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Reservoir Parameters TCP-Project

A Thin-section Study of the Öskjuhlíð Samples

A progress report on a collaborative study between Orkustofnun and Hitaveita Reykjavíkur, and Chamlers - CHT, GEUS (Geological Survey of Denmark and Greenland), and RF - Rogaland Research

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Elsa G. Vilmundardóttir

Prepared for the Resources Division of Orkustofnun

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Abstract:
The report describes a thin-section study done to compare visible pores in rock samples from Öskjuhlíð, Reykjavík, with measured porosity and permeability. The work is a part of a comprehensive study of reservoir parameters currently being carried out in Iceland. In that connection several tens of rock samples were collected from one and the same lava flow in Öskjuhlíð in Reykjavík. The rock is a shield lava of an olivine tholeiite composition from the 2nd or 3rd last interglacial. The results of the thin-section study reveal quite clearly that high-permeability in some of the low porosity samples relates to the intercrystalline pores, which seem to be connected like pores in a sponge in 3D space. Conversely, a striking feature in some of the high porosity rocks, which reveal low permeability, is that the low permeability seems to relate to a finer grained mineral matrix and a sealing glass in some instances, and obviously a lack of interconnections between the large gas pores. The permeability contribution related to microcracks remains uncertain.

Key words:
Öskjuhlíð, reservoir parameters, rock samples, pores, thin-sections, statistical analysis, rock texture, porosity, permeability

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LIST OF CONTENT

1. INTRODUCTION

A comprehensive study of reservoir parameters is currently being carried out in Iceland. In that connection, several tens of rock samples were collected from one and the same lava flow in Öskjuhlíð in Reykjavík. A thin-section study was done to compare visible pores in the Öskujuhlíð samples with the measured porosity and permeability. Thin-sections were made of most of the samples for this purpose, altogether 84 thin-sections, whereof 8 were impregnated by fluorescent resin and studied under the microscope in both fluorescent- and plain polarized light, while standard thin sections were made of the remaining samples. The sampled shield lava is of an olivine tholeiite composition dating from the 2nd or 3rd last interglacial. Late Pleistocene coarse grained lavas of this composition are commonly called grágrýti in Icelandic, in this case the Reykjavík grágrýti. A part of the Öskjuhlíð samples have also been chemically analysed. The different datasets are presently being studied and compared. This report, however, only deals with the thin-section study.

2. THIN-SECTIONS

Thin-sections were made of most of the Öskjuhlíð samples. In order to detect possible microfractures, 8 samples were impregnated with fluorescent resin and studied briefly in fluorescent light for microcracks. These samples were representative of the different sample groups, and of those samples which showed both low- and high-permeability at similar low porosity values. In short, no significant microfractures were detected in these samples, which seems to rule out the possibility that the different permeability values observed were related to secondary microfractures from weathering or dynamite blasts in the Öskjuhlíð-quarry. Three of the attached photos (Figs 15, 17 and 18), taken in fluorescent light, show the difference between a weathered sample of the same rock type and one of our samples. The result of this test did not call for fluorescent resin impregnation of the remaining samples. In retrospect, however, coloured resin impregnation would have improved our statistical approach a bit, as small pores are easier to detect in coloured resin.

It may be noted here that oblique microcracks would be difficult to detect in standard thin-sections as would be the smallest pores. Pores smaller than 30 microns (approx. thin-section thickness) will be missed. Microcracks are only a few microns wide. They are seen in all types of minerals, both within them as cleavage planes and secondary cracks, and along crystal boundaries. A good example of such microcracks can be viewed in the Öskjuhlíð samples where iddingsite partly replaces olivine along such microcracks. Iddingsite is a weathering product of olivine, left behind were relatively cold water has interacted with olivine along cleavage planes, microcracks or crystal boundaries. It is seen as a redbrown stain in the olivine, clearly visible in all the attached microscope photos taken in visible light. This type of microcracks (i.e. cleavage planes, twinning planes, crystal boundaries and secondary cracks) are in fact the common case in all rocks and minerals, and are here distinguished from the secondary microfractures discussed above. Here, microcracks are not considered as a significant permeability contributor, which may be an under estimation. Within the same rock type, however, the microcracks will probably establish a permeability background value for the rock type concerned, and as such may be considered as a constant for the Öskjuhlíð samples. Considering the variation in crystal grain size in the samples, this assumption may not be valid, and perhaps a closer attention should be paid to the contribution of microcraks to the permeability. The case will be rested here with reference to Fig 18, which shows microcracks of this sort in fluorescent light at high magnification (200x). The microcracks are clearly visible as short and faint bands or lines, narrower and more disconected than those we were looking for as a significant permeability contributor.

3. STATISTICAL ANALYSIS

In the statistical analysis, 200 points were counted in each thin-section, covering about 50 % of the thin-section area. A separation was made between all the different primary minerals and glass, two different types of pores, and opaline silica, partly filling some of the pores. The analyses were mostly done with 10 x 10 occulars in plain polarized light, the nicols crossed upon need for mineral identification. The result of the statistical analysis is shown in table 1.

The result is presently being compared with a measured porosity/permeability dataset, as well as with the geochemistry which will be discussed elsewhere. The texture and the grain size of the rock need to be described a bit further here.

4. ROCK TEXTURE

All the samples come from one and the same flow unit, an olivine tholeiite shield lava of late Pleistocene age. The lava matrix is fairly coarse grained, showing characteristic sub-ophitic to ophitic texture, almost doleritic. In the case of the more scoriaceous part of the flow, the lava maybe somewhat finer grained and partly chilled, revealing chilled glass. This is found neatly developed around some vesicles, as shown by the attached sequence of photos. In other cases no chilling is observed around the vesicles.

Another striking feature is the clear distinction between the type of porespace in the samples. As shown by the attached photos, a clear distinction can be made between "normal" spherical gas vesicles (**gp**), 1-5 mm across (or more) as shown in Figs 1 and 2, and the order of magnitude smaller intercrystaline pores (**ip**) also seen in Figs 1 and 2 between the gas pores (gp). The intercrystalline pores (ip) are almost the only pores in Figs 3 and 4. Figs 1-4 show enlarged (4x) thin-sections of the rock samples involved, all of which are impregnated by fluorescent resin. The photos are taken in plain polarized light.

Figs 6 to 12 show closeups (ca 33x) of some part of Figs 1-4. Figs 13 and 14 show example of gp and ip in the fifth sample, where no glass is observed at the gas vesicle rim. A scale for Figs 6-14 is shown in Fig 5.

Figs 1-14 show all the essential elements dealt with in the thin sections, i.e. the primary minerals, glass, secondary minerals and porespace.

The distiction between the different types of pores need not always be clearcut but regular enough to justify the separation. Evidently the sum of the different type of porespace can be treated as total porespace. Further details are given in the figure captions.

5. DISCUSSION

By comparing some of the data given in the figure captions below it is quite clear that high-permeabilty in some of the low porosity samples, quite clearly relates to the intercrystalline pores which seem to be connected like pores in a sponge in 3D space.

Conversely, a striking feature in some of the high porosity rocks which reveal low permeability, is that the low-permeability seems to relate to a sealing effect of a finer grained mineral matrix and glass, and obviously a lack of interconnections between the large gas pores.

The contribution to permeability from the third class of pores, the microcracks, remains uncertain.

TABLE 1: Statisitcal data on thin sections

Thin-section	Sample	gas-		intercrystaline		total pores	plagioclase		pyroxene		olivine		opaque		glassrim at gp		opaline silica		remarks	group
number	number	pores	%	pores	%	%		%		%		%		%		%		%		
16682	R-32		0	42	19,5	19,5	78	39	55	27,5	13	6,5	12	6		0		0	coarse grained	I
16683	R-33		0	39	12	12	73	36,5	53	26,5	6	3	27	13,5		0	2	1	coarse grained	I
16684	R-34		0	24	21	21	60	30	59	29,5	20	10	36	18		0	1	0,5	coarse grained	I
16685	R-35		0	42	18	18	72	36	54	27	12	6	20	10		0		0	coarse grained	I
16686	R-36		0	36	12	12	83	41,5	51	25,5	14	7	13	6,5		0	3	1,5	coarse grained	I
16687	R-37		0	24			81	40,5	61	30,5	16	8	18	9		0		0	coarse grained	I
2734	R-38		0	10	5	5	66	33	68	34	15	7,5	41	20,5		0		0	coarse grained	I
16688	R-40		0	42	21	21	75	37,5	43	21,5	15	7,5	25	12,5		0		0	coarse grained	I
16689	R-41		0	37	18,5	18,5	73	36,5	49	24,5	18	9	23	11,5		0		0	coarse grained	I
16690	R-42		0	40	20	20	79	39,5	60	30	10	5	11	5,5		0		0	coarse grained	I
16691	R-43		0	28	14	14	82	41	47	23,5	14	7	29	14,5		0		0	coarse grained	I
16692	R-44		0	41	20,5	20,5	76	38	48	24	23	11,5	12	6		0		0	coarse grained	I
16693	R-45		0	40	20	20	70	35	56	28	13	6,5	20	10		0	1	0,5	coarse grained	I
16694	R-46		0	27	13,5	13,5	83	41,5	47	23,5	19	9,5	24	12		0		0	coarse grained	I
16695	R-47		0	39	19,5	19,5	87	43,5	40	20	10	5	22	11		0	2	1	coarse grained	I
16696	R-54	8	4	66	33	37	49	24,5	45	22,5	13	6,5	15	7,5	4	2		0	fine grained	II
16697	R-55	9	4,5	77	38,5	43	44	22	42	21	11	5,5	14	7	3	1,5		0	fine grained	II
2742	R-56	29	14,5	15	7,5	22	48	24	43	21,5	9	4,5	25	12,5	31	15,5		0	fine grained	II
2743	R-57	41	20,5	22	11	31,5	48	21,5	42	21	22	11	12	6	18	9		0	fine grained	II
16698	R-58	27	13,5	31	15,5	29	56	28	44	22	18	9	13	6,5	11	5,5		0	fine grained	II
16699	R-63	12	6	14	7	13	59	29,5	63	31,5	19	9,5	25	12,5	8	4		0	medium grained	III
16700	R-64		0	37	18,5	18,5	75	37,5	42	21	19	9,5	27	13,5		0		0	coarse grained	III
16701	R-65		0	36	18	18	88	44	43	21,5	13	6,5	20	10		0		0	coarse grained	III
16702	R-66	3	1,5	30	15	16,5	72	36	51	25,5	10	5	33	16,5	1	0,5		0	coarse grained	III
16703	R-67		0	46	23	23	74	37	51	25,5	16	8	13	6,5		0		0	medium grained	III
16704	R-68	5	2,5	33	16,5	19	59	29,5	51	25,5	17	8,5	30	15	5	2,5		0	medium grained	IV
16705	R-69		0	43	21,5	21,5	53	26,5	62	31	17	8,5	25	12,5		0		0	medium grained	IV
16706	R-70	2	1	40	20	21	67	33,5	45	22,5	18	9	27	13,5	1	0,5		0	medium grained	IV
16707	R-71	2	1	43	21,5	22,5	57	28,5	54	27	17	8,5	25	12,5	1	0,5	1	0,5	fine grained	IV
16708	R-72		0	26	13	13	51	25,5	71	35,5	19	9,5	33	16,5		0		0	medium grained	IV
16709	R-73		0	39	19,5	19,5	47	23,5	64	32	22	11	28	14		0		0	medium grained	IV
16710	R-74		0	34	17	17	52	26	62	31	20	10	32	16		0		0	fine grained	IV
16711	R-76	10	5	57	28,5	33,5	54	27	58	29	9	4,5	11	5,5	1	0,5		0	medium grained	V
16712	R-77	17	8,5	59	29,5	38	46	23	50	25	9	4,5	16	8	3	1,5		0	medium grained	V
16713	R-78	6	3	69	34,5	37,5	53	26,5	55	27,5	5	2,5	9	4,5	3	1,5		0	fine grained	V
16714	R-79	85	42,5	15	7,5	50	47	23,5	37	18,5	4	2	10	5	2	1		0	fine grained	V
16715	R-80	46	23	23	11,5	34,5	48	24	53	26,5	10	5	18	9	2	1		0	fine grained	V
16716	R-81	77	38,5	15	7,5	46	42	21	41	20,5	8	4	13	6,5	4	2		0	medium grained	V
16717	R-82	62	31	14	7	38	44	22	46	23	7	3,5	16	8	7	3,5	4	2	fine grained	V
16718	R-83	38	19	10	5	24	66	33	49	24,5	19	9,5	13	6,5	5	2,5		0	fine grained	V

File: /os/gof/fordafr/por-perm/thinsection-statistic.exe

TABLE 1: Statisitcal data on thin sections (cont.)

Thin-section	Sample	gas-		intercrystaline		total pores	plagioclase		pyroxene		olivine		opaque		glassrim at gp		opaline silica		remarks	group
number	number	pores	%	pores	%	%		%		%		%		%		%		%		
16719	R-85	50	25	19	9,5	34,5	60	30	43	21,5	15	7,5	10	5	2	1	1	0,5	medium grained	VI
16720	R-88	36	18	15	7,5	25,5	60	30	54	27	12	6	15	7,5	7	3,5	1	0,5	fine grained	VI
16721	R-90	21	10,5	18	9	19,5	56	28	67	33,5	12	6	23	11,5	3	1,5		0	medium grained	VI
2740	R-91	31	15,5	19	9,5	25	63	31,5	48	24	9	4,5	17	8,5	8	4		0	fine grained	VI
16722	R-92	111	55,5	9	4,5	60	31	15,5	32	16	6	3	10	5	1	0,5		0	fine grained	VI
16723	R-93	57	28,5	11	5,5	34	48	24	62	31	9	4,5	11	5,5	2	1		0	medium grained	VI
16724	R-94	65	32,5	14	7	39,5	47	23,5	50	25	6	3	11	5,5	7	3,5		0	medium grained	VI
16725	R-95	60	30	17	8,5	38,5	50	25	50	25	15	7,5	3	1,5	5	2,5		0	medium grained	VI
16726	R-96	23	11,5	8	4	15,5	58	29	71	35,5	15	7,5	8	4	15	7,5	2	1	medium grained	VI
16727	R-97	34	17	18	9	26	42	21	68	34	15	7,5	14	7	9	4,5		0	fine grained	VI
16728	R-98	45	22,5	17	8,5	31	51	25,5	61	30,5	15	7,5	6	3	5	2,5		0	medium grained	VI
16730	R-100	46	23	21	10,5	33,5	38	19	60	30	15	7,5	8	4	11	5,5	1	0,5	fine grained	VI
16731	R-101	34	21	9	5,5	26,5	36	23	44	27,5	8	5	6	4	15	9,5		0	med.grained 159pt	VI
16732	R-102	28	14	15	7,5	21,5	63	31,5	59	29,5	16	8	11	5,5	6	3	2	1	fine grained	VI
16742	R-103	86	43	10	5	48	43	21,5	46	23	5	2,5	6	3	4	2		0	medium grained	VI
16733	R-104	49	24,5	11	5,5	30	57	28,5	63	31,5	8	4	10	5	2	1		0	medium grained	VI
16734	R-105	50	25	21	10,5	35,5	52	26	49	24,5	10	5	13	6,5	5	2,5		0	medium grained	VI
16735	R-106	41	20,5	25	12,5	33	54	27	49	24,5	16	8	11	5,5	4	2		0	medium grained	VI
16736	R-107	40	20	14	7	27	61	30,5	70	35	7	3,5	4	2	4	2		0	coarse grained	VII
16737	R-108	6	3	21	10,5	13,5	80	40	67	33,5	15	7,5	8	4	3	1,5		0	coarse grained	VII
16738	R-110	8	4	27	13,5	17,5	70	35	69	34,5	19	9,5	7	3,5		0		0	coarse grained	VII
16739	R-111	8	4	20	10	14	71	35,5	76	38	18	9	7	3,5		0		0	coarse grained	VII
16740	R-112	7	3,5	25	12,5	16	80	40	69	34,5	15	7,5	4	2		0		0	coarse grained	VII
2736	R-113	2	1	17	8,5	9,5	71	35,5	80	40	19	9,5	10	5			1	0,5	coarse grained	VII
16741	R-114	74	37	20	10	47	49	24,5	48	24	3	1,5	3	1,5	3	1,5		0	coarse grained	VII
2737	R-115		0	10	5	5	68	34	85	42,5	23	11,5	12	6	1	0,5	1	0,5	coarse grained	VII
16743	R-116	2	1	28	14	15	68	34	74	37	14	7	14	7		0		0	coarse grained	VII
16744	R-117	4	2	21	10,5	12,5	71	35,5	69	34,5	25	12,5	9	4,5	1	0,5		0	coarse grained	VIII
16745	R-118		0	17	8,5	8,5	86	43	71	35,5	18	9	8	4		0		0	coarse grained	VIII
16746	R-119		0	37	18,5	18,5	78	39	62	31	9	4,5	11	5,5	2	1	1	0,5	coarse grained	VIII
2738	R-123		0	30	15	15	81	40,5	60	30	17	8,5	12	6		0		0	coarse grained	VIII
2739	R-124	3	1,5	21	10,5	12	68	34	70	35	17	8,5	21	10,5		0		0	coarse grained	VIII
16748	R-124	4	2	37	18,5	20,5	75	37,5	53	26,5	26	13	5	2,5		0		0	coarse grained	VIII
16749	R-125		0	32	16	16	71	35,5	68	34	21	10,5	8	4		0		0	coarse grained	VIII
16750	R-126		0	39	19,5	19,5	63	31,5	70	35	19	9,5	9	4,5		0		0	coarse grained	VIII
16751	R-127		0	27	13,5	13,5	83	41,5	63	31,5	22	11	5	2,5		0		0	coarse grained	VIII
16752	R-128		0	35	17,5	17,5	71	35,5	65	32,5	25	12,5	4	2		0		0	coarse grained	VIII
16753	R-129	2	1	26	13	14	76	38	66	33	21	10,5	9	4,5		0		0	coarse grained	VIII
16754	R-130	46	23	18	9	32	53	26,5	49	24,5	7	3,5	13	6,5	14	7		0	medium grained	IX
2741	R-131	5	2,5	25	12,5	15	72	36	58	29	12	6	20	10	8	4			medium grained	IX
16755	R-132	2	1	24	12	13	73	36,5	71	35,5	5	2,5	15	7,5	10	5		0	medium grained	IX
16756	R-133	32	16	18	9	25	66	33	56	28	5	2,5	7	3,5	16	8		0	medium grained	IX
16757	R-134	61	30,5	16	8	38,5	56	28	46	23	5	2,5	8	4	8	4		0	medium grained	IX

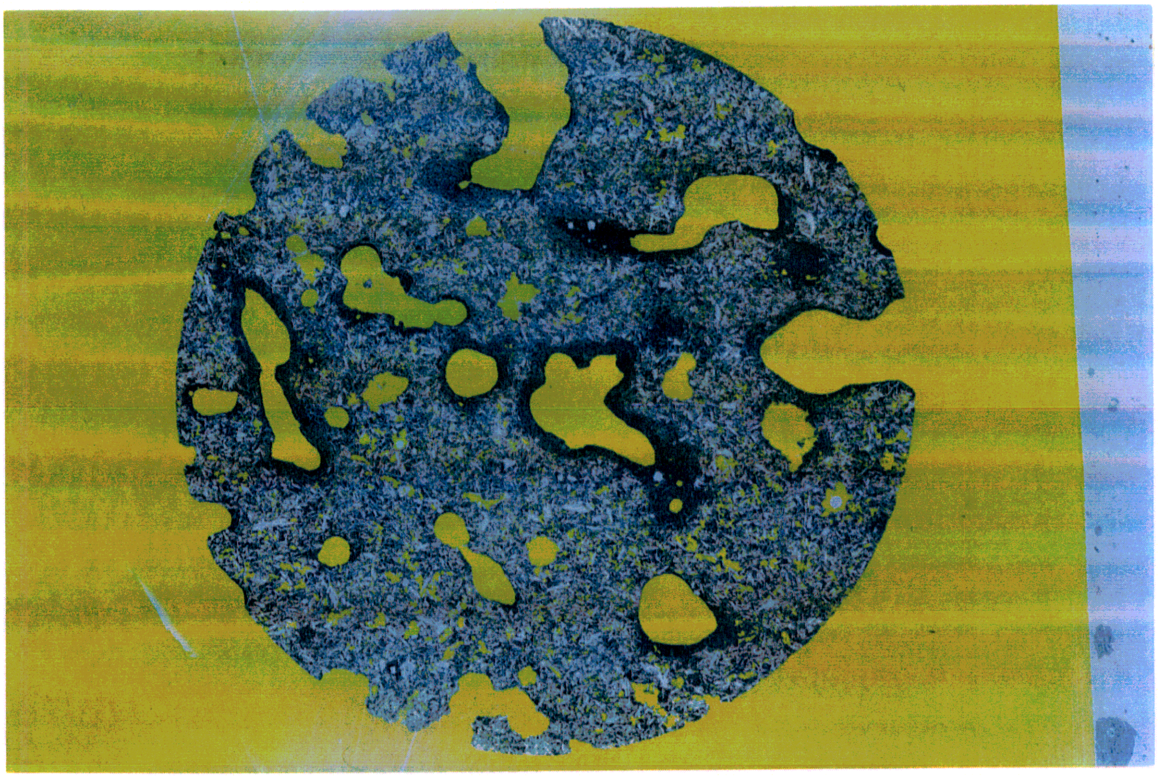

Figure 1. Sample R-56. Group II. (Thin-section 2742, from a scoriaceous stone, photo 10A). Texture: fine grained. Core diameter ca. 1" or 25 mm, enlargement ca 4x. The photo shows large gaspores with well developed glassrim around the vesicles. Intercrystalline pores do not develop chilled glass. Statistic: gas pores **(gp)**: 14,5%; intercrystaline pores **(ip)**: 7,5 %; plagioclase **(pl)**: 24%; pyroxene **(px)**: 21,5%; olivine **(ol)**4,5%; opaque **(opq)**: 12,5%; glassrim **(gl)**: 15,5%; opaline silica **(osi)**: 0%; Ø: 26,7%; k: 0,23 mDarcy; GD: 3,05 g/cm^3 .

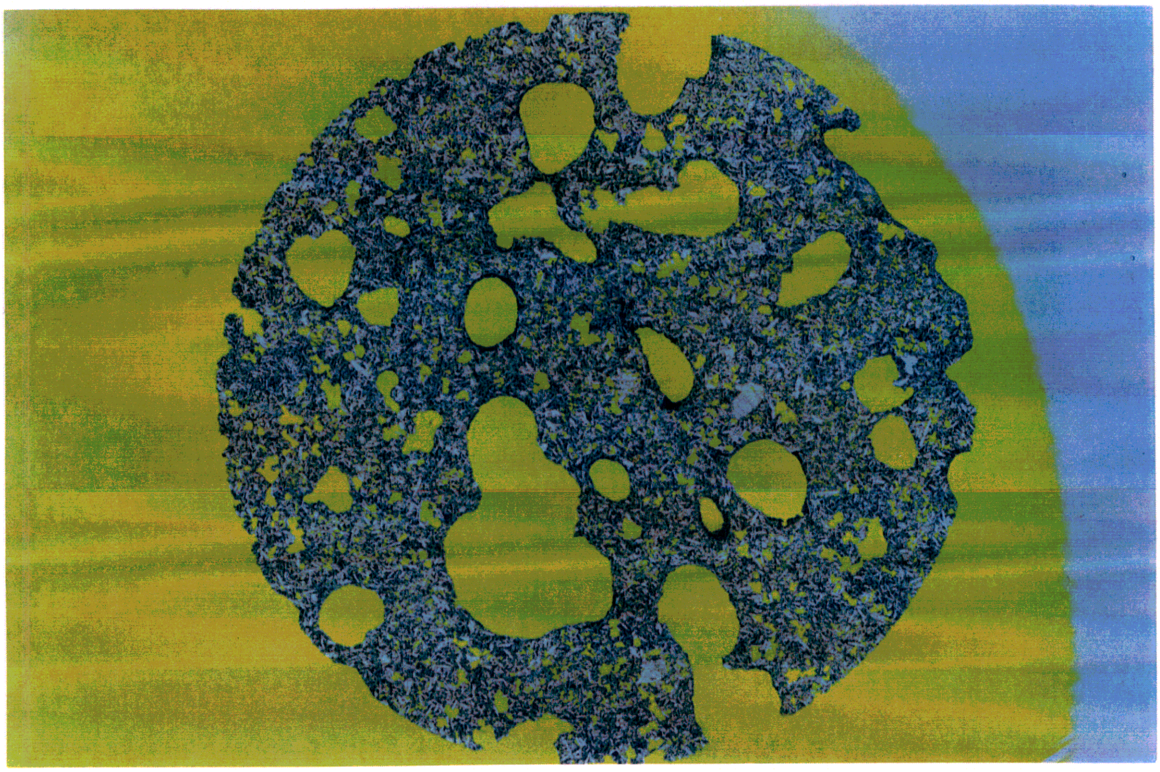

Figure 2. Sample R-57. Group II. (Thin-section 2743, from a scoriaceous stone, photo 9A). Texture: fine grained. Core diameter ca. 1" or 25 mm, enlargement ca 4x. The photo shows large gaspores with poorly developed or no glassrim around the vesicles. Statistic: **gp**: 20,5%; **ip**: 11 %; **pl**: 21,5%; **px**: 21%; **ol**: 11%; **opq**: 6%; **gl**: 9%; **osi**: 0%; Ø: 36,3%; k: 0,40 mDarcy; GD: 3,05 g/cm^3 .

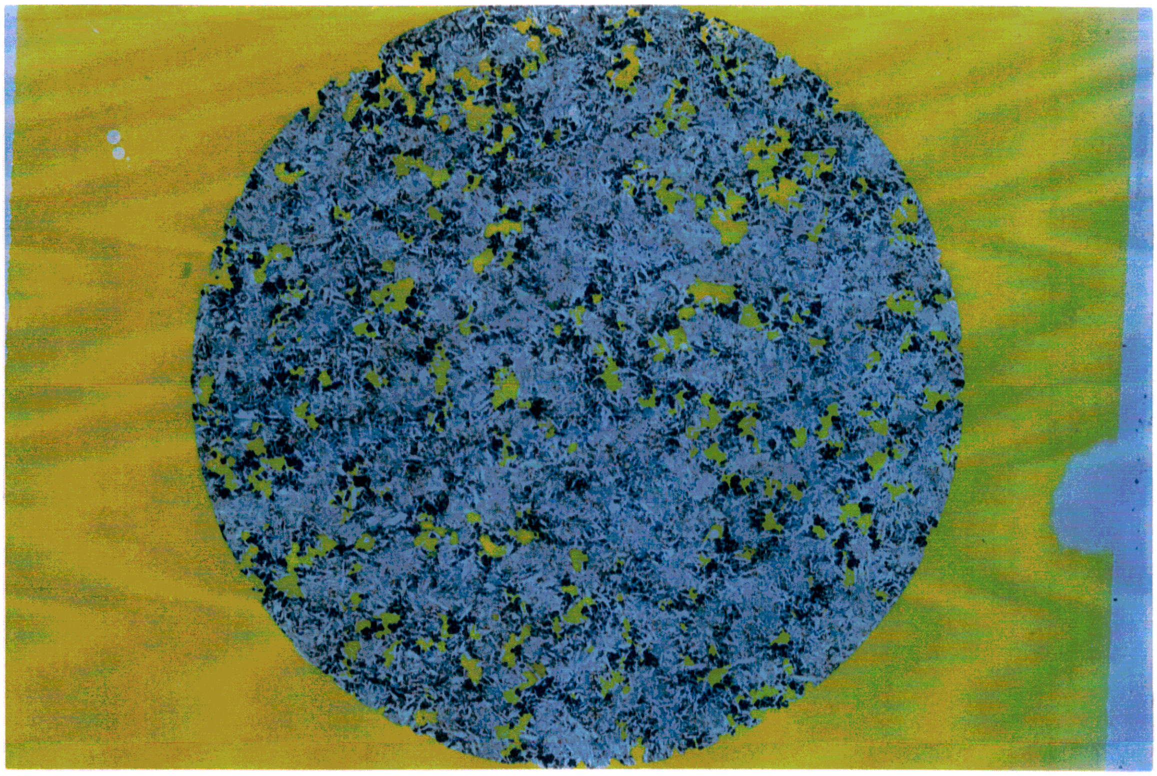

Figure 3. Sample R-38. Group I. (Thin-section 2734, from lava middle, horizontal to the N, parallel to flow banding, photo 11A). Texture: coarse grained, subophitic. Core diameter ca. 1" or 25 mm, enlargement ca 4x. The core only shows intercrystaline pores Opaque content high. Statistic: **gp**: 0%; **ip**: 5 %; **pl**: 33%; **px**: 34%; **ol**: 7,5%; **opq**: 20,5%; **gl**: 0%; **osi**: 0%; **Ø**: 12,32%; k: 14,92 mDarcy; GD: 3,06 g/cm^3 .

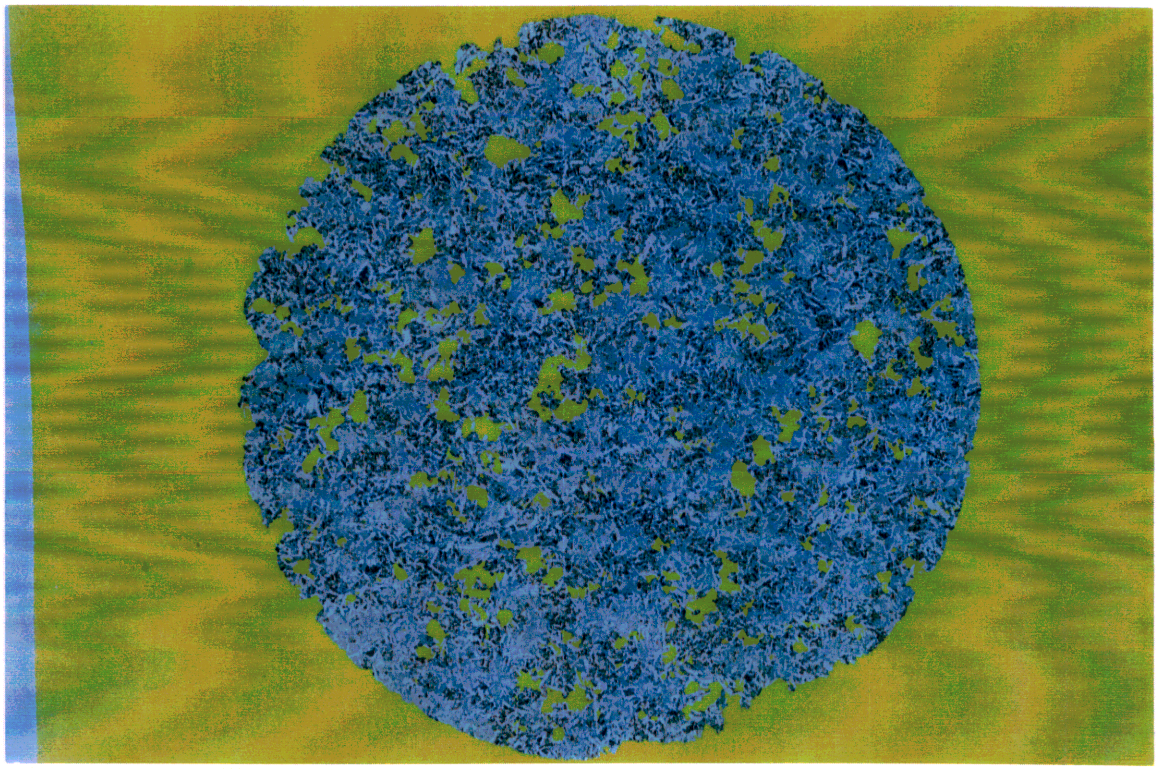

Figure 4. Sample R-124. Group VIII. (Thin-section 2739, from lava middle, vertical (down), perpendicular to flow banding, photo 12A). Texture: coarse grained, subophitic. Core diameter ca. 1" or 25 mm, enlargement ca 4x. The core mostly shows intercrystaline pores. Statistic: **gp**: 1,5%; **ip**: 10,5 %; **pl**: 34%; **px**: 35%; **ol**: 8,5%; **opq**: 10,5%; **gl**: 0%; **osi**: 0%; **Ø**: 11,96%; k: 1,88 mDarcy; GD: 3,07 g/cm^3 .

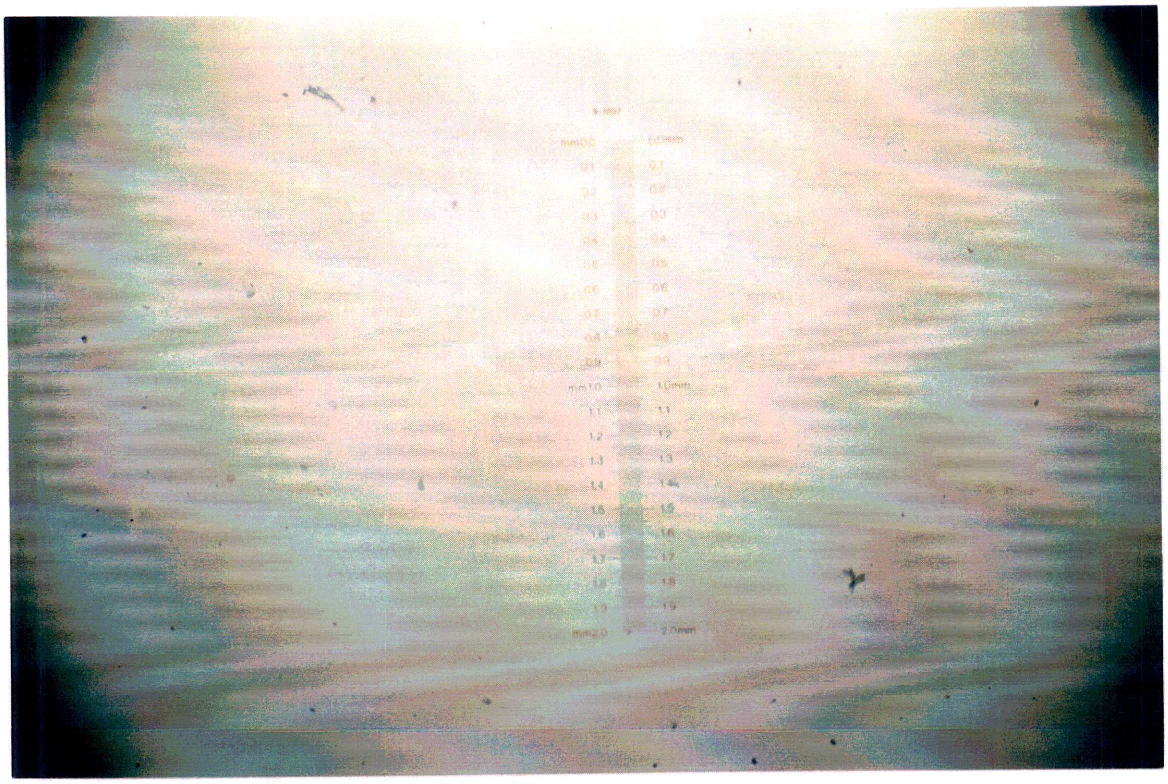

Figure 5. Scale used for figures 6-14. Scale ca. 33 x enlargement (occular 4/0,12), photo 19A.

Figure 6. Sample R-56. Group II. (Thin-section 2742, photo 15A). Texture: fine grained. Gas pores with glassy rim, and intercrystaline pores with no glass. The larger feldsparlaths are 0,5-1 mm long and 0,1 mm accross. See Fig 1 for comparison.

Figure 7. Sample R-57. Group II. (Thin-section 2743, photo 16A). Relatively fine grained rock (same stone as R-56) showing nice intercrystalline pores between larger gas pores. Note the red stain which is due to iddingsite which partly replaces olivine. Compare with Fig 2.

Figure 8. Sample R-57 (section 2743, photo 17A), same section as in Figs 7 and 2 showing an olivine phenocryst (ca 1,4 x 0,7 mm), also seen in Fig 2.

Figure 9. Sample R-38 (thin section 2734, photo 18A). Opaline silica infilling (brownish) forming layers in the bottom of some intercrystalline pores and filling others. Red brown stain is iddingsite after olivine. The **px** and **ol** enclosing the **pl** are 0,5 - 0,8 mm accross. Note: The sparse silica infillings in this sample did not show in the statistical analysis.

Figure 10. Sample R-38 (section 2734, photo 22A). Same sample as in Fig 9, showing 1 intercrystalline pore filled by opaline silica. Note the abundance and size of the **opaque** ore minerals as compared to the other photos.

Figure 11. Sample R-124 (thin section 2739, photo 20A). Coarse grained subophitic to ophitic texture where the **pl** is enclosed in **px** and **ol** which are 0,5-1 mm across. Red brown iddingsite, which is a weathering product of olivine, is quite clear. Note the size difference of the **opq** ore in this sample as compared to R-38 in Figs 9 and 10. Both are from the middle part of the lava flow.

Figure 12. Sample R-124 (thin section 2739, photo 21A). Same sample as in Fig 11. These intercrystalline pores must be more or less interconnected in 3-D space.

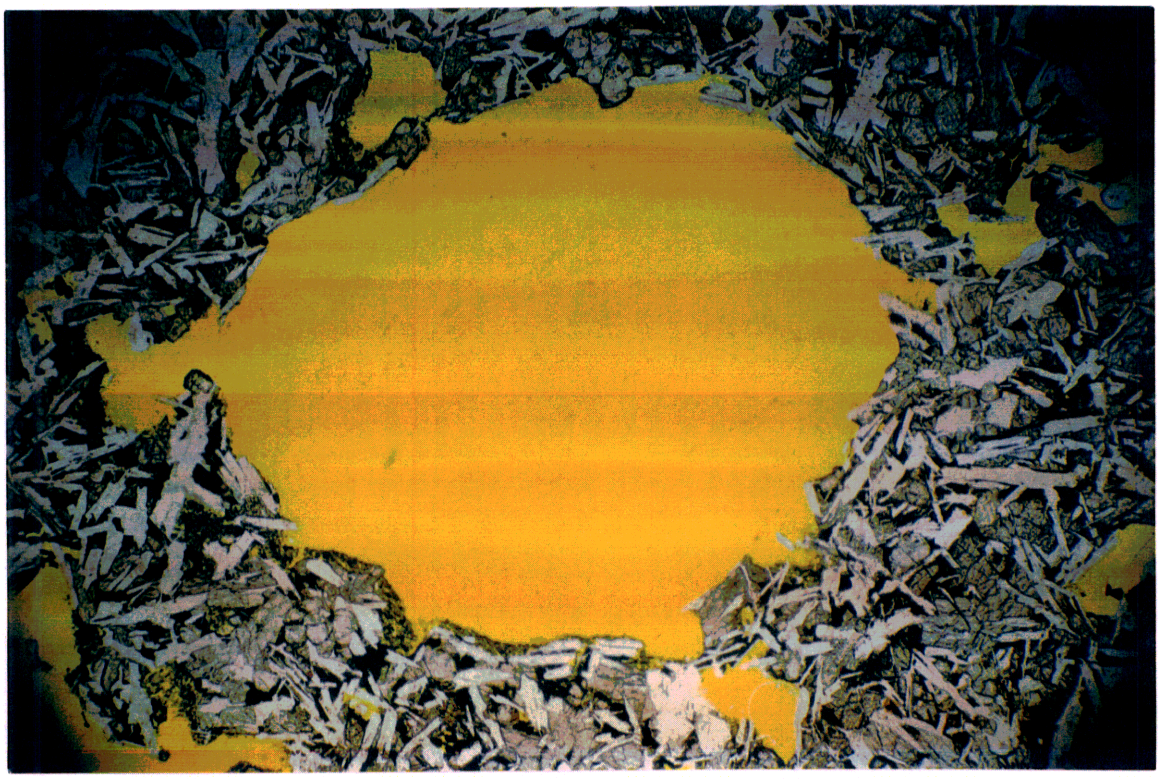

Figure 13. Sample R-131 (thin section 2741, photo 23A). A coarse grained rock with large (ca > 2 mm) gas pores without any glassrim. Ø: 24,95%; k: 0,32 mDarcy; GD: 3,055 g/cm^3.

Figure 14. Sample R-131 (thin section 2741, photo 24A). Same as in Fig 13, a well developed mesh of apparently interconnected intercrystalline pores - i.e. in 3-D space.

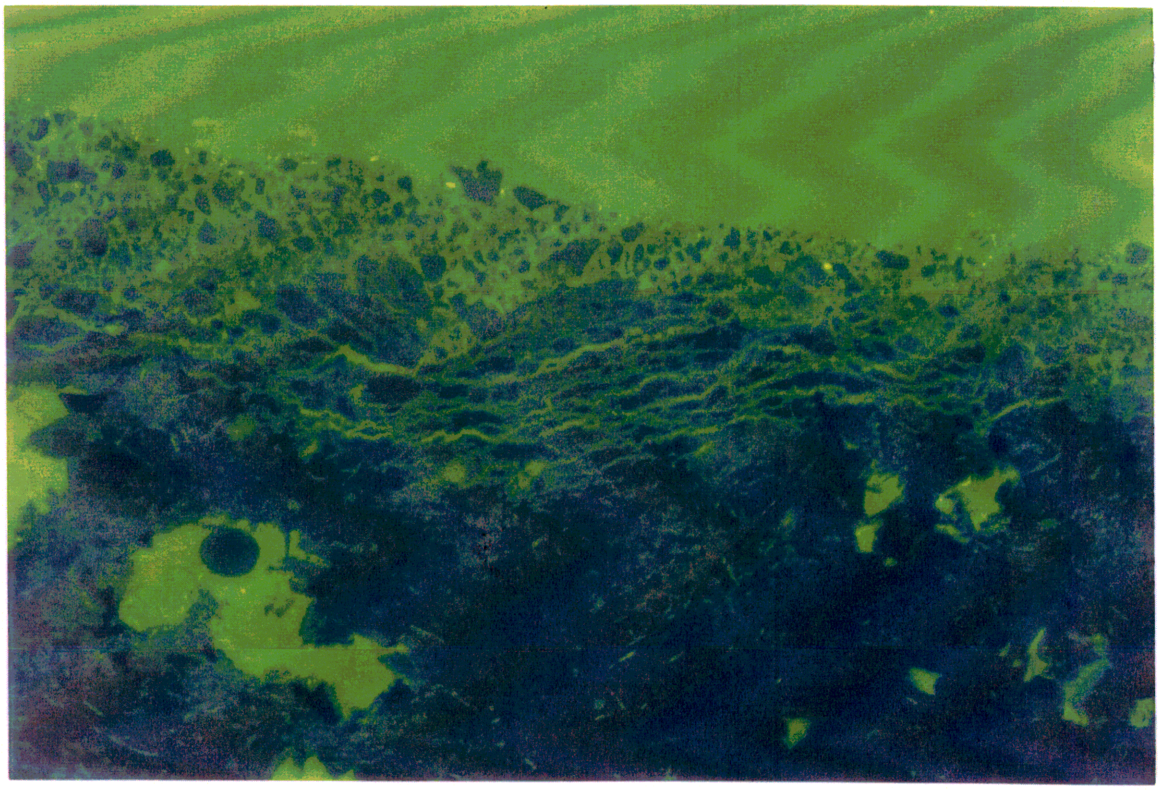

Figure 15. A fluorescent view of micro fractures due to weathering of an olivine *tholeiite* lava from the Althingshus (the Parliament building) in Reykjavik. The quarry was at Skólavörduholt, ca 1 km from Öskjuhlid, and the lave is from the same late Pleistoncene lava formation (the Reykjavik grágrýti).

Figure 16. Same view as in Fig 15 but in plain polarized light. (Sample and thin-section 1833 from Dr. Gísli Guðmundsson at the Icelandic Building Reasearch Institute (Report nr. 95-27, IBRI, 15 p.)). (Magnification , occulars 10x3.2; the length of the photo ca 4 mm).

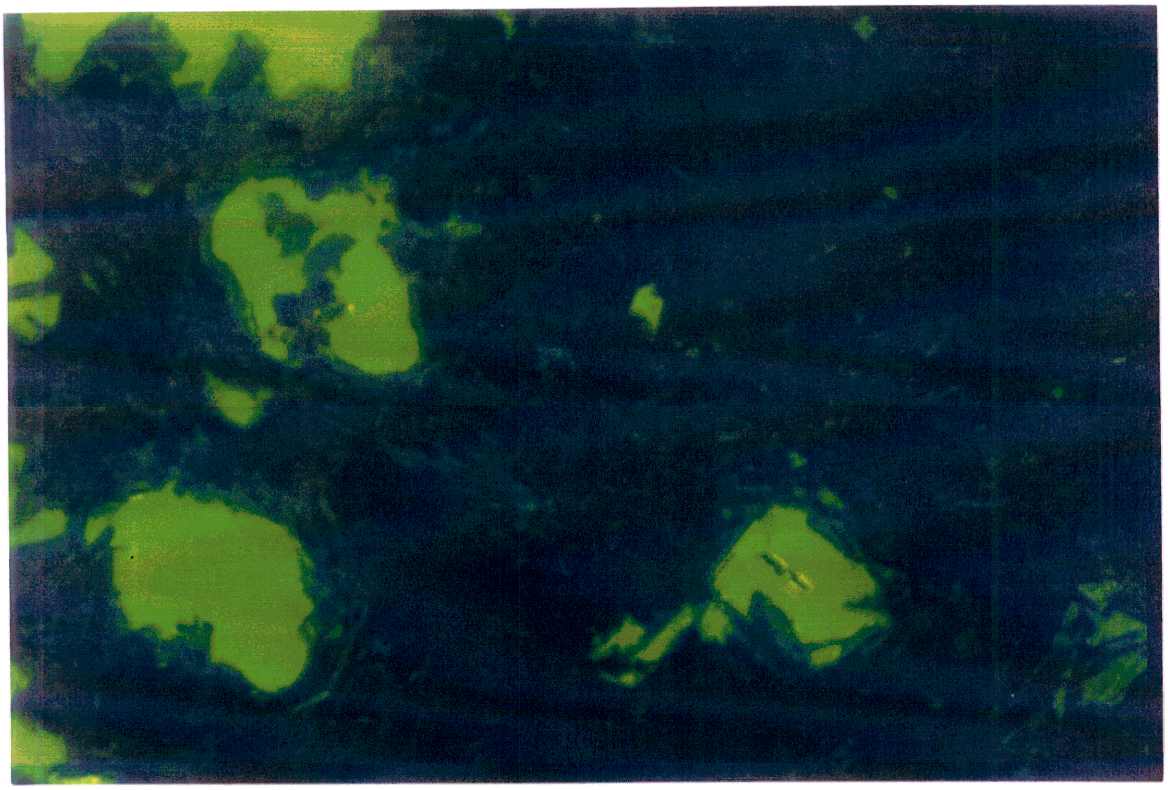

Figure 17. A fuorescent view of sample R-124 (section 2739) from the Öskjuhlid samples. None of the Öskjuhlid samples impregnated with fluorescent resin showed any significant microfractures (see text for further discussion). (Magnification , occulars 10x3.2; the length of the photo ca 4 mm).

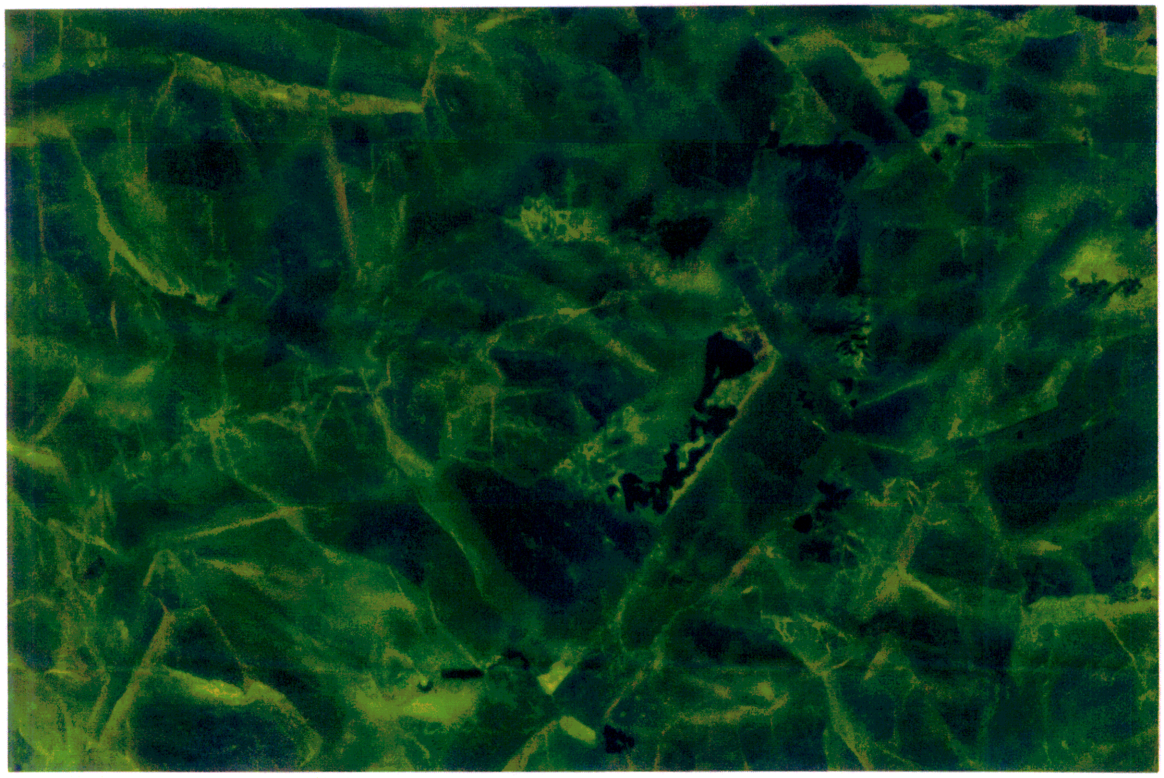

Figure 18. A fuorescent view of sample R-124 as in Fig 17, but at 6-7x higher magnification (ca 200 x) None of the Öskjuhlid samples impregnated with fluorescent resin showed any significant microfractures but disconnected microcracks of this short are common (see text for further discussion).