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^{40}Argon-^{39}Argon Dating of Impact Craters

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The spectra from an ^{40}Ar-^{39}Ar study of 13 impact craters from Canada, Scandinavia, and Australia can be categorized broadly according to shape. Despite the fact that samples from eight of the craters show plateaus or near plateaus, the determination of ages for the cratering events is not straightforward. Melt rocks from Siljan (best age estimate from this study of the event, one sigma, 368 ± 1.1 Ma), Mien (121 ± 2.3 Ma), Pilot (445 ± 2 Ma), and Carswell (115 ± 10 Ma) all show near plateaus with varying degrees of structure. Only Clearwater West (445 ± 2 Ma) and Dellen (102 ± 1.6 Ma), however, give good to excellent plateaus over most of the gas released. Samples from Strangways, (<470Ma) Saaksjarvi (<330 Ma), and possibly Moinerie (400 ± 50 Ma) and Couture (430 ±25 Ma) all show spectra whose fraction ages rise with increasing temperature. Clearwater East (<460 Ma) and Nicholson (<400 Ma) give saddle-shaped spectra with greater ages at both the lowest and highest temperature steps. In addition, not all samples from the same crater site agree in age or spectral type. This study indicates that while ^{40}Ar-^{39}Ar dating is preferable to K-Ar for crater studies, multiple samples need to be analyzed from each site. Typical analytical errors quoted with age determinations on melt rocks are often misleading because the complex argon signatures do not lend themselves to simple interpretations and other information may be necessary to ascertain the correct age.

INTRODUCTION

Impact melt rocks typically appear as glassy to fine-grained, igneous textured rocks, often containing minerals and lithic clasts of the original target rock. In theory, these melt rocks should give a K-Ar age that closely approximates that of the impact for several reasons. The target rocks are melted instantaneously, allowing previous accumulations of radiogenic argon in the rock to escape. The melt usually occurs in surface or near-surface locations, often as melted pools in breccia lenses at simple craters or as annular sheets surrounding the central uplift at complex craters. As the melt rapidly cools, it once again begins to accumulate radiogenic argon. Since many of the currently recognized impact craters are located in stable Precambrian shield areas, the argon clock often has not been disturbed by other major geological events since the time of impact.

There are several factors that could potentially affect this simple description. Since the clasts in the melt rocks predate crater formation, they must be thoroughly outgassed to ensure that the melt rock is giving a geologically meaningful age. For example, the melt matrix could record the time of impact but the clasts could remember their own age of formation, with the result that the whole rock age will be a mixed age, greater than the true age of impact. However, the melt rocks are superheated at the time of impact and clasts interact with the matrix, eventually coming into thermal and often chemical equilibrium (*Grieve,* 1975). This gives the argon favorable opportunities to diffuse from the clasts and escape the melt-clast mixture.

In some cases, however, the argon degassed by these clasts may not fully escape and could be adsorbed elsewhere in the melt rock unit, where it will appear as inherited argon, possibly confusing the apparent age. If this component of argon achieves a locally uniform distribution in the impact melt, and the potassium is also uniformly distributed, a false ^{40}Ar-^{39}Ar plateau might be obtained. Since this would be a local phenomenon dependent on the type of clasts and the temperature in the immediate area, it may be possible to identify these false plateaus by dating several samples of spatially separated melt rocks from the same crater, and by dating separated mineral phases with different potassium concentrations.

If a melt rock comes into equilibrium with a sizable amount of inherited ^{40}Ar uniformly distributed throughout the rock, shapes other than false plateaus could be generated. Consider a melt rock that consists of a mixture of K-poor clasts (e.g., quartz) in a potassium rich matrix. The matrix will be the site of most of the ^{40}Ar production after impact. Upon analysis, the K-poor clasts will release only the initially inherited ^{40}Ar, which it shared with the matrix at the time of cooling. If the matrix and K-poor clasts release at different temperatures during heating in the laboratory, then the K-poor phase will give a false, elevated age because it has little offsetting K to match its relatively large inherited ^{40}Ar content. The argon from the K-rich phase could produce another false plateau segment, which would correspond to a mixture of the true radiogenic argon trapped since impact and the inherited argon. This false plateau would approach the true age of impact if the ratio of the radiogenic to inherited argon is very large. A similar effect could be produced if the melt has partially cooled by the time the inherited argon is baked out of the clast or the surrounding country rock by residual heating. Only that portion of the melt

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rock that was still above the blocking temperature for argon diffusion would show the effects of this inherited argon. This could result in a spectrum displaying two plateaus or some other indication of a mixture of two argon phases.

Another factor influencing spectral shape is the degree of devitrification. Since these rocks cool quite rapidly there can be a fair amount of glass in the matrix. Devitrification can be a serious problem as argon can be lost during this process (*Fleck et al.,* 1977), which may result in ages that are different from the ages of fresh glass.

EXPERIMENTAL TECHNIQUES

Melt rocks from 13 craters in Europe, North America, and Australia were selected for this project (Table 1). To minimize potential interpretation problems, samples with the freshest glass matrix and fewest clasts were chosen. Almost all of these clasts showed evidence of being reequilibrated with the matrix material. The ages of most of these craters were not well known.

This project utilized our established laboratory ^{40}Ar-^{39}Ar procedures using RF induction heating in a high vacuum followed by mass analysis on an MS10 mass spectrometer. Whole rock samples were weighed and wrapped in aluminum foil before being loaded into the irradiation container. A few samples, consisting of powdered mineral separates, were sealed in quartz vials and placed around the periphery of the can. The samples were irradiated in the McMaster University nuclear reactor, which typically ran at a power level of 1 MW during the irradiations. After irradiation the samples were allowed to cool for a period of several weeks to allow short-lived isotopes to decay. The samples were then unwrapped and placed in a degassed molybdenum crucible. The crucible was loaded into the fusion system and the entire system was then baked at 200°C for several days to reduce the atmospheric argon blank. After a typical fusion run of eight one hour steps, each fraction was analyzed for the five isotopes of argon in the mass range 36-40.

In the accompanying figures, the error for each individual fraction is indicated by the vertical width of the corresponding step on the plateau diagrams. This is the uncertainty in the argon measurement and associated corrections. The error in the integrated ages (Table 2) includes both the error in the fractions plus the experimental error assigned to the measurement of the standards. The standards used in this study included the hb3gr hornblende (1071 ± 7 Ma) and the Obedjiwan biotite (963 ± 9 Ma). All the laboratory errors are quoted at the one sigma level. These errors are not the geological uncertainty in the age of the crater; they represent the accuracy and reproducibility with which the argon ratio can be measured in the rock sample and standard. Detailed tables of all the relevant argon data are available in *Bottomley* (1982).

TABLE 1. A listing of the impact craters dated in this study, along with the sample code used for sample numbering on the figures.

Code	Crater Name	Location
CA	Carswell	Alberta, Canada
CWE	Clearwater East	Quebec, Canada
CWW	Clearwater West	Quebec, Canada
D	Dellen	Sweden
GW	Gow Lake	Saskatchewan, Canada
LC	Lac Couture	Quebec, Canada
LM	Lac La Moinerie	Quebec, Canada
M	Mien	Sweden
NC	Nicholson	Northwest Territories, Canada
P	Pilot	Northwest Territories, Canada
S	Siljan	Sweden
SJ	Saaksjarvi	Finland
ST	Strangways	Northern Territory, Australia

TABLE 2. The best interpretation of the age of impact as determined by this study.

Crater	Age (Ma)	Comment
Carswell	115 ± 10	error represents scatter
Clearwater East	460	maximum age estimate
Clearwater West	280 ± 2	plateau
Dellen	102 ± 1.6	plateau
Gow Lake	250	possible maximum age
Lac Couture	430 ± 25	error represents scatter
Lac La Moinerie	400 ± 50	error represents scatter
Mien	121 ± 2.3	structured plateau
Nicholson	400	maximum age estimate
Pilot	445 ±2	plateau
Siljan	368 ± 1.1	integrated age
Saaksjarvi	330	maximum age estimate
Strangways	470	maximum age estimate

RESULTS

In this study, certain spectra were found to have a straightforward interpretation, and the corresponding age of impact can be ascertained with some confidence. However, other samples display complex spectra such that only an estimate based on the best interpretation of the data can be put on the age of the impact event. While some researchers restrict the use of the term "plateau" to only those cases where the age of fractions are identical to each other, within the stated errors, in reality "plateau" is a subjective criterion that can vary depending on the type of samples being analyzed, heating schedule, and the number of contributing fractions. While the narrow definition is useful when dating single mineral grains, it is unnecessarily restrictive when dating whole rock samples as complex as melt rocks and ignores much of the chronological information available in the sample. We use the term "plateau" in this study to indicate a general agreement in age between adjacent fractions representing a significant portion of the argon released during the fusion. We also use the term "structured plateau" to describe samples where there is broad concordance of fraction ages in a general range that appears to have significance in terms of a thermal event such as impact but where there is also a definite pattern such as a general tilting or hump shape in the spectrum.

Lake Mien and the Siljan Ring Complex, Sweden

Interpretations of the data from these two craters have previously been published (*Bottomley et al.,* 1978), and will be summarized here with ages updated to the decay constants of *Steiger and Jager* (1977). Lake Mien (56°25′N, 14°52′E) is a rhombic-shaped lake with an average diameter of 5 km excavated in Precambrian granite and granitic gneiss of Gothian (1.7-1.3 Ga) and Dalslandian (1 Ga) age. Previously Whelin (1975) had found a spread in K-Ar ages from 103 to 114 Ma but suggested that the crater was formed between 112 and 122 Ma ago. *Storzer and Wagner* (1977) reported a fission track age of about 92 Ma.

Two samples of impact melt were dated and gave slightly different spectral shapes (Fig. 1). The basic petrographic character of the samples is described in *Bottomley et al.* (1978). Sample M15 presents a fairly well defined plateau over most of its temperature range. It also shows the slight drop with age, which gives a slightly tilted structural plateau that is sometimes characteristic of impact melt samples. Sample M17, on the other hand, shows a shallow hump shape with a high-temperature dip and recovery in the last few fractions. Both samples show concordant ages of 118 Ma in that portion of the spectra, which represents 50-90% of the gas released. The first fraction of each sample is distinctly lower in age than the plateau. Thus, an integrated ^{40}Ar-^{39}Ar age, which is equivalent to a conventional K-Ar date, would be 5% lower than the plateau age for the same rock. These low first fraction ages probably represent weakly bound argon from some of the matrix microlites and alteration products, which may have incompletely held their argon since the formation of the melt (*Bottomley et al.*, 1978).

Excluding the first fraction of each spectrum and the last three tiny fractions of M17, all ages are in the 115-124 Ma range. The average age of the plateau fractions M15 and M17 is 121 Ma. The integrated ages are slightly lower (116 and 114 Ma respectively) due to the low-temperature variable age gas fraction that mixes with the older argon to yield a mixed age in the first fraction. Although the argon spectra show some structure, there is general agreement between the two samples of melt rock dated and the best estimate of the age is 121 ± 2.3 Ma.

Siljan (61°02′N, 14°52′E) is a large (45 km) ring-shaped feature in central Sweden, which has a pronounced central uplift of shocked Precambrian (1.7 Ga) granite. An annular depression that surrounds the uplift is partially filled with lakes and contains Silurian to Ordovician sediments. Two impact-melt samples from a small dikelet were analyzed. In both spectra (Fig. 2), the low-temperature fractions make up the bulk of the gas released (600-730°C) and are generally concordant in age at ~365 Ma. The most distinctive feature of the Siljan samples is their high-temperature dropoff. ^{40}Ar-^{39}Ar dating of some fine-grained lunar samples gave monotonically decreasing spectra, even though their total gas-integrated ^{40}Ar-^{39}Ar was in agreement with Rb-Sr ages on the same rock. It was suggested that this was due to a closed system redistribution of argon caused by ^{39}Ar recoil during irradiation in the reactor (*Huneke and Smith*, 1976; *Turner and Cadogan*, 1974). Further experimental work (*Villa et al.*, 1983) has convinced most researchers that recoil is a real effect. Due to the short recoil range (~0.1 μm), the effect will be dominant in micron- to submicron-size grains and will decrease as the grain size increases. The matrices of the Siljan samples contain feldspars, which average 5 μm in diameter, and lesser amounts of pyroxene, which tend to be about 30 μm in diameter. The samples are described in more detail in *Bottomley et al.* (1978). The glassy K-rich matrix components are about the same size as the feldspars. It seems likely, therefore, that neutron-induced ^{39}Ar recoil out of the potassium-rich glass and into the pyroxene is responsible for the plateau shapes seen in Fig. 2. These K-poor phases tend to release their argon at higher temperatures. In both samples, the first three fractions make up 80-90% of the gas released (600°-730°C). In the absence of more spectral resolution in these early fractions, the best estimate of the age of impact would be either the age of the plateau fractions (365 Ma) or the total integrated age (368 Ma). As recoil is probably involved in the high-temperature age decline, the integrated age of 368 ± 1.1 Ma is the best estimate of the formation age.

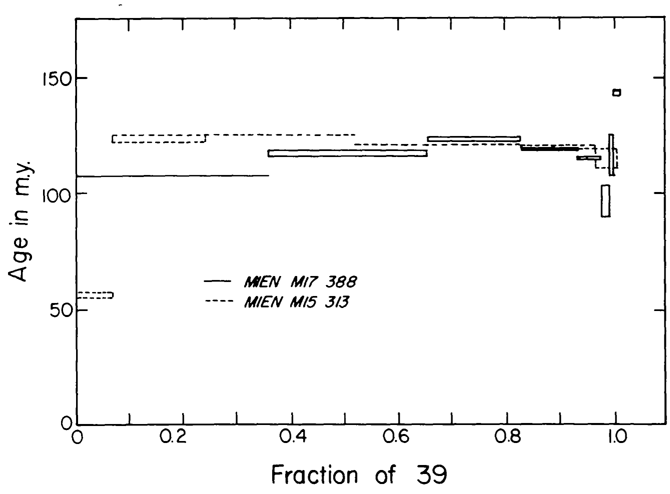

Fig. 1. Spectra from Lake Mien, Sweden.

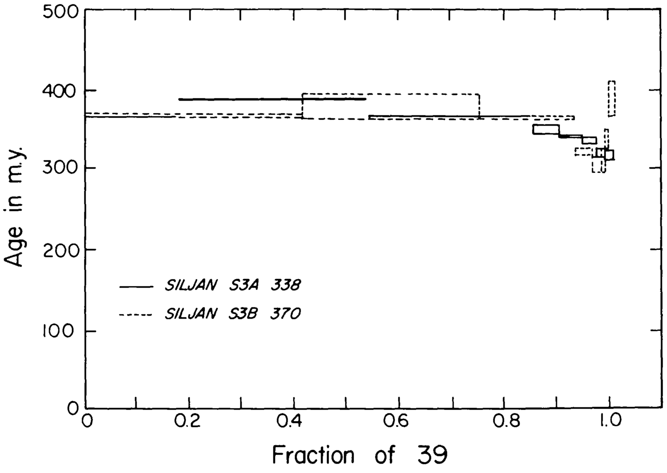

Fig. 2. Spectra from Siljan, Sweden.

Strangways, Australia

The Strangways crater (15°12′S, 138°35′E) is 20 km in diameter in Precambrian terrain of Proterozoic age. There is a 5-km core of granitic gneiss containing breccia and melt rock. There are no previous age determinations, but there are

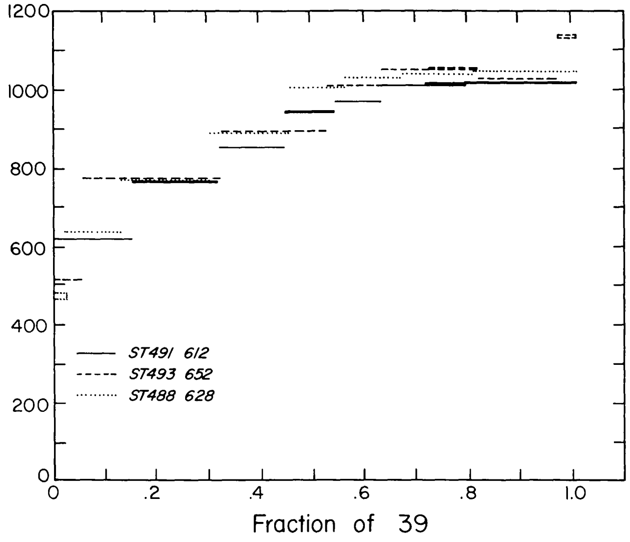

Fig. 3. Spectra from Strangways crater, Australia.

clean, mid-Cambrian limestones in the area, which are probably precrater sediments (M. R. Dence, personal communication, 1979). Three samples from sites some kilometers apart present very similar spectra (Fig. 3). All three samples are very fine-grained melt rocks. They have 10% clasts, which are relatively unrecrystallized. The samples are heavily stained with hematite. Their spectra show an apparent plateau (30-40% gas) at the highest temperature. These plateau segments indicate an age of 1000-1020 Ma. At the present time the age of the Precambrian country rock surrounding the crater is not known. It is possible that this high-temperature age records the age of the undisturbed country rock rather than the impact itself. The low-temperature portions of the Strangways spectra display a monotonic increase in age with temperature and are also quite similar in age except for the first fraction, which varies from 470-620 Ma between the samples.

Similar monotonically rising spectral shapes were modeled theoretically by *Turner* (1968). He calculated theoretical age spectra for a sample of spherical mineral grains that had undergone various degrees of argon loss. In situations like this, the low-temperature age can reflect a maximum estimate of the time of the reheating event. The "plateau" in the higher temperature fractions could be either a real plateau that reflects the undisturbed age of the rock before the reheating event or a false plateau representing a partial resetting of the most argon-retentive sites. These Strangways samples seem to be examples of thermally overprinted mineral systems that have not been totally reset by the impact. The lowest first fraction age (472 Ma) comes from the run on ST488, which had the smallest first fraction volume (2.5%), while the highest first fraction age (620 Ma) belongs to ST491, which has the largest first fraction volume (15%). Such a correlation between age and size of the first fraction is consistent with Turner's model, which suggests that the 472-Ma age is an upper limit for the age of the Strangways cratering event. This interpretation is also supported by local stratigraphic relationships, which have led Dence to believe that the crater is post-Cambrian (M. R. Dence, personal communication, 1982). Thus, the best estimate is a maximum age of 470 Ma based on the age of the lowest temperature fraction.

Saaksjarvi, Finland

Saaksjarvi (61°23'N, 22°25'E) is a 5-km-diameter crater in Precambrian gneissic and granodioritic terrain of Karelian-Svecofennian age (1.7-2.6 Ga) (*Papunen,* 1969). Four Saaksjarvi spectra show a similar pattern to the Strangways samples (Fig. 4). However, three of these are samples of one fine-grained melt rock in which clasts of quartz and feldspar make up 15% of the sample and are relatively unrecrystallized. (SJ125 354 and SJ125 439 are replicates and SJ125L 69L is a light density mineral separate from the same sample.) The two whole-rock spectra from SJ125 show good reproducibility and level off at higher temperatures, with 30-40% gas giving an age of 500 Ma. The age of the low-temperature fractions of both these samples are quite reproducible. However, unlike the Strangways samples, SJ125 439 has two small fractions reflecting the same age as a larger first fraction of SJ125 354, indicating that this may be a significant minimum age. The mineral separate SJ125L 691 has a larger first fraction and gives a slightly higher age (Fig. 4). The fourth stepwise rising sample, SJ105, is distinct in that its ages at every point are higher than the corresponding fractions of the SJ125 family. Its high-temperature plateau is marginally older than SJ125 at about 510 Ma, with a 530 Ma fraction at the end. The fact that it is higher in age at every temperature indicates that it was less completely reset than SJ125 and its low-temperature minimum age may not be as reliable as the low-temperature age of SJ125 for estimation of the time of impact. These four spectra can be interpreted in a fashion analogous to the Strangways spectra. This would indicate a maximum age of 330 Ma for impact and a high temperature approach to a plateau that, if real, would indicate a lower limit to the age of the country rock of about 510 Ma.

Sample SJ106 431 (Fig. 5) gives a totally different shape. Unlike most impact melt samples, this rock released most of its gas (70%) above 1000°C. The spectrum has a hump in the low-temperature fractions with an initial age of 430 Ma, which

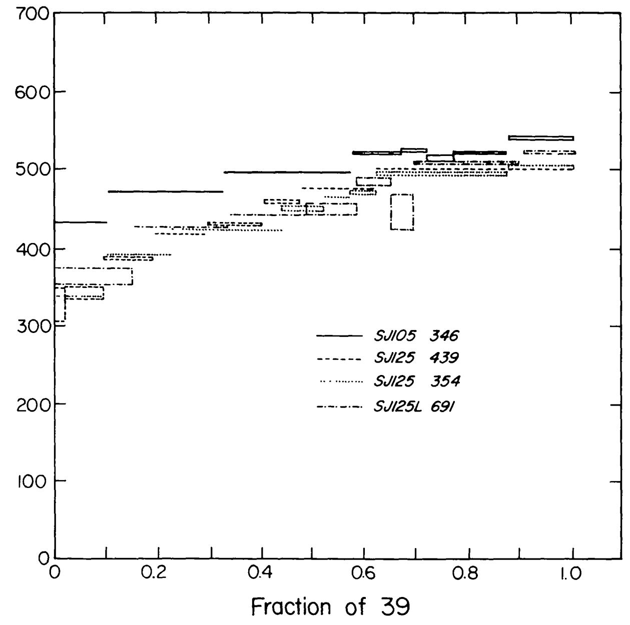

Fig. 4. Spectra from Saaksjarvi, Finland.

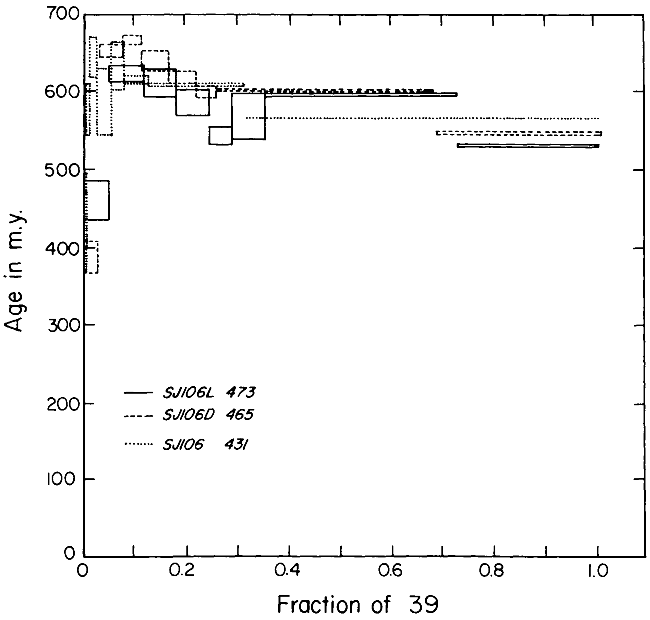

Fig. 5. Spectra from Saaksjarvi sample SJ106 and light and dark mineral separates.

quickly peaks at 640 Ma before falling to a small plateau at 600 Ma, then it releases 65% of its gas in one large high-temperature fraction (560 Ma). Two mineral separates SJ106L (light colored) and SJ106D 465 (dark colored) showed very similar behavior, with SJ106D showing the greatest exaggeration (Fig. 5). Its low-temperature age was 390 Ma and its peak 670 Ma, while SJ106L had 460 Ma and 625 Ma respectively. Both showed larger 600-Ma plateaus than the whole rock, and their 600-Ma fractions were larger in total volume than the corresponding high-temperature 550-Ma fraction. The integrated ages were all within 580 ± 10 Ma. This type of shape is common in melt rocks and when less exaggerated gives a structured plateau (e.g., Mien M15). The 550-600-Ma range of ages evident in the higher temperature fractions of SJ106 may be recording the same age or event as the high-temperature steps in the SJ125 spectra. It is not known whether the basement rocks of this area are in this age range.

The two large high-temperature fractions in the SJ106 family are associated with a high K/Ca phase, which typically has a K/Ca ratio that is 3-4 times higher than the preceding fraction. In spite of this, in all three samples the age of the last low K/Ca fraction and the next high K/Ca fraction are identical. The drop in age with temperature in the mid-temperature fractions may be correlated with a drop in the K/Ca ratio. The main mineralogical difference between the Saaksjarvi samples seems to be in the amount of quartz clasts. SJ105 and SJ125 contain approximately 20-25% inclusions. About 50-60% of these inclusions are reequilibrated quartz clasts. SJ106 has about 15% inclusions but only 5% are quartz. SJ105 and SJ106 have devitrified glass in their matrix, while SJ125 may not.

If we assume that the spectra from samples SJ105 and SJ125 are evidence of a partial thermal overprinting similar to the Strangways samples, a best estimate of the age of formation is 330 Ma or younger. It should be remembered, however, that the upper temperature fractions (even from the SJ106 samples, which do not show stepwise rising shapes) seem to be recording a 500-Ma age, considerably younger than the Precambrian country rock. Since the fractions making up the low-temperature hump and the high-temperature plateau are related to different K/Ca regimes, they probably represent release from mineral phases with different argon blocking temperatures. This suggests an alternate explanation for the SJ106 spectra, where they represent melt rock in which the lower temperature fractions cooled below their argon blocking temperatures in an environment of excess argon. The excess ^{40}Ar could have diffused from the nonmelted but severely heated target rock, which originally enclosed the melt rock unit. By the time the argon had diffused enough to produce a significant excess concentration, the higher temperature sites in the melt rock had already cooled below their blocking temperature. They were unaffected by the excess argon diffusing into the still open lower temperature sites. The very lowest temperature sites with lower apparent ages in SJ106 may just represent loss from later postimpact minor alteration. However, until more data are available from this crater, the preferred interpretation of these spectra is that the impact took place 330 Ma ago or less and that the country rock gives a K-Ar age of between 500 and 600 Ma.

Dellen, Sweden

Dellen (61°55′N, 16°32′E) consists of two arcuate-shaped lakes partially filling an annular depression. Separating the lakes is a long peninsula. The structure is a complex crater some 15 km across excavated in crystalline Precambrian gneiss and granodiorite of Karelian and Svecofennian age (1.7-2.6 Ga) (*Svensson,* 1968). Dellen spectra fall naturally into two families. Both show good plateau, but one is about 100 Ma and the other about 240 Ma. Samples D1 423, D3 404, D3 396, and D5 362 (Fig. 6) all overlap at 100 Ma with about 90% of their gas giving a clear plateau. All these samples are petrographically similar, consisting of partially devitrified glass with feldspar phenocryst laths up to 1 mm long and rare pyroxene phenocrysts. Clasts are relatively rare. The spectra have small low-temperature fractions with ages between 50-70 Ma. The

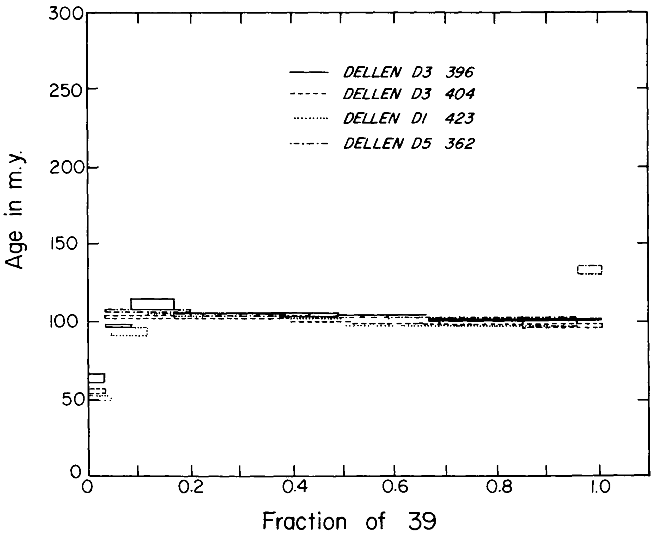

Fig. 6. Spectra from Dellen, Sweden, which define the primary plateau.

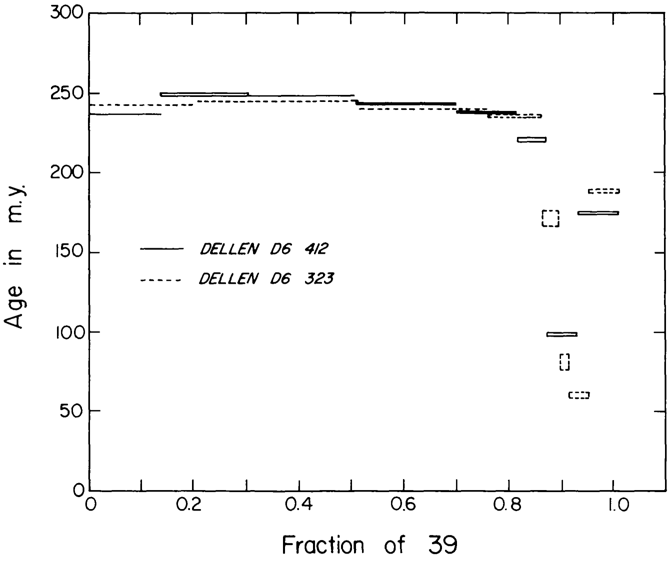

Fig. 7. Spectra from whole rock sample Dellen D6.

spectra rise quickly to plateaus, which are slightly tilted towards the right, showing an incipient monotonic decrease with higher temperature.

The concordance of the plateaus from samples Dl, D3, and D5 indicates an age of 100 Ma for the impact event. However, the spectra of D6 (D6 323 and D6 412) are totally different (Fig. 7). Petrographically D6 is similar to the other Dellen samples, with slightly more mineral clasts (up to 10%). The first 80% of the gas gives a structured plateau at 240 Ma. This is followed by a precipitous drop to lower ages (60-90 Ma) over the last 10-15% of the gas released. This shape is remarkably similar to some spectra observed by *Mak et al.* (1976) in Mistastin samples. Their high-temperature dip always fell to about 30 Ma at 85-97% of the gas released. The authors noted that this was accompanied by a drop in the 39/37 ratio (by a factor of 3 to 5), and attributed this dip to apparent recoil effects in pyroxene. In D6, the K/Ca dropoff is by a factor of about 2. In this case, however, the plateau portion gives a much higher age than the best estimate of the age of impact based on the other melt samples. In addition, the high-temperature dip drops to ages relatively close to the inferred age of impact.

In an attempt to choose the best interpretation, three density separates were prepared. These have been designated dark (D), intermediate (I), and light (L). The spectrum from each of these separates is distinctive (Fig. 8). All three have released 80% of their gas by the 800°C step. Sample D6D 505 most resembles the whole rock spectra, except that it displays a more distinct hump shape with its maximum at only 230 Ma. It is also apparent from the volume of radiogenic argon that it is this dark fraction that is releasing the bulk of argon in the whole rock sample. The intermediate sample (D6I 530) displays a very pronounced hump shape starting at 200 Ma and rising to 240 Ma before dropping to a minimum at 70 Ma. The last 10% of the gas then gives an age of 350 Ma. This phase contributes five times less gas than the dark phase to the whole rock age. Light sample D6L 456 gives an enormous gas pulse (50%, 180 Ma) at the first 500°C fraction, then rises marginally before plunging to 5 Ma. The last 25% of the gas rises in age, with three small volume steps followed by a final large fraction (18%) at an age of 1300 Ma.

The 240 Ma age seems associated with a single low-temperature mineral, which is totally degassed by 800°C. This phase has a characteristic 39/37 ratio of about five. The small amount of gas released in the temperature range 900-1600°C seems to be both lower in K/Ca and age. In general, the minerals in Dl, D3, and D5 show a much wider range of K/Ca and the 100-Ma age is found in both high and low K/Ca regimes.

Two interpretations of D6 spectra seem plausible: (1) The low-temperature mineral has not been completely reset, yielding a false plateau at 240 Ma. Alternatively, since it cooled through its argon blocking temperature after the high-temperature phases, it may have been exposed to an argon atmosphere that had much more excess ^{40}Ar. The high-temperature dip reflects a phase that has either been approximately reset to the impact age (~100 Ma) or has lost ^{40}Ar (through geological or reactor processes) or has gained ^{39}Ar (by recoil in the reactor). (2) The 240-Ma age is a correct plateau and the high temperature dip reflects perturbations either through geological or reactor processes.

While interpretation (2) would explain the spectra of D6, we would then have to assume that the three concordant samples with 100-Ma plateaus were in error. As they represent three separate samples and a variety of K/Ca regimes, it seems unlikely that D6 is a more reliable age.

Interpretation (1) seems to explain the anomalous age more satisfactorily, if we assume that during irradiation some ^{39}Ar recoiled out of the fine-grained potassium-rich matrix into phases that released argon at higher temperature. There appear to be two distinct argon regimes in sample D6. The first is a partially reset mineral that releases all its gas by 800°C. The second phase is a refractory mineral that is concentrated

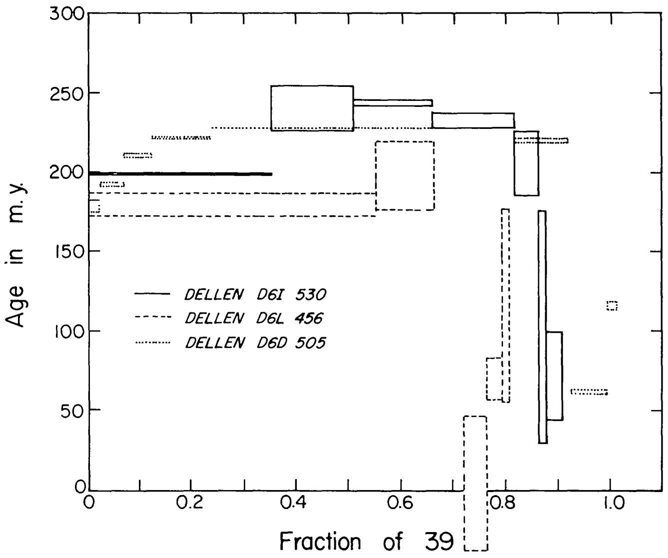

Fig. 8. Spectra from mineral separates from Dellen, sample D6.

mainly in the intermediate and light fractions, probably a partially reset country rock clast of about 1300-Ma age. As the first phase ends its degassing at about 800°C and its contribution gets smaller and smaller, more and more of the high-temperature phase's argon is released. The initial part of this release has a lower age, because of the excess ^{39}Ar it received via recoil. As more retentive sites release their argon, the age rises reflecting the older ages still retained by the clasts. However, only in the light fraction do we see it rise to its final age of 1300 Ma. In the whole rock and dark separate, slight amounts of residual low-temperature argon mix with the clast argon to produce an intermediate mixed age. In the separates of D6 the low-temperature fractions display, in varying degrees, the stepwise rising pattern found in the Strangways samples. This supports the suggestion that the low-temperature mineral was only partially reset by the impact.

Thus, the best age of Dellen would appear to be the average of the plateaus of the younger samples at about 102 ± 1.6 Ma. The results, when taken in total, show the remarkable complexity of the argon systematics in melt rocks and strongly emphasize the importance of examining a variety of melt rocks from a single crater.

Lac La Moinerie, Quebec, Canada

Moinerie (57°26′N, 66°36′W) is a roughly circular lake 8 km in diameter with a central uplift, represented by a circular ring of islands some 4 km in diameter. The crater is found in Precambrian gneissic terrain of Hudsonian age and is deeply eroded. Samples of melt rock along with impact breccias were found as glacial float on the northern side of the lake. Also recovered were apparently unshocked Silurian limestones, presumably scoured by the ice from the now submerged crater floor. If these represent postcrater sedimentation, then the crater may be pre-Silurian (>400 Ma) (*Robertson and Grieve,* 1975).

Three impact-melt samples were dated. All samples have glassy to cryptocrystalline matrices, with approximately 15% mineral clasts (mostly quartz and feldspar). The clasts show only minor thermal effects from the matrix. Sample LM15 209 gives a monotonically increasing age spectrum, with a low-temperature age of 230 Ma and a high-temperature age of 430 Ma (Fig. 9). There is no high-temperature plateau. There is, however, a very large third fraction with an age of 400 Ma (55% gas, 830°C) and a small last fraction of 750 Ma (2.5% gas, 1600°C). The remaining two samples show shallow hump-shaped spectra. Sample LM6 232 starts at 320 Ma and rises to a maximum age of 400 Ma before falling back to a final age of 370 Ma. It also has a high last fraction age of 660 Ma (1.5% gas). Sample LMll 271 has a similar shape but is higher in age at every step, starting at 350 Ma, and rising to 420 Ma before falling back to 400 Ma. It has a much larger last fraction (16% gas), which is 460 Ma in age.

The interpretation of these spectra is difficult. There is a general overlapping of most of the gas fractions in the range of 400 ± 20 m.y, which suggests a common event. All three samples have 80-90% of their gas giving ages in this range. However, LM15 clearly seems to be similar to a Strangways type of sample, and the two hump-shaped samples may be less severe examples of the Dellen D6 phenomena, which did not reflect the time of impact. If LM15 is a partially reset sample, then the crater should be no older than 230 Ma, the age of the lowest temperature fraction. Yet, if the general concordance of all three samples means anything, then it would appear that 400 Ma might be a better age. The major difference between these spectra and a true Strangways type is that only the first few fractions rise steadily and in LM6 and LM4 this rise is correlated with an increase in K/Ca. The shallow hump shape in the plateau portion of the spectra can probably be explained by minor amounts of ^{39}Ar recoil, especially in LM6 and LMll, as these are extremely fine-grained rocks. Although there is a step-like structure in the first fractions of these spectra, the best estimate of the age would be about 400 Ma based on the 80% of the argon in the more retentive sites. There is a fair degree of scatter in these structured plateaus and a fairly broad age of 400 ± 50 Ma is the preferred estimate of the age of impact. However, the possibility that the crater may be 230 Ma or younger should be kept in mind until better samples are dated.

Lac Couture, Quebec, Canada

The Couture crater (60°08′N, 75°18′W) is the island-free, deep-water portion of a slightly larger lake. It has a diameter of 10 km. The country rock consists of Precambrian gneissic terrain of Hudsonian age. There is no evidence of sedimentary crater fill and no published ages (*Beals et al.,* 1967). Three samples of Lac Couture melt rock were dated. The samples contain approximately 10% clasts, mostly quartz and feldspar, of which 30% are recrystallized. The melt matrix is generally cryptocrystalline, although in sample LC5 287 feldspar microlites are identifiable.

Samples LC12A 240, LC12B 280, and LC5 287 show similar ages and spectral shapes (Fig. 10). All present structured plateaus whose ages show a very shallow monotonic rise with temperature. Sample LC12A has the lowest first fraction age of 340 Ma. This is followed by a large fraction (65%) at 415 Ma and another (18%) at the slightly higher age of 440 Ma. The remaining gas executes a small high-temperature dip (min-

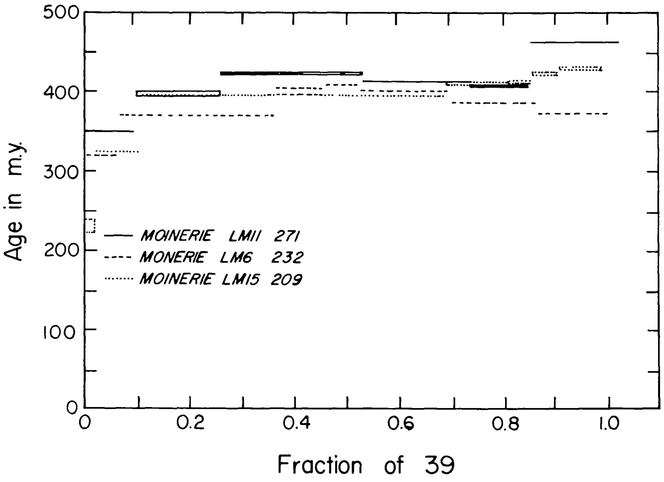

Fig. 9. Spectra from Lac la Moinerie, Canada.

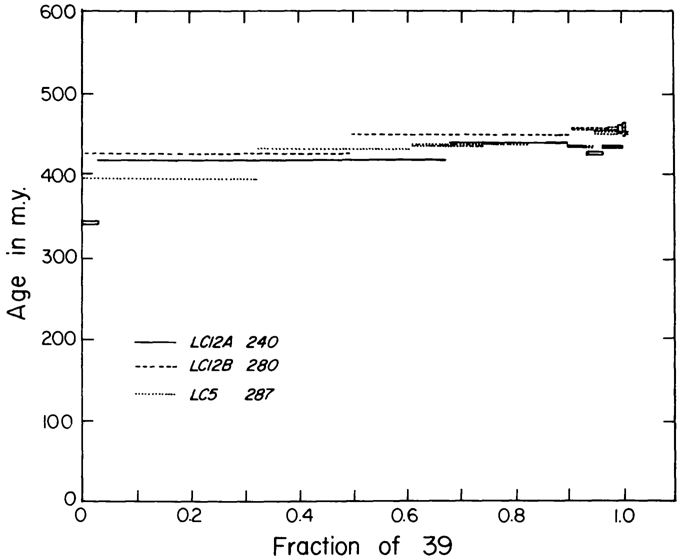

Fig. 10. Spectra from Lac Couture, Canada.

imum at 423 Ma), before shooting up to 700 Ma in the final fraction. LC12B has two large fractions (430 Ma, 50% and 450 Ma, 40%) that are followed by four small fractions (total 10%) with an age of 455 Ma. The last fraction contains less than 1% of the gas and yields an 800-Ma age. Sample LC5 287 starts with an age of 395 Ma (30%) followed by seven fractions at about 435 Ma before a slight rise to 450 Ma (6%).

These samples, like Moinerie, could have two interpretations. They show a very shallow stepwise rise from an age in the 400-Ma to 450-Ma range. One small first fraction (LC12A) gives an age of 350 Ma but the first fractions of the other two samples, as well as the second fraction of LC12A, are extremely large (40-70% of the total ^{39}Ar released). This very large volume in the argon sites of lowest retentivity sets these samples apart from the more steeply rising step-wise shapes of Strangways and Saaksjarvi. Although the rocks show no true plateaus, 95-100% of their gas gives an age between 400 and 450 Ma. The best age estimate for the cratering event is 425 ± 25 Ma based on this analysis. However, the data can permit the secondary interpretation that the crater has a maximum age of 350 Ma, based on these spectra being interpreted as Strangways types.

Clearwater, Quebec, Canada

Clearwater (56°10′N, 74°15′W) is a pair of circular lakes (West - 32 km, East - 22 km) located in Precambrian granodiorites, quartz monzonites, and granite gneisses of Archean age. A central uplift represented by a ring of islands is found in the west lake, where melt rock gives ages of 270-290 Ma by both K-Ar and Rb-Sr (*Wanless et al.,* 1966 and unpublished data). The central uplift at Clearwater East is submerged and not readily accessible. However, drilling has recovered samples from a melt rock zone at a depth of some 1000 ft. Two samples of melt rock from one core (separated by 20 ft) were dated along with one sample of melt rock from Clearwater West. A Rb-Sr date on this former material gives an isochron of 287 ± 26 Ma (*Reimold et al.,* 1981), supporting the widely held belief that both craters were formed simultaneously.

The Clearwater West sample, which is a fine-grained melt rock with 10% clasts set in a feldspar pyroxene matrix, gave a good plateau age of 280 Ma, in clear agreement with the previous determinations (Fig. 11). The last three fractions are indistinguishable in age and comprise some 85% of the released gas. The first fractions, although quite small, show the characteristic hump-shaped pattern of many melt rocks. However, the two samples of melt rock from Clearwater East (Fig. 11) show pronounced U-shape spectra. These samples are texturally similar to each other and the West Clearwater sample. Spectra with this U-shape have been identified as indicating excess argon (*Lanphere and Dalyrmple,* 1976; *Harrison and McDougall,* 1981) or contamination by a small amount of older material (*Lo Bello et al.,* 1987). This would appear to be the case with these samples. Sample CWE1090 starts with a small fraction at 1075 Ma (1%), then falls to a minimum at 465 Ma before increasing to 640 Ma in the final step. CWE1070 644 has a much broader U-shape with four fraction plateaus at the mid-temperature fractions (460 Ma, 80% gas) with a low-temperature age of 590 Ma and a high-temperature age of 1150 Ma. The general concordance of the ages at the bottom of the U-shaped trough at about 460 Ma indicates that the excess argon is rather uniformly distributed throughout the melt sheet, as sampled by this core.

It appears that an Ar isotopic age of Clearwater East cannot be recovered from these two samples and until melt rock from near the edge of the melt sheet or different cores can be sampled, the best age for both craters is the 280-Ma age given by the melt rock from Clearwater West and the Rb-Sr age from Clearwater East. The excess argon was apparently trapped in the melt rock as the hot mixture degassed after impact. Its quick burial and cover by fallback breccia apparently did not allow all the gas to escape before cooling through the argon blocking temperature.

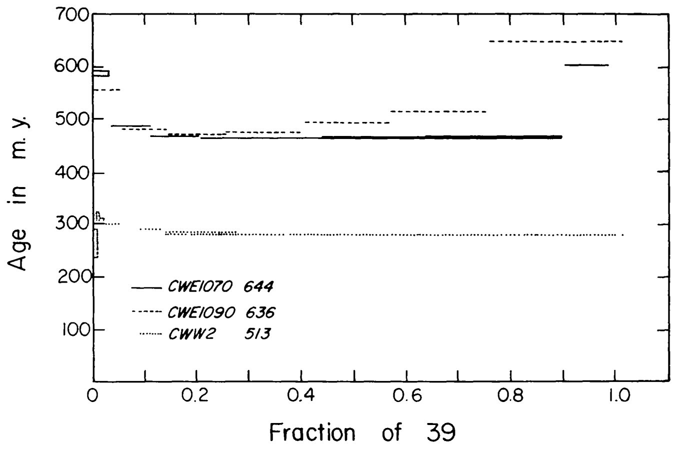

Fig. 11. Spectra from Clearwater Lakes, Canada.

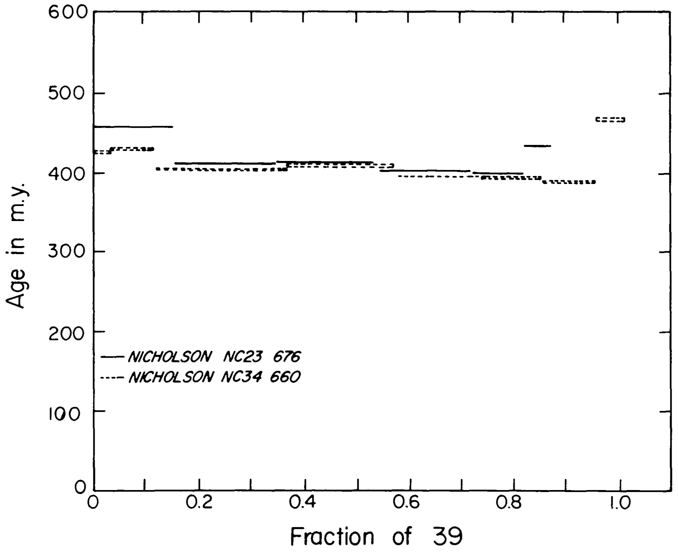

Fig. 12. Spectra from Nicholson Lake, Canada.

Nicholson, Northwest Territories, Canada

Nicholson Lake (62°40′N, 102°41′W) is an oval shaped lake 12.5 km in diameter. There is a large central island along with a sizable promontory jutting into the lake from the western side. The lake occupies a shallow depression in Precambrian gneissic and granitic terrain of Hudsonian age. Several small islands in the northern end of the lake preserve outcrops of Middle Ordovician dolomite. These are the only Palaeozoic rocks within a radius of 320 km, and were apparently protected from erosion by the crater structure. In addition, fragments of similar rock are found as glacial float around the lake (*Dence et al.,* 1968).

Two samples (Fig. 12) gave almost identical release spectra, despite the fact that they are petrographically distinct. Sample NC23 is more of a breccia than a true melt rock, with clasts of melt glass cemented by recrystallized matrix, which comprises 30% of the rock. NC34 is a cryptocrystalline melt rock with 35% clasts (mostly recrystallized quartz and feldspars). In both samples, 70-90% of the gas gave a shallow hump-shaped plateau in the mid-temperature range (400 Ma). However, this structured plateau itself appears to be the bottom of an even broader saddle-shaped curve that encompasses the low- and high-temperature fractions. NC34 660 starts out at 425 Ma before dropping to about 400 Ma in its mid-temperature fractions. The last 5% of the gas rises to 465 Ma. NC23 676 begins with an age of 450 Ma, dropping to its 400 Ma plateau before rising to a final age of 620 Ma. The third fraction of NC23 and the fourth fraction of NC34 rise in age very slightly, while the remaining plateau fractions drop slightly thereafter. This happens at about the same temperature in both samples (800-850°C). This would appear to be related to the release behavior of a specific but unidentified mineral phase. Although the saddle shape is much shallower than in the case of the Clearwater samples, it indicates excess argon, suggesting that the 400-Ma age of the structured plateau is a maximum estimate of the age of the cratering event.

Carswell, Saskatchewan, Canada

Carswell (58°27′N, 109°30′W) is a large (37-km-diameter) structure lying within the Athabasca Basin of northern Saskatchewan. It consists of an outer ring of Precambrian dolomites and siltstones (~1.5 Ga) that surround an inner ring of deformed Athabasca sandstone with ages of 1.9-2.3 Ga, and a central core of uplifted granitic basement (*Bell,* 1985).

Sample CA15 683 is a slightly vesicular impact melt rock. Clasts make up 5% of the rock and are generally recrystallized quartz and feldspar. The melt matrix contains feldspar microlites up to 0.1 mm long with minor partially chloritized pyroxene set in a very fine-grained quartz-feldspar matrix. The spectrum displays a structured plateau very similar in shape to Mien M17. If interpreted as such, it indicates an age of about 115 Ma. However, it is not clear that this is the age of the impact event. K-Ar ages reported for breccia dikes, which appear to cut all other structural aspects of the crater, have been reported as 485 ± 50 Ma (*Currie,* 1969). The disagreement between the CA15 683 age and that of the breccia might be explained by the breccia being only partially reset, as we have found to be the case with the breccias at the Slate Islands impact site (*Bottomley,* 1982). Carswell is of some commercial interest because of a large uranium find at Cluff Lake, and there is a large body of uranium-lead data on the minerals from various mines in the Athabasca Basin area. *Koeppel* (1968) found evidence of six episodes of uranium mobilization in deposits near Beaverlodge, Saskatchewan. These were 2350 Ma, 1920 Ma, 1780 Ma, 1125 Ma, 270 Ma, and 0-100 Ma.

Thus, it appears that there could have been some event in the Athabasca basin near 100 Ma that remobilized uranium. It is possible that the argon system in the Carswell sample is also recording this event. It is clear that more samples of both melt rock and breccia should be dated by the ^{40}Ar-^{39}Ar method in an effort to place the formation of this structure accurately within the framework of U-Pb dates for events in the Athabasca Basin.

Gow Lake, Saskatchewan, Canada

Gow Lake (56°27′N, 104°29′W) is a deeply eroded lake 5 km in diameter with a central uplift, represented by a 1-km-diameter island. The target rock is Precambrian granites and gneisses of Hudsonian age. *Thomas and Innes* (1977) have estimated its age as 100 Ma, based on depth of erosion and comparisons with the nearby Deep Bay crater. Sample GW12 668 (Fig. 13) starts with a large (30%) pulse of gas giving an age of 250 Ma. It displays a stepwise rising release pattern over the first 70% of its gas, with a short plateau segment of four fractions (20%) and a last fraction age of 540 Ma. In the absence of other samples, we interpret this as a Strangways type of sample and estimate the maximum age of formation as 250 Ma or less based on the first fraction. The sample has a cryptocrystalline melt matrix with approximately 15% lithic and mineral clasts. Most of the clasts are not recrystallized.

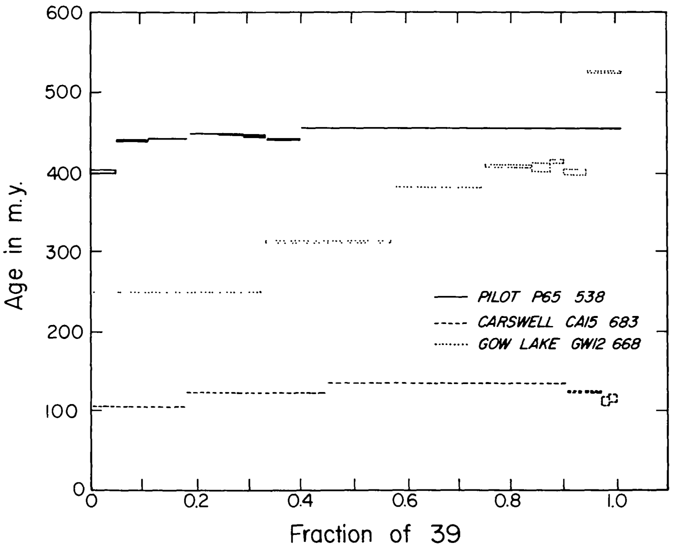

Fig. 13. Spectra from Pilot Lake, Carswell, and Gow Lake, Canada.

Thus, they could easily retain some memory of ages older than impact and, thereby, be responsible for the older high-temperature ages.

Pilot Lake, Northwest Territories, Canada

Pilot Lake (60° 17′N, 111°W) is about 6 km in diameter in granitic and gneissic terrain of Hudsonian age. Melt rock was obtained from glacial float on the western side of the lake (*Dence et al.,* 1968). No sedimentary fill has been found at Pilot Lake. *Dence et al.* (1968) believed the crater was middle to late Palaeozoic on the basis of erosion level. Sample P65 538 is rather atypical of most melt rocks, which release the bulk of their argon below 900°C. In the first seven temperature steps, up to 1100°C, only 40% of the gas is released (Fig. 13). This portion of the spectrum appears to be a slightly structured plateau. The eighth and last fraction contains 60% of the gas with an age of 450 Ma, which is not that different from the average age of 440 Ma given by the previous six fractions. It appears that this sample contains more high-temperature phases than a typical melt rock. Indeed, when examined petrographically it contained 50% clasts, of which only some 30% had been recrystallized. The clasts are set in a devitrified and hematized glassy matrix and the sample is intermediate between a melt matrix breccia and a well defined impact melt rock. The simplest interpretation of the age spectrum is that the Pilot Lake crater was excavated about 445 ± 2 Ma ago. However, dates on single samples from craters should be viewed with caution.

DISCUSSION

Our best estimate of the age of formation of the 13 craters studied is given in Table 2. This study has demonstrated, however, that melt rocks are not the simple material for argon age determinations that they might appear to be in principle. There remain significant ambiguities, which need to be investigated further. The spectra of melt rocks often fall into distinct groups based on shape. The variety of shapes often makes it difficult to interpret the age of impact with any degree of certainty. However, in all cases studied, the rocks do show ages considerably younger than the country rock that surrounds them. The various spectral shapes identified in this melt rock study and their interpretation are

1. *Classical plateau spectra.* The age interpretation of this plateau pattern is straightforward and represents an ideal, undisturbed, loss-free K-Ar system that has not been disturbed since it last cooled through its blocking temperature (Clearwater West, Pilot).

2. *Structured plateaus.* The structured plateau, seen in samples such as Mien, results when most of the age fractions appear to be about the same, yet the individual ages of contiguous fractions do not overlap at the one sigma level. This is an understandable evolution of the classical plateau, when many different effects begin to modify the argon system in melt rocks. Spectra with a small amount of structure apparently can also give reliable ages. While, in some cases, a portion of this structure is undoubtedly due to ^{39}Ar recoil during irradiation, it is primarily due to the nature of the rock that has target rock clasts imbedded in a finer grained matrix (Mien, Siljan, Carswell, Couture, Moinerie).

3. *Dual plateau spectra.* At Dellen there appeared to be samples that gave reasonable, structured plateaus, but at two distinctly different ages. Although we call this "dual" plateau, there could presumably be any number of different plateaus from any given site (Dellen).

4. *Stepwise rising spectra.* The stepwise rising spectra appear to be the result of partial thermal overprinting of less retentive sites in the rock, wherein progressively higher temperature phases retain more of their initial pre-impact ^{40}Ar. In cases such as this, the low-temperature fractions are probably the best indications of the age of impact (Gow, Saaksjarvi, Strangways).

5. *Hump-shaped spectra.* The hump-shaped spectra seen in some melt rocks are the most difficult to explain. The most common type (e.g., SJ106) has a low age in the first fraction rapidly rising to a high age at moderate temperature before leveling off to an intermediate age in the high-temperature fractions. The lowest temperature fractions are probably affected by postformation argon loss from the lowest retentivity sites and this same effect is observable on the age spectra of almost any type of rock. The hump at low- to medium-temperature may be caused by several effects, including exposure of the low-temperature sites to an argon environment different from that seen by the high-temperature sites (which close earlier to argon diffusion), and ^{39}Ar recoil from the intermediate temperature minerals into the phases that release at higher temperature. The complex clast-matrix relationships that exist in any given sample could also contribute to this shape. These different factors are not independent of each other and make it difficult to assign an unambiguous cause in all cases (Saaksjarvi SJ106).

6. *Saddle-shaped spectra.* Saddle-shaped spectra have been shown to indicate excess argon and the lowest part of the saddle gives a maximum estimate of the age of the resulting event (Clearwater East, Nicholson).

If a sample suite does not yield good plateaus, the errors assigned to the crater ages, when published, should represent the geological scatter in the sample ages, as well as the analytical errors assigned to the mass analysis. In Table 2 we have indicated the type of assigned error in the comments column. Only in the case of reasonable plateaus have the usual analytical errors been used. The complexities in the dating of impact events should introduce a cautionary note to the interpretation and use of crater ages. This is particularly relevant to those workers who take them at face value when constructing hypotheses of events such as periodic cometary showers that may affect the biological evolution of the earth (*Alvarez and Muller,* 1984; *Grieve et al.,* 1985).

It is clear from the variety of spectra observed in terrestrial impact melt rocks that ^{40}Ar-^{39}Ar dating should be used in preference to conventional K-Ar technique. Conventional K-Ar ages on many of the rocks dated during this project would be quite different than the best age as determined by analysis of the argon spectra. As samples from the same impact can, at times, give different ages and different spectral signatures, it is important that as many different samples as possible from the same crater be dated. In some cases, as at Dellen, the multiplicity of samples may enable the aberrant samples to be identified. By the same token, as much other evidence on the crater age as is available should be used to try to identify which samples are the most reliable. This would include petrographic study, stratigraphy of sedimentary units involved in the crater structure, and other isotopic dating methods. It appears that only through fully integrated studies will reliable ages of impact be determined for many craters with any degree of confidence.

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