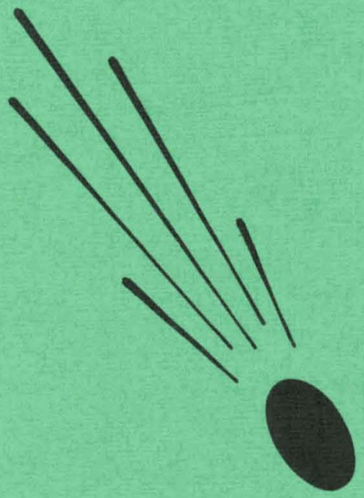
GEOLOGICAL SURVEY OF FINLAND



SYMPOSIUM

Fennoscandian Impact Structures

May 29–31, 1990

Espoo & Lappajärvi

FINLAND

PROGRAMME and ABSTRACTS

Edited by **L.J. Pesonen & H. Niemisara 1990**

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FENNOSCANDIAN IMPACT STRUCTURES

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IMPACT
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1990

PROGRAMME
and
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L.J. Pesonen and H. Niemisara

Geological Survey of Finland

Espoo 1990

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The Symposium on Fennoscandian Impact Structures was held during May 29-30, 1990 in the 'Mining Building' of the Faculty of Materials Science of the Helsinki University of Technology, Otaniemi Campus, Espoo, Finland. The excursion took place to the Lake Lappajärvi impact crater on May 30-31,1990.

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PREFACE

The Earth Sciences experienced a revolution in the 1960´s when the theory of Plate Tectonics was discovered. It is only recently that geoscientists have been looking for alternative tectonic processes that shape the crusts of planets and their satellites. The success of planetary exploration during the 1970´s and 1980´s, together with the development of high resolution remote sensing and satellite geophysical maps, have turned the eyes of geoscientists to the peculiar ring-shaped structures on the Earth which are strikingly similar with those seen on Mercury, Mars and other planets. Coupled with new morphological observations, geochemical and mineralogical data and theoretical modelling results of crater forming processes, the study of terrestrial craterform structures has become a lively and promising topic in the Earth Sciences. Impact cratering is now recognized as an ubiquitous and important geologic process in planetary evolution. The results have indicated heavily cratered surfaces on most solid bodies in the solar system. On planets that have preserved portions of their earlier crust, the record is clear that impacts were common in early planetary history. The problem is to understand how the cratering process works and how it has affected the crustal evolution.

The Earth has been bombarded by several hundreds (thousands) of hypervelocity extraterrestrial bodies (meteorites, asteroids, or comets). It is quite probable that a huge bombardment took place at the end of Cretaceous period producing a biological mass extinction. However, to distinguish the scars left by the extraterrestrial bodies from the volcanic explosion craters (cryptoexplosions) is by no mean an easy task and involves detailed ground-truth data and well defined criteria (based on geochemistry, crater morphology, signs of shock metamorphism, geophysical features, etc.). There are some 130 proven terrestrial craterform structures which have been caused by hypervelocity extraterrestrial bodies. The discovery rate of such craters is something like 3 to 5 per annum. The amount of impact craters found on the Earth is much smaller than on other terrestrial planets: this is due to the dynamic "removing" processes which take place on our planet (erosion, volcanism, sedimentation, subduction, etc). The geophysical and other methods, however, clearly demonstrate that we can see traces of ancient craters at different depth levels. Hence, the present erosion surface displays a 3-dimensional view of the craters depending on the age of the impact event, on the target rock property, on the size, velocity and arrival angle of the impacting body, and so on.

The *Fennoscandian Shield* is in a unique position for impact cratering research due to several reasons: (i) the cratonic part of the shield is stable, accessible and exposed reasonable well, (ii) there are more than 40 craterform structures in Fennoscandia of which some are of extraterrestrial origin, and (iii) there exist high resolution satellite (Landsat, SPOT, radar) and geophysical (aeromagnetic, gravity, wide band electromagnetic) maps in the same regional scale (say 1:100 000) as the geological bedrock maps. These maps are particularly suitable for constructing 3-dimensional pictures of impact structures and together with geochemical and mineralogical studies the maps can distinguish between the extraterrestrial and endogenic origin of the craters.

The original idea behind the Fennoscandian Impact Symposium was born out in 1986 when I was a visiting scientist in Uppsala (SGU) and discussed of the Fennoscandian impact craters with my colleagues H. Henkel and L. Eriksson. We made a tentative plan of this symposium with a hope to strengthen the impact cratering research in Fennoscandia and to build up the database of Fennoscandian impact craters.

The **Symposium on Fennoscandian Impact Structures**, to be held in Espoo and Lappajärvi, on May 29-31, 1990 is the first of this kind ever arranged in Scandinavia. The main purpose of the Symposium is to bring together Scandinavian and other scientists interested in impact structures so that they can discuss problems concerning the interpretation of craterform structures in the light of geological, geochemical, morphological, geophysical and satellite remote sensing data. We also hope that the Symposium will bring out results which will help in identifying features indicative of an extraterrestrial, or alternatively, endogenic (cryptovolcanic) origin of these structures.

In this volume of **Programme and Abstracts** of the Fennoscandian Impact Structures we present the lecture and poster abstracts roughly in the same order as in the programme of the Symposium. Included in the abstract volume are also the daily programme of the Symposium, the list of participants, the author index and some other relevant data.

On behalf of the organizing committee I welcome you in the Fennoscandian Impact Symposium and hope that you will enjoy the early days of summer in the city of Espoo and at the impact crater of Lake Lappajärvi.

Otaniemi, May 14, 1990

Lauri J. Pesonen
chairman

PROGRAMME

Tuesday, May 29

Session 1: **Global impact record** *chaired by* ***M. Lehtinen***

8:30 *Opening remarks*

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

Garvin, J.B. and Schnetzler, C.C. : Remote sensing of impact structures

Pohl, J. : Comparative gravity and magnetic studies of impact structures

Coffee

Session 2: **Lake Lappajärvi impact crater, Finland** *chaired by* ***I. Kukkonen***

10:40 **Pipping, F.** and Vaarma, M. : Lappajärvi impact crater: geology and structure

Lehtinen, M. : Petrology and mineralogy of impact melt and breccias in the deep drill core, Lake Lappajärvi, Western Finland

Kivekäs, L. et al.: Physical properties of kärnäite and related rocks from the Lappajärvi meteorite crater, Finland

Elo, S. et al. : Geophysical investigations of the Lake Lappajärvi impact structure, Western Finland

12:20 *Lunch*

Session 3: **The Siljan and other Swedish impact structures** *chaired by* ***F. Pipping***

13:30 **Ramseyer, K.** et al. : Mineral modifications in granite rocks from the Siljan impact structure

Henkel, H. : Geophysical aspects of impact craters in eroded shield environment

Lindström, M. : The newly identified Lockne impact, Jämtland, Sweden

15:10 **Poster session** *chaired by* ***L. J. Pesonen***

Coffee

Session 4: **Paleomagnetic case histories of impact sites** *chaired by* ***H.C. Halls***

16:20 **Elming, S-Å** and Bylund, G. : Paleomagnetism and the Siljan impact structure, Central Sweden

Pesonen L.J. and Marcos, N. : Palaeomagnetism of the Lake Lappajärvi impact structure, Central-West Finland

Halls, H.C. : The Slate Island meteorite impact site: a study of shock remanent magnetization

Poornachandra Rao, G.V.S. and Bhalla, M.S. : On the separation of shock component at Lonar impact crater, India - a study of multicomponent NRM

18:00 *End of sessions*

-

19:00 *Symposium Dinner at Restaurant El Mar in Hotel Dipoli*

Wednesday, May 30

Session 5: **Other Fennoscandian impact sites** *chaired by **S. Elo***

8:30 **Lehtovaara, J.J.** : Söderfjärden, Western Finland - a Cambrian-filled meteorite crater 100 km west of Lappajärvi

Puura, V. and Suuroja, K. : Ordovician impact structure at Kärdla, Island of Hiiumaa, Estonia

Kakkuri, J. : Traces of a few impact craters in the gravity field

Korhonen, J.V. : The concentric structure of Central Finnish Lapland, an astrobleme?

Coffee

Session 6: **New discoveries** *chaired by **H. Henkel***

10:20 **Witschard, F.** : Traces of ancient mega-impacts on the Baltic Shield

Bouchard, M.A. et al.: Reconstruction of the Nouveau-Québec crater (Ungava) and Pleistocene erosion of the glaciated Canadian shield

Schnetzler, C.C. et al. : Search for the source crater of the Australasian strewn field

11.40 *Lunch*

Session 7: **Mineralogy, impact mechanism, dating** *chaired by **J. Garvin***

13:00 **Deutsch** et al. : Rb-Sr and Sm-Nd -dating of impact melts: Dellen (Sweden) and Araguainha (Brazil)

Müller, N. et al. : ^{40}Ar-^{39}Ar dating of some Fennoscandian impact craters

Vrána, S. : Probable impact melt rocks at the Sevetin structure

14:40 *Concluding remarks, coffee*

-

15:00 *Buses leave for Lappajärvi excursion*

Posters

P14 **Aaro, S.**: Regional geophysical investigations in the Siljan Ring area, Sweden

P 1 **Avermann, M.** and **Brockmeyer, P.** : The Onaping Formation of the Sudbury Structure (Canada): An example for allochthonous impact breccias

P 3 **Brockmeyer, P.**, **Deutsch, A.** and **Buhl, D.** : Sudbury impact structure (Ontario, Canada): Isotope Systematics

P 4 **Elo, S.** et al. : Recent studies of the Lake Sääksjärvi meteorite impact crater, Southwestern Finland

P 5 **Engström, E.U.**, **Ekelund, A.** and **Rudberg, S.** : Tuff breccia from the western part of the Dellen structure, Sweden

P 6 **Henkel, H.** and **Pesonen, L.J.** : Impact craters in Fennoscandia and Baltic regions

P 7 **Henkel, H.** : The Lake Dellen impact crater, Sweden

P 9 **Metzler, A.** and **Stöffler, D.** : Siljan impact structure, Sweden: Dyke breccias within the crater floor

P10 **Müller-Mohr, V.** : The Sudbury Structure (Canada): Breccias in the basement of a deeply eroded impact structure

P11 **Nicolaysen, L.O.** : An "internal" origin proposed for Siljan, Dellen and Lappajärvi structures

P15 **Pirrus, E.** and **Tiirmaa, R.** : The meteorite craters in Estonia

P16 **Raitala, J.** and Halkoaho, T.: Shock metamorphic schists of Lake Jänisjärvi, Karelia

P12 **Rondot, J.** : Siljan before erosion

P13 **Saarse, L.** et al. : Formation of the meteorite crater at Lake Kaali (Island of Saaremaa, Estonia)

Papers not presented

Cohen, A. J.: Lappajärvi could be cryptovolcanic !

Collini, B. and **AlDahan, A.A.**: Geological results of the borings in the Siljan Ring structure, Sweden

Lakomy, R. : Sudbury (Canada): Implications for cratering mechanics from footwall breccia

Lakomy, R. : Implications for transient cavity dimensions of complex impact craters

Landström, O., **Collini, B.** and **AlDahan, A.A.** : Distribution of U, Th and REE in the rocks of the Gravberg-1 deep well, Sweden

LECTURE ABSTRACTS

in order of appearence

THE TERRESTRIAL IMPACT CRATER RECORD

Grieve, R.A.F., Geological Survey of Canada, Ottawa, Canada
Pesonen, L.J., Geological Survey of Finland, Espoo, Finland

Approximately 120 hypervelocity impact craters have been recognized on Earth, with 3 to 5 new discoveries being made per annum. The known record is a sample of a much larger population and is temporally and spatially biased towards geologically young, large craters on the cratons. For example, although known craters range from a few tens of thousands years to approximately 2 b.y. old, over 50%, are younger than 200 m.y. Terrestrial erosion serves not only to obscure the cratering record but also exposes impact structures to various depths. Thus, the terrestrial record supplies directly ground-truth data on the subsurface structural and lithological character of impact craters that is not available elsewhere. For example, it indicates, that simple, bowl-shaped craters have a sub-surface interior breccia lens and that the central structures of complex craters consist of shocked target rocks uplifted from depths of approximately 1/10 the final crater diameter. These types of observations provided much needed constrains on the nature of large-scale cratering processes. The record also supplies data on the average cratering rate in the Phanerozoic time and a means to evaluate such hypothesis as that suggesting the Earth is subject to periodic cometary showers.

The terrestrial cratering record will be presented in a form of global map. The map shows the craterform structures which are considered to be the result of the impact of interplanetary bodies with the Earth (see Grieve and Robertson 1987). The map and associated catalogue lists the crater names, their geographic coordinates, estimated crater diameters and ages. A special focus will be given to the impact craters of Fennoscandia (see Henkel and Pesonen, this volume). We will also highlight the major achievements and findings that have been obtained recently in the studies of terrestrial impact craters, and outline some of the most important, and yet unresolved, questions in the research of the craterform structures. Finally, we will describe some of the new methods and techniques that are available to answer these questions.

References:

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

Henkel, H. and Pesonen, L.J., 1990: Location map of impact crater structures in Fennoscandia. Geofysikrapport FRAP 90 401, April 15, 1990, SGU/Geofysik, 3 pp (with a map and list of Fennoscandian craters).

REMOTE SENSING OF IMPACT STRUCTURES

Garvin, J.B. and Schnetzler, C.C., NASA Goddard Space Flight Center, Greenbelt, MD, USA

Impact structures are ubiquitous landforms on the inner solar system planets, yet the record of impact processes on the Earth remains elusive, in part because of extremely rapid crater obliteration rates. Refinement of the terrestrial cratering rate requires systematic methods for discovering the "missing" population of craters predicted by current flux estimates (e.g., ~1000 with D>20 km in the past 1 AE). In order to assess how effective broad-area remote sensing (e.g., Landsat, SPOT, radar) surveys might be for targetting potential new impact sites, we have investigated the multispectral and radar backscatter signatures of a selected set of well-preserved impact structures. Together with youthful simple craters in various types of targets such as *Barringer* (sedimentary), *Lonar* (basalt) and *New Québec* (crystalline shield), we have analyzed the signatures of the three youngest complex craters in the Earth record: *Zhamanshin* (13 km, 0.87 Ma), *Bosumtwi* (10.5 km, 1.1 Ma), and *Elgygytgyn* (23 km, 3.75 Ma). In addition, we have developed techniques for analyzing detailed digital elevation data for structures as *Zhamanshin*, *Elgygytgyn*, *Popigai* (100 km, ~35 Ma), the *Ries* (22 km, 14.8 Ma), *Bigatch* (8 km, 6 Ma) and *Barringer* (1.2 km, 0.05 Ma). Our goal has been to develop objective and quantitative criteria for recognizing larger impact features in the Earth record on the basis of topographic, structural, textural, and spectral signatures and to use this information to search wide areas for which few impact landforms have been recognized (e.g., the Brazilian Shield). We have discovered that various impact related deposits (e.g., allogenic breccias, suevites, impact glasses and bombs) display diagnostic spectral signatures in the near infrared, and that preserved ejecta has a characteristic meter-scale texture (from radar scattering studies). In addition, we have been investigating the effect of target properties on initial crater morphology. Indeed, our Landsat Thematic Mapper studies of *Zhamanshin*, together with supporting field studies, suggest that the initial crater never displayed the classic geometry observed at (e.g.) *Bosumtwi*, perhaps as a consequence of target characteristics or due to an extremely oblique impact. Our analyses of the *Popigai* multiringed structure in the Anabar Shield indicate that only a subtle spectral anomaly remains associated with this tremendous impact, yet there is a well-defined topographic expression of the original crater geometry. We are led to the conclusion that the "main sequence" of crater morphologies observed on the Moon cannot be simply applied to the problem of reconstructing initial crater morphologies on the Earth; the final form of complex terrestrial craters appears to be controlled in part by target properties. We look forward to the observed record of complex impact forms on the planet Venus, which will be imaged at high resolution by NASA's *Magellan* radar mapper mission commencing in September of 1990. At least two *Popigai*-class multiringed impact features (*Klenova* and *Lise Meitner*) have been observed on Venus from low-resolution Earth-based or orbital radar images. Both of these structures display preserved ejecta regions and polygonal patterns of interior rings not unlike the topographic expression of similar features at *Popigai*. Perhaps the pristine surface expression of large, complex impact features on Venus (where a global crystalline crust is likely) such as *Klenova* and *Lise Meitner* will provide clues to the pre-erosional expression of such features on Earth's shield areas.

COMPARATIVE GRAVITY AND MAGNETIC STUDIES OF IMPACT STRUCTURES

Pohl, J., Institut für Allgemeine und Angewandte Geophysik, Universität München, München, F.R.G.

Impact structures show a great variety of gravity and magnetic signatures.

Gravity effects in the impact area are due to shock-induced modified density, structural modifications of preimpact target and postimpact erosion and sedimentation. Gravity data are used to delimit the extent of the structure, to determine internal structural elements and eventually depth estimates. Mass deficiency provides a means to estimate the impact energy. In small structures the gravity signature consists generally of a simple negative anomaly and the interpretation is not problematic. In large complex structures the gravity anomalies can be quite complex too. The separation of impact related anomalies from regional anomalies is often difficult and ambiguous. Field transformation techniques can be useful to reveal concentric impact related features.

The magnetic signature is due to the content of ferromagnetic minerals in the target rocks and in the impact formations. During heating of the target to high temperatures by the shock wave and during the postimpact cooling of the high temperature impact formations important mineralogical modifications can take place and very strong magnetization can be generated. Shock demagnetization and magnetization, brecciation and structural displacements also can alter the magnetic characteristics of the target rocks. The ensuing new or modified magnetic anomalies in the impact structure are used to localize these impact formations and their structural position and environment.

LAPPAJÄRVI IMPACT CRATER, GEOLOGY AND STRUCTURE

Pipping, F. and Vaarma, M., Geological Survey of Finland, Espoo, Finland

Lake Lappajärvi was early noted as a peculiar structure containing rocks considered to be volcanic. The impact origin was proven by the shock metamorphic minerals and textures found in the rocks of the crater. An almost circular gravity low of about 17 km diameter within the lake basin enhanced the impact crater theory.

The crater was drilled by the Geological Survey of Finland in 1988-89. The first research drillhole was placed 3 km NW of the centre of the crater. Three types of melt rock called kärnäite was met with in separate layers down to 145 m depth. Beneath was found suevite and impact breccia to about 175 m depth. Technical difficulties in drilling the impact breccia ended the hole at 217.75 m. The shock metamorphism was already low at this point .

The second hole was drilled also inside the crater but near the edge of the gravity low. With the results of wide-band electromagnetic soundings and a detailed gravity profile it was assumed that the hole would penetrate some kind of impact rock. However, after a very thick Quaternary overburden of 75 m had been drilled through, a layer of meso- to neo-proterozoic sediments was met with, about 20 m thick. The sandy-silty sediments are hardly consolidated and were discordantly deposited on strongly weathered micagneiss of paleo-proterozoic age. Unweathered fresh mica gneiss prevailed from about 130 m to 165.75 m were the drilling was ended.

The drilling results can be interpreted as follows:

- the layer of rocks generated by the meteorite impact is shallow near the centre of the crater.
- the meso- to neo-proterozoic sediments are situated in an annular down faulted shallow graben along the margin of the crater.

PETROLOGY AND MINERALOGY OF THE IMPACT MELT AND BRECCIAS IN THE DEEP DRILL CORE, LAKE LAPPAJÄRVI, WESTERN FINLAND

Lehtinen, M., University of Helsinki, Helsinki, Finland

The 1988 deep drilling down to 217 m at Lake Lappajärvi meteorite impact crater penetrated a sequence of 144 m of kärnäite (allochthonous impact melt) and ca. 5 m thick layer of suevite underlain by fine- to coarse-grained polymict breccia of the crushed target rocks.

The kärnäite layer is very homogeneous although its upper 24 m and lower 26 m has not a spherulitic glassy but crystallized dim melt matrix. The target rock inclusions consist of granite, granite pegmatite and granodiorite showing different degrees of shock metamorphism and assimilation. The quartz inclusions may be unshocked, fractured or filled with shock lamellae or show thermal effects (conchoidally broken 'ballenquartz') but always have a corona of orthopyroxene microlites. Feldspar inclusions are 'checker-board' plagioclase or consist of a felt of microlites. There are dark inclusions having a extremely fine-grained heart of spinel + magnetite (?) surrounded by crystallites of pyroxene and plagioclase or cordierite. The matrix glass contains crystallites of orthopyroxene, plagioclase and cordierite. The common cordierite is twinned to form 'cross-sexuplets' or 'stars'. Small black sulfide or metal spherules are common.

Chemically the kärnäite layer is extremely homogenous, e.g SiO_2 65.50 ± 1.34, Al_2O_3 15.44 ± 0.55, Fe_2O_3 (tot.) 7.09 ± 0.52, CaO 2.55 ± 0.12, Na_2O 2.90 ± 0.12 and K_2O 3.62 ± 0.24 (means with st. dev. of 29 whole rock analyses). Ni, Co and Cr are highly enriched in kärnäite relative to the target rocks.

The thin suevite layer is a polymict breccia which contains, in addition of to mineral and rock fragments of all the target rocks, vesicular, fluidal glass fragments, too. Fragments of quartz, feldspars and biotite show different degrees of shock metamorphism.

The basal polymict breccia is rich in rock and mineral fragments of mica gneiss and granite. The gneiss fragments may contain also garnet, sillimanite or tourmaline as main minerals. Fragments of skarn rocks and possible of siltstone, observed in the second drill core near the crater rim, are rare. Within 149 - 161 m the breccia consists of weakly shocked mineral fragments but within 161 - 175 m the fragments are more strongly shocked. In the lower part of the drill core the marks of shock rapidly weaken or disappear and the size of clasts (= rock fragments) increases.

PHYSICAL PROPERTIES OF KÄRNÄITE AND RELATED ROCKS IN THE LAPPAJÄRVI METEORITE CRATER, FINLAND

Kivekäs, L., Kukkonen, I. and Paananen, M.,
Geological Survey of Finland, Espoo, Finland

Drill hole logging results and petrophysical studies of 190 drill-core samples taken from the 218 m deep drill hole R-301 are reported. The logging methods included galvanic resistivity, electromagnetic conductivity, magnetic susceptibility, gamma-gamma density, natural radiation, and temperature. Apart from this, the hydraulic conductivity of the rocks was estimated with the help of pumping tests made during drilling. The drill core samples taken at 1 m intervals were measured in the laboratory for density, porosity, resistivity, susceptibility, natural remanent magnetization and P-wave velocity.

Logging results revealed that the rocks are very weakly ferrimagnetic with local spike-like highs which can attributed to local disseminations and pore fillings by pyrrhotite and possibly magnetite. Resistivity is relatively high with sharp lows at depths of fracture zones and occasional conductive sulphide minerals. Density variations were noted to reflect changes in mineral composition and porosity.

Petrophysical results correlate nicely with lithology. The drill hole intersects three types of shock metamorphic rocks: kärnäite (impact lava) from surface to the depth of 145 m, suevite from 145 to 150 m, and impact breccia from 150 to 170 m. The kärnäite layer consists of three zones. The top and the bottom zones have same magnetic susceptibility 730 x 10^{-6} SI and their mean densities 2585 and 2595 kg/m^3 are quite close to each other. These zones are petrophysically more homogenous than perlitic middle zone. The mean density, susceptibility, resistivity and porosity of perlitic kärnäite are 2530 kg/m^3, 490 x 10^{-6} SI, 20000 Ωm, and 1.0 %. The top and bottom kärnäite zones differ from each other in values of porosity (0.8 and 1.4 %) and resistivity (25000 and 3200 Ωm). The mean density, susceptibility, resistivity and porosity of suevite are 2295 kg/m^3, 220 x 10^{-6} SI, 50 Ωm and 18 %. Seismic P-wave velocity is about 5400 m/s in kärnäite and 3300 m/s in suevite. Unfortunately, samples of impact breccia disintegrated quickly in the water, and comparable measurements of density, resistivety and P-wave velocity were impossible.

GEOPHYSICAL INVESTIGATIONS OF LAKE LAPPAJÄRVI IMPACT STRUCTURE, WESTERN FINLAND

Elo. S., Jokinen, T. and Soininen, H., Geological Survey of Finland, Espoo, Finland

Interpretations of subsurface structure of terrestrial craters are needed in order to develop solid theories of cratering process comprising the whole range of crater types and diameters. A good way to do this is to carry out geophysical studies in connection of drilling. Aerogeophysical, gravimetric and electromagnetic wide band (Sampo EM) methods have been used to investigate Lappajärvi impact structure.

A circular negative Bouguer anomaly approximately 10 mgal in amplitude and 17 km in diameter is associated with Lappajärvi structure. The related mass deficit is 440 x 10^{14} g. Mean densities of different types of impact lavas range from 2530 to 2595 kg/m^3, and of different sets of mixed breccia and shocked bedrock from 2200 to 2400 kg/m^3. Mean density of a set of suevites is 2295 kg/m^3, and mean density of surrounding bedrock about 2700 kg/m^3. The Bouguer anomaly pattern suggests that there is a circular moat between the area of central uplift and the rim of the crater. There are positive residual anomalies between the circular moat and the centre of the crater. Lappajärvi structure seems to be of complex peak ring type.

According to aerogeophysical and gravity data, the cratering was controlled by approximately NE-SW and NW-SE trending pre-existing faults. There are few modest magnetic anomalies in the crater area, which is mostly characterized by a lack of magnetized material. Strong magnetic anomalies, which appear outside the crater, have been destroyed in the crater area.

A detailed 4 km long Sampo EM profile was measured radially across the circular moat between the centre and the rim of the crater. The profile coincides with one of the gravity profiles. The following three layers were interpreted. Thickness of the uppermost layer, mostly conductive overburden, is about 100 m and resistivity 65 - 200 Ωm. In the circular moat there is a 100 - 200 m thick layer of mixed breccia with resistivity of about 40 Ωm beneath the uppermost layer. The resistive lowermost layer depicts the base of mixed breccia. Some separate soundings were carried out near the centre of the crater. According to one of these soundings, there is a conductive layer of mixed breccia with resistivity of 30 - 40 Ωm beginning at depth of 140 m beneath the exposed impact lava.

MINERALOGICAL MODIFICATIONS IN GRANITE ROCKS FROM THE SILJAN IMPACT STRUCTURE

Ramseyer, K., Department of Geology, University of Bern, Bern, Switzerland
AlDahan, A.A. and Collini, B., Institute of Geology, University of Uppsala, Uppsala, Sweden
Landström, O., Studsvik Energiteknik AB, Nyköping, Sweden

Cathodolumiscence (CL) and chemical analysis of several minerals in the granitic rocks from the Siljan impact structure have revealed distinctive features. Quartz shows three CL colours; non-luminescent, pinkish-red and bluish. The latter quartz type dominates in granites where bright-blue K-feldspar and bright-yellow and pink plagioclase are common. Bluish quartz also dominates in cataclastites and mylonites.

Pinkish and non-luminescent quartz dominate in the upper 2000 m of the Gravberg-1 well and within a 3 - 5 km radius of the well. Non-luminescent quartz is also found as fracture fillings. Feldspars in the granites show mostly dull, brownish and pale-brown CL colours corresponding to low temperature pure orthoclase and albite end members.

The mineralogy supports textural evidence of localised post-magmatic modifications related to the impact itself and to post-impact fluid circulation.

GEOPHYSICAL ASPECTS OF IMPACT CRATERS IN ERODED SHIELD ENVIRONMENT

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The impact cratering process removes huge amounts of crustal materials, transforms some into a melt sheet, and brecciates a still larger volume of the upper crust. Remaining structures are only marginally changed in their geometry but subsequent crater wall collapse forms a ring shaped structure on top of the unroofed basement. Erosion continuously produces a wide range of situations with variable contrasts in rock physical properties and, as a consequence, very variable geophysical anomaly patterns. As crater sizes increase, the pre-crater structures tend to dominate in potential field anomalies. As erosion continues smaller craters will disappear while the central uplifts of larger craters continues to be an anomalous structure visible in the gravity field. The last remaining feature is the low electrical resistivity caused by the brecciation of the crater surroundings. This abundant brecciation also promotes more extensive oxidation and a decrease in magnetic susceptibility. Created melt sheets often have a dominant remanent magnetization which together with the shallow distribution causes highly irregular magnetic anomalies.

THE NEWLY IDENTIFIED LOCKNE IMPACT, JÄMTLAND, SWEDEN

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The Lockne area has for almost a century been known for its exceptional Lower Paleozoic geology. Its features can now be related to the existence of a medium-sized impact. The principal evidence for the impact is 1) a regionally distributed breccia consisting of intensely crushed rocks from the local Proterozoic basement, for which there is no other reasonable explanation, 2) a subcircular depression of the basement with a radius of almost 4 km about which the distribution of the breccia is concentrated, 3) the presence of shocked quartz and clasts of melt in local post-impact sediment. The following sequence of events is deduced to have occurred. Soon after the beginning of Middle Cambrian alun shale sedimentation a meteorite struck near Tramsta farmhouse to the west of lake Locknesjön. The meteorite was not large enough to form a central melt (magnetometric evidence) but crushed the local bedrock very intensely thereby forming the so-called arkose-like breccia, excavated a crater at least a couple of 100 m deep and nearly 8 km wide, and a concentric system of minor faults just outside the crater. After being covered by normal facies Middle to Upper Cambrian and Lower to Middle Ordovician sediment, the crater area was affected by a drastic lowering of sealevel in the early Caradoc. As a result the limestones and shales of the normal facies deposited on the raised crater rim were destabilized and formed debris flows, which constrititute the second major breccia of the area, and the most spectacular one. This so-called Lockne Breccia contains megaclasts of the major earlier lithologies, including the arkose-like breccia, as well as shocked quartz and fragments of impact melt. The circumstance that they were included in the Lockne Breccia has led to the interpretation that this breccia is indeed the impact breccia. However, this interpretation leaves the arkose-like breccia as well as other features of the area without explanation.

PALEOMAGNETISM AND THE SILJAN IMPACT STRUCTURE, CENTRAL SWEDEN

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The Siljan impact structure is considered the largest meteorite crater in Western Europe. With the aim of identifying magnetizations related to the impact, a paleomagnetic study of preferentially dolerites occurring inside and outside the impact structure was carried out. Four different generations of magnetizations were defined in the dolerites outside the structure. This was used as a reference for unshocked dolerites when studying the dolerites within the impact area. In the central part of the structure, where the rocks have been subject to intense shock (>17 GPa), three different components of magnetizations were identified, all different from those recognized in the "undisturbed" dolerites. These components were isolated in order of increasing coercivity (Hc) and blocking temperature (T_B). The high Hc and T_B component is carried by hematite, which was formed in oxidizing conditions caused by circulating meteoric water in the fractured rock after the impact. Another component is identified in a lower T_B range and probably carried by magnetite. This magnetization was isolated in pseudotachylite and related dolerites and is interpreted to originate from the impact. Whether its origin is a Shock Remanent Magnetization (SRM) or a Thermal Remanent Magnetization (TRM) will be discussed. A third low Hc and T_B component is interpreted as a late post-impact magnetization probably carried by goethite.

PALAEOMAGNETISM OF THE LAKE LAPPAJÄRVI IMPACT STRUCTURE, CENTRAL-WEST FINLAND

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We have carried out an extensive palaeomagnetic study of the Lake Lappajärvi impact structure located on a Proterozoic (1.9 Ga) Svecofennian terrane in the Fennoscandian Shield, Central-West Finland. The study is an extension of our earlier pilot study (Pesonen et al., 1984). Altogether 60 oriented samples were collected of which 40 yielded useful palaeomagnetic data. Petrophysical properties (susceptibility, density, Koenigsberger ratio) together with magnetic hysteresis properties and Curie-points were measured to study the nature and origin of the NRM and to identify the remanence carriers.

The NRM in the melt rocks is generally very weak (Jr < 100 mAm^{-1}) and semistable during a.f. or thermal demagnetization. The characteristic NRM component is carried mainly by pyrrhotite (causing the poor stability) and yields a mean direction of D = 32.6°, I = 54.5° (k = 116.5 , α_{95} = 6.2°, N = 6 sites) with a palaeomagnetic pole of Lat = 55.6°N , Long = 151.6°E (dp = 6.2°, dm = 8.8°). The pole position suggests a remanent magnetization acquisition age of ca. 200 Ma, when plotted on the European or Fennoscandian APW master curves. The palaeomagnetic data from the first 140 meters of the deep drill core R 301 (see Kivekäs et al., this volume) are generally consistent with the data from the surface rocks although the drill core data display a slightly shallower inclinations and occasional anomalous declinations. The anomalies are probably caused by the errors in the drill core orientations.

The "palaeomagnetic" age obtained from the melt rocks differs from the ^{40}Ar-^{39}Ar radiometric age of 77 Ma for the Lappajärvi impact event (Jessberger & Reimold, 1980). The discrepancy is explained either by the "spot-nature" of the NRM (i.e., the long-term secular variation of the Earth´s magnetic field is not averaged out), or by the local structural tilting that the impact melt layer has suffered after the acquisition of the NRM. The required structural tilting is only 15 degrees and may have taken place during the late stages of the crater rebounds.

The above mentioned impact related NRM component (Lappajärvi component) has also been isolated from three lithologically different Svecokarelian basement rocks around the lake as a weak and poorly determined (shock?) overprint in both thermal and a.f. demagnetization treatments. On the other hand, the basement rocks also retain their primary "non-impact" component with a typical 1.9 Ga old remanence direction supporting the impact cause for the Lappajärvi component. Thus the palaoemagnetic evidence supports the concept reached earlier through gravity, aeromagnetic, mineralogical, petrological, and geochemical data, that the Lake Lappajärvi craterform structure is a geologically young (less than 200 Ma) impact site, caused by a hypervelocity body.

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THE SLATE ISLAND METEORITE IMPACT SITE: A STUDY OF SHOCK REMANENT MAGNETIZATION

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A secondary component of remanent magnetization at the Slate Islands impact site, Canada, appears to be a Shock Remanent Magnetization (SRM) on the basis of field relationships, models of impact crater formation and laboratory investigation.

Evidence for this rare type of naturally-formed remanence is that:

(a) the component is confined to rocks having experienced intense shock (50 to more than 100 kb) on the basis of shatter-cone development and the presence of planar features in quartz and feldspar,

(b) the component appears to have been acquired instantaneously in terms of normal geological processes as a combined paleomagnetic-shatter cone analysis suggests that it was formed within a time interval (perhaps several minutes in duration) between the moment of impact and the formation of the central uplift,

(c) the extent of magnetic resetting decreases with increasing distance from the centre of the impact site, and

(d) the degree of resetting increases with the abundance of low coercivity magnetic grains as given by H_{cr}, a relationship found by other investigators for experimentally-produced SRM.

Intrusive breccias found on the islands yield a secondary component of TRM or TRCM origin which was frozen in after central uplift formation. Increased convergence of shatter cone axes to a central focus after rotation of host rock blocks according to palaeomagnetic data, suggests that the SRM had a same direction as that found in the breccias and hence was aligned with the ambient field at the time of impact.

ON THE SEPARATION OF SHOCK COMPONENT AT LONAR IMPACT CRATER, INDIA - A STUDY OF MULTICOMPONENT NRM

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Lonar Lake (19°59'N, 76°34'E) is a unique feature in the Deccan Traps in Buldana district of Maharashtra state. It is now considered to be a meteorite impact crater on the basis of several studies carried out over the last century and quarter. One of these includes magnetic (Bhalla et al., 1974) and paleomagnetic (Poornachandra Rao and Bhalla, 1984) evidences which also support a meteorite impact origin for this crater. The laboratory alternating magnetic field demagnetization data has been examined by analytical methods such as Zijderveld diagrams, vector difference analysis, converting circles of remagnetization etc., to isolate the shock component and to assign the probable age of meteorite impact. Upon examination of vectors that were cancelled in very low fields of 5 - 10 mT, a secondary component of D = 9° and I = +47° (k = 47.66, α_{95} = 6.41°) has been isolated by vector difference analysis which is very much similar to the magnetization in the present field at the site while the stable primary vector is similar to that of Lower Tertiary period reverse magnetization. This component of secondary shock magnetization is in support of other age estimates of meteorite impact by fission track dating of shock melted glass, geomorphological features and sediment thickness studies of Lonar Lake.

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SÖDERFJÄRDEN, WESTERN FINLAND - A CAMBRIAN-FILLED METEORITE CRATER 100 KM WEST OF LAPPAJÄRVI

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In the middle of the 1970's, geological interest was directed in a strikingly circular field, Söderfjärden, with a diameter of about 5 km, situated on the western coast of Finland. Bedrock is not exposed up to the crater rim and consists of an inhomogenous porphyritic granitoid, the Vaasa granite. The circular depression was first thought to be formed by block faulting, especially as only subordinate deformation was found in blocks of the Vaasa granite. A concentric gravity anomaly of -6 mgal and seismic velocities soon suggested Söderfjärden as a crater, volcanic or meteorite-excavated. First drillings confirmed the existence of a central uplift, 40 m below surface, consisting of finely crushed material chemically identical to the Vaasa granite and without any signs of a lava. The most clear shock effects are shock lamellae of quartz in the crushed bedrock, but such features are relatively rare. Further drilling revealed a lower ring-shaped infill of Cambrian shales and sandstones around the central uplift at depths of 84 - 318 m. The crater can then probably not be younger than 550 Ma. At the drilling site to the deepest point of the crater bottom, 1300-1400 m off-center, the bedrock only contains very weak shock effects like kinked and deformed minerals. On the basis of the geophysical data as well as the not strongly developed mineralogical shock effects and including the suggestive general geological setting, Söderfjärden is an old meteorite-impact crater, the impact effects of which were possibly reduced by a shallow Cambrian sea existing at the impact site.

In comparison with the near-by Lappajärvi impact crater, only 77 Ma in age, the Söderfjärden site is much older and yet well preserved because of its sedimentary infill. Besides, Söderfjärden is decidedly smaller and less deformed by the impact.

ORDOVICIAN IMPACT CRATER AT KÄRDLA, ISLAND OF HIIUMAA, ESTONIA

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During the post-impact history the crater at Kärdla was buried under a cover of marine sediments (20 - 140 m). Most of more than 100 bore-holes locate on the ring wall and also in the crater proper and its surroundings. Gravimetry and magnetic contour maps well discover the location of the crater structure.

Environments in the time of cratering have been established: a shallow-water shelf near to the northern shore-line of the Ordovician Baltic epicontinental sea. The geological sequence of the target during the cratering, from the top: (sea water 20 m) Middle and Lower Ordovician limestone 15 m, Cambrian and Vendian sand and clay 140 m, Precambrian crystalline rocks 185 m (upper part 5 - 45 m, weathered). The biostratigraphically determined level of the layer of reworked impact-derived debris in the unerupted succession of marine sediments outside the crater - lowermost part of the Idavere Regional Stage, Lower Caradocian - corresponds to the age of 455 Ma.

Lateral dimensions of the impact structure:

Diameter of the crater (on the top of the buried ring wall)	4 km
Diameter of the crater on the level of target surface	3.3 km
Diameter of the uplifted area outside the crater, which in Idavere time occurred as a ring-shaped island in the sea	12 km
Diameter of the area with impact-derived debris layer (0,03 - 20 m thick) in the Idavere Stage	not less than 50 km

Vertical dimensions:

Depth of the crater below the target surface		400 m
Height of the wall above the target surface		0 - 100 m
Height of the central high		50 m
Thickness of fall-back sediments:	in the crater	up to 50 m
	outside the wall	0 - 14 m
Thickness of the upper layer of fall-back sediments reworked [in the back current conditions]:	in the crater	up to 120 m

Shock metamorphism from the stage of planar deformation structures and diaplectic glasses up to the stage of partly melted rock has been fixed in the autochtonous breccia of the central high and in the fall-back breccia in the crater.

TRACES OF A FEW IMPACT CRATERS IN THE GRAVITY FIELD

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Traces of a few meteorite impact craters are clearly recognizable as anomalies in the Earth's gravity field. The Manicougan crater of Canada as well as Lappajärvi, Sääksjärvi and Paasvesi craters of Finland are given as examples. The study is made using available Bouguer gravity anomalies and high resolution geoids computed for this purpose.

THE CONCENTRIC STRUCTURE OF CENTRAL FINNISH LAPLAND, AN ASTROBLEME?

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The highly magnetic central part of the schist belt in Central Finnish Lapland forms a circular segment 80 km to the north of its curvature center located in lat = 66°86' N and long = 25°18' E. The arc continues to the south as the Peräpohja schist belt but is more asymmetric there. Inside the arc occur mainly Early Proterozooic granitoids and Archean gneisses, while the arc itself consists of clastic and pelitic sediments plus volcanic and some plutonic rocks. The iron, copper and gold deposits are concentrated at distances of 80 to 115 km from the centre. The age of the volcanism varies from 2213 to 1834 Ma. The granite complex partly belongs to the rare age interval from 2216 to 2136 Ma and partly to the late Svecofennian interval from 1843 to 1770 Ma.

The granite is fairly magnetic (M=0.6 A/m with Q=0.2) and light (ρ=2595 kg/m^3). It causes a fractured anomaly pattern within 30 km of the centre, but elsewhere the magnetic anomalies are linear. The Bouguer anomaly is 35 mGal higher in the central part of the structure than near the schist belt. This corresponds to a 2 km thicker mafic mass below the centre. The average Bouguer gravity inside the circle of r=80 km roughly equals the modal Bouguer anomaly of Northern Fennoscandia (-31 mGal). Thus the masses of the structure seem to be isostatically compensated as a whole and there must be dense counterpart of the light granite at depth.

If the structure is an astrobleme the initial crater depth was of the order 16 km with the crushing of the rock extending well below the Moho and fractures reaching the lithosphere - astenosphere boundary. The ejected mass would have been compensated by intrusion of mafic magma above the Moho. The intrusion may have been 14 km thick in its central parts. The transported heat partially melted the 30 km thick crust above it and fluids removed iron and other metals. The granite preserved remnants of original structures in the form of variations in magnetite content. The schist belt and ore deposits were formed from the rim, extruding magma and fluids during the filling of the crater and cooling of the chamber. The original ring structure was distorted in its southern parts during the following Svecokarelian orogeny.

TRACES OF ANCIENT MEGA-IMPACTS ON THE BALTIC SHIELD

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The Study of Landsat imagery in the near-infrared wavelengths covering the Baltic Shield shows faint traces of quasi-circular and arcuate structures of variable size and grades of distinctiveness.

The possible cosmogenic origin of these major structures is discussed. It implies that they represent the sequential inheritance of very old, deep weakness zones, throughout geological time. This, in turn, implies certain constraints regarding early crustal evolution and crustal thickness. Some aspects of this problem are discussed.

Some of the largest of these structures are thought to be implied in ore genesis and in the formation of the ore provinces. Various mechanisms of ore formation related to impact are discussed. In a general manner, the main effect of giant impacting is to produce thermally, and thus geochemically anomalous portions of the crust. These might slowly develop to become metallogenic provinces.

A strongly brecciated column of crust resulting from impacting, associated with localized zone of deep endogenic thermal activity is known to be favorable to certain types of ore bodies.

RECONSTRUCTION OF THE NOUVEAU-QUÉBEC CRATER (UNGAVA) AND PLEISTOCENE EROSION OF THE GLACIATED CANADIAN SHIELD

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The Nouveau-Québec (NQ) meteorite crater is a near-perfectly circular bowl shaped depression, more than 430 m deep and 3.4 km in diameter. Its Pleistocene age of 1.3 Ma was established by ^{39}Ar-^{40}Ar laser dating of impact melt rocks discovered in 1988. Total amount of erosion of the Shield surface in Ungava is deduced from reconstruction of the original crater rim height based on dimensional analogies with lunar craters and structural models including subsurface data derived from other comparable terrestrial craters, notably Brent in Canada and Barringer in Arizona. Total erosion of the rim is estimated to be from 41 to 63 m, yielding an average rate of erosion of about 40 mm ka^{-1}. At this rate the crater rim would be erased from the Shield surface as a positive relief feature in about 3.25 Ma. Assuming a thickness of 700 m for the allochtonous breccia below the present crater floor, the crater would be completely erased in an additional 17.5 Ma. Estimates of glacial erosion based on the volume of hornblende in till dispersed from the rim range from 1.5 to 3 m during the last glaciation suggesting that much of the erosion of the NQ crater was achieved through earlier glacial cycles. The age distribution of 22 craters on the Canadian Shield indicate that the estimated Pleistocene rate of erosion, due mostly to glacial action, is considerably higher than the average Phanerozoic erosion rates. Small craters less than 400 Ma old (West Hawk Lake, Ile Rouleau) are still recognisable indicating average rates not exceeding 10 mm ka-1. Small craters older than 400 Ma (Brent, Holleford, Pilot Lake) that should have been eroded are still preserved because of a protective Paleozoic sedimentary cover from which they were later exhumed.

SEARCH FOR THE SOURCE CRATER OF THE AUSTRALASIAN STREWN FIELD

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The youngest large terrestrial impact occurred approximately 700,000 years ago in southeast Asia, but the crater has not yet been identified. The only evidence we have for this impact is the large amount of ejecta, in the form of tektites on land and microtektites in drill cores from the sea floor, found over about one-tenth of the Earth's surface. Size, abundance and aerodynamic ablation evidence indicate that the source should be somewhere within or near Indochina. We examined the oceanic areas near Indochina through sea surface height as measured by Seasat (to look for traditional central negative anomaly associated with impact craters). An extremely large surface depression of approximately 1.5 meters over an area of 100 km diameter, centered at 13°47'N/110°37'E, was discovered; this corresponds to a gravity anomaly of about -50 mgal. There is a sea floor topographic depression of more than 200 meters in part of this gravity anomaly. We recently proposed that this anomaly may be due to the impact structure which produced the Australasian strewn field.

To this hypothesis, we examined the distribution and density of sites, heterogeneity of chemical composition, and size of samples of both the Muong Nong and splash form-type tektites in Indochina. These data do not support (or refute) our proposal of an off-shore origin. They do point, however, to an approximately 250 km diameter area in eastern Thailand and southern Laos (centered at about 16°N/105°E) as a likely area for the source crater. We have examined a detailed digital elevation data set for Indochina. Several candidate structures were found, but the most promising is a 35 km diameter circular feature in south Laos, on the edge of the coastal mountain range, within the area previously suggested by chemical and physical evidence from tektites. This structure, centered at 16°20'N/106°09'E, has an extremely flat floor which is completely encircled by hills elevated 100 to 400 meters above the floor level. There is also an elevated structure in the middle which rises about 100 meters above the floor. At this time we feel both the off-shore and the Laos structures are prime candidates; the off-shore anomaly should be examined geophysically and field work at the Laotian structure should provide evidence as to its origin.

Rb-Sr AND Sm-Nd-DATING OF IMPACT MELTS: DELLEN (SWEDEN) AND ARAGUAINHA (BRAZIL)

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The discussion about periodic impacts on Earth, and the possible connection of large cratering events with mass extinctions demonstrate the urgent need for precise dating of impact structures. For Dellen, published ^{40}Ar-^{39}Ar-degassing spectras for the impact melt resulted in "plateau ages" ranging from 230 Ma to 100 Ma (1, 2). Such a large variety points to significant $^{40}Ar_{excess}$ in the melt lithology which still may be present in the sample with the lowest "age". As incomplete degassing during shock melting is frequently observed, even well defined plateau ages need further confirmation using other decay schemes.

Therefore we analyzed an impact melt from Dellen consisting of exceptional fresh glass, H-shaped labradorite laths and orthopyroxene. An internal Rb-Sr-isochron using handpicked mineral fractions and the corresponding WR yields a precise age of 90.3 ±1.5 Ma (I_{Sr} = 0.83573 ± 0.00003; 2σ) for the Dellen event. Sm-Nd data of the identical mineral separates just point to a complete Nd isotope homogenization during melting, yet the young age prevent dating by this method. $T_{DM}{}^{Nd}$-ages for the impact melt of 2.3 Ga and $\varepsilon_{Nd}{}^{T=90Ma}$ of -19 confirm an exclusively crustal origin for the impact melt.

For Araguainha in Matto Grosso, Brazil (16°46'S, 52°59'W), we do not get unequivocal ages. An internal Rb-Sr-isochron of 450 ±9 Ma (I_{Sr} = 0.7140 ± 0.0007) set a lower limit for the intrusion of the uplifted alkaligranite in the centre of the structure which is shocked to ~28 GPa (3). Preliminary Rb-Sr-data on K-feldspar separates from the silica-rich impact melt (ε_{Nd} = -13; $T_{DM}{}^{Nd}$ = 1.74 Ga) give an upper limit of 280 ± 6 Ma for the Araguainha event. This age conflicts with the stratigraphically derived age, as the Passa Dois Formation of Lower Permian age was comprised by the impact (3). Extremely fine grained sericite, pseudomorphous after cordierite (?) with a Rb-Sr-model age of 238 ±3 Ma set a strict lower age limit for the Araguainha Structure. The data point to lack of Sr isotope homogenization as well as to post-impact reopening of the Rb-Sr system; both phenomena are commonly recorded in terrestrial impact melts.

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^{40}Ar-^{39}Ar DATING OF SOME FENNOSCANDIAN IMPACT CRATERS

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^{40}Ar-^{39}Ar age measurements were made for three whole rock melt samples produced during impact events which formed the Dellen, Jänisjärvi, and Sääksjärvi craters on the Fennoscandian shield. An age of 109.6 ± 1.0 Ma was obtained for the Dellen sample based on an age spectrum plateau. The age spectrum shows a small (7%) loss of radiogenic ^{40}Ar from the low temperature fractions. Ages of 698 ± 22 Ma and 560 ± 12 Ma were obtained from isochrons for the Jänisjärvi and Sääksjärvi samples, respectively. Data obtained by laser degassing support the Sääksjärvi result. The presence of excess ^{40}Ar is indicated in lower temperature fractions of both samples and is correlated with K concentrations in the Sääksjärvi sample. Models explaining these results may require a change in the local "atmospheric" Ar isotopic compositions as cooling of the melt rocks proceeded. However, it cannot be excluded that devitrification and or alternation changed the Ar budget.

PROBABLE IMPACT MELT ROCKS AT THE SEVETIN STRUCTURE

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The Sevetin circular structure has been described as a strongly eroded and faulted impact structure, D=46 km (Vrána 1987, 1988, 1989). Two types of dyke rocks - quartz monzodiorite and microgranodiorite - in the central uplift and in the area of the former circular trough are interpreted as probable injections of impact melts in the fundament. K-Ar dating on dyke rock (Jessberger and Buzek, 1987) gave 228 - 277 Ma (3 samples). Extensive chemical data, including concentrations for 53 elements in dyke rocks will be presented. Microgranodiorite has chemistry closely comparable to the regional sillimanite-biotite paragneiss. Monzodiorite, though similar in composition to mafic granulite, has REE and Th/U which indicate an additional strongly differentiated component (? cover sediments). Concentrations of Ir, Ni, Cr, Co and Mg show that microgranodiorite and monzodiorite could be derived from ordinary crustal rocks plus 5 - 7 wt.% of a component similar to primitive mantle.

Lechatelierite, very fine-grained skeletal zircon, Cr-bearing ilmenite, and and the presence of four pyroxenes (monzodiorite) point to very high temperatures during the early stages of dyke rocks solidification and to high cooling rates in the range of high temperatures. Chlorite spheroids (distinct from local vesicles), persistent through all known localities of monzodiorite, are interpreted as former drops of an immiscible melt. These features support interpretations of monzodiorite and microgranodiorite as impact melt rocks.

Since excavations of transient craters must be accompanied by a brief opening of fractures in fundamental, it is suggested that injection dykes of impact melt may represent the relatively more projectile-contaminated (pivotal) portions of melt and they may betray former existence of impact structures in significantly eroded areas.

POSTER ABSTRACTS

in alphabetical order by authors

REGIONAL GEOPHYSICAL INVESTIGATIONS IN THE SILJAN RING AREA, SWEDEN

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The Geological Survey of Sweden (SGU) makes regular airborne magnetic, electromagnetic (VLF) and radiometric measurements as well as gravity and petrophysical measurements within the geological mapping programmes. For current work, the airborne measurements are made at a flight altitude of 30-40 metres and a line spacing of 200 metres.

The results of the airborne geophysical surveys in the province of Dalarna show that the meteorite impact some 360 million years ago created a structure which today has an outer diameter of about 45 km. Interesting to note is that the magnetic anomalies, caused by the steeply dipping NNW-SSE trending dolerite dikes (900-1000 Ma), are almost continuous across the Siljan Ring area and nearly undisturbed by the impact. The airborne VLF (Very Low radio Frequency) data contribute, in an excellent way, to define the lateral distribution of the paleozoic rocks in the Siljan Ring and naturally to delimit the water filled fracture zones (inside and outside the Ring); both features have higher conductivities than the surrounding Proterozoic rocks. The frequency of fracture zones is considerably increased in the central uplift of the structure. Furthermore the geophysical and geological information show that the eastern part of the Siljan Ring structure is on a border zone between the oldest Svecokarelian rocks in the east and the postorogenic Svecokarelian rocks in the west. This border zone coincides with a geophysically well defined north-south striking fault zone, here called the East Siljan Fault Zone (ESFZ). A preliminary quantitative interpretation of the geophysical data indicates that the contact between these old and young Svecokarelian rocks is steeply dipping and that both rock units have considerable depth extensions.

Examples of geophysical, geological, and altitude maps of the Siljan Ring area and some interpretation profiles will be presented.

THE ONAPING FORMATION OF THE SUDBURY STRUCTURE (CANADA): AN EXAMPLE FOR ALLOCHTHONOUS IMPACT BRECCIAS

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The Sudbury Structure is considered as the deeply eroded remnant of a multi-ring basin (1). The polymict breccias of the Onaping Formation (OF) are underlain by the 1.85 Ga old (2) Sudbury "Igneous" Complex (SIC) which is composed of a noritic and a granophyric layer. From bottom to top the OF consists of Basal-, Gray-, Green- and Black Member (3). The SIC and the lower part of the OF (Basal Member) are interpreted as the impact melt system (1, compare also 4). The nature of the OF was discussed controversially (5,6) but all geological and petrographical observations can be satisfied by an impact origin. The Basal Member is characterized by a crystalline matrix consisting of K-feldspar, pyroxene and quartz with granophyric to quench textures. Based on chemical and isotopic analysis the fine to medium grained matrix is fairly homogeneous on a small scale (7). The high fragment content of this breccia layer mainly consists of metasediments of the Huronian Supergroup whereas Archean lithologies from the basement are nearly absent. In the upper part of the impact melt ("granophyre") a similar fragment population is observed. Due to the heat of the impact melt many fragments are corroded or even disintegrated and shock metamorphic features were obliterated. The overlaying suevetic breccias ("Gray Member") show a clastic matrix. Rock and mineral clasts in this unit display shock metamorphic features, and recrystallized irregularly shaped melt particles and bombs are frequent. Breccia bodies within these breccias and internal contacts found during mapping give evidence for turbulent movements during the emplacement of the Gray Member. Derived from the petrographic character the lower part of the Gray Member is interpreted as ground surge which grades into fall back breccias as documented by aerodynamically formed melt particles and a decreasing fragment size. The continuous uniform breccia layer ("Green Member") on top of the Gray Member is characterized by a microcrystalline matrix with filled vesicles and a high content of small mineral clasts (3). The Green Member is unique compared to other impact structures. The uppermost unit of the OF ("Black Member") consists of two different breccias. While the lower part still shows petrographic features of suevitic breccias, the upper part is dominated by lithic fragments and altered "glassy" fragments. Clast population and size, an increasing carbon content in dark, clastic matrix, and sedimentary structures as well as signs of multiple brecciation indicate that the uppermost unit originated as washed-in material (1) originally deposited outside of the crater. The chemical variation observed in the breccia sequence (Gray and Black Member) was severely disturbed during the Penokean orogeny (7, compare also 3).

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SUDBURY IMPACT STRUCTURE (ONTARIO, CANADA): ISOTOPE SYSTEMATICS

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In the 1.85 Ga old Sudbury Structure (1) several breccia units forming up to 1800 m thick layers beneath and on top of the impact melt ("Sudbury Igneous Complex") are seen as crater floor and suevitic formations (2, 3). Sr-Nd isotope data for components of such polymict rocks help to identify precursor materials, and therefore, to test cratering models.

In the Sudbury case, all impact-related formations (cf.3) display rather uniform $\varepsilon_{Nd}{}^{T=1.85\ Ga}$ values clustering at -10, and $T_{DM}{}^{Nd}$-ages ranging from 2.7 to 3.2 Ga. These signatures match data for the unshocked Archean basement. Thus Sm-Nd fractionation by sedimentary processes prior to the impact, by shock melting and the brecciation event itself, or during weak post-impact regional metamorphism seems very unlikely.

Sr isotope parameters of the impact melt, as well as of matrix and most lithic fragments from the suevitic Lower Onaping Formation correspond to data for evolved crustal rocks in the Superior and Southern Provinces. Yet, low and scattering $\varepsilon_{Sr}{}^{t=1.85\ Ga}$ values for "glassy" particles and for highly shocked clasts in these suevitic breccias indicate precursor lithologies from the lower crust which is not supported by our petrographic observations.

In T_{UR} vs. $1/f_{Rb}$ diagrams proposed by (4), an age around 1.6 Ga can be derived for the last prominent Rb-Sr fractionation in the upper part of the impact melt and in the suevitic rocks of the Lower Onaping Formation. This reopening veils primary Sr isotope characteristics to a great extent. However, data array for both units point to a prominent contribution by Huronian metasediments. Such an information is not provided by the widely used ε_{Sr} - ε_{Nd} plots.

References:
(1) Pye et al. (eds.) Ontario Geol. Survey. Spec. Vol. 1 (1984)
(2) Deutsch et al. (1989) EPSL 93
(3) Avermann & Brockmeyer (1990); Müller-Mohr (1990); Lakomy (1990) this volume
(4) Shaw & Wasserburg (1982) EPSL 60

RECENT STUDIES OF LAKE SÄÄKSJÄRVI METEORITE IMPACT CRATER, SOUTHWESTERN FINLAND

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Regional gravity and airborne magnetic, electromagnetic and radiometric measurements have been carried out in the area of Sääksjärvi impact structure. A circular negative Bouguer anomaly -6.5 mgal in amplitude and 5 km in diameter is associated with Sääksjärvi impact structure. The crater area is mostly characterized by lack of magnetized material. Strong magnetic anomalies, which appear outside the crater, have been destroyed in the crater area. Conspicuous aeroelectromagnetic anomalies are associated with crater area indicating resistivities from 10 to 50 Ωm for the uppermost layer.

Impact lavas or suevites do not outcrop anywhere in the crater area. In order to get samples of material in the crater, four drill holes were planned on the basis of geophysical interpretations. Drilling requires a strong ice-cover and must be carried out in the winter, since all the drilling sites are situated on the lake. The first hole was drilled in late winter 1988 in the western slope of the crater. The aim of this drilling was to get a cross-section of the impact formation into mildly shocked bedrock with a shallow hole as quickly as possible.

The drilling commenced and proceeded 105 meters in brecciated mica gneiss with zones of aphanitic impact breccia up to some meters each. Some undeformed tonalitic blocks were drilled through. Impact lava was not encountered. Poor ice conditions owing to mild winters have prevented completion of the drilling program.

Petrophysical measurements of drill core samples indicate abnormally low densities and high porosities for most of the samples.

Major and trace element chemistry of rocks from drill core, of impact lava and breccia boulders, and of country rocks will be presented.

TUFF BRECCIA FROM THE WESTERN PART OF THE DELLEN STRUCTURE, SWEDEN

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The Dellen Lakes (lat. 61°50'N., long. 16°45'E.) situated approximately 300 km NNW of Stockholm, have been well established in literature as an impact site. According to Wickman (1988), the extension and stratigraphy of the Dellen rocks is not well known, due to lack of outcrops. However, dellenite, tuff breccias and tuff dominate.

We here report the findings of tuff breccia blocks accumulated outside the western edge of the structure. The area is free from outcrops.

In October 1949 one of us (SR) made a reconnaissance trip to the Dellen area, after a breccia block had been pointed out by the late professor J. Frödin. A preliminary block mapping showed a concentration around Änga, approximately half-way between Delsbo and Bjuråker.

During 1989 a reinvestigation of the tuff breccia material was initiated and the tuff breccia localization was confirmed in field.

The localization is approximately SW of the center of the structure. The late Weichselian ice movement is more or less toward SE. The finding of the tuff breccia could be explained by one of the following assumptions:

1) The material emanates from the NW edge of the original crater and was deposited by the ice.
2) The Lake Dellen structure has generated local turbulence of the ice flow.
3) The tuff breccia is short-transported from the underlying bedrock by the ice movement.
4) Post impact tectonic deformations have caused a relative movement of the site towards NW.

The authors tend to support an explanation based on above mentioned point 3, perhaps in combination with 4. However, core drilling in the area is necessary before a final answer may be given.

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IMPACT CRATERS IN FENNOSCANDIA AND BALTIC REGIONS

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A map has been prepared showing the known meteorite impact craters in Fennoscandia and the Baltic Regions. A number of other rounded structures, many of which could be interpreted as impact craters are also displayed. Altogether 53 sites are documented. The map includes an Appendix (catalogue) which lists the crater names, the Nordic country, their coordinates (Lat., Long.), morphological character types, the crater diameters of each crater, approximate age (Ma), method used to identify its extraterrestrial (or non) origin, evidence class (range from A (strong) to D (suspect)), and status of documentation. Methods used to identify the crater as an extraterrestrial (impact) crater include topographical, magnetical, gravimetry, electromagnetism and geology (lithology, geochemistry etc.).

THE LAKE DELLEN IMPACT CRATER, SWEDEN

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Detailed geophysical and geological maps are presented for the Lake Dellen crater, including aeromagnetic, gravity, VLF, radiation, and petrophysical measurements. The different major rock types are also displayed.

SILJAN IMPACT STRUCTURE, SWEDEN: DYKE BRECCIAS WITHIN THE CRATER FLOOR

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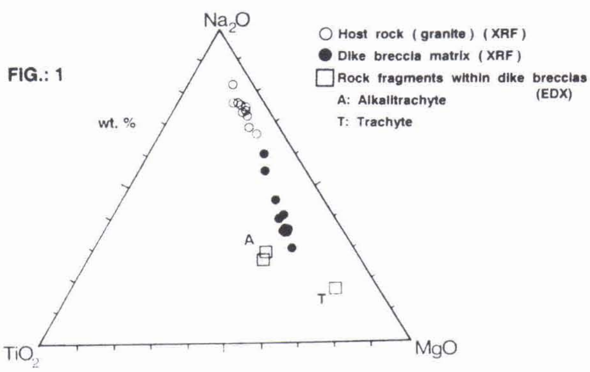
Deep drilling in the Siljan impact area by Vattenfall - Swedish State Power Board, made it possible to get information about the central granitic subcrater floor in this complex impact crater. The central borehole (BH5, Hättberg; depth in rock: 603 m) shows mainly monomict brecciated granite, which at several levels (e.g. 226 - 258.5 m) is sharply cut by several dark grey to black, flow banded, and fragment loaden breccias (thickness between < 1 cm and several m). The dike breccias basically consist of rock and mineral fragments, that are embedded in a fine grained clastic or crystallized matrix, which can be classified as pseudotachylites and clastic matrix dike breccias. Based on mineralogical and chemical observations, the fragments within these breccias are partly derived from the granitic host rock, but many dike breccias also contain fragments of more basic rocks. There are numerous fragments of Ti-rich clinopyroxenes, that cannot originate from the host granite, but rather from trachytic and alkalitrachytic rocks. Such rocks were found as rock fragments within the breccias. The existence of these fragments points to the fact, that the Siljan dike breccias have not been formed by a simple, impact induced friction melting and fracturing of the granitic host rock, but are mixtures of granitic material and a more basic rock component. These conclusions are confirmed by chemical (XRF) data of breccia matrices and the granitic host rocks, that reveal characteristic differences between these lithologies. As demonstrated in Fig. 1, the breccia matrix compositions (filled circles) plot along a mixing line between the granite compositions (open circles) and the compositions of the trachyte and alkalitrachyte fragments (open squares). The source of these basic rocks, consisting of Ti-rich clinopyroxene, alkalifeldspar, plagioclase and mesostasis is yet unknown, because there are no outcrops of this material in the Siljan area. Indeed, the seismic data of this area (1) reveal a set of horizontal reflectors, possibly mafic sills, that are most probably preimpact in origin. The uppermost reflectors are missing within the crater floor, probably indicating their destruction by the impact event (1). The material of these mafic sills might be a possible candidate for the basic mixing component of the Siljan dike breccias. Since mixing calculations (9 elements) show, that the dike breccia matrices consist of material, that has been mixed up 8 to 98 wt.% basic (trachytic and alkalitrachytic) rock component (mean value 54 wt.%), a process is required, that leads to a preferred fracturing and melting of this basic component (basic sills) during the formation of the dike breccias.

FIG.: 1



Model: The propagating shock wave passing the density discontinuities across the interfaces of the both lithologies caused by a strong relative motion at the interface as a consequence of the different shock impedance in granite and mafic rocks. The resulting narrow zones of brecciation and melting affected the mafic sills and the granitic country rock which were mixed during the process. The resulting highly mobile material was also injected into the surrounding brecciated granite to form the dike breccias observed in the Siljan drill core.

We wish to thank Prof. Collini for providing rock samples and his friendly cooperation.

References:

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THE SUDBURY STRUCTURE (CANADA): BRECCIAS IN THE BASEMENT OF A DEEPLY ERODED IMPACT STRUCTURE

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The Sudbury Structure is interpreted as the possible remnant of multi-ring basin (1). The elliptical shape of the inner part of the basin is outlined by the 1.85 Ga (2) old "Sudbury Igneous Complex" (SIC) which is interpreted as a part of the impact melt (1).

Due to deep erosion impact-related features are exposed in the basement of the structure up to a radial extension of several km from the outer rim of the impact melt, e.g. shatter cones up to 17 km and brecciation up to 80 km (2). The most important phenomenon supporting the impact origin are pseudotachylite-like dike breccias ("Sudbury Breccia"), ranging in size from mm thick seams to several 10's of m thick dikes, crosscutting high-metamorphic Archean to Proterozoic rocks. One of these dikes can be traced as far as 11 km. Regarding structure and texture of the matrix and content of fragments the Sudbury Breccia is grouped into breccias with: (I) a fine grained-aphanitic, massive matrix; (II) a fine grained-aphanitic matrix with schlieren-type textures; (III) an igneous-looking matrix crystallized out of a melt phase possibly originating by frictional processes; (IV) a clastic matrix dominated by monomict fragment content.

Shock metamorphic features within breccia fragments and country rock, such as decorated planar elements in quartz and feldspars, kink bands in biotite, and characteristic crack patterns in apatite and zircon, confirm shock stage 0-I in the basement. Shock features exceeding stage I, e.g. diaplectic quartz or feldspar, could not be recorded in the basement rocks. Planar elements in quartz can be found up to a distance of 9 km from the SIC. These features are obliterated in the contact metamorphic aureole around the SIC.

The spatial distribution of the Sudbury Breccia in sector along Highway 144 northwest of the impact melt indicates two zones of high breccia density. The first zone comprises a 10 km wide aureole adjacent to the impact melt, the second zone is located between 27 and 35 km north of the impact melt, corresponding to an almost concentric system of ring fractures (2). According to (2) this regional distribution pattern can also be found in the northern and northeastern parts of the structure. Coexistence of different types of breccia within one dike points to multiple brecciation processes. Consequently, continuous movements during the emplacement of the breccia last most probably through the end of crater formation (modification stage) (see also 3). Textural relationships within these composed breccias indicate that type (IV) represents the latest phase of brecciation. Deducing from the mostly local derivation of breccia fragments and the absence of highly shocked fragments no intense vertical injection of material especially from the transient crater (e.g. impact melt) can be assumed.

References:
(1) Stöffler, D. et al. (1989): Meteoritics, Abstr. subm.
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(3) Melosh, H.J., in Roddy, R.O. et al. (1977): p. 1245 - 1260, Pergamon Press.

AN "INTERNAL" ORIGIN PROPOSED FOR SILJAN, DELLEN AND LAPPAJÄRVI STRUCTURES

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Did Siljan, Dellen and Lappajärvi cryptoexplosion structures originate through action of internal or external (impact) agencies? Nicolaysen and Duane (1987) suggested that large-scale fluid permeation preceded storage and violent venting of fluids, in their "internal" scenario for the Siljan structure. Nicolaysen and Ferguson's (1990) criteria for internally-driven structures may be employed:

Criteria favouring an "internal" origin	Do Siljan, Dellen, Lappajärvi meet the listed criterion ?
a. Alignment on a lineament exhibiting seismic activity	Yes. Seismicity on an NE-trending intraplate lineament demonstrated by Slunga et al. (1984) and Bungum et al. (in press)
b. Location at intersection of tectonic features	Yes, Siljan lies at intersection of the above lineament and a major structural boundary
c. Association with carbonatites, alkalic rocks and fenitisation	Yes, Alnö alkalic complex lies very near to the lineament
d. Enrichment of melt rocks in two contrasted tracer element suites	Yes
e. Shatter cones (interpreted as distinctive "hydrofracts", forced open by high pressure pore fluids)	Yes, undoubted shatter cone failures are present at Siljan

Because this trio of Fennoscandian cryptoexplosion structures meets the tabulated criteria, they probably originated by explosive venting of fluids. Fluid-loaded alkaline magmas periodically reactivated a deep lithosphere zone of weakness, ascended and then released high pressure fluids into the country rock.

THE METEORITE CRATERS IN ESTONIA

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At present five meteorite craters or their groups are known in Estonia. The oldest one is the gigantic crater at Kärdla, buried under Upper Ordovician, Silurian and Quaternary deposits. The others are all relatively young and they represent the splash-explosion type of craters well expressed in the present-day relief. Meteoritic material has been found only on the field of Kaali meteorite craters. In other cases the meteoritic origin of the structures was established by morphological, geophysical and geological features. The age of the structures was dated by radiocarbon, palynological and paleontological methods.

A well-known and well-expressed group of meteorite craters is located at *Kaali* on Saaremaa Island, being composed of the main crater and 8 secondary craters. The group of meteorite craters at *Ilumetsa* comprises three craters, two of which are well expressed in the relief and carefully explored. The nearby individual *Tsöörikmäe* meteorite crater is older and less expressed in the relief. Due to denudational processes it has been levelled out. The crater is filled with a 4.5-m-thick peat layer. The wall shows deformation of strata characteristic of the explosion structures. The presumable traces of a meteorite impact on the surface of Ordovician hard limestones smoothed by glaciation were discovered at *Lasnamäe* in Tallinn. The place of impact is an abraded shallow depression up to 5 cm deep and 20 - 30 cm diameter with cracks radiating from it. The meteorite crater at *Kärdla* on Hiiumaa Island, 4 km in diameter, is filled and can be explored only by boring and geophysical methods.

Data on Estonian meteorite craters are presented on Table 1.

Name	Coordinates	Morph. char.	Ind. meth.	Diam. (m)	Depth (m)	Ring wall, hight (m)	Age (years)	Evid. class	A: country rocks B: structure data C: crater fillings	Discov. (year)	Proof (year)	Document.
KAALI	58°24' N 22°40' E	R	T G M B				3500	A	A: thick bedded silurian dolomite covered with clayed till	1827	1937 (met. mat. iron-IA)	P
The Main crater - Kaali järv				110	22	4-7			B: crater wall dolomite blocks underlain by rock powder, mixture of dolomite splinders and clayey till			
The sec. craters									C: Mud and peat on the bottom - 6.4 m			
No. 1				39	4	disc.-1				1927		
No. 3				33	3	flat.				1927		
No. 4				20	1	disc. -0.5			impact trace on the bottom	1927		
No. 5				13	.9	flat.			impact trace on the bottom	1927		
No. 6				26	.6	flat.				1937		
No. 7				15	1	flat.				1965		
No. 2/8 S/N				36/25	3/2	disc./-1				1927		
ILUMETSA	57°56'N	R	T				6000	A	A: deposits (till) Devonian sandstone B: lenticular layer of shattered Devonian sandstones mixed Quarter. deposits (boulder clay, sand). The wall consists of uplifted beds with overlying ejecta	1938	1961 no met. mat. traces of weak impact metam.	P
Põrguhaud				80	12.5	4			C: filling peat - 3.0 m			
Sügavhaud				50	4.5	1.5						
Tondihaud				24	1.5	flat.			C: filling peat - 1.5 m	1957		
TSÖÖRIKMÄE	58°05'N 27°28'E	R	T	40	6.5	1 - 1.5	9500		A: till (Q) B: cratering did not reach the Devonian bedrock C: filling peat - 4.5 m	1968	1984	P
LASNAMÄE	59°27'N/24°53'E			0.2	0.05		20000		impact trace on Ord. the limestone surface			
KÄRDLA	58°58'N 22°48'E	R D	M G B	4000	500	flat.	400 mill.	A	A: O&G sedimentary and PG crystalline rocks B: crater and partly preserved walls C: crater is filled and covered by Upper Ord., Sil. and Quat. deposits	1967	1980	P

SHOCK METAMORPHIC SCHISTS OF LAKE JÄNISJÄRVI, KARELIA

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Shock metamorphism in primary minerals of Lake Jänisjärvi impact crater (Carstens, 1975; Masaytis, 1975) are studied from samples of unaltered Proterozoic staurolite-garnet schist, its shock metamorphic variant, tagamaite and suevite. Geochemical changes in primary garnet, staurolite and biotite in unaltered and shock metamorphic schist are inspected more closely.

Mineralogical changes from unaltered schist to shocked one are rather physical than chemical. Most important chemical changes included slightly increased Fe^{2+} in borders of shock metamorphic garnets (almandine 72.5 to 83.5 %) and low garnet Al_2O_3 and high staurolite Al_2O_3 and MnO contents in shock metamorphic schists. Borders of shock metamorphic garnets have less Mg^{2+} than their centres and garnets in the unaltered rock. Shock seems to increase Ca^{2+} in the middle of the garnet crystals. Shock metamorphic staurolites have lower FeO, TiO and ZnO than unaltered ones. Chemical changes are, however, so small that, beside Fe^{2+} zonation in garnet, they may display primary variations in mineral composition. Shocked crystals are mostly broken. Original biotite is present as equally distributed small crystals. Shocked biotite displays clear physical (porphyroblasts) and chemical (chloritization) changes. It has less SiO_2 and K_2O and more water than unaltered one.

Shock metamorphic schists display effects of the first metamorphic phase (100 kbar pressure and 100°C temperature; King, 1976) where physical mineral changes are most obvious. Tagamaite and suevite have met the second metamorphic phase with higher pressures and temperatures. Their mineralogy is changed from that of the original schists. The main new shock-induced phase in tagamaite and suevite is glass. Re-crystallized tagamaite has almonds consisting of quartz and glass while the fine groundmass is made of quartz, glass, andesine, K-feldspar, sericite and ilmenite. Totally re-crystallized suevite consists of quartz, glass, andesite-labradorite, K-feldspar needles, altered biotite and ilmenite. Schists have albitic plagioclase while increase in shock seems to make it more anorthitic. Ilmenite in tagamaite has more TiO_2 and less FeO than suevite.

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King, E.A., 1976: Space Geology: An Introduction, John Wiley & Sons Inc., New York
Masaytis, V.L., 1975: Int. Geol. Rev. 18: 1249-1258

SILJAN BEFORE EROSION

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The astrobleme of Siljan, Sweden, of almost the same size as the Charlevoix astrobleme (D = 56 km), is also composed of a Precambrian basement and Paleozoic cover (Hjelmqvist, 1966, Sver. Geol. Ser., Ca. No. 40). However, (1) - the thickness of the cover is more important: 4 to 500 m instead of 150 to 200 m for Charlevoix, (2) - the impact was continental and allochtonous breccia are hematitized, (3) - the structure was peneplaned and the relief (0,007D) is a third of that of Charlevoix (Rondot, 1975, Bull. Geol. Int. U. Uppsala N.S. 6 pp. 85 - 92). In their study of seismic reflection in Siljan, Juhlin and Pedersen (1987, JGR, 92 pp. 14113 - 14122) gave a profile of deep modification with central uplift and annular graben similar to that of Charlevoix (Rondot, 1983, Annales Sci. U. Clermont-Fd. France). Figure 1 shows 1 km of erosion in the shield (0.5 km P + 0.5 km PC), 0.8 km in the center if there was a central peak which probably explains their low shock metamorphism, and 0.6 km on the central plateau (0.4 km of impact + breccia + 0.2 km of Precambrian). The listric slip surface may attain a depth of 11 to 13 km.

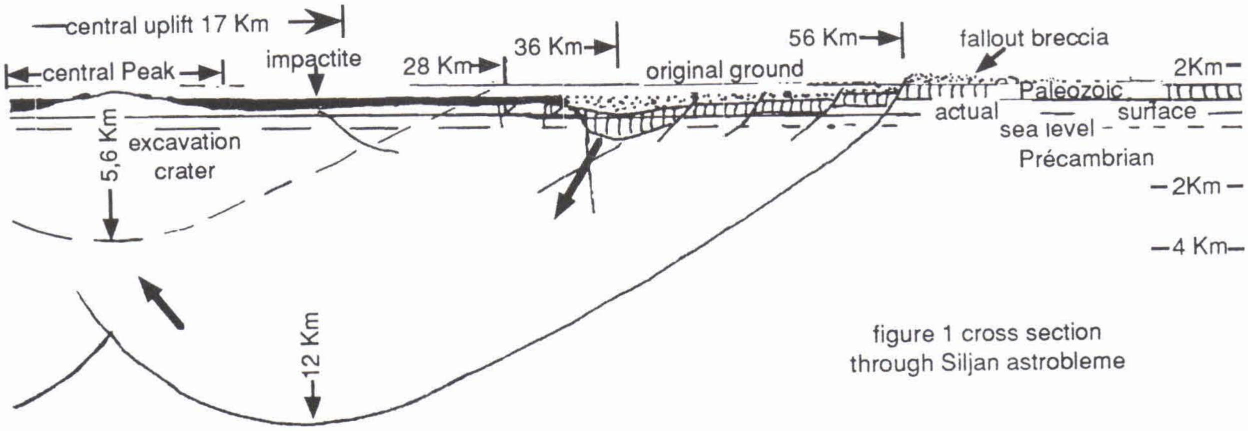

figure 1 cross section
through Siljan astrobleme

FORMATION OF THE METEOR CRATER LAKE KAALI (ISLAND SAAREMAA, ESTONIA)

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Geology of the meteor crater Lake Kaali on the Island Saaremaa has been profoundly studied. Its area is about 0.1 ha, diameter 40 - 60 m, maximum water depth is 1.5 m (Fig. 1). Total crater diameter is 110 m and depth 16 m. Lake bottom is covered by silt, overlain by thin lacustrine lime layer, peaty gyttja, silty gyttja, woody peat and gyttja with maximum thickness up to 6.8 m (Fig. 1). Two spore and pollen diagrams together with the bottom-most radiocarbon dates indicate that the sedimentation in Lake Kaali started in Subboreal, about 3500 B.P. It means, that the lake basin could have formed about 4000 - 3500 B.P.

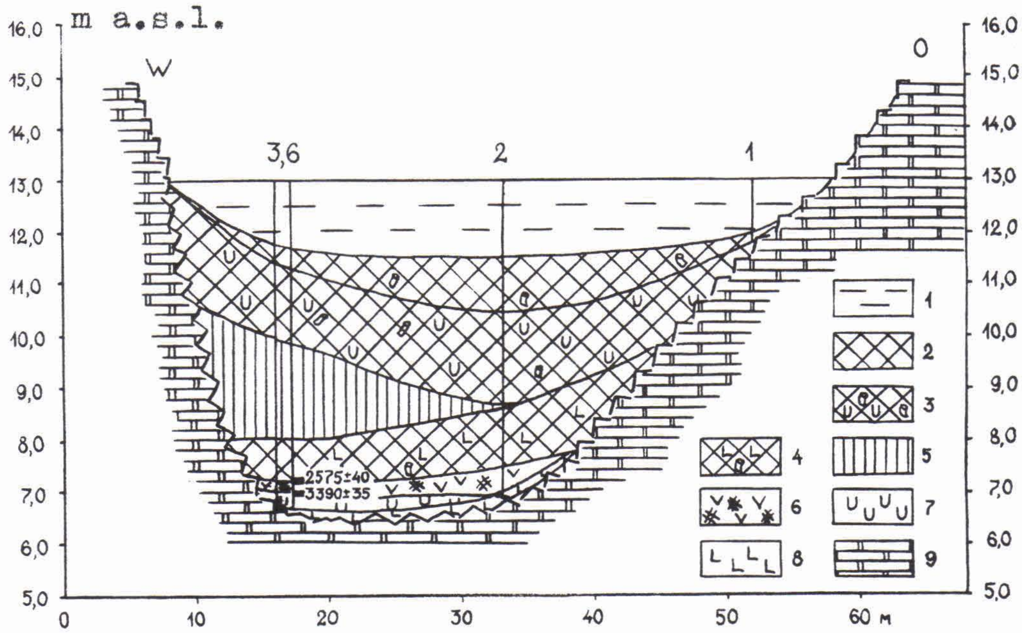

Fig. 1 Simplified geological profile of Lake Kaali. 1 - water, 2 - gyttja, 3 - calcareous gyttja with woody remnants, 4 - silty gyttja, 5 - woody peat, 6 - peaty gyttja, 7 - lacustrine lime, 8 - silt, 9 - dolomite

PAPERS NOT PRESENTED

LAPPAJÄRVI COULD BE CRYPTOVOLCANIC !

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A second visit to Lappajärvi (L) (earlier visit in June 1969) during July 1979 and a tour of the skewed island very near the northwestern shore was made to collect the lava-like glass and devitrified breccia. Having visited many cryptoexplosion craters in North America and Europe, it occurred to me that geologists had gone from one extreme to another, namely that all structures exhibiting shock metamorphism have to be meteorite, asteroid, or comet produced and that none of cryptovolcanic as favored by Bucher and Eskola in an earlier time. With this in mind, an overnight visit was made to Alajärvi (A) south-east of (L). Although no evidence could be found that it was not an ordinary lake, (L) and (A) were on a line with a third lake, Iso-Räyrinki. No evidence was found at this third lake other than its inconclusive circular shape.

There should be a serious study of these lakes to see if a lineament is involved. This suggests that further investigations of lakes along a common line with the above three lakes, as is Evijärvi to the north of (L), should be made. Perhaps one might even establish a conjunction of several major faults at (L) such as one finds at Alnön east of Sundsvall, Sweden. Possible relationship with Sääksjärvi in this regard should be investigated.

Convincing conclusions concerning impact can only be made after extensive drilling such as has been done at the Southeast Clearwater Lake in Canada, at Nördlinger Ries in Bavaria, and now at Siljan in Sweden. Until extensive investigation is made over a period of time one must err on the conservative side, as should always be the way in geology. One concludes that each crater must be investigated in detail before a conclusion can be reached whether it is cryptovolcanic or comet-asteroid impact in origin.

The difficulty in funding for this research makes it long term in nature although rewards in discovery of commercial minerals may result.

GEOLOGICAL RESULTS OF THE BORINGS IN THE SILJAN RING STRUCTURE, SWEDEN

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The Deep Gas Project in Sweden was launched by Vattenfall (The Swedish State Power Board) in the early 1980's. In the Siljan Ring Structure, one of the areas selected for closer investigations, the research started in 1983. In the years 1983 - 1985 all kinds of relevant surface investigations were performed, including ten core borings with a total length of 3668.6 m. In the years 1986 - 1989 the Gravberg-1 deep well was drilled down to a true vertical depth of 6779 m, under management of Vattenfall and Dala Deep Gas Co.

The geological results being presented refer mainly to the Gravberg-1 well. Bases on analyses of main and trace elements of cores and cuttings the rocks of the well, granite types and dolerites, are characterized. The reliability of the cuttings analyses are discussed, as well as the possible occurrence of remnants of rocks older than the Dala granites in the deeper parts of the well. Chemical and mineralogical variations of the granites are correlated. New datings of rocks from Gravberg-1 well as well as from surrounding areas are discussed.

SUDBURY (CANADA): IMPLICATIONS FOR CRATERING MECHANICS FROM THE FOOTWALL BRECCIA

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The Sudbury Structure in the Canadian Shield represents the deformed remnant of a multi-ring impact basin (1). In the northern part of the basin, the 1.85 Ga old (2) Sudbury impact melt system is underlain by the up to 150 m thick discontinuous Footwall Breccia layer. This breccia grades into fractured and shocked rocks of the subcrater megabreccia (3 to 5, Müller-Mohr, this vol.). Clast population statistics, major and trace element data along with Sr-Nd model parameters document the parauchthonous character of all components in the Footwall Breccia (5, 6). The incomplete mixing of megablock-sized fragments in the breccia layer indicates that clasts lack large scale movement relative to their precursor lithologies (4, 5). The breccia contains mineral and lithic fragments, which have suffered shock pressures of up to 20 GPa, along with clasts of reworked breccia dikes originating from the subcrater basement. The originally clastic breccia matrix has been thermally annealed by the Sudbury melt system resulting in partial melting and the development of various igneous textures of the matrix. Annealing is also indicated by a Rb-Sr isochron age of 1.825 ± 0.021 Ga for the matrix (5, 6).

For cratering model calculations, a cover of 10 km of metasedimentary rocks (Hunorian Supergroup) in the Sudbury region on top of high-grade basement gneisses (Superior Province) at the time of impact is assumed. The radial extent of the subcrater megabreccia (4) point to an original crater diameter between 180 and 200 km. Comparison of the radial extent of shock-induced phenomena in basement rocks of Sudbury with equivalent shock features in other complex craters resulted in a transient cavity diameter of 100 km. Using these constrains, an impact melt volume of 12500 to 22500 km^3 of the Sudbury crater has been computed according to models of (7 to 10). This melt volume is consistent with an estimate of the present volume of Sudbury melt system (11). Assuming the validity of the applied impact model predictions the maximum depth of shock melting has been ~27 km. This depth is in accordance with a crustal origin of the Sudbury melt system as required from Nd isotope composition (12, 13). Field relations of impact melt sheets in complex craters (14) suggest that the Footwall Breccia layer represents a part of the uplifted crater floor directly beneath the Sudbury melt system.

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IMPLICATIONS FOR TRANSIENT CAVITY DIMENSIONS OF COMPLEX IMPACT CRATERS

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The observed morphological variety of complex impact craters formed as a consequence of gravity-driven collapse of s deep bowl-shaped cavity (1 to 5). The transient cavity established at the end of the excavation phase or crater formation consists of 2 components: ejected material and rocks displaced downward and outward beneath the expanding cavity floor and wall (2). With respect to the basic concepts of impact cratering mechanics (6), the original transient crater diameter (D_t), which equals the diameter of excavation, can be deduced from geological observations and from various geometric parameters. The following parameters can be analyzed in final complex terrestrial and lunar craters: (I) the maximum radial extent of dikes of suevitic breccia and of impact melt rocks; both were injected into crater cavity and are presently exposed in uplifted basement rocks; (II) the innermost boundary of the megablock zone peripheral to the central uplift. This parameter is deduced from seismic data and from remnants of downfaulted strata overlying crystalline basement; and (III) the diameter of the steepest Bouguer gravity anomaly measured at the present surface.

The distribution of shock-induced features in subcrater basement rocks is also considered. The outer limit of the zone of shock deformation structures in quartz (7) and of the present distribution of shatter cones (8) as a function of the apparent crater diameter, D_a, shows: (I) apparent shock pressures of less than about 30 GPa, which are confined to the central basement uplift (3, 9, 10), attenuate to about 10 GPa at a radial range (R_{sq} = outer radius of shocked quartz) $R_{sq} = 0.19 - 0.24\ D_a$. (II) The outer extent of shatter cones (R_{sc}) is limited to $R_{sc} = 0.25 - 0.3\ D_a$. Assuming inward displacement of these shock contours during transient cavity modification, shock pressures at the cavity rim are in the 1 to 2 GPa range (6).

Ejecta volumes (V_e) have been determined for simple and complex lunar craters (11). The observed volumes have been tested against ejecta volumes predicted by constant Z, EDOZ-model calculations after (2,12). With a depth of excavation, d_e, limited to $d_e = 0.1 - 0.12\ D_t$ (2) the quantity of V_e can be used to scale relation between the transient cavity diameter and the apparent diameter of complex craters.

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DISTRIBUTION OF U, Th AND REE IN THE ROCKS OF THE GRAVBERG-1 DEEP WELL, SWEDEN

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The Gravberg-1 deep well in the Siljan Ring structure is part of the Deep Gas Project in Sweden launched by Vattenfall (The Swedish State Power Board). After extensive surface investigations, the drilling, managed by Vattenfall and Dala Deep Gas Co., was performed in the years 1986 - 1989 down to a true vertical depth of 6779 m.

Besides the main purpose of the drilling, temperature measurements were made in the borehole. Heat production, heat flow, and thermal conductivity of the bedrock are being investigated in order to give the background to the temperature gradients found. Extensive chemical analyses are being made. In the poster some of the relevant chemical data are presented, with an attempt at correlation with rock compositions.

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