The Projectile of the Lappajärvi Impact Crater

Elke Göbel, Uwe Reimold *, Hildegard Baddenhausen, and Herbert Palme
Max-Planck-Institut für Chemie (Otto-Hahn-Institut), Mainz, Germany

Z. Naturforsch. **35a**, 197–203 (1980); received January 9, 1980

Dedicated to Prof. Dr. Heinrich Hintenberger on the occasion of his 70th birthday

Two impact melt samples from the Lappajärvi crater (Scandinavia) are highly enriched in siderophile elements, such as Ir, Re, and Os. This indicates the presence of a meteoritic component. The simultaneous enrichments of Ni, Co, Cr, and Se suggest a chondritic projectile. Because of the relatively large indigenous contributions to Ni, Co, and Cr, it is not possible to distinguish between a normal and a carbonaceous chondrite. The high concentrations of relatively volatile elements could point towards a volatile-rich projectile.

The two melt samples have high Re/Ir ratios compared to chondritic ratios. Enrichment of Re relative to Ir is very unusual in terrestrial impact melts. Loss of Re, because of volatilisation under oxidizing conditions or by weathering is frequently observed.

The high Re/Ir ratios and the high abundances of relatively volatile elements either indicate the presence of a volatile rich phase or they characterize a type of meteorite, which has not been sampled. Some lunar highland rocks have a pattern of meteoritic elements rather similar to that observed for the Lappajärvi meteorite.

The Lappajärvi crater is, after Rochechouart, the second European crater where a significant amount of meteoritic component has been found.

A melt sample from the Lake St. Martin crater (Manitoba), did not show any enrichment in meteoritic elements.

1. Introduction

Craters of all sizes are covering the surfaces of Moon, Mars, Mercury and most other solid objects of our solar system. There is no doubt that the majority of these craters formed as a result of impact. In recent years scientists have become increasingly aware of the fact that the Earth cannot have escaped the bombardment of large meteorites (with diameters up to several km). Indeed some 80 terrestrial craters have now been identified as hypervelocity impact craters [1]. The projectiles should be found among Apollo asteroids. With their eccentric orbits they cross the orbit of the Earth from time to time. Identification of the projectiles of large terrestrial impact craters would significantly enhance our knowledge of Apollo asteroids. These asteroids must ultimately be derived from long lived sources, such as main belt asteroids or comets [2].

Since the impacting material will completely evaporate in a large hypervelocity impact, we cannot expect to find pieces of the asteroid (comparable to the meteorites in our collections) at multi-kilometer impact craters. If the chemical composition of the asteroid is sufficiently different from that of the target rocks, the projectile will, however, leave its chemical imprint on the rocks generated during the impact. By analysing these rocks for meteoritic indicator elements, such as Ir, Os, Ni, Cr, Se, etc., the projectiles of several large terrestrial impact craters have been identified [3 – 7]. From the few reliable meteoritic elements it appears that these projectiles have compositions within the range of known meteorite groups.

Among European impact craters the Ries crater has been extensively investigated. No large enrichments of siderophile elements have been found in any of the analysed samples [6]. From this and other evidence, Morgan et al. [6] conclude that the projectile most likely was an aubrite. From the presence of Cr-bearing metal veins El Goresy and Chao [8], however, infer a chondritic projectile. Rochechouart was the first large European crater with clear evidence for meteoritic contamination. It was suggested that its projectile was a II A iron meteorite [3].

Preliminary analyses of a sample from the Lappajärvi crater (Scandinavia) showed significant enrichments of Ir, Ni, and Cr. We, therefore, decid-

Reprint requests to Dr. H. Palme, Saarstr. 23, D-65 Mainz.
* Institut für Mineralogie, Universität Münster, Münster, Germany

0340-4811 / 80 / 0200-0197 $ 01.00/0. — Please order a reprint rather than making your own copy.

ed to analyse more samples for more elements including a representative basement rock, in order to determine the projectile of the Lappajärvi crater.

Enrichment of Ni in melt rocks from Lappajärvi has already been reported by Lethinen [9]. Fregerslev and Carstens [10] have found FeNi-particles in these rocks.

2. The Lappajärvi Crater

Lake Lappajärvi is located in the Svecofennian gneiss mass of Central Finland (63°09′N/23°42′E) about 250 km northwest of Helsinki (Figure 1). The original size of the crater is not well known. Gravity measurements [11] suggest a diameter of about 17 km.

Up to the 1950's the lava-like rocks of that area were suggested to be of volcanic origin [12, 13]. The possibility that the Lappajärvi structure might have been produced by meteoritic impact has been first suggested by Fredriksson and Wickman [14].

In 1976 Lehtinen published a detailed mineralogical, petrographical, and chemical study of the various rock types occurring around the Lappajärvi Lake, namely "impact breccias", "suevite" and melt rock ("kärnäite") [12]. Lithic clasts in these rocks display all grades of shock metamorphism. Lethinen identified the high pressure phase coesite in the shocked rocks, thus confirming the impact origin of the Lappajärvi structure. Recently, Lappajärvi rocks were investigated petrographically by Maerz [16].

The age of the Lappajärvi crater was unknown until Jessberger and Reimold [17] performed $^{40}Ar/^{39}Ar$ analyses of four samples of impact melt taken from various outcrops. They resulted in an age of 77.3 ± 0.4 m.y. for the impact melt rocks.

3. Samples and Methods

Two melt samples and one basement rock were chosen for RNAA (radiochemical neutron activation analysis). The melt samples were taken from autochthonous kärnäite which occurs on several islands in the center of the crater area, and from allochthonous boulders of kärnäite from glacial deposits southeast of the lake (Figure 1). The basement sample, a quartz and biotite-rich mica schist was collected some kilometers south of the lake (Figure 1). Only fresh samples without any sign of alteration were selected. All samples have been previously analysed by INAA (instrumental neutron activation analysis). These

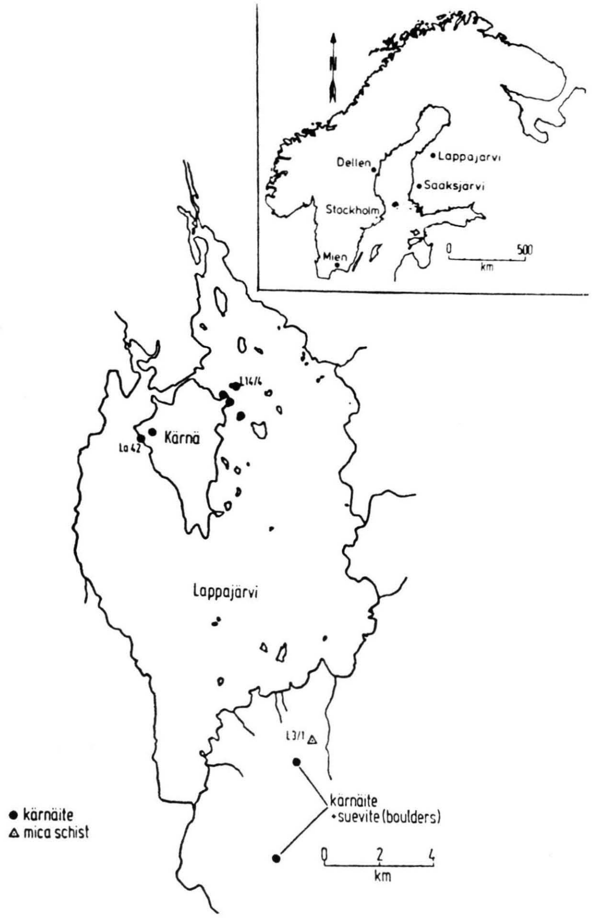

Fig. 1. Location of the Lappajärvi impact crater.

data are discussed in Reimold and Stöffler [18] and Reimold [19].

A sample from the Lake St. Martin crater (Manitoba) was also analysed. The fine grained vesicular melt sample was collected 8 km from the center of the crater.

Suitable standards were prepared and a 60 mg sample from the Murchison meteorite (C 2) was also included. Samples and standards were irradiated at the FR-2 reactor, Karlsruhe, for half a day at a neutron flux of 10^{14} n/cm^2 sec.

The radiochemical procedure was an abbreviated and modified version of the procedure used by Wänke et al. [20] for lunar samples. Arsenic and Ge were extracted together and the 11.3 d activity of Ge-77 was counted with an intrinsic Ge-detector. The same detector was used for the combined Re, Se fractions. It was therefore possible to separate the

137.2 KeV activity of Re-186 from the 136.0 KeV activity of Se-75. The Re-188 activity (155 KeV) gave, within statistical errors, the same results, when samples were counted on a large Ge(Li)-detector.

4. Results and Discussion

The results of the RNAA together with some INAA analyses for the five samples are presented in Table 1. Generally, there is a good agreement between the Murchison data of this study and earlier analyses from this laboratory. The largest discrepancy is observed for Re. The use of Murchison as standard would lower the observed Re concentrations by some 20%; the Re abundances in the melt would still be exceptionally high.

The Lake St. Martin sample does not show any enrichment in siderophile elements. The Cr concentration is also fairly low. Therefore, any achondritic meteoritic component could only contribute less than one percent. The low concentration of siderophile elements set an upper limit of 0.01 percent of a chondritic component. There are other large craters, where in spite of a large number of analyses, a noticeable meteoritic component has not been found in impact melts, e. g. Mistastin and Manicouagan [4, 5, 21].

a) Homogeneity of the Melt and Basement Correction

Reimold and Stöffler [18] and Reimold [19] demonstrate the excellent chemical homogeneity of the melt in Lappajärvi, with respect to non-meteoritic as well as meteoritic elements. Mixing calculations by these authors show that the melt can be modelled by a mixture of 76% mica schist, 11% granite pegmatite and 13% amphibolite. Sample L 3/1 is representative for the mica schist component, which contributes the majority of the melt. We have, therefore, corrected the meteoritic component of the melt samples by subtracting indigenous concentrations observed in L 3/1. From Table 1 it is obvious that indigenous contributions for Co, Cr, and Ni are significant. The small pegmatic and amphibolitic component would not significantly change these data. Figure 2 demonstrates this basement correction for Ni and Co. The corrected Ni/Co ratios are near the chondritic ratio. The indigenous Co correction may be slightly higher than measured in sample L 3/1. One can, however, not expect a perfect fit because of two reasons.

α Meteoritic Ni and Co may be slightly decoupled, because of slight fractionations within the melt sheet. This has been observed in the East Clear-

Table 1. Siderophile and volatile elements in impact melts from Lappajärvi and Lake St. Martin craters.

		Lappajärvi			Lake St.Martin	Murchison	
		Melt		Basement	Melt	This work	Unpublished
		L 14/4	La 42	L 3/1	LSM-19-78		data this laboratory
Re	ppb	2.9	3.0	0.5	—	62	51
Ir	ppb	10.4	6.1	<0.06	<0.03	664	660
Os	ppb	10.8	7.6	<0.6	<0.5	≡870	870
Ni	ppm	313	197	61	<2	—	13700
Co	ppm	29.2	19.7	10.8	8	—	589
Cr	ppm	177	124	92	24.4	—	3500
Au	ppb	6.76	1.86	0.73	0.30	152	150
Cu	ppm	55.0	44.3	<3.5	18.3	137	141
Ge	ppm	2.3	0.15	1.62	0.9	≡231	231
Se	ppb	664	735	4	36	13.3	12.7
Ga	ppm	22.2	19.5	18.1	20.5	8.2	7.4
As	ppm	0.76	0.55	32.6	0.95	1.93	1.86
Zn	ppm	92	83	92	48	191	176
Cd	ppb	30	12	100	55	345	379 [a]

[a] Krähenbühl et al. [29].
Standard deviations: <5% Ir, Ni, Co, Cr, Au, Ga, As, Se, Zn; 5—10% Os, Cu, Ge; 10—20% Re, Cd; Ni, Co, and Cr data for Lappajärvi samples from Reimold [19].
Lake St. Martin sample: R. A. F. Grieve, Dept. of Energy, Mines and Resources, Ottawa, Canada.

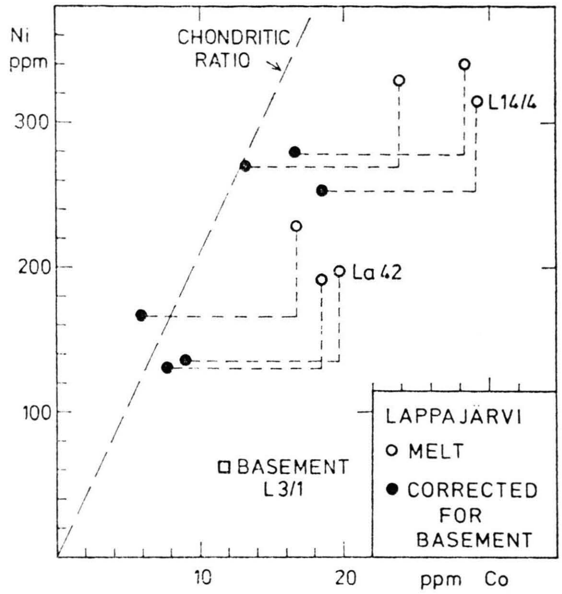

Fig. 2. Ni vs. Co in Lappajärvi impact melts. Correction for indigenous contributions by subtracting Ni, Co concentrations of basement rock L 3/1 leads to nearly chondritic Ni/Co ratios. Data from four impact melts from Reimold [19]. Other data, see Table 1.

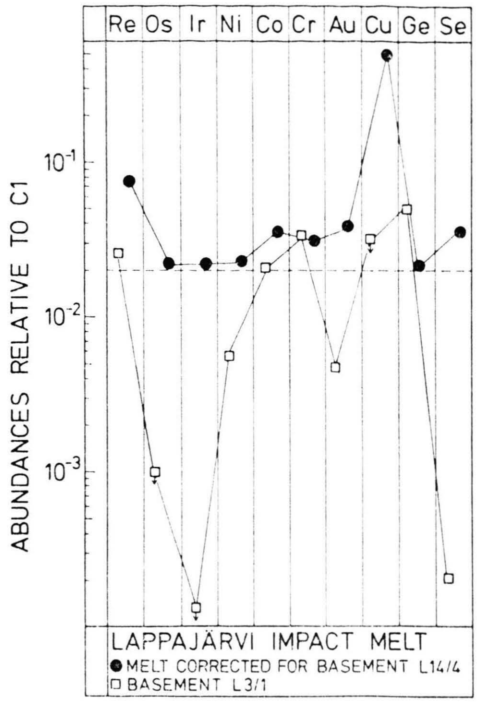

Fig. 3. C 1 normalized pattern of impact melt L 14/4. The sample has been corrected for indigenous contributions by subtracting the abundances of basement rock (a mica schist) L 3/1. The C 1 normalized abundances are also plotted.

water melt, where the more siderophile Ni shows high local concentrations, while Co is more homogeneously distributed [22].

β There may be variations in basement rocks. To get a better average one would have to analyse a large number of basement rocks. This could be important in the Lappajärvi crater, since here the basement corrections are substantial. In view of these uncertainties, Fig. 2 suggests that our basement correction is justified.

b) Non-volatile Meteorite Elements

In Fig. 3, C 1 normalized data for siderophile elements and Cr and Se are plotted. These data have been corrected for indigenous contributions. The basement values for the same elements are shown for comparison.

The emerging pattern is basically chondritic. In the past we have used two main criteria to make sure that the meteoritic signature is chondritic.

α If the Ni/Ir ratio is around 20 000 (Orgueil data from this laboratory: Ni 10770 ppm, Ir 0.475 ppm), there is a good chance that the projectile was a chondrite. Most iron meteorites have Ni/Ir ratios very different from the chondritic ratio (see Fig. 3 of Scott and Wasson [23], Fig. 3 of Janssen et al [3]). However, chondritic Ni/Ir ratios lie within the range of several iron meteorite groups.

β If in addition the Ni/Cr ratios are around 3 – 4, there is little doubt that the projectile was a chondrite, since generally iron meteorites do not contain Cr.

In addition the rather volatile element Se has proven to be a good indicator of a chondritic component. Impact melts from East Clearwater, Brent, and Lappajärvi are enriched in Se over basement rocks [4, 22]. A large fraction of Se may nevertheless be lost during the impact [22].

The basement corrected Ni/Ir ratios of our two Lappajärvi samples are 24 230 and 22 300, the respective Ni/Cr ratios are 2.96 and 4.25. We, therefore, conclude that the Lappajärvi projectile was a chondritic meteorite.

The next step is to ask what type of chondrite the projectile was, carbonaceous or normal chondrite. This is an important point, because spectral reflectance data from asteroids can be used to distinguish between normal and carbonaceous chondrites, e. g. [24]. Different groups of chondrites have different Ni/Cr and Co/Cr ratios, respectively. These differences have been useful in establishing the nature of the projectile at East Clearwater and Brent [4, 5, 22]. Because of the rather high indigenous corrections for these elements, the corrected Ni, Co, and Cr data of the two melt samples (Table 1) are not sufficiently well defined to discriminate between normal and carbonaceous chondrites.

c) *Volatile Elements*

A major difference between the chemistry of carbonaceous and normal chondrites are the generally lower concentrations of volatile elements in the latter group of meteorites. The pattern of volatile elements is unfortunately heavily disturbed through volatilisation processes during the impact [22]. Nevertheless, the concentrations of volatile and especially moderately volatile elements are remarkably high in Lappajärvi melt samples, compared to impact melts from other terrestrial craters. In sample L 14/4 Au, Cu, and Se are, after indigenous corrections, significantly enriched relative to Ni and Ir (Figure 3).

Figure 4 shows the parallel patterns of (uncorrected) meteoritic and volatile elements. The meteoritic contributions to Ga, As, Zn, and Cd are negligible (As and Cd are higher in basement rocks than in the melt, Table 1). This suggests that the general pattern of Fig. 4 was established after meteoritic and non-meteoritic material was mixed together either in the vapor phase or in the melt.

The high abundance of Cu in the Lappajärvi melt may reflect inhomogeneous distribution of this element within the melt. Similar high concentrations of Cu have been observed in the lower part of the melt sheet of East Clearwater. Here, the excess Cu in the lower part was compensated by a deficiency of Cu in the upper part of the melt sheet. The average Ni/Cu ratio was chondritic [22]. From the available data it appears that Cu is predominantly of meteoritic origin in East Clearwater as well as in Lappajärvi melt rocks.

A comparison of Au and Se data of Lappajärvi with other terrestrial craters shows that these two elements have significantly larger concentrations in the Lappajärvi impact melt than in Brent or East Clearwater melts (Figure 5). Since the East Clear-

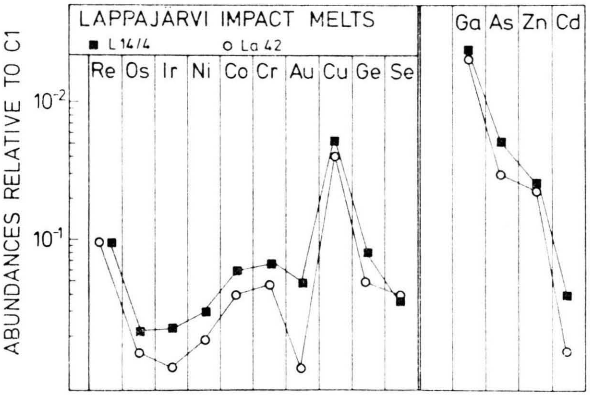

Fig. 4. Comparison of the two impact melts discussed in this paper. With the exception of Re and Se, all siderophile and volatile elements (of meteoritic and non-meteoritic origin) are depleted in La 42 compared to L 14/4. This suggests that the different patterns were established after meteoritic and non-meteoritic material have been mixed.

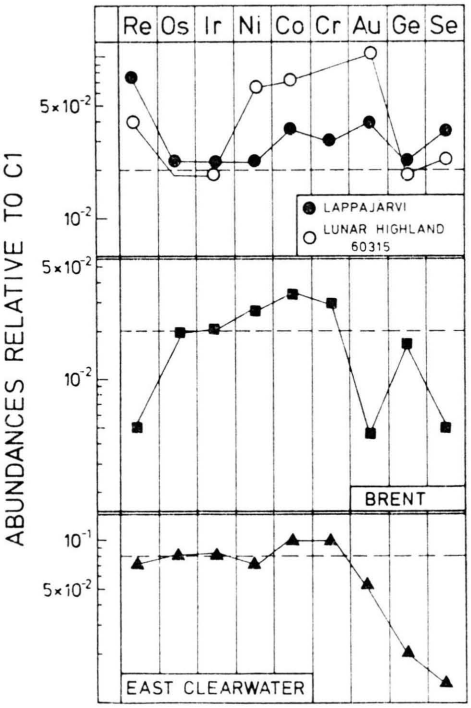

Fig. 5. Comparison of the abundance patterns of meteoritic elements for craters with a chondritic projectile. The unique pattern of Lappajärvi is compared to the abundance patterns of a lunar highland sample.

water meteorite was a carbonaceous chondrite, probably a C 1 or C 2 chondrite [5, 22], it must have had high concentrations of Au and Se. There is some evidence for a slight loss of Au and there is a large deficiency in Se [4, 22], but in no case are these elements enriched, compared to cosmic values. Weathering has probably removed some Au in Brent samples (Fig. 5, [4]).

Loss of Se (and some Au) during impact on Earth has also been observed by Morgan [25]. Glasses from the Lonar crater are depleted in Se relative to basement rocks, although a meteoritic component has not been detected in these glasses.

The simultaneous high abundances of Au, Cu, Ge, and Se in L 14/4 could perhaps be understood in terms of the presence of a volatile rich phase. Sample La 42, which was collected several kilometers away from L 14/4 (Fig. 1) has indeed lower concentrations of volatile elements (Figure 4). While the Ge concentration is, however, lower by a factor of 15 the Se concentration in La 42 is even slightly higher than in L 14/4. There is the possibility that there is a basement rock high in Se, which has not been analysed. But the similar high abundances of Au, Ge and Se, elements of very different volatilities, could also indicate a volatile rich meteorite as projectile.

d) The Rhenium Anomaly

From Figs. 3 and 5 it is apparent that there is a Re excess in the Lappajärvi melt. Loss of Re has been observed in impact melts, either because of the large volatility of Re under oxidizing conditions or by weathering processes [4, 25]. Again the high Re concentrations of the two Lappajärvi melt rocks (from very different geographical positions, Fig. 1), could be due to the presence of a component rich in volatile elements, or there are basement rocks high in Re, which have not been sampled.

The third possibility is again, a meteorite with high Re/Ir ratios, since we know that the Re/Ir ratio is not constant in chondritic meteorites (Fig. 5, [5]). Although meteorites with such high Re/Ir ratios have not been directly analysed, there is a meteoritic component in lunar highland rocks with larger Re/Ir ratios than those observed in meteorites (e. g. Fig. 8, [26]). This component also happens to be enriched in volatile elements [26, 27]. The pattern of meteoritic elements for the Apollo 16 breccia 60315 is plotted for comparison in Fig. 5, [28]. Here, no indigenous correction has been applied, in contrast to the Lappajärvi pattern of Figure 5. The similarity of the two patterns especially the simultaneous enrichment of Re, Au and Se, could suggest that the Lappajärvi crater was made by an object similar to those which hit the Moon 3.9 b.y. ago. Before discussing some interesting inferences of this possibility, we are planning to analyse more melt and more basement samples of Lappajärvi to make sure that the agreement is not fortuitous.

5. Summary

We believe to have shown that the Lappajärvi meteorite was a chondritic meteorite. The evidence comes from the observed simultaneous enrichment of highly siderophile elements (Ir, Os, etc.) and Cr and Co as well as the rather volatile element Se. Since basement corrections for elements such as Ni, Co, and Cr are substantial, we cannot specify the type of meteorite class by using element ratios, like e. g. Ni/Cr. These ratios are slightly different for different classes of chondrites. The general high abundances of volatile elements would suggest a volatile rich projectile. The simultaneous enrichment of Re and volatile elements is characteristic for a meteoritic component in lunar highland rocks.

The 2.1% or 1.3% of C 1 equivalent meteoritic component in the Lappajärvi impact melt is similar to what has been observed for the much smaller Brent crater. The two other craters, whose projectiles were chondrites, East Clearwater [5, 22] and Wanapitei [7] have 6 – 8% and 1 – 2%, respectively of C 1-equivalent meteoritic component.

[1] R. A. F. Grieve and M. Dence, Icarus **38**, 230 (1979).
[2] G. W. Wetherill, Geochim. Cosmochim. Acta **40**, 1297 (1976).
[3] M. J. Janssens, J. Hertogen, H. Takahashi, E. Anders, and P. Lambert, J. Geophys. Res. **82**, 750 (1977).
[4] H. Palme, R. Wolf, and R. A. F. Grieve, in: Lunar and Planet. Sci. X, p. 856, Lunar and Planet. Sci. Inst. Houston 1978.
[5] H. Palme, M. J. Janssens, H. Takahashi, E. Anders, and J. Hertogen, Geochim. Cosmochim. Acta **42**, 313 (1978).
[6] J. W. Morgan, M. J. Janssens, J. Hertogen, J. Gros, and H. Takahashi, Geochim. Cosmochim. Acta **43**, 803 (1979).
[7] R. Wolf, A. Woodrow, and R. A. F. Grieve, preprint, submitted to Geochim. Cosmochim. Acta (1979).

[8] A. El Goresy and E. C. T. Chao, Earth Planet. Sci. Lett. **31**, 330 (1976).
[9] M. Lethinen, Bull. Geol. Soc. Finlande **42**, 89 (1970).
[10] S. Fregerslev and H. Carstens, Contr. Mineral. Petro. **55**, 255 (1976).
[11] S. Elo, Geol. Surv. of Finland, preprint (1976).
[12] P. Eskola, Bull. Comm. Geol. Finlande **55**, 13 (1921).
[13] C. R. Saksela, Soc. Geol. Finlande **22**, 19 (1949).
[14] K. Frederiksson and F. Wickman, Svensk Naturvetenskap **16**, 121 (1963).
[15] M. Lethinen, Geol. Surv. of Finland, Bull. **282**, p.1 (1976).
[16] U. Maerz, Diploma Thesis, Westf. Wilh. Universität, Münster 1979.
[17] E. K. Jessberger and W. U. Reimold, in preparation.
[18] W. U. Reimold and D. Stöffler, Meteoritics, in press (1980).
[19] W. U. Reimold, Ph. D. Thesis, University Münster 1980.
[20] H. Wänke, R. Rieder, H. Baddenhausen, B. Spettel, F. Teschke, M. Quijano-Rico, and A. Balacescu, Proc. Apollo 11 Lunar Sci. Conf., Suppl. Geochim. Cosmochim. Acta **1970**, 1719.
[21] J. W. Morgan, H. Higuchi, R. Ganapathy, and E. Anders, Proc. Lunar Sci. Conf. 6th, Suppl. Geochim. Cosmochim. Acta **1975**, 1609.
[22] H. Palme, E. Göbel, and R. A. F. Grieve, Proc. Lunar and Planet. Sci. Conf. 10th, Suppl. Geochim. Cosmochim. Acta, in press (1979).
[23] E. R. D. Scott and J. T. Wasson, Rev. Geophys. Space Phys. **13**, 527 (1975).
[24] M. J. Gaffey and T. B. McCord, in: Comets, Asteroids, Meteorites (Ed. A. M. Delsemme), The University of Toledo 1977, p. 199.
[25] J. W. Morgan, Proc. Lunar and Planet. Sci. Conf. 9th, Suppl. Geochim. Cosmochim. Acta **1978**, 2713.
[26] E. Anders, Proc. Lunar and Planet. Sci. Conf. 9th, Suppl. Geochim. Cosmochim. Acta **1978**, 161.
[27] J. Gross, H. Takahashi, J. Hertogen, J. W. Morgan, and E. Anders, Proc. Lunar Sci. Conf. 7th, Suppl. Geochim. Cosmochim. Acta **1976**, 2403.
[28] H. Wänke, H. Palme, H. Kruse, H. Baddenhausen, M. Cendales, G. Dreibus, H. Hofmeister, E. Jagoutz, C. Palme, B. Spettel, and R. Thacker, Proc. Lunar Sci. Conf. 7th, Suppl. Geochim. Cosmochim. Acta **1976**, 3479.
[29] U. Krähenbühl, J. W. Morgan, R. Ganapathy, and E. Anders, Geochim. Cosmochim. Acta **37**, 1353 (1973).