Meteoritics & Planetary Science 36, 1087–1095 (2001)
Available online at http://www.uark.edu/meteor

Ion microprobe uranium-lead dating of zircons from the Lappajärvi impact crater, western Finland

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(Received 2000 October 30; accepted in revised form 2001 May 2)

Abstract–The lake Lappajärvi impact crater lies in Paleoproterozoic Svecofennian metasedimentary rocks, on the western side of the Central Finland granitoid complex (~1.9 Ga). Two conflicting ages have been reported for the meteorite impact: an age of 77.3 ± 0.4 Ma on the basis of Ar-Ar whole-rock data from impact melt samples and a paleomagnetic age of 195 Ma. During studies on impact crater indicator minerals at Lappajärvi, zircons with an atypical appearance were found in suevite boulders. These zircons seemed to have been affected by impact shock metamorphism and it was considered that they would be good candidates for ion microprobe U-Pb dating, allowing a new and independent age estimate for the impact event at Lappajärvi. Four spot analyses on two black-coated zircons plotted close to the upper intercept end of the concordia curve giving an approximate age of 1.8 Ga for the source rock. Seventeen analyses were done on three dull zircon grains showing patchy impact-related partial recrystallization. Most of these data fell fairly well on a single discordia line with intercept ages of 73.3 ± 5.3 Ma and 1854 ± 51 Ma. However, five of the data spots near the lower intercept end fell on the younger side of the line. This was interpreted to indicate post-impact loss of lead. Importantly, the new ion microprobe U-Pb age of 73.3 ± 5.3 Ma is in a very good agreement with the previously reported Ar-Ar age.

INTRODUCTION

Dating of terrestrial impact events is important to the attempt to define cratering rates on Earth. In turn, better knowledge of cratering rates is needed to critically study the effects of impact events on the atmosphere, biosphere, hydrosphere, and lithosphere. Impact events have usually been dated by Ar-Ar (*e.g.*, Sharpton *et al.*, 1992; Swisher *et al.*, 1992; Trieloff *et al.*, 1998; Claeys *et al.*, 1998; Spray *et al.*, 1999), conventional U-Pb (*e.g.*, Krogh *et al.*, 1993a,b; Kamo *et al.*, 1996; Ames *et al.*, 1998), Pb-Pb (*e.g.*, Woodhead *et al.*, 1998), and fission track (*e.g.*, Bonte *et al.*, 1991; McHone and Sorkhabi, 1994) methods. In recent years, the ion microprobe has become an important tool for the dating of impact events (Gibson *et al.*, 1997; Koeberl *et al.*, 1997). Two incompatible ages have been published for the Lappajärvi impact event. Jessberger and Reimold (1980) obtained an Ar-Ar whole-rock age of 77.3 ± 0.4 Ma from impact melt samples and Pesonen *et al.* (1992) reported a paleomagnetic age of 195 Ma.

Studies of Quaternary sediments with the aim of finding impact crater indicator minerals were initiated at the Geological Survey of Finland in 1996. During this study, various indicator minerals, including impact diamonds and shock-metamorphosed apatite, were separated from suevite boulders (Koivisto, 1997a,b; Koivisto and Korhonen, 1997; Masaitis *et al.*, 1998; Langenhorst *et al.*, 1999). In addition to zircons of normal appearance, bluish-to-yellowish and black-coated zircons were found in the same suevite boulder. We consider these zircons to have been affected by impact shock metamorphism and, accordingly, good candidates for ion microprobe U-Pb dating and determination of the age of the impact event at Lappajärvi (Mänttäri *et al.*, 1998; Koivisto and Mänttäri, 2000). In this study we report an ion microprobe U-Pb age for the shock-affected zircons from the Lappajärvi impact crater.

THE UPPER CRETACEOUS IMPACT CRATER

The Lappajärvi impact crater (Fig. 1) is situated in western Finland (63°09' N and 23°42' E), in the middle part of the Fennoscandian Shield. It is surrounded by Paleoproterozoic (~1.9–1.8 Ga) supracustal and plutonic rocks (Vaarma and Pipping, 1997). It was identified as an impact crater in 1968 by Svensson and then by Lehtinen (1970, 1976). Since then the crater has been the target for numerous studies: on the structural, petrological, geochemical, geophysical, petrophysical, and paleomagnetic characteristics of the crater, on the impact rocks, and on the microfossils in the sediments

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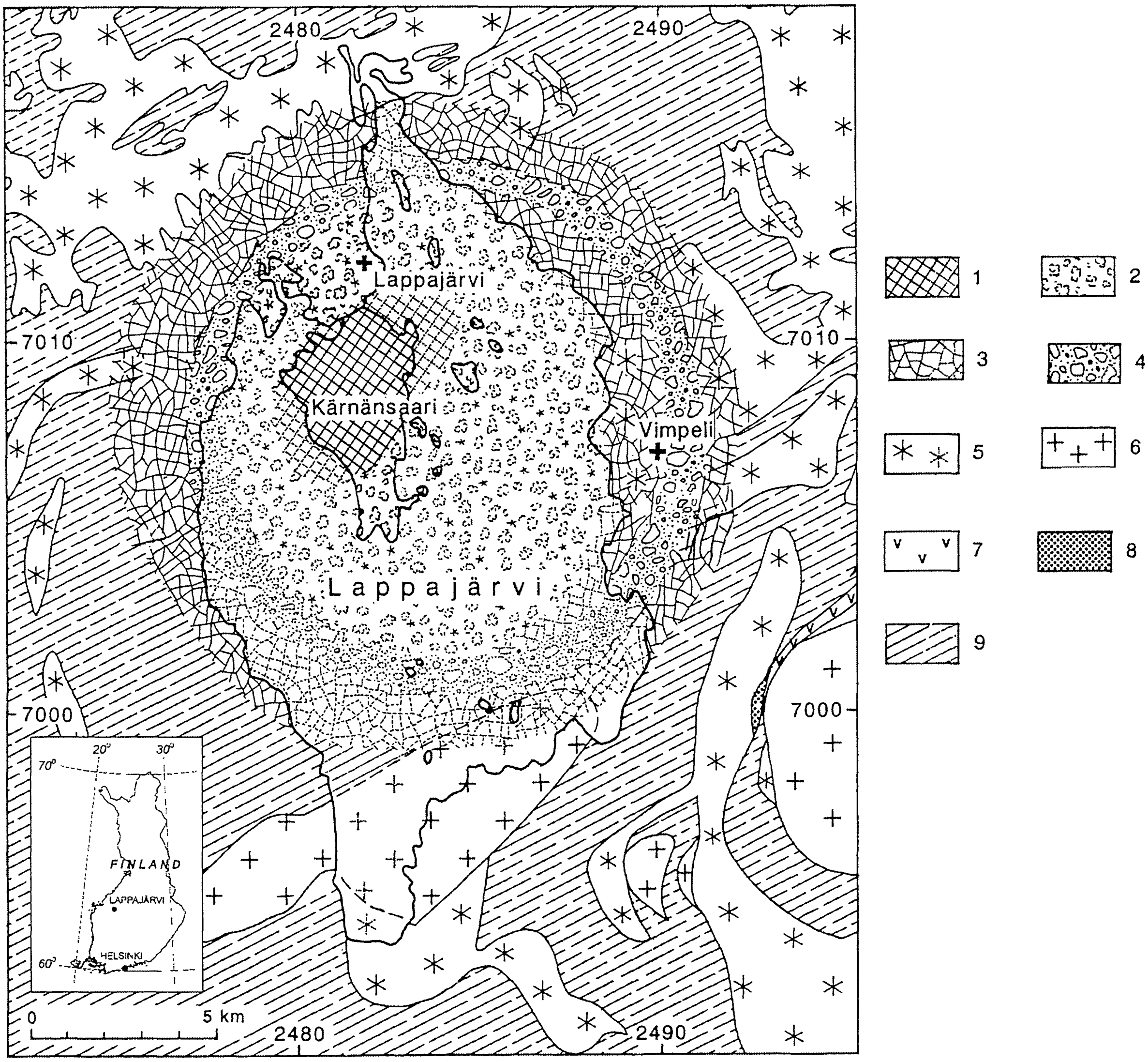

FIG. 1. Lithological map of the Lappajärvi meteorite crater area (Vaarma and Pipping 1997: Fig. 12 with legend). (1) Impact melt rock. (2) Suevite and impact breccia. (3) Autochthonous breccia zone (the terrace zone of the crater), *in situ* brecciated target lithologies of the impact area: metagraywacke, mica gneiss, pegmatite, granodiorite, and regoliths within them. (4) Mesoproterozoic sedimentary rocks. (5) Granite pegmatite. (6) Granodiorite and tonalite. (7) Mafic and intermediate metavolcanic rocks. (8) Limestone. (9) Metagraywacke and mica gneiss.

(Pipping, 1989, 1991; Elo *et al.*, 1992; Pipping and Lehtinen, 1992; Kukkonen *et al.*, 1992; Pesonen *et al.*, 1992; Uutela, 1990; Jessberger and Reimold, 1980).

The crater is deeply weathered and mostly covered by thick Quaternary sediments. The Lappajärvi impact structure is associated with a circular gravity anomaly low ~17 km in diameter (Elo *et al.*, 1992). The impact rocks include impact melt called kärnäite, fallback ejecta called suevite, and impact breccias (Lehtinen, 1976; Pipping, 1989, 1991). Kärnäite is found only in the central part of the crater on the island of Kärnänsaari. Suevite with glass patches occurs underneath and around the kärnäite. In drill core sections, suevite gradually gives way first to allochthonous and then to autochthonous impact breccia, and finally to fresh Paleoproterozoic metapelitic, pegmatitic, and granodioritic/tonalitic rocks (Fig. 1; Vaarma and Pipping, 1997). The circular depression surrounding the crater terrace is filled with Mesoproterozoic sedimentary rocks, which are not present outside the depression.

ION MICROPROBE URANIUM-LEAD DATING

Material and Methods

Kärnäite is usually considered to be best impact material from which to separate zircons for dating because it is little affected by weathering. However, no zircons were found in several earlier attempts to separate zircons from Lappajärvi kärnäites (Matti Vaasjoki, pers. comm.).

The zircons for our ion microprobe U-Pb dating were separated from a suevite boulder (Fig. 2) found in a nearby esker at a distance of ~10 km from the crater center. It was transported by a glaciofluvial stream flowing southwards ~10 500 years ago. Suevite is light brown, soft, easily weathered rock, which contains shocked or fresh rock and mineral fragments as fallback ejecta. The concentration of rock fragments in suevites may be as high as 30–40%, while the concentration of glass is about 20–50%. The matrix (20–30%) is composed of diminutive glass particles and very small mineral clasts ($\phi \leq 0.01$ mm) with admixture of smectitic minerals and calcium carbonate.

The suevite boulder was crushed to 0.2 mm size fraction and a heavy liquid (CH_2I_2) was used to separate the minerals into density fractions <3.25 g cm^{-3} and >3.25 g cm^{-3}. Nonmagnetic and paramagnetic/magnetic minerals from the >3.25 g cm^{-3} density fraction were separated with use of a Franz electromagnetic separator. The final nonmagnetic fraction contained zircons of normal appearance, as well as zircons of atypical appearance. Most of these atypical zircons were thorough dull, had a glassy shine on the surface, and showed bluish-to-yellowish tints of colour. In addition, some zircons were covered with thin black coatings and a few contained surface fractures, probably related to the impact event (Fig. 3). Recently, similar impact shock-affected zircons were identified in impact melt rocks and suevites from the Sääksjärvi impact crater in Finland. Thirty shock-affected zircons were selected for the ion microprobe U-Pb dating.

The chosen zircons were mounted in epoxy, polished, and coated with gold. The ion microprobe U-Pb analyses were made using the Nordic Cameca IMS 1270 at the Swedish Museum of Natural History, Stockholm, Sweden. The spot-diameter for the 4 nA primary O_2^- ion beam was ~30 μm and oxygen flooding in the sample chamber was used to increase the production of Pb^+ ions. Three counting blocks, each including three cycles of the Zr, Pb, Th, and U species of interest, were measured from each spot. The mass resolution ($M/\Delta M$) was 5400. The raw data were calibrated against a zircon standard (91500; Wiedenbeck *et al.*, 1995) and corrected for the background at mass 204.2 and modern common lead (T = 0; Stacey and Kramers, 1975). For details of the analytical procedure see Whitehouse *et al.* (1997, 1999).

RESULTS

Four U-Pb analyses were done on two black-coated zircons 30 and 31, which showed only minor recrystallization in their backscattered electron (BSE) images (Fig. 4). The data indicated only a slight loss of lead and a source age of ~1.8 Ga for these zircons (Table 1 and Fig. 5). This age is typical for

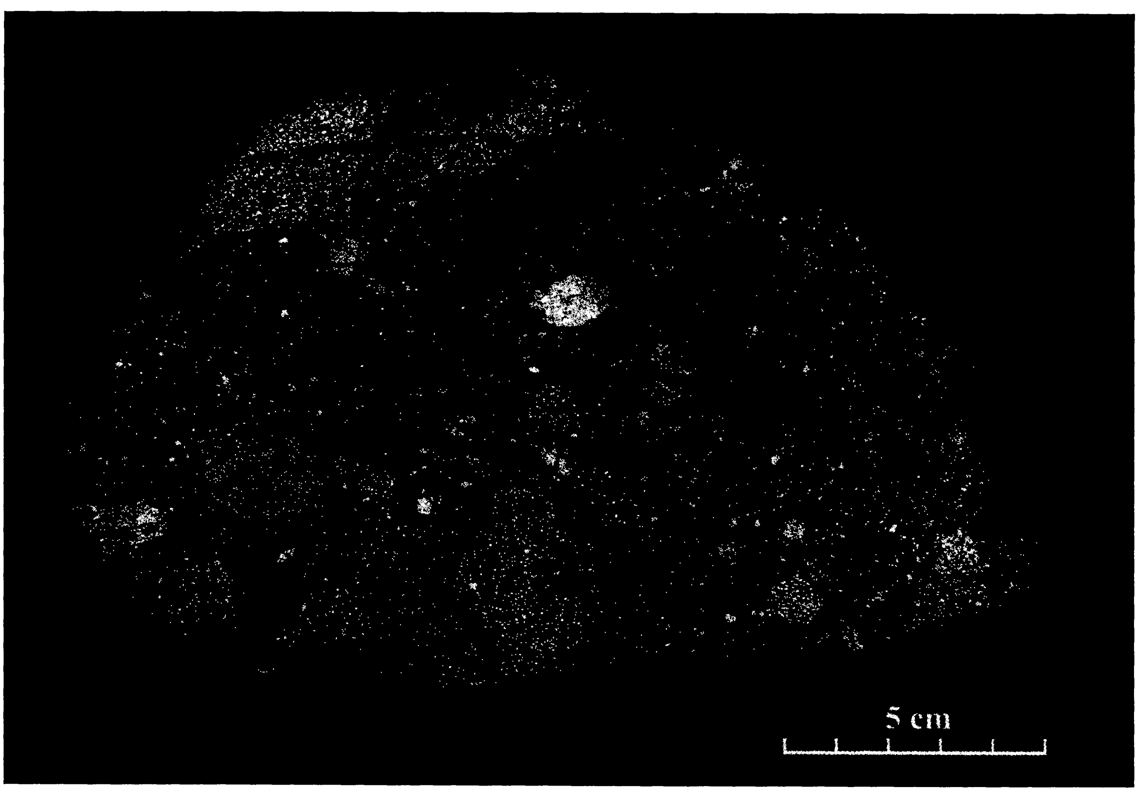

FIG. 2. Suevite boulder from which the zircons for the U-Pb dating were separated.

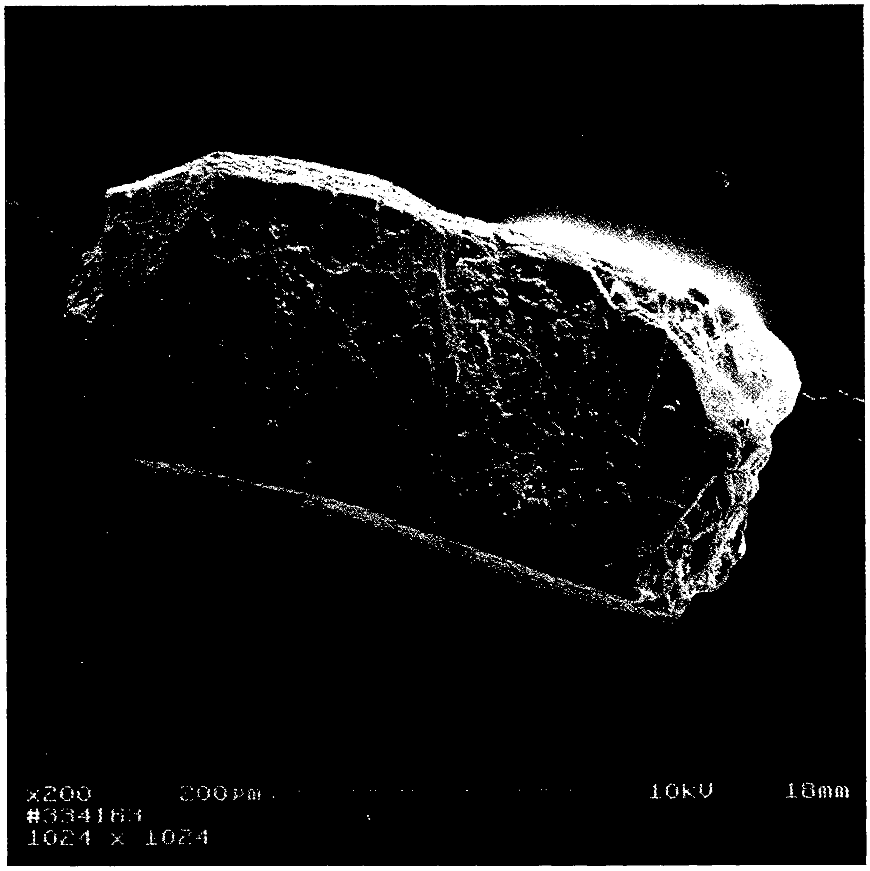

FIG. 3. Scanning electron micrograph image of shock-affected zircon (04), possibly showing impact-related fracture networks on its surface.

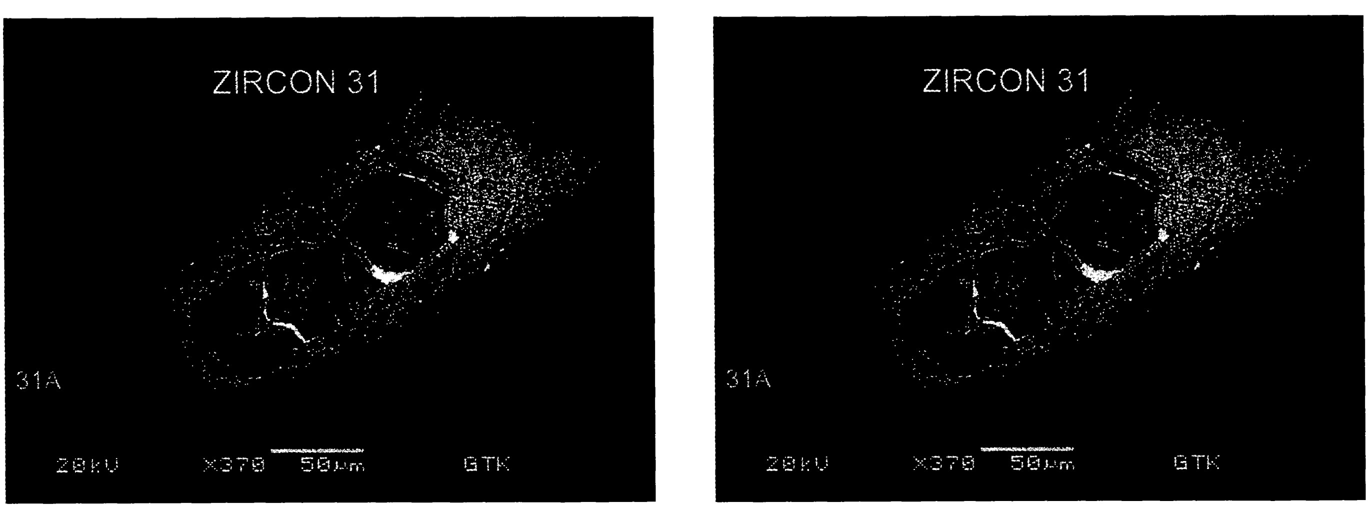

FIG 4. BSE images of zircons 30 (a) and 31 (b). Sites of the spot U-Pb analyses are marked.

TABLE 1. Ion microprobe U-Pb data from zircons from the Lappajärvi suevite.

Sample/ spot #	Derived ages (Ma)*			Corrected ratios†						Rho‡	Elemental data			$^{206}Pb/^{204}Pb$ measured
	$^{207}Pb/^{206}Pb$ ± σ	$^{207}Pb/^{235}U$ ± σ	$^{206}Pb/^{238}U$ ± σ	$^{207}Pb/^{206}Pb$	σ (%)	$^{207}Pb/^{235}U$	σ (%)	$^{206}Pb/^{238}U$	σ (%)		[U] (ppm)	[Th] (ppm)	[Pb] (ppm)	
n159-02a	745 ± 36	127 ± 3	97 ± 2	0.0641	1.70	0.1336	2.90	0.0151	2.35	0.81	2364	93	38	2010
n159-02b	274 ± 32	84 ± 2	77 ± 2	0.0517	1.39	0.0857	2.69	0.0120	2.30	0.86	5999	210	76	1850
n159-02c	1283 ± 17	265 ± 6	165 ± 4	0.0836	0.89	0.2984	2.50	0.0259	2.33	0.93	2484	91	70	2583
n159-02d	784 ± 24	127 ± 3	95 ± 2	0.0653	1.17	0.1333	2.59	0.0148	2.31	0.89	4980	91	79	2133
n159-02e	1502 ± 17	341 ± 7	196 ± 4	0.0937	0.93	0.3994	2.49	0.0309	2.32	0.93	2713	106	92	1508
n159-04a	1130 ± 28	211 ± 7	138 ± 4	0.0773	1.43	0.2304	3.46	0.0216	3.16	0.91	1832	69	43	2249
n159-04b	1363 ± 12	315 ± 7	192 ± 4	0.0871	0.62	0.3638	2.40	0.0303	2.32	0.97	3048	109	101	10853
n159-04c	573 ± 26	92 ± 2	74 ± 2	0.0592	1.18	0.0947	2.60	0.0116	2.32	0.89	4129	193	51	4237
n159-04e	976 ± 24	169 ± 4	117 ± 3	0.0716	1.17	0.1811	2.60	0.0183	2.32	0.89	4107	151	81	4129
n159-04f	1230 ± 30	225 ± 6	141 ± 4	0.0814	1.54	0.2483	3.09	0.0221	2.68	0.87	2889	119	70	1288
n159-04g	1507 ± 8	407 ± 8	241 ± 5	0.0939	0.43	0.4924	2.34	0.0380	2.30	0.98	3133	113	131	17215
n159-12a	599 ± 41	101 ± 3	81 ± 2	0.0599	1.94	0.1042	3.04	0.0126	2.35	0.77	3679	460	50	994
n159-12b	1638 ± 31	527 ± 12	308 ± 7	0.1008	1.70	0.6800	3.01	0.0489	2.49	0.83	1606	89	88	2725
n159-12c	776 ± 33	91 ± 2	67 ± 2	0.0650	1.57	0.0940	2.78	0.0105	2.29	0.83	4847	526	56	1121
n159-12d	249 ± 42	62 ± 2	57 ± 1	0.0512	1.85	0.0631	2.96	0.0089	2.30	0.78	5605	520	54	1292
n159-12e	893 ± 23	132 ± 3	94 ± 2	0.0688	1.12	0.1391	2.56	0.0147	2.30	0.90	3175	256	51	2456
n159-12f	416 ± 96	90 ± 4	78 ± 2	0.0551	4.43	0.0923	5.03	0.0121	2.39	0.47	3884	94	50	592
n159-30a	1778 ± 28	1807 ± 26	1832 ± 41	0.1087	1.54	4.9293	3.01	0.3288	2.59	0.86	811	62	302	2362
n159-30b	1809 ± 25	2324 ± 30	2954 ± 68	0.1106	1.40	8.8646	3.19	0.5814	2.87	0.90	1045	104	692	2333
n159-30c	1781 ± 10	1657 ± 20	1560 ± 32	0.1089	0.52	4.1117	2.38	0.2738	2.32	0.98	889	61	275	13630
n159-31a	1768 ± 7	1591 ± 20	1461 ± 31	0.1081	0.41	3.7911	2.42	0.2543	2.39	0.99	1171	50	334	13908

*Errors are at 1σ level.

†Corrected for modern common lead ($T = 0$; Stacey and Kramers, 1975).

‡Error correlation for $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ratios.

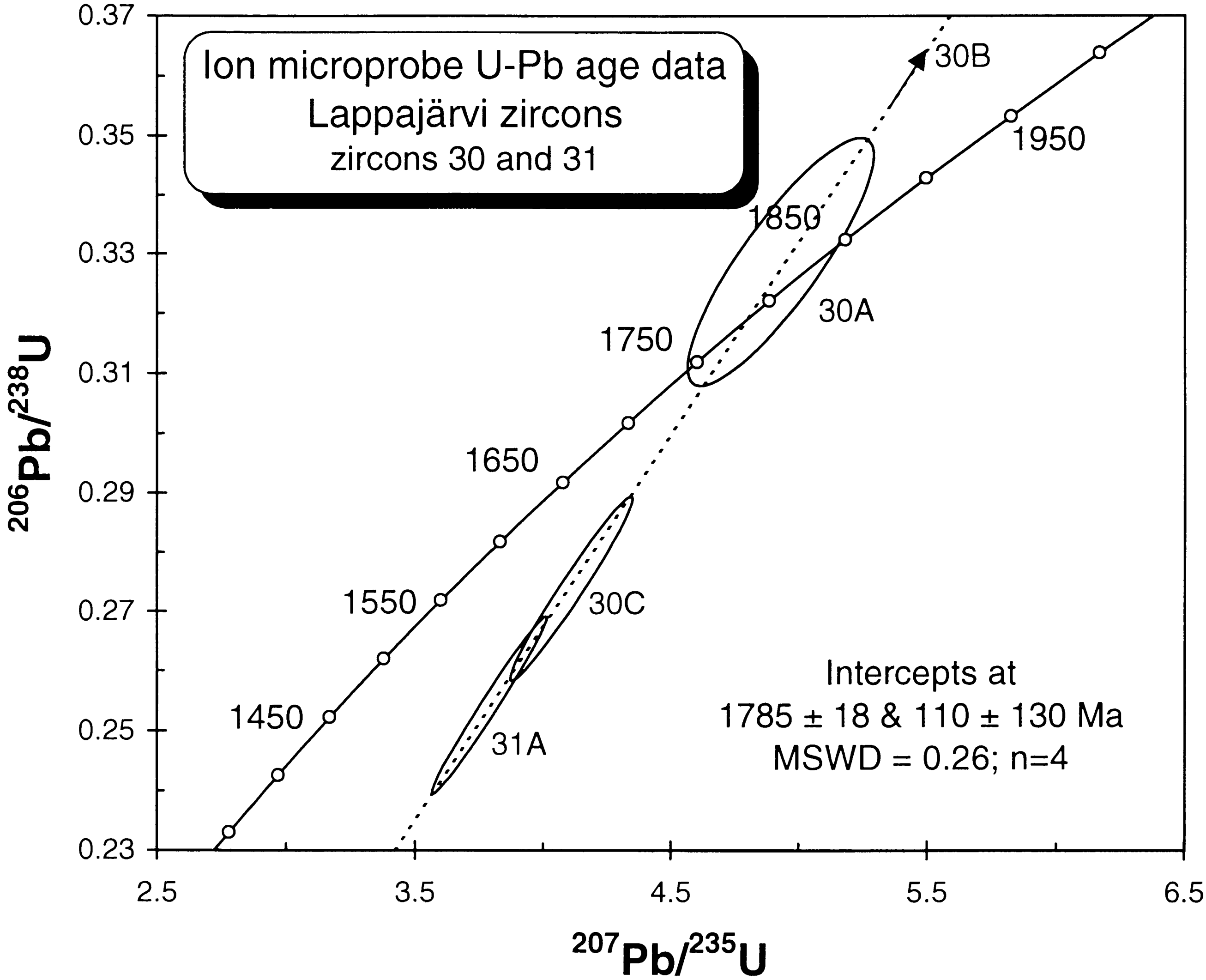

FIG. 5. Concordia plot of the ion microprobe U-Pb age data from black-coated zircons 30 and 31 indicating the source rock age. All errors are at 2σ level.

the youngest Svecofennian granites and pegmatites in western Finland.

Eighteen spot analyses were done on zircons 02, 04, and 12 (Table 1 and Fig. 6). One analysis done on zircon 04 was rejected because of the extremely large errors. The analyses were preferably directed at zircon domains exhibiting recrystallization in their BSE images (Fig. 7). The recrystallization was presumed to have occurred at the time of the impact event.

Although suevite material could feasibly contain several zircon populations, we presume that the U-Pb data are related to just two main components—the protolith age and the impact event. If this is true, all the data for zircons 02, 04, and 12 should fall on a single discordia line. Twelve of the 17 analyses were consistent with a single discordia line (Fig. 6), with the intercept ages of 73.3 ± 5.3 Ma and 1854 ± 51 Ma (mean square of weighted deviates = 3.3; n = 12). However, five analyses near the lower intercept end of the concordia curve plotted on the younger side of the discordia line.

DISCUSSION

The lower intercept age of 73.3 ± 5.3 Ma is interpreted as the time of the impact event at Lappajärvi and of simultaneous voluminous lead loss from zircons. The lead loss and partial recrystallization of the zircons cannot have been related to another geological event because the bedrock in the Lappajärvi area consists entirely of much older rocks: Svecofennian schists and granitoids (~1.9 Ga) and granites and pegmatites (~1.8 Ga). Even the youngest magmatic rocks in western Finland are diabase dykes dated at ~1.27 Ga (Suominen, 1991). Furthermore, the zircons separated from a suevite boulder that were used in the dating were of atypical appearance suggesting

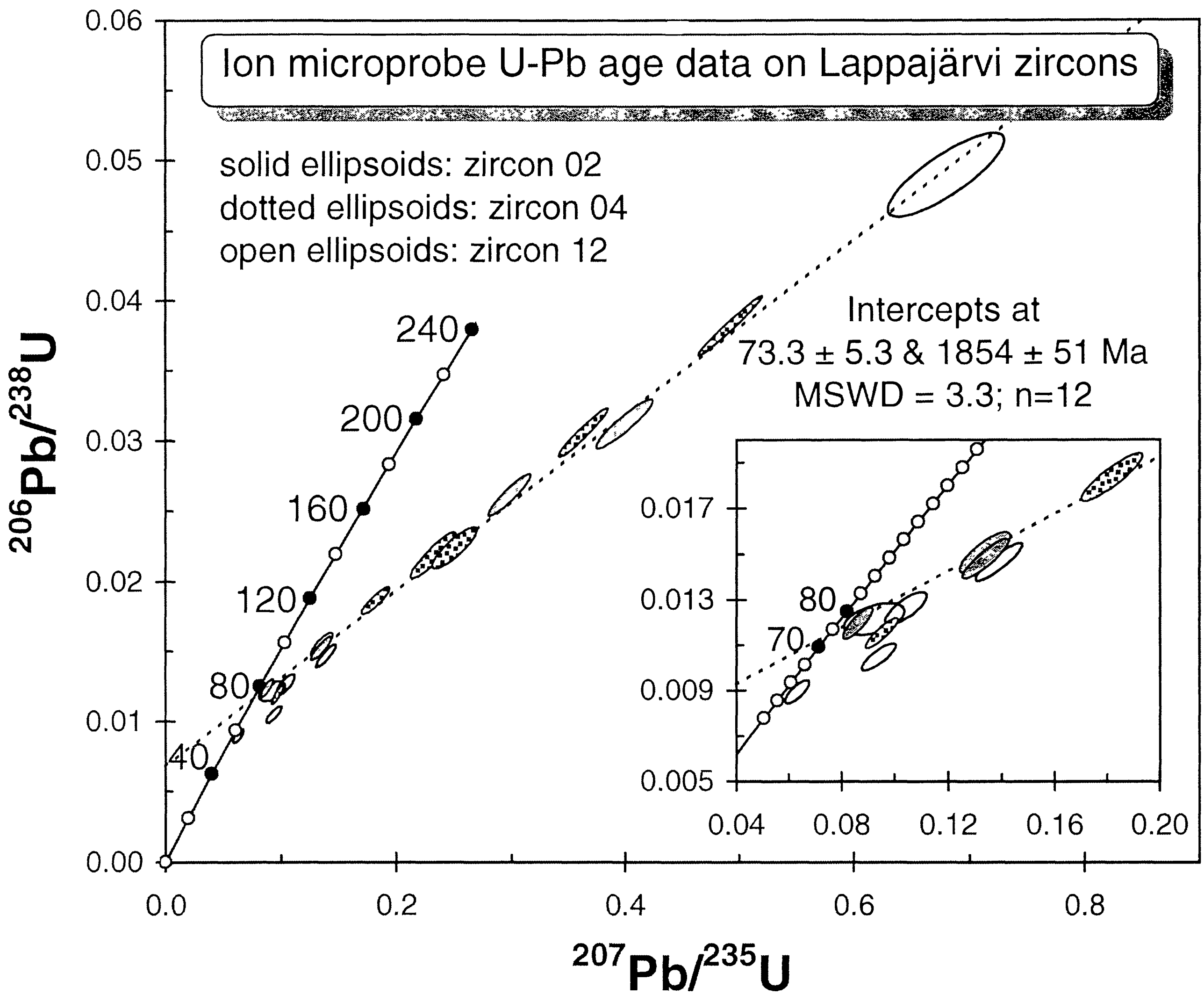

FIG. 6. Concordia plot of the ion microprobe U-Pb age data from zircons 02, 04, and 12 showing the impact-related lead loss and the time of the impact event. Several analyses near the lower intercept end indicate a post-impact loss of lead. All errors are at 2σ level.

the effect of impact shock metamorphism. Further evidence supporting the impact origin was the finding of impact diamonds in suevite boulders (Langenhorst *et al.,* 1999) from the same sampling site.

The U-Pb data falling on the younger side of the discordia line must reflect a post-impact lead loss, which would be expected to occur especially from the fractured domains and non-recrystallized domains of metamict zircons. It is worth noting that the uranium concentrations of the samples indicating source rock age are significantly lower than the uranium concentrations of the zircons indicating severe impact-related lead loss (see Table 1). Therefore, in the case of Lappajärvi zircons, the metamict zircons must have been more susceptible to recrystallization during the impact event.

The upper intercept age of 1854 ± 51 Ma must reflect the age of the source rock. This age is entirely reasonable in relation to the age of the surrounding bedrock. However, it is very plausible that the system had already suffered some lead loss before the impact event and, therefore, the upper intercept age after the impact-related lead loss may not be strictly meaningful: depending on the slope of the lead-loss trajectory, the upper intercept age could be younger or older than the true source age.

Our age estimate of 73.3 ± 5.3 Ma for the Lappajärvi impact event, based on the ion microprobe U-Pb dating of three atypical zircon crystals, is in very good agreement with the previous whole-rock Ar-Ar age of 77.3 ± 0.4 Ma determined from impact melt rocks (Jessberger and Reimold, 1980). Pesonen *et al.* (1992) reported that the paleomagnetic pole position of the Lappajärvi impact event suggests an age of ~195 Ma for the Lappajärvi impact. This age is very much greater than the Ar-Ar age of 77 Ma reported by Jessberger and Reimold (1980), and

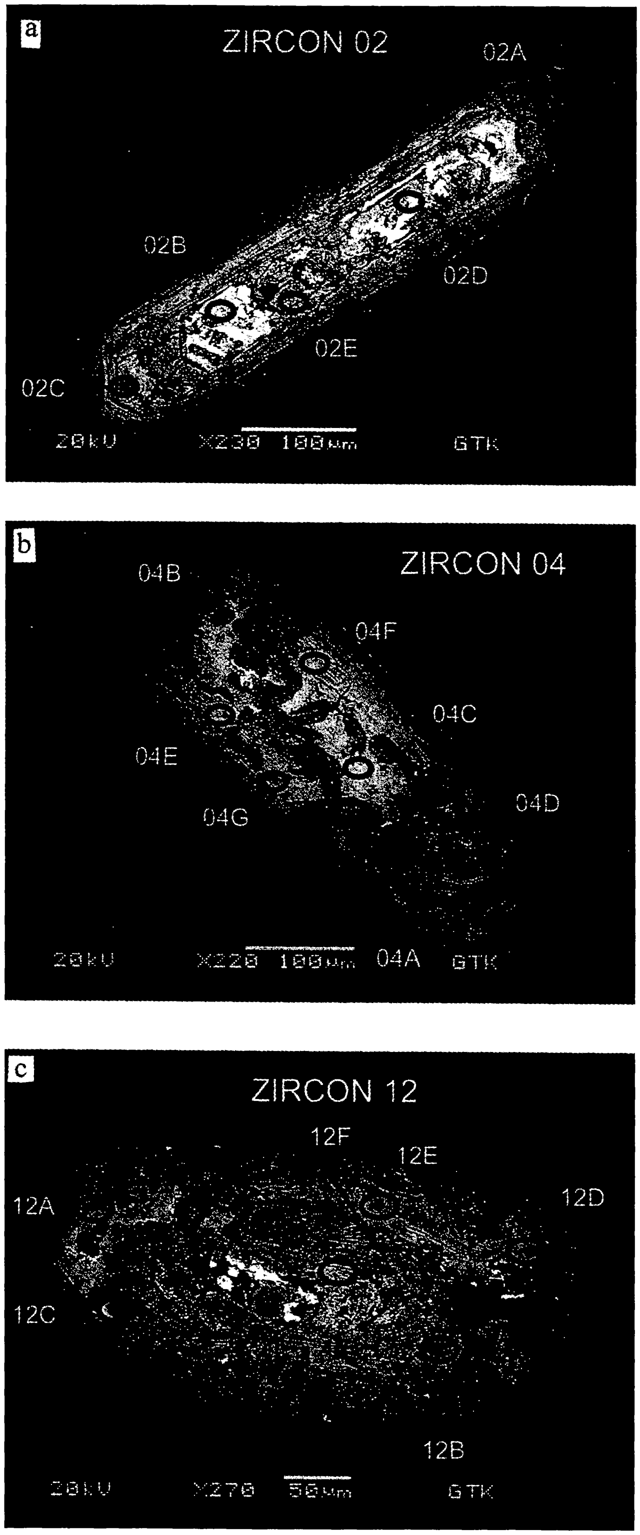

FIG. 7. BSE images of shock-affected zircons: (a) 02, (b) 04, and (c) 12. Sites of the spot U-Pb analyses are marked.

the ion microprobe age of 73 Ma given in this work. Possible reasons for the clearly older paleomagnetic age include secular variation, magnetic anisotropy, bias of natural remanent magnetization (NRM) by present Earth's field (PEF), and post-impact tectonic movements. These have been discussed in detail by Pesonen *et al.* (1992).

Ion microprobe U-Pb dating of zircons affected by shock metamorphism can be considered as an alternative method to Ar-Ar dating of impact rocks. It is especially useful in cases where the Ar-Ar method gives ambiguous age results and when impact melt related zircon growths (see Gibson *et al.*, 1997) are not available.

Acknowledgments–We thank the personnel of the NORDSIM laboratory for keeping the instrument in good running order and Juha Korhonen for cooperation in the earliest phases of this study. Juha Karhu is acknowledged for his valuable comments on the manuscript. Journal reviews by T. Ireland and an anonymous reviewer and editorial comments by E. Zinner improved the manuscript significantly. Funding was provided by the Academy of Finland (project 40553).

Editorial handling: E. Zinner

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