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^{40}Ar-^{39}Ar ages of Dellen, Jänisjärvi, and Sääksjärvi impact craters

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Abstract—^{40}Ar-^{39}Ar age measurements were made for three whole rock melt samples produced during impact events which formed the Dellen, Jänisjärvi, and Sääksjärvi craters on the Baltic Shield. An age of 109.6 ± 1.0 Ma was obtained for the Dellen sample based on an age spectrum plateau. The age spectrum shows a small (7%) loss of radiogenic ^{40}Ar from low temperature fractions. Ages of 698 ± 22 Ma and 560 ± 12 Ma were obtained from isochrons for the Jänisjärvi and Sääksjärvi samples, respectively. Data obtained by laser degassing support the Sääksjärvi result. The presence of excess ^{40}Ar is indicated in lower temperature fractions for both samples and is correlated with K concentrations in the Sääksjärvi sample. Models explaining these results may require a change in the local "atmospheric" Ar isotopic composition as cooling of melt rocks proceeded. However, it cannot be excluded that devitrification and/or alteration changed the Ar budget. A crater production rate on the Baltic Shield based on measured ages of 6 craters is $(0.3 \pm 0.2) \cdot 10^{-14}$ 20-km-and-larger craters per km^2 per year, in satisfactory agreement with previous estimates.

INTRODUCTION

THE SURFACES OF THE terrestrial planets and most satellites of the Jovian planets are marked with craters produced by impacts of smaller solar system bodies. Relative ages of these surfaces can be determined from the crater densities on them and absolute ages if an appropriate crater production rate is known. For lunar mare surfaces Neukum *et al.* (1975) combined crater populations with absolute radiometric ages of corresponding mare basalts and established crater production rates valid for the Moon in the time range 3.2 to 3.9 billion years ago. For the Earth, crater production rates are best obtained by determining the ages of individual impact craters in a geologically stable area. This yields an estimate of the production rate valid for approximately the last one billion years (Grieve and Robertson, 1979). The results reported here will contribute to this latter approach by providing improved ages for three additional impact craters on the Baltic Shield.

Furthermore, the suggested connection between mass extinctions and large impact events (Alvarez *et al.,* 1980) and the possibility of related periodicities of extinctions and impacts (Raup and Sepkoski, 1984; Alvarez and Müller, 1984; Durrheim and Reimold, 1986, 1987; Grieve *et al.,* 1985) demands an improvement of the current data base of absolute ages for terrestrial impact structures. Currently there exist reliable ages for only 16 craters and questionable ages for 6 additional craters (Durrheim and Reimold, 1987).

Locations and sizes for the Dellen, Jänisjärvi, and Sääksjärvi crater structures, together with those for the Lake Mien, Siljan, and Lappajärvi structures, all on the Baltic Shield, are presented in Table 1. The structures are heavily eroded and have been classified as "probable" impact structures by Grieve and Robertson (1979). In contrast to the Lappajärvi crater, where the impact melt rocks were found to be contaminated by identifiable meteoritic siderophile elements (Göbel *et al.,* 1980; Reimold, 1982), no equivalent contamination has been found in the Dellen, Sääksjärvi (Palme, 1980) and Jänisjärvi melt rocks. However, Palme (1980) describe an enrichment of Ir, Ni, Co and Cr in all 5 melt rocks from Sääksjärvi analysed in their study.

In the Dellen and Jänisjärvi cases coherent melt bodies exist near the centres of these structures. Sääksjärvi melt breccias (and suevite) can only be sampled in glacial deposits to the south/southeast of the crater lake. However, from available reports on breccia formations at these craters (monomict and polymict clastic breccias, suevite, melt breccias) and findings of shock metamorphic effects indicative of shock pressures up to 40 GPa and more (Svensson, 1968; Papunen, 1969; Masaitis *et al.,* 1976; Maerz, 1979; our own observations), it appears that the three crater structures, Dellen, Jänisjärvi, and Sääksjärvi, are of impact origin. The shock metamorphic effects include planar elements in quartz, diaplectic quartz and feldspar glasses and their annealed equivalent (*e.g.,* ballen-quartz), as well as partially (checkerboard feldspar) and completely fused mineral and lithic clasts. (For further description of shock textures *cf. e.g.,* Reimold, 1982 and references therein.)

Ages obtained previously (Grieve and Robertson, 1979) are 230 Ma for Dellen and 490 Ma for Sääksjärvi, both based on ^{40}Ar-^{39}Ar spectra (Bottomley *et al.,* 1977), and 700 Ma for Jänisjärvi, based on a conventional K-Ar analysis (Masaitis *et al.,* 1976). The sample from Dellen dated by Bottomley *et al.* (1977) yielded a well defined age plateau and was described as fresh glass containing some xenoliths. However, these authors also reported a second plateau age of about 100 Ma for another sample from Dellen, a partially devitrified melt specimen. For the Sääksjärvi case Bottomley *et al.* (1977) argued that the more complex spectra obtained could be indicative of only partial degassing of their samples by the impact event and that this would indicate a maximum crater age of about 330 Ma.

SAMPLES

Selection Criteria and General Petrography

The three samples analysed in this study were obtained from the impact melt collection of the Institute of Planetology, Münster. Selection criteria were that the samples should be as homogeneous, fresh and clast-free as possible. Fresh glassy specimens were available in abundance for the Dellen crater (Maerz, 1979), but for the Sääksjärvi structure only boulders could be collected from glacial deposits. Based on their direction of transport it can be assumed that the moraine-derived melt specimens

TABLE 1. Craters on the Baltic Shield.

Crater	Location	Diameter km	Age Ma	Reference
	Lat., Long.			
Lappajärvi	Finland 63°09′N, 23°42′E	14	77	Jessberger and Reimold, 1980
Dellen	Sweden 61°55′N, 16°32′E	15	109	This work
Lake Mien	Sweden 56°25′N, 14°52′E	5	119	Bottomley *et al.*, 1978
Siljan	Sweden 61°02′N, 14°52′E	52	362	Bottomley *et al.*, 1978
Sääksjärvi	Finland 61°23′N, 22°25′E	5	514	This work
Jänisjärvi	Soviet Union 61°58′N, 30°55′E	14	698	This work

TABLE 2. Modal composition of impact melts.

Crater sample designation	Dellen[a] De-36	Jänisjärvi[b] Jä-1	Sääksjärvi[b] S-9/1
Matrix			
Plagioclase	14.7	43.8	20.5
Pyroxene	3.3	23.1	19.7
Opaques	0.5	*	*
Mesostasis + opaques	*	23.1	28.3
Mesostasis + glass	81.5	*	*
Vesicles	—	**	7.1
Mineral clasts			
Checkerboard feldspar	—	1.6	6.8
Recrystallized feldspar	—	0.2	2.2
Other feldspar	—	0.8	0.6
Quartz	—	0.7	7.1
Rock fragments			
Granodiorite	—	1.7	0.4
Gneiss	—	0.2	—
Quartzite	—	1.1	—
Recrystallized	—	1.8	—

Values given are volume percent.
* Category not specified.
— None observed.
** With many small bubbles.
[a] Maerz (1979).
[b] Reimold (1980).

originated from a coherent melt body within the now eroded crater. Sample S-9/1 is the least altered specimen from the Sääksjärvi collection. Jänisjärvi sample Jä-1 was provided to W. U. R. by Prof. Carstens, University of Århus, Denmark. Modal analyses of our samples De-36 from Dellen (Maerz, 1979), S-9/1 from Sääksjärvi, and Jä-1 from Jänisjärvi, are listed in Table 2.

Dellen Sample De-36

A detailed petrographic description of this sample was provided by Maerz (1979). It is a very homogeneous glassy (81.5 vol.% mesostasis, Table 2) melt, relatively free of clasts. A single ballen-quartz fragment constitutes the complete clast content in the thin section studied by Maerz. Perlitic cracks and vesicles are abundant (Fig. 1a). Within the light–dark brown glass microlites of lathy or H-shaped (Carstens, 1975) plagioclase crystals of labradorite composition, as well as euhedral, sometimes skeletal hypersthene and titanomagnetite crystals are observed. The sample is extremely fresh, although strong pleochroism of some pyroxene crystals is indicative of incipient alteration. Average plagioclase and pyroxene grain sizes are about 100–140 μm. The modal composition of specimen De-36 (Table 2) clearly indicates that its clast content is negligible.

Sääksjärvi Sample S-9/1

The sample (Figs. 1b–d) is a cryptocrystalline melt breccia (<28.3 vol.% mesostatis). Plagioclase, in the form of laths or tabular crystals, and prismatic pyroxene are the most important matrix constituents. Vesicles are present (7.1 vol.%), nearly all of which are filled with clay minerals (*e.g.*, nontronite and chlorite, Fig. 1e). Carbonate fillings were not observed. The pyroxene laths are partially altered along their margins. Average grain sizes for matrix plagioclase and pyroxene are 60–120 μm and 25–50 μm, respectively. The clast content, 16.7 vol.%, is significant, but far less than in all other Sääksjärvi melt breccias studied. Clasts are, in approximately equal proportions, feldspar and quartz fragments (Table 2). Besides a small amount of unshocked plagioclase, checkerboard feldspar (mostly plagioclase) (Figs. 1c,d) and totally recrystallized feldspar clasts (Fig. 2a) are abundant. The checkerboard texture originates from partial melting in crystallographically controlled zones within a crystal (for details *cf.* Maerz, 1979). Quartz fragments are generally unshocked; only one grain of diaplectic quartz glass (Fig. 1f) and one with a single set of planar elements were observed in our sample. Lithic fragments are rare (0.4 vol.%, Table 2) and consist of relics of biotite-feldspar gneiss. The few clasts of this kind are all partially melted as is indicated by pervasive recrystallization zones (Fig. 2c). A single lithic clast was seen to contain a ballen-quartz grain (Figs. 2c,d). The range of deformation textures observed in clasts is very similar to that described in melt rocks from Lappajärvi impact crater (Reimold, 1982) and other probable impact structures (*e.g.*, Grieve, 1975). In general, the Ar-bearing minerals in clasts show strong thermal effects. It is considered unlikely that a significant proportion of inherited Ar could have been retained in these minerals during cooling of the impact melt body.

Jänisjärvi Sample Jä-1

Sample Jä-1 (Figs. 2b,e,f) is a much finer-grained cryptocrystalline melt specimen than S-9/1, but with similar subophitic texture. The matrix consists largely of small (<60 μm) plagioclase laths and platelets and pyroxene prisms that also display partial alteration. Small (<120 μm) clasts consisting mainly of feldspar and rarely quartz are abundant. Larger clasts are identified as relics of granitic and quartzitic (possibly quartz-pegmatite) target rocks. Small feldspar clasts frequently display checkerboard texture or irregular partial recrystallization. The small quartz clasts are generally unshocked, some minor annealing effects have occasionally been observed.

In lithic clasts, which are up to 4 mm in size, ballen-quartz, fracturing of feldspar, and sometimes quartz grains with a single set of planar elements are observed. Several clasts consist of diaplectic quartz glass (Figs. 2e,f). In several completely or partially melted clasts brownish-to-black oxidation products of primary mafic minerals, probably biotite or hornblende, were seen. No pristine Ar-bearing mafic minerals were found.

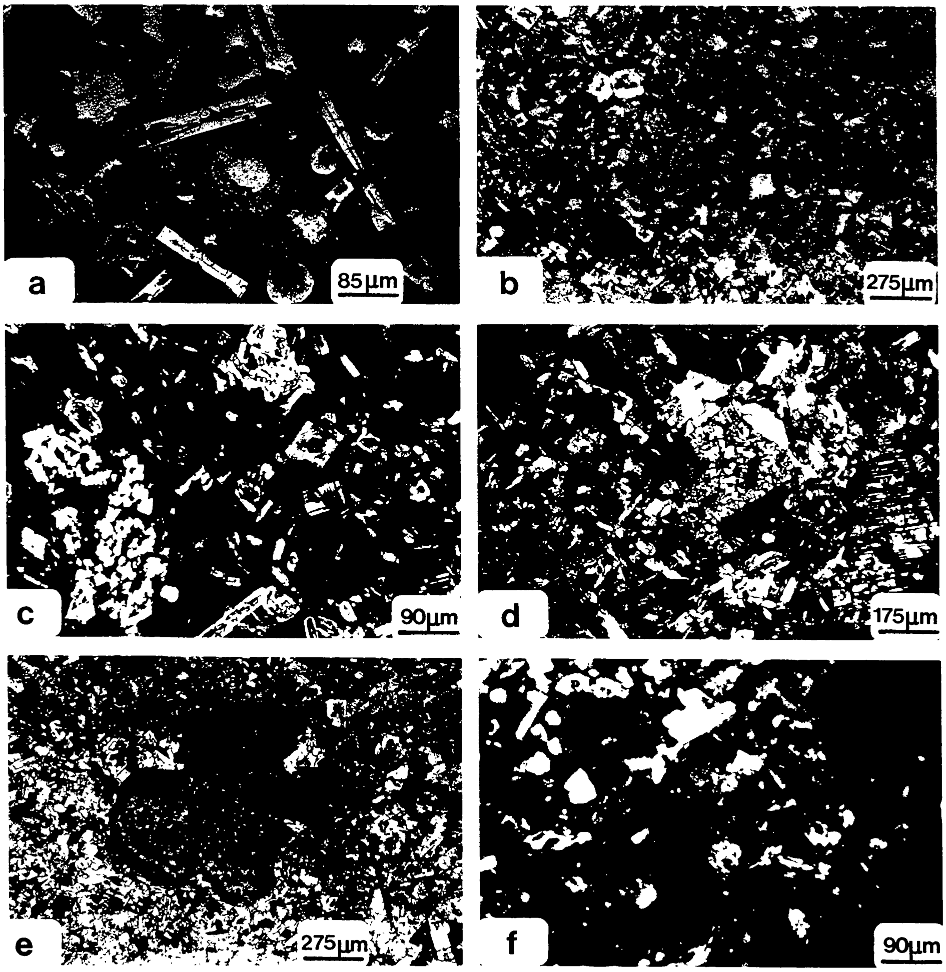

FIG. 1. a) Dellen 36 (From Maerz, 1979, Fig. 15). H-shaped plagioclase microlites and skeletal pyroxene (upper right) in glassy melt. Roundish white objects are vesicles. Mean length of plagioclase laths: *ca.* 130 μm. Plane polarized light. b) Sääksjärvi, S-9/1. Crystalline matrix consisting of lathy or tabular plagioclase (white) and prismatic pyroxene (grey with lighter rims) displaying alteration rims. The center is occupied by a larger checkerboard plagioclase clast (also Fig. 1c). Width of field of view: 2.2 mm. Plane polarized light. c) Enlargement of central area of Fig. 1b with several checker-board feldspar xenocrysts. Width: 720 μm. Crossed nicols. d) S-19/1. Chlorite-filled vesicle (centre). Pyroxene laths show alteration rims. Width: 1.4 mm. Crossed nicols. e) S-9/1. Vesicle filled with clay mineral spherulites. Width: 2.2 mm. Plane polarized light. f) Small clast (center, dark) of diaplectic quartz glass in S-9/1. Width: 720 μm. Crossed nicols.

Vesicles, up to 3 mm in diameter are abundant (*ca.* 2 vol.%). They are filled with either fresh, undevitrified or with recrystallized quartz glass (Fig. 2b). Fillings of vesicles consisting of secondary minerals, such as clay minerals, carbonates or zeolites, were *never* observed.

Overall, the amount of unmelted or thermally unaffected clasts containing Ar-carriers, mafic minerals or feldspar, is estimated to be less than 0.5 vol.% of the total sample. However, in places matrix pyroxene is significantly altered.

^{40}AR-^{39}AR ANALYSIS

Whole rock samples were irradiated together with two B4M age monitors (Jäger, 1969) and one CaF_2 glass at the FR2 reactor in Karlsruhe, FRG for three days. A fast neutron dose of about $4 \cdot 10^{15}$ n/cm^2 was obtained. The sample container was shielded by Cd to lower the thermal neutron flux. After a cooling time of three months, the samples were placed in the extraction line of a noble gas mass spectrometer system and baked at 200 °C for one day to remove adsorbed gases. Stepwise heating of the samples was done in a radiofrequency heated furnace for 55 minutes per step in the presence of a hot Ti-getter. After removal of reactive gases by three additional getters, the argon isotopic composition was measured mass-spectrometrically. The mass discrimination and the sensitivity of the spectrometer were determined each day with pipetted amounts of atmospheric argon. The measured data were reduced as described previously (Jessberger *et al.,* 1974). The furnace blank, determined before and after sample measurements and found to be stable, was of atmospheric isotopic composition with negligible ^{39}Ar and ^{37}Ar at all temperatures. The blank amounts above about 1200 °C are strongly temperature dependent. As an example, the blank amounts at 1500 °C (calculated for a fictitious sample weight of 100 mg to ease comparison with De-36 in Table 3) were for ^{36}Ar: $50 \cdot 10^{-12}$, ^{37}Ar: $0.3 \cdot 10^{-11}$, ^{38}Ar: $10 \cdot 10^{-12}$, ^{39}Ar: $1.5 \cdot 10^{-11}$, ^{40}Ar: $1.5 \cdot 10^{-8}$ (in units of cc STP/g). Because these values are either small compared to measured values or produce essentially

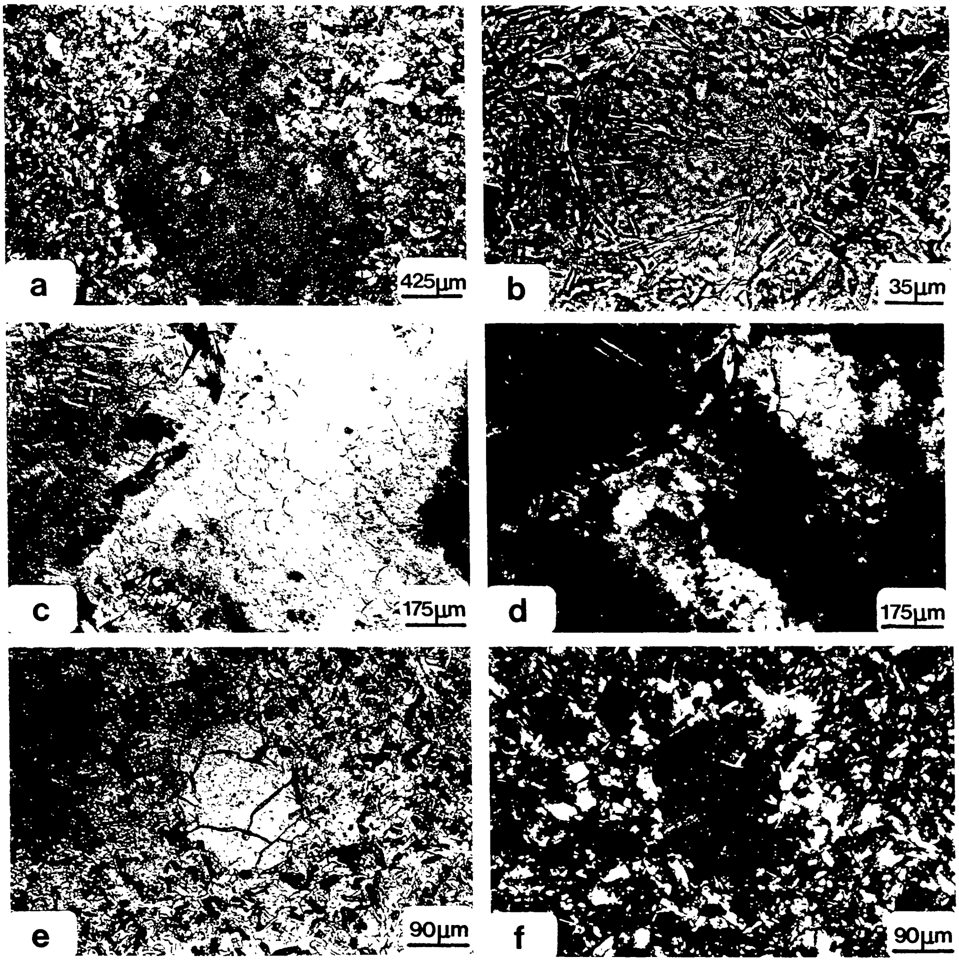

FIG. 2. a) S-9/1. Completely fused clast, fine-grained recrystallized (compare Fig. 3B, Reimold, 1982). Light roundish patches are vesicles in the clast, confirming total melting. Width: 3.4 mm. Crossed nicols. b) Jänisjärvi, Jä-1. One of the rare vesicles filled with nearly undevitrified glass in rather fine-grained matrix. Width: 285 μm. Plane polarized light. c) S-9/1. Ballen-quartz clast, interpreted as annealing product after diaplectic quartz glass (*cf.* also Carstens, 1975), probably formed via transformation into cristobalite (Lehtinen, 1976). Width: 1.4 mm. Plane polarized light. Part of partially melted gneiss xenocryst. Note feldspathic melt vein appearing in upper left part of photograph. d) S-9/1. Annealing texture of quartz crystal. Crossed nicols. e) Jä-1. A clast consisting almost completely of diaplectic quartz glass. Matrix plagioclase - light, pyroxene - grey with slightly darker alteration rims. Width: 720 μm. Plane polarized light. f) as e), but with crossed nicols. Note nearly complete isotropy of the quartz glass clast.

atmospheric isotopic ratios, no blank corrections were applied. The argon isotopic data, after correction for ^{37}Ar decay during and after neutron irradiation and after subtraction of Ar isotopes produced from K and Ca in undesired side reactions, but *before* correction for atmospheric argon are given in Table 3 for each extraction fraction together with the apparent ages, which are calculated after subtraction of the atmospheric component.

^{36}Ar/^{38}Ar ratios below 5.35, the normal atmospheric value, are attributed to the presence of chlorine in the samples. The Cl contents were calculated using a previously determined production factor for ^{38}Ar$_{Cl}$ for neutron-irradiation behind a Cd-shield (Jessberger *et al.,* 1980) and adjusted to the J-value of the present irradiation. The resulting Cl concentrations for each sample are given in Table 4.

A polished section from the Sääksjärvi specimen was irradiated separately (J-value: 0.0663) and the gases were extracted by spotwise laser fusion of individual minerals (Müller, 1985). In laser extraction work the blank is, though much lower than in stepwise heating, not necessarily of atmospheric isotopic composition. For our setup typical values are (in units of ccSTP) for ^{36}Ar: $(15 \pm 10)\cdot 10^{-15}$, ^{37}Ar: $(0.2 \pm 0.15)\cdot 10^{-13}$, ^{38}Ar: $(1.5 \pm 1)\cdot 10^{-14}$, ^{39}Ar: $(4 \pm 3)\cdot 10^{-14}$, and ^{40}Ar: $(10 \pm 6)\cdot 10^{-13}$. The argon data are listed in Table 5 after corrections for blanks, for ^{37}Ar decay, and for products of undesired side reactions, but again *not* corrected for atmospheric argon. This last correction, however, has been done before the calculation of apparent ages also given in Table 5.

RESULTS

Dellen Sample De-36

The K/Ca and apparent age spectra for the Dellen sample are shown in Fig. 3. Apparent ages generally increase and K/Ca ratios decrease with increasing extraction temperature. Comparing results of a defocussed beam analysis of De-36 matrix by Maerz (1979), who obtained (6.2 ± 0.6) wt.% K_2O and (0.9

TABLE 3. Argon isotopic data and apparent ages for the Dellen, Jänisjärvi, and Sääksjärvi samples.

Temp. [°C]	^{36}Ar 10^{12}	^{37}Ar 10^{11}	^{38}Ar 10^{12}	^{39}Ar 10^{11}	^{40}Ar 10^{8}	Age [Ma]
Dellen De-36						
400	524/4	485/3	2062/71	618/1	543/1	58.6/0.1
500	384/4	1910/7	4400/280	2495/4	2598/2	92.0/0.1
600	244/3	3118/10	6260/370	3517/6	4139/3	106.5/0.1
700	258/3	4010/16	3940/290	2584/4	3159/2	109.7/0.1
800	317/4	5233/15	1990/120	1040/1	1332/1	109.5/0.1
900	114/4	4616/14	630/47	317/1	362/1	95.6/0.1
1000	19/2	2816/8	224/16	82/1	84/1	87.7/0.2
1100	14/1	391/3	87/26	10/1	14/1	85.9/0.6
1200	20/2	263/3	77/25	8/1	14/1	84.8/0.6
1300	33/2	662/6	156/30	16/1	27/1	100.4/0.4
1450	145/3	438/3	310/6	13/1	77/1	230.1/0.8
1600	608/3	276/2	1136/11	7/1	196/1	193.0/1.2
1800	1121/4	124/2	2125/24	5/1	340/1	161.6/1.4
Total	3802/12	24 341/31	23 400/570	10 713/8	12 885/4	101.2/0.1
Jänisjärvi Jä-1						
400	7233/21	533/3	1473/8	988/2	351/1	989.0/1.6
500	5307/17	500/7	1090/7	1378/2	402/1	1188.5/1.3
600	4441/22	623/6	932/9	3813/7	598/1	896.1/1.2
700	2892/15	1351/7	620/16	9703/13	1011/1	733.3/0.7
800	2141/16	2531/19	422/16	12 666/61	1230/6	712.3/0.8
900	5229/16	3467/14	1128/23	20 487/26	2147/1	744.8/0.1
1000	7403/26	5019/13	1550/25	22 582/27	2511/1	771.2/0.7
1100	1999/8	1714/9	485/10	6180/9	637/1	721.0/0.8
1200	1011/6	874/5	226/8	3236/7	329/3	713.9/1.4
1300	594/4	631/11	143/8	2268/4	221/1	696.8/1.1
1400	1598/6	318/3	330/6	1115/4	147/1	695.4/2.1
1500	924/5	294/4	177/4	1060/2	124/1	705.9/1.2
1600	1898/6	297/4	366/5	1038/2	149/1	694.9/0.8
1650	1412/8	204/7	277/2	736/1	107/1	688.5/0.6
1750	2183/11	382/13	438/7	1443/2	194/1	698.4/0.8
1800A	3414/10	1090/6	705/6	4006/5	477/1	723.3/0.8
1800B	5918/8	245/5	1124/5	899/2	254/1	687.5/1.1
Total	55 596/57	20 072/38	11 487/48	93 600/75	10 889/7	754.3/0.3
Sääksjärvi S-9/1						
400	4092/8	159/3	771/4	80/1	1149/1	—
500	4972/12	659/4	1047/8	377/1	1571/1	235.3/0.7
600	7541/16	1196/8	1441/6	1639/3	3234/2	505.3/0.7
700	4126/11	6731/17	770/8	5393/8	4925/4	556.1/0.6
800	4437/10	9307/17	866/10	8832/11	7762/4	586.1/0.6
900	1999/16	4784/17	468/16	13 814/19	10 906/7	597.3/0.6
1000	1399/12	5297/14	386/26	25 161/29	10 504/6	578.3/0.5
1100	693/8	3326/8	332/12	11 020/16	7165/5	517.1/0.6
1200	249/6	871/7	129/5	3818/5	2438/1	508.5/0.6
1300	316/5	907/10	161/8	4980/10	3244/2	517.9/0.9
1400	361/5	445/3	111/6	2678/4	1812/1	521.0/0.7
1600	2103/8	470/3	429/7	1972/3	1839/1	506.8/0.7
1800	7028/18	1376/12	1438/13	5106/7	5256/2	510.4/0.6
1850	6146/14	151/5	1174/5	568/1	2151/1	484.7/1.0
Total	45 461/43	35 678/40	9524/41	85 437/43	71 957/13	554.6/0.2

The quoted numbers are to be divided by the factors given below the isotope identification to yield concentrations in cm^3 STP/g. Errors (1σ) are indicated following the slash and give the uncertainty of the least significant digits. Decay of ^{37}Ar and undesired side reactions on Ca and K have been corrected for. The determined correction factors are: $(^{36}\mathrm{Ar}/^{37}\mathrm{Ar})_{\mathrm{Ca}} = (6.64 \pm 0.03)\cdot 10^{-4}$; $(^{38}\mathrm{Ar}/^{37}\mathrm{Ar})_{\mathrm{Ca}} = (2.85 \pm 0.02)\cdot 10^{-4}$; $(^{39}\mathrm{Ar}/^{37}\mathrm{Ar})_{\mathrm{Ca}} = (10.0 \pm 0.1)\cdot 10^{-4}$; $(^{38}\mathrm{Ar}/^{39}\mathrm{Ar})_{\mathrm{K}} = 0.0141 \pm 0.0001$. Contributions of atmospheric Ar have *not* been subtracted.
For calculating the apparent ages given in the last column, ^{40}Ar was corrected for atmospheric contributions ($^{40}\mathrm{Ar}_{\mathrm{atm}} = 295.5\cdot{}^{36}\mathrm{Ar}$). The J-value of 0.00526 was determined from two 18.5 ± 0.2 Ma-old B4M monitors (Jäger, 1969) irradiated together with the samples. The 1σ-uncertainty of the apparent ages does not include the uncertainty of the monitor age.

± 0.1) wt.% CaO, we find that our log K/Ca ratios for low temperature fractions are similar to that for the De-36 matrix. The plagioclase microlites surely yielded the lower K/Ca ratios. Therefore, we conclude that the mesostasis of De-36 preferentially lost argon. The age calculated for Ar released from the more retentive plagioclase crystals at higher temperatures is probably a reasonably good approximation to the true age of the melt rock. The 700 °C and 800 °C fractions contain about 34% of the total ^{39}Ar released and may represent a plateau. If so, then the corresponding age, 109.6 ± 1.0 Ma, may be taken

TABLE 4. Summary of results of ^{40}Ar-^{39}Ar analyses.

	Dellen	Jänisjärvi		Sääksjärvi	
Sample mass [mg]	115.54	52.42		53.56	
K-concentration [%][a]	2.9	2.6		2.3	
Ca-concentration [%][a]	1.5	1.1		2.2	
Cl-concentration [ppm][a]	180	120		115	
K-Ar age [Ma][b]	101.2 ± 0.1	754.3 ± 0.3		554.6 ± 0.2	
^{40}Ar-^{39}Ar plateau age [Ma][c]	109.6 ± 0.1		703 ± 13	588 ± 10	515 ± 6
Range [% ^{39}Ar]	69–96		77–100	9–55	55–99
Temperature range [°C]	600–800		1100–1800	800–1000	1100–1800
^{40}Ar-^{39}Ar isochron age [Ma][d]	no	687 ± 7	709 ± 7	580 ± 4	514 ± 4
Ordinate intercept	isochron	565 ± 36	292 ± 16	311 ± 48	303 ± 37
Temperature range [°C]		500–900	1100–1800	500–1000	1100–1850
Age of impact melt [Ma][e]	109.6 ± 1.0	698 ± 22		514 ± 12	

[a] The uncertainties for the K, Ca and Cl contents are between 5% and 10%.

[b] Based on the total amounts of ^{40}Ar$_{rad}$ and ^{39}Ar released. The uncertainties include only those related to measuring those amounts.

[c] The uncertainties include the statistical variation of ages for temperature fractions specified to be a part of the plateau.

[d] The uncertainties include only those related to determining the slope of the isochron.

[e] The given uncertainty is the absolute uncertainty for the ^{40}Ar-^{39}Ar age determination. It does not contain the uncertainty in the half-life of ^{40}K.

as the age of the crater. Then about 7% of all radiogenic ^{40}Ar produced since 110 Ma was lost subsequently. If not, then the given age is a minimum value. The quoted uncertainty is 1σ and consists of uncertainties related to counting statistics and the monitor age.

At temperatures above 900 °C small amounts of gas (~4% of ^{39}Ar) are released which yield lower apparent ages. This may be an effect due to ^{39}Ar recoil during irradiation (Turner and Cadogan, 1974).

The data are also shown on an isochron plot in Fig. 4. The points do not fall on a single line, so no isochron age for the sample can be given with confidence. This is what is expected for a sample which had suffered loss of radiogenic argon. The line shown is a reference line corresponding to an age of 109.6 Ma.

TABLE 5. Argon isotopic data and apparent ages obtained by laser extraction from a polished section of Sääksjärvi S-9/1. The status of data reduction is the same as in Table 3. The analyses are arranged in the order of increasing apparent ages.

^{36}Ar 10^{15}	^{37}Ar 10^{13}	^{38}Ar 10^{14}	^{39}Ar 10^{14}	^{40}Ar 10^{13}	Age [Ma]
Mesostasis					
72/26	102/4	24/5	1017/16	657/3	453/74
65/43	38/3	–/–	3736/36	2180/12	542/24
80/27	58/3	29/11	4621/30	2663/9	544/19
160/40	93/1	24/14	6627/24	4001/7	547/10
68/45	68/3	14/9	3830/39	2274/11	554/24
73/37	71/2	18/14	6234/30	3673/13	562/11
19/37	18/1	–/–	3032/18	1853/4	598/23
18/24	64/2	–/–	914/12	602/3	598/71
77/27	78/4	37/3	238/6	385/2	656/287
Plagioclase					
29/31	6/3	–/–	369/7	261/2	487/235
40/30	94/2	–/–	1669/13	990/2	542/40
0/24	3/1	5/4	317/13	199/2	628/159
Pyroxene					
83/28	41/3	21/11	4930/210	2757/99	522/19
38/19	23/2	27/7	3241/19	1899/4	560/21
38/38	56/3	44/15	6491/33	3758/8	578/12
44/22	60/2	11/8	3624/31	2195/6	582/23
28/28	57/3	–/–	4691/25	2803/5	590/15
Quartz					
0/46	4/3	–/–	189/20	269/9	1200/440

In light of the previously reported ^{40}Ar-^{39}Ar age of 100 Ma for a Dellen impact glass (Bottomley *et al.*, 1977), we note that the 109.6 Ma age from this study is in good agreement with their result and conclude that it represents the time of formation of the Dellen crater. We consider their 235 Ma age obtained for a sample containing "some xenoliths" (*op. cit.*) to be due to radiogenic argon derived from xenoliths that were insufficiently degassed during the rapid cooling of that specimen. We note that W. U. R. encountered several Dellen melt specimens that strongly resembled melt *ejecta*. Should Bottomley *et al.*'s sample fall into this category, the cooling rate for that specimen would have been much higher than for samples from the coherent melt body near the center of the structure exposed on the island of Hälsjoholmen, the source of our sample, De-36.

Jänisjärvi Sample Jä-1

The K/Ca and age spectra for the Jänisjärvi sample are shown in Fig. 5. The age spectrum is complex, so no simple interpre-

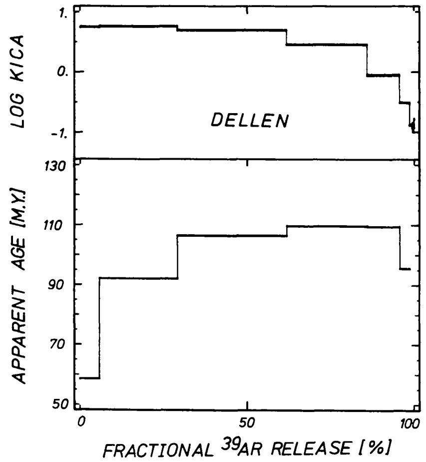

FIG. 3. K/Ca and apparent age spectra for sample, De-36, from the Dellen crater.

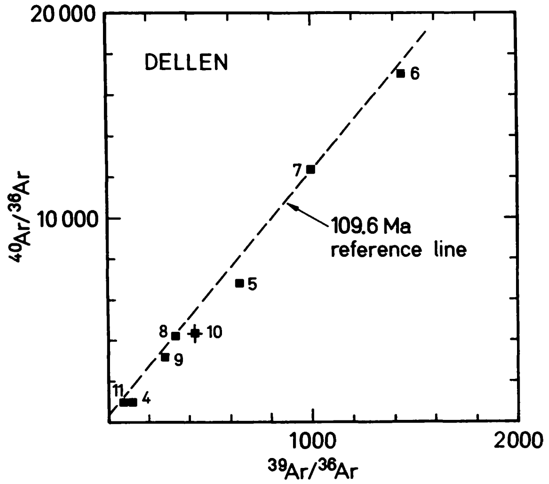

FIG. 4. Isochron plot for sample, De-36, from the Dellen crater.

tation can be given. The low temperature fractions (~5% of ^{39}Ar) show the highest apparent ages and the remaining fractions vary around 700 Ma. A correlation between the K/Ca and apparent age spectra is not observed, but it should be noted that the low temperature fractions yielding higher ages are associated with very low K/Ca ratios.

In an isochron plot (Fig. 6) all of the data points, except for the 1000 °C fraction, fall on two lines, one corresponding to low release temperatures, the other to high release temperatures. The slopes of both lines are nearly the same and indicate apparent ages of 687 ± 7 Ma and 709 ± 7 Ma, respectively. We conclude that the best age for the Jänisjärvi crater is the average of the two values, 698 ± 10 Ma (1σ uncertainty). This is an excellent agreement with a conventional K-Ar age of approximately 700 Ma (Masaitis *et al.,* 1976).

The ordinate intercept values of ^{40}Ar/^{36}Ar for the lines are 565 ± 36 and 292 ± 16, respectively. The latter, the high-temperature value, is indistinguishable from the atmospheric ratio, 295.5 (Nier, 1950). The former value suggests the presence of excess ^{40}Ar in the low temperature fractions.

Sääksjärvi Sample S-9/1

The K/Ca and age spectra for the Sääksjärvi sample are shown in Fig. 7. The lowest temperature fractions (less than 10% of ^{39}Ar) yielded low ages, probably because of radiogenic argon loss by diffusion. The remainder of the age spectrum shows a reversed two-plateau pattern: gases released at lower temperatures yielded relatively high ages (550–600 Ma), gases released at higher temperatures yielded lower ages (~500 Ma). No direct correlation between the K/Ca and age spectra is apparent, although the highest K/Ca ratios determined can be related to the high temperature "plateau."

As was the case for the Jänisjärvi sample, the data displayed on an isochron plot (Fig. 8) again fall onto two lines corresponding to ages of 580 ± 4 Ma and 514 ± 4 Ma. Ordinate intercept values for ^{40}Ar/^{36}Ar are 311 ± 40 and 303 ± 37, both indistinguishable from the atmospheric ratio.

The results of the laser extraction dating of S-9/1 are given in Table 5. The apparent ages and log(K/Ca)-values are plotted in order of increasing apparent age obtained versus cumulative ^{39}Ar amounts in Fig. 9. Most log(K/Ca) values from laser extractions are between 0.4 and 0.8 and are similar to those from stepwise heating, thus adding credibility to the laser extraction data. The "pseudo" age spectrum seems to show two age regimes, one below 550 Ma, the other at almost 600 Ma. The lack of any correlation of age with the analysed mineral, however, precludes taking either of them too seriously. At best, the weighted average age, which is 560 ± 16 Ma, can be taken as the result of the laser extraction dating of S-9/1. This value agrees remarkably well with the age obtained from stepwise heating, 555 Ma (Table 3).

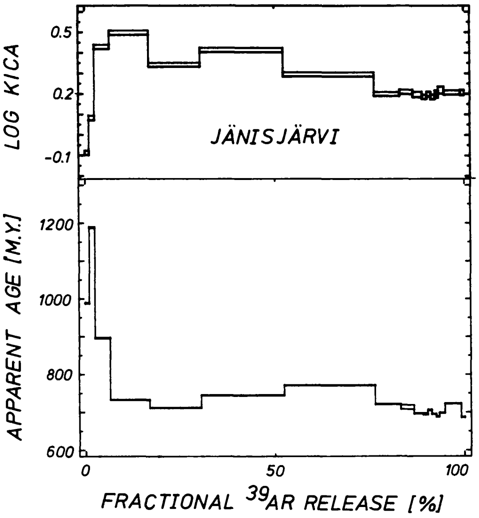

FIG. 5. K/Ca and apparent age spectra for sample, Jä-1, from the Jänisjärvi crater.

DISCUSSION

In the case of the Dellen sample the age spectrum obtained was interpreted to indicate ^{40}Ar loss from low temperature sites. Only by assuming that no ^{40}Ar was lost from high temperature sites could we estimate an age for the sample. If this assumption is not valid, then only a lower limit to the age of the sample can be given. However, since only 7% of the radiogenic argon is lost, no significant reduction in the plateau age would be expected (Turner, 1969). For the Sääksjärvi sample the effect of ^{40}Ar loss can also be regarded as insignificant.

In the previous section we inferred the presence of excess ^{40}Ar in the Jänisjärvi sample. Any quantity of ^{40}Ar in the system not attributable to either the atmosphere or the *in situ* radioactive decay of ^{40}K is excess ^{40}Ar. In terrestrial samples atmospheric ^{40}Ar is always present but may be corrected for based on the measured amount of ^{36}Ar in the sample and the known ^{40}Ar/^{36}Ar ratio in the atmosphere. All ^{36}Ar is assumed to be atmospheric. The presence of excess ^{40}Ar leads to anomalously high ages.

In the case of the Jänisjärvi sample the high apparent ages of the lowest temperature fractions may indicate the presence of excess ^{40}Ar. We find support for this hypothesis. When data for five low temperature fractions, excluding the lowermost fraction, are presented in an isochron plot, the points form a straight line, which lies above and nearly parallel to a similar line based on data for the high temperature fractions. The similar slopes

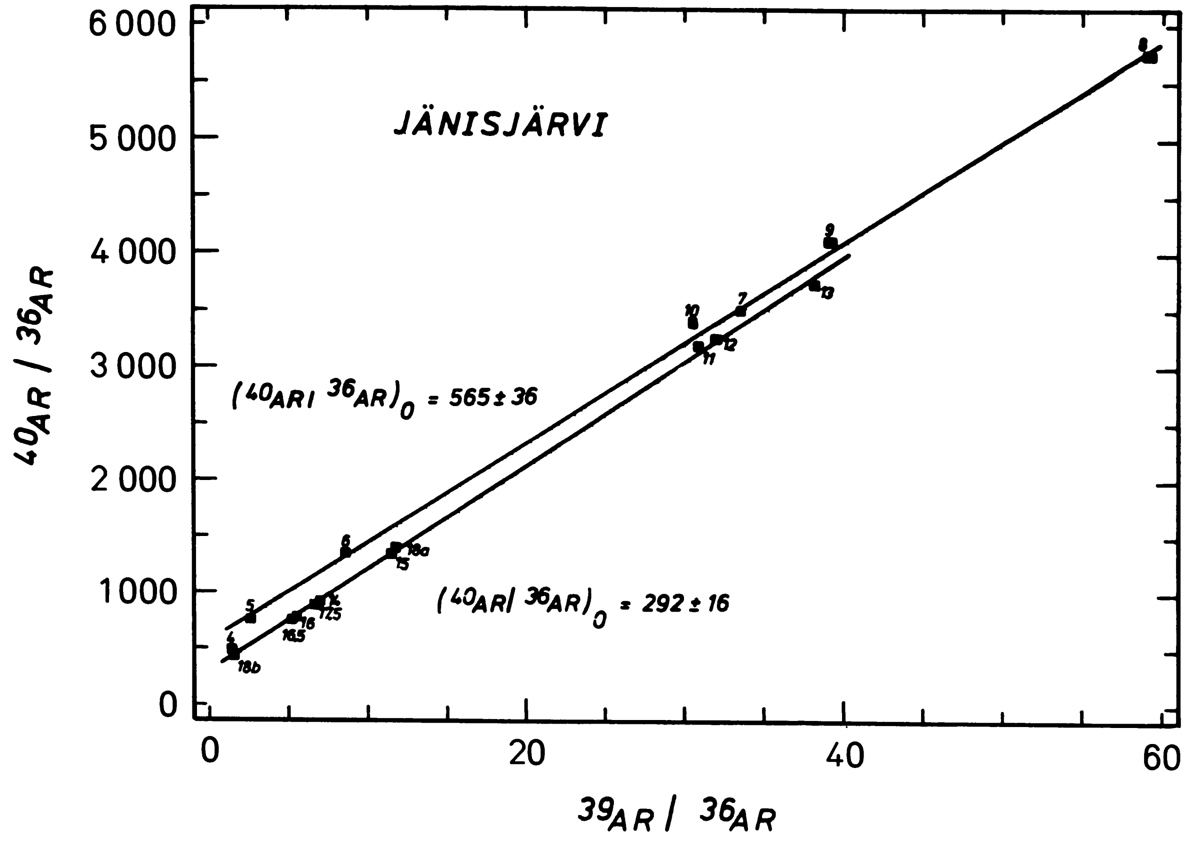

Fig. 6. Isochron plot for sample, Jä-1, from the Jänisjärvi crater.

of the two lines indicate the age of the sample. Both high and low temperature sites closed at about the same time, 690 Ma ago. The two lines, however, intercept the ordinate at different points suggesting different initial $^{40}Ar/^{36}Ar$ ratios. Therefore, a reservoir of ^{40}Ar must have existed at the time of system closure, which, when combined with atmospheric ^{40}Ar, had an $^{40}Ar/^{36}Ar$ ratio of about 565. To explain the observed characteristics of the data we imagine two types of sites in the sample, degassing at high and low temperatures, respectively, and two reservoirs of argon, one of atmospheric composition, $^{40}Ar/^{36}Ar$ = 295.5, and one enriched with ^{40}Ar so that its $^{40}Ar/^{36}Ar$ ratio was 565. We conclude the high temperature sites closed first and must have been exposed only to normal atmosphere. Subsequently, after a geologically short time, the low temperature sites closed, but at the time of closing were exposed to the ^{40}Ar-enriched atmosphere.

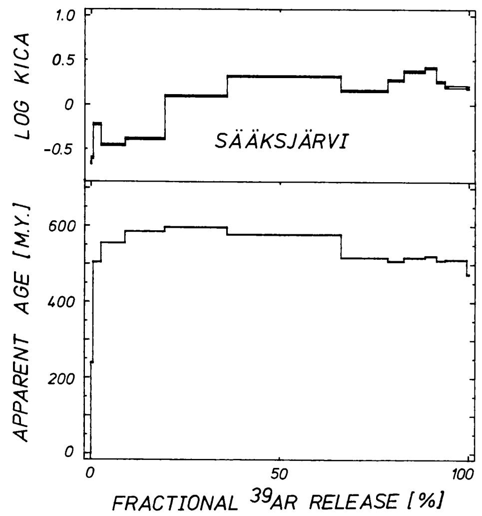

Fig. 7. K/Ca and apparent age spectra for sample, S-9/1, from the Sääksjärvi crater.

To explain these data we consider a geologic model where the sample has been totally degassed during the impact. While undergoing initial cooling, presumably buried at some depth, it was exposed to normal atmosphere and high-temperature sites began to retain ^{40}Ar. After a short time, the atmosphere was modified by the addition of radiogenic ^{40}Ar derived from the heating of nearby country rock or brecciated material which was not degassed by the impact itself. The source of the heat would be the residual heat left after passage of the shock wave. One can imagine a temperature wave propagating away from the impact site and engulfing larger and larger volumes, but at lower and lower temperatures. Nevertheless, ^{40}Ar may be released and incorporated into lower temperature sites. Cooling must have occurred fairly quickly since no age difference is observed between closure of high and low temperature sites.

In the case of the Sääksjärvi sample, even though the lowest temperature fractions show ^{40}Ar loss, intermediate fractions, those corresponding to release temperatures of 800 °C, 900 °C,

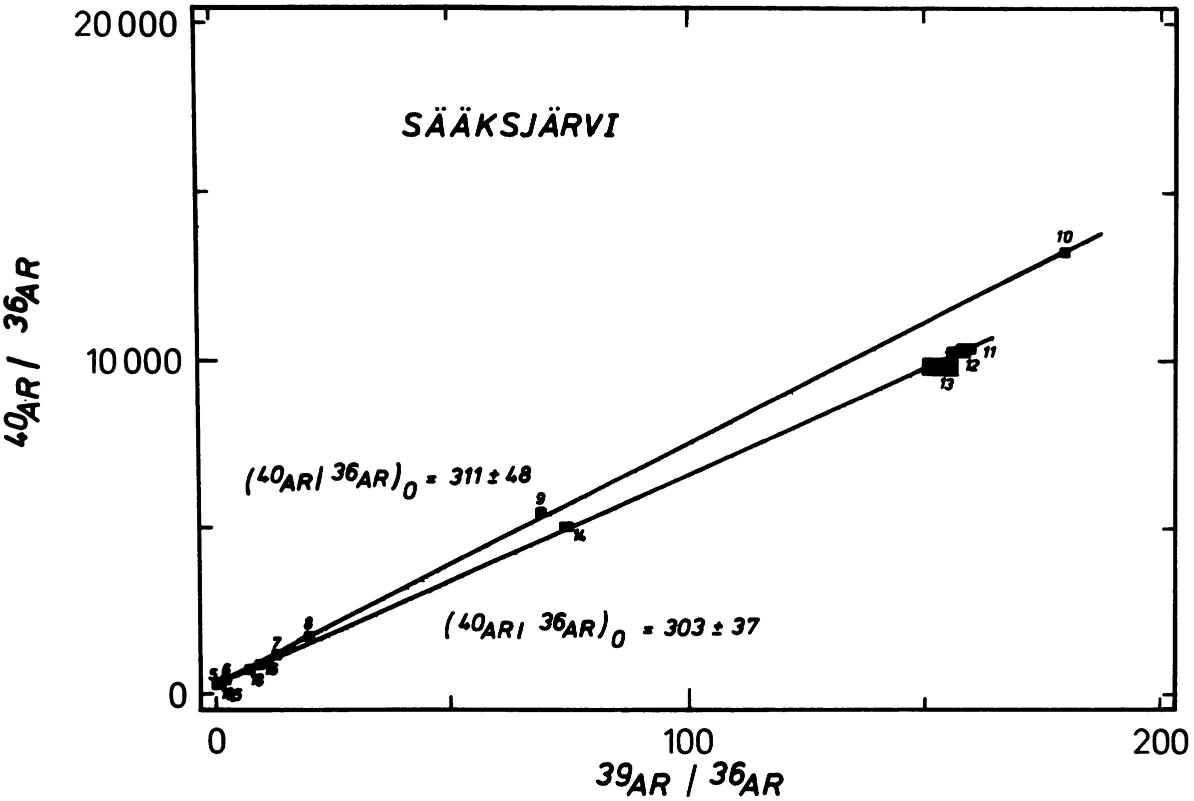

FIG. 8. Isochron plot for sample, S-9/1, from the Sääksjärvi crater.

and 1000 °C, have the highest ages. This suggests the presence of excess argon in these fractions. Furthermore, when displayed in an isochron plot, data for intermediate temperature fractions (800 °–1000 °C) fall along a line which is distinctly different from a line corresponding to the high temperature data (1100 °–1800 °C) (Fig. 8). Initial ^{40}Ar/^{36}Ar ratios for both lines are, within the uncertainties, equal to the atmospheric value. If we assume that the slopes of both lines indicated different ages of two types of sites in the sample, we are forced to conclude that the low-temperature sites were older, that is, had begun to retain ^{40}Ar *before* the high-temperature sites closed. This is contrary to a basic assumption of the ^{40}Ar/^{39}Ar method, namely that ^{40}Ar released at higher temperatures during a laboratory analysis was initially in nature trapped or retained at higher temperatures upon formation *in situ* by the radioactive decay of ^{40}K. This, however, applies only to a rock in which the minerals after their formation did not undergo substantial changes. And this might have been the case for the Sääksjärvi sample.

The Sääksjärvi sample is characterized by an abundance of vesicles (about 7 vol.%, Table 2) which are filled with various secondary possibly K-bearing clay minerals. Many of the vesicles are surrounded by a pyroxene-rich reaction rim, often displaying strong pyroxene alteration, which completely shelters them from their surrounding. ^{40}Ar may have relatively easily diffused out of them after their formation and before the alteration, but now in the laboratory ^{40}Ar would only be released at higher temperatures. Effects on the Ar budget during secondary mineralization are not understood at present. Finally, as gen-

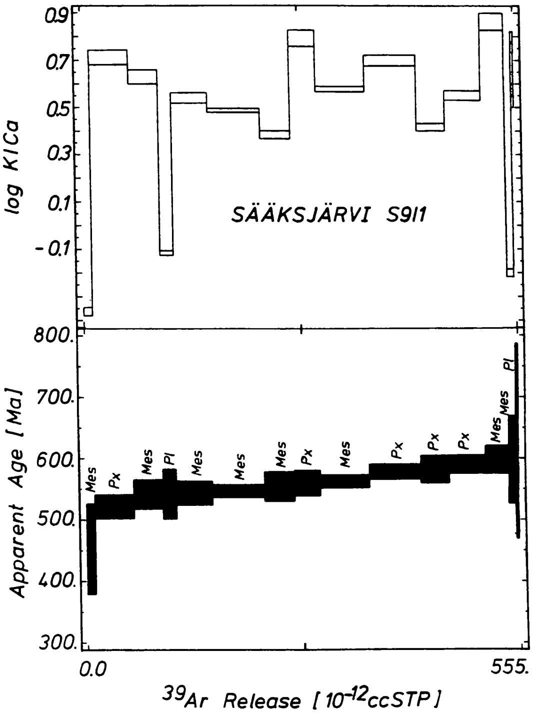

FIG. 9. Apparent ages and K/Ca ratios of laser extractions from the Sääksjärvi sample. Abbreviations indicate the following: Mes: mesostasis; Px: degassed region contained pyroxene and mesostatis; Pl: degassed region contained plagioclase and mesostasis.

erally with analysis of glassy or fine-grained melt samples the possibility that devitrification, in addition to alteration, could lead to either loss of radiogenic Ar or loss of K should be considered.

In conclusion, we believe that the ages obtained in this study—De-36: 109.6 ± 1.0 Ma, Jä-1: 698 ± 22 Ma, S-9/1: 560 ± 16—are, so far, the best values for the respective impact events. The interpretations of the data presented here should, however, only be regarded as suggestions. There may be other ways to explain them. To further resolve issues raised by these data requires additional experimental work involving microprobe analysis of mineral phases, as well as ^{40}Ar-^{39}Ar dating of mineral separates, in conjunction with application of new techniques such as spot-wise laser probe argon extraction, in order to determine precisely where various Ar components are hosted.

CRATER PRODUCTION RATE

With the completion of this work (Table 3), ages of the six known craters on the Baltic Shield have now been determined. Shown in Table 4 are their ages, sizes, and locations. The magnitude of the cumulative size distribution index, -1, is less than that for craters on the Eo-European craton or for all of the craters on the Earth (Grieve, 1984). This suggested that a number of smaller craters are lacking and may not yet have been recognized or may have been lost due to erosion. Consequently, data for craters less than 10 km in diameter are not used in the following calculation.

For comparison with the production rates given by Grieve (1984) the number of craters was reduced to a common diameter of 20 km using a size distribution index of -2 to extrapolate from other crater sizes.

The resulting number of craters 20 km in diameter or larger observed on the Baltic Shield is 2^{+2}_{-1}. If we take the area of the Baltic Shield to be $0.9 \cdot 10^6$ km^2 and the exposure duration to be 700 Ma (the age of the oldest crater), then the production rate of greater than 20-km-diameter craters is $0.3 \cdot 10^{-4}$ km^{-2} a^{-1}, which is in reasonable agreement with the rate determined using craters formed during the last 120 Ma on the North American and European cratons $(0.54 \pm 0.27) \cdot 10^{-14}$ km^{-2} a^{-1} (Grieve, 1984).

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