundary curve at 1000 kg/cm². Paradoxically the triangle points *away* from the thermal minimum, contrary to the geometry of three-phase triangles in the experimentally determined system (Tuttle and Bowen, 1958). This relationship may, however, be a secondary one, as an unknown quantity of constituents may have been lost from the tuff with the vapour phase of the liquid on eruption, as well as during post-depositional leaching, thus prohibiting an exact comparison with the experimental system.

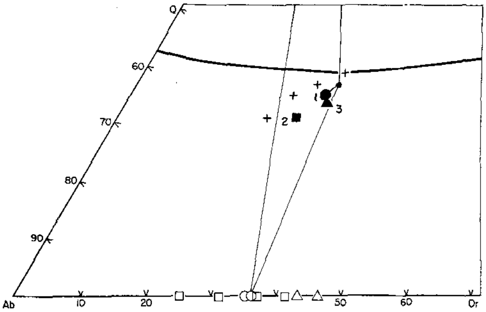

FIG. 1. Part of the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2, with the quartz–feldspar boundary at 500 kg/cm². Crosses indicate minima for 1000, 2000, and 4000 kg/cm² water pressure. Closed symbols, normative composition of the three alkalic rhyolites: 1, Grundarmön Tuff (circles); 2, Midhyrna Obsidian (squares); 3, Lýsuskard Glassy Dyke (triangles). Small filled circle, calculated liquid composition of no. 1. Composition of corresponding feldspar phases shown on Ab–Or base-line. The compositional triangle for no. 1 is drawn.

Composition of the Midhyrna obsidian is plotted in fig. 1, where the relationship of the feldspar phases and bulk liquid composition is shown in terms of SiO_2–Ab–Or, and 95·7 % of the normative composition of the obsidian is represented by this system, as the rock contains only 0·2 % CaO. The absence of a silica phase suggests that this liquid had not reached the boundary curve separating the silica and feldspar fields, and the presence of alkali feldspar (Or_{35-41}) testifies to crystallization (early), either in or near the 'thermal valley' of the feldspar field. These criteria indicate that during the early crystallization of alkali feldspar the liquid was held at water pressures in excess of 1000 kg/cm² and probably near 2000 kg/cm². By fortunate coincidence the Midhyrna obsidian ($Qz_{31}Ab_{42}Or_{27}$) is virtually identical to one of the mixtures used by Tuttle and Bowen in their experimental runs at 2000 kg/cm² ($Qz_{32}Ab_{41}Or_{27}$, no. Q1–13H, table 10, p. 60). This charge gave glass only at 700 °C, but when quenched at 680 °C it contained a feldspar of the composition Or_{42}. Similarly, the obsidian contains early feldspar with up to Or_{41} but ranging to Or_{35}.

In addition to alkali feldspar phenocrysts formed at moderate pressure, the Midhyrna glass contains smaller and rare anorthoclase crystals, which are interpreted as the product of crystallization at very much lower pressure or at the surface. The decrease in pressure during ascent of the magma or on extrusion resulted in a shift of the temperature minimum on the quartz–feldspar boundary line to the right (fig. 1), thus placing the acid liquid in the trace of the thermal valley, or possibly on the plagioclase side of it. Crystallization at progressively lower pressures resulted in precipitation of feldspars (anorthoclase) ranging in composition from Or_{31} to Or_{25}.

The considerable water pressures invoked here to account for phase relations in the Midhyrna obsidian correspond to a depth of the order of 3 to 4 km, not in excess of that expected on geological grounds. More unusual is the position of this acid rock and the Grundarmön tuff in the system SiO_2–Ab–Or, in an area usually considered out-of-bounds to liquids that are associated with an origin by fractionation of basaltic magmas (Carmichael, 1963), and furthermore strikingly different from the position of previously described Icelandic acid liquids.

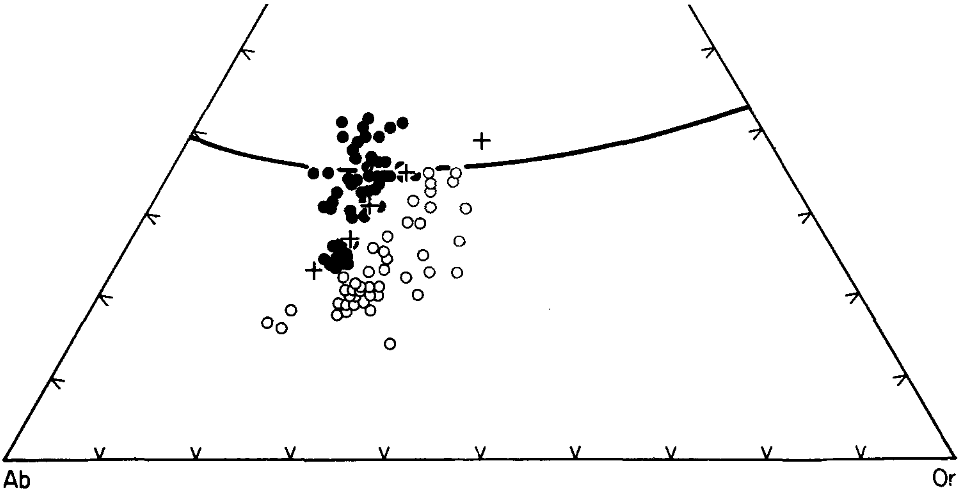

FIG. 2. A plot of 95 Icelandic acid volcanic rocks in the system Ab–Or–SiO_2. Open circles, alkalic rhyolites, and comendites from volcanic centres rich in alkalic or transitional basalts. Filled circles, acid rocks from centres with tholeiitic affinities. The quartz–feldspar boundary curve for 2000 kg/cm^2 is drawn; crosses indicate thermal minima in the system at 500, 2000, 4000, 5000, and 10 000 kg/cm^2 water pressure.

The third acid rock described, the glassy comendite dyke from Lýsuskard, contains 8 % acmite in the norm, and thus comparisons of this natural liquid with the granite system are not directly relevant. Carmichael and MacKenzie (1963) and Thompson and MacKenzie (1967) give the liquidus relations for the system SiO_2–Ab–Or at P_{H_2O} = 1000 bars, including varying amounts of acmite and sodium metasilicate. Their experimental findings indicate that with increasing excess of soda the minimum on the feldspar–quartz boundary curve shifts progressively toward more silica-rich compositions and toward the SiO_2–Or sideline. Plotted in Thompson and MacKenzie's diagram for SiO_2–Ab–Or with 5 % acmite added, at 1000 bars P_{H_2O} (1967, fig. 3), the Lýsuskard comendite falls near, but on the feldspar side of, the silica–feldspar boundary curve. The presence of quartz and alkali feldspar phenocrysts in this glass is an indication of the liquid having equilibrated at a similar pressure.

The two Icelandic acid magmas. The three alkalic rhyolites described here are characterized by their normative position in the thermal valley of the system SiO_2–Ab–Or, in contrast to acid glasses of eastern Iceland and other Icelandic rhyolites associated with tholeiitic centres, which plot on the Ab side of the thermal valley at low pressures. In fig. 2 some 95 unpublished X-ray fluorescence analyses of Icelandic rhyolites are plotted in the system SiO_2–Ab–Or; in all cases the sum of normative quartz, albite, and orthoclase of the rock exceeds 85 % of the total. Acid rocks from the volcanic centres of Ljósufjöll, Setberg (centre 2), Eyjafjallajökull, and Torfajökull form a distinct group (open circles), consisting of comendites and alkalic rhyolites with anorthoclase (ranging to sodic sanidine) and quartz phenocrysts, as well as sodic pyroxene. In these centres the alkalic rhyolites are associated with rock series of mildly alkalic and transitional basalts.

In contrast are the acid lavas found in centres with tholeiitic affinities (closed circles, fig. 2), such as Setberg (centre 1), Drápuhlídarfjall, Álftafjördur, and the eastern Iceland pitchstones, where sodic plagioclase forms the only feldspar phase, but Walker (1966) has pointed out the similarity of these rocks to calc-alkalic rhyolites, such as those of the central volcanic zone of North Island, New Zealand.

The peralkaline rocks in the Icelandic alkalic rhyolite group are typically associated with transitional and mildly alkaline magma series, but such associations of comendites and pantellerites with transitional basalts have been noted elsewhere, notably in the Tweed Shield volcano, Australia (Wilkinson, 1968), and Tutuila, Samoan Islands (Macdonald, 1944). The subdivision of the Icelandic acid rocks into alkalic rhyolites and rhyolites with calc-alkalic affinities is not only convenient for the purpose of description, but may also be an aid in identifying associated basaltic magmas. Acid rocks intermediate to the two groups do occur, however, and most notably the products Hekla and Mýrdalsjökull.

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