Report Q 29.1 /90/2
Laboratory for Paleomagnetism
Geological Survey of Finland
Espoo 1990

PALAEOMAGNETIC, ROCK MAGNETIC AND OTHER GEOPHYSICAL RESULTS FROM THE LAKE LAPPAJÄRVI IMPACT CRATER, CENTRAL-WESTERN FINLAND

L.J. PESONEN & N. MARCOS
Laboratory for Palaeomagnetism
Department of Geophysics
Geological Survey of Finland
SF-02150 Espoo, Finland

F. PIPPING
Department of Petrology
Geological Survey of Finland
SF-02150 Espoo, Finland

Espoo 1990

PALAEOMAGNETIC, ROCK MAGNETIC AND OTHER GEOPHYSICAL RESULTS FROM THE LAKE LAPPAJÄRVI IMPACT CRATER, CENTRAL-WESTERN FINLAND

L.J. PESONEN & N. MARCOS
Laboratory for Palaeomagnetism
Department of Geophysics
Geological Survey of Finland
SF-02150 Espoo, Finland

F. PIPPING
Department of Petrology
Geological Survey of Finland
SF-02150 Espoo, Finland

Abstract

We present palaeomagnetic, rock magnetic and other geophysical and mineralogical results for rocks from the 77 Ma old Lake Lappajärvi complex meteorite impact structure, Central-Western Finland (Lat. 63.2°N, Long. 23.7°E). Oriented samples were collected of the impact melt rocks in the central island of the crater and of the Mesoproterozoic (Svecofennian) target rocks at the crater rim. The **NRM** of the melt rocks is generally weak and semistable during demagnetization. The characteristic NRM component, carried by pyrrhotite, yields a palaeomagnetic pole (lat. 55.4°N, long. 152.6°E, dp=6.2°, dm=8.7°, 6 sites) of normal polarity suggesting an age of ~195 Ma for the impact. The results from a drill core through the impact melt rock display similar palaeomagnetic directions but with slightly shallower inclinations. The palaeomagnetic age differs from the ^{40}Ar-^{39}Ar age of 77±0.4 Ma for the impact. Assuming that the ^{40}Ar-^{39}Ar age is correct, the discrepancy between palaeomagnetic and radiometric ages is best explained by post-impact (and post-cooling) tilting of the melt layer. The tilting (15 degrees) may be due to isostatic rebounds along joints in the melt. Impact remanence has also been isolated in a few target rocks at the rim. This poorly defined overprint could be a mild shock remanent magnetization superimposed with the 1.9 Ga old Svecofennian direction. This interpretation is supported by the observation that the NRM intensity is enhanced in the specimens with the impact overprint. The palaeomagnetic results are consistent with other interpretations based on geophysical, morphological, mineralogical and geochemical data that the Lake Lappajärvi structure is a complex meteorite impact site less than 200 Ma old.

Introduction

The record of terrestrial craterform structures comprises ~130 craters caused by collisions of extraterrestrial bodies (meteorites, asteroids or comets) with the Earth (Grieve and Robertson, 1989; Grieve and Pesonen, 1992). The majority (=70%) of these craters are younger than 200 Ma (Fig. 1).

The age distribution of the impact events has led to the suggestion (e.g., Rampino and Stothers, 1984; Alvarez and Müller, 1984) that there exists a ~30 Ma cyclicity in the cratering record. As roughly similar periodicities (ranging from 26 to 34 Ma) have

also been claimed for mass extinctions (Raup and Sepkoski, 1984) and for the Earth's magnetic field reversals (Stothers, 1987), a causality for these phenomena has been invoked (e.g., Alvarez and Müller, 1984; Müller and Morris, 1984; see Fig. 2), with the causal agent being the impact collision. A link between these processes would be of fundamental importance for the geological and biological evolution of our planet (see e.g., Grieve, 1980; Hallam, 1987; Grieve, 1990).

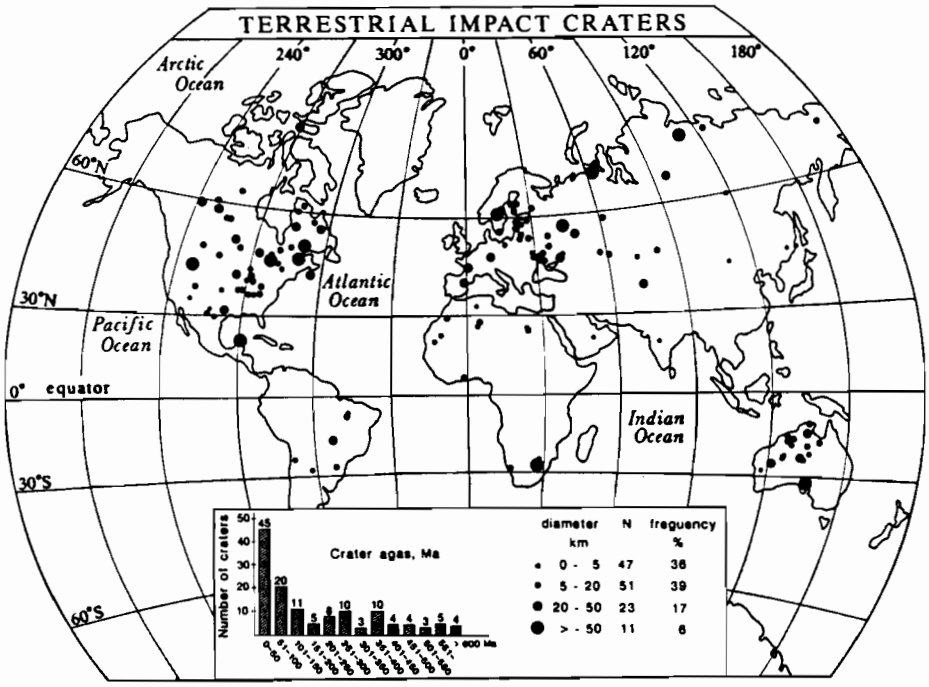

Fig. 1. Terrestrial impact crater map showing the 131 (at the end of 1990) craters classified into 4 diameter classes as shown in inset figure (from Grieve and Pesonen, 1992). Also shown (see inset) is the distribution of crater ages.

However, a thorough survey of the ages of the impacts and a time series analysis of the crater database have cast doubts on the ~30 Ma periodicity (Raup and Sepkoski, 1985; Grieve & Pesonen, 1992). The crucial issue in the search for periodicity in a database with a small number of events is the reliability of the ages of the events, since the time series analysis is very sensitive to errors in age data (Baksi, 1990). However, it is not easy to obtain a reliable age for an impact event owing to the difficulty of dating shock-affected rocks: a good example is the spread of ages from 56 Ma to 230 Ma for the Dellen structure in Sweden (Müller et al., 1990; Deutsch et al., 1992). The accuracy on dating craters can best be improved by applying independent dating methods to each crater and by examining the concordance of the ages so obtained.

EARTH'S MAGNETIC FIELD REVERSALS (last 165 Ma)

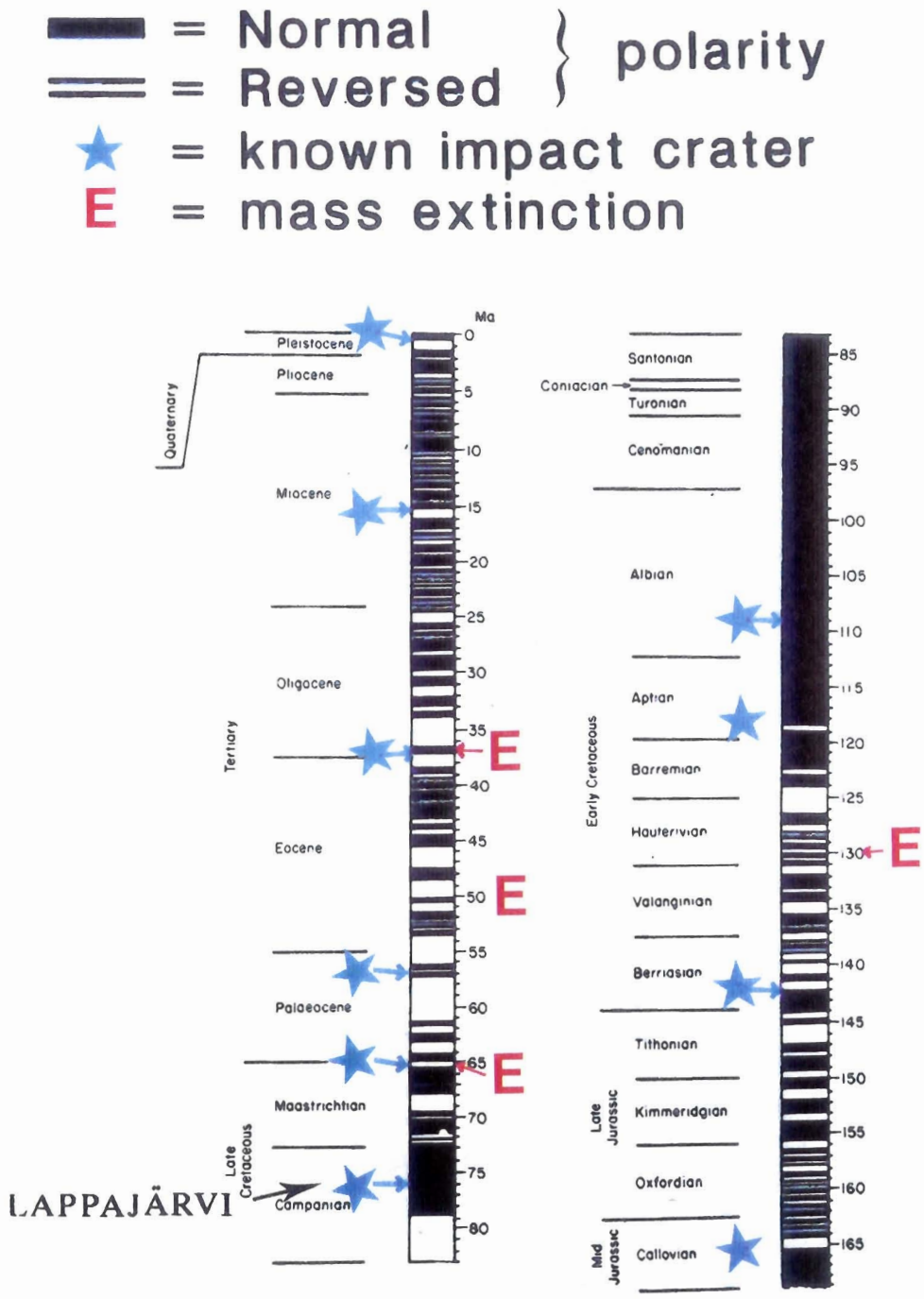

Fig. 2. Some correlations (and non-correlations) between the Earth's magnetic field reversals (black=N, white=R polarity, respectively), known impact craters (*) and major mass extinctions (=E) for the last 170 Ma.

The impact crater data base for Fennoscandia (Henkel and Pesonen, 1992; Fig. 3) lists 62 craterform structures, of which 15 have been confirmed as of impact origin: the Lappajärvi structure (No 31 in Fig. 3) in Central-Western Finland is the best documented of these (see e.g., Lehtinen, 1976; Reimold, 1982; Pesonen et al., 1992; Pipping & Lehtinen, 1992; Elo et al., 1992). Jessberger and Reimold (1980) obtained a ^{40}Ar-^{39}Ar age of 77±0.4 Ma for the Lappajärvi event. This age is not consistent with the ~30 Ma periodicity in the crater record (see e.g., Alvarez and Müller, 1984). Before claiming that the ~30 Ma periodicity in the record is invalid, we decided to date the Lappajärvi event by palaeomagnetic methods. We were encouraged by previous successful palaeomagnetic datings of some other impact structures, for example the Manicouagan (Robertson, 1967), the Charlevoix (Hargraves and Roy, 1974), the Lake Dellen (Bylund, 1974) and the Acraman (Schmidt and Williams, 1991) structures. We also sought to establish if there were any changes in natural remanent magnetization (NRM) vectors caused by post-impact tectonic effects (e.g., Gault et al., 1968; Pohl, 1977). After all, the Lappajärvi structure is located in a tectonically still active area as shown by Fennoscandian uplift measurements and recent earthquakes in the area (e.g., Nikonov, 1980; Veriö, 1981; Slunga and Ahjos, 1986).

This report is divided into four parts. *First*, we present geophysical, geological and morphological (e.g., gravity, Landsat-satellite, topography, bathymetry) of the Lake Lappajärvi structure taken mainly from literature (e.g., Lehtinen, 1976; Elo, 1976; Korhonen & Airo, 1982; Pipping & Lehtinen, 1992). *Second*, we review palaeomagnetic findings on the Lappajärvi impact structure (see Pesonen et al., 1984; Pesonen et al., 1992), including data on the central melt layer and on the target rocks in the rim. These data can be used to obtain a palaeomagnetic age for the impact which is important not only for checking the validity of the ~30 Ma periodicity in the global crater record but also for calculating the impact cratering rate in Fennoscandia in the past (Müller et al., 1990; Henkel and Pesonen, 1992). *Third*, we present petrophysical, rock magnetic and mineralogical data for identifying remanence carriers and their grain sizes in the Lappajärvi melt rocks and for isolating any mild shock (?) remanence in the target rocks (e.g., Pohl and Soffel, 1971; Robertson, 1975; Halls, 1975). *Fourth*, we compare the vertical palaeomagnetic data of the core (R301) drilled through the melt sheet with those on the surface outcrops

(horizontal data). We believe that the palaeomagnetic results will be of general interest in efforts to establish the post-impact (and post-cooling) evolution of complex impact craters, as they emphasize the role of isostatic rebound movements in the natural remanent magnetization (NRM) which may take place long after the main crater forming processes have ceased (e.g., Pohl, 1977).

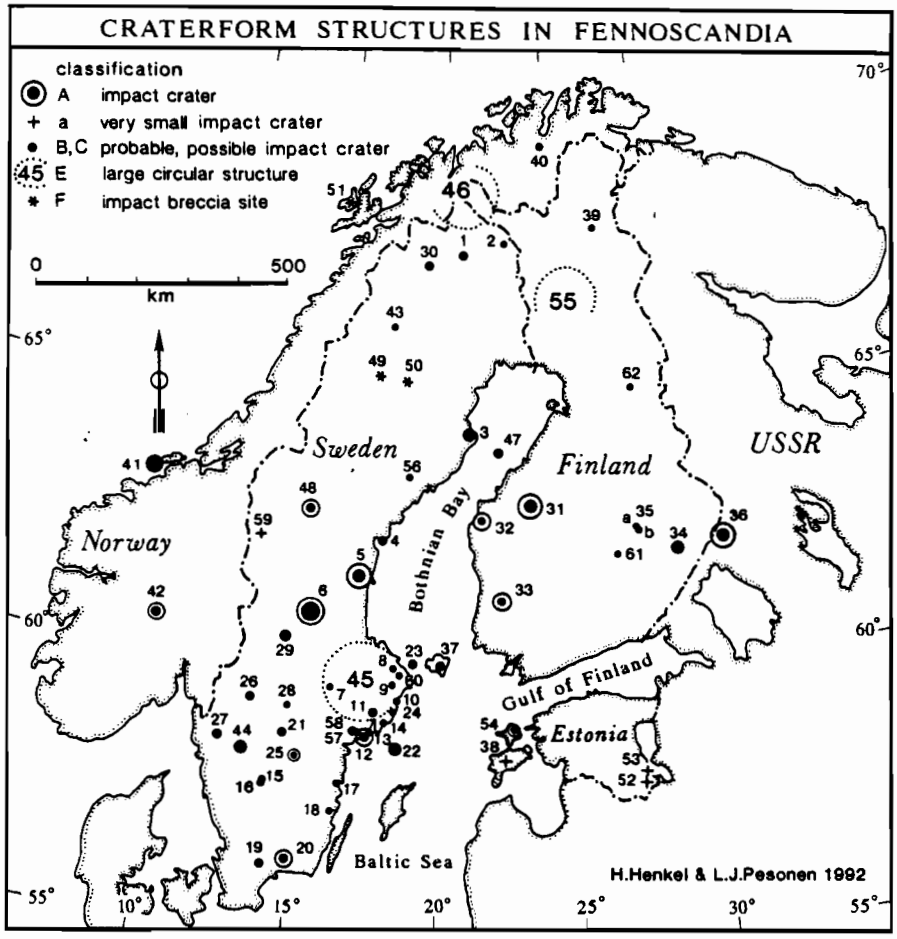

Fig. 3. Impact crater map of Fennoscandia. For crater classification (classes from A to F), see Henkel and Pesonen (1992) and the inset.

Geological setting and sampling

The Lake Lappajärvi craterform structure (lat. 63.2°N, long. 23.7°E) is located in Central-Western Finland, roughly 350 km north of Helsinki. Fig. 4 shows the Landsat-4 satellite imagery of the Lappajärvi structure.

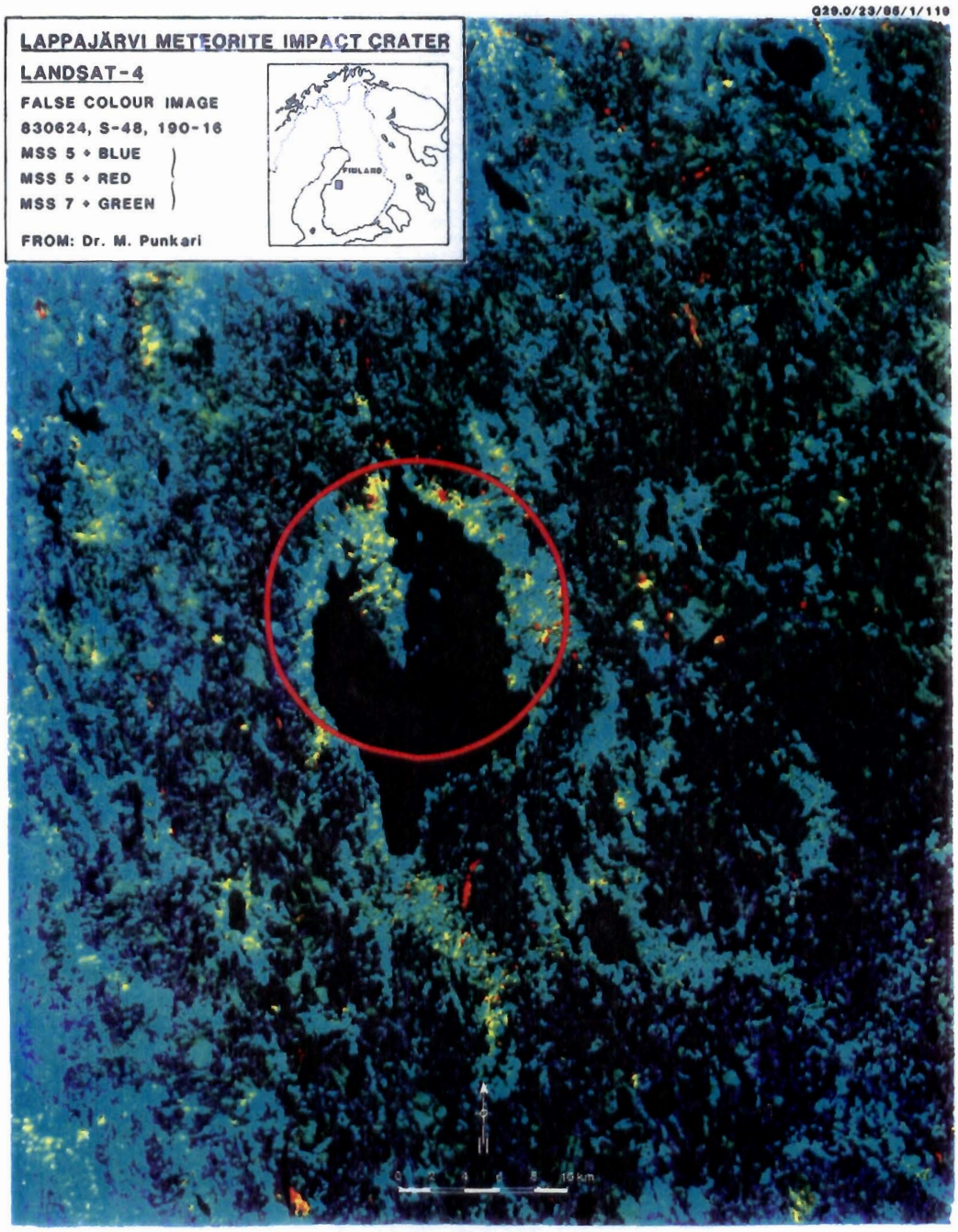

Fig. 4. Landsat-4 satellite imagery depicting the Lake Lappajärvi impact crater (prepared by Pesonen and Punkari, 1985; unpublished map).

Fig. 5 show the summer (5a) and winter (5b) satellite imageries, respectively, where the Lappajärvi circular (or elliptical) structure is strikingly evident. Fig. 6 depict the topography and bathymetry of the Lake Lappajärvi area, respectively (see Lehtinen, 1976). The present lake is nearly circular, or elliptical, in shape, being 23 km long and 12 km wide. It is of pre-glacial origin, but its exact age is unknown. The main rock types (Fig. 9) in the crater structure, impact melt, suevite and impact breccia and

unshocked target rocks of Svecofennian age, are overlain by Quaternary overburden (Pipping and Lehtinen, 1992). However, a thin late Precambrian (late Riphean to Vendian) allochtonous sedimentary layer has also been found through drillings (e.g., Pipping and Lehtinen, 1992; Uutela, 1990). The rocks display the inverted stratigraphy typical of complex impact craters (Lehtinen, 1976; see also Chao, 1974). The breccia material of the original crater fill and the fractured and brecciated bedrock surrounding the crater have had low resistance to erosion, but the total erosion since the impact event is unknown.

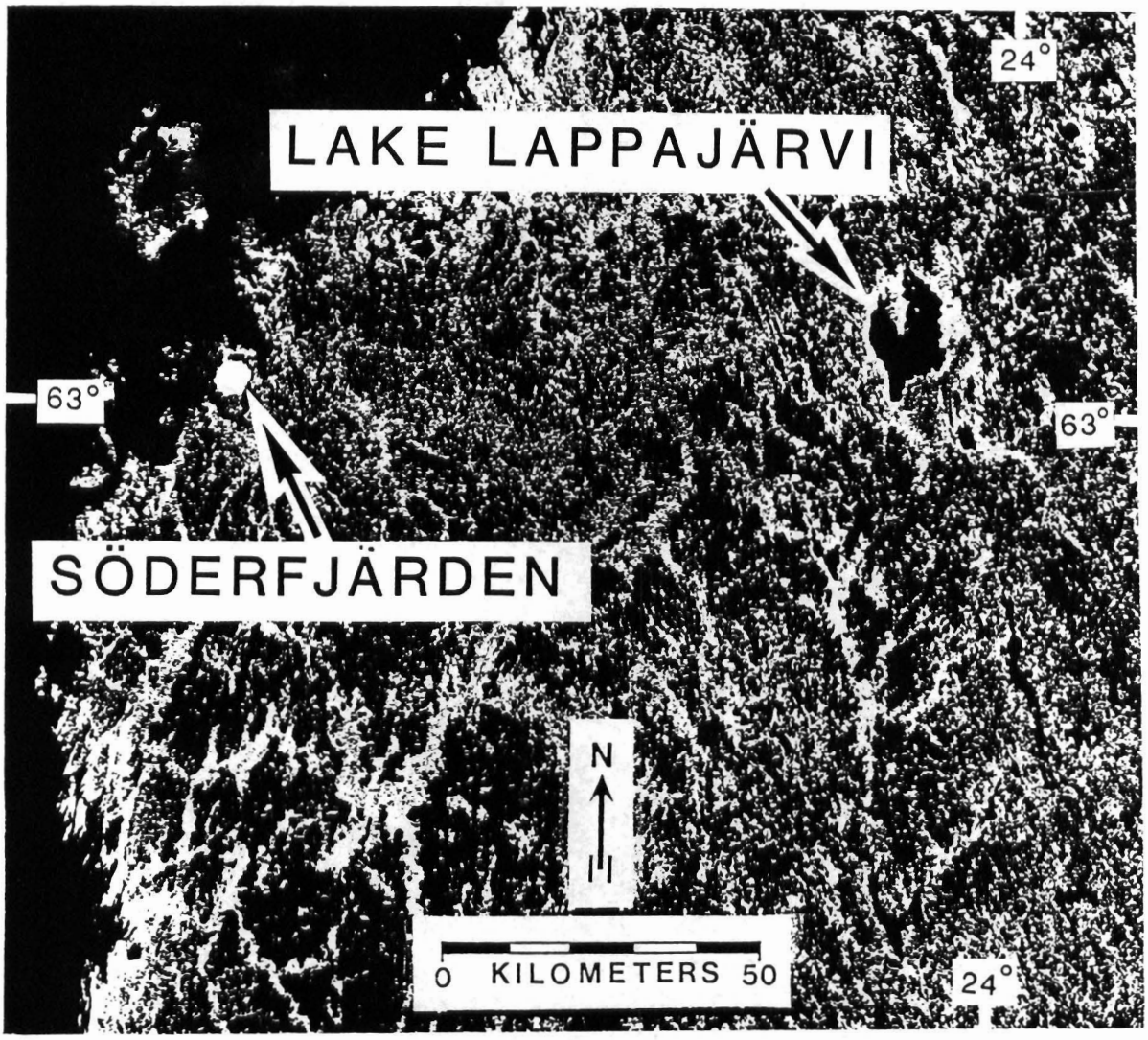

Fig. 5. Erts-satellite imageries of the Lake Lappajärvi area showing the craterform structure. (a) summer, (b) winter imagery.

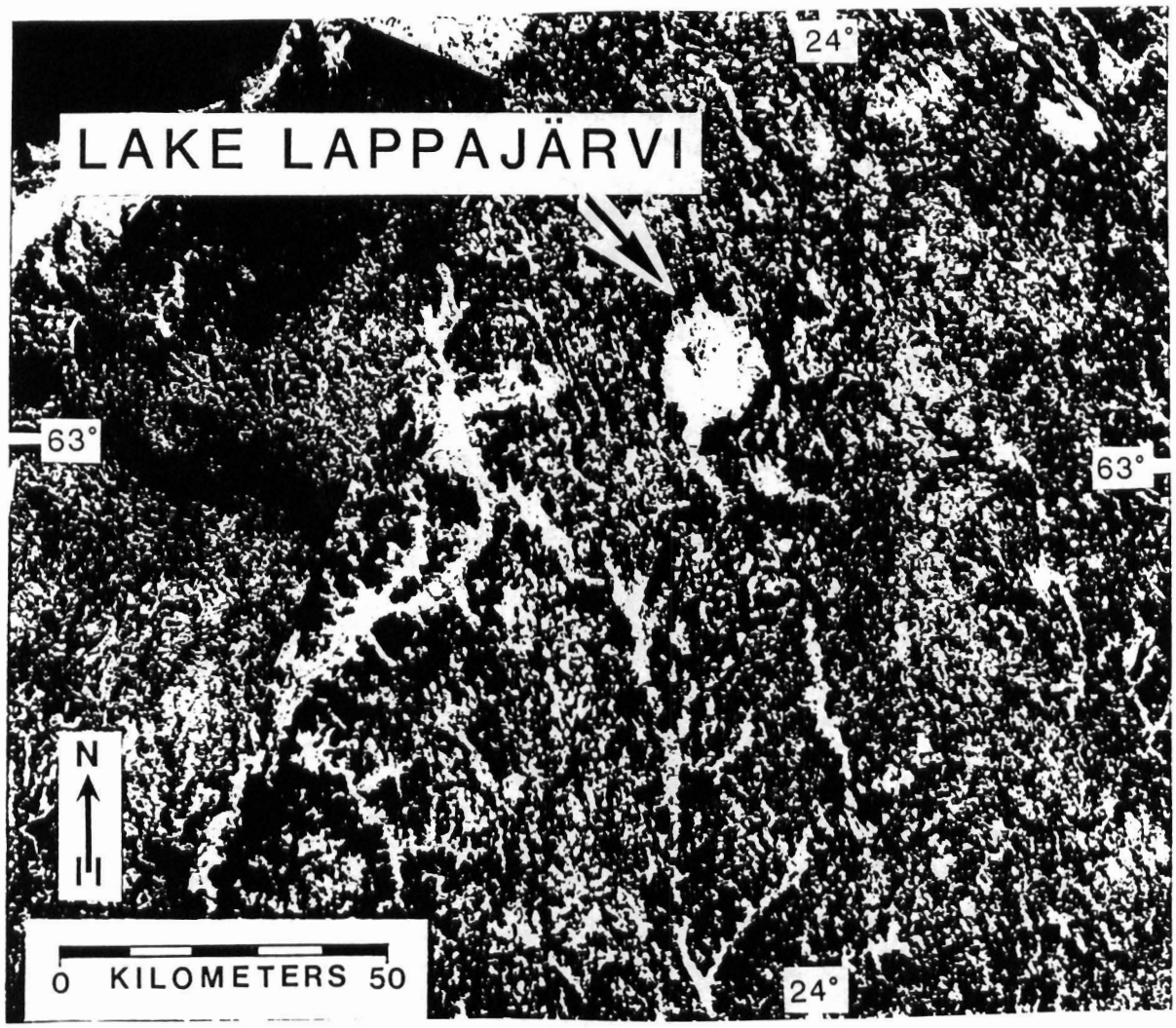

Fig. 5b (see caption in Fig. 5a).

Fig. 7 and 8 show the gravity and low altitude aeromagnetic maps of the Lappajärvi structure, respectively (Elo, 1985, personal communication; Elo et al., 1992; Korhonen and Airo, 1982).

The diameter (D) of the crater is approximately 17 km according to gravity data (Elo, 1976; Elo et al., 1992) but 23 km if measured from rim to rim. The centre of the crater is close to the eastern shore of the central island (Fig. 9). Two major throughs or fracture zones can be delineated from the bathymetric map of the lake (Fig. 6; see also Lehtinen, 1976 & Odenvall, 1934): one is close to the eastern shore and the other close to the western shore. These zones are of tectonic (Precambrian?) origin, but they have also been active since the impact as verified by repeated land levellings (Veriö, 1981) and by recent earthquakes in the area (Slunga and Ahjos, 1986). For a more detailed description of the geophysical and morphological characteristics of the Lappajärvi structure, see Elo et al. (1992).

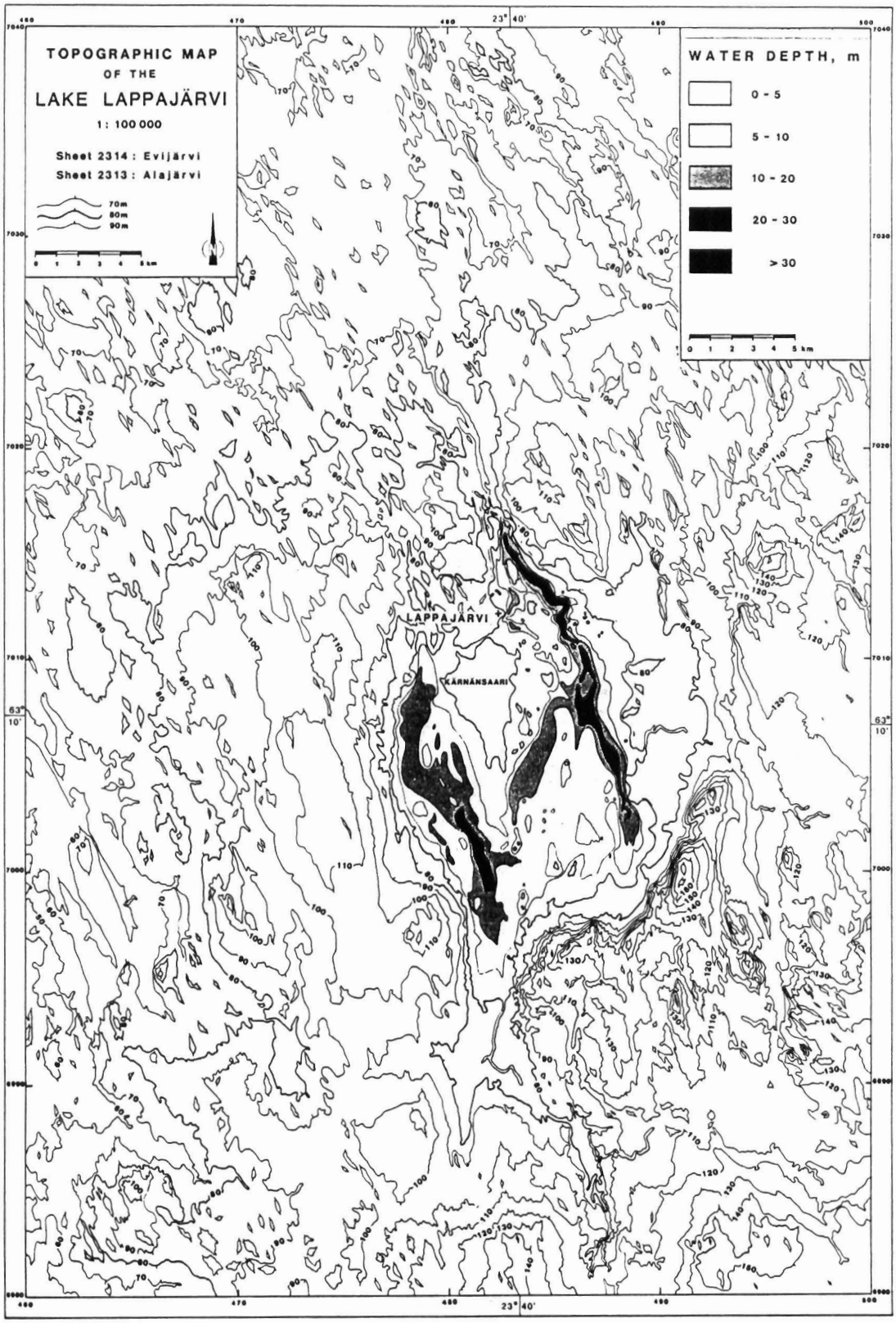

Fig. 6. Topographical map of the Lappajärvi area including the lake bathymetry (sheets 2314 Evijärvi (N) and 2313 Alajärvi (S). Sources: Lehtinen (1976) and Odenvall (1934).

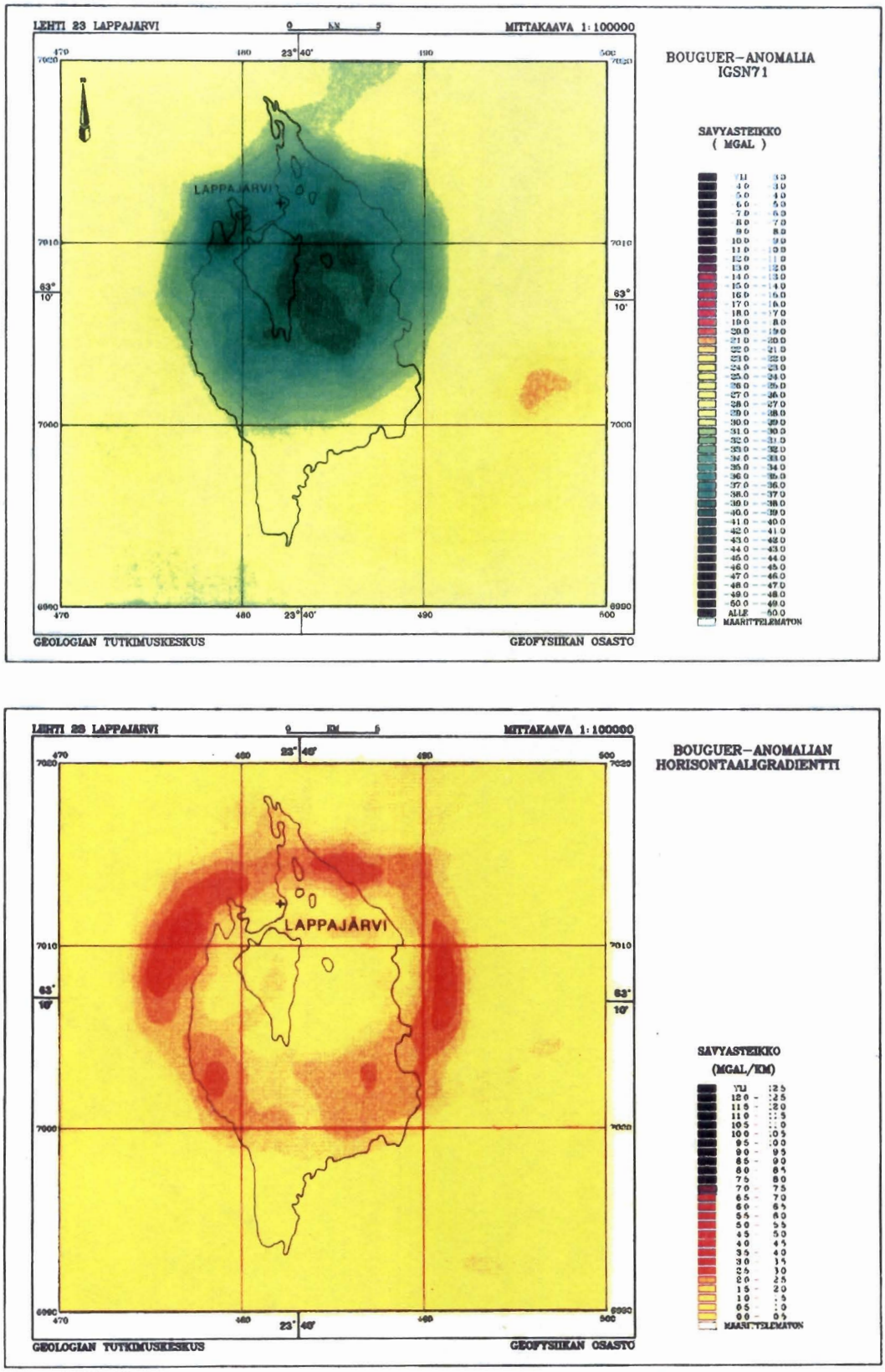

Fig. 7. Bouguer anomaly maps of the Lake Lappajärvi impact crater. (a) Bouguer anomaly, (b) horizontal gradient of the Bouguer anomaly. From S. Elo (1985, personal communication; see also Elo et al., 1992).

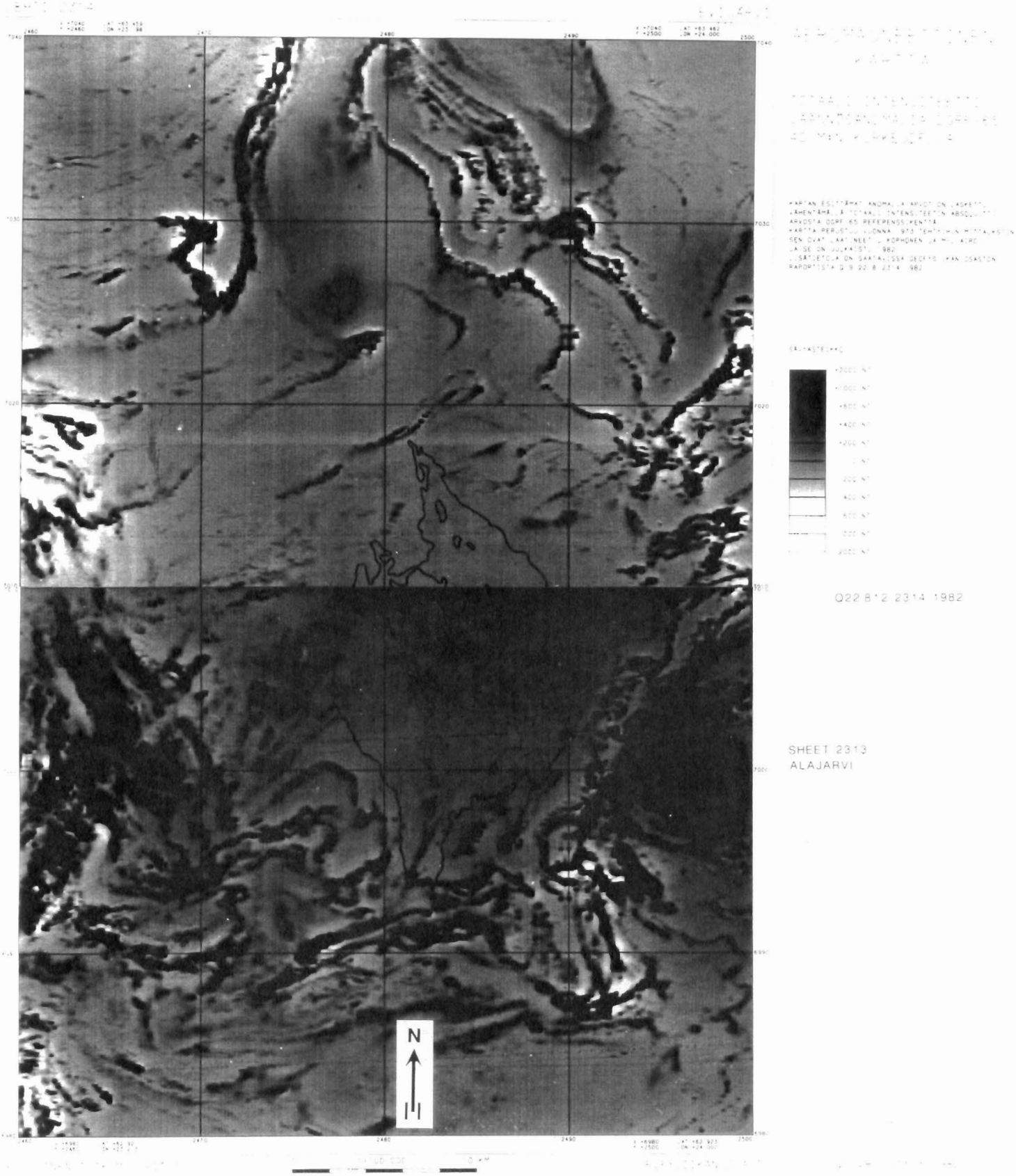

Fig. 8. Low-altitude greytone aeromagnetic map of the Lake Lappajärvi area (sheets 2314 Erijärvi and 2313 Alajärvi) from Korhonen and Airo (1982).

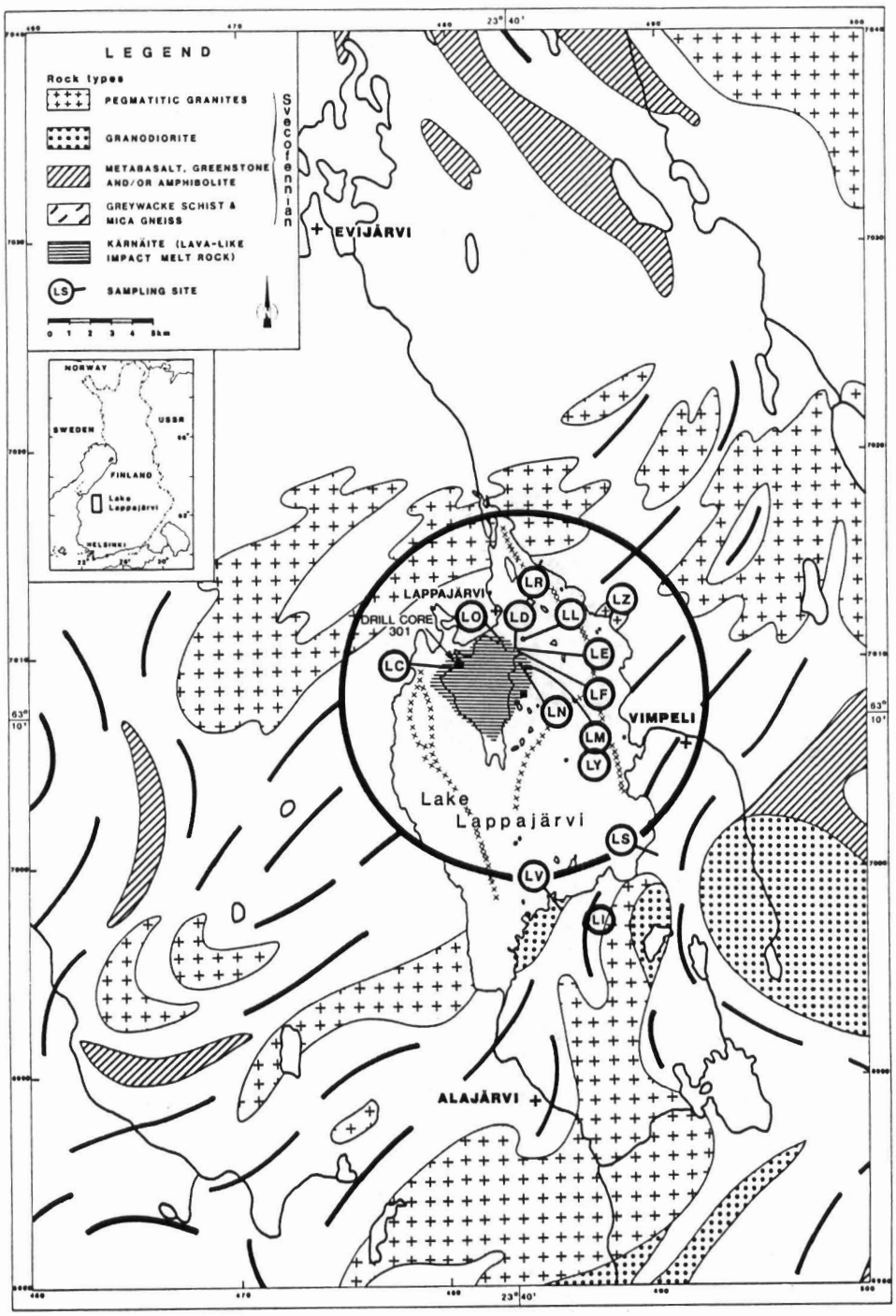

Fig. 9. Location of the Lake Lappajärvi meteorite impact structure in the Svecofennian (1.9 Ga old) terrane, Central-Western Finland (see inset). The circle denotes the crater diameter (17 km) as defined by gravity data (Fig. 7). The major throughs or fracture zones in Lake Lappajärvi are indicated as lines of crosses. The sampling sites, rock types and distances from the crater centre (closed square) are shown in Table 1.

The main impact-generated rock type in the central island of the lake is an

extremely homogeneous, fine grained dacitic melt rock called kärnäite (after Kärnänsaari, the name of the central island). The kärnäitic melt shows a very homogeneous modal composition with plagioclase, quartz and orthopyroxene as the main minerals, and cordierite and opaques as the major accessory minerals. The melt also contains small FeNi spherules (e.g., Fregerslev and Carstens, 1976), analysis of which suggests that the projectile was probably a C chondrite (Göbel et al., 1980). There are probably four types of kärnäite, but for present purposes, the melt rocks are divided into type I kärnäites (sites LC, LO and LL) and suevitic kärnäites (sites LE, LF, LD; Fig. 9) depending on their clast content (Lehtinen, 1976). The former contains clearly less bedrock clasts than the latter (which is similar to the type II or type III kärnäite of Lehtinen, 1976). The two melt types may represent different stratigraphic levels of the melt, with the type I kärnäite referring to the upper and the suevitic kärnäites to the lower part of the melt sheet, respectively. The petrological difference between the type I kärnäite and the suevitic kärnäite may also reflect a difference in the alteration degree, the suevitic kärnäites being more altered (metamorphosed) than the type I kärnäites.

True suevites and impact breccias were not found in surface outcrops but were collected as boulders (site LI, Fig. 9). Similarly, perlitic kärnäite is only found in drill core R301 stratigraphically below the uppermost type I kärnäite (see Fig. 24). Although petrologically very similar to each other, the suevitic and perlitic kärnäites show distinct differences in petrophysics, and are therefore treated separately (see also Kukkonen et al., 1992).

At three sites (LN, LM and LY, Fig. 9) the impact melt rocks were collected as oriented boulders to determine the role of viscous contamination by the Earth's present magnetic field during the last post-glacial era (i.e., last 10,000 years). The boulders, which were found on small islands close to the crater centre (Fig. 9), are glacial erratics not far from their source outcrops. Petrologically they are of type I kärnäite (Table 1). One suevite and one impact breccia sample were collected (as unoriented boulders) from the southern part of the structure (site LI) to compare their magnetic properties with those of the impact melts.

The target rocks, which are of Svecofennian (~1.9 Ga old) age, are found at a few basement exposures close to the lake shore or in the topographically elevated rim (Fig. 9). Lithologically they are greywacke (mica) schists (sites LR and LS),

granodiorite (LV) or granitic pegmatite (LZ). The distance from the centre of the crater to the basement sites ranges from 5.8 km (LZ) to 10.5 km (LV). Thus, sites LR and LZ are inside the crater and sites LS and LV are slightly outside it, in the elevated rim area (Fig. 9).

Altogether 75 oriented samples from 11 sites were collected from the outcrops (Fig. 9), the majority as oriented hand samples, but a few as drill cores. Standard 2.28 (height) x 2.54 (diameter) specimens were cored from the hand samples in the laboratory: altogether 260 specimens were taken, but only 173 yielded reliable palaeomagnetic data (Table 3). The sampling, drilling and orientation techniques were as described previously (Mertanen et al., 1987).

Table 1: Petrophysical properties of Lake Lappajärvi rocks.

rock type (sites)	B/n	D	k	NRM	Q	J_{20}/J_0
			outcropping rocks			
impact melt rocks						
type I kärnäites (LC, LL, LO)	3/116	2579	748	106	3.7	0.30
suevitic kärnäites (LD, LE, LF)	3/39	2478	1260	67	1.8	0.56
bedrocks						
with L_n overprint (LR, LS, LV, LZ)	4/7	2689	199	2	0.2	0.70
without L_n overprint (LR, LS, LV, LZ)	4/41	2697	171	0.2	0.05	0.92
			boulders			
kärnäites (LN, LM, LY)	3/23	2549	698	92	5.3	0.36
suevites	1/1	2357	580	403	17.5	0.57
impact breccias	1/1	2220	185	—	—	—

rock type: for type I kärnäite see Lehtinen (1976); suevitic kärnäite is probably type II kärnäite of Lehtinen (1976). Bedrock types are shown in Fig. 1: LR and LS are greywacke (mica) schists, LV is granodiorite and LZ is pegmatite granite. L_n overprint denotes a specimen from which a Lappajärvi impact component has been isolated (see text). For boulders, see Fig. 1 and text.

N/n = number of sites/specimens

D = density (kgm^{-3})

k = volume susceptibility (10^{-6} SI)

NRM = intensity of natural remanent magnetization (mAm^{-1})

Q = Koenigsberger ratio

J_{20}/J_0 = the hardness of NRM during a.f. demagnetization, where 20 (0) are cleaning fields in milliteslas.

Hole R 301 was drilled down to 218 m (see Pipping & Lehtinen, 1992). The orientation marks were put on the foot side of the core during the drilling procedure with a simple marking device which uses free gravity. This method permits absolute orientation of the core to within ±5 degrees, provided that the occasionally broken core pieces could be remounted to fit each other (which they generally could). R301 was sampled at 2 m intervals down to a depth of ~140 m (after which the core became too fragmentary) by drilling oriented cylinders perpendicular to the main core. Altogether 75 oriented specimens were obtained with this method, but as the results show, some problems with orientation were met. The palaeomagnetic and petrophysical results of the R301 core will be discussed later.

Table 2
Hysteresis properties of impact melt rocks, Lake Lappajärvi structure

specimen	rock type	J_s (mT)	J_{sr} (mT)	H_c (mT)	H_{cr} (mT)	J_{sr}/J_s	H_c/H_{cr}	k (10^{-6} SI)	J_{sr}/k (mT)	J_{sr}/kH_{cr}	grain size (μ)
LE1-1b	suevitic kårnäite	0.37	0.19	46	86	0.51	0.53	580	327	3.81	<20
LC2-3b	kårnäite 1	0.84	0.22	26	60	0.26	0.43	670	328	5.52	<100

J_s, J_{sr} = saturation magnetization, saturation (isothermal) remanence (milliteslas; 1mT = 0.796 kAm^{-1})
H_c, H_{cr} = coercive force, coercivity of remanence (milliteslas)
k = volume susceptibility (10^{-6} SI)
grain size estimated from Dekkers (1988)

Age determinations

Geological estimates assign the Lappajärvi impact crater ages as disparate as Precambrian and pre-Quaternary (see e.g., Svensson, 1968; Grieve, 1977). Attempts have been made to date the melt rocks with Rb-Sr methods (Fullagar, 1972, in Lehtinen, 1976; Mäerz et al., 1979; Reimold ,1982) but without success, because the isotope data do not show enough spreading for an accurate isochron to be fitted. Nevertheless, although failing to yield an age, the Rb-Sr isotope data show clearly that the melt was produced through the fusion of pre-existing target rocks and was not derived from the mantle, thus supporting the impact origin for Lappajärvi (e.g., Reimold, 1982).

Jessberger and Reimold (1980) were able to date the Lappajärvi event with the ^{40}Ar-^{39}Ar method. They obtained an average plateau age of 77 ± 0.4 Ma for four melt samples, thus indicating a late Cretaceous age for the impact (Fig. 10). Although the data have a high internal precision, the presence of well established plateaus is no guarantee of an exact age for an impact owing to the inherent Ar-retention or Ar-excess problems, as discussed by Müller et al. (1990) and Deutsch et al. (1992).

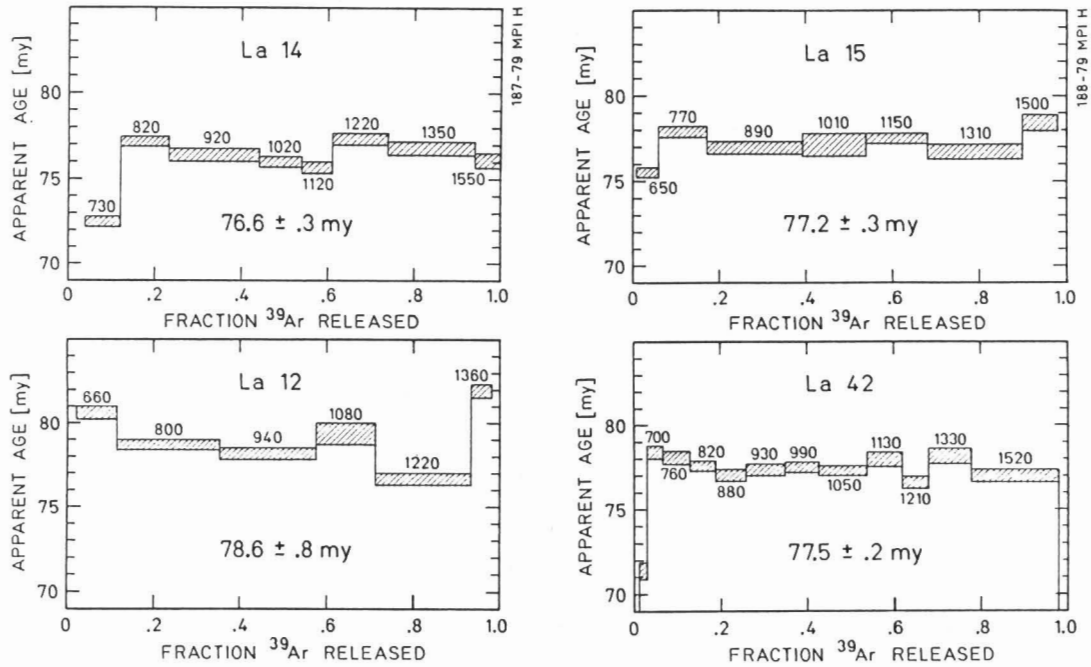

Fig. 10. Four ^{40}Ar-^{39}Ar plateaus defining the age of the Lappajärvi impact event at 77±0.4 Ma (from Jessberger and Reimold, 1980).

However, for lack of any other radiometric age results on Lappajärvi melt rocks (Rb-Sr, U-Pb (zircon or baddeylite)) we assume that the impact took place 77 Ma ago. The reference pole with which we compare the palaeomagnetic pole is therefore the 77 Ma old pole on the European apparent polar wander path (APWP) (Irving, 1977).

Country rocks

A few radiometric age data are available from the Svecofennian country rocks in the area. Syntectonic intrusive rocks in the nearby Evijärvi-Vimpeli area (see Fig. 9) yield U-Pb (Zr) ages ranging from 1890 Ma to 1923 Ma (Kouvo and Tilton, 1966; Vaarma, 1990), and micas in the surrounding Svecofennian schists give somewhat lower Rb-Sr and K-Ar ages of about 1610 to 1800 Ma (Kouvo, 1964, Kouvo and Tilton, 1966;

Mäerz et al., 1979). These latter ages indicate the age of the last stage of Svecofennian metamorphism in the area. The reference pole with which we compare the poles of the unshocked target rocks is thus the 1.8-1.9 Ga old Svecofennian pole of Fennoscandia (Pesonen et al., 1989).

LABORATORY MEASUREMENTS

Petrophysics

Susceptibility and density were measured at the Petrophysics Laboratory of the Geological Survey of Finland (GSF) using instruments and techniques described elsewhere (Puranen and Puranen, 1977; Mertanen et al., 1987). The anisotropy of susceptibility was measured in the Palaeomagnetic Laboratory of the GSF using a Czech KLY-2 bridge. The hysteresis properties were measured at the Technical Research Centre of Finland using a vibrating sample magnetometer (see Mertanen et al., 1987). The palaeomagnetic measurements were made at two laboratories: the majority (90%) at the GSF Laboratory including both thermal and alternating field (a.f.) treatments of the rocks. The specimens were demagnetized in an a.f. up to 100 or 110 mT in steps of 5 to 10 mT using a Schonstedt single axis a.f. demagnetizer (Pesonen et al., 1983). However, most specimens started to behave erratically at steps higher than 70 mT, in which case the demagnetization was terminated. The cause of the overall instability is the complexity of pyrrhotite (main remanence carrier, see p. 24) in many melt specimens, or the coarse grain size of remanence carriers in country rocks. Twenty specimens (10%) were measured at the Erindale Laboratory of the University of Toronto, where they were demagnetized with steps ranging from 2.5 to 10 mT up to 100 mT. The thermal cleaning (at the GSF) was done in a Schonstedt TSD-1 furnace in 50°C steps up to 275°C and then in 5° to 25°C steps up to the pyrrhotite Curie point (~330°C). After this temperature the intensity of the melt specimens was either below the measurement noise level or the specimens behaved erratically.

The palaeomagnetic vector data obtained in the course of demagnetizations were analysed with the mathematical data processing techniques described in Mertanen et al. (1987). Owing to the general instability of the rocks in responding to

demagnetization, the characteristic remanences were best obtained by combining analysis of principal components and inspections of vector endpoint directions on stereo projections.

The Curie-point of one melt specimen was determined at the Palaeomagnetic Laboratory of the University of Bergen using the saturation magnetization vs. temperature technique. In addition, a few melt rock specimens were investigated under the microsope (carried by late Lea Aho in GSF) to identify the main opaque minerals.

RESULTS

Petrophysical properties of the rocks

The petrophysical data on the rocks are summarized in Table 1 and plotted as relation diagrams in Fig. 11. The hysteresis data are summarized in Table 2.

Impact melt rocks

The petrophysical properties (susceptibility, density, NRM intensity and Q value) of the impact melt rocks are very different from those of the target rocks (Fig. 11). For example, the melt rocks have lower density and higher susceptibility than the target rocks (Fig. 11 a). The differences in density and susceptibility are due to mineralogical (compositional) changes that took place when the target rocks were fused during the impact. The increased NRM and Q-values in the melt rocks (Fig. 11 b), though, are partly attributable to different types of natural remanence: in the melt rocks the NRM is not a pure TRM (Fig. 11) but probably a TCRM acquired during rapid cooling, whereas in the target rocks it is probably a TCRM acquired during slow metamorphic cooling and that has suffered considerable viscous changes (both viscous decay of primary TCRM and also a new VRM) since Mesoproterozoic times. The differences in petrophysical properties are partly causing the gravity and magnetic anomalies that characterize the Lappajärvi impact structure (e.g., Elo, 1976; Elo et al., 1992).

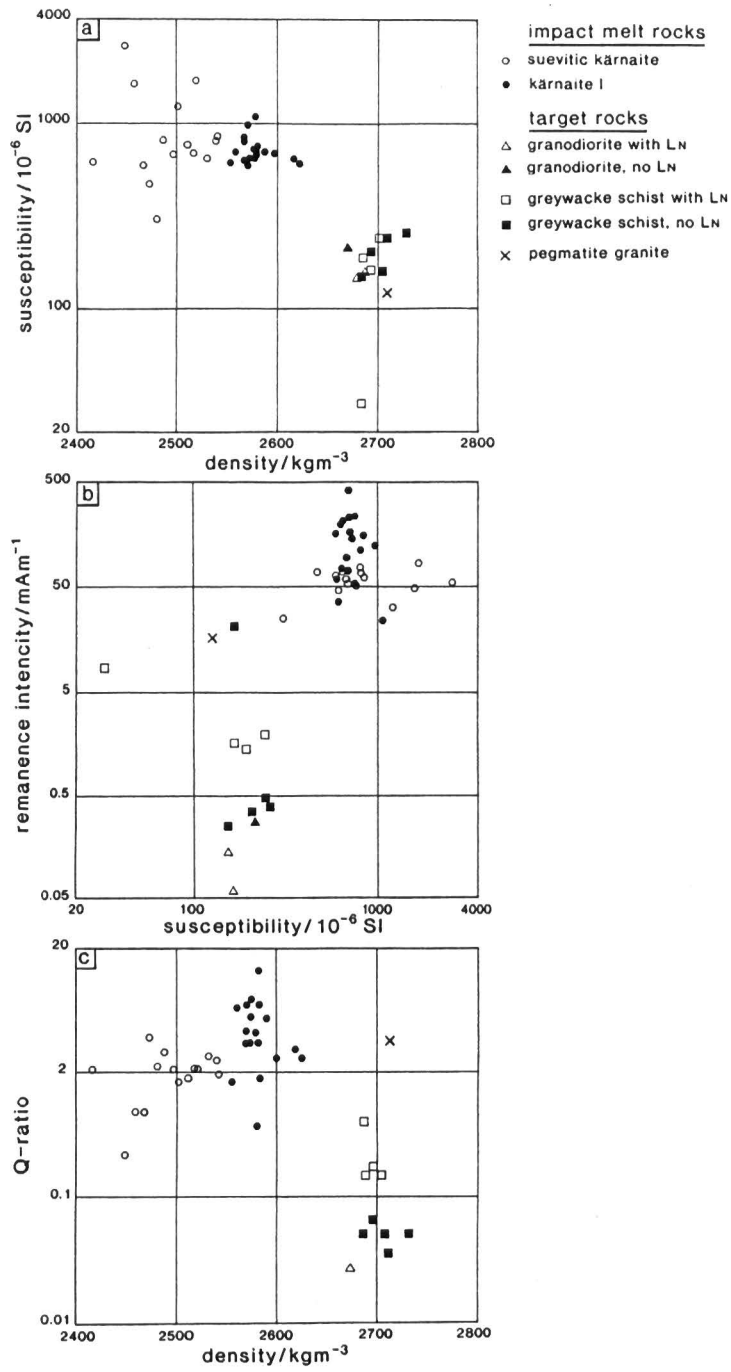

Fig. 11. Petrophysical relation diagrams for Lake Lappajärvi rocks. (a) susceptibility vs. density, (b) remanence intensity vs. susceptibility, (c) Q ratio vs. density. Note the enhanced Q values (due to shock remanence?) are found in those bedrock specimens that reveal the characteristic impact remanence (L_n).

The melt rocks form two distinct clusters in the petrophysical relation diagrams: type I kärnäite and suevitic kärnäite (Fig. 11 a-c), respectively. The former has a higher

density and Q value but a slightly lower susceptibility than the latter one owing to differences in mineralogical composition, texture, porosity, grain size and alteration degree. For example, the suevitic kärnäite has a much higher abundance of basement clasts, leading to increased porosity and hence to lower density than the more solid (denser) type I kärnäite. The higher porosity makes the suevitic kärnäite more vulnerable to hydrothermal alterations than the type I kärnäite, as has also been observed microscopically (Fig. 15). The higher degree of alteration in suevitic kärnäites has resulted in reduced density and NRM-intensity values (Fig. 11 a, b).

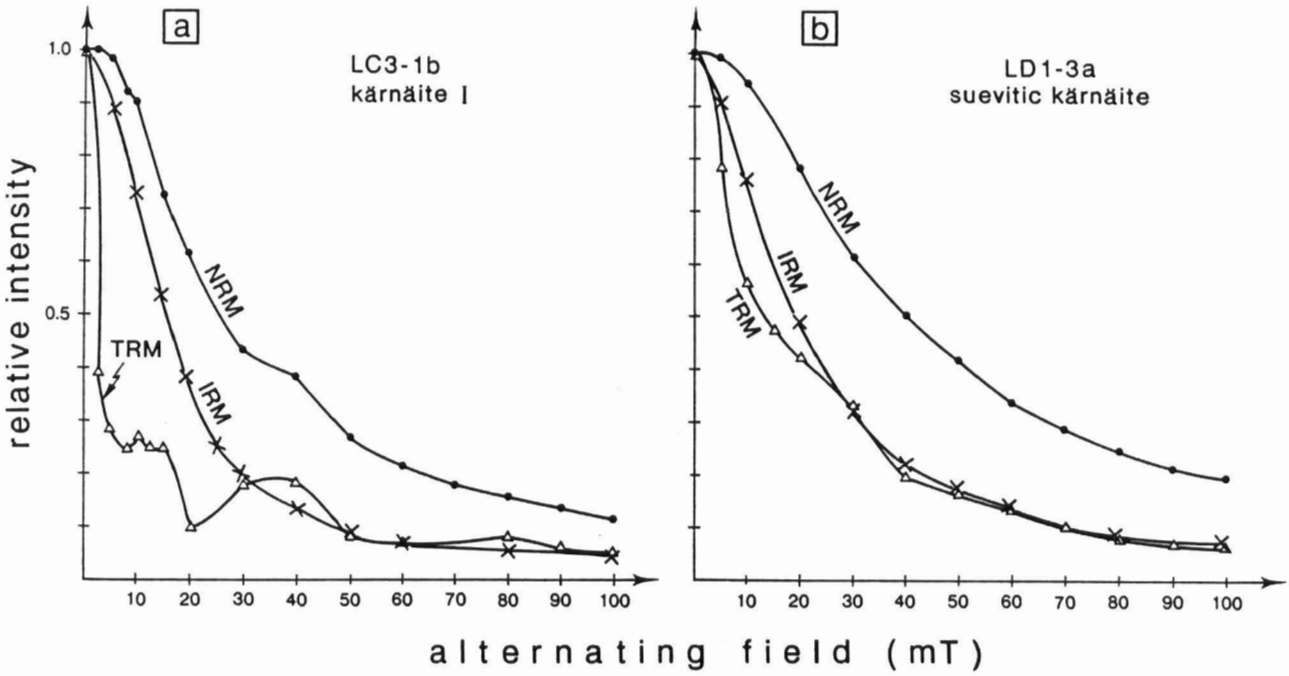

Fig. 12. Alternating field demagnetization curves of NRM, TRM and IRM for two melt specimens carrying the L_n component. IRM = isothermal remanent magnetization (H_{lab} = 1.4 T) and TRM = thermoremanent magnetization (H_{lab} = 0.05 mT, ΔT = 680°C-20°C). Note that the NRM departs clearly from TRM and IRM and for suevitic kärnäite the TRM and IRM curves are nearly identical, whereas for type I kärnäite the TRM is very complex (due phase changes?).

The hysteresis data (Fig. 13, Table 2) show higher J_{sr}/J_s and H_c/H_{cr} values for the suevitic kärnäite than for the type I kärnäite, suggesting a smaller grain size of the opaques in the former type consistent with microscopic observations (Reimold, 1982; see also Fig. 15). On the basis of hysteresis data of natural pyrrhotites (Dekkers 1988), the average pyrrhotite grain sizes in the suevitic kärnäite and in the type I

kärnäite are ~20μm and ~60 μm, respectively. Both types plot roughly within the PSD-SD grain size range (Dekkers, 1988). A.f. demagnetization show that the suevitic kärnäite is magnetically harder than the type I kärnäite as expected from grain size and hysteresis data (Fig. 12).

Petrophysically, the suevitic kärnäite resembles the perlitic kärnäite in drill core R301 (see Fig. 11 a,b), although a closer look reveals a slightly lower density for the suevitic kärnäite (mean 2478 kgm^{-3}) than for the perlitic kärnäite (mean ~2530 kgm^{-3}; see also Kukkonen et al., 1992).

Despite the high internal (magnetocrystalline) anisotropy of pyrrhotite (e.g., Schwarz, 1975; Thomson, 1990), the melt rocks do not show marked susceptibility anisotropies (less than 2%).

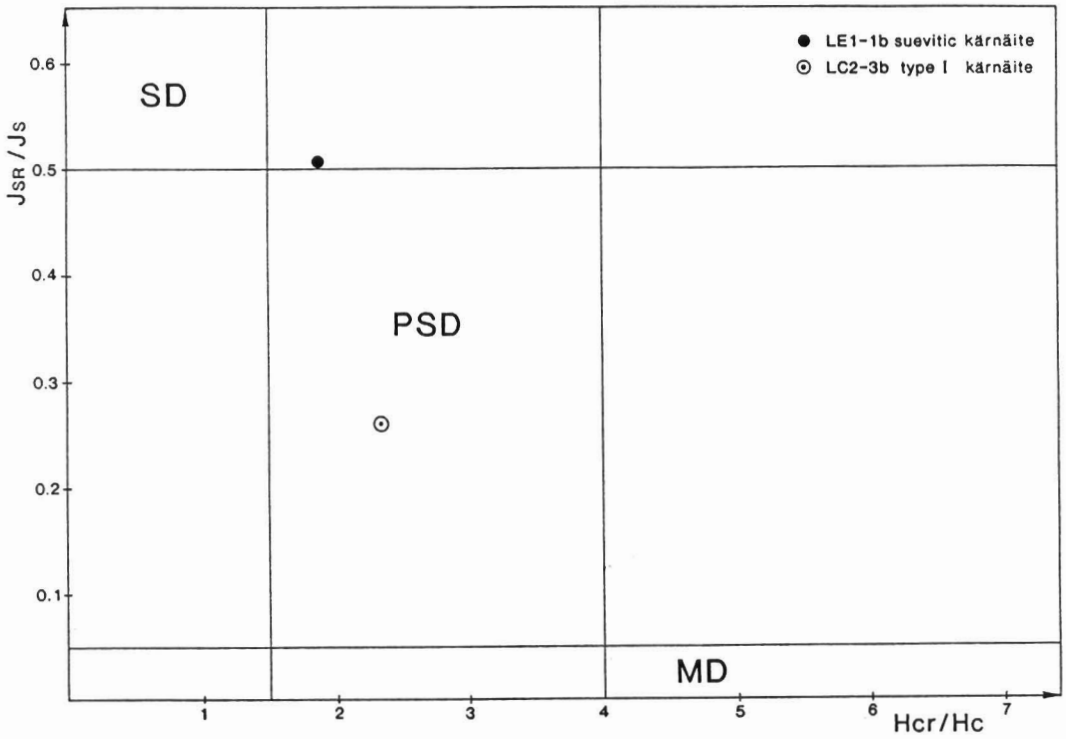

Fig. 13. The hysteresis data of two melt specimens plotted on a J_{sr}/J_s vs. H_{cr}/H_c-plot.

Boulders

The petrophysical properties of the boulders are similar to those of the type I kärnäites (Table 1). The suevite bolder from site LI (Fig. 9) has a distinctly lower density (2357 kgm^{-3}) than the type I kärnäite (mean 2579 kgm^{-3}), with a very high Q value (17.5; Table 1). Similar observations of low densities and enhanced Q values have also been observed in suevites of the Ries crater (Pohl, 1977) and in drill hole

R301 at the Lappajärvi crater (Kukkonen et al., 1992).

Basement rocks

In Table 1 and Fig. 11 a, b, the basement rocks are divided into two groups. Group one (open symbols) consists of specimens from which the Lappajärvi impact remanence component (overprint L_n) was isolated in cleaning (see p. 28), and group two of data (closed symbols) without this overprint. The most striking difference in the physical properties is the much higher Koenigsberger ratio (average Q~2) in group one than in group two (average Q~0.05). The enhanced Q values in some of the target rocks may be due to their mild shock remanent magnetization (SRM). It is not known why some specimens have been affected by the shock and some have not. We emphasize here that the division of target rocks into two groups correlates only roughly with the distances of the samples from the impact centre: thus component L_n is more common in sites closer to the crater centre (LR, LZ) than further away from it (LS, LV). Owing to their coarse grain size the target rocks (greywackes, mica schists, pegmatoid granitoids) are not ideal rock types for recording and preserving the palaeomagnetic information. Thus identification of the L_n component in the country rocks is not easy. Probably the presence of L_n in some samples reflects their vulnerability to shock overprint. The increased vulnerability may be a function of the texture or porosity of the rock, or of the type of opaque mineral or its grain size. The observation, however, that the specimens showing the impact overprint have higher Q values than the others implies shock influence. Unfortunately, due to the lack of exposures, no systematic profile data are available across the Lappajärvi crater. Systematic trends in magnetic properties as a function of distance from the impact centre have previously been reported from Lonar crater (Poornachandra Rao and Bhalla, 1984).

Remanence carriers

Optical studies of the impact melt rocks at Lappajärvi have established the presence of magnetite, hematite, goethite, pyrhhotite, pentlandite, pyrite and small FeNi spherules (Lehtinen 1976; Reimold, 1982; this work). The pilot study (Pesonen et al., 1984) already verified that pyrrhotite ($Fe_{1-x}S$) is the main carrier of natural

remanence in the melt rocks. The hysteresis parameters, i.e. high J_{sr}/J_s, H_{cr}/H_c and J_{sr}/k values (Table 2), are all consistent with pyrrhotite being the main opaque in the melt rocks (Dekkers, 1988). This is confirmed by the saturation magnetization vs. temperature (J_s-T) of a suevitic kärnäite showing a dominant Curie point at ~330°C (Fig. 14).

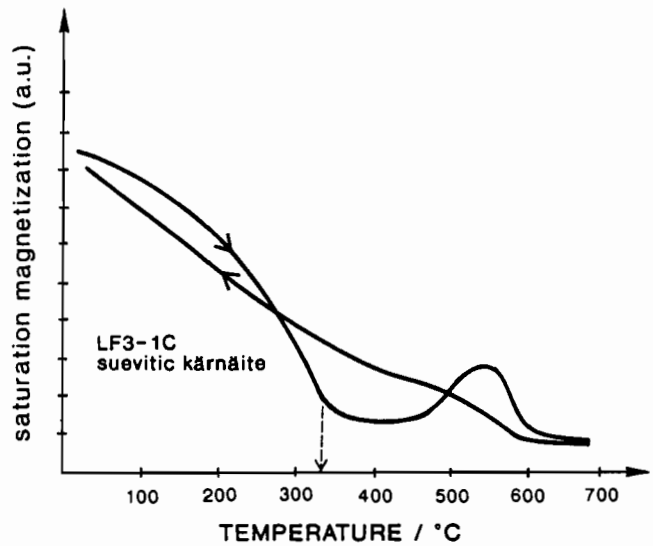

Fig. 14. Saturation magnetization J_s (in arbitrary units) vs temperature (T°C) for a suevitic kärnäite. Note the complex and irreversible heating curve with a dominant pyrrhotite Curie point at ~330°C. Vertical axis in arbitrary units of intensity.

Thin section studies also reveal pyrrhotite as one of the main opaques oxides (Fig. 15). Ilmenite and hematite are also occasionally seen in microscope.

The J_s-T curve is, however, irreversible and complex, implying the existence of other Curie points as well (one at ~270°C (goethite?), and one at ~570°C (magnetite?)). Other opaques (hematite, FeNi) with higher Curie points (see Fig. 14) were probably present in the melt rocks, or they were produced during heating in the laboratory. Their role as carriers of NRM, however, is unimportant, as demonstrated by numerous thermal demagnetizations of melt rocks with dominant unblocking temperatures near pyrrhotite Curie points (e.g., Fig. 17). No Curie-point determinations or hysteresis data are available for the target rocks, and their remanence carriers are unknown.

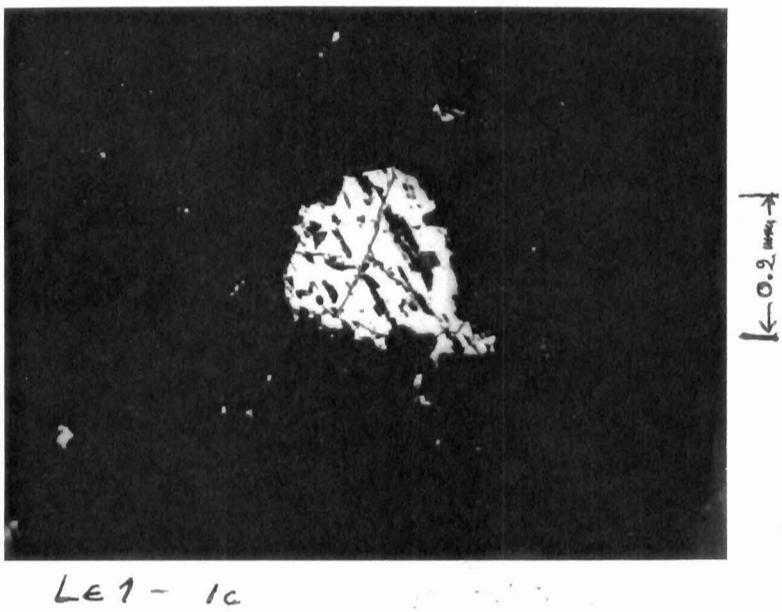

Fig. 15 a. Thin section study of a melt rock (LEI-1C, kärnäite) reveals pyrrhotite grains (in the center) in addition to disseminated ilmenite and pyrite grains. (photo by late Lea Aho, 1979)

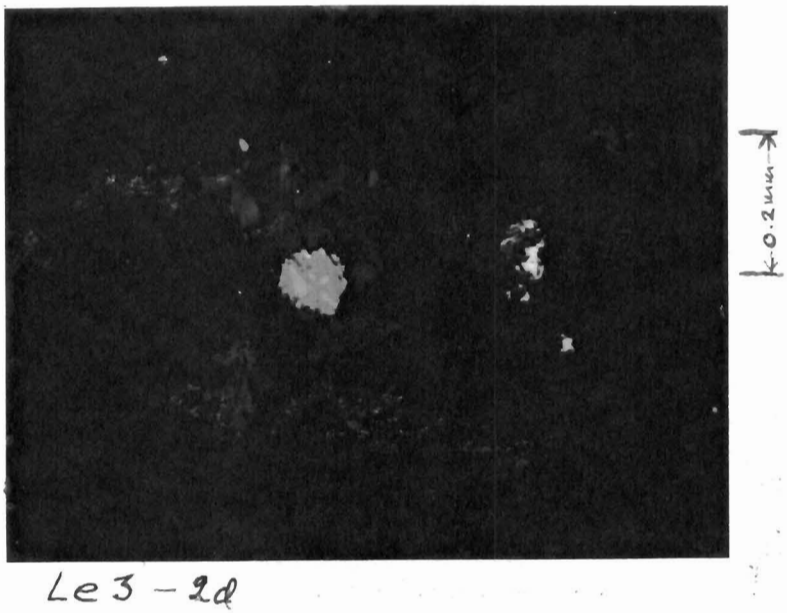

Fig. 15 b. Ilmenite with hematite grains in the center of ilmenite grain and a pyrrhotite grain at the right (photo by late Lea Aho, 1979).

PALAEOMAGNETIC RESULTS

Impact melt rocks

Both a.f. and thermal demagnetization treatments (see Figs. 16, 17 for examples) were used to separate the remanence components in the melt rocks. Unfortunately, many of the samples (ca. 30%) behaved erratically in demagnetization, and no reliable component separations were possible. The reason for the high rejection percentage is obscure, but pyrrhotite is known to be an unreliable or difficult carrier of palaeomagnetic signals (e.g., Schwarz, 1975; Thomson, 1990). Since the results of a.f. and thermal demagnetization are comparable (Figs. 16 & 17), the rotational remanent magnetization (RRM; Thomson, 1990) produced in pyrrhotite during a.f. treatment is not significant in the Lappajärvi rocks. The complex behaviour of the samples at higher fields could be due to the inherent magnetocrystalline anisotropy of pyrrhotite (Schwarz, 1975; Dekkers, 1988).

The reason for the erratic behaviour of most of the country rocks is not known, but previous studies on Svecofennian metamorphic schists or coarse grained pegmatoid granitoids have shown that they are not ideal for establishing a reliable palaeomagnetic signal (see also Hargraves and Perkins, 1969). It is thus not surprising that the palaeomagnetic results of this work can be assigned to only the C (melt rocks) or D (target rocks) class in the grading scheme of Pesonen et al. (1989).

Three remanence components were isolated from most melt rock samples during the a.f. and thermal treatments. The most common magnetization component, hereafter called impact component L_n, has a mean direction of D = 32°, I = 55° (k = 117, α_{95}= 6.2°, 6 sites). This does not differ significantly from that of the pilot study (Pesonen et al., 1984). Examples of this component are shown in Fig. 16 (= a.f. treatment) and in Fig. 17 (= thermal treatment). Both treatments show that L_n differs from the Earth's present magnetic field direction (PEF) and also from the 1.9 Ga old Svecofennian direction (S_k). It became obvious at an early stage of this study that L_n does not confirm with any known Precambrian direction in the Fennoscandian database, but is close to the Mesozoic palaeomagnetic directions of Fennoscandia (Pesonen et al., 1989).

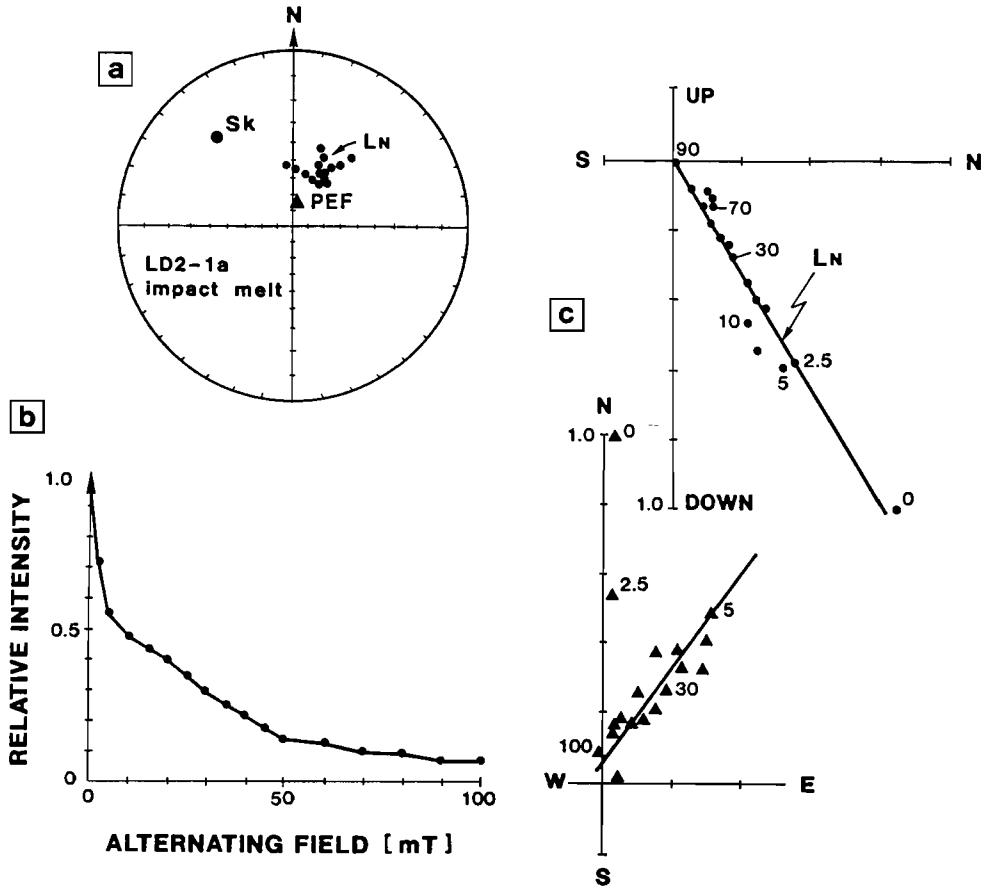

Fig. 16. Alternating field demagnetization example of the impact component L_n in a suevitic kärnäite (specimen LD2-1a). (a) directions on a stereonet, where open (closed) symbol denotes upper (lower) hemisphere. (b) intensity decay curve and (c) orthogonal vector plots, where triangles represent data on N-S vs. up-down, and dots N-S vs. E-W projections, respectively. PEF = Earth's present magnetic field direction; S_k = mean Svecofennian (1.9 Ga old) remanence direction in the Fennoscandian Shield.

Thermal demagnetization of melt rocks supports the interpretation that the NRM is carried by pyrrhotite with major unblocking temperatures of ~320°-350°C (Fig. 17). It is possible that magnetite and hematite (or FeNi) also carry a small portion of the residual NRM, but it was not possible to reliably isolate any high temperature components since the samples behaved erratically at temperatures higher than ~350°C. The origin of pyrrhotite in the melt rocks is not known. Some target rocks (e.g., mica schists) contain iron and sulphur in sufficient abundance to form pyrrhotite when these rocks are fused (Lehtinen, 1990, personal communication; see also El Goresy, 1968).

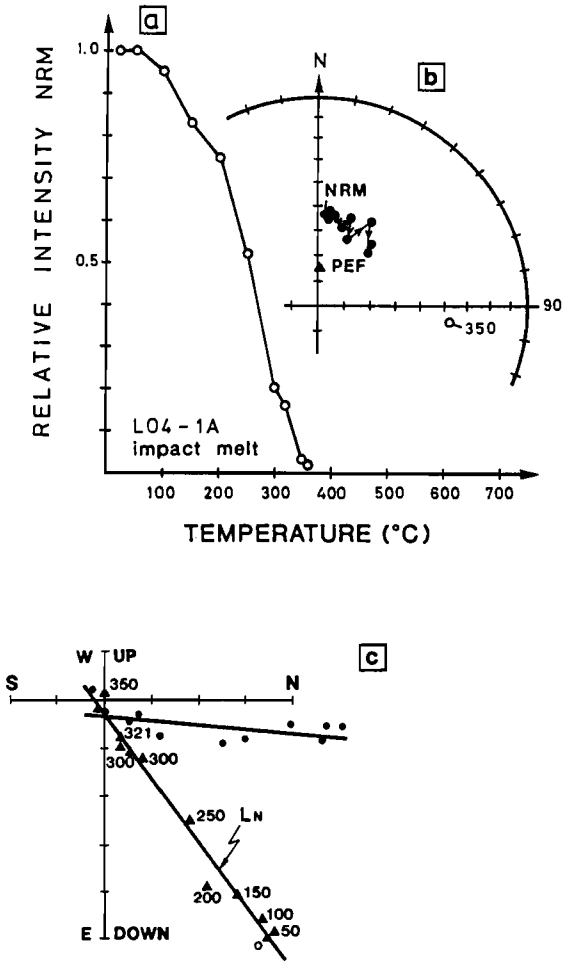

Fig. 17. Thermal demagnetization example of component L_n as carried by pyrrhotite (sample LO4-1a, type I kärnäite). For symbols see Fig. 16.

Other less important remanence components are also present in the melt rocks. One is PEF, which differs from L_n at the 95% confidence level (Fig. 16). We shall return to the role of PEF in the 'boulder-test' (p. 40). Another component is L_x, which has a mean direction of D=209°, I=59°, κ=19.2, α_{95}=13°, N=8 samples with R polarity. Because L_x was also isolated from a few target rocks (see below) it appears to be real. In the majority of samples it occurs as a high coercivity or high blocking temperature component. We do not have any satisfactory explanation for it, but it may be a laboratory artifact of the intrinsic anisotropy of pyrrhotite.

Suevites

Only unoriented (boulder) samples of suevites were available. The demagnetization of one sample (Fig. 18) reveals clearly a two-component NRM. The softness of remanence suggests that one of the component may be due to PEF. The suevite has a very high Q-value (Table 1).

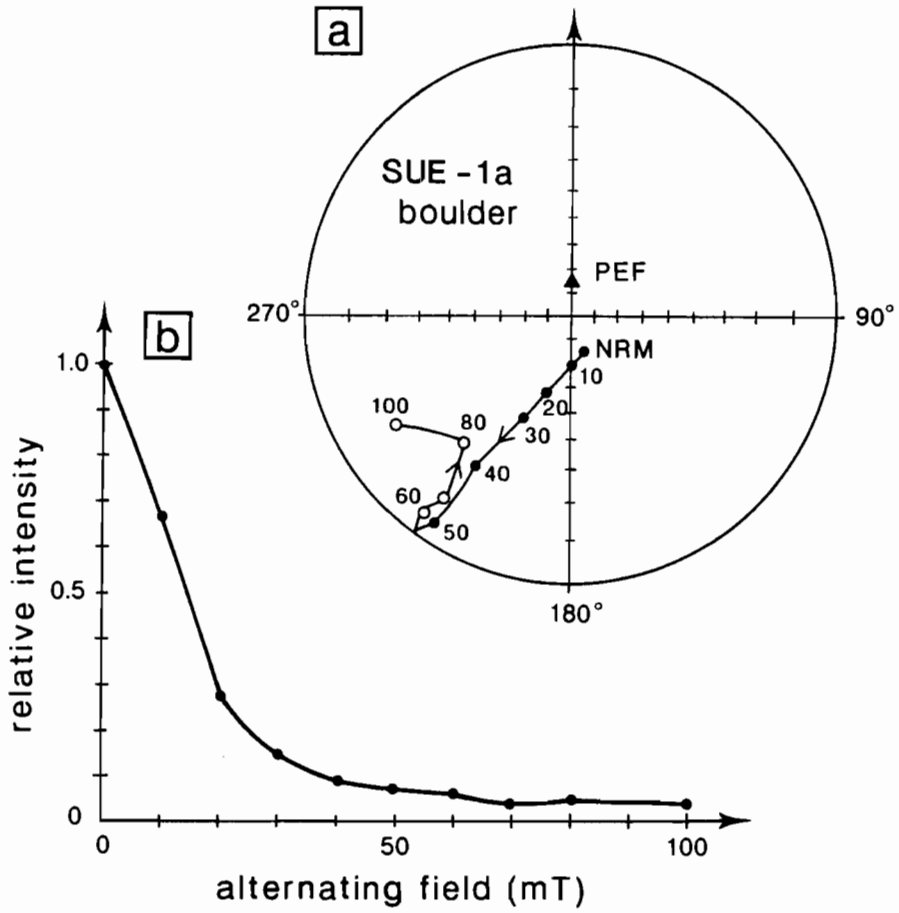

Fig. 18. A. f.-demagnetization of a suevite (boulder) sample.

Target rocks

In general the target rocks behaved erratically during demagnetization. However, we were able to isolate two remanence components (in addition to PEF) with reliability from a few of them. The most common component is the NNW moderate shallow component S_k, which is clearly the Svecofennian direction, as expected for the 1.8-1.9 Ga old target rocks. Due to its complex behaviour during cleaning, S_k either could not always be isolated or then it showed a considerable scatter in the

western hemisphere. The other components, L_n and L_x, are the same as found in impact melts (see previous chapter). The impact component L_n was isolated with sufficient reliability in fourteen specimens (Table 3). In most cases, L_n occurs in the target rocks as a low coercivity overprint (see e.g., Fig. 19 a) and less frequently as a high coercivity component (Fig. 19 b). Thus, if the L_n in these rocks is shock remanent magnetization (SRM), the acquisition mechanism varies from sample to sample. It is noticeable, however, that specimens which carry the L_n have an enhanced NRM intensity and Q value, supporting the acquisition mechanism by shock wave (Pohl, 1971, 1977; Cisowski and Fuller, 1978; Poornachandra Rao and Bhalla, 1984). L_n tends to be present more often in sites (LZ, LR), closer to the impact centre, in consistency with the shock interpretation. However, owing to the shortage of detailed profile data from crater center outwards this may be accidental. The mean direction of L_n in the target rocks is coincidental (at 95% confidence) with the L_n in the melt rocks although it is much more scattered in the former rock type (Table 3, Fig. 20).

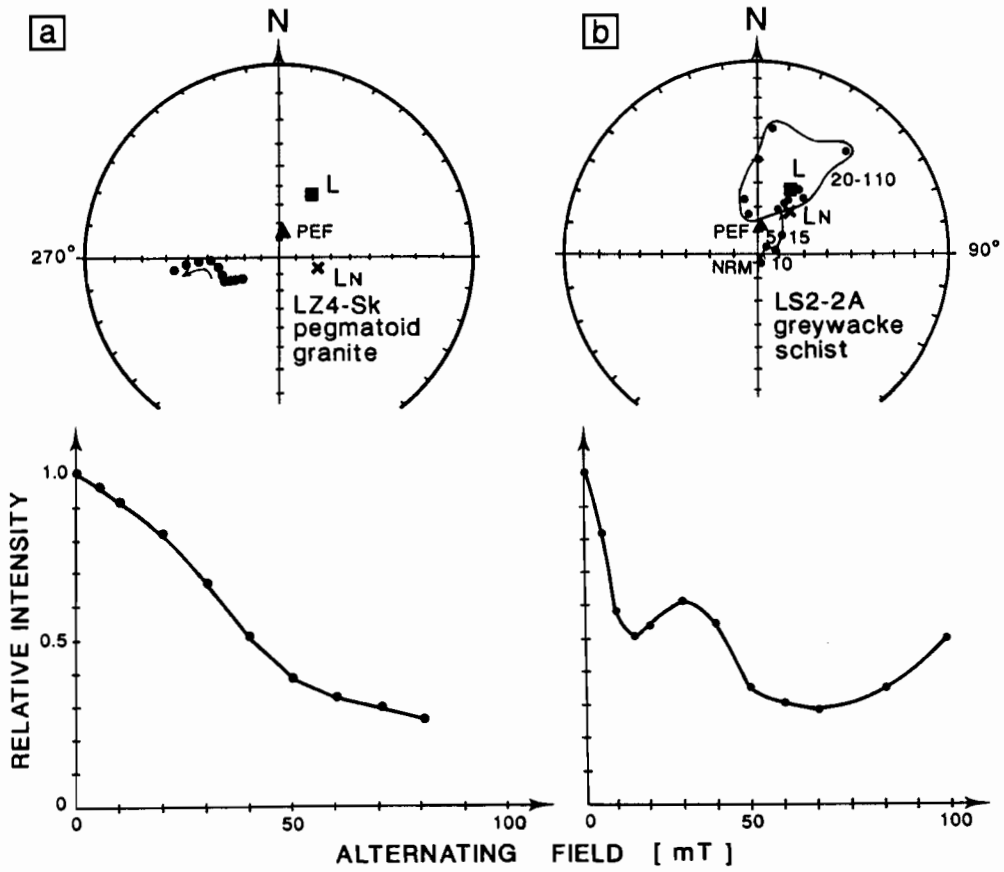

Fig. 19. Alternating field demagnetization examples of basement rocks which reveal two superimposed remanence components, a possible impact component L_n and a Svecofennian component S_k. (a) L_n as a low coercivity overprint (pegmatite granite, site LZ) and (b) L_n as a high coercivity component

(greywacke schist, site LS) . For symbols see Fig 12.

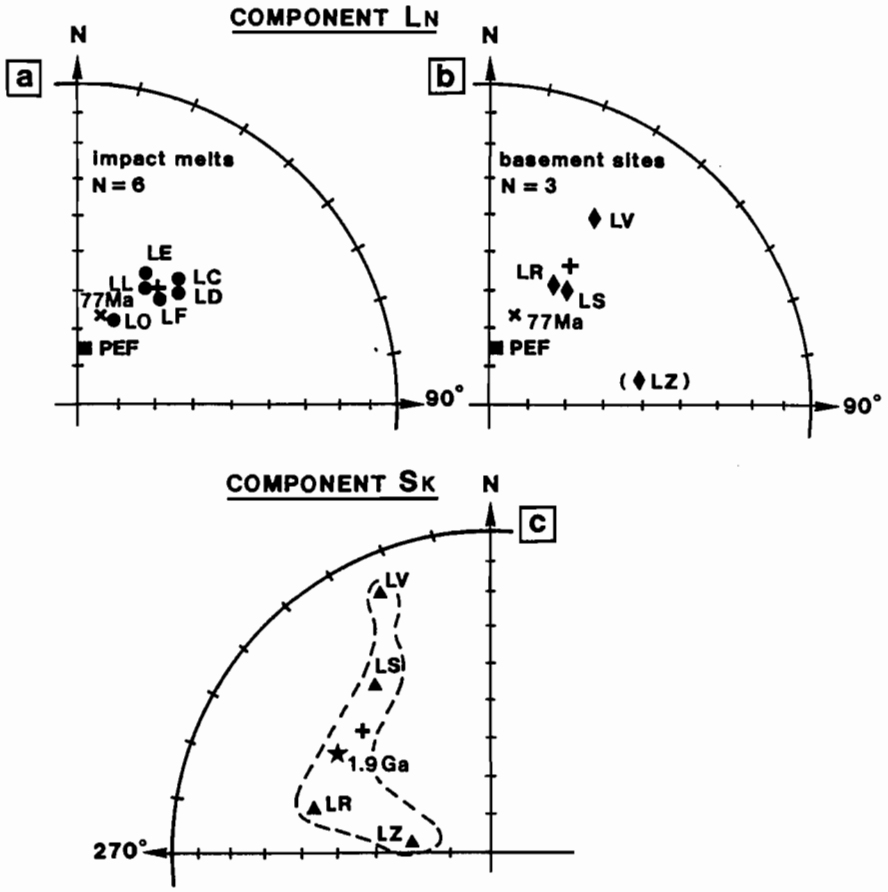

Fig. 20. Site mean directions of component L_n in (a) impact melts and (b) basement sites. (c) component S_k in basement sites. + denote the mean directions. The 77Ma (cross) denotes the reference direction calculated from the European APWP curve of Irving (1977) for Lappajärvi assuming an Axial Geocentric Dipole Field. The star in (c) denotes the mean direction of Svecofennian rocks (1.9 Ga) of Fennoscandia (from Pesonen et al., 1989). For symbols see Fig. 12.

PALAEOMAGNETIC AGE OF THE LAPPAJÄRVI IMPACT

The mean palaeomagnetic directions and corresponding poles are listed in Table 3 and plotted in Figs. 21-23. The characteristic remanence direction of the melt rocks (D = 32.6°, I = 54.5°, k = 39, α_{95} = 6.2°, 6 sites) gives a palaeomagnetic pole position at Lat. = 55.4°N, Long. = 152.6°E, dp = 6.2°, dm= 8.7°. This pole, of normal polarity, is plotted on the European mean APW curve of Irving (1977) in Fig. 21 (pole L_n). The pole does not plot directly on the APWP, but an extrapolation onto it yields a

palaeomagnetic age of ~195 Ma for the Lappajärvi impact event. The pole (L_b) of the corresponding component in the target rocks (pole position: Lat. = 52.4°N, Long. = 148.6°E, dp = 19.9°, dm = 28.8°, also normal polarity) is not significantly different from that of the melt rocks, but it has a much higher level of uncertainty (Table 3, Fig. 20).

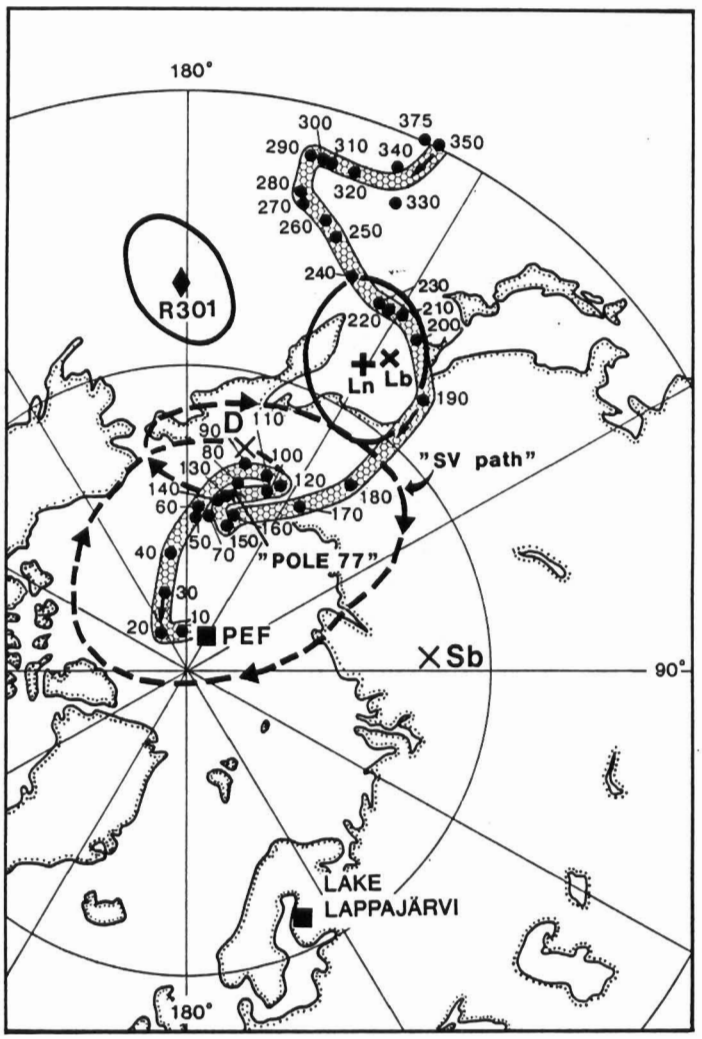

Fig. 21

Palaeomagnetic poles of component L_n in melt rocks (pole L_n) and in basement rocks (pole L_b) plotted on the late Phanerozoic European APWP of Irving (1977). Pole "77" is the 77 Ma old reference pole.R301 is the pole of the L_n component in the drill core R301. D is the pole for the Lake Dellen meteorite impact (in Sweden), ~109 Ma old (Bylund 1974), and PEF is the virtual pole (VGP) calculated from the PEF direction at Lappajärvi. The broken path is the calculated secular variation curve (SV) which would be observed if the present Earth's magnetic field (IAGA Bull. 47) would experience the present day westward drift around the 77 Ma old pole.

Table 3
Palaeomagnetic results of Lake Lappajärvi rocks.

site	rock type	Lat. , Long.	s/D	B/N/n	p	D , I	κ	α95	Plat, Plon	dp , dm	g
				Impact component (L_n) in melt rocks							
LC	kärnäite I	63.19, 23.50	0.21	5/10	N	39.1, 48.0	5	38.9	47.7, 148.5	33.2, 50.8	
LL	kärnäite I	63.20, 23.67	0.15	5/18	N	29.2, 54.6	11	24.5	56.7, 157.1	24.4, 34.6	
LO	kärnäite I	63.20, 23.67	0.16	6/28	N	20.7, 65.9	56	9.1	71.2, 156.8	12.1, 14.8	
LD	suevitic kärnäite	63.19, 23.67	0.13	5/11	N	39.9, 50.3	49	17.8	49.2, 146.5	16.0, 23.9	
LE	suevitic kärnäite	63.19, 23.67	0.12	5/32	N	26.8, 52.4	126	6.8	55.4, 161.9	6.4, 9.3	
LF	suevitic kärnäite	63.19, 23.67	0.12	3/18	N	35.2, 55.0	39	20.1	54.9, 149.0	20.2, 28.5	
Mean	impact melt rocks	63.19, 23.64		6/29/117	N	32.6, 54.5	117	6.2	55.4, 152.6	6.2, 8.7	C
				Impact component (L_n) in basement rocks							
LR	greywacke schists	63.25, 23.67	0.37	3/5	N	26.4, 54.8	21	27.8	57.7, 160.9	27.8, 39.3	
LS	greywacke schists	63.10, 23.68	0.59	2/3	N	31.3, 54.0	--	--	55.5, 154.6		
LV	granodiorite	63.08, 23.67	0.62	2/3	N	28.0, 33.6	--	--	41.3, 167.3		
LZ	pegmatite granite	63.22, 23.68	0.34	3/3	N	76.0, 62.9	56	16.6	44.6, 100.7	20.5, 26.1	
Mean	basement rocks	63.16, 23.67		4/10/14	N	36.8, 52.8	20	20.9	52.4, 148.6	19.9, 28.8	D
				Svecokarelian direction (S_k) in basement rocks							
LR	greywacke schist	63.25, 23.67	0.37	3/15	N	285.6, 40.5	10	40.7	27.5, 290.9	29.8, 49.2	
LS	greywacke schist	63.10, 23.68	0.59	3/12	N	324.0, 37.3	9	44.0	41.3, 230.6	30.4, 51.7	
LV	granodiorite	63.08, 23.67	0.62	3/12	N	337.0, 13.1	13	35.0	31.1, 230.7	18.2, 35.7	
LZ	pegmatite granite	63.22, 23.68	0.34	3/3	N	272.8, 70.1	23	26.0	47.4, 323.8	38.6, 44.8	
Mean	Svecokarelian direction	63.16, 23.67		4/12/42	N	312.5, 42.9	7	38.1	40.7, 265.6	29.2, 47.2	D

rock types: kärnäite I = type I kärnäite of Lehtinen (1976), suevitic kärnäite is probably similar to type II kärnäite of Lehtinen (1976). For basement rock types, see Fig. 1 and Pipping (this volume).

Lat., Long. = coordinates of the sampling site (°N,°E)

s/D = distance from the crater centre normalized to crater diameter of 17 km; if **s/D**≤0.5, the site is inside the crater, otherwise outside.

B/N/n = number of sites/samples/specimens

p = polarity: N=normal , R= reversed

κ, α95 = Fisherian precision parameter, 95% circle of confidence (Fisher, 1953)

Plat, Plon = Palaeomagnetic pole position (°N,°E)

dp, dm = 95% confidence oval for the pole (degrees)

g = reliability grade of the pole (for the applied grading scheme, see Pesonen et al. (1989))

Other poles

The other poles of this study (S_k and L_x) were also plotted on the APWPs for Europe or Fennoscandia (Fig. 23). Pole (Plat = 41°N, Plon = 266°E, dp = 29°, dm = 47°) S_k plots directly on the Precambrian APWP of Fennoscandia and yields a palaeomagnetic age of ~1920 Ma, thus being a typical Svecofennian pole of normal polarity. This, however, suggests a slightly older age for this Svecofennian NRM,

since the K-Ar and ^{87}Rb-^{86}Sr age data imply an age of 1610-1800 Ma for this terrain (Kouvo, 1964; Kouvo & Tilton, 1966). This discrepancy is not significant as the S_K pole is of D class only in the Fennoscandian grading scheme (Pesonen et al., 1989). The pole of the anomalous L_X component (Plat = -15°S, Plon = 181°E, dp = 14°, dm = 19° with R polarity) does not fit onto any segment of the European (or Fennoscandian) APWP. The closest intersection with the Fennoscandian APWP of Pesonen et al. (1989) would indicate a Silurian (~430 Ma old) magnetization age (Fig. 23).

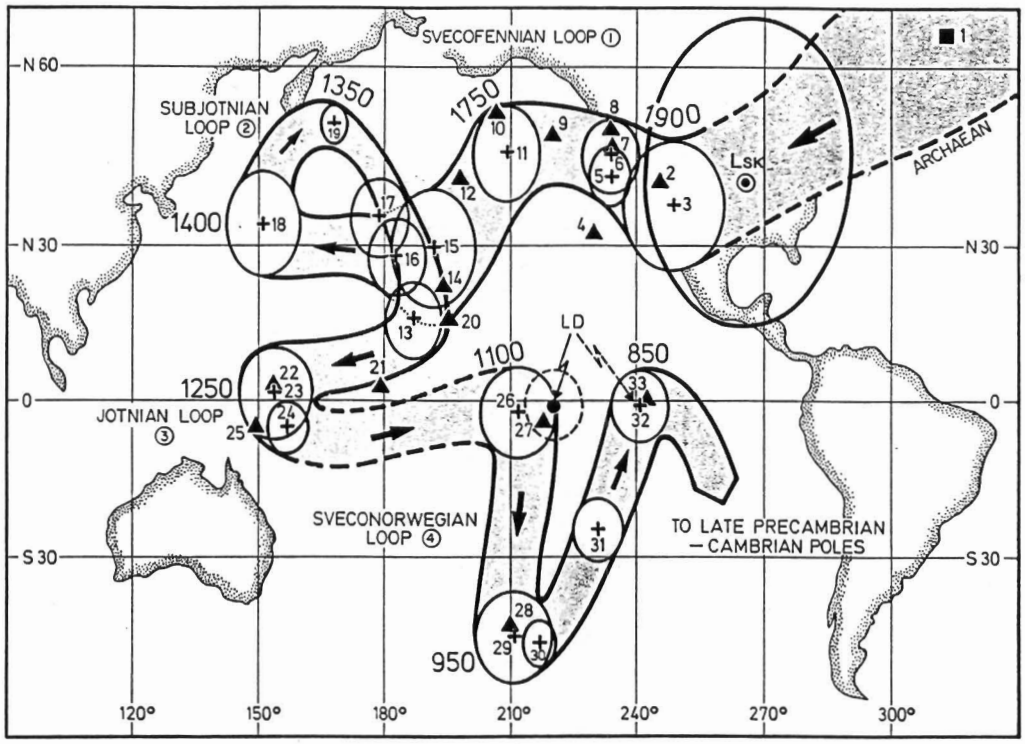

Fig. 22. The pole S_K from the target rocks plots directly on the Svecofennian APW track of Pesonen et al. (1989).

Palaeomagnetism of drill core R 301

The petrology, mineralogy, geochemistry and petrophysics of the samples from the drill core R301 are reported in detail elsewhere (see Kukkonen et al., 1992; Pipping & Lehtinen, 1992). One example demonstrating the enrichement of some siderophile elements down the core R301 (Pt, Ir, Ru, Pd) is shown in Fig. 24 (from Pipping, 1991).

The palaeomagnetic data on R301 are plotted in Fig. 25, together with the petrophysical data of Kukkonen et al. (1992) and the total iron contents (Pipping, 1991). The natural remanent magnetization in Fig. 25 is the characteristic impact component L_n after a.f treatments ~30 mT to ~80 mT. The direction of L_n, based on

five-point running means down the core is also plotted on a stereonet (Fig. 26) to allow comparison with the data on surface outcrops (Fig. 20). We can conclude that the L_n-direction of R301 is generally in good agreement with that of the surface outcrops but with a slightly (~20 degrees) shallower inclination. This could be partly due to problems in with the orientation technique of the deep core, as evidenced by the anomalous declination. The palaeomagnetic pole of the L_n in R301, shown in Fig. 21, thus diverges slightly to the east from the L_n poles of surface outcrops.

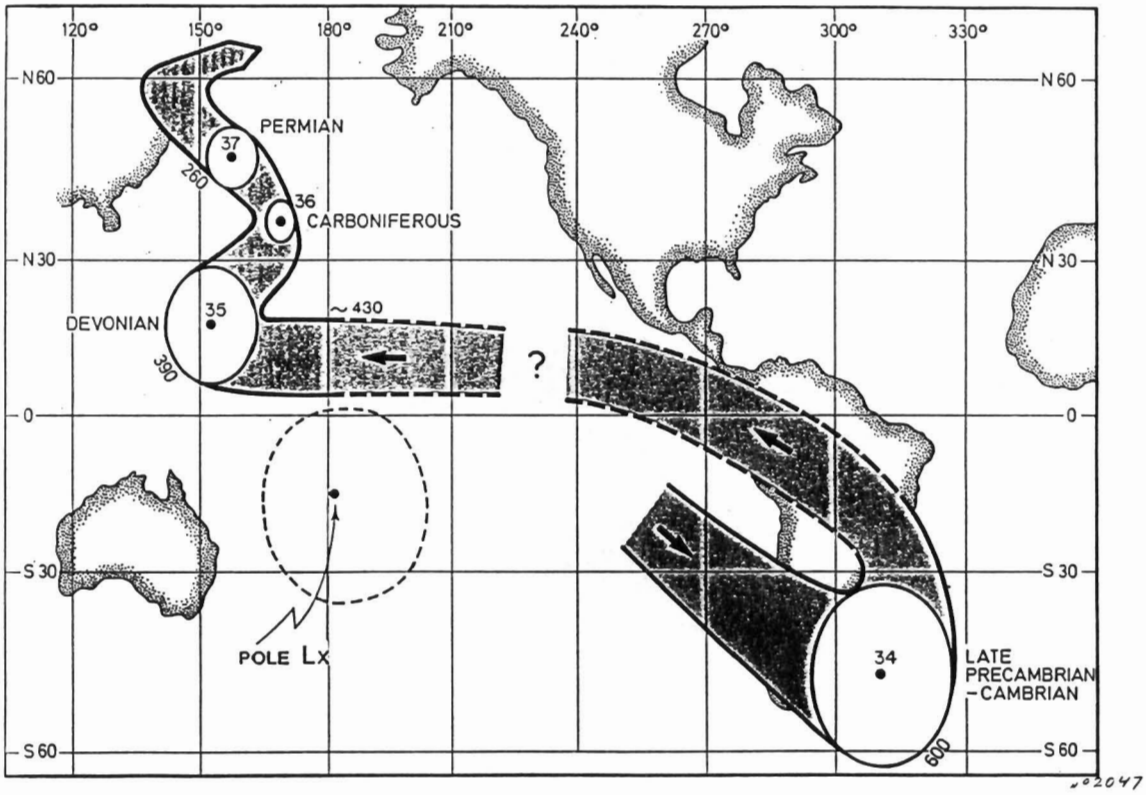

Fig. 23. The pole L_x with its confidence oval on the Phanerozoic APWP of Fennoscandia (Pesonen et al., 1989).

Also shown in Fig. 25 are the NRM intensity values that delineate the different impact melt rock types (kärnäite, perlitic kärnäite, suevite and impact breccia) in a similar fashion to the susceptibility and density data of R301. Note that the susceptibility and NRM intensity correlate negatively with the total iron content of the deep core samples. Thus, the content of pyrrhotite and its grain size control the susceptibility and NRM more than does the total Fe.

Lappajärvi Impact Crater

DRILLHOLE 1

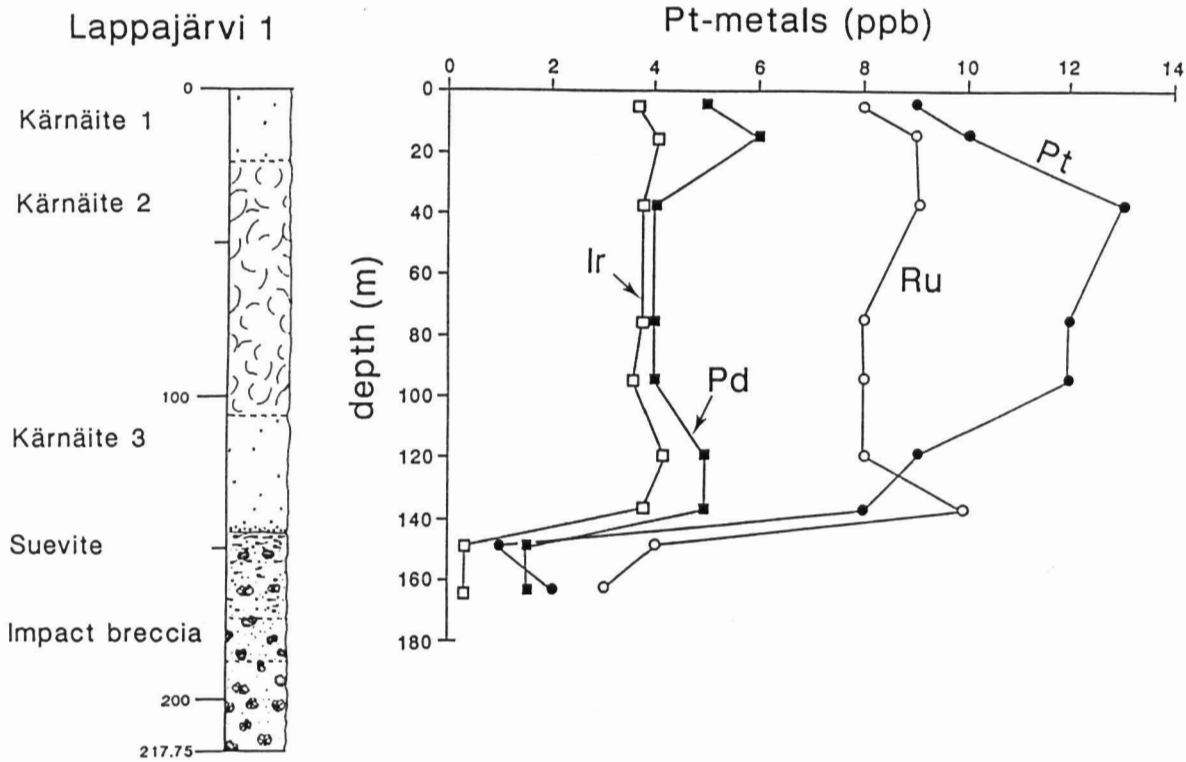

Fig. 24. Profile of drillhole 1 (=R301), with lithology. Some Pt-group metal contents (Pt, Ru, Pd and Ir) are also shown (see Pipping and Lehtinen, 1992).

DISCUSSION

The palaeomagnetic pole position of the Lappajärvi impact event (poles L_n and L_b in Fig. 21) suggest a magnetization age of ~195 Ma for the Lappajärvi impact rocks. This age differs from the well-defined plateau age of 77 ± 0.4 Ma based on ^{40}Ar-^{39}Ar determinations (Jessberger and Reimold 1980). Neither the radiometric age (77 Ma) nor the palaeomagnetic age (195 Ma) fit the ~30 Ma periodicity of Rampino and Stothers (1984) or Alvarez and Müller (1984). We believe that the L_n-direction represents the acquisition (blocking in) of remanence in pyrrhotite during late stages of the post-impact cooling of the melt, and that it is a reasonably good estimate of the magnetization time. The question thus arises as to whether the ^{40}Ar-^{39}Ar plateau age of Jessberger and Reimold (1980) is in error due to inherent Ar problems (e.g., Deutsch et al., 1992). The morphological features of the Lappajärvi structure and the total amount of erosion in southwestern Finland, have prompted Lehtovaara (1982) to

suggest that the Lappajärvi impact is considerably older than 77 Ma. However, no quantitative calculations of erosion in Lappajärvi area have yet been made.

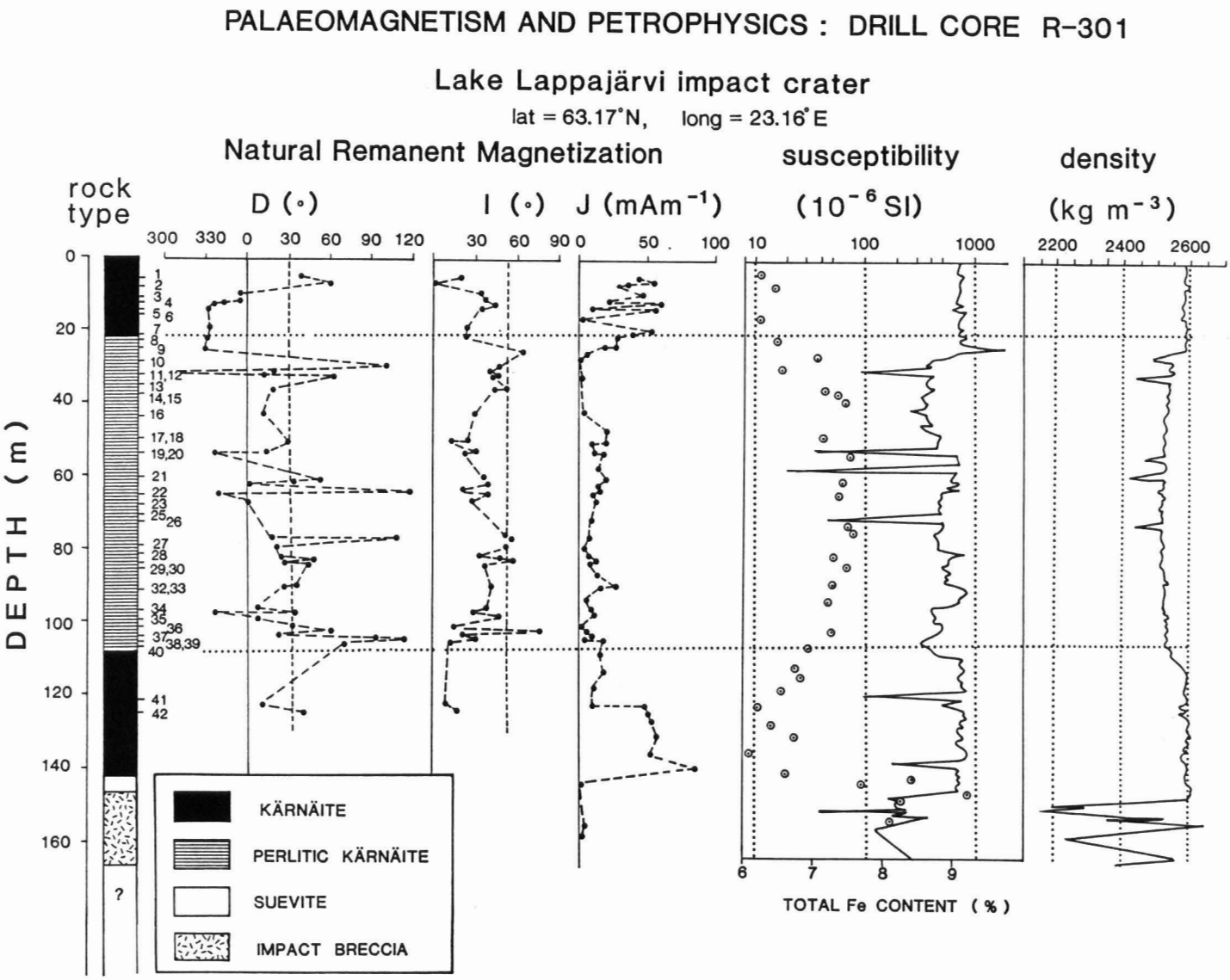

Fig. 25

Palaeomagnetic and petrophysical data on drill core R301 (see Fig. 9). In NRM, only the characteristic component L_n is plotted (after a.f. demagnetization). The susceptibility and density are from Kukkonen et al. (1992) and total Fe content from Pipping (unpublished data, 1990). The numbers on left are specimen numbers as also shown in Fig. 26.

Assuming that the 77 Ma old ^{40}Ar-^{39}Ar age is, however, a valid estimate for the Lappajärvi impact event, we are forced to seek other explanations for the palaeomagnetic age (195 Ma). There are four possible explanations for the

discrepancy: 1. secular variation (SV), 2. magnetic anisotropy, 3. bias of NRM by PEF, and 4. post-impact tectonic movements. In the following we shall discuss each one in this order.

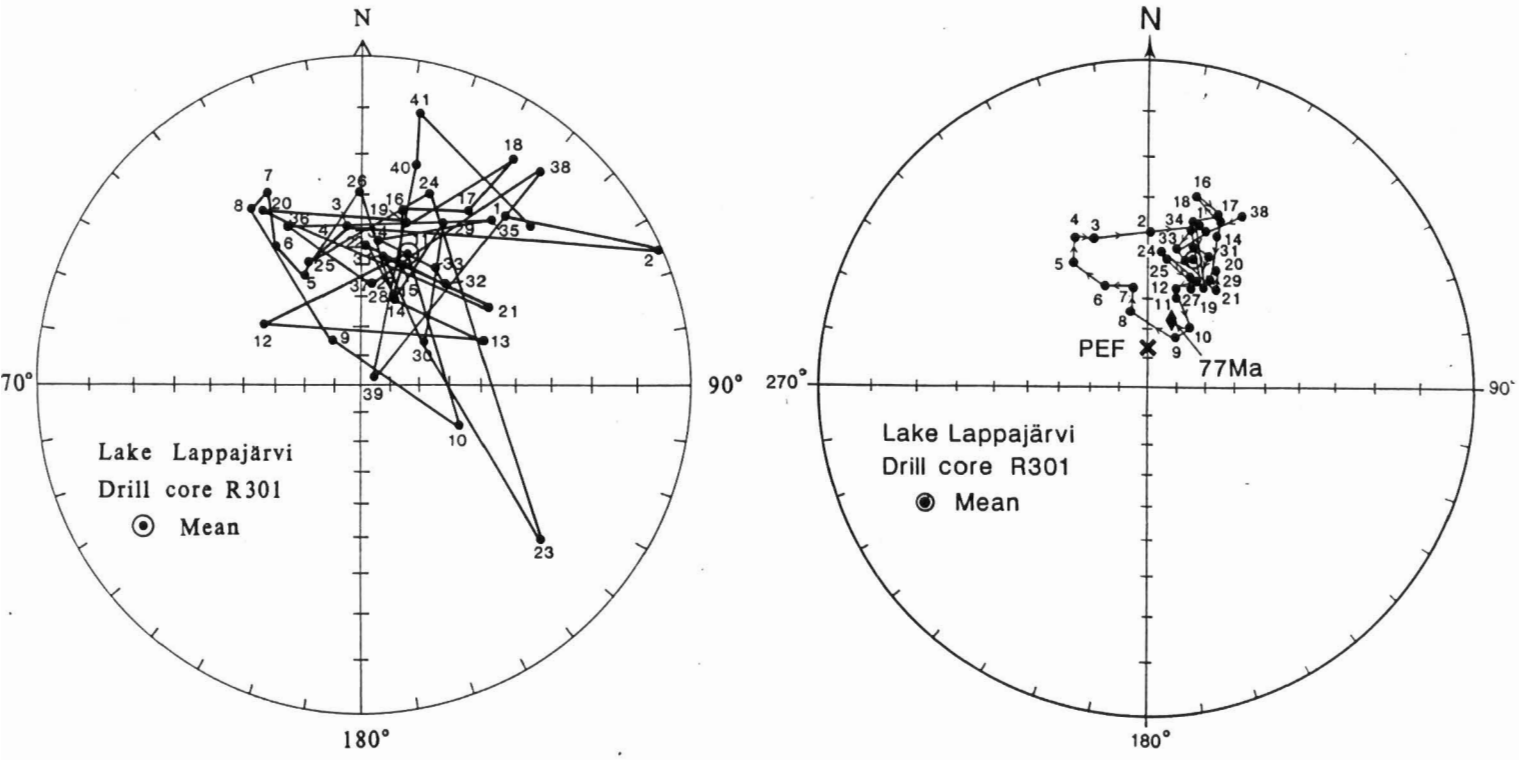

Fig. 26. (a) The a.f. cleaned palaeomagnetic directions plotted in successive (time or depth) order representing the path of secular variation during cooling of the melt layer. Specimen numbers and depths are shown in Fig. 25. **(b)** Same as (a) but the data represent successive five-point running means. Note that the envelope (secular variation) deviates from the PEF-value (cross) and also from the 77 Ma-direction.

Secular variation

The Earth's magnetic field vector undergoes secular variation due to changes in dipole (D) and non-dipole components (ND). The most important contribution of SV to palaeomagnetic data is due to westward drift (WD) of the ND field, which has a characteristic period of roughly 1800 years. This is also the time required to average out the deflection by WD on the palaeomagnetic record (see Irving, 1964). Generally, palaeomagnetic sampling is done so that SV is averaged out. If the magnetization is shock remanent magnetization (SRM) (see Pohl, 1977; Cisowski and Fuller, 1978), it will be acquired in less than seconds, which is a too short a time to average out the

SV. Thus we can anticipate that the L_n component in the target rocks 5 to 8 km from the impact point was acquired under conditions of normal temperature and at slightly elevated pressure due to shock in periods of less than seconds. Hence the NRM in these rocks would record a spot reading of the ambient magnetic field and may be deflected by 20 degrees from its long-term mean value due to SV. For the melt rocks the case is different as the NRM is more likely a TCRM acquired during late stages of cooling of the melt. Because the opaque grains are nearly in the PSD-SD range (Fig. 13), the blocking temperature interval for pyrrhotite is ~350°C to ~150°C as also observed in thermal demagnetization (see e.g., Fig. 17). The cooling rate of the melt at Lappajärvi can be calculated using the modified Carslaw-Jaeger conductive cooling theory (Jaeger, 1957), which takes into account the latent heat and the initial high onset temperature for cooling (~1800°C; Lehtinen, 1976; Pohl, 1977; Onorato et al., 1978; Floran et al., 1978). The calculations (Onorato et al., 1978) reveal that it takes roughly 2500 years for a 200 meters thick melt layer to cool from 1800°C to 300°C. If we further assume that the six surface sites (Fig. 9) were not on the same stratigraphic level when the cooling took place, as suggested in p. 14, they will record the Earth's magnetic field direction at different times and would thus, on average, yield a record of SV in their distribution of site-mean palaeomagnetic directions. The mean of this distribution would represent a typical palaeomagnetic direction in which the SV is averaged out (e.g., Robertson, 1967). Two observations suggest that this is what happened. First, the pattern of the vertical drill core (R301) palaeomagnetic directions is strikingly similar to that of the horizontal site means (Figs. 20 and 25), implying that the SV is averaged out in both data sets. Second, the calculated SV pole path around the 77 Ma reference pole (Fig. 21) does not include the drill core mean pole nor the surface site mean pole. Therefore the observed difference between the two poles, L_n (melt rocks, Table 3) and 77 Ma (reference), is unlikely to be caused by non-averaged SV. We thus reject the SV explanation for the age discrepancy.

Magnetic anisotropy

Magnetic anisotropy can deflect the NRM from its theoretical direction in two ways. *First*, the NRM may be deflected due to some preferred grain orientations if the samples have fabric or inherent magnetocrystalline anisotropy. Although pyrrhotite is a likely candidate for rendering samples to behave anisotropically due to its strong

inherent magnetocrystalline anisotropy (Schwarz, 1975), this is not the case in Lappajärvi melt rocks as the measured bulk susceptibility anisotropies are less than 2%, and the laboratory TRMs record the applied laboratory field directions to within ±3 degrees (L. J. Pesonen, unpublished data).

Another possible source of anisotropy is magnetic refraction when the impact melt layer is acquiring its NRM under the Earth's prevailing magnetic field at the time of impact and subsequent cooling. The effect of this shape-anisotropy, however, is heavily dependent on susceptibility and will be negligible for Lappajärvi impact melts due to their low susceptibilities (Table 1). We believe that anisotropy is not the explanation for the age discrepancy.

Bias of NRM due to PEF

The close similarity between L_n and PEF makes us suspect that we are misinterpreting L_n as a real palaeomagnetic direction, although this is in fact the PEF, acquired viscously (VRM) during the last Brunhes normal period (Irving, 1964). This possibility is particularly relevant for the L_n in target rocks where it is very vaguely isolated (see e.g. Fig. 27a). However, four observations contradict the significant role of PEF in the Lappajärvi rocks. First, PEF is a minor component together with L_n in many specimens (melts and basement) and appears to be distinct from L_n (e.g., Fig. 27b). Second, when the first vector differences are plotted on a stereonet (Fig. 27b), they are neither perfectly random nor clearly concentrated around PEF, pointing to a minor role of PEF. Third, not all specimens show PEF at all but show L_n or S_k instead (e.g., Fig. 16). Fourth, when the characteristic components of the melt boulders are plotted on a stereonet (Fig. 27a), they are nearly random, once more indicating very minor contamination by PEF, at least during the last post-glacial era (the last 10,000 years). We conclude that only a slight bias of L_n towards PEF may be present in the Lappajärvi rocks, but that PEF contamination is not the explanation for the age discrepancy. Moreover it would in fact bias the L_n-direction towards the 77 Ma reference direction, not away from it as actually observed (see Fig. 20).

Post-impact and post-cooling tectonism

When using palaeomagnetic methods in dating we should always check that the NRM, being a vector property, has not moved from its original position due to tectonism. In impact craters we should first define the acquisition time of NRM relative to the tectonic processes that have taken place during or since the impact event. In the case of melt rocks we can neglect the major crater forming tectonic processes (Gault et al., 1968; Grieve, 1991) such as true crater formation, central uplift and the rim slumping and sliding, because the NRM, acquired during cooling, post dates these events by thousands of years. This is not, however, the case for the L_n in the target rocks, as it is probably acquired by the passage of the shock wave through the rim. It is thus likely that the L_n in the target rocks is not at its original attitude but is deflected due to rim slumping and sliding that took place immediately after the shock wave had generated the L_n. The small difference between the directions of L_n in the melt and target rocks (Fig. 20) may partly be attributed to this. However, because the L_n in the target rocks is only of D class, it does not allow any tectonic corrections to be made. In the next we shall search for a model to explain the departure of the more precisely defined L_n in the melt rocks from the 77 Ma old reference direction by looking for post-cooling tectonic tilting. The rationale behind the idea that the Lappajärvi area has been affected by post-impact tectonism derives from Fennoscandian uplift data (Nikonov, 1980; Veriö, 1980), from earthquake observations (Slunga and Ahjos, 1986) and from joints and vesicle orientations in the melt layer (this work; Lehtinen, 1976). The area is known to be tectonically active today, because the Lappajärvi-Alajärvi zone (Fig. 9) is an active earthquake belt (Slunga and Ahjos, 1986). The last major earthquake (magnitude ~4.5) occurred near Alajärvi in 1979 and the fault-plane solutions (Slunga and Ahjos, 1986) and repeated levellings before and after this earthquake (Veriö, 1980) reveal that both horizontal and vertical (up to ~10 mm) movements have taken place on both sides of the eastern fracture (Fig. 9; see also Veriö, 1980). Non-vertical vesicle orientations also suggest that the melt layer has tilted after the original crystallization and cooling of the melt (Lehtinen, 1976; Mäerz et al., 1979; see Fig. 30).

Tilting due to Fennoscandian uplift

Lappajärvi is located in an area of active uplift due to the last glaciation (i.e., the last 10^4 years). According to Nikonov (1980) and Kakkuri (1990, personal communication), maximum downwarping due glacial load in Lappajärvi was some 600 m (Fig. 29). Most of the downwarping has been isostatically compensated for since the glacial load began to lighten (~13 Ka), and today only about 130 m remain for future uplift. The maximum downwarping would deflect any remanent magnetization vectors (older than 13 Ka) by no more than 0.08° with respect to a stable reference level beyond the impact of ice loading. The remaining (130 m) downwarping would indicate a deflection of 0.02° of NRM and is hence insignificant in palaeomagnetism. Post-glacial uplift is not the cause of the age discrepancy.

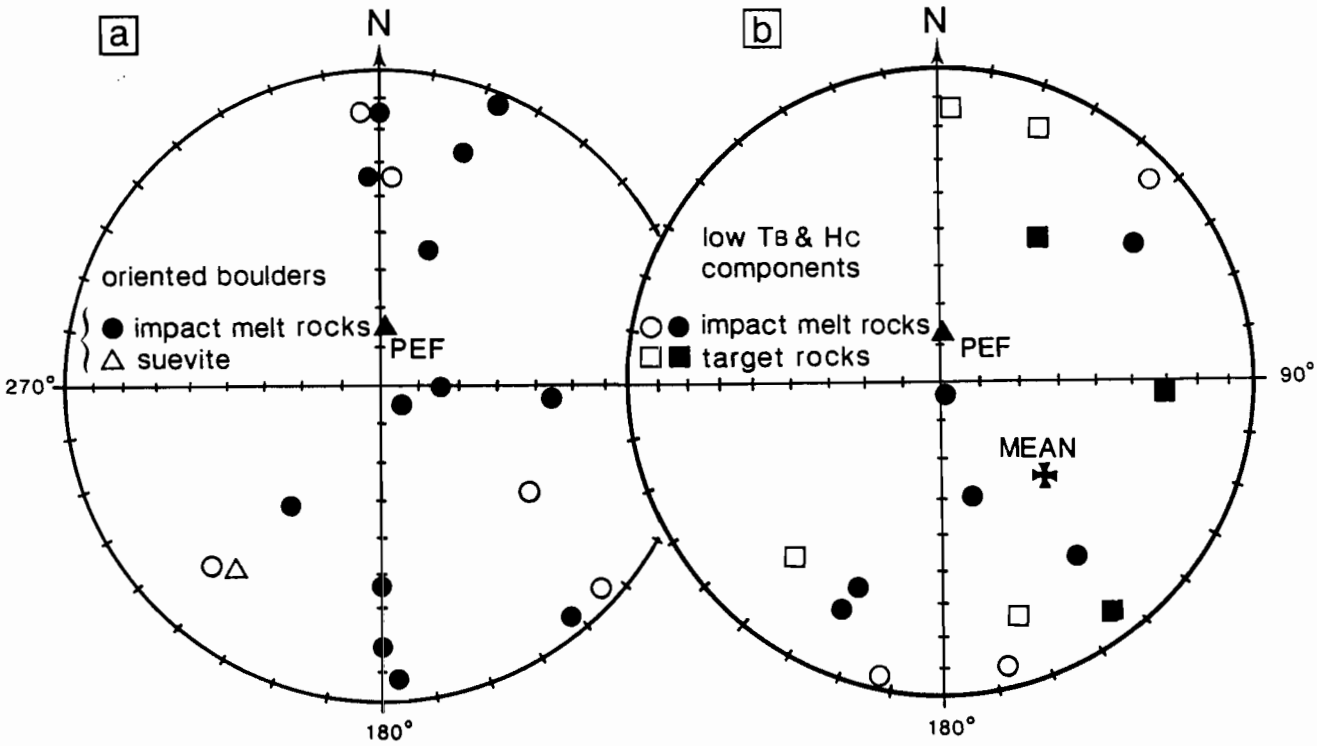

Fig. 27. (a) Directions of characteristic NRM in oriented boulders on a stereonet (see text), (b) the vector substracted low T_b & low H_c components in melt or target rocks on a stereonet.

Other post-cooling tectonic tiltings

Vesicle test

The orientations of the vesicles at site LC were measured in situ and in the laboratory from oriented blocks. In Fig. 30a we have restored the observed vesicle orientations into the vertical position by assuming that they were originally formed by air or gas bubbles rising vertically upwards due to buoyancy. To restore the vesicles back to vertical requires a tectonic tilting with a tilt-attitude of a strike 7°NNE and dip 23° as shown in Fig. 30a. This post-impact tilting shifts the remanence direction from L_n to L_n', and thus away from the 77 Ma old reference direction. Therefore, the present non-vertical orientation of the vesicles does not solve the palaeomagnetic age problem. It is possible that the vesicles did not originally rise exactly vertically but were forced to rise at an angle owing to prevailing stresses.

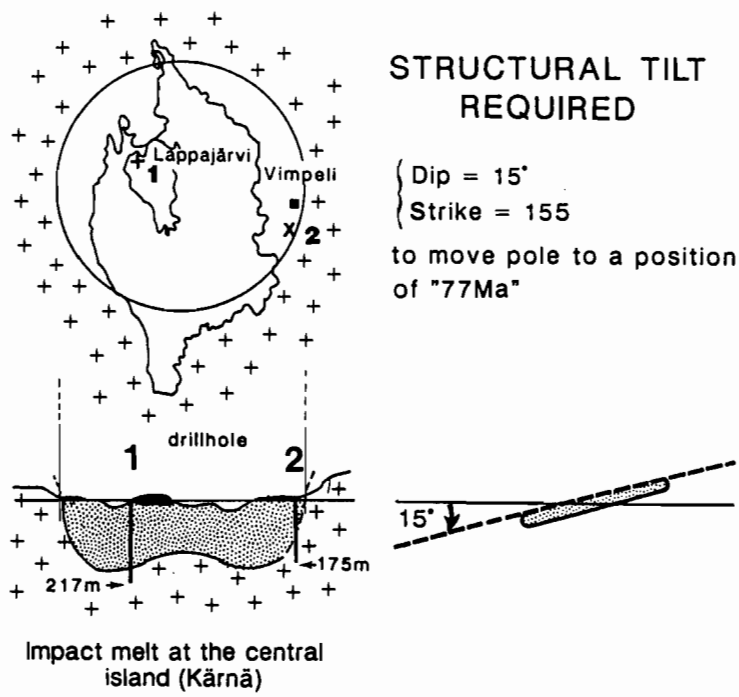

Fig. 28. Simplified diagram to envisage the structural tilt required for Lappajärvi mean NRM to represent the 77 Ma direction.

Tilting along joints

The final, and most probable, candidate for tectonic tilting is the mechanism whereby the melt blocks are tilted as small blocks defined by orthogonal joint lines (e.g.,

Lehtinen, 1976). The joints serve as lines of weakness and allow the blocks to tilt in a 'rocking chair' fashion. The joints form two orthogonal directions: one trenting roughly SSW-NNE, the other being perpendicular to this (Fig. 30). We assume that the joints are primary cooling cracks and were formed before the pyrrhotite carrying remanent magnetization was blocked in. It is conceivable that these blocks could tilt around horizontal axis defined by these joints relative to each other and relative to stable "unshocked" areas. If we allow the melt blocks at sites LC, LE, LF (the three sites where joints can be seen) to be tilted by 15 degrees along the major joint directions (W to SW) (strike of tilting perpendicular to joints; Fig. 30b), the observed magnetization directions L_n will move into positions L_n', which are remarkably close to the 77 Ma old reference direction.

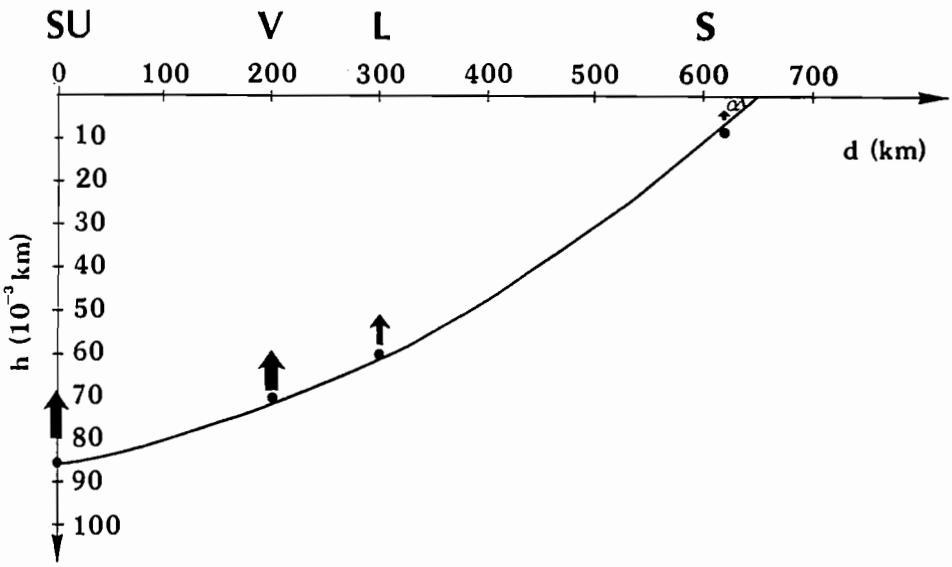

Fig. 29. Fennoscandian uplift (in meters) due to Holocene ice load measured along an W-E profile passing four cities (Su = Sundsvall, V = Vaasa, L = Lappajärvi and S = Sortavala). Data from Nikonov (1980) and Kakkuri (1991), personal communication.

The amount of tilt (15 degrees) was obtained by minimizing the departures of L_n' from this reference direction. Thus, it is not impossible that post-impact tilting has taken place along the joint lines, since the Lappajärvi area is still tectonically active. Veriö (1980), for example, has shown that after the Alajärvi earthquake in 1979, the block on the western side of the main fracture zone rose vertically by ca 10 mm with respect to the eastern stable block, thus indicating relative tilting between these two

blocks. The earthquake and associated relative movements may be due to rebounds caused by Fennoscandian uplift or effects of the active plate tectonics (e.g., spreading of the Atlantic) (Talbot and Slunga, 1989). We propose that the post-impact block movements within the melt layer are a feasible explanation for the departure of the palaeomagnetic directions from their original positions. This explanation is, of course, not valid for the impact direction L_b in the target rocks, which do not have the same joint system; their NRMs are, however, so poorly defined that no attempt was made to measure any post-impact tilting for them.

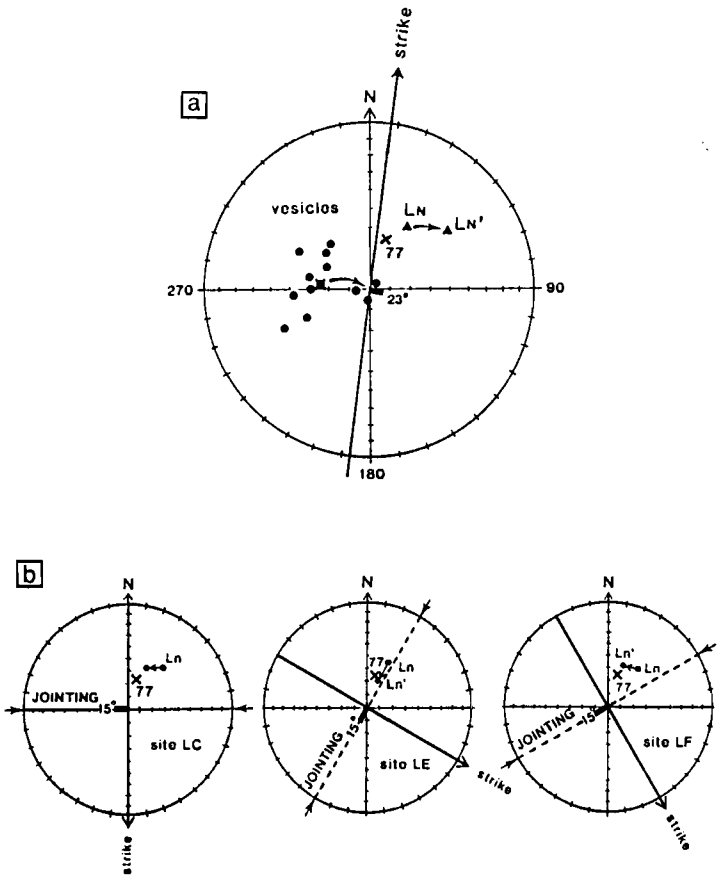

Fig. 30. Tectonic tests. In (a) the observed vesicle orientations in kärnäite site LC (closed dots) are restored to the vertical by tilting the melt layer 23° around a horizontal axis pointing N7°E (=strike). This shifts the palaeomagnetic mean direction (triangle) from L_n to L_n', i.e. away from the 77 Ma reference direction (cross). In (b) the melt blocks were tilted 15 degrees at three sites (LC, LE, LF) around the horizontal axis pointing 90° from the direction of the major joints. This tectonic correction restores the palaeomagnetic vectors from L_n to L_n', i.e. close to the 77 Ma reference direction (see text).

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Geophysical, morphological and topographic data all suggest that the Lake Lappajärvi structure is a fairly young (<200 Ma) complex meteorite impact crater.

2. The palaeomagnetic data on the Lake Lappajärvi rocks indicate that the impact took place in Mesozoic time, ~195 Ma ago. This age differs clearly from the ^{40}Ar-^{39}Ar age of 77 Ma, and so either the radiometric age is wrong or, more likely, the palaeomagnetic result is inaccurate.

3. The NRM of the melt rocks is carried by pyrrhotite, which results in the poor magnetic stability and complex behaviour of the melt rocks at higher steps of demagnetization. The characteristic remanence component in the melt rocks records cooling of the melt sheet. A similar component has been detected in a few country rocks inside the crater or in the rim, thus supporting an impact origin for the characteristic remanence. The poorly defined overprint in the country rocks could be a mild shock remanence. It occurs in specimens which have enhanced remanences (Q values).

4. The age discrepancy can be attributed to a number of factors, e.g. problems with radiometric or palaeomagnetic data, the difficulty of averaging out the secular variation or interference by magnetic anisotropy. We prefer the post-impact tectonic movements of the melt blocks along joints as the cause of the age discrepancy. These movements are associated with isostatic rebound due to recent uplift or due to Mesozoic plate tectonics.

Acknowledgements

We wish to thank Matti Leino, Kari Kuusa and Aulis Lammi for help with the field work. Thanks are due to Henry Halls for suggesting this research topic to us and for his help in the field work during the early stage of this project. We are also grateful to Martti Lehtinen and Kari Kinnunen for their interest on this project. Hilkka Kumpunen and

Christine Blackburn carried out most of the palaeomagnetic measurements. M-L. Airo made the Curiepoint measurement at the University of Bergen, and Tor Meinander the hysteresis property measurements at the Instrument Laboratory of the Technical Research Centre of Finland. Thanks are due to Kirsti Blomster and Sisko Sulkanen for drafting and to Tomi Pylvänäinen for word processing. The English was corrected by Gillian Häkli.

REFERENCES

Alvarez, W. and Müller, R. A., 1984. Evidence from crater ages for periodic impact on the Earth. Nature, 308: 718-720.

Baksi, A. K., 1990. Search for periodicity in global events in the geologic record: Quo vadimus? Geology, 18 (No. 10): 983-986.

Bylund, G., 1974. Palaeomagnetism of the probable meteoritic impact, the Dellen structure. Geol. Fören. Stockholm Förh. 96, 275-278.

Carstens, H., 1975. Thermal history of impact melt rocks in the Fennoscandian shield. Contrib. Mineral.Petrol.50, 145-155.

Chao, E. C. T., 1974. Impact cratering models and their application to lunar studies - a geologists' view. Proc. fifth Lun. Conf., Suppl. 5, Geochim. Cosmochim. Acta, 1: 35-52.

Cisowski, S.M. and M. Fuller, 1978. The effect of shock on the magnetism of terrestrial rocks. J. Geophys. Res., 83, No.B7: 3441-3458.

Dekkers, M. J., 1988. Magnetic properties of natural pyrrhotite Part I: Behaviour of initial susceptibility and saturation magnetization-related rock-magnetic parameters in a grain-size dependent framework. Phys. Earth Plan. Int. 52: 376-393.

Deutsch, A., Buhl, D. and Langenhorst, F., 1992. R_b-S_r and S_m-N_d dating of impact melts: Dellen (Sweden) and Araguainha (Brazil). *In*: L. J. Pesonen and H. Henkel, (editors), 1992. Terrestrial impact craters and craterform structures with a special focus on Fennoscandia. Tectonophysics (in print).

Elo, S., 1976. A study of the gravity anomaly associated with Lake Lappajärvi, Finland. Report Q20/21/1976/2. Geophysics Department, Geological Survey of Finland. 23 pp.

Elo, S., Jokinen, T. and Soininen, H., 1992. Geophysical Investigations of the Lake Lappajärvi Impact Structure, western Finland. *In*: L. J. Pesonen and H. Henkel (editors). Terrestrial impact craters and craterform structures with a special fucus on Fennoscandia. Tectonophysics (in print).

Fisher, R. A., 1953. Dispersion on a sphere. Proc. Roy. Soc. London A, 217: 295-305.

Floran, R. J., Grieve, R. A. F., Phinney, W. C., Warner, J. L., Simonds, C. H., Blanchard, D. P. and Dence, M. R., 1978. Manicouagan impact melt, Quebec, 1, Stratigraphy, petrology and chemistry. J. Geophys. Res., 83 (No. B6): 2737-2759.

Fregerslev, S. and Carstens, H., 1976. Fe-Ni metal in impact melt rocks of Lake Lappajärvi, Finland. Contrib. Mineral. Petrol., 55: 255-263.

Gault, D. E., Quaide, W. L. and Oberbeck, V. R., 1968. Impact cratering mechanics and structures. *In*: B. M. French & N. M. Short (editors), Shock metamorphism of natural materials. Mono Book Co., Baltimore: 87-100.

El Goresy, A., 1968. The opaque minerals in impactite glasses. *In*: French, B. M. and Short, N. M. (editors), Shock Metamorphism of Natural Materials, ed. by B. M. French and N. M. Short, Mono Book Corp., Baltimore: 531-553.

Grieve, R. A. F., Dence, M. R. and Robertson P. B., 1977. Cratering processes: As interpreted from the occurrence of impact melts. *In*: Roddy, D. J., Pepin, R. O. and Merrill, R. B. (editors), Impact and Explosion Cratering, Pergamon Press, New York: 791-814.

Grieve, R. A. F., 1980. Impact bombardment and it's role in proto-continental growth on the early Earth. Prec. Res., 10: 217-247.

Grieve, R. A. F., 1984. The impact cratering rate in recent time. J. Geophys. Res., 89: B403-B408.

Grieve, R. A. F. and Robertson, P. B., 1987. Terrestrial Impact Structures, Geological Survey of Canada, Map 1658A, scale 1:63 000 000.

Grieve, R. A. F., 1990. Impact cratering on the Earth. Sci. Amer., April 1990: 44-51.

Grieve, R. A. F., 1991. Terrestrial impact: The record in the rocks. Meteoritics, 26: 175-194.

Grieve, R. A. F. and Pesonen, L. J., 1992. The terrestrial impact cratering record. *In*: L.

J. Pesonen and H. Henkel (editors). Terrestrial impact craters and craterform structures with a special fucus on Fennoscandia. Tectonophysics (in print).

Göbel. E., Reimold, U., Baddenhausen, H., and Palme, H., 1980. The Projectile of the Lappajärvi Impact Crater. Zeit. Schr. Naturforsch. 35: 197-203.

Hallam, A., 1987. End-Cretaceous Mass Extinction Event: Argument for Terrestrial Causation. Science, 238: 1237-1242.

Halls, H. C., 1975. Shock-induced remanent magnetization in Late Precambrian rocks from Lake Superior. Nature 255: 692-695.

Hargraves, R. B. and Perkins, W. E., 1969. Investigations of the effect of shock on natural remanent magnetism. J. Geophys. Res., 74: 2576-2589.

Hargraves, R. B. and Roy, D. W., 1974. Palaeomagnetism of anorthosite in and around the Charlevoix cryptoexplosion structure, Quebec. Can. J. Earth Sci., 11: 854-859.

Henkel, H. and Pesonen, L. J., 1992. Impact craters and craterform structures in Fennoscandia. *In*: L. J. Pesonen and H. Henkel, (editors), Terrestrial impact craters and craterform structures with a special focus on Fennoscandia. Tectonophysics (in print).

International Geomagnetic Reference Field 1980 - Charts and Grid Values. IAGA Bull. No 47, UGSG Survey Circular 873.

Irving, E., 1964. Palaeomagnetism and its application to Geological and Geophysical problems. J. Wiley & Sons, New York, 399 p.

Irving, E., 1977. Drift of the major continental blocks since the Devonian. Nature 270: 304-309.

Jaeger, J. C., 1957. The temperature in the neighborhood of a cooling intrusive sheet. Am. J. Sci., 255: 306-318.

Jessberger, E.K., and Reimold, W.U., 1980. A Late Cretaceous ^{40}Ar-^{39}Ar age for the Lappajärvi Impact crater, Finland. J. Geophys., 48: 57-59.

Korhonen, J. and Airo, M.-L., 1982. Aeromagnetic maps Q 22.812/2313/1982 and Q 22.812/2314/82. Geological Survey of Finland.

Kouvo, O., 1964. Kallioperämme ikäsuhteista. Geologi 16: 13-20. (in Finnish)

Kouvo, O. and Tilton, G. R., 1966. Mineral ages from the Finnish Precambrian. J. Geol. 74: 421-442.

Kukkonen, I.T., Kivekäs, L. and Paananen, M., 1992. Physical properties of kärnäite (impact melt), suevite and impact breccia in the Lappajärvi meteorite crater, Finland. *In*: L. J. Pesonen and H. Henkel (editors). Terrestrial impact craters and craterform structures with a special fucus on Fennoscandia. Tectonophysics (in print).

Lehtinen, M., 1976. Lake Lappajärvi, a meteorite impact site in western Finland. Geological Survey of Finland, Bulletin 282, 92pp.

Lehtinen, M., 1990. Petrology and mineralogy of the impact melt and breccias in the deep drill core, Lake Lappajärvi, western Finland. *In*: L. J. Pesonen and H. Niemisara (editors), Symposium on Fennoscandian Impact Structures, Espoo and Lappajärvi, Finland. Programme and Abstracts, Geological Survey of Finland, p. 19.

Lehtovaara, J., 1982. Palaeozoic sedimentary rocks in Finland. Annales Academicae Scientiarum Fennicae, Series A, No. 133: 35 pp.

Mertanen, S., Pesonen, L. J., Huhma, H., Lähde, S., Lammi, A. and Leino, M. A. H., 1987. Palaeomagnetism and rock magnetic studies on the Early Proterozoic layered intrusions, northern Finland. Open file report Q 29.1/87/4, Geophysics Department, Geological Survey of Finland, 132 p.

Müller, R. A. and Morris, D. E., 1986. Geomagnetic reversals from impacts on the Earth. Geoph. Res. Lett., 13, No. 11: 1177-1180.

Müller, N., Hartung, J. B., Jessberger, E. K. and Reimold, W. U., 1990. ^{40}Ar-^{39}Ar ages of Dellen, Jänisjärvi and Sääksjärvi impact craters. Meteoritics 25: 1-10.

Mäerz, U., Reimold, W. U. and Stöffler, D., 1979. Preliminary results of the Lappajärvi impact melt. Proc. Lunar. Plan. Sci. X: 769-771.

Nikonov, A. A., 1980. Manifestations of glacio-isostatic processes in Northern countries during the Holocene and present. *In*: N-A Mörner (editor), Earth's Rheology, Isostacy and Eustacy. John Wiley & Sons, New York, XX-XX.

Odenvall, E., 1934. Lake Lappajärvi. Bathymetric chart, notes on thermal conditions. C. Hydrografisen toimiston tiedonantoja VI, Helsinki, 24 p.

Onorato, P. I. K. and Uhlmann, D. R.,1978. The thermal history of the Manicouagan

Impact Melt Sheet, Quebec. Jour. Geophys. Res., 83 (No B6): 2789-2803.

Pesonen, L. J., Leino, M. A. H. & Lammi, A., 1983. Palaeomagnetism of the Baltic Shield - a state of art review. *In*: S. E. Hjelt (editor), The development of the deep geoelectric model of the Baltic Shield, Part 2. Proceedings of the 1st project symposium, Department of Geophysics, University of Oulu, Report No. 8.

Pesonen, L.J., Pipping, F., and Halls, H.C., 1984. Palaeomagnetic study of the Lake Lappajärvi impact crater, western Finland. Terra Cognita 4 (No.3): p.371.

Pesonen, L. J., Torsvik, T. H., Elming, S-Å and Bylund, G., 1989. Crustal evolution of Fennoscandia-palaeomagnetic constraints. Tectonophysics, 162: 27-49.

Pesonen, L. J., Torsvik, T. H., Elming, S-Å., Bylund, G. and Mertanen, S., 1991. Palaeomagnetic directions and poles from Fennoscandia: Archaean to Tertiary. Tectonophysics (in press).

Pesonen, L. J., Marcos, N. and Pipping, F., 1992. Paleomagnetism of the Lappajärvi impact structure, western Finland. *In*: L. J. Pesonen and H. Henkel (editors). Terrestrial impact craters and craterform structures with a special fucus on Fennoscandia. Tectonophysics (in print).

Pipping, F., 1991. Lappajärven meteoriittikraatterin kairausten tuloksista. Geologi 43: 14-19.

Pipping, F. and Lehtinen, M., 1992. Geology, stratigraphy and structure of the Lappajärvi meteorite crater, western Finland: preliminary results of deep drilling. In: L. J. Pesonen & H. Henkel (editors), Terrestrial Craterform Structures with a Special Focus on Fennoscandia. Tectonophysics (in print).

Pohl, J., 1971. On the origin of the magnetization of impact breccias on Earth. J. Geophys. 37: 549-555.

Pohl, J. and Soffel, H., 1971. Palaeomagnetic age determination of the Rochechouart impact structure, France. J. Geophys., 37: 857-866.

Pohl., J., 1977. Paläomagnetische und gesteinmagnetische Untersuchungen an den Kernen der Forschungsbohrung Nördlingen. Geologica Bavarica, 75: 329-348.

Poornachandra Rao, G. V. S and Bhalla, M. S., 1984. Lonar Lake: palaeomagnetic evidence of shock origin. Geophys. J. Roy. Astr. Soc., 77: 847-862.

Puranen, R. and Puranen, M., 1977. Apparatus for measurement of magnetic susceptibility and it´s anisotropy. Geol. Surv. Finl., Rep. Inv., 28, 46 pp.

Rampino, M. and Stothers, R.,1984. Terrestrial mass extinctions, cometary impacts and the Sun´s motion perpendicular to the galactic plane. Nature, 308: 709-712.

Raup, D. M. and Sepkoski, J. J., Jr., 1984. Periodicity of extinctions in the geologic past. Proc. Nat. Acad. Sci. USA, 81: 801-805.

Reimold, W.U. and Stöffler, D., 1979. Isotope, major and trace element chemistry of the Lappajärvi impact melt. Meteoritics, 14: 526-528.

Reimold, W. U., 1979. Rb-Sr und Multielement-Analysen von Gesteinen des Lappajärvi Meteoritenkraters. Fortschritte der Mineralogie, 57(1): I-II, p.123

Reimold, W.U., 1982. The Lappajärvi meteorite crater, Finland: Petrography, Rb-Sr, major and trace element geochemistry of the impact melt and basement rocks. Geochim. Cosmochim. Acta, 46: 1203-1225.

Robertson, P. B., 1967. Manicouagan, Quebec, palaeomagnetic results. Can. J. Earth Sciences, 4: 641-649.

Robertson, P. B., 1975. Experimental shock metamorphism of maximum microline. J. Geophys. Res. 80: 1903-1910.

Robertson, P. B., 1975. Zones of shock metamorphism at the Charlevoix impact structure, Quebec. Geol. Soc. Am. Bull., 86: 1630-1638.

Schmidt, P. W. and Williams, G. E., 1991. Palaeomagnetic correlation of the Acraman impact structure and Late Proterozoic Bunyeroo ejecta horizon, South Australia. Austral. Jour. of Earth Sciences, 38: 283-289.

Schwartz, E. J., 1975. Magnetic properties of pyrrhotite and their use in applied geology and geophysics. Can. Geol. Surv., No. 74-59.

Slunga, R. and Ahjos, T., 1986. Fault mechanism of Finnish earthquakes, crustal stresses and faults. Geophysica 22(No. 1-2): 1-13.

Stothers, R. B., 1987. Do slow orbital periodicities appear in the record of Earth´s magnetic reversals? Geophys. Res. Lett., 14 (No. 11): 1087-1090.

Svensson, N-B., 1968. Lake Lappajärvi, Central Finland: a possible meteorite impact structure. Nature 217: 5127l.

Thomson, G. F., 1990. The anomalous demagnetization of pyrrhotite. Geophys. J. Int. 103 (No. 2): 425-430.

Uutela, A., 1990. Proterozoic microfossils from the sedimentary rocks of the Lappajärvi impact crater. Bull. Geol. Soc. Finl., No. 62, Part 2: 115-121.

Vaarma, M., 1990. Pohjanmaan liuskevyöhykkeen geologia Evijärven alueella. Phil. Lic. dissertation, University of Helsinki, Department of Geology, 101 pp.

Veriö. A., 1981. Vaaitustuloksia Lappajärveltä ennen ja jälkeen järistyksen. Teoksessa: M. Leppäranta (toim.) X Geofysiikan Päivät, Geofysiikan Seura, ss. 179-181 (in Finnish with English Abstract).