IMPACT
4th ESF WORKSHOP

Meteorite Impacts in Precambrian Shields

PROGRAMME AND ABSTRACTS

Edited by Jüri Plado and Lauri J. Pesonen

Lappajärvi – Karikkoselkä – Sääksjärvi
Finland, May 24 – 28, 2000

Geological Survey of Finland

Geophysics Department University of Helsinki

Geological Museum University of Helsinki

4th Workshop of the European Science Foundation Impact Programme

METEORITE IMPACTS IN PRECAMBRIAN SHIELDS

May 24-28, 2000
Lappajärvi-Karikkoselkä-Sääksjärvi, Finland

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Edited by

J. Plado[1] and L.J. Pesonen[1,2]

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Espoo 2000

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The 4th ESF Workshop on Meteorite Impacts in Precambrian Shields was held during May 24-26, 2000 in Lappajärvi Hall of Hotel Kivitippu, Lappajärvi, Finland. The excursion to Karikkoselkä and Sääksjärvi impact structures, and to the Murronmäki micrometeorite outcrop in Köyliö, Satakunta, took place on May 27-28, 2000.

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Special thanks to:
Staff of the Department of Geophysics, Geological Survey of Finland, for helping us in organizing the Workshop and in preparing this Abstract Volume.

PREFACE

The 4th Workshop in the series of workshops by the ESF-IMPACT Programme focuses on the characterization of meteorite impact structures of all ages and sizes occurring in Precambrian shields, where the majority of the recognized impact structures on the Earth have been found. The Workshop takes place in Kivitippu Spa Hotel ("Falling Rock Hotel") within the Lappajärvi impact crater, central Finland, during May 24-26, 2000. The Workshop is addresses to the following topics: (i) global perspective of impact structures with a special focus on Precambrian shields, (ii) remote sensing and structural aspects, (iii) geophysical identification and modelling of impact structures, (iv) shock effects in rocks from microstructures to mega fractures, and (v) geochemistry and dating of impact structures. A special session on the Popigai impact structure, Siberia, summarizing the results of the International Popigai Expedition, takes place in the afternoon of May 26. A short excursion to Lappajärvi impactite outcrops is arranged during the workshop. A post-workshop excursion to the Karikkoselkä and Sääksjärvi impact craters takes place on May 27-28, 2000 on the return route from Lappajärvi to Helsinki. En route to Helsinki a stop is planned to visit the Satakunta sandstone, which hosts the world's oldest micrometeorites.

In this Special Volume we present the "Programme and Abstracts" of the Workshop. The abstracts of the oral talks and poster presentations are listed in order of appearance. Most of the abstracts are published as they were received from the authors: however, they are edited here to appear in a common style. In a few cases the editors of this volume have done minor editorial corrections. We take full responsibility of these corrections. At the end of the Special Volume you will find a list of the authors and their addresses as well as a reference to the page(s) where they appear in the volume.

We acknowledge the support by the Geological Survey of Finland during the preparation of this volume. Special thanks are due to the sponsors of this workshop; they are listed in the beginning of the volume. We warmly thank the members of the organizing committee for their continuous help in preparing this volume. We also thank all participants of the Workshop who contributed valuable papers and who participated in discussions.

The Workshop could not be organized without financial support by the European Science Foundation, and by the Academy of Finland.

We welcome you all to the land of impacts!

Helsinki, May 20, 2000

Lauri J. Pesonen and Jüri Plado

Welcome to Kokemäki

In behalf of Kokemäki town I wish all the representatives of ESF-IMPACT meeting welcome to Kokemäki. I hope you will have a few memorable days here and the possibility to enjoy our light summer nights. In Kokemäki you can visit an interesting meteorite crater lake Sääksjärvi and relax at the sports center at the lake Pitkäjärvi.

Martti Jalkanen
Mayor

Kokemäki is a rural town in Satakunta; an ideal place for its 9000 inhabitants to live and enjoy life in beautiful surroundings. The river Kokemäenjoki, which flows through the town, is one of the most well-known rivers in Finland. Kokemäki has also many lakes, the most famous of them the lakes Pitkäjärvi and Sääksjärvi. In Kokemäki you can enjoy different kinds of sport; we have e.g. a trotting course, a gliding center, an ice-hockey center and car racing courses.

Our biggest enterprises are transport companies Viinikka Oy and Teljän Kuljetus Oy, Sinituote Oy, which manufactures cleaning equipment, and many companies representing graphic industry, 33 % of our population earns its living in industry, 53 % in services and 14 % in agriculture. Our farms ar often specialized, e.g. in growing vegetables or potatoes. Kokemäki is also one of the most important regions for growing strawberries in Finland.

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PROGRAMME

Wednesday, May 24

14.20 - 14.30 Get together at the Meeting Point of the Helsinki Railway Station.

14.58 - 18.16 Intercity train from Helsinki to Seinäjoki.

18.30 - 19.20 Bus from Seinäjoki to Kivitippu Spa Hotel via Lappajärvi.

19.20 - 20.20 Settling down in the Hotel, free time, poster fixing, *etc.*

20.20 - 21.00 Opening ceremony at the Restaurant Rantakirppu.

21.00 - Dinner at the Kivitippu Restaurant.

Thursday, May 25

06.50 - 07.10 Morning walk along the "Meteorite Pathway" (L.J. Pesonen).

07.00 - 08.30 Morning sauna&swim in the spa, Breakfast.

Session 1: Impact structures – global perspective *Chair: S. Elo*

08.45 - 08.50 **L.J. Pesonen**: Opening remarks.

08.50 - 09.10 E. P. Turtle and **E. Pierazzo**: Thermal heating during formation of the Vredefort structure. *(Invited)*

09.10 - 09.25 **L.J. Pesonen**, A. Abels, M. Lehtinen and J. Plado: Impact cratering record of Fennoscandia – a new look at the database.

09.25 - 09.40 **M.R. Dence**: Re-examination the significance of key data from impact craters on the Canadian shield.

09.40 - 09.55 A.M. Therriault, **R.A.F. Grieve** and A.D. Fowler: The Sudbury igneous complex: A classic example of a differentiated impact melt sheet?

09.55 - 10.10 **V.L. Sharpton**: The global impact-studies project.

10.10 - 10.30 Coffee break.

Session 2: Remote sensing and structural aspects *Chair: M. Dence*

10.30 - 10.45 R.J. Wagner, **W.U. Reimold** and D.U. Brandt: A remote sensing investigation of the Bosumtwi impact structure, Ghana.

10.45 - 11.00 **C. Koeberl**, D. Boamah, X. Dai and W.U.Reimold: Geological, petrographic, and geochemical studies at the Bosumtwi impact structure, Ghana: A progress report.

11.00 - 11.15 **A. Abels**, L. Bergman, M. Lehtinen and L.J. Pesonen: Structural constraints and interpretations on the formation of the Söderfjärden and Lumparn impact structures, Finland.

11.15 - 11.30 **I. von Dalwigk** and T. Kenkmann: Structural investigations in the Siljan structure.

11.30 - 11.45 **T. Kenkmann** and I. von Dalwigk: Material flow during crater modification: Volumetrical modelling and implications from the Siljan impact structure.

11.45 - 13.30 Lunch and posters.

Session 3: Geophysics of impact structures I *Chair: M. Pilkington*

13.30 - 13.45 **B.A. Ivanov**: Size-frequency distribution of impact craters in Precambrian shields.

13.45 - 14.00 **B. Milkereit**, P. Janle and J. Kolouris: Geophysical signature of large impact craters on Earth - a search for common denominators.

14.00 - 14.15 **J. Plado**, L.J. Pesonen and V. Puura: Processes responsible for gravity and magnetic anomalies of meteorite impact structures: An overview.

14.15 - 14.30 **H. Zumsprekel** and L. Bischoff: The Shoemaker Teague Ring impact structure, Western Australia: Remote sensing and GIS analysis of a deeply eroded Precambrian impact structure.

14.30 - 14.45 **H. Henkel** and R. Lilljequist: Geophysics of the 300 km Uppland structure of south central Fennoscandia.

14.45 - 15.05 Coffee break.

Session 4: Geophysics of impact structures II *Chair: J. Plado*

15.05 - 15.20 **S. Elo**, L. Zhdanova, A. Chepik, L.J. Pesonen, L. Philippov and A. Shelemotov: Geophysical description and modelling of Lappajärvi and Jänisjärvi impact structures, Fennoscandian shield.

15.20 - 15.35 **L. Kivekäs**: Porosity and density in altered target rocks of meteorite impacts.

15.35 - 15.50 **U. Schärer**, A. Galdeano and S. Gilder: Magnetic intensity pattern of the Rochechouart impactites.

15.50 - 16.05 **S. Werner**, P. Janle and L.J. Pesonen: Suvasvesi N - modeling gravimetric and aeromagnetic data of an impact structure in central east Finland.

16.05 - 16.25 **L.J. Pesonen**, D. Mader, E.P. Gurov, K. Koeberl and K.A. Kinnunen: Paleomagnetism and ^{39}Ar-^{40}Ar age determinations of impactites from the Ilyinets Impact Structure, Ukraine.

16.50 - 18.00 Excursion to Lappajärvi impactite site.

18.00 - 20.00 Free time (look for posters, visit spa, *etc.*).

20.00 - Dinner at Taavintupa Country Style Restaurant.

Friday, May 26

06.50 - 07.10 Morning walk along the "Meteorite Pathway" (L.J. Pesonen).

07.00 - 08.30 Breakfast

Session 5: Breccias and other evidence of impacts *Chair: F. Langenhorst*

08.30 - 08.45 **L.I. Glazovskaya**: Impact transformation of the crystalline basement in the Logoisk astrobleme.

08.45 - 09.00 **H. Askvik**: Breccias of assumed impact origin in the Precambrian of Northern Hardangervidda, central south Norway.

09.00 - 09.15 **T. Mutanen**: The big Pechenga bang.

09.15 - 09.30 **R. Lilljequist**, H. Henkel and W.U. Reimold: Breccia occurrences generated in the Uppland structure, Sweden - a suspected impact structure.

09.30 - 09.45 **Y.W. Isachsen** and K. Hanley: Panther mountain buried impact crater is confirmed.

09.45 - 10.05 Coffee break.

Session 6: Dating, shock effects and geochemistry *Chair: M. Lehtinen*

10.05 - 10.20 U. Schärer and **A. Deutsch**: Conditions governing radiochronometers in impact regimes.

10.20 - 10.35 **F. Langenhorst**: Minerals in the transient state of shock.

10.35 - 10.50 **K. Kirsimäe**, S. Suuroja, J. Kirs, A. Kärki, M. Polikarpus, V. Puura and K. Suuroja: Hornblende alteration and fluid inclusions in Kärdla impact crater, Estonia - an indication for impact induced hydrothermal activities.

10.50 - 11.05 **P.J. Pihlaja** and H. Kujala: Some geochemical features of impact melts, suevites and target rocks at Sääksjärvi impact structure, Finland.

11.05 - 11.20 **V.I. Fel'dman**, L.V. Sazonova, E.A. Kozlov and Yu.N. Zhugin: Migration of chemical components under shock wave loading of rocks and minerals.

11.20 - 12.45 Lunch and posters.

Session 7: Impacts into shallow sea, tektites and spherules *Chair: B. Ivanov*

12.45 - 13.00 **J. Ormö**, E. Sturkell, J. Nõlvak and Å. Wallin: Distant resurge influenced sediments at the Lockne marine-target crater, Sweden.

13.00 - 13.15 **V. Puura**: Scenarios of cratering and crater survival in Precambrian shield and shallow Palaeozoic platform areas in the Baltic Sea region.

13.15 - 13.30 **M.V. Gerasimov**, Yu.P. Dikov, O.I. Yakovlev and F. Wlotzka: The formation of differentiated melted spherules during an impact.

13.30 - 13.45 **D.D. Badjukov**, J. Raitala and T.L. Petrova: Metal and sulfide from projectile in impact melts of the Lappajärvi crater.

13.45 - 14.00 **N.A. Artemieva**: Tektite origin in oblique impact: Numerical modeling.

14.00 - 14.15 **V. Shuvalov**: Numerical modeling of the impacts into shallow sea.

14.15 - 14.35 Coffee break.

Special session: Popigai impact structure *Chair: R. Grieve*

14.35 - 14.55 **V.L. Masaitis**: Popigai impact crater: General geology. *(Invited)*

14.55 - 15.15 **M. Pilkington**, L.J. Pesonen, R.A.F. Grieve and V.L. Masaitis: Geophysics, petrophysics and paleomagnetism of the Popigai impact structure, Siberia. *(Invited)*

15.15 - 15.35 **J. Whitehead**, J.G. Spray, R.A.F. Grieve, D.A. Papanastassiou, G.J. Wasserburg and V.L. Masaitis: Popigai impact melt rocks and upper Eocene microspherules. *(Invited)*

15.35 - 15.50 **R. Tagle** and P. Claeys: Petrology and geochemistry of the Popigai impact crater (Siberia).

15.50 - 16.05 **A. Deutsch**, B. Kettrup, L. Kerschhofer and V.L. Masaitis: Popigai: Melt-coated bombs as flight recorder and automatic probe of the fire-ball.

16.05 - 16.20 **M.V. Naumov**: Impact-generated hydrothermal systems: Data from Popigai, Kara, and Puchezh-Katunki impact structures.

16.20 - 16.50 **H. Kujala**, M. Lehtinen, P. Pihlaja and M. Vaarma: Excursion to Lappajärvi, Karikkoselkä and Sääksjärvi impact structures - a review.

16.50 - 16.55 **L.J. Pesonen**: Concluding remarks.

16.55 - 17.45 Free time and preparing for the boat trip.

17.45 - 19.30 Boat trip on Lake Lappajärvi (with local music).

20.30 - Special **Workshop Dinner** at the Restaurant Kivitippu.

Saturday, May 27

Excursion to Lappajärvi, Karikkoselkä and Sääksjärvi impact structures.
Lead by H. Kujala, M. Lehtinen, P. Pihlaja and M. Vaarma

07.00 - 08.30	Breakfast
08.30	Excursion buses will depart.
09.00 - 09.30	Hietakangas gravel pit, Lappajärvi: Suevite boulders.
12.00	Arrival in Karikkoselkä impact structure, Petäjävesi. Field lunch (outdoors) in granitic outcrops with shatter cones. Exhibition of the drillcores.
13.30	Buses continue towards Sääksjärvi impact structure.
17.00 - 17.30	Short stop in Köyliö at the Murronmäki sandstone site where the world oldest micrometeorites were discovered.
18.00	Arrival in Kokemäki. Settling down in Pitkäjärvi Activity Center and other accommodation facilities.
18.00 - 20.30	Free time: Sauna, health club. Exhibition of samples from Sääksjärvi impact structure.
20.30 -	Dinner in the Pitkäjärvi Activity Center.

Sunday, May 28

07.00 - 08.00	Breakfast at each accommodation facility.
08.00	Departure to Sääksjärvi from the Pitkäjärvi Activity Center.
08.30 - 11.30	Excursion around Sääksjärvi (3 stops). Field lunch outdoors.
11.30	Departure towards Helsinki-Vantaa International Airport.
14.00	Arrival at the airport. Bus will continue to Helsinki.
15.00	Arrival at Helsinki Railway Station. **End of Workshop.**

Posters

1. A. Abels, L.J. Pesonen, L. Bischoff and A. Deutsch: Characterization of the Lappajärvi impact structure, Finland, by integrated spatial analyses of multisource geodata.
2. T. All and V. Puura: Aeromagnetic signatures of the Neugrund structure, Gulf of Finland, NW Estonia.
3. V.I. Fel'dman, L.V. Sazonova, E.A. Kozlov and Yu. Zhugin: Feldspars in impacted rocks as a geobarometer of shock metamorphism.
4. E.P. Gurov, E.P. Gurova and T.M. Sokur: The Zapadnaya impact structure in the Ukrainian shield. *(Invited)*
5. H. Henkel and W.U. Reimold: Magnetic modelling of the central uplift of the Vredefort impact structure.
6. O. Kákay-Szabó: Genetic types of the micrometeorites from the impact regions.
7. T. Karp, B. Milkereit, P. Janle, S. Bussat, S.K. Danour, J. Pohl, B. Scheu, M. Froehler, H. Berckhemer, B. Baier, G. Zacher and C.A. Scholz: Geophysical investigation of the Lake Bosumtwi impact crater.
8. D. Kettrup, A. Deutsch and L.J. Pesonen: Cosmic spherules in the Satakunta sandstone, Finland: Preservation – separation.
9. J.K. Korteniemi: Meteorite impacts in the Solar System in general and a closer look at impact structures on Mars and Earth.
10. S.I. Kotelnikov and V.I. Fel'dman: Clinopyroxene as a source of impact loading strain data.
11. T. Kuivasaari, L.J. Pesonen, S. Elo, J. Plado and M. Lehtinen: Paasselkä - the ninth meteorite impact structure in Finland.
12. R. Lilljequist: Mineral deposits in Sweden related to suspected Precambrian meteorite impact craters.
13. T. Mutanen: New possible impact sites in northern Finland.
14. T. Öhman, L.J. Pesonen, J. Raitala, A. Uutela and P. Tuisku: The Saarijärvi crater – older and larger than assumed?
15. J. Ormö and H. Miyamoto: Computer modelling of the water resurge at the Lockne crater, Sweden.
16. V. Petersell and K. Suuroja: The sulphide mineralization in the rocks of the Kärdla impact structure.
17. M. Pilkington and A.R. Hildebrand: Three-dimensional magnetic imaging of the Chicxulub crater. *(Invited)*
18. J. Plado, H. Henkel and B. Oloffson: Geophysical studies at the Ilumetsa meteorite impact site.
19. V. Puura, M. Konsa, A. Kleesment, J. Kirs, K. Kirsimäe and K. Suuroja: Carbon-rich and magnetic spherules and particles from Kärdla ejecta, Estonia.
20. A. Raukas and R. Tiirmaa: Dating of Ilumetsa impact craters, SE Estonia.
21. A. Rimša and I. von Dalwigk: Preliminary mineralogical and geochemical studies of the impactites of the Dellen impact structure, Sweden.
22. J. Rondot: Meteoritic impact effects on earth basement in large structures.

23. L.V. Sazonova, V.I. Fel'dman, E.A. Kozlov and Yu.N. Zhugin: Shock metamorphism and melting of the Jänisjärvi astrobleme target rocks (Karelia, Russia) – comparison of natural and experimental data.
24. G. Schöngruber: Studies of the applicability of remote sensing data on geomorphological questions concerning impact structures; demonstrated by the Roter Kamm impact crater (Namibia).
25. G.I. Shafranovsky: Structure of apographitic impact diamonds from Lappajärvi crater.
26. O.N. Simonov, M.V. Naumov and M.S. Mashchak: Drilling in the Popigai crater: status of the drill core and further exploration goals.
27. T.M. Sokur and E.P. Gurov: The Zapadnaya impact crater: Shock metamorphism of rocks and minerals. *(Invited)*
28. K. Suuroja and S. Suuroja: The mineral resources related to the Kärdla impact crater (Hiiumaa Island, Estonia).
29. S. Suuroja and K. Suuroja: The Neugrund impact structure (Gulf of Finland, Estonia) on the geological and geophysical maps.
30. A.S. Vishnevsky, I.A. Balagansky and S.A. Vishnevsky: The Popigai impact event: numerical simulation of initial stages of the cratering.
31. S.A. Vishnevsky: Impact-hydrothermal origin of the Witwatersrand ores: The possible sources of fluid and gold.
32. S.A. Vishnevsky, L.N. Gilinskaya, V.E. Istomin, N.A. Pal'chik and S.M. Lebedeva: Impact glasses and tektites of ZH-facies: Some features of the rocks and models of their origin.
33. R.J. Wagner, W.U. Reimold and D.U. Brandt: A remote sensing investigation of the Bosumtwi impact structure, Ghana.
34. J. Whitehead, J.G. Spray, R.A.F. Grieve, D.A. Papanastassiou, G.J. Wasserburg and V.L. Masaitis: Popigai impact melt rocks and upper Eocene microspherules. *(Invited)*
35. O.I. Yakovlev, Yu.P. Dikov and M.V. Gerasimov: Experimental data on impact-vapor differentiation.
36. H. Csadek: Video presentations: 62nd Annual Meeting of the Meteoritical Society (Part 1: Witwatersrand University and Tswaing crater; Part 2: Vredefort excursion and De Wildt Cheetah Centre; Part 3: Eclipse)

GEOTECHNICAL ENGINEERING AND SOIL INVESTIGATIONS

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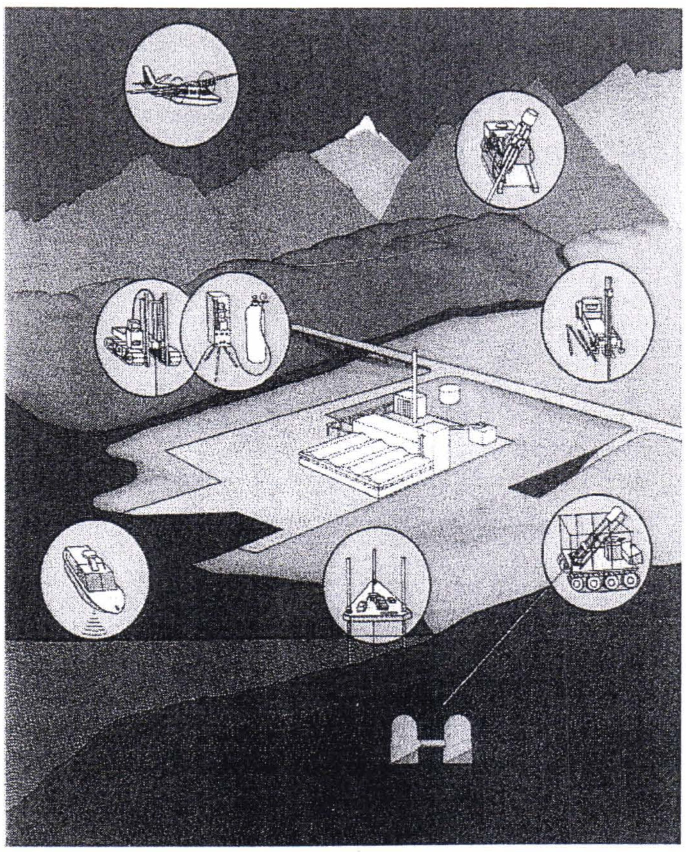

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STRENGTHS

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- Appropriate surveying and investigation equipment
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- Long traditions – founded in 1965
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- Quality system

YEAR 1999

- Number of employees
  - design 7
  - surveying 8
- Turnover about FIM 8 Million
- Distribution of turnover
  - rock core drilling approx. 20 %
  - design approx. 35 %
  - soil surveys approx. 30 %
  - hydrography approx. 15 %

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LECTURE ABSTRACTS

IN ORDER OF APPEARANCE

Thermal heating during formation of the Vredefort structure

E.P. Turtle and E. Pierazzo

Lunar and Planetary Laboratory, University of Arizona, Tucson, USA; turtle@lpl.arizona.edu

Significant heating of the target occurs during large asteroid/comet impacts. The temperatures achieved in these events affect the post-impact metamorphism of the target rocks [1]. Furthermore, formation of hydrothermal systems beneath the site of a large impact [2] may play a role in the creation of suitable environments for life to develop [3]. We present the thermal results from our simulations of the impact event that produced the Vredefort structure in South Africa, about two billion years ago [4].

The simulations model the impact of an asteroid 7 to 20 km in diameter with a target that approximates the stratigraphy at the Vredefort site. The best correlation of the model results with field studies of shock-produced features occurs for a projectile 10 km in diameter. This would create a transient crater about 80 km in diameter and result in a structure whose final crater diameter is in the 120-160 km range. We employed the 2D hydrocode CSQ [5] coupled with the equation of state ANEOS [6] to model the contact and compression phase. The thermal, as well as pressure, history of 100 lagrangian tracers was used to reconstruct the conditions of material in the target after the passage of the shock wave. The excavation and collapse of the transient crater were then simulated using the finite-element code Tekton [7]. The motions that occur in these stages were applied to the tracers to determine the thermal state of the material surrounding the final crater. The temperature change in the target is shown in Figure 1.

These simulations show that, at least initially, there is little heating outside the final crater itself. Large temperature changes (over about 100°C) are limited to about 1/3 of the final crater diameter, reaching depths of about 20 to 30 km. We plan to expand our modeling to investigate the thermal evolution of the impact structure and its implications.

References: [1] Gibson, R.L., 1999. Meteoritics & Planet. Sci. Supp., 34, A42-A43. [2] Ames, D.E. et al., 1998. Geology, 26, 447-450. [3] Newsom, H.E. et al., 1996. JGR, 101, 14951-14955. [4] Turtle, E.P. and Pierazzo, E., 1998. Meteoritics & Planet. Sci., 33, 483-490. [5] Thompson, S.L., 1979. CSQIII An Eulerian finite differences program for two-dimensional material response: Users Manual, Sandia Natl. Labs. [6] Thompson, S.L. and Lauson H.S., 1972. Improvements in the CHART D radiation-hydrodynamic code III: Revised analytical equation of state. Tec. Rep. SC-RK-61 0714, Sandia Natl. Labs. [7] Melosh, H.J. and Raefsky, A., 1980. Geophys. J. R. Astr. Soc., 60, 333-354.

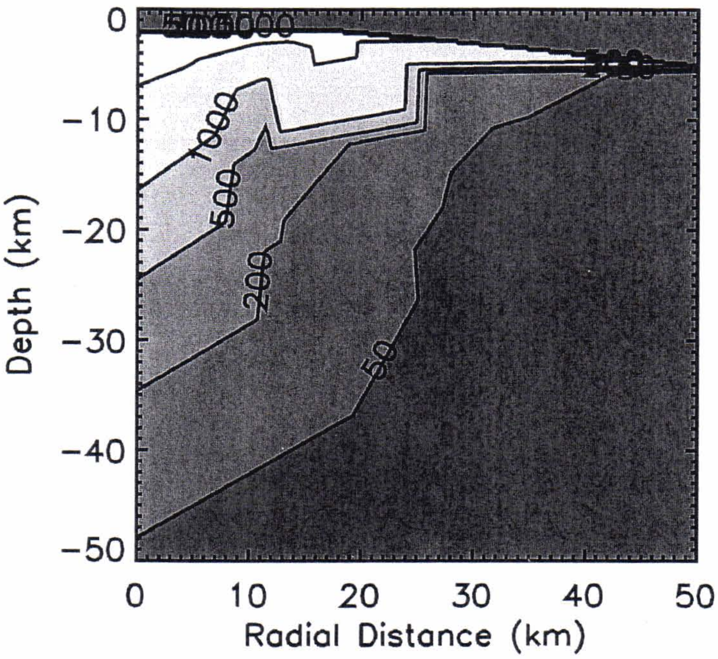

Figure 1. Contours (50, 200, 500, 1000 and 3000 K) of change from initial temperature immediately after crater collapse (small jags in contour lines are artifacts of interpolation from the unevenly distributed tracer locations to a regular grid).

Meteorite impact structures in Fennoscandia - a new look at the database

L.J. Pesonen[1,2], *A. Abels*[3], *M. Lehtinen*[4] *and J. Plado*[2,5]

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The current database of the Fennoscandia-Baltic region contains twenty seven structures of confirmed meteorite impact origin. In addition, there are at least four small craters or crater fields which are likely to be caused by impact, but definite evidence of meteoritic material or shock is still lacking. Twelve structures (Lockne, Gardnos, Iso-Naakkima, Mjølnir, Suvasvesi N, Lumparn, Karikkoselkä, Neugrund, Saarijärvi, Suavjärvi, Tvären and Paasselkä) have been confirmed as impacts during 1990's. The high rate in finding impact craters in a Precambrian shield is due to various factors: (i) an increased research towards impacts in general, (ii) application of geophysical and geochemical methods to suspected structures, (iii) deep drilling into suspected structures, (iv) comprehensive petrographic studies of drillcores, and (v) application of new techniques in tracing eroded structures. The majority of the structures have been found in Proterozoic crystalline target rocks. The present diameter of the structures ranges from 0.08 km to 45 km and the age from pre-historic to ~2.4 Ga. Due to erosion, some original diameters have, however, been considerable larger. So far, there are no traces of an Archean impact structure or event in Fennoscandia, for example, in a form of ejecta layer or impact breccia dyke. In a few cases geochemical analysis have lead to an identification of the projectile type. For example, the Sääksjärvi impact structure has recently been interpreted to be caused by an iron meteorite, whereas the Lappajärvi projectile was a chondritic body.

Three characteristics appear in the record. First, there is a relatively large number (11) of small (~5 km) but old (>200 Ma) impact structures. This is mainly a result of success of the high-resolution geophysical surveys on a shield area with a thin Quaternary overburden (*e.g.*, Suvasvesi N, Iso-Naakkima). Second, there is a tendency of the structures (Jänisjärvi, Paasselkä, Suvasvesi N, Iso-Naakkima, Karikkoselkä, Lappajärvi, Söderfjärden, Dellen, Siljan, Lockne and Gardnos) to be located south of 63.5°N, in a "belt" from western Karelia to south-central Norway. Third, at least seven structures are of Cambro-Ordovician age forming a noticeable peak in the histogram of Fennoscandian crater ages. These biases, if real, may reflect possible variations in the influx rate of projectiles colliding with the Earth or differences in tectonic, erosional or preservational conditions between the terranes containing or lacking impact structures. In this regard, it is remarkable that eight of the structures have preserved an impact breccia lense. Since the ages of the these breccia lenses vary by an order of magnitude (Lappajärvi 70 Ma and Jänisjärvi 700 Ma, respectively), the preservation of the older breccias against erosion must be due to that they have been down-dropped and covered by younger "capping" sediments. This concept is supported by presence of either pre-impact (*e.g.*, Lappajärvi, Karikkoselkä) or post impact (*e.g.*, Lumparn, Saarijärvi) sediments in some of the structures.

Although the global database reveals at least ten impact structures with diameters >80 km, there are no large impact structure known in Fennoscandia so far. This could be simply due to the relatively small size of Fennoscandia (as compared with Laurentia, for example) or due to its more complex geologic history. Some of the large circular structures in satellite images and geophysical maps may represent deeply eroded remnants of deformed impact craters, albeit shock-metamorphic features or impact rocks, have not been found so far, or they are not preserved anymore. If they are not the result of impact, we have to find convincing tectonic explanation for them, *e.g.*, a fault bounded tectonic block or a mantled gneiss dome.

Re-examining the significance of key data from impact craters on the Canadian Shield

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A broad consensus now exists on hypervelocity impact crater mechanics, based on field observations, theory and computer simulations. Refinement requires closer attention to key parameters observable in better preserved terrestrial craters. Among them, simple and complex craters on the Canadian Shield, which range in size over almost two orders of magnitude, have the advantage of being formed in crystalline rock targets with relatively uniform physical properties. This compensates in part for the general lack of structures which allow displacements to be determined directly. In re-examining data which have largely been published before, particular attention is directed at features which change with crater size, including:

1. levels of shock metamorphism in para-autochthonous basement rocks;
2. the profiles of gravity anomalies;
3. the prominence of pseudotachylites;
4. the distribution of melts rocks and associated mixed breccias.

A number of propositions can be derived from this set. Thus, the change in shock levels at the boundary between para-autochthonous basement and overlying melt rocks and breccias ranges from an estimated <10 GPa on the axis of simple craters to >20 GPa in large (>50 km) complex craters. It follows that proportionally less material is mobilized as breccia and melt in the larger craters. However, more of the underlying basement rocks is displaced in late stage movements. Reasonable estimates of structural displacement in simple craters can be derived by comparing the apparent shock attenuation with exponential rates near -2 obtained theoretically and experimentally for actual shock attenuation. The data at larger craters appears to require a higher rate of attenuation for basement rocks beyond the central peak area, but no change of rate with size is needed if the rocks originally lay within the near-surface zone.

The central low characteristic of gravity anomalies at simple craters is maintained through the transition at a diameter of 4 km to central peak craters but at diameters >30 km, where ring structures become evident, the anomaly profile changes to a subdued high within a peripheral low. An interpretation is that central uplifts do not rise above their present position in craters <30 km across but in larger structures rise well above the original surface before subsiding to their present level. In the largest complex craters the total vertical motion of para-autochthonous rocks underlying the point of impact can be estimated to be comparable to the diameter. In the process fracture porosity is largely sealed and pseudotachylites, which are rare and small in craters <30 km but increasingly conspicuous with rising crater size, are generated and emplaced. Similarly, as the transient central peak rises, allochthonous melt rocks and breccias lining the crater walls slide towards the margins, being concentrated at the ring or beyond it in the peripheral trough.

The Sudbury igneous complex: A classic example of a differentiated impact melt sheet?

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As the Sudbury Structure (N46°36',W81°11') is a complex impact structure with a diameter on the order of 250 km was formed in a mixed target consisting predominantly of crystalline rocks and, thus, a thick coherent impact melt sheet with a granodioritic bulk composition was produced. This melt sheet is represented by the Sudbury Igneous Complex (SIC). Compared to other terrestrial impact melt sheets, the SIC differs its lithological layering and its great thickness of 2.5-3.0 km. No contacts *per se* or chilling are observed between the lithologies (all petrographical and geochemical variations are gradational from one layer to the next) and no chilled margin is observed at the base of the SIC. Phase layering and cryptic layering, but neither rhythmic layering nor finer cm-scale layering, are observed within the SIC. The regular chemical and mineralogical variation from the bottom to the top of the SIC is evidence of its crystallization as a single melt system. This is perhaps best shown by the systematic increase in abundance of REEs and the substantial uniformity in REEs patterns (excluding Eu anomalies) between the SIC lithologies, with no real change in the light to heavy rare earth elements ratio. The chemical variation of various mineral phases and of the major, trace and rare earth elements is consistent with a fractional crystallization history for the SIC.

Oxidation of magnetite crystals, uralitization of pyroxene crystals, saussuritization of plagioclase crystals, and, in some parts of the SIC, leaching of magnetite and primary hornblende crystals are indicative of deuteric alteration. This deuteric alteration, together with the presence of primary hornblende and biotite, indicate that the SIC contained a hydrous phase during its crystallization history. The voluminous micrographic and granophyric intergrowths observed in the SIC are most likely due to a combination of high water pressures and rapid undercooling conditions caused by the exsolution of the fluid from the melt. Thus, the SIC melt was water-rich, an unusual characteristic of granitic composition melts emplaced at shallow depth. [1] show that water-saturated granitic melts intersect their solidus (*i.e.*, tend to be crystallized) by the time the pressure falls to 0.1 GPa, which is equivalent to the emplacement depth of the SIC, *i.e.*, ~ 3 km.

The SIC is currently the only known differentiated terrestrial impact melt sheet. In order to differentiate into a series of distinct lithologies in the terrestrial environment, igneous bodies must be at least a few 100s m thick (*e.g.*, [2]). It is concluded that the total volume, and especially the thickness, of melt formed in an impact are among the most obvious factors in determining the potential for differentiation processes to occur within the impact melt sheet. When thick enough and their composition permitting, impact melt sheets on Earth will undergo igneous differentiation. This may have had implications for crustal evolution of the early Earth.

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The global impact-studies project

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Within the last quarter century, the world has turned an interested eye toward the study of large body impact because of its potential role in the formation and evolution of Earth and the life that dwells upon it. Recognizing the growing need to coordinate and encourage scientific studies of the terrestrial record of meteorite impact, The International Lithosphere Program initiated in 1998 a new project "Global Impact-Studies Project (GISP)" under the general Theme III "Continental Lithosphere". The mission of GISP is to promote, encourage and guide international studies of terrestrial impact structures. The main emphasis will be on gaining a better understanding of cratering processes and their effects on the lithosphere and biosphere of planet Earth.

The project is believed to be central to the principal goals of the International Lithosphere Program because large body impacts have had dominant effects on the evolution of the lithosphere in the Archean epoch, as recorded on the moon, and decisive effects during the Proterozoic and Phanerozoic times not only on the lithosphere but also on the atmosphere and biosphere (impact-induced mass extinctions). Analysis of large impact structures, particularly of those in the upper size range of some 50 to 300 km diameter, require international and interdisciplinary cooperation. GISP wants to support (1) coordinated research on a set of well accessible craters of various states of erosion from which a comprehensive insight into the cratering process can be gained and (2) interdisciplinary systematic research on specific very large craters such as Chicxulub (200 km diameter), Mexico, which are instrumental to a better understanding of the global effects of impact cratering.

The principal assistance that GISP can provide to the international impact research community is to act as an information and support center that should coordinate closely with the long-term European Science Foundation Programme "Response of the Earth System to Impact Processes" which started in 1998 and is led by C. Koeberl (Chairman, Austria) and P. Claeys (Secretary, Germany) and 13 Steering Committee members.

At a meeting of the board of chairmen of GISP in March 1999 at Houston, an Advisory Board and the near-term activities of GISP were defined. A subsequent meeting of the Advisory Board, held on July 16 in conjunction with the 62nd Annual Meeting of the Meteoritical Society in Johannesburg, South Africa identified some ways that GISP could facilitate collaborations across disciplinary and geographic boundaries. These include:

1. Implementation of an electronic Newsletter (Internet web site) in close cooperation with the ESF Programme "Response of the Earth System to Impact Processes" in order to provide for the expedient exchange of information, ideas, and data worldwide.
2. Establish contact with and petition relevant international and national funding agencies to support impact crater research.
3. Support new programs of impact research in developing countries.
4. Help organize meetings, field excursions, and seminars for scientists to interact and exchange ideas (in cooperation with the ESF Impact Programme).

A remote sensing investigation of the Bosumtwi impact structure, Ghana

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The 10-km-wide Bosumtwi crater in Ghana is a confirmed impact structure, which is well-known for its relationship to the Ivory Coast tektites, which are coeval with this impact structure [1]. Bosumtwi is located in a completely rain-forested area, with very little geological exposure (with the exception of some excellent outcrops on the crater rim [2]). The center of the structure is filled with an approximately 9 km wide lake; the crater rim rises 250-300 m above the lake level. A very subtle topographic feature has been noted on topographic maps, at a radial distance between about 8 and 10 km from the crater rim [2, 3]. Here we report on the results of a remote sensing study of Bosumtwi. Any advanced modeling of common multispectral data sets, such as Landsat TM, is difficult due to the dense vegetation cover. However, vegetation effects often can be linked to underlying geological contrasts. In this case, the TM data show detailed structure of the crater rim, including arrays of radial, concentric, and tangential or oblique fractures, with respect to the crater center. These cratering related trends are superimposed on the regional fabric (recognizable in the eastern sector where the cratering related deformation superposes the Obuom Range). A broad vegetation effect annular to the lake extends radially for 10-11 km from the crater center and is possibly related to distribution of impact ejecta. The apparent width of the crater rim is asymmetric (1.5 km wide on the western side; 2.5-3 km on the northern and eastern sides). Surface sensitive radar data and available topographic information captured in the GIS produced an improved picture of the crater morphology. With digitized topographic information, different perspective views were generated and could be - in future - integrated with other geo-referenced information. Existent topographic data were captured digitally and a digital elevation model (DEM) was generated. Different processing and display of this DEM, and overlays with the radar data show the impressive crater rim as well as a second circular feature of comparatively subdued elevation at about 10-11 km from the lake center. Views from different angles and directions further support this observation, which is consistent with earlier findings based on topographic data only [3]. Lithological differences can not be detected directly with the remote sensing data. Vegetation obscures such information. However, using again geomorphological data sets, additional information such as drainage patterns can be interpreted and potentially used to differentiate between different lithologies.

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Geological, petrographic, and geochemical studies at the Bosumtwi impact structure, Ghana: A progress report

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The Bosumtwi impact crater is located in the Ashanti Province of Ghana, near the town of Kumasi, centered at 06°32'N and 01°25'W. The structure, which has an age of 1.07 Million years, is almost completely filled by Lake Bosumtwi and has a rim-to-rim diameter of about 10.5 km. The first suggestions that the Bosumtwi crater is the source crater for the Ivory Coast tektites were made in the early 1960s. Ivory Coast tektites were first reported in 1934 from a geographically rather restricted area in the Ivory Coast (Cote d'Ivoire), West Africa. Microtektites were reported from deep-sea sediments of corresponding age from the eastern equatorial Atlantic Ocean west of Africa. Ivory Coast tektites and the Bosumtwi crater have the same age (1.07 Ma; [1]), and there are close similarities between the isotopic and chemical compositions of the tektites and crater rocks (for references and details, see [2]). These observations strongly support a connection between the crater and the tektites.

The crater was excavated in lower greenschist facies metasediments of the 2.1-2.2 Ga Birimian Supergroup. While, in general, the regional geology is dominated by graywackes and sandstone/quartzitic rocks, in the northeastern and southern sectors shale and minor mica schist attain some importance. Several Proterozoic granitic intrusions occur in the region around the crater, and a small number of strongly weathered granitic dikes were observed in the crater rim as well. The granitic component of the target region is estimated at <2 %. In January 1997 and January 1999, field work was conducted at the Bosumtwi impact crater, in order to obtain a representative suite of target rocks and impactites, and to study the structural aspects of the crater rim (*e.g.,* [3]). Rock samples were collected along new roadcuts through the crater rim. Suevite occurs as large blocks of up to several meters width and as patchy massive deposits outside and north of the crater rim. Previously reported suevite occurrences to the south of the crater could be confirmed but are badly weathered. From massive exposures, suevite samples were recovered for petrographic, geochemical, and paleomagnetic studies. [2] found that the target rocks do not show any unambiguous evidence of shock metamorphism. Distinct impact-characteristic shock effects (PDFs) were identified only in clasts within suevite-derived melt fragments. The compositional range of the target rocks is significantly wider than that of the Ivory Coast tektites, but overlaps the tektite compositions. These authors found initial $^{87}Sr/^{86}Sr$ ratios of 0.701 and ε_{Nd} values of -17.2 to -25.9‰ in the Bosumtwi rocks. In 1997, an aerogeophysical survey of the crater was flown in cooperation with the Geological Survey of Finland. The results, especially of the radiometry, indicated the presence of an annular feature with a diameter of about 18 km. In 1999, a shallow drilling project was undertaken on the north side of the crater rim in cooperation with the Ghana Geological Survey Department, to determine the extent of the ejecta blanket around the crater and to determine the nature of the radiometric anomaly. Seven drill cores were obtained. The maximum thickness of the suevite was determined to be about 15 meters.

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Structural constraints and interpretations on the formation of the Söderfjärden and Lumparn impact structures, Finland

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The surficial expression of the *Söderfjärden* (530-510 Ma) impact structure is that of a ~5.5 km wide plain surrounded by an up to ~55 m high discontinuous elevated rim. A drilled central uplift, covered by ~40 m glacial drift and ~1 km across, is encircled by a moat as suggested by gravity and seismic studies [1]. The well preserved crater reveals a marked asymmetry in all geophysical data sets. The eastern moat-rim transition appears distinctly shallower than the western slope. This might be an effect of post-impact tectonic modification, non-uniform slumping, or of an oblique impact (20-30° from the horizontal) with a trajectory from the west. The latter two interpretations are mutually not exclusive, and could also explain, inter alia, the comparatively higher elevations of the northern and southern rim, the apparent lack of extensive breccias in the western moat and the westward offset of the central uplift relative to the topographic rim (*e.g.,* [2]). In 1998 pseudotachylites have been found (P. Virransalo) within glacially polished gneisses at the northeastern crater limit and on the northern rim. The dark dikelets are mostly a few millimeters thick and form anastomizing networks. Offsets (max. 30 cm) without a preferred sense of shear are evident and indicate a generation by rapid small-scale slip. The same features have been observed in gneissic boulders on the southern rim. A single reddish granitoid block from the same area reveals a ~20 cm thick breccia dike with a black melt matrix. As granitoids have been drilled in the western crater moat, it may be of impact-origin.

The *Lumparn* impact structure (age 443-600 Ma) appears as a rhomb-shaped bay with ~10 km long sides. A combined evaluation of seismic profiles and bathymetric charts suggests that the preserved sub-water craterform is ~7 km across. A central uplift does not appear in these data, but its presence is indicated by a central drill core that encountered strongly shocked, parautochthonous granites below Pleistocene drift [3]. Analyses of topographic and ERS radar data yielded no hints for potentially impact-related radial or concentric fracturing beyond the shores of the bay. The present structural setting clearly points to post-impact tectonic modifications along NW and N-trending faults. At two localities on the south-shore (Rödhäll) and on the islet of Röda Kon shallow dipping clastic dikes have been observed that contain severely brecciated material. Their textures indicate a forceful injection, but no shock features have been recognized so far. In one of these dikes two generations of breccia occur, of which the older one, consisting solely of granite, contains dm-sized rounded fragments. If this material was injected during impact, the coeval presence of a weathering crust not covered by sedimentary rocks is likely. The younger injected material exploited the pre-existing zone of weakness and penetrated through the granitic breccia. It is of sedimentary origin and contains mm-sized fragments of formerly lithified clastic rocks. Striations at the sharp contact between granitic and sedimentary breccia point to injection during block movements. If this material was injected during impact, a sedimentary cover existed at that time. In-situ brecciation is generally frequent on the granitic shores, yet it appears very localized often with decreasing intensity away from a central master fracture.

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Structural investigations in the Siljan impact structure

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The Siljan Impact Structure (61°2', 14°52'E), radiometrically Late Devonian, is one of the largest impact structures of Western Europe. The centre of the structure consists mainly of shocked and brecciated postorogenic Svecokarelian Dalagranites. They form a topographical high of approximately 30 km diameter, which is surrounded by a concentric depression. The ring-shaped depression contains deformed sedimentary rocks of Ordovician and Silurian age with stratigraphically underlying Proterozoic supracrustals in the northwest sector. The granites within the centre of the structure have been interpreted as the central uplift of a complex impact structure. The apparent diameter of the structure was assumed to be 52 km [1] which coincides with the outer limits of the Palaeozoic Ring Structure.

In order to find new constraints for a reconstruction of the original size of the Siljan Impact Structure we investigated the intensity and distribution of fractures outside the Palaeozoic Ring Structure. Gradients in both fracture density and the fracture pattern towards the Palaeozoic Ring can be used to distinguish impact-related from tectonically induced faults.

Fractures and veins that can be related to the impact event can be observed in a zone of approximately up to 7 km away from Palaeozoic Ring. The geometry of the dark veins resembles pseudotachylites. They display anastomosing networks of subparallel veins with blind injections and vary in thickness. Their thicknesses commonly range between 0.2 to 0.5 cm; a maximum thickness of 1.5 to 2 cm has been recorded. Most of the fractures are not strictly concentric or radial but they dominantly occur in an acute angle to the radial orientation with respect to the proposed impact centre.

The lack of these fractures beyond the 7 km zone proofs the relationship to the impact event. The zone of intense fracturing of the crater basement has a diameter of 65 +/- 1 km. This diameter may coincide with the initial diameter of the impact structure and indicates a considerably larger impact than previously proposed [1]. Based on this value and using crater morphometrical laws [2] we assume a transient crater diameter of 42 km. If the apparent diameter of the Siljan Impact Structure of 65 km is correct, the central peak diameter is 15 km, which is not in accordance to the uplifted area of the Siljan Structure, which is about 30 km in diameter. The large diameter of the uplifted region may be explained by assuming the existence of a peak ring. The existence of a peak ring is confirmed by the distribution of the Siljan and the Järna granite. Siljan granite intruded in a higher crustal level than the Järna granite. Within the central uplift the Järna granite occupies a central position, surrounded by the Siljan granite.

In our calculations, assuming a transient crater diameter of 42 km the inward movement of the Palaeozoic is in the order of at least 6 km, which is in agreement with field studies [3] and numerical models [4].

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Material flow during crater modification: Volumetrical modelling and implications from the Siljan impact structure

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The modification of impact craters under gravity induces a centro-symmetrical material flow field. The conservation of volume requires structural adjustments to compensate converging or diverging particle trajectories.

A converging material flow is induced by inward movements of coherent masses (landslides) which flow from the crater crest into the cavity. Three types of mechanisms are possible to overcome space incompatibilities during convergent inward flow: (1) bulk thickening of material in motion by pervasive, for instance intergranular or cohesionless flow, (2) bulk thickening by folding, thrusting and doubling of sequences (3) localised thickening at the edges of individual landslides by oblique collision of juxtaposed landslides. Since a horizontal deposition during oblique collision is not possible, rock masses must be transferred to the free surface along thrust faults which may join a steep fault of radial orientation at depth. Squeezing-out of material leads to the formation of structural highs and may even produce morphological ridges of radial orientation. In terms of structural geology the resulting structure is similar to a "flower structure". Being an analogue to transpression zones of continental strike-slip zones we denote such ridges in impact craters as radial transpression ridges (RTR). RTR's may start to grow where distal terraces form. They end where the collapsing central uplift overthrusts the inward sliding masses. Volume, width and height of the RTR's should increase towards the centre of an impact structure.

Outward movements induces diverging particle trajectories in a centro-symmetrical material flow field. They dominate when the central uplift collapses and forms a peak ring. In such a radial extensive strain field, again, three types of adjustment mechanisms are possible: (1) bulk thinning of material by pervasive superplastic flow, (2) bulk thinning by normal and detachment faulting including block rotation and folding (3) formation of localised graben and troughs along radial directions which are denoted as radial transtension troughs (RTT). A hummocky appearance of the central uplift/peak ring which is often observed at extraterrestrial craters point to (2).

The converging and diverging particle field collide with each other at the outer margin of the central uplift/peak ring. This is a zone of most complex thrusting and stacking. The thrust faults strike concentrically and may dominantly dip towards the impact centre. The collapsing central uplift acts as an obstacle preventing landslides to move further towards the crater centre. From numerical modelling we suggest that the final deformation increments concentrate on this collision zone.

A simple geometrical model is presented for converging particle trajectories to infer the amount of bulk thickening and transpression thickening of inward sliding masses during crater modification. The principle assumption of the model is the conservation of volume involved in converging movements. The model is applied to Siljan Impact Structure, Sweden, (61°2'N, 14°52'E) where five RTR's have been identified at those localities characterised by a restricted width of the so-called Palaeozoic Ring. Inward movements of the deformed Palaeozoic strata are in the order of 6 to 7 km. It is estimated that 10-20 % of the additional volume increment is involved into the formation of the RTR's and 80-90 % contribute to bulk thickening of the down-faulted masses. In general, the identification of the mechanisms of structural adjustment in a centro-symmetrical vector field rests upon the degree of erosion of the impact crater.

Size-frequency distribution of impact craters in Precambrian shields

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Astronomical observations (and meteor records) give a snapshot of the small body population. The stability of the observed picture needs additional modeling of celestial mechanics problems to study stability of orbits and possible evolution paths. Planetary cratering records show a picture integrated through the whole geologic lifetime of the studied surface. One need to compare surfaces of various ages on different planets to reveal spatial and temporal variation of the crater-forming projectile flux.

Precambrian shields on Earth give a rare opportunity to study an impact crater population which is well dated. In opposite, the recalculation of the crater size-frequency distribution from the moon to Earth gives an estimate of a potential number of impact craters accumulated in a specific area during a given time.

The presented work is devoted to various issues of the moon/Earth comparison of cratering records. The lunar calibration curve has been recently modified [1]. The modified calibration curve gives a good framework for the moon/Earth comparison. Fig. 1 shows the fit of the lunar calibration curve scaled for the terrestrial gravity and the projectile flux. The scaled lunar curve well fits the data for terrestrial cratons [2].

The inter-planetary correlation creates the useful tool to make a prognosis of how many craters of a given size were formed in the area of interest and what is a largest size of a crater which can be formed in a specific area during a specific period of time.

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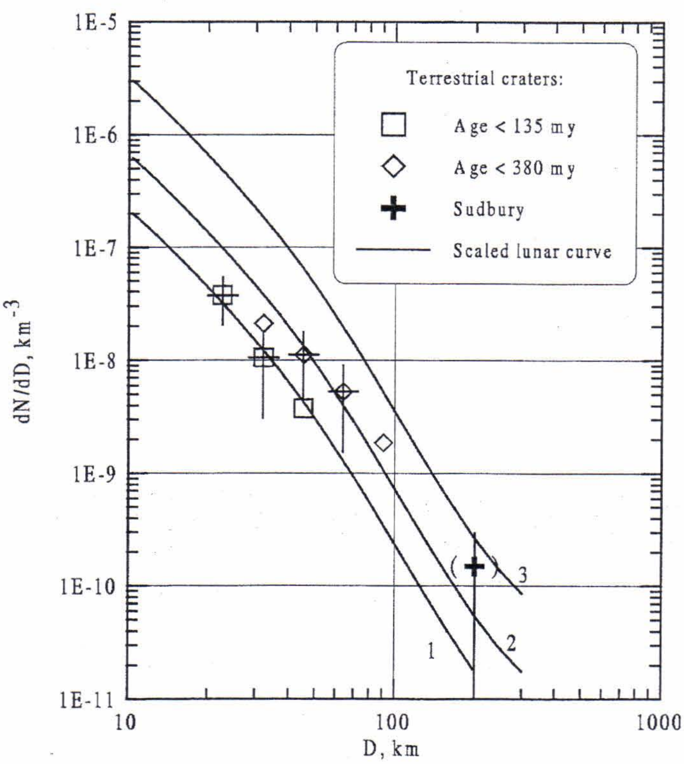

Figure 1. The comparison of terrestrial and scaled lunar data for two sets of cratering records. An assumption of the constant cratering rate allows to fix the Sudbury crater as the largest structure which is possible to predict for 2 Gy old shield.

Geophysical signature of large impact craters on Earth - a search for common denominators

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Integrated seismic surveys, potential field studies and results from exploration drilling programs constrain the size and shape of transient craters and provide first images of impact basin morphology. Common features of the geophysical studies across the Vredefort (South Africa - diameter: 300 km; age: 2006 Ma), Sudbury (Canada - 250 km; 1850 Ma), Chicxulub (Mexico - 180 km; 65 Ma), Ries (Germany - 24 km; 15 Ma), and Bosumtwi (Ghana - 10 km; 1 Ma) structures are:

- a reflective target stratigraphy,
- "quiet" post impact sedimentation,
- prominent magnetic anomalies.

The reflective target stratigraphy reveals the size of the transient crater and marks the collapse of the transient crater (broad terraces, fault offsets and slumped blocks). The "quiet" post-impact sedimentation follows the re-distribution of ejecta by high energy wave action. Prominent magnetic anomalies of large impact craters are attributed to remanent magnetization as thermal effects induce extremely high Q-values. Magnetization of melt, breccias and footwall complex are related to the thermal evolution of large impact craters: from a single heat pulse to long-lived hydrothermal processes and associated alterations (and mineral deposits?) in the footwall and hanging wall.

Understanding the nature and extent of excavation, brecciation, melt generation, slumping, alteration, erosion and late adjustments is essential to determining both, the energy release of the impact event and original shape and evolution of large impact craters. At present, lithology determinations in the deep craters remain problematic. Only the magnetic data seem to give indications of lithological control, although the physical mechanisms (such as cooling of melt and breccias and/or post-impact hydrothermal alteration) need to be studied in more detail.

Processes responsible for gravity and magnetic anomalies of meteorite impact structures: An overview

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The role of geophysical techniques in impact research has recently increased due to three factors. *First*, because most of the directly observable impact structures have already been discovered, indirect methods are needed. *Second*, geophysical data provide a 3-dimensional view of an impact structure. *Third*, coupled with drillings, the geophysical data have helped in discovering and characterizing of impact-related economic deposits in some structures. The most useful geophysical methods in impact studies are gravity, magnetic and electric, but also electromagnetic, seismic and radioactive techniques have been successfully used. Most of the processes that are producing the observed gravity and magnetic anomalies over impact structures take part during the excavation and modification stages of cratering.

For **gravity**, these include:

- fracturing and brecciation of target rocks and minerals (major negative gravity effect),
- formation of high-pressure polymorphs (minor positive gravity effect),
- mineralogic diaplectic changes (minor negative gravity effect),
- uplift of the crater rim wall (positive effect, surrounding the central negative anomaly); a-d are due to propagation of shock and/or rarefaction waves.
- elastic rebound gives rise to the central uplift and usually the central positive gravity anomaly of complex structures,
- gravitational infill of the cavity and formation of the allochthonous breccias and melt sheets (major negative gravity effect).

For **magnetics**, the propagation of shock and rarefaction waves at the presence of an ambient magnetic field may generate:

- shock remanent magnetization (SRM),
- shock demagnetization,
- mineralogical changes, producing (or destroying) magnetic minerals.

- Formation of the crater rim wall and central uplift redistributes the target magnetizations.
- Infill of the cavity creates a random orientation of pre-impact and impact-caused magnetizations in the allochthonous breccias.
- In those parts of the structure, where shock or post-shock temperatures are higher than the Curie-temperatures of magnetic carriers, the impactites may acquire a thermoremanent (TRM) or thermochemical (TCRM) magnetization during the cooling that completes at the post-impact stage.

A wide range of post-impact processes, like hydrothermal alteration, sedimentation, erosion, metamorphism, tectonics, *etc.*, are able to overprint, mask, destroy or remove the specific impact-generated physical properties, and therefore change the geophysical anomalies. Therefore, dependent on the geostructural and geographic position of an impact site, size and geological history of the event, geophysical signatures of impact structures may differ from each other substantially.

Geology and geophysics of the Proterozoic Kelly West and Teague Ring impact structures, Western Australia

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Kelly West and Teague Ring (Shoemaker) are two of the Proterozoic impact structures of the Australian continent. Geologic mapping and gravity surveys of these structures better elucidate the details of the structures.

Kelly West, in Northern Territory (19°56'S; 133°57'E), was originally recognized on the basis of widespread shatter cones. Only the central peak of the structure is exposed. Mapping indicates the central peak is composed of uplifted Proterozoic Hatches Creek Group rocks (largely sandstone with some shale). These rocks are deformed by radial folds, thrusts and normal faults; overall the Hatches Creek rocks form a circular anticline over the outer parts of the central peak. The core of the central uplift is structurally depressed and contains both an impact-produced authigenic breccia and a post-impact sedimentary breccia (possibly an alluvial deposit). The deformed strata are overlain by undeformed Middle Cambrian Gum Ridge Formation (chert and limestone). A gravity survey was conducted over the structure. A complex gravity anomaly is associated with the central uplift, but an anomaly is not associated with the remainder of the structure. The central uplift is marked by a circular gravity high with an inset gravity low. The high is ~1.5 km in diameter and has an amplitude of +0.3 to 0.4 mGal (with respect to the surrounding region); the central low lies at approximately -0.4 mGal (0.4 mGal below the surrounding terrain and 0.7 mGal below the surrounding high). The anomaly correlates well with the geology - the high occurring over the White Sandstone and Lower Red Sandstone of the Hatches Creek Group and the low over the authigenic and sedimentary breccia that occurs in the center of the uplift. The absence of an anomaly associated with the region outside the central peak indicates that there are no significant density anomalies outside the central peak. The geologic structure and the gravity signature of the central uplift, suggest that Kelly West may have a small peak ring rather than a simple central peak.

Teague Ring, in Western Australia (25°52'S; 120°53'E), has been renamed the Shoemaker Impact Structure by the Western Australia Geologic Survey, in honor of Eugene Shoemaker. The structure is characterized by a circular outcrop of Proterozoic Earaheedy Group rocks, most notably the banded iron units of the Frere Formation rocks, and is cored by Archean granites. The structure is about 30 km in diameter. Around the margins of the granitic core, the Earaheedy Group rocks dip away from the structure and then at greater distances turn up, forming a broad encircling syncline. The eastern margin of the structure has been mapped in detail and is characterized by a numerous outward dipping thrust faults which intersect and repeat the stratigraphic section. A gravity survey of the structure indicates a large-scale anomaly of -12 mGal centered over the granitic core rocks. The gravity low is suggested to be the result of the density contrast between the Earaheedy Group rocks and the granitic core; the apparent low densities of the core granites are suggested to result from shattering of the rock as a result of impact. Teague Ring/Shoemaker is a structure which apparently has been deeply eroded; perhaps several kilometers of material has been removed. Shock features (*e.g.,* shatter cones) are rare suggesting a deep level of exposure.

The Shoemaker Impact Structure, Western Australia: Remote sensing and GIS analysis of a deeply eroded Precambrian impact structure

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The Shoemaker Impact Structure (SIS), formerly known as Teague Ring [1], is located in Western Australia (25°52'S; 120°53'E). The age of the structure - although only poorly constrained by whole rock Rb-Sr isotopic analysis - is estimated at ca. 1.63 Ga and places the SIS as the oldest Australian impact structure known to date [2, 3].

The structure occurs near the unconformity between gently (5-10°) northeast dipping Paleoproterozoic (1.8 - 1.65 Ga) sediments of the Earaheedy Basin and the underlying granite-greenstone basement of the Yilgarn Craton [4]. The central uplift consists of Archean granites and syenites that are surrounded by a rim syncline of clastic and chemical sedimentary rocks. Dips of the rim strata are gentle to subhorizontal in the southwest, whereas in the northeast of the syncline sediments are steeply oriented and locally overturned. The general picture is a symmetry about a northeast plane, but an asymmetry about a northwest plane, possibly resulting from a decreasing erosion level in SW-NE direction [5].

All impact lithologies have been removed in case of the SIS. The only field criteria for recognizing the impact are scattered, coarsely developed shatter cones in granular ironstones, sandstones and granites. The outcrop conditions are quite limited, as much of the area is covered by alluvial deposits, salt lakes deposits and aeolian sand dunes.

Though field investigations are restricted, the SIS offers good conditions for a case study of a deeply eroded impact structure using remote sensing and GIS analysis. The crater is a noticeable ring anomaly from air and space, as the rim syncline can be easily traced by dark, massive granular ironstones. Except for multispectral Landsat TM data which have been processed to enhance the discrimination of lithotypes affected by the impact, the remote sensing analysis is based on complementary radar imagery (ERS-2), point located geophysical airborne data (^{40}K, ^{232}Th, U; aeromagnetics) and elevation data. In order to relate and evaluate the interpretation of Landsat TM imagery, spectras of rock types have been measured over the range of 400 to 2500 nm. Ground truth knowledge of the area has been compiled from previous geological field studies [2, 3, 5, 6], a recent geological remapping of the Nabberu map sheet [7] and fieldwork conducted during the field season of 1999. The integration of remote sensing, geological information and spectral measurements into a GIS leads to a comprehensive picture of the SIS. It allows the appropriate visualization of the impact geology and the combination of different geodata to point out causal connections of crater forming processes.

Acknowledgements: We acknowledge support by the Australian Geological Survey Organisation and the Geological Survey of Western Australia.

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Geophysics of the 300 km Uppland structure of south central Fennoscandia

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The Uppland region in south central Fennoscandia has been suggested as a large approximately 300 km diameter ring structure from remote sensing data [1], and as a complex impact structure based on geophysical data [2]. Scattered occurrences of several different breccia types have however so far not revealed any shock metamorphic overprints.

Recently, complete coverage with relatively detailed gravity and very detailed aeromagnetic measurements has been achieved by the Geological Survey of Sweden. These data allow an improved regional interpretation of crustal features and the distinction of structural patterns in the uppermost crust.

In ***gravity*** data, the regional variation shows three large structural units of the crust: a west-east striking gravity low in part associated with the Sörmland gneiss belt, a ring of low anomalies around a ring shaped central high anomaly with approximately 60 km diameter. A geological model of these features has been calculated, indicating a 12 km deep ring depression into the denser, 2.8 Mgm^{-3} part of the upper crust [3]. These denser rocks are exposed as quartz diorites and tonalites in a correspondingly 12 km high central rise. Within the entire Uppland structure, a lack of coherent anomaly patterns is typical in the residual gravity field.

The ***magnetic*** data were selected in a 200 m grid. The whole Uppland lacks larger continuous magnetic structures. The Sörmland gneiss belt in the southern part of the structure is for example broken up into numerous approximately 10 km sized blocks. In the northern 2/3 of the structure, the strike of magnetic sources is roughly concentric with the central gravity high. Several intrusives are seen and the western part of the structure is dissected by an extensive regional 1 Ga old magnetic dyke swarm. Frequent occurrences of magnetic ore concentrations are scattered over the whole structure.

The structural patterns seen in magnetic and gravity data are best explained by old regional structures overprinted by a large impact event, which in turn is dissected by dyke intrusions. The crustal model derived from gravity data contains the typical dimensions expected for an approximately 300 km diameter complex impact structure with a 60 km diameter central ring uplift.

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Comparative geophysical description and modelling of Lappajärvi and Jänisjärvi impact structures, Fennoscandian shield

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The aim of this paper is to bring together data and interpretations of two separate but sufficiently similar craters (Lake Lappajärvi and Lake Jänisjärvi) with an age difference of about 620 million years. Both craters were first interpreted as volcanic but at present they are regarded as proven meteorite impact structures.

The Lappajärvi structure is located in western Finland (63.2°N; 23.7°E). The diameter of the present crater is about 22 km. The target rocks are Palaeoproterozoic mica schists and pegmatitic granites. The impact rocks are impact melts, impact breccias, suevites, and fragmental breccias. Peneplanation and weathering was followed by deposition of thin layers of Mesoproterozoic siltstones and sandstones. The meteorite impact has been dated to 77 Ma. A circular negative Bouguer anomaly of approximately -11 mGal with a half-amplitude width of 13.8 km is associated with the structure. The minimum amount of impact melt rock was interpreted from the positive residual anomaly within the crater as being 1.5-2.0 km^3. There are few small aeromagnetic anomalies up to 180 nT at an altitude of 40 m within the crater, which mostly is characterized by a lack of magnetized material. Strong magnetic anomalies (a few thousand nT) which are abundant in the surroundings disappear in the crater area, which, however, is associated with a broad central high of ~40 nT. The airborne electromagnetic (AEM) data show strong anomalies with in-phase/quadrature ratios close to 1, indicating moderately conducting material within the crater. In a digital elevation model, a topographic rim with a diameter of about 22 km surrounds the lake.

The Jänisjärvi impact structure is situated in the Russian Karelia (62.0°N, 30.9°E). The diameter of the present crater is about 16 km. The target rocks are metasedimentary gneisses of the lower Kalevian Ladoga Formation. The present crater is deeply weathered with impact rocks exposed only on the small islands near the centre of the lake. They are allochthonous impact breccia, suevites and melt rocks (tagamites). The meteorite impact has been dated to 698 Ma. A circular negative Bouguer anomaly approximately -7 mGal with a half-amplitude width of 8.5 km is associated with the structure. According to the low-altitude (65m) aeromagnetic map, local magnetic anomalies, which are abundant in the surroundings, disappear in the crater area. The diameter of the subdued magnetic anomaly is about 18 km. In the middle of the lake, there are a few residual magnetic highs of about +110 nT in amplitude. The structure is surrounded by circular aeroradiometric K- and Th- anomalies with a diameter of about 16 km. These probably are associated with the topographic rim.

We will present a new compilation of geophysical and petrophysical data and results from recent three-dimensional modelling of both structures for discussion during the workshop.

Porosity and density in altered target rocks of meteorite impacts

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The porosities of fresh crystalline rocks are generally lower than 1%, and the differences between dry and wet bulk densities are not significant. In weathered, altered or fractured rocks, porosity ranges from 1% to 20%, being as high as 30% in some meteorite impact rocks. Three different densities are needed for porous samples: dry bulk density ($\mathbf{D}_{bd}$), which is the mass of a dry sample divided by the bulk volume; wet bulk density ($\mathbf{D}_{bw}$), which is the mass of a water-saturated sample divided by the bulk volume of the sample; and grain density ($\mathbf{D}_g$), which is the ratio of the dry mass to the volume of the grains constituting the rock material, in other words, the bulk volume of the sample minus the pore volume. Water immersion methods [1] determine effective porosity ($\mathbf{P}_E$) and measure only interconnected pores, so that calculated grain densities may be underestimated.

Porosity and density data (Table 1) on samples from underneath of meteorite impact craters of Lake Sääksjärvi and Lake Karikkoselkä are examples of strongly deformed target rocks. The porosities of mica gneiss and granitic rock samples are about ten times higher compared to fresh crystalline rocks. The dry densities of seven altered mica gneiss samples range from 2329 to 2681 kg/m^3. The mean value 2731 kg/m^3 of their grain densities with a standard deviation of only 30 kg/m^3 is near the mean density 2739 ± 53 kg/m^3 of 129 mica gneiss samples located within 50 km radius from the Sääksjärvi crater. The dry densities of granitic samples ranges from 2263 to 2541 kg/m^3 and the mean 2642 kg/m^3 of grain densities corresponds well to the mean value 2635 ± 39 kg/m^3 of 128 porphyritic granite samples around the Karikkoselkä crater. Knowledge of grain density is useful in studying the source of the matrix of porous rocks. As wet bulk density corresponds to in-situ bedrock conditions, it is the best density estimate for gravity modelling. Porosity also affects strongly electric conductivity and seismic velocity.

Table 1. Porosity and density averages of altered target rocks from drill holes in the meteorite impact craters of Lake Sääksjärvi (SJ), SW-Finland and Lake Karikkoselkä (KS), central Finland. Measured bulk densities (dry D_{bd} and wet D_{bw}), effective porosity (P_E) and calculated grain density (D_g).

Rock type Samples (depths)	Number of samples		$\mathbf{P}_E$ %	$\mathbf{D}_{bd}$ kg/m^3	$\mathbf{D}_{bw}$ kg/m^3	$\mathbf{D}_g$ kg/m^3
Mica gneiss	7	**Mean**	**7.4**	**2528**	**2596**	**2731**
SJ2 (227-241m)		St Dev	3.8	113	79	30
Granitic rocks	12	**Mean**	**8.6**	**2415**	**2501**	**2642**
KS1 (149-183m)		St Dev	2.0	76	59	40
Granitic rocks	20	**Mean**	**7.7**	**2439**	**2516**	**2642**
KS2 (130-159m)		St Dev	2.3	67	47	23

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Magnetic intensity pattern of the Rochechouart impactites

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Magnetic anomaly patterns are among the most promising geophysical methods to discover hidden impact structures, as successfully applied to the K/T-boundary Chicxulub crater. To describe and quantify magnetic characteristics of such impactites, we have measured intensities (Am^2g^{-1}) of the various rock types exposed in the 20 km wide Rochechouart structure, with the idea to eventually compare the results with the newly established aeromagnetic map of the region. This approach has the potential to directly correlate aeromagnetic patterns with the spatial distribution of shocked rocks in a crater area. Fifty measurements were performed on precisely weighed cubes cut from seven different rock types, selected from the freshest exposures in the crater area. The samples are representative of the different Rochechouart impact lithologies, which are totally melted, highly vesicular granitoid rocks, the suevites of Montoumeand Chassenon, and the polymict breccia of Rochechouart, which is the most abundant facies among the preserved lithology in the crater. For comparison, an unshocked intrusional rock, typical for the crustal derived granites of the region was included. Individual measurements and mean values for each rock sample are displayed in the figure below, illustrating that magnetic intensities of all impactites are very weak (1×10^{-12} and 4.8×10^{-8} Am^2g^{-1}) being of the same magnitude of limestones and other weakly magnetized sedimentary rocks. None of the samples approach intensities specific for volcanic or some metamorphic rocks (10^1 to 10^{-3} Am^2g^{-1}). The Montoume suevite has the highest mean value, followed by one of the polymict breccia and the totally melted granite. Intensities for other polymict breccia samples and three Chassenon Suevites are all significantly lower (see Fig. 1), and the unshocked granite yields the lowest value being typical for such S-type granites. Since the rock-cubes were cut from 1-2 kg blocks, the mean values and their analytical uncertainties include the natural variations present across these samples, with their 2σ st. error lying between 15 and 30%.

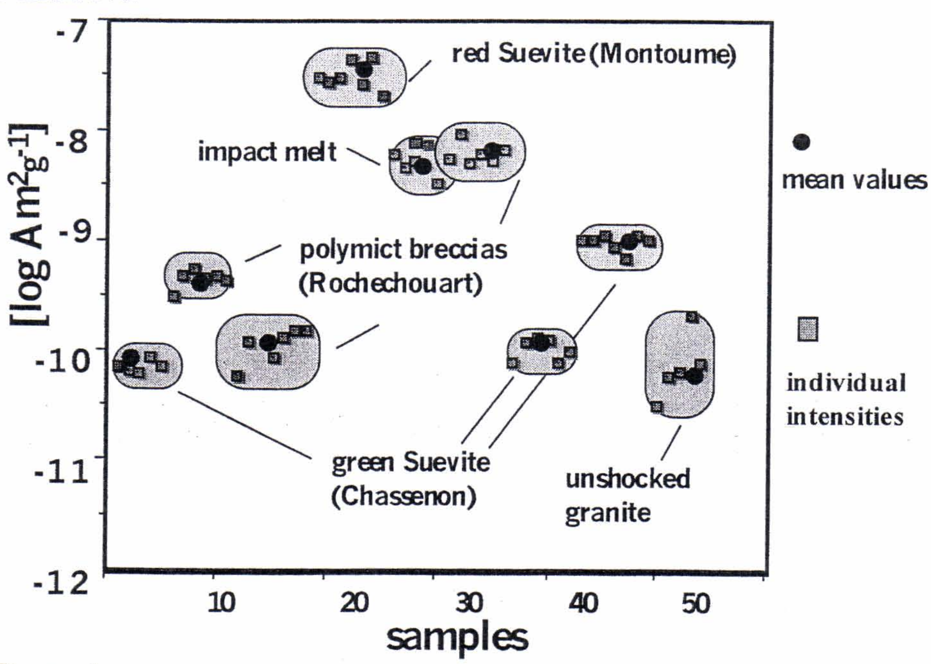

Figure 1.

Suvasvesi N - modeling gravimetric and aeromagnetic data of a Finnish impact structure

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A weak aeromagnetic signature with a diameter of about 4 km, which roughly follows the shoreline of the northern part of Lake Suvasvesi, apparently represents the rim of an impact structure, Suvasvesi N. It is located in the southeast of central Finland at 62°41'N and 28°11'E. In addition to airborne geophysical survey, the Geological Survey of Finland has carried out a gravity survey and collected petrophysical and paleomagnetic data. In addition, bathymetric data of the National Land Survey of Finland was utilised. Preliminary interpretations of the aeromagnetic and palaeomagnetic data indicate that the central negative anomaly is caused by strong remanent magnetization of impact melt breccias, probably of Permian age [1].

This work [2] aims at delineating 3D subsurface structure by modelling gravity data and evaluating the results of magnetic interpretation to obtain a better estimate of the crater's shape and age. From two detailed gravimetric profiles perpendicular to each other, a 2D and later a 3D gravity model, calibrated by hand samples from shoreline and drill core from the centre of the magnetic anomaly, were constructed. The Suvasvesi N impact structure appears to be a complex crater with a diameter of about 4 km, a depth of 260 m (from lake surface) and a central uplift with a height of 80 m. This is mirrored in the dimensions of the lake and the weak aeromagnetic relief. Comparing the 3D gravity model and aeromagnetic survey data, the structure does not show the expected radial symmetry. A probable reason for asymmetric features in the gravity data is the crater's location on the Raahe-Ladoga fault zone [3]. First results of a magnetic reinterpretation indicate a natural remanent declination of 180° and inclination of -60°, which slightly differs from the previous estimate (declination of 235° and inclination of -60°). This direction yields a pole position slightly off from the Phanerozoic apparent polar wander path of Fennoscandia but still suggests an age of less than about 300 Ma for the impact [4].

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Paleomagnetism and ^{39}Ar-^{40}Ar age determinations of impactites from the Ilyinets Impact Structure, Ukraine

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The Ilyinets meteorite impact structure is located in the western part of the Ukrainian Shield (centered 49°07'N; 29°06'E), where the target rocks consist of Archean and Proterozoic granites and amphibolites. Most of the structure is buried under Quaternary sediments. This complex impact structure, with a diameter of ~8 km, has a central uplift, which is surrounded by an annular trough filled with allogenic breccias, suevites and melt bodies. Impact melt rocks occur within and on top of the suevites as several sheetlike bodies. The age of the impact was poorly known but was generally thought to be between 400 and 500 Ma [1]. Seventeen oriented hand samples were collected from five outcrops in old quarries along the Sobik River in the southern part of the structure for paleomagnetic study. The investigated samples consist of impact melt rocks, melt-breccias, suevites, suevite breccias and of autochthonous brecciated target granites [1, 2]. Three impact breccias and one impact glass samples from our previous collection [1] were used for ^{39}Ar-^{40}Ar determinations. Here we present new paleomagnetic and ^{39}Ar-^{40}Ar dating results in an attempt to obtain a better age for the Ilyinets event. We also present new petrographic results of these samples which show clear hydrothermal alterations.

Petrophysical results. Based on petrophysics (density, susceptibility, NRM intensity and Q-ration) the impactites can be grouped into two groups: (1) impact breccias and melt rocks and (2) suevite breccias and suevites. The impact breccias and melt rocks have clearly higher densities (2300-2350 kgm^{-3}) than the suevite breccias and suevites (1950-2100 kgm^{-3}). The breccias and melt rocks also have slightly lower susceptibilities, NRM's and Koenigsberger ratios than the suevite breccias and suevites. These trends in petrophysical properties of impactites is very similar to those observed in many other (*e.g.*, Lappajärvi, Mien) impact structures containing allogenic breccia lenses with impact melt bodies.

Petrography. Petrographic evidence of shock metamorphism in the clasts include shatter cones, kinkbanding in biotite, PDF's in quartz [1] and impact-induced high-pressure phases as coesite and diamond [3]. It should be noted that there is no indication of lechatelierite although the presence of impact diamond shows that the shock pressure exceeded 35 GPa. One logical explanation to this contradiction is hydrothermal alteration, which altered the more susceptible phases to secondary minerals. Accordingly, in the Ilyinets crater all impact breccias and the melt rocks are strongly altered mainly to clay-like minerals but in addition sporadic silicification was observed in some impact metamorphic rocks. The silicification is of two main types: silcrete-like silicification or earlier, mainly matrix minerals, and void-filling agates with diameter up to 16 cm [1]. The silicification can be interpreted to have formed in low-temperature post-impact hydrothermal activity corresponding to the formation of agates in the Sääksjärvi impact crater [4]. At present, Ilyinets and Sääksjärvi are the only craters known to contain agate-filled voids in their impact melt rocks.

Paleomagnetic results. The alternating field demagnetization treatments show that the characteristic remanent magnetization of impactites is often hard and stable, particularly in melt rocks and in melt breccias. Only a single upward pointing remanence component was identified, although occasionally, there are evidences in melt breccias of another component which can be (?) a reversed component to the characteristic one. It is noteworthy that the two fractured allogenic granite samples yielded very different remanent magnetization directions than the impactites. Based on the well defined APWP of Baltica and on less well defined APWP of the

Ukrainan Shield, the paleomagnetic data suggests an age of ~430 Ma for the Ilyinets impact event.

^{39}Ar-^{40}Ar datings. Three samples yielded good plateau ages (sample I-11, impact breccia, 409.9 ±3.7 Ma; I-12, impact breccia, 424.7 ±3.8 Ma; I-17, impact glass, 438.3 ±3.9 Ma). The one total gas ^{39}Ar-^{40}Ar age (I-13, impact breccia, 431.1 ±3.8 Ma) is within the range of the plateau ages. Together, the ^{39}Ar-^{40}Ar and paleomagnetic data thus confirm an age of ~430 Ma for the Ilyinets event.

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Impact transformation of the crystalline basement in the Logoisk astrobleme

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Logoisk astrobleme (Bielorussia, diameter about 9 km, 29 boreholes have been drilled on it's area) is a crater with a two-layered target: (I) granite gneiss of the crystalline basement, which are overlied by (II) flat-lying sediments: the upper Proterozoic sandstones of various composition, mudstones and siltstones; and Devonian carbonate rocks. The thickness of the sediments is about 300 m. The average age of Logoisk structure is 42.3 ±1.1 Ma that is close to the Eocene 2 - Eocene 3 boundary of Paleogene period of the Earth geologic history.

The aim of our investigation is to discuss the formation mechanism and composition of an impact melt in a crater with a two-layer target.

Geophysical data indicate a gradual attenuation of clastation with depth under the crater bottom and a transition to the undeformed basement. Borehole has been drilled in the central of crater to the depth of 1254 m, including 700m into the basement. However, it did not go out of the zone of fragmentation.

Impactites. Thickness of the layer consisting impact melt breccias is ~11 m. In the center of the structure impact melt breccias were penetrated by holes. Suevites that contain up to 40% of glass, compose large part of the central massif or occur as a rather thin cover around the allogenic breccias. In the upper part of suevites section, the fragmental matrix consists of the fragments of granite gneisses, fragments of sedimentary cover. The maximum thickness of suevites is ~126 m. The allogenic breccias overlie the granite gneisses inside the crater and abut upon the normal sedimentary sequence in its sides. The allogenic breccias contain fragments of rocks, varying in lithology and age.

We distinguished fine fragmental breccias, which occur as 2 to 40 m thick lenses or interlayers at different depths. The fine fragmental breccias are either devoid of impact glasses, or contain it less than 10%.

Major chemical elements - our results (about 400 microprobe analyses, 25 chemical analyses) showed that the major part of the impact melt in Logoisk structure had been produced by the melting of the granite gneisses of the crystalline basement despite the two-layer target. Only in fine fragmented breccias in the upper part of impactite section there is the melt with the rocks of the sedimentary cover (Upper Proterozoic sandstones and siltstones). Most of sedimentary cover occurs as blocks and clasts in impactites. Our results showed that impact melt of the Logoisk crater has a different degree of melt homogeneity (electron microprobe analysis and small-angle scattering technique). The peculiarities of the chemical composition of impact glasses have higher degree reduction of the iron and accumulation of K and Na in the glass of suevites comparing with matrix.

Trace elements – using quantitative spectrum analysis and microprobe analysis. Sandstones and siltstones of sedimentary cover are different from granite gneisses on concentrating of Mn, Na, and Li. Mostly, the composition on trace elements of impact glasses from suevites and impact melt breccias corresponds with granite gneisses. There are some peculiarities: in impact melt breccias the content of V and Ga is a little higher than in granite gneisses; in suevites more Ti and Cr occur. There are differences between matrix and glasses from suevites – in matrix less V, Ni, Ti, Y and Mn (on statistic approach).

Rare-earth elements – on neutron activation technique and ICP technique. Our data show that impact glasses from suevites and impact melt breccias are inherited geochemistry of granite gneisses of crystalline basement, but there are some peculiarities: the concentration of Ce in impact glasses is variable and most likely depends on the temperature of the impact melt.

Breccias of assumed impact origin in the Precambrian of Northern Hardangervidda, central south Norway

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In the Precambrian Basement of South Norway in the northern part of Hardangervidda a dozen of structures characterized by dark matrix lithic breccias occur. The localities are situated 50-200 m below the level of the subcambrian peneplain.

The best exposed of the breccias is situated near Finse at 60°33'30"N, 7°1'58"E (UTM 32VMN195151), northeast of the Hardangerjøkulen glacier. Within an area of about 250m × 150 m the granitic rocks are deformed, containing irregular patches of dark breccia bodies (50m × 20m and smaller). The country rock which surrounds the dark breccias may be slightly brecciated or fractured, containing narrow "dikes" of dark breccia or may have no visible deformation.

The dominating breccia rock (impactite) is in general a dark, white-spotted, medium-grained, coherent clastic rock with white, angular grains in a dark, fine-grained matrix. Under the microscope the original granitic rock is seen to have disintegrated to separate mineral grains and small lithic grains. The individual mineral grains are also fractured to various degrees. An opaque, black and very fine-grained material is disseminated in the rock and fills in between the mineral grains and in fractures within the grains. Hydrothermal calcite and also quartz occur in addition to low temperature secondary minerals. The black material has proved to be carbon, and the concentration of the carbon varies a lot. For one sample of dark breccia the carbon isotopes has been analyzed and $\delta^{13}C$ is –29,1‰.

Within the areas of the white-spotted breccia an even more fine-grained breccia occur, characterized by a slacky and pitted weathered surface. In part the rock contains irregular voids, some of them with coarse crystalline calcite. Under the microscope this rock is seen to be even more fine-grained brecciated with crushed mineral grains and with black material (carbon) disseminated in the rock. This breccia represents the most intensely deformed rock.

Granite pegmatites can be followed in the breccia by means of the large clastic feldspar grains in the black matrix indicating only small scale relative movement of the clasts.

A number of similar breccias occur in the generally poorly exposed area between Hallingskeid and Ustaosed and also north of Hallingskarvet.

The texture of the breccias suggests a strong and unevenly distributed shock metamorphism, and as the rocks are similar to some of the rocks, especially the "Black-Matrix Breccia", in the Gardnos impact structure [1] situated 55-85 km east of the breccias in question, it is suggested that also these have an impact origin and that the present exposures represent a deep section in the structure. The $\delta^{13}C$ value for a dark matrix breccia from Finse is similar to the $\delta^{13}C$ values from the breccia rocks from Gardnos where a C-rich shale is proposed as source, thus indicating the same source for the carbon in the Finse breccia.

The age of the structures is rather uncertain, supposed to be between late Precambrian and the time of the Caledonian orogeny. May be the impact structures indicates a meteorite swarm connected to the Gardnos impact?

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The big Pechenga Bang

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The semi-circular Pechenga monocline (or brachysyncline; Fig. 1) consists of several series (suites) of S-dipping metavolcanic/sedimentary rocks, stacked 2.33 - 1.97 Ga ago. The lower series consist of basalts, andesites and minor acid volcanites. Basalts and ferropicrites abound in the uppermost, and thickest (<2.5 km), Pilguyarvi Series (PiS). Ultramafic intrusions in the sedimentary "productive suite" of PiS host the world-class Ni-Cu ores. Beyond the Porytash NW-trending fault zone, the S. Pechenga volcanic and sedimentary rocks include peculiar acid melt rocks. Further SW are large granitoid domes and gneisses.

A discrete layer of acid volcanic-looking rocks runs for tens of kilometers 600 m above the base of PiS volcanites. These have been described as tufosilicites and ultrafelsic tuffs, and interpreted as liquids immiscible with ferropicritic melt, or halmyrolytically altered acid tuffs. The layer (Fig. 2), generally 6-9 m thick, may thin out or swell to 50 m. Faulting and folding faked recurrences. The base is sharp, with deep chasms; the top is often banded, vitreous. Internal subaqueous slumping (reminiscent of olistostromes), folding and cross-bedding attest to tumultuous topographic upheavals and tsunamis. The rocks are exceptionally trim, thanks to tender metamorphism (prehnite-pumpelleyite grade). Coarse to fine-grained breccias prevail, with lithoclasts (gneisses, granitoids, gabbros, Pechenga volcanites, soft sediments), siliceous vitroclasts and various crystallo-clasts, all in wanton paragenetic disequilibrium. Planar deformation features (PDF's) in quartz clasts (Fig. 3) imply an impact origin for the layer, and warrant appropriate terms. The layer is called suevite-metatektite (SMT) henceforth. SMT compositions, reflecting proportions of siliceous base, vitroclasts and exotic clasts, accord with tektites (*e.g.,* high Si, Fe, Cr, Ni, Ni/Co, decreasing Al but constant Na+K with increasing Si). Quartz clasts have tektitic overgrowths, largely peeled off. I found various vitreous globules, accretionary lapilli and micro shatter cones in quartz. Besides Archean zircon (2.7 Ga) the SMT contains prismatic 1.97 Ga zircon, the age of ferropicrites and Ni-Cu ore intrusions.

Synvolcanic low-angle thrust folds should be partly due to the Bang, partly to crater's later tectonic perestroika. Vergences (NW to E) radiate away from the dome area, a site fit for the central uplift and original bull's eye, where from ejecta was hurled around. The acid melt rocks of S. Pechenga (only zircon xenocrysts dated, 2.4 - 2.6 Ga) are in a position, and of composition, of impact melt bodies. The dome zircon ages (1.94 ±0.04 Ga) are within bounds of the Bang age.

A hit into an active volcanic area certainly boosted lava production. The Bang and crater collapse caused tsunamis and drastic mass movements in the crater and beyond. It has not escaped my notice that the impact may have triggered the generation of, and teared pathways for, the intrusion of magmas of the Ni-Cu ores. The Alla-Akkayarvi Ni-Cu ores amidst high-grade gneisses 15 km SW of the Kaskelyarv dome, diametrically opposite to Pechenga field, have ore and rock compositions similar to Pechenga's. The estimated diameter of the original crater structure is 80 km, but the ejecta blanked passed much farther.

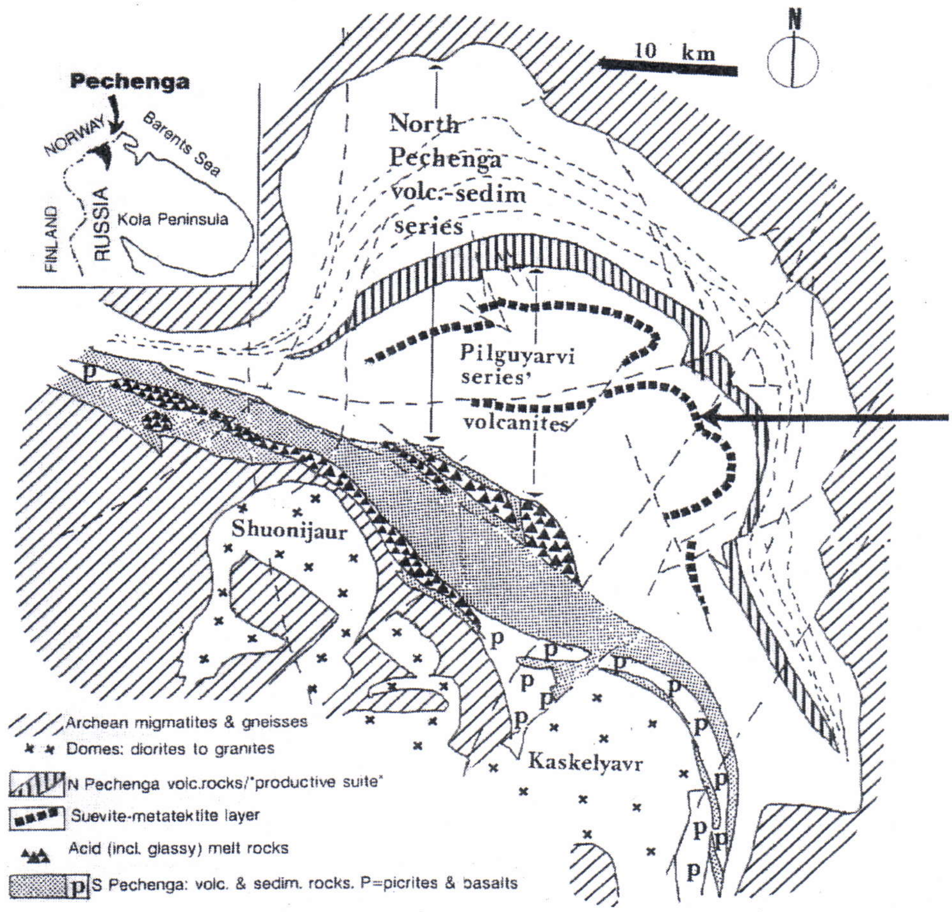

Figure 1.

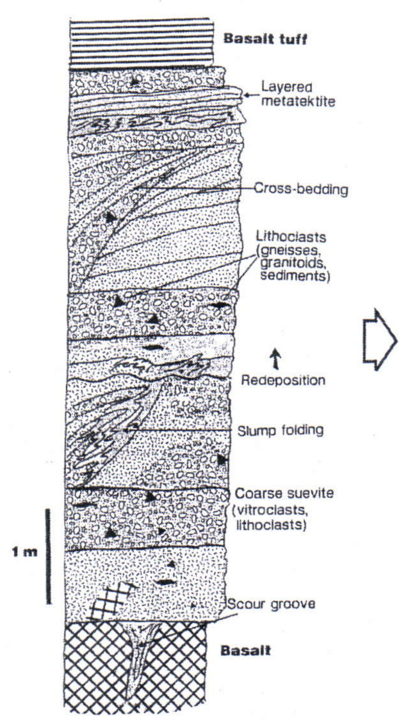

Figure 2.

Figure 3.

Breccia occurrences generated in the Uppland structure, Sweden - a suspected impact structure

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A 320 km diameter structure in central Sweden has been proposed as a possible impact crater by [1], and [2]. The supposed age is 1.8 Ga, based on the age of the Stockholm granite, interpreted by these authors as possible impact melt rock.

The main evidences for a deeply eroded impact structure are a central gravity high, an almost circular arrangement of geological units and magnetic structures. The erosional remains of the rocks referred to the impact event are non-deformed and less metamorphosed than the underlying strongly deformed and metamorphosed granite-gneiss and supracrustal rocks. Large areas of intense hydrothermal alterations are widespread in both the gneiss granites and the supracrustal rocks.

The occurrence of several localities with various types of breccia within the Uppland Structure will be briefly described and discussed. The breccia occurrences can be divided into several sub-groups:

- Melt with lithic and mineral clasts (Länna, Vallentuna, Dannemora, Strängnäs).
- Polymict breccia with melt matrix (Likstammen, Breven).
- Polymict to monomict breccia forming the base of the Jotnian sandstones.
- Monomict autochthonous breccia (Knivsta, Uppland, Rappsmälingen).
- Polymict breccia resembling the Onaping breccias of the Sudbury impact structure (Uppsala, Digerberg).
- Polymict breccia with large clasts (Pellesberget, Holtäkt, Årsunda).
- Pseudotachylithic breccia (Valloxen).

Samples of all these breccias have been studied, and a range of microtextural types has been identified. To date, none of our samples has provided any concrete evidence of shock metamorphism. However, given the large size of this structure and possibly extreme erosion depth, it is not impossible that bona fide, impact-diagnostic deformation may be discovered. Considering the general difficulties to identify large and old impact structures, this line of work needs to be further pursued. In addition, better time constraints on the formation event(s) for these breccias need to be obtained, in order to establish whether tectonic and/or impact events could be responsible for their existence.

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Panther mountain buried impact crater is confirmed

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Panther Mountain, located in the Catskill Mountains, New York, is a circular mass, 10 km in diameter, defined by an anomalous circular drainage pattern. Earlier surface and gravity studies led to the conclusion that the circular valley reflects the rim of a buried impact crater 10 km in diameter [1].

The nearest subsurface information is provided by well cuttings from the 2000 m-deep Herdman gas test well located near the northern edge of Panther Mountain. Some 660 bags of washed cuttings were searched microscopically for spherules and microtectites. Seven black magnetic spherules, measuring 200-950 micrometers in diameter were found in the Herdman well at the Middle-Upper Devonian boundary and three much smaller ones (100 micrometers) at the same stratigraphic position in the Armstrong well, one crater diameter to the west. Most spherules retain a core of iron $\pm$ nickel beneath an ablation rind of magnetite, and are considered to be of cosmic origin. Their presence, combined with their decrease in size and number going outward from the structure, support the existence of a buried complex impact crater, but do not prove it. Current studies, however, confirm the existence of an "intact impact" beneath Panther Mountain. Seventy-five thin sections of quartz-rich layers in the Herdman and Armstrong wells were prepared to search for pressure deformation features (PDF's), which would prove impact. Examination of several thousand grains to date reveals numerous examples of such shocked quartz. Initial thin-section study focused on the stratigraphic intervals where spherules had been found earlier in both wells. In the Herdman well, a 10 meter interval near the Middle-Upper Devonian boundary contains both PDF's and metallic cosmic spherules. PDF's and spherules are also found at this stratigraphic position in the Armstrong well. Thus PDF's exist in both the fallback zone and the fallout apron.

Inasmuch as the central fracture zone of the crater transects Lower and Middle Devonian strata, which contain numerous gas producing formations in central and western New York State, the structure possesses economic potential for gas production and storage.

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Conditions governing radiochronometers in impact regimes

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Fundamental parameters to describe the behaviour of isotope clocks in minerals and rocks are temperature, reaction kinetics (including diffusion), and to a much lesser extent, pressure. Compared to magmatic and metamorphic processes affecting terrestrial planetary bodies, impact is a very specific event, characterized in particular by its very short duration, extreme peak temperature and pressure, and drastic T-P variations. All these features, and the wide range of induced disequilibrium processes are a crucial handicap to understand the behaviour of isotope systems in rocks and minerals, and radiometric ages are often very difficult to interpret. Simple time and volume dependent diffusion or re-equilibration of a systems during slow cooling do not describe the systems any more, and very detailed and selective sample preparations have to be applied. From natural impact sites, in combination with experimental work it has been shown that passage of a 50 GPa shock wave does not measurably disturb the U-Pb chronometer in accessory minerals [1, 2]. On the other hand, these minerals may re-crystallize in the hot vapor plume in time scales of sec to min. Zircons from the K/T boundary show that such "flash" annealing in the vapor plume causes large disturbances of the U-Pb system, allowing dating in the concordia diagram [3], however, particularly favourable conditions are required to preserve these grains in distant ejecta deposits.

Promising are also impactites where post-shock high-temperature regimes were sufficiently long-lasting to allow cooling on "geological" time-scales, with re- and new-crystallization of minerals and matrix, and hence, total re-equilibration of the radiochronometers. Such conditions exclusively occur in impact melts lithologies of considerable volume, covered and thermally protected by a blanket of fast-cooling breccias [4].This approach was successful for Rb-Sr dating of matrix glass and minerals formed from melts devoid of clasts [*e.g.,* 4], and for U-Pb dating of newly grown accessory minerals in melt layers [*e.g.,* 5, 6]; however, even in such cases, equilibrium is not necessarily reached and dating of different samples is required to confirm the real age of impact event [*e.g.,* 4]. Since formation of large melt volumes is restricted to large impacts, smaller craters but also deeply eroded structures are very difficult to date. For instance, melts in the 20 km wide strongly eroded Rochechouart crater lack newly formed accessory minerals because they cooled faster to subsolidus conditions than times required for even minor crystal growth. On the other hand, particular circumstances or specific features occasionally allow dating of small craters, such as the presence of autigenic minerals in crater lakes [7], pseudotachylites in the crater basement, or for very young craters, blocks allowing exposure age dating [8].

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Minerals in the transient state of shock

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Shock metamorphism is an omnipresent process in the solar system [1], which is caused by hypervelocity collisions. At the scale of rocks, such natural impacts cause the formation of breccias and large impact melt volumes. At the scale of minerals, a great diversity of natural shock effects is induced. These latter phenomena have been reproduced, to a large extent, in laboratory experiments and can serve as barometer.

Under shock compression, minerals undergo deformation, transformation, decomposition, melting, and vaporisation [2]. Shock deformation is exclusively produced in solid state and results in the formation of one (dislocations)- to three (mosaicism)-dimensional lattice defects. Shock-induced activation of dislocations is mainly observed in silicate minerals in which SiO_4-tetrahedra are not three-dimensionally linked. The chain and island silicates clinopyroxene and olivine, respectively, develop numerous dislocations, whereas shocked quartz is essentially free of dislocations. On the other hand, quartz reacts under shock compression by the formation of planar fractures (PF's) and planar deformation features (PDF's). Another mode of deformation behaviour is mechanical twinning. Clinopyroxene and calcite are instructive examples for this type of deformation. A three-dimensional defect is mosaicism which can be regarded as internal fragmentation of crystals.

High-pressure minerals form in shock events either by solid-state transformation or by crystallisation from high-pressure melt. The formation of diamond is the only clear case of solid-state transformation. The diamonds result from martensitic-like transformation of graphite and, as a consequence, inherit morphological and internal characteristics of the parent graphite. Crystallisation from high-pressure melt is known for phases that are regarded as typical mantle minerals (*e.g.*, coesite, stishovite, wadsleyite, ringwoodite, majorite, hollandite, silicate ilmenite, and silicate perovskite). They are observed in shock-fused glasses or pseudotachylites within strongly shocked L6 chondrites or basement rocks in impact craters. Another type of transformation is a crystalline-amorphous transition. The amorphous phase is termed diaplectic glass or, in case of feldspar, maskelynite. Diaplectic glass retains the shape and internal features of the precursor crystal, and is densified compared to synthetic glass with the same composition. Diaplectic glasses are restricted to framework silicates and have been recently interpreted as quenched high-pressure melts.

The response of minerals to high shock and post-shock temperatures is decomposition, melting, and vaporisation. Shock-induced decomposition of volatile-bearing minerals, *e.g.*, carbonates, sulfates, and hydrous silicates, is considered as critical factor for the evolution of atmosphere, climate, and life.

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Hornblende alteration and fluid inclusions in Kärdla impact crater, Estonia - an indication for impact induced hydrothermal activities

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Kärdla impact crater formed in a shallow Ordovician sea in the two layered target composed of thin (~200 m) unconsolidated sedimentary layer above the crystalline basement of migmatite granites and gneisses alternating with amphibolites. The major geochemical changes in impacted basement rocks involve depletion with respect to Na and Ca, and enrichment with K, which is mineralogically expressed by replacement of plagioclase with K-feldspar [1].

Plagioclase alteration is accompanied with the later hydrothermal degradation of hornblende that is often totally replaced with secondary mineral phases. The main hornblende alteration products are chlorite and mixed-layered chlorite-smectite (corrensite) type phases. Amphibolitic clasts within allochthonous air-fall breccia are completely replaced with alteration end-member chlorite and/or chlorite-corrensite, quartz and calcite. The maximum alteration in the fractured basement and in autochthonous breccias is related to alteration haloes around the fracture systems. The most intensive chloritization occurs in permeable breccias and heavily shattered basement around and above the central uplift. This was most possibly due to hydrothermal fluids convective passage and discharge through central areas of the crater. Widespread Fe-chlorite formation in upper part of the shattered basement and in allochthonous suevite breccias denotes the highest temperatures above 200°C. Chloritization intensity decreases with decreasing fracturing downward into crater floor where chlorite occurs only in immediate close to the fracture planes and corrensite dominates within macroscopically unaltered amphibolite blocks indicating temperatures below 200°C.

Temperature estimated from chloritic minerals stability range agrees with quartz fluid inclusion homogenization temperatures at 150-300°C from allochthonous breccia cements. Fluid inclusion trails which cross-cut the quartz planar deformation elements (PDF's) show that they postdate the impact event whereas the primary inclusions were lost during impact. This confirms that the fluids entrapped in samples are of hydrothermal origin. Rather low salinity of fluids of less than 13 wt.% of $NaCl_{eq}$ (in most ≤5 wt.%) in Kärdla crater suggest the hydrothermal system recharged either by infiltration of meteoric waters from cater rim walls raised above the sea level after the impact, or by intrusion of sea water (3.0-3.5 wt.% $NaCl_{eq}$) through disturbed sedimentary cover and fractured crystalline basement. Kärdla crater is characterized by moderate size (4 km), high water/rock ratio and by absence of distinctive impact melt-sheet. Therefore the hydrothermal system with high temperature and intensive fluid exchange, and consequently high rate pervasive hydrothermal alteration processes could exist only relatively short time of about several hundred years until the impact heated basement reached equilibrium with surroundings.

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Some geochemical features of impact melts, suevites and target rocks at Sääksjärvi impact structure, Finland

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Impactites and country rocks from the 4.5 km diameter, deeply eroded Lake Sääksjärvi structure (~560 Ma) were analysed for major and trace element abundances. The target rocks consist of tonalite gneisses and migmatitic mica gneisses of the Svecofennian orogenic belt (1.90-1.87 Ga). These basement rocks are genetically the same and geochemically quite uniform, too. So, the target rock analyses give a good possibility to determine of the indigenous contribution of siderophile elements to impactite abundances. No impact melt rocks or suevites are exposed. Six holes (860 m) have been drilled in the crater area. The drilling in the centre of gravity low down to 242 m penetrated 180 m of suevite and breccias before reaching a deformed target mica gneiss. No coherent melt sheet has been found by drillings. Studied samples are drill cores and glacial boulders.

The impact melt rocks, vesicular and brecciated suevites show characteristic shock textures and effects. The matrix of the impact melt is perlitic cracked glass, which contains pyroxene and plagioclase microlites. Mineral fragments are feldspar and quartz, often with shock lamellae. Clasts of diaplectic quartz glass, ballen-quartz, checkerboard plagioclase and biotite with kink bands are common. The suevite is a polymictic breccia, which contains, in addition to mineral and rock fragments of all the target rocks, fluidal glass fragments and vesicles filled with clay mineral spherulites and zeolites, too.

Major element data show that Na and Ca are depleted and Mg and especially K enriched in impactites relative to the target rocks. Similarly minor lithophile Rb and Ba are enriched and Sr strongly depleted. The changes are greater in suevites (= fallback breccias) than in melt rocks due to their different genesis. After melting and vaporization of the target rocks during early stages of impact event, some of the evaporated highly volatile elements *e.g.* K recondensed into the impact rocks especially into allochthonous or fallback facies. The enrichment in K and depletion in Na and Ca in impactites are consequence of replacement of structurally damaged shocked plagioclase with a secondary K-feldspar and clay minerals (shock metamorphism and metasomatism during post-impact cooling).

The chondrite-normalized REE abundance patterns of the various impactites are uniform and closely follow the target rock patterns: the melt rock and suevite REE patterns are slightly lower or coincides with the mica gneiss patterns while they are a little higher than the tonalite gneiss patterns. In general, the REE patterns support the idea that the impactites were derived from tonalite gneiss and mica gneiss target rocks.

Both impact melts and suevites are enriched in siderophile elements: strongly enriched in Ir, Pt, Pd, Ni and Cr and clearly enriched in Ru, Au and Co relative to the target rocks. The indigenous contents are estimated from the basement rocks in the area as 25 μg/g for Ni, 20 μg/g for Co and 75 μg/g for Cr and from interelement correlation plots as 1.3 ng/g for Ru, 1.1 ng/g for Pt, 0.4 ng/g for Pd, 0.7 ng/g for Au and 17.5 μg/g for Co.

[1] have proposed a possibility of stony iron meteorite (pallasite) as projectile because high Ni/Ir ratios excludes chondrites and simultaneously enriched Cr rules out an iron meteorite. According to [2] the Sääksjärvi highly siderophile element pattern is qualitatively similar to magmatic IIAB and IIIAB iron meteorites.

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Migration of chemical components under shock wave loading of rocks and minerals

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Research results of the migration of seven main chemical components (Si, Al, Na, K, Ca, Mg, Fe^{2+}) under shock wave loading of granite, pegmatite, enstatite, wollastonite rock and plagioclase-garnet-hedenbergite periscarnic rock are presented.

For the experiments according to the method and technique [1] the samples were prepared in the form of the sphere, 40-50 mm in diameter. They were welded up in vacuum 10^{-5} torr into the hermetic jackets of stainless steel and were subjected to loading by a spherically convergent detonation wave. The variation of the loading impulse amplitude and duration was realized on the external surface of the hermetic jackets by using the layers of high explosive of different power and thickness. In the described experiments the impulse loading duration amounted to 1-3 μs. Pressures realized in the spheres were changed from 20-30 GPa on their surface up to 250-300 GPa at the radius of 1 mm. The initial rates of the compressed material cooling in the process of unloading have been estimated to be approximately equal to 10^8-10^9 degrees per second, but after unloading they have not exceeded 10^3-10^4 degrees per second.

Five minerals have been investigated [1, 2, 3], namely: potassium feldspar, plagioclase, hedenbergite, enstatite and wollastonite. Two minerals – K-feldspar and plagioclase – are rendered amorphous at the solid-phase stage of their compression up to the beginning of their melting on the isentrope [3]. Three minerals - hedenbergite, enstatite and wollastonite – do not reveal their amorphization in the whole interval of loading up to their melting at the spherically converging shock wave fronts (on the Hugeniot) [1, 2]. In all the studied ions having the fourfold coordination – Si and Al – do not take part in the migration processes up to the beginning of the substance melting. Ions taking the cation positions in the lattice – Na, K, Ca, Mg and Fe – undergo exportation at the solid – phase stage of the substance transformation prior to the beginning of the general melting in stress waves. In K-feldspar and plagioclase the migration intensity increases in the row of Ca – K – Na, but in pyroxene – in the row of Mg – Ca – Fe [3]. It is possible to propose that the migration characteristics of cations in stress waves are determined by the bond strength of the ions with their surrounding in a particular lattice of one or another mineral under the action on a crystal substance having a complex structure.

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Distant resurge influenced sediments at the Lockne marine-target crater, Sweden

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The Lockne impact event took place in a Middle-Ordovician (455 Ma) epicontinental sea. The impact resulted in an, at least, 13.5 km wide, concentric crater in the sea floor. Lockne is one of very few known impact sites where parts of an ejecta layer have been preserved outside the crater structure. The ejecta from the Lockne impact rests on progressively higher stratigraphic levels with increasing distance from the crater, hence forming a slightly inclined discontinuity surface in the pre-impact strata to a distance of 12 km from the crater center. [1] interprets this surface as part of the final crater formed in the seafloor and the water mass, thus leading to an even greater crater diameter. In this study we report on an approximately 30 cm thick sandy layer occurring in a Middle-Ordovician limestone sequence at Hallen, 45 km south of the crater centre. Since it was formed, Caledonian thrusting has moved the locality some distance to its current position. However, this movement has predominantly been tangential to the crater center and has not changed the original distance to the Lockne crater to any significant extent. The layer has a coarse-grained fining upward clast deposit in its lower part, followed by a sandy/silty deposit with low-angle cross-laminations indicating two opposite current directions. The layer is rich in quartz grains with planar deformation features, and contains numerous, up to 15 cm large, granitic clasts from the crystalline basement at the Lockne impact site. Microfossil dating of the limestone immediately below and above the layer gives the same age as published datings of the Lockne crater. The biostratigraphic study shows that some erosion may have occurred due to deposition of the impact layer. The Hallen outcrop is, at present, the most distant accessible occurrence of ejecta from the Lockne impact and the most distant location where the resurge of water towards the crater has affected the bottom sediments.

The Hallen locality is situated about five crater radii beyond the currently estimated position of the crater rim. A greater crater diameter than hitherto assumed, thus representing greater impact energy, might explain the extent of the ejecta. Fluidisation of ejecta, to be expected at a marine-target impact, might furthermore have facilitated the wide distribution of the ejecta.

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Scenarios of cratering and crater survival in Precambrian shield and shallow Palaeozoic platform areas in the Baltic Sea region

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After the formation of the continental crust in the processes of Svecofennian orogeny in Palaeoproterozoic, the Baltic Sea region (the present Fennoscandian Shield and east Baltic platform area) developed mostly as a continental shield area. During the latest Neoproterozoic (Vendian) and almost the whole Palaeozoic, this area was either a submerged sedimentation area or lowland with the basement hidden under the sedimentary cover. During the Late Palaeozoic (starting from Permian) and Meso-Cenozoic continental period was established in the present shield and most of the platform area. As a result of rapid erosion of Fennoscandia, the basement was re-exposed there. In the continental Baltic area, the thickness of sedimentary cover was reduced in some degree due to erosion. During Meso-Cenozoic, the remnant sedimentation basins regressed into restricted SW Baltic area, where impact structures are presently unknown.

Essential differences in geological environments of cratering [1, 2, 3] and their subsequent evolution between structures located in Fennoscandia and those located in the east Baltic region started, hence, as late as in the end of Palaeozoic.

In Precambrian, cratering into the shield-type environments all over the Baltic Sea region took place (examples: Söderfjärden, Jänisjärvi in present shield area, Mizarai in the present platform area [2]). All these structures were before the Phanerozoic sedimentation deeply eroded, but only in the shield area re-exposed in Meso-Cenozoic and, thus, once more eroded. In Palaeozoic, cratering into the complex cover + basement target occurred all over the Baltic Sea region. The Palaeozoic craters of the shield area were later subjected to erosion and only the deep parts of their primary architecture are survived and exposed (Tvären, Lumparn, Sääksjärvi, Hummeln [1], Siljan). Coeval craters in the platform area, even if subjected to primary erosion, remained either covered or were re-exposed in their upper parts only (Kärdla, Neugrund). The latest Palaeozoic and Meso-Cenozoic craters in the shield area have undergone the post-impact changes in on-land shield environments only (Lappajärvi, Dellen). Glacial erosion, however, smoothed the service in cratering areas. Craters of this period formed in the platform environments either penetrated (Mishinogorskaya) or did not penetrate (Dobele, Kaali, Ilumetsa) into the basement. The first have brought fragments of basement rocks onto the surface. Depending on the age and intensity of erosion, the suprastructure of latest Palaeozoic and Meso-Cenozoic craters is more or less cut off.

Generally, the degree of survival of the upper-most structure elements and lithologies very much depended on the scenarios of post-impact developments of surrounding environments. The best-preserved impact structures are those, which formed in a marine platform area and afterwards remained covered with sedimentary deposits (Kärdla, Neugrund [2]), or formed recently (Kaali).

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The formation of differentiated melted spherules during an impact

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The main problem of the relation of ejected melted spherules and target rocks in impact structures is the unknown degree of their differentiation during the high-temperature stage. An investigation of trends of chemical differentiation of melted droplets during impact simulated processes can give a certain evidence for the discrimination in melt and target rocks relation in impact sites.

Experimental investigation of differentiation of mafic melts shows that spherules in the beginning of mass loss process are loosing Si, Fe, alkalis, and their composition enriches in Mg, Ca, Al, and Ti. With developed mass loss spherules looses Mg while Si is still present in the system. Even Na is not totally lost. Greater mass loss results in the enrichment of Ca, Al, and Ti in the system (see Table 1). The end members of the mass loss process depend on the temperature of volatilization. Volatilization under 3000 K results in Al-rich spherules and volatilization at temperatures over 3000 K results in Ca-rich spherules. The constant Al/Ca ratio during nearly the whole mass loss process can be indicative about the relation to a target rocks. This effect is not strict since the ratio can be ruined by a volatilization of Ca in a wollastonite like cluster.

The ratios of "refractory" elements are not necessarily indicative of their initial ratios. At temperatures of volatilization, which are characteristic to impact vaporization, some classically refractory elements are behave as volatile due to formation of volatile molecular clusters. Acidic melts are effectively loosing Al due to it volatilization as nepheline like cluster. Ca can be mobilized as wollastonite cluster. REEs are also effectively volatilized and are enriched in the vapor phase.

A certain problem for the relating of melt spherules and target rocks is the mixing of target rocks and projectile material. The formed spherules can represent a continuous row of mixed compositions which is modified by volatilization of elements during high temperature processing.

Table 1. Mean values of the composition of some groups of droplets in experiment with augite.

Object Number of droplets	Initial sample	Droplets 6	Droplets 10	Droplets 17	Droplets 7
Na_2O	2.75 ±0.14	1.28 ±1.07	1.15 ±1.00	1.28 ±0.67	0.71 ±0.62
MgO	13.09 ±0.08	14.79 ±1.65	16.90 ±1.05	7.89 ±0.79	3.91 ±0.99
Al_2O_3	9.98 ±0.09	11.05 ±0.37	17.56 ±1.21	24.41 ±1.80	31.39 ±1.04
SiO_2	49.29 ±0.10	50.05 ±0.77	37.68 ±1.79	34.16 ±1.84	23.29 ±0.73
CaO	15.46 ±0.11	15.13 ±2.25	20.54 ±3.25	26.94 ±1.37	35.58 ±2.66
TiO_2	1.13 ±0.03	1.19 ±0.22	1.73 ±0.20	2.38 ±0.19	3.38 ±0.26
MnO	0.07 ±0.02	0.13 ±0.10	0.17 ±0.14	0.10 ±0.09	0.12 ±0.09
FeO	8.22 ±0.10	6.28 ±1.12	4.20 ±0.52	2.63 ±0.55	1.51 ±0.18

Metal and sulfide from projectile in impact melts of the Lappajärvi crater

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The enrichment in siderophile elements of the Lappajärvi impact melts (kärnäite) indicates a presence of a chondrite matter [1-3]. The impact melts contain numerous metal inclusions too [4] that are proposed to originate from a projectile. However, the containing metal chondrite projectile should contain troilite too and, hence, shock-reworked meteorite troilite can be presented as sulfides in the melts. In the work we consider data on some sulfide inclusions which can come into kärnäite from the projectile.

Relative large rounded pyrrhotite particles are very common in fresh impact melts. Most particles are smaller than 2 mm in diameter. Practically always the particles contain black globules rich in Fe and very often with some Ni, Co, and S. High Ni globules contain dusty sulfide (pentlandite?). There are globules with groundmasses poor in SiO_2, (0.5-2 wt%) and rich (up to 50 wt%). CaO and MgO contents vary from 1 to 7 wt%. SiO_2-rich globules have Al_2O_3 (3-20 wt%) and lower Fe contents than SiO_2-poor globules. All microprobe broad-beam analyses have totals 60 - 90 wt% what proposes a presence of some volatiles. Globule-containing sulfide consists of poly- or monocrystalline monoclinic pyrrhotite with Fe content of 46 at%. The average Ni content in pyrrhotite is 0.5 wt%. Some pyrrhotite masses include blebs of Ni-containing metal, inclusions of pentlandite forming exolution textures, and Zn-containing chalkopyrite. Obviously Fe-rich globules are not located at approximate centres of the pyrrhotite particles but are displaced. Directions of the displacements are the same for all particles in a given section. In some cases globules are separated from pyrrhotite groundmasses by a K-rich glass.

Metal blebs in the pyrrhotite inclusions can originate from a projectile due to their Ni and Co concentrations and Ni/Co ratios close to the ratios for kamacite [5, 6] in chondrites [7]. Precursors for inclusions with medium Ni concentrations can be kamacite whereas highest in Ni metal can be formed by kamacite-taenite mixing because of the lower Ni/Co ratios.

Ni-Co relationships in black globules appear to be very close to the ones for Ni-rich metal. It means that they can have the same source as metal inclusions, namely meteorite metal. The suggestion is supported by structures of gravitational settling like asymmetric positions of globules and their separation by a silicate melt from pyrrhotite groundmasses. Post-impact events can oxidize metal and modify its composition. Further, we suppose that pyrrhotite can originate from meteorite troilite because: a) a significant amount of sulfide should come in impact melts together with meteorite metal; b) projectile metal practically always associate with pyrrhotite; c) rounded shapes and an enrichment of pyrrhotite in Ni indicate an close association of projectile metal and sulfide in a molten state.

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Tektite origin in oblique impact: Numerical modeling

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Although the Moon-hypothesis of tektite origin is still alive, modern study of tektites supports the idea of their terrestrial origin by cometary or asteroidal impact. Four strewn field of these natural centimeter-sized glasses are known, and at least two (Moldavites and Ivory Coast) are located few hundred kilometers from possible impact source craters (Ries and Bosumtwi, respectively). The ages of tektites are similar to the ages of impact melt in these craters. Geochemical and isotopic analysis of tektites shows that:

1. Composition of tektites strongly resembles composition of the upper layer of target rocks.
2. Contamination by siderophile elements is negligible, if any.
3. Tektites are strongly depleted in water and other volatiles.
4. All the Fe remains in the glasses as FeO.

So, tektites may originate from high-temperature melts of surface material, and solidify practically in vacuum (or low-density air) conditions.

Nevertheless, there are a number of dynamical problems associated with tektite origin in terrestrial impact events: liquid jets would break up into a fine mist before traversing hundred of kilometers and tektites could not be widely distributed (it should be mentioned that these estimates have not taken into account the real atmospheric flow just after the impact).

In the present study the Earth-impact hypothesis is checked with numerical simulations. The multidimensional SOVA hydrocode allows to model complex hydrodynamical flows of different material with accurate definition of their boundaries. Most likely the impact should be oblique - strewn field as well as ejecta deposition are asymmetric. Consequently, we use three-dimensional variant of SOVA (Fig. 1). Impact velocity varies from 12 to 30 km/s, impact angle -from 30 to 75. More than 20,000 tracer particles are used to define trajectory and thermodynamical history of the near-surface material.

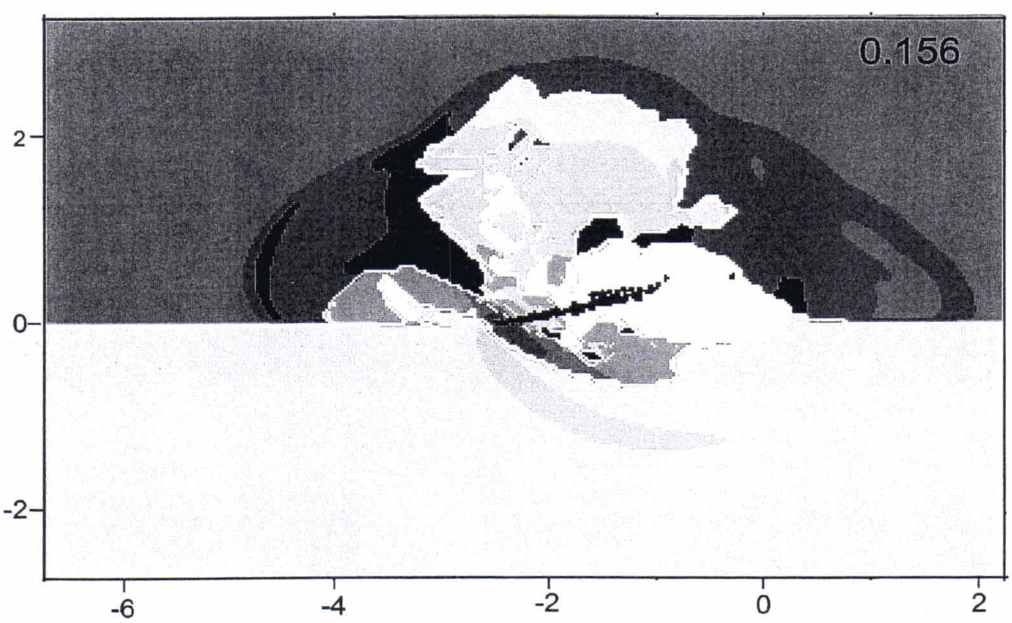

Figure 1. The initial stage of the impact – the compression is over, jets of target and projectile materials go ahead. Black points mark high-velocity (>5 km/s) near surface material.

Numerical modeling of the impacts into shallow sea

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Most cosmic bodies impacting the Earth hit the sea. Nevertheless, the process of cratering and the special features of marine-target craters are poorly known yet. The craters covered by the sea are less accessible for geological investigation, and our knowledge about impact processes is based mainly on the study of the impacts on the land. However, the size and morphology of the craters formed in the seabed can significantly differ from those on the land.

Recently, several marine-target craters have been studied [1]. Most of them were formed continental shelves. The water depth is crucial for the cratering process. At shallow (relative to the crater size) water the crater resembles that formed on the land. In the deeper sea a smaller crater is formed in the basement and the second (outer) crater arises in sediment [2]. The size of the outer crater seems to coincide with the size of a transient water cavity. The ratio of diameters of the outer crater and the central crater depends on the relative (to the impactor size) depth. The nested-crater structure is considered to be created when the sea depth exceeds a height of the rim wall [1]. This qualitative description of the impact cratering at sea was partially justified by experiments of [2]. However, these results were obtained for velocities of 2 to 7 km/s, which are considerably smaller than typical impact velocities.

The purpose of the present paper is to study impacts into the shallow water with detailed numerical simulations. The SOVA multi-material hydrocode [3] is used to model impacts of 200-500 m cosmic bodies (both asteroids and comets) into sea with depth ranging from 100 to 500 m. The size of a transient cavity (in the crystalline basement, sediment layer, and water) is calculated as well as the further propagation of tsunami-like waves and the resurge flow.

200-300 m impactors can be disrupted, deformed and even decelerated during the flight through the Earth's atmosphere. These effects and their influence on the cratering are also investigated. The results show that atmospheric disruption of the falling body can increase the outer crater and decrease the central depression size for the same impact energy.

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Popigai impact crater: General geology

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The Popigai impact crater (71°38'N, 111°11'E) has the diameter about 100 km, and was originated by collision of ordinary chondrite body 35.7 Ma ago. The target is represented by crystalline basement (Archean) and sedimentary cover (Proterozoic to Cretaceous), composed mostly of terrigeneous and carbonate rocks. The crater is characterized by negative gravity anomaly with the inner ring of gravity high, and may be regarded as complex impact structure. Its main morphostructural elements are:

1) a central circular depression (D = 40 km) with flat central uplift of true bottom;
2) a peak ring of shocked crystalline rocks (D = 45 km), partly exposed in the NW sector;
3) an annular trough (D = 60 km) and
4) an outer flat annular terrace (D = 100 km), where disturbed sedimentary rocks can be observed.

Shallow radial troughs occur on the surface of the terrace. The depth of the central depression is about 2 km, and that of the annular trough is up to 1.5 km. The central depression, annular through and radial troughs are filled with allogenic polymict breccias and impactites (suevites and tagamites). Small isolated fields of similar ejected rocks occur in the surrounding area of undisturbed target rocks out to a distance of about 70 km from the crater center. The allogenic breccias (blocky and fine-grained facies) consist of shocked and mixed fragments and blocks of different kind of target rocks with an admixture of glass bombs and particles. The allogenic breccia is overlain by a complex blanket of suevites and tagamites. In the central depression fine-grained breccia alternates with suevite lenses in the upper part of the sequence.

The coherent impact melt rocks (tagamite) form sheet-like, lens-like and irregular bodies with a thickness up to 600 m or more, and are hemicrystalline or holocrystalline and coherent numerous inclusions of shocked and annealed gneiss fragments. Most of the impactites bear impact diamonds produced by the solid transformation from precursor graphite, which is present in gneisses.

The giant Popigai impact crater is well preserved from the erosion, and is characterized by large amount of impact melt rocks and their various facies, as well of facies of impact breccias. Extensive geological exploration program, which included drilling and geophysical survey, was carried out at this structure during last three decades. All these studies provide the wide spectra of data on inner structure of the crater, on composition of impact breccia and impactite, on processes of their formation and origin on impact diamonds.

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Geophysics, petrophysics and paleomagnetism of the Popigai impact structure, Siberia

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The 100-km diameter Popigai structure was formed 35.7 Ma ago in a target consisting of ~1-1.5 km of Proterozoic and Cambrian sedimentary rocks overlying Archean crystalline basement. The structure is characterized by a gravity anomaly low of -35 mGal, one of the largest gravity anomalies associated with a terrestrial impact structure. Superimposed on the gravity low is a ring-shaped high at ~45 km diameter that coincides with uplifted Archean basement. Magnetic data indicate a -300 nT simple anomaly low over the structure. Both the gravity and magnetic signatures of Popigai are unlike those of other impact structures of comparable size, being distinguished by the lack of a central circular gravity high related to a central structural uplift or high-amplitude magnetic anomalies caused by thick melt/suevite deposits.

Two-dimensional forward modelling of an E-W profile through the crater is initialized using existing and recently-acquired petrophysical data and a structural cross-section based on geologic mapping and drill hole information. Petrophysical measurements indicate that lithologies making up the crater fill have susceptibilities nearly two orders of magnitude less than the basement. Crater fill densities are also reduced, with values up to 0.4 g/cm^3 less than the surrounding target rocks. Gravity data modelling indicates the presence of low-density crater fill plus an extensive region of reduced-density fractured basement beneath the crater floor. The magnetic data also suggest a significant volume (down to ~5 km depth) of fractured basement below the true crater floor is required to produce the observed anomaly.

Popigai impact melt rocks and upper Eocene microspherules

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The Popigai impact structure in Siberia is the largest of the five impact events that are known to have occurred towards the end of the Eocene (Popigai, Chesapeake, Mistastin, Logoisk and Wanapitei). Impact melt rocks derived by melting of the target gneisses remain in the impact structure, and are known locally as tagamites. Our tagamite samples were collected from thirteen drill cores located in the south-west of the structure. The samples span a radial distance of 6.4 km, a rim-concentric distance of ~2 km and were collected from depths ranging from 0 to 780 m in the drill cores. Thin-section and microprobe analyses of the mineral clasts, glass clasts, igneous phases, mesostasis glasses, decomposition glasses and reaction glasses exhibit a remarkable degree of compositional homogeneity. Bulk rock major and trace element geochemistries of thirty-four samples exhibit a similar degree of homogeneity. We have sampled both the so-called high-temperature (HT) and low-temperature (LT) tagamites. We present statistical data on various characteristics of the HT and LT tagamites in order to further characterise their differences and similarities.

Some of the impact melt rocks were ejected from the transient cavity. Semicrystalline ejected impact melts, known as microspherules, have been sampled from upper Eocene marine sediments from the Pacific and Indian oceans. Some workers have suggested that these microspherules were derived from Popigai, though geochemical evidence has been lacking. Here, we present major element data, Rb-Sr and Sm-Nd isotopic data to address this issue.

The microspherules exhibit a range of opacities and colours: from opaque black and brown (melanocratic) to translucent-clear yellow, cream and white (leucocratic). Major element analyses of impact melt rocks from the previously noted upper Eocene impact structures possess discrete compositions. The melanocratic microspherules possess a composition similar to that of the Popigai impact melts, and different from the melt rocks from the other impact structures. This suggests a Popigai source to these microspherules.

Studies of Rb-Sr and Sm-Nd in ejected impact melts have established that samples from known strewn fields have distinctive radiogenic Sr and Nd isotopic compositions, which can be used to help determine their provenance from distinct crustal materials of well-defined mean ages. Sr and Nd isotopic ratios of the melanocratic microspherules have a signature similar to that of homogeneous Popigai impact melt rocks, and distinct from melt rocks from other broadly contemporaneous impact structures. This indicates that the melanocratic microspherules were derived from the ejection of the homogenised melt, and not by melting and surface jetting of near surface sedimentary rocks, as is documented for tektites from other impacts.

Leucocratic microspherules that were sampled from the same layer as the melanocratic microspherules (indicating contemporaneous deposition), possess a range of isotopic signatures that do not exhibit a clear affinity with any of the impact melt rocks from the upper Eocene impact structures. However, these could have a Popigai source if they are melts that were derived from: 1) isotopically-diverse cover rocks that are present above the Popigai basement gneisses, or; 2) early melts that were ejected prior to isotopic homogenisation of the remaining impact melts. We discuss their possible provenances in light of new Rb-Sr and Sm-Nd isotopic data for trapped early glass clasts and leucocratic lithic clasts.

Petrology and geochemistry of the Popigai impact crater (Siberia)

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The Popigai structure, located in NW Siberia is probably the largest Cenozoic crater. Dating (35.5 Ma) indicate that the Popigai crater is coeval with both the impact layer found in the Late Eocene type section at Massignano (Italy) and with the Cheasapeake bay impact crater offshore Maryland [1]. Petrology analysis of a set of melt samples from the Western part of the Popigai crater revealed two different types of melt-rock which probably formed under slightly different cooling conditions [2, 3]. Unmelted clasts in these samples are mainly composed of gneiss, gabbro and quartzite fragments derived from the Anabar shield target rock. Geochemical analyses of the samples indicate that the Popigai melt-rock is homogenous in terms of major and trace element compositions (Table 1). A selected set of melt-rock samples from Popigai from different localities is being analyzed for PGE by ICP-MS concentrations using NiS fire assay (Table 2). The PGE concentration pattern appears homogenous and shows little fractionation compared to CI chondritic composition (Fig. 1). Chondritic material in Popigai impact melt is around 0.2%. PGE concentration in gneiss samples from the target rock is 3 to 7 times less than in the melt-rock. The comparison of this data with the Massignano impact layer could also allow a geochemical correlation of Popigai and distal ejecta.

References: [1] Bottomley, R., et al, 1997. V. Nature, 338, 365-368. [2] Tagle, R., 1998. Diplomarbeit. Universität Leipzig. [3] Tagle R. EOS Trans. 79, 45, F546.

Table 1. XRF analysis of the melt-rock.

Element As ox.	Ave. [wt. %]	S [wt. %]
SiO_2	62.9	0.6
TiO_2	0.7	0
Al_2O_3	14.7	0.4
Fe_2O_3	6.8	0.2
MnO	0.1	0
MgO	3.5	0.2
CaO	3.8	0.4
Na_2O	2	0.1
K_2O	2.8	0.2
P_2O_5	0.1	0
SO_3	0.1	0.1
LOI	1.1	0.6
Total	98.7	
Element	Ave.	s
Ba	867	35
Ce	116	16
Co	24	4
Cr	178	21
Ni	96	16
Rb	88	3
Sr	239	10
V	103	7
Zr	282	15

Table 2. Average concentration of PGE's and gold in the melt-rock and the Gneiss from Popigai.

ppb	Popigai melt average	Gneiss
Ru	2.15	0.29
Rh	0.47	0.07
Pd	2.11	0.63
Ir	0.87	0.19
Pt	2.45	0.65
Au	1.05	1.37

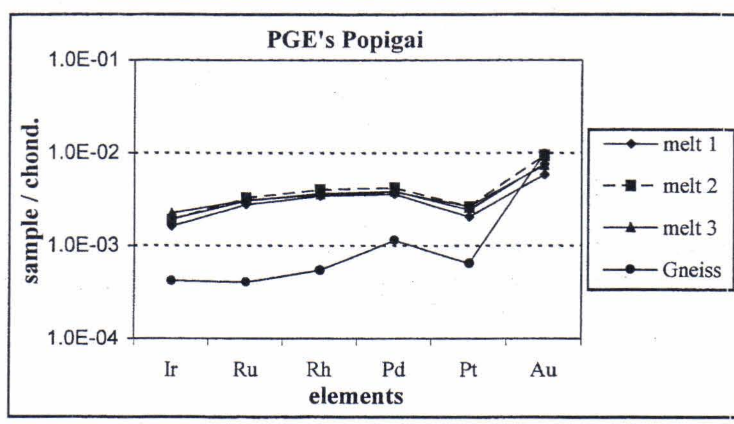

Figure 1. Chondrite-normalized PGE diagram for Popigai melt-rock and gneiss from the target-rock.

Popigai: Melt-coated gneiss bombs as flight recorder and automatic probe of the fire-ball

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Popigai is an excellently preserved complex impact crater [1]. There, numerous gneiss bombs (∅ up to 40 cm) are embedded in suevites and fragmental breccias ("coptoclastites"). The gneissic cores of the bombs are shocked to various degrees, and in part annealed. The cores display sharp contacts to the coatings that consist of differently coloured impact melt films, up to 3 cm thick, with more or less sharp internal contacts. *The gneiss cores, and the melt coatings record the time-temperature path* which the material experienced in a few seconds, starting from the passage of the shock and rarefaction waves, ejection on a trajectory through the expanding vapor plume and deposition [2, 3]. Particular melt types form the coatings, namely *(i)* fresh, colourless transparent glass, *(ii)* zones with alternating thin layers and lenses of light- and dark-coloured, mostly brownish, non-transparent crypto-crystalline glasses, and *(iii)* various mixtures of these glass varieties. These different melt films reflect most probably compositional variations of melt droplets in the fireball, and admixtures of local melt on the surface of the gneiss bombs [2, 3]. *The melt coatings* differ in their major element compositions, and in Sr isotope systematics [3] - the materials *provide* otherwise not obtainable *information on the heterogeneity* of the vapor and melt *in the fireball.*

Quenching of the melt coating occurred very fast, hence, only tiny crystallites are present. We have discovered quite exotic laths (<6 µm in length) with an orthopyroxene structure (Pbca; electron diffraction). According to ATEM analyses, these opx have low (Fe,Mg)O contents, whereas, Al_2O_3 range up to 10 wt%. Similar Al-rich natural opx are reported from the melt sheet at the Boltysh crater (<7 wt% Al_2O_3; EMPA [4]), and from a gneiss in the Aldan Shield (~10 wt%; EMPA [5]). In "normal" magmatic/metamorphic regimes, opx with high Al contents crystallize only at high pressure [5] - yet high pressure certainly is absent in an expanding vapor plume. For the Popigai gneiss bombs, therefore, specific conditions are required to explain the presence of Al-rich opx in the glass-coatings. They certainly have grown far away from thermodynamical equilibrium during rapid quenching of the ?superheated melt which has accumulated in the fireball on the much colder surfaces of the ejected gneiss clasts. We emphasize that this process occurred at ambient, not at enhanced pressure.

Acknowledgments: This work is supported by DFG grants De 401/12, and GRK 189/3. We thank A. Ariskin, B.A. Ivanov, F. Langenhorst and O. Simonov for discussions.

References: [1] Masaitis, V.L., 2000, this volume; Masaitis, V.L. et al., 1998. Diamond-bearing impactites of the Popigai astrobleme, VSEGEI Press, St. Petersburg, Russia, 179pp (in Russian); Masaitis, V.L., 1998. MAPS, 33, 34. [2] Masaitis, V.L. and Deutsch, A., 1999. LPS, XXX, Abstract #1237, CD-ROM. [3] Kettrup, B. at el., 2000. LPS, XXXI, Abstract #1353, CD-ROM. [4] Kerschhofer, L. et al., 2000. LPS, XXXI, Abstract #1360, CD-ROM. [5] Grieve, R.A.F. et al., 1987. Contrib. Mineral. Petrol., 96, 56. [6] Prewitt, C.T. (ed.), 1980. Pyroxenes. Rev. in Mineralogy 7, Min. Soc. Am.

Impact-generated hydrothermal systems: Data from Popigai, Kara, and Puchezh-Katunki impact structures

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Any impact into water-bearing planetary surfaces produces the long-term hydrothermal activity in formed craters. Potential parameters of hydrothermal circulation system are assigned by the kinetic energy of impact, whereas the intensity of alteration is depended by potential amount of fluid transferring agents due to water reserves of system. The evidences of impact-induced hydrothermal activities (mainly the presence of appropriate associations of minerals) are obtained from more than 60 terrestrial craters. However, a little of them give an opportunity to reveal 3D space distribution of hydrothermal mineralization and to construct thereby a reliable evolutionary model of post-impact circulation system. Three giant impact structures in Russia – the Popigai (D=100 km), the Kara (D=65 km), and the Puchezh-Katunki (PK) (D=80 km), are the best available objects in this respect due to detail investigations including wide core drilling carried out there. These craters are distinct in their inner structure, target rocks compositions, amount and distribution of impact melt, so that post-impact hydrothermal systems in various environments were considered.

During cratering, the main hot-water circulation system is arisen in the central uplift area (the central area of post-impact hydrothermal alteration), and some local convection cells are generated by impact melt bodies filling the annular depression (the peripheral area). Hydrothermal mineralization in the central area is the best examined in the PK where it is traced down to 5.3 km of depth [1]. It is in first place characterized by vertical zonation of space distribution: two main alteration zones named after principal minerals are distinguished there: smectite-zeolite zone (upper) and chlorite-anhydrite one (lower). The Kara structure represents mainly a model of hydrothermal alteration of thick suevite sheet filling the annular depression. Although secondary mineral associations (smectites, chlorites, calcite, zeolites, pyrite, etc) developed there are similar to ones in authigenic breccia, but no zonation in their space distribution is observed; the constancy of type features of main secondary minerals is also manifested. Nevertheless, in thick complex sheets composing of diverse impact lithologies (tagamites, suevites, various lithic breccia), some features of zonation closed to above-mentioned one are marked, *e.g.* in the Popigai crater.

Despite of some differences caused mainly by variations in composition of target rocks from craters, some common features of impact-induced hydrothermal mineralization are established using data from other impact structures as well. They are manifested by similarity of both mineral associations from different craters and type properties of minerals, *e.g.* the enrichment by silica of main minerals (phyllosilicates, zeolites); higher Fe content in Fe-Mg minerals of variable composition; lower content of trace elements in pyrite; imperfection of crystal structures of hydrothermal clay minerals; *etc.* So peculiarities of impact-generated hydrothermal mineralization are determined by interference of two influences: the target rocks composition and special features of the substrate caused by preceding shock and thermal metamorphism.

As a result, general model of an impact-induced hydrothermal system is suggested, based on both petrological analysis of appropriate mineral associations in large craters considered, combined with data from other objects of this kind, and simulation of the thermal evolution of impact craters, taking into consideration the decisive force of temperature field on parameters of hydrothermal process.

References: [1] Naumov, M.V., 1999. In: Deep drilling in the Puchezh-Katunki impact structure, SPb, VSEGEI Press, 276-286 (in Russian).

Excursion to Lappajärvi, Karikkoselkä and Saarijärvi impact structures - a review

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STOP 1. Thursday, May 25. Lappajärvi, Kärnänsaari NW, "Kärnäite quarry"

An outcrop of impact melt rock, kärnäite on the NW shore of Kärnänsaari island, near drill hole No. 1. Lappajärvi community opened this "quarry" on May Day 1994 as a point of interest for natives and tourists. The site is in the vicinity of the classic kärnäite outcrop at Kannanranta known since 1858. Here you can study the devitrified and randomly amygdaloidal texture of the upper kärnäite and smoothly curved wedge like E – W trending near vertical jointing. Mineral and lithic fragments from target lithologies, *e.g.* feldspars, pegmatites, granites, and gneisses are present, some of which show vesiculation due to shock phenomena. Hammering and sampling are allowed.

References: Pipping, F. and Lehtinen, M., 1992. Tectonophysics 216, 91-97.

STOP 2. Saturday, May 27. Gravel pit of Hietakangas – to collect impactite specimens

This is the place where it was – in addition to kärnäite - first found numerous suevite and impact breccia boulders on August 8th, 1967 and later in July 1968. Some suevite specimens are strongly weathered and resemble heaps of clay or muck. You can collect here specimens of kärnäite, suevite and breccias and brecciated rocks (granite, pegmatite and gneiss). Suevite contains *e.g.* vesiculated feldspars, coesite and impact diamonds and gray glassy clasts with fluidal texture.

STOP 3. Lake Karikkoselkä, Petäjävesi – crater with shatter cones. Private area.

The bowl-shaped crater (diameter 1.4 km, maximum water depth 25.5 m) was found in 1995. The bedrock consists of porphyritic (microcline phenocrysts) red granite. There are several outcrops on the southeast lakeshore full of shatter cones usually pointing to the center of the lake.

Two deep drillings from ice cover in 1998 revealed ~130 m thick chaotic crater fill of mixed and brecciated sedimentary rocks (sandstone, siltstone). The upper part of underlying granitic bedrock is brecciated and contains injection breccia dykes. Like a local specimen of impact breccia, the dykes consist of granitic rock and mineral clasts of varying sizes cemented by rock powder. Quartz clasts contain PDF's (three or four sets of different orientations), feldspars show mosaicism and incipient vesiculation, biotite flakes are strongly kinked *etc.* No melt rocks or suevites have been found. The gravity data reveal a low of 3.8 mGal, and the structure is associated with very strong airborne electromagnetic (AEM) anomalies.

Microfossils show that the crater is younger than Ordovician, paleomagnetic data suggest a Triassic age.

References: Lehtinen, M. et al., 1996. 27th Lunar and Planetary Science Conference, Houston. Lunar and Planetary Institute, 739-740; Pesonen, L.J. et al., 1997. Conference on Large Meteorite impacts and Planetary Evolution (Sudbury 1997). LPI Contribution No. 922, Lunar and Planetary Institute, Houston, 39.

STOP 4. Murronmäki, Köyliö - site of micrometeorites. Private area.

The Mesoproterozoic Satakunta sandstone (~1.4 Ga) in SW-Finland contains the world's oldest micrometeorites. Over 60 cosmic spherules (melted micrometeorites) have been identified from five localities. They belong to the S (stony) group displaying an either porphyric or barred-olivine texture.

At the Murronmäki outcrop, the moderately sorted, medium-grained sandstone is bedded on the decimeter scale, and occasionally interlayered by thin siltstone beds. The purplish red bed containing micrometeorites is an arkose with a fine-grained matrix of authigenic quartz, clay minerals and chlorite, in which detrital quartz, microcline, plagioclase, as well as few mica plates and zircon grains are embedded.

References: Deutsch, A. et al., 1998. Nature, 395, 146-148.

STOP 5. Sunday, May 28. Kulkkila, Kokemäki – to view the crater lake

A short stop for admire the scenery of Lake Sääksjärvi. The topography of the crater area is rather flat, and this is the best location to get an overview of the area.

STOP 6. Kaitalannokka, Kokemäki – Lake Sääksjärvi impact structure. Private area.

Lake Sääksjärvi is a deeply eroded, 4.5 km wide impact structure (~560 Ma) with circular Bouguer anomaly minimum of -6.5 mGal. No melt rocks or suevites are exposed. Five holes (656 m) have been drilled in the crater area. The deep drilling in the center of gravity low down to 242 m penetrated 180 m of suevite and breccias before reaching deformed target mica gneiss. Studied samples are drill cores and glacial boulders. The impact melt rocks, vesicular and brecciated suevites show characteristic shock textures and effects: planar deformation features (PDFs), diaplectic quartz glass, ballen-quartz, checkerboard plagioclase and biotite with kink bands are common. Ir, Pd, Pt, Ni, Co, and Cr are notably enriched in impact melt; high potassium content is remarkable, too.

At Kaitalannokka, the outcrops of migmatitic mica gneiss are the closest ones to the crater. Shatter cones have not been seen. Hammering and sampling not allowed.

References: Elo, S. et al., 1992. Tectonophysics 216, 163-167; Pihlaja, P., 1994. Geological map of Finland, 1:100 000. Pori. Pre-Quaternary rocks, sheet 1143, Geol. Surv. of Finland.

STOP 7. Kotkanniemi, Kokemäki - to collect impactite samples

A half kilometer's walk to the shore of cape Kotkanniemi. No outcrops, but the scree contains plenty of impact boulders, mainly suevites. Sample collecting is allowed. If the water level in the lake is abnormally high, this stop will be cancelled.

From Kotkanniemi, Kokemäki the buses will drive directly (ca. 230 km) to Helsinki-Seutula airport and the main railway station in Helsinki.

POSTER ABSTRACTS

IN ALPHABETICAL ORDER

Characterization of the Lappajärvi impact structure, Finland, by integrated spatial analyses of multisource geodata

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Reliable statements on the present and hence original geometry of eroded impact structures often require a combined study of independent data. In addition, the setting during impact and the subsequent regional development must be taken into account. The ~71-Ma-old Lappajärvi impact structure, Finland, has been chosen for an integrated approach by employing the following data sets: aerogeophysics (magnetics, electromagnetics, radiometrics), gravity, Landsat-TM, ERS-1, digital elevation model including bathymetry, geology (outcrops, drill core logs). The data were appropriately worked up with procedures being inherent in customary GIS and image processing software focussing on merged analysis and visualization.

Lappajärvi is associated with a ~17 km wide negative gravity anomaly of up to -10 mGal [1]. The onset of the gravity low closely matches with the region in which pre-impact aeromagnetic trends have been at least partially subdued. Synoptic representations of horizontal gradients of the gravity and magnetic potential fields are suggestive of a 1.0 to 1.5 km wider terrace zone on the eastern than on the western side of the crater, in accordance with the aeroelectromagnetic signature. The discrepancy may be due to structural control of the crater collapse by the pre-existing structural grain [1, 2]. It appears more significant in the western periphery where all interpreted slumping faults are rather straight, whereas on the east side more curvilinear trends are present. Within a distance of ~3 km from the lake shore (and from a low-land on the east) the surface rises up to ~56 m above the lake-level; only to the southeast some hills reach up to ~106 m high. These elevations form a discontinuous ring around the crater, about 22.5 km across. Beyond the surface slopes gently up to a distance of ~18 km from the center. This aureole is well perceptible in Landsat and radar data, especially because of a relatively higher forest density. In combination with the topography it can be traced around the whole crater [2], yet a bounding continuous ring fault is not apparent. The feature is interpreted as an area of structural uplift and disturbance already established during the excavation stage, when the rarefaction wave induced (1) an upward-directed pressure-gradient behind the shock wave (*i.e.,* the upward-and-outward excavation flow), and (2) tensile stresses that exceeded overburden pressure and the tensile rock strengths. Lappajärvi has been considerably scoured by warm-based glaciers indicated by a drumlin field to the NW extending into the lake. However, this erosion was selective and mainly affected already disintegrated rock volumes, *i.e,* impact-breccias and weathering crusts developed in pre-Pliocene times. Therefore, the surface of the exposed resistant impact-melt rock on the northwestern slope of an inferable central uplift (max. ~7 km across) may be close to the initial apparent crater depth (at most ~50 m below). This is corroborated by the presumed maximum extent of a potential former central peak (smaller than ~15 km^2) interpreted from spatial relationships of outcrops, drillings and geophysics. The 22.5 km-chain of hills does not, in sections, mark the initial crater rim, when considering the geophysical signatures and the expected erosion level. The original rim-crest diameter is estimated to ~19 km. In view of published scaling relations the original apparent and true crater depth may have reached ~0.5 km and ~0.9 km, respectively.

Acknowledgements: Supported by DAAD-Finnish Academy of Science grant to AD and LJP. We are grateful to Seppo Elo, Maija Kurimo (both GSF) and Erkki Tomppo (METLA) for placing gravity, aerogeophysical and Landsat data, respectively, at our disposal.

References: [1] Elo, S., et al., 1992. Tectonophysics, 216, 99-109. [2] Pipping, F., 1994. Lockne-94, 2nd International Workshop of ESF network "Impact Cratering and Evolution of Planet Earth", Östersund, 1 p.

Aeromagnetic signatures of the Neugrund structure, Gulf of Finland, NW Estonia

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Two well preserved Early Palaeozoic impact structures have been identified in NW Estonia: Kärdla and Neugrund. The Kärdla crater [1] is studied by deep drillings, whereas the Neugrund structure, located in a shallow near-shore part of the Gulf of Finland, is poorly studied only by sea-bottom observations and shallow seismic profilings. Pleistocene glaciations eroded the re-exposed uppermost parts of the Neugrund's rim and re-deposited a large amount of impacted rocks [2]. The structure is located in an area of positive north-north-easterly linear magnetic anomalies, the central part is superposed to a relative magnetic low. We have attempted to interpret magnetic anomalies in the Neugrund area.

To interpret the magnetic anomalies, the following circumstances are essential:

- In surroundings, the pre-impact and lowermost part of post-impact deposits has been survived. The distant ejecta layer is found inside the Lower Cambrian marine deposits by drillings [2]. Inside the structure, impact breccias should be well preserved as well as the melt lens (if formed at all). Post-impact Ordovician limestones that are identified by submarine observations fill the structure. The crest of the rim wall is exposed under the shallow ($\geq 2m$) seawater;
- We can expect almost analogues effects on potential fields of the Neugrund and Kärdla structures because of almost similar size, time and target of impacts. The age of Neugrund impact, determined by geological settings, is ~470-500 Ma, closed to the Kärdla impact (~455 Ma). Spatially these two structures are also located close to each other, within the same structural zone of crystalline basement [3].

On aeromagnetic anomaly map an arc of positive anomalies (up to 400 nT), corresponding to the northern, eastern and south-eastern parts of the rim wall, is observable. It disturbs the NE-SW trending linear anomaly pattern, typical for surrounding orogenic Svecofennian rocks. A magnetic minimum is located at the central part of the Neugrund structure.

The circular negative anomaly is due to:

- low magnetization of post-impact sedimentary infill;
- low magnetization of allochthonous impact breccias (because of the random orientation of magnetizations);
- shock demagnetization of the target;
- low or reversed magnetization of melt (if present at all).

References: [1] Puura, V. and Suuroja, K., 1992. Tectonophysics, 216, 143-156. [2] Suuroja, K. and Suuroja, S., 1999. Estonia Maritima, 4, 161-189. [3] Koistinen, T. et al., 1996. Geol. Surv. of Finland Special Paper, 21, 21-57.

Feldspars in impacted rocks as a geobarometer of shock metamorphism

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Under shock loading of igneous and metamorphic rocks in nature and in the experiment a zone of the gradual transition from K-feldspar to plagioclase is observed. In laboratory experiments, the samples of the fine-grained pegmatite and biotite granite were used. The sample of pegmatite having density ρ_{00}=2.570 g/cm^3 contains 55-60% of microcline, 25% of quartz, 12-17% of plagioclase An_3 and up to 2-3% of muscovite. The sample of granite having density ρ_{00}=2.617 g/cm^3 contains about 40% of K-feldspar, about 30% of plagioclase An_7, 25% of quartz, 5-7% of biotite. The ball-shaped samples, 47.47 and 47.84 mm in diameter, were welded up in vacuum into steel hermetic jackets and were subjected to explosive compression [1, 2] at the detonation on them of the spherical layer of high explosive composition TNT/RDX-30/70, whose thickness was h_{HE}=8 mm and the external radius of the explosive layer R_{HE}=40 mm. As a natural analogue, the samples of AR biotite gneisses of the target of the Popigai astrobleme from Russia were studied. This gneiss contains about 50% of plagioclase An_{29}, about 20% of K-feldspar, 20-25% of quartz and up to 10% of biotite.

In all three cases, the zone of the gradual transition from K-feldspar to plagioclase was observed. The zone is nonhomogeneous along and across the boundaries of the neighbouring grains of feldspars that is associated with their different orientation with respect to the shock wave front. In the region of the solid-phase transformation of minerals in stress the width of this zone varies from some micrometers to about 300 μm. This width depends on the amplitude of the shock wave, the direction of its propagation and also on the content of Ca in the initial rock subjected to impulse loading.

The statistic processing of the relationships between the zone width of the mutual migration of Na and K and the shock wave amplitude has shown that for the investigated samples with different content of Ca this dependence is described by simple relationships:

$\sigma_{XX} = 20.7 + 0.0977$ L;	s = 2.14;	r = 0.964;	n = 13;	An = 3;
$\sigma_{XX} = 24.4 + 0.137$ L;	s = 3.99;	r = 0.666;	n = 10;	An = 7;
$\sigma_{XX} = 28.6 + 0.262$ L;	s = 4.55;	r = 0.851;	n = 10;	An = 29.

Where: s - standard deviation; r - pair correlation coefficient; n - number of investigated boundaries (pairs of grains); An - amount of anortite component in the primary plagioclase (%); σ_{XX} – shock wave amplitude (GPa); L – boundary zone width (the zone of the mutual migration of Na and K; μm).

Thus, for the wide range of impact actions (for $\sigma_{XX} \leq 45$ - 55 GPa) the estimation method of the shock wave amplitude $\sigma_{XX} = \sigma_{XX}$ (L, An) in rocks containing two feldspars was proposed.

References: [1] Kozlov, E.A. et al., 1998. DAN, 361, 333-336 (in Russian), also in Phys.-Dokl., 43, 419-422 (in English). [2] Kozlov, E.A. et al., 1998. XXIX LPSC Abstract volume, 1091.

The Zapadnaya impact structure in the Ukrainian shield

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The Zapadnaya crater is a complex impact structure in the western part of the Ukrainian Shield. The crater is formed in the Precambrian crystalline rocks, predominantly garnet-biotite granites, and rarely gneisses. The Quaternary and Neogene sediments about 40 m thick cover the impact crater but its structure is known from more 100 boreholes drilled by Melnichuk and Golubev for the crater study and search of impact diamonds in it [1, 2].

The Zapadnaya impact structure is a depression of complex form with sizes from 3.2 km from north-west to south-east and to 2.3 km from north-east to south-west. An uplifted horst-like block of cataclased crystalline basement rocks, about 0.5 km wide, separates the impact structure on two unequal parts [2].

The north-western part of the impact structure is a hemicircular depression, about 0.5 × 0.6 km, boundaried from south-east by uplifted block of crystalline basement rocks. Depression is filled with suevites to 100 m thick.

The biggest south-eastern part of the impact structure contains a central uplift about 0.8 × 0.4 km in diameter and to 200 m height. The uplift is surrounded from east, south-east and south by circular trough to 230 m deep. The crater is filled with allogenic breccias and suevites. All structural elements of that part of the crater are limited from north-west by horst-like uplift of basement rocks.

The polymict allogenic breccia, to 50 m thick, occurs as a broken layer on the surface of brecciated basement rocks and sometimes forms lenses in suevites. The biggest part of the crater volume is filled with suevite layer up to 150 m thick. Glass content in suevites reaches up to 40-60 % within their upper horizon.

Diamond-bearing impact melt rocks and impact melt breccias form dyke-like bodies within brecciated basement, especially within the central uplift, but their occurrence form is very complex and still remains poorly known.

References: [1] Gurov, E.P. et al., 1985. Doklady Akademii nauk Ukr.SSR., 1, 9-12 (in Russian). [2] Gurov, E.P. et al., 1999. Mineralny resursi Ukraini, 3, 30-32 (in Russian).

Magnetic modeling of the central uplift of the Vredefort impact structure

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The Vredefort impact structure is, with an estimated original diameter of, at least, 250 km [1], the largest astrobleme so far detected on Earth. Aeromagnetic data and measurements of the magnetic properties of rocks from surface exposures provide a basis for modeling of the structure of the central uplift (the Vredefort Dome) of this impact structure. Additional constraint is derived from our gravity model [1; *cf.* also for detail on modeling method]. Three different magnetic models were obtained, each with increasing complexity of source structures, progressively accounting for more aspects of the cratering process: Model A shows a uniform layer of remanent magnetised lithologies; model B comprises individual magnetic sources in the collar and core of the Dome, respectively; and model C represents an assemblage of magnetic source structures in both collar and core. All three models reproduce the measured magnetic anomalies; all represent structures that extend from the surface to restricted depths, and all involve remanent magnetised source structures with properties similar to those measured on surface. Layer model A demonstrates that variation of the negative anomaly can be accounted for by variation of the layer thickness, which gives information about the lateral and depth extents of reversed magnetisation. Thus, remanence extends radially for ~30 km from the center of the Dome and to a depth of ~2 km. As it is unlikely that the remanent source structure is so uniform, model B would be more realistic; it demonstrates that the magnetic structure of the crystalline core follows its antiformal shape. A remanent envelope is seen around the top of the central uplift. Depth extent of remanence is somewhat deeper in this envelope than in the central part of the dome. Model C is based on the findings of the earlier models, but also considers out- and downward sliding of upper parts of the central uplift. This overprint disrupted the conformal arrangement of lithologies of the pre-impact target and the geometry during uplift. The collapse phase also involved overturning of the collar sequence. The reversed remanence reflects the ambient geomagnetic field shortly after the impact event. It appears that it was imprinted into highly coercive magnetic grains probably formed by shock dissociation of Fe-Mg silicates, by excess temperature introduced by a now eroded impact melt body, and the rise of deeper crustal rocks. The region of shock dissociation, which originally was concentric to the point of impact, now forms an envelope around originally deeper, less strongly shocked rocks. The remanence seen is a thermoremanence acquired long after the impact event when the rocks cooled below the blocking temperature of ferrimagnetic minerals. The distribution of a remanent magnetic envelope mirrors the zoned distribution of shock degrees, which originally were spherically arranged, but after uplift changed into an anticlinal structure. The magnetic boundaries within this updomed envelope indicate the effect of the collapse of the central rise by outward flow of upper segments along low-angle shear zones.

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Genetic types of the micrometeorites from the impact regions

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The micrometeorites were collected from impact region of a meteorite impact at Kaba (Hajdu-Bihar County, East Hungary). The impact occurred in 1857 and a 3,75 kg weight [CV3] carbonaceous chondrite meteorite was recovered then; the impact region was reconstructed recently. The collected material contains micrometeorites of different genetic types as seen from their chemical compositions and morphology, obtained using SEM and EDS. The micrometeorites, drops and splints reveal the process which created them, [1, 2, 3].

The examined micromaterials may be classified by the following genetic types:

A: **Blenddrops sprayed in the upper part of the atmosphere.** These micrometeorites have formed as blenddrops from the cold meteorites, which were abruptly heated up in the atmosphere and then burst and disintegrated into elements. They formed plasticblenddrops of iron and silicate:

1. Glassy drops (Si).
2. Magnetodrops (Fe).
3. Glassy siderodrops (Si-Fe).

B. **Blenddrops separated from heated meteorites in the lower layer of the atmosphere.** The upheated blenddrop, because of the decrease of its caloric energy (CE), separates into droplets, the iron and silicate content of which depends on the quantity of their CE. This CE is a function of the distance between the place of the separation from the meteorite and the Earth's surface. These micrometeorites are distributed into four types in the meaning of their chemical composition and morphology:

They are:

1. Microsplints with disintegrated siderodrops (Fe-SiFe).
2. Perfectly disintegrated siderodrops (Fe-SiFe).
3. Non perfectly disintegrated siderodrops (Si-Fe).

Conclusions: The different types of micrometeorites permit us to draw conclusions as to the genetic processes which occurred when the meteorites arrived to the Earth's atmosphere. Similar micrometeorites were found in the placer of Crisu Negru (Bihar County,SW Romania) and also from the impact region of the meteorite of Mócs [4] and from the Kaali meteorite craters area (western Estonia) [5]. The results of the researches [1, 3, 4, 5] prove that the meteorites, which are heated up upon their arrival into the Earth's atmosphere, produce micrometeorites. These are useful for locating the impact sites of the cosmic objects, because conserved in the sediments.

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Geophysical investigation of the Lake Bosumtwi impact crater

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The Lake Bosumtwi Structure is one of the largest, youngest craters on Earth. It is located in Ghana and approximately 1 Ma old. The crater has a rim diameter of 10 km and is very well preserved. The structure is associated with the Ivory Coast tektites [1]. Remote sensing and digital topography data indicate an outer ring structure of 20 km diameter. The crater is almost entirely filled by Lake Bosumtwi (depth up to ~75 m) and post-impact sediments of unknown thickness. Little is known about the deeper structure of the crater. Aeromagnetic surveys indicate the presence of magnetized bodies, probably suevitic impact breccias or impact melts in the central area of the lake [2, 3]. In the fall of 1999 first gravity measurements were conducted on land. Refraction seismic data were acquired in co-operation with a reflection seismic survey of the University of Syracuse, USA, using the *R/V Kilindi*, a new portable, modular research catamaran. A new platform is constructed for future geophysical work as well as for further disciplines.

Approximately 160 gravity stations were measured on land around the lake and on the shore of the lake, using differential GPS for location and elevation determination. The gravity data show the expected minimum associated with the crater structure resulting from the water in the lake, the sedimentary filling of the lake, low density impact formations, brecciated and fragmented basement and the pronounced effect of the significant morphology of the crater structure, which has yet to be determined. Additional measurements will be carried out on the lake later this year.

Refraction and wide angle reflection seismic data were collected by three Ocean-Bottom-Hydrophones (OBH) on one profile across the lake. They show good signal penetration despite pronounced 'shallow gas curtains' within in the lake's margin. Refracted and reflected arrivals are recorded to an offset of more than 6 km, and their pattern shows a complex subsurface structure.

Initial interpretation of refraction data indicates low seismic velocities (less than 2 kms^{-1}) in the unconsolidated shallow sediments and high basement velocities (more than 6 kms^{-1}). Prominent steep and wide angle reflections are also visible although partly obscured by a strong bubble pulse. We will develop a model of the crater's subsurface structure (possible uplift, thickness and distribution of breccias, fragmentation zones *etc.*) based on the integration of gravity, magnetic and seismic data.

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Cosmic spherules in the Satakunta sandstone, Finland: Preservation - separation

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The oldest known micrometeorites - MMs - occur in the Mesoproterozoic Satakunta red bed formation, Finland [1,2]. So far, about 90, strongly magnetic cosmic spherules have been recovered from rock samples of four different outcrops of this sandstone [3]. All the MMs are excellently preserved: they lack clear signs for mechanical abrasion, the matrix is still glassy, and serpentinization of olivine is absent. Separation of the MMs from their host rocks with conventional technique is a quite time-consuming, and not very effective task: during processing in the jaw crusher, we obviously have destroyed a significant number of the fossil MMs by breaking. A test with an electrodynamical fragmentation device - the so-called FRANKA of the Forschungszentrum Karlsruhe [4] - however, yielded almost 50 MMs from one sample with a starting mass of about 3.5 kg [5]. To avoid a bias in the yield of micrometeorites - either due to natural or artificial reason, we have used for this experiment a rock piece cut perpendicular to the layering. Based on this result, we assume that the number of MMs recovered from conventionally crushed samples [5] does not reflect the true number of MMs in a sedimentary rock.

The Satakunta sandstone is a clastic fluvial formation [6]. Characteristic features include planar and through cross-bedding, horizontal and laminated bedding. Sandy and pebbly components dominate. Lithological variations are drastically even at short distances, indicating frequent changes of the transport direction. At the current stage of knowledge, MMs seem to occur preferentially in badly sorted, minor transported arkose rocks. From transport simulation experiments, we know that the MMs are apparently highly resistant against fluviatile transport despite their seemingly "delicate" surface textures [7]. The Satakunta rocks display an extreme grade of lithification [8] caused by silicification (*e.g.*, epitaxial overgrowth, and crystallization of microcrystalline quartz in the pore spaces, intergrowths of matrix clay by secondary quartz). We assume that this fast "sealing" of the sediments by authigenic quartz inhibited very efficiently circulation of fluids along grain boundaries and in the pore spaces. This silicification probably represent the key factor for the remarkably good preservation of the MMs in the Satakunta Formation. Another important aspect is the absence of significant thermal events in the region as preliminary fission track (FT) data indicate [9].

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Meteorite impacts in the solar system in general and a closer look at impact structures on Mars and Earth

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When a meteor impacts a solid body, the resulting crater is dependent on at least three major topics:

1) The qualities of the impactor (speed, size, material, *etc.*),
2) the type of material in the impacted area (silicate, ice, solid, liquid, *etc.*), and
3) the overall environment of the impacted body (atmosphere, gravity, speed *etc.*).

All of these characteristics vary greatly from one body of the solar system to the next, and thereby the resulting marks of the impacts differ from place to place.

On Earth, the atmosphere changes the speed, the size and the shape of the projectile before the crash, and surface processes such as water, air and tectonics eventually change the appearance of the crater created. In addition, Earth is the biggest solid crusted object in the solar system, as well as one of the most active ones, and thus represents only one 'side of the story' when impact craters in the solar system are discussed.

As other planets, moons and asteroids have distinct gravity wells, atmospheres, surfaces, distances from the Sun *etc.*, they are also affected differently by impacts. For example, Venus allows even fewer meteors than Earth to penetrate all the way to the surface due to the immense pressure of the atmosphere, and this pressure contributes to the way craters are formed. On the other hand, the smaller moons and asteroids are usually not very dense and have no protective atmospheres, and thus an impact can be more destructive on such objects than on a planet. Furthermore, there usually are no major processes (other than impacts and impact-related events) deforming the surface of these small bodies afterwards. All in all, the crater shape and structure varies greatly, depending on the solid body in question.

This article discusses these differences and the variability of impact craters on different planets and moons. It gives a short overview on the diversified nature of impacts in the solar system.

Lastly, topography and appearance of some craters on the Martian northern plains are studied and compared to similar sized craters on terrestrial soil. Mars was chosen for this because of the new accurate data obtained by the Mars Global Surveyor, and because it gives the best possible match we have Earth to compare with in the whole solar system. The Martian environment, although totally unique with its own processes, has undergone several events (such as volcanism, tectonics and probable water related phenomena) similar to the terrestrial one, and is also somewhat affected by an atmosphere.

Clinopyroxene as a source of impact loading strain data

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The general aim of any petrologic investigations is the estimation of P-T parameters of the formation of studied rocks. As for impacted objects, the problem of shock pressure calculation is very complex. At present there is the only shock geobarometer based on diaplectic deformations in quartz [1] and it is possible to construct geobarometer with help of feldspar investigation [2], but such methods cannot be applied in rocks with predominant number of mafic minerals. They are strongly stable under shock and the most of their characteristics are not changed significantly. It has been noticed the increase of "asterism degree" [3] which takes place for all rock-forming minerals. However this property can be quantitatively studied under single-crystal study and it is very difficult to determine shock pressure precisely because of the different orientation of the grains and of the irregularity of shock influence upon rock.

Our investigation of experimentally and naturally shocked clinopyroxene shows that there is another important characteristic, which can be used for shock geobarometry construction, namely dislocation density. Its increase under shock is also usual effect for all rock-forming minerals. It is observed at electron microscopy investigation (in olivine, for example [4]) and at X-ray study. As for clinopyroxene we have found the broadening of X-ray maxima for both experimental and natural deformed mineral. This effect does not depend on the chemical composition of clinopyroxene. For (22 –1) reflection we calculated the pressure dependence of X-ray maxima broadening degree: $P=131b+7.8$ (P – shock pressure (GPa); b – broadening (degrees 2θ)). This equation allows estimating shock pressure in rocks with clinopyroxene up to 30 GPa. Besides, this study demonstrates the possibility of the construction of similar geobarometer with help of other mafic minerals (orthopyroxene, olivine, *etc.*).

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Paasselkä – the ninth meteorite impact structure in Finland

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Lake Paasselkä is an oval-shaped bay of a larger lake Orivesi in south-eastern Finland. The diameter of the relatively deep bay is about 10 km and its maximum depth is 74 m. The bedrock of the area mainly consists of Karelian mica schists (~1.9 Ga) with black schist intercalations. Numerous granite and pegmatite dykes occur around the lake. The structure is distinct due to its nearly circular shape in topographic maps and satellite images, as is the lack of islands except near to the shore. In bathymetric maps, the shape gets more elongated or trough-like in NW-SE direction with increasing depth. Airborne and ground magnetic data reveal a low magnetic relief over the lake with a negative anomaly (~300 nT) near to the center. The structure is associated with a gravity minimum of –8 mGal [1].

An earlier attempt [1] to explain the origin of the structure as a meteorite impact site failed due to the missing signs of shock metamorphism in the surrounding outcrops and in glacial drift boulders. Deep drilling was seen as the only possibility to get conclusive evidence, but it was regarded as too expensive.

In March 1999, the Geological Survey of Finland and Geotek Drilling Company (Finland), as the contractor, carried out a deep drilling project at Paasselkä [2]. The operation took place from ice cover. The drilling site (62°8'45"N, 29°23'10"E) was located above the negative magnetic anomaly, near the center of the structure. The depth of water at the site was 48 m, following 20 m of Quaternary mud and glacial moraine. Unlike in some other Finnish impact structures, Paasselkä appears to be avoiding of layers of pre-impact or post-impact sedimentary rocks. The bedrock is moderately fractured mica schist and minor black schist down to the depth of 252 m, where the drilling was terminated. Some granite and pegmatite veins cut the schists. The brecciation is locally so strong that the target rock has been totally crushed into mortar-like mass, where sharp-edged rock clasts or single minerals are embedded in very fine-grained matrix. These injection breccia dikes, occur more commonly in the top 20 m of the drill core after which they are rather occasional; the lowermost dike was found at the depth of 246 m. The width or thickness of the dikes varies from 2.6 meters to some millimeters. Study of thin sections of the dike samples reveals unequivocal evidence of shock metamorphism: quartz has PDF's in two to three orientations and biotite shows strong deformation and kink banding. PDF's can be observed at least down to the depth of 116 m.

Petrophysical measurements show that the breccias have, as expected, relatively low densities (<2500 kg/m^3) and weak susceptibilities (<300 × 10^{-6} SI). The intensity of NMR is also low. At the depth of 212–232 m the drill penetrated black schists with impregnation and blebs of pyrrhotite. The black schist has very low resistivity, high susceptibility and high remanent magnetization ($Q > 20$) with negative inclination. Tentative geophysical modeling suggests that this iron sulphide layer is, instead of expected impact melt layer, causing the negative magnetic anomaly near the center of the structure. Based on petrographic observations, geophysical signatures and morphology, the Lake Paasselkä structure is a hypervelocity meteorite impact site. Its age is still unknown.

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Mineral deposits in Sweden related to suspected Precambrian meteorite impact craters

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A large number of mineral deposits are related to several structures in Sweden, suspected to have originated as impact craters. In this paper deposits related to the Uppland, Duobblon and Gallejaur structures will be described, and tentatively interpreted.

From Uppland, [1] has described so called "ball ores" and compare these with mineral deposits in the Sudbury basin. One of these deposits in Central Sweden is Saxberget, where the lithostratigraphic column is tectonically reversed.

Within the gneiss granites in Central Sweden, large alteration zones and related iron ore deposits are found, superimposed on the gneiss banding and schistosity, and unrelated to volcanic events. These alteration zones have been described as large fragments of iron ore with or without enveloping "leptite" in the gneiss granites [2].

However a large number of iron ores are quartz and carbonate banded, representing Precambrian BIF horizons, and now found in a vertical to subvertical position. These are interpreted as pre-impact deposits.

Three deposits from the Gallejaur Structure will be mentioned. A polymict breccia with large granite clasts of Jörn type is found at the contact to the Rakkejaur deposit [3]. The Holmtjärn deposit is partly localized in autochthonous brecciated volcanic rocks and sulphides occur also as breccia filling. Autochthonous brecciation is also found in drill-holes from the surroundings to the Svartliden deposits, where large parts of the bedrocks are brecciated or form polymict breccias.

At Duobblon a uranium deposit has been described within an ignimbritic-like rock [4, 5] which is interpreted as an impact melt. Close-by sulphides with gold are situated within autochthonous brecciated granite.

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New possible impact sites in northern Finland

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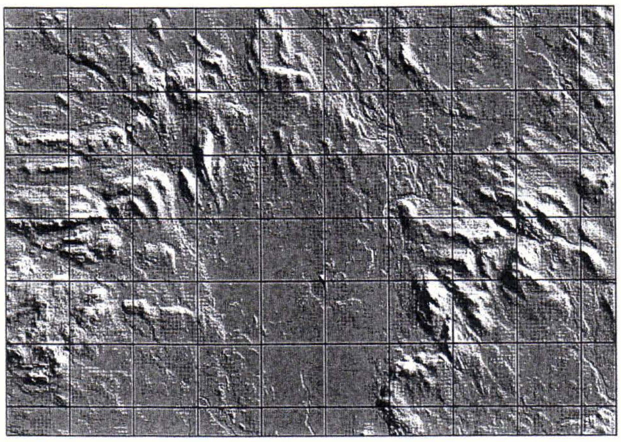

The only confirmed meteorite impact crater (MIC) in northern Finland is Saarijärvi in Taivalkoski. With the crater density of southern Finland, 10-20 MICs should remain to be discovered in the north. Since 1999, study of relief maps, low-altitude aerogeophysical and regional Bouguer anomaly maps has revealed several circular features suggesting MICs. Eroded, filled by younger sediments and covered by Quaternary glacial deposits, the suspected MICs have few outcrops. In ice divide areas with weak glacial erosion friable preglacial weathered subcrops are common.

Grussification-weathering of mica-bearing rocks, cum solution of sulfides and carbonates, prevailed during humid, temperate late Tertiary to early Quaternary. The brecciated, comminuted and chemically reactive MIC rocks were elect sites of deep weathering. And after these visitations, periglacial frost-shattering ravaged most of what was left of solid outcrops. Lakes are less than in southern Finland; the lower terrain is blanketed by a network of wide aapa mires. Field studies depend on geophysical (particularly gravity) traverses, diamond core drilling and sampling of till, glaciofluvial and fluvial deposits for indicators (shocked quartz, coesite, moissanite, impact diamond). Economic objects are kaolinite, impact diamonds and zeolites.

The possible MICs discoveries are: 1) Sakkala-aapa (D = 16 km) has plain topographic (Figure) and geophysical expressions. Outcrops occur in the central uplift area. The magnetic grey-tone map pictures are distinctly bounded, shattered and jumbled "pot". An EM anomaly field covers the ring-shaped depression. Vertical faults of the western rim are supposedly associated with isostatic-tectonic re-arrangement of the crater. 2) The Lake Arajärvi vally (D = 4 km), 25 km NNE from Sakkala-aapa coincides a magnetic low. EM conductors occur beneath the lake and mires. 3) Vuontisjärvi, in the north near the Norwegian border, is a roundish, flat buried valley (D = 2 km) amidst rocky high ground. Ground geophysical traverses are due in April 2000. 4) Kypäsjärvi in SW Lapland has a large discordant magnetic low (D = 16 km). In its centre a ring-shaped magnetic high (D = 4 km) coincides with an EM anomaly chain. 5) The flat Lake Kostonjärvi valley in SE Lapland in the Archean basement area is a bull's eye of a 70 km-diameter circular multi-ring topographic feature. Diamond drill holes at the lake intersected breccias with strongly kinked albite and strongly deformed quartz, with inclusion trails reminiscent of PDF. This may be an annealed impact breccia but the evidence is inconclusive. 6) The Elijoki structure, 95 km NNE of Kostonjärvi, amid lower Proterozoic mafic metavolcanites, is asharply-bounded circular magnetic low with a central magnetic peak and a 4-5 km-broad, high-magnetic but perturbed surround. A deep Bouguer low (-10 to -15 mGal) and a field of EM conductors coincide with the magnetic low. No outcrops are known there.

Several other MIC candidates are within scope. Surely, many MICs could be easily found in northern Sweden, Norway and Russia using good topographic and geophysical data.

The Saarijärvi crater - older and larger than assumed?

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Background: The Lake Saarijärvi impact structure (centered 65°17.4'N 28°23.3'E) in Taivalkoski, northern Finland is a small and highly eroded impact structure situated in the Archaean basement. The target rock mainly consists of gneissose granitoids. Crosscutting Palaeoproterozoic (most probably 2440 Ma and 2100 Ma) diabase dykes are also typical for the area. In 1997, drilling to the center of the structure resulted in a discovery of fragile granitic breccia with multiple sets of planar deformation features (PDF's) from the depth of 156.38 m, thus providing the impact origin for the structure. This interpretation is supported by gravity, airborne and ground magnetic and electromagnetic data and by seismic refraction surveys. The age of the impact is not known but has been thought to be between 2450 Ma to 600 Ma based on the age of the diabase dykes and Vendian microfossils discovered from drill-core samples of sand- and claystones preserved in the crater [1, 2, 3].

Results and hypotheses: An amateur geologist (Jarmo Moilanen) discovered the first shatter cones from Saarijärvi in 1998 [4]. Geological mapping of the area in 1999 revealed weaklier developed shatter cones with the apices of the cones pointing roughly to the center of the structure. The most distant shatter cones were approximately 1 km north from the center. Therefore it could be possible that the original diameter of the crater was at least 2 km, instead of 1.5 km as previously assumed [1, 2]. Results from density measurements of diabases are also consistent with the hypotheses of a larger crater. New microfossil studies were also carried out, and according to them also Cambrian sediments (543-500 Ma) are present. Petrographic, electron probe microanalyzer and SEM-EDS research of brecciated granitoids from the central island showed narrow, partly glassy veins, originally discovered by Dr. Dmitry Badyukov [5]. Some of them are composed almost entirely of SiO_2 and Al_2O_3, while others include also significantly Mg and Fe. These together with amphibolitic veins discovered in diabases gives the rocks of the central island resemblance to pseudotachylites found in impact structures [6]. However, even the proposed 2 km diameter is too small for any significant melting, or to the explanation of the island as a central uplift. Preliminary paleomagnetic results of samples from the central island (diabases, granite breccias and granites) and rocks in the NE part of the crater yielded three remanence components. The first most likely indicates the time (~2440 Ma) of intrusion of the diabase dykes. The second, ~1870 Ma, is a clear overprint of the Svecofennian orogeny. The third component is anomalous, and we interpret it as caused by the impact. This component plots slightly out of the apparent polar wander path of Fennoscandia but could have been acquired either during ~2100 Ma (reversed polarity option) or ~1200 Ma (normal polarity option), respectively. Both of these ages are consistent with the very deeply eroded appearance of the present Lake Saarijärvi impact structure.

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Computer modelling of the water resurge at the Lockne crater, Sweden

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Cosmic impacts on Earth most often occur at sea. The craters that sometimes form in the seafloor at such events show some distinct differences in shape and morphology from craters formed on land [1]. Especially conspicuous are the features created by the resurge of water back into the crater. These include radial gullies through the crater rim and a resurge breccia that fills much of the crater depression, the gullies, and, in some cases, parts of the crater surroundings. The resurge breccia within the crater often constitutes one, thick fining upward sequence that represents a large fraction of the crater infill. This indicates that the resurge has filled the crater rapidly. In order to study the behaviour of the resurge flood we have conducted 2D and 3D numerical modelling based on the Lockne crater. The geology and morphology of this crater is well defined through numerous works (for references see [1]) which makes Lockne suitable for this study. Paleogeographic reconstructions, and the evidence for a massive resurge, indicate that the Lockne event occurred at intermediate water depth, possibly shelf depth [2]. The exact water depth is not known but was most likely much deeper than 200 m [1].

In order to calculate water movements at collapse of the crater, we developed 2D and 3D numerical codes with a technique developed for gradually varied flood flows in a civil engineering field. Equations to be solved in the model are Saint-Venant equations with the diffusion wave approximation. This approximation reduces numerical costs greatly from the full solution of dynamic wave equations. For these, preliminary, calculations we assume that the water moves as a fully-developed turbulent flow, whose viscous resistance can be neglected, and that turbulent resistance can be estimated by the empirical Manning equation. We took a fully implicit expansion with the upstream method for the basic equations, and Newton-Raphson scheme to overcome nonlineality of them. For the simplification, the calculation does not account for erosion so the topography is fixed. We used the concentric morphology of Lockne presented by [1] as topographic base for the resurge as an initial condition. The crater consists of a 24 km in diameter, shallow crater with a deep, 7.5 km wide, nested crater at the center. Initial water depth is zero at inside the crater, and sea level at outside. Water depth at 30 km from the center of the crater is kept to the sea depth, which is the only boundary condition.

Two modellings were done with target depth set to 100 m in one model and 500 m in the other, to see how different depths influence the process. Manning roughness coefficient is a fixed 0.1, larger than standard floods, because of the possible presence of topographic undulations immediately after the impact. The most clear difference between the two water depth alternatives is seen in the time it takes to fill the crater; 600 seconds (100 m) and 400 seconds (500 m). In both cases a low water front moves towards the inner crater. The rim of the inner crater is reached after 200 seconds (100 m) alt. 90 seconds (500 m). This gives less than 400 seconds for the gully formation. The results are preliminary.

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The sulphide mineralization in the rocks of the Kärdla impact structure

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In the area of the Kärdla impact structure provisionally two types of mineralization can be distinguished: stratiformal sphalerite-galenite-pyrite mineralization and cross-cutting pyrite-galenite-sphalerite mineralization.

The evidence of stratiformal mineralization is related to the Dictyonema shale (an analogue of alumo shale) distributed at the boundary of the Upper Cambrian and Lower Ordovician. Between the sea and the northeastern part of the Kärdla structure at a distance of 1–2 km from the crater rimwall after the Kärdla event the Dictyonema shale has preserved at two different levels. Differently from Northern Estonia, where the widely distributed Dictyonema shale is underlain by up to 30-cm thick layer of pyrite or pyritised sandstone, in the Kärdla area pyrite is found in the base of both Dictyonema shale layers, and has been partly replaced by galenite and sphalerite. In drill-cores K–14 and K–15 in the Kärdla region in pyrite bed (thickness some to 10 cm) average Pb content reaches 2.65% and that of Zn 1.28%.

The cross-cutting mineralization is younger and occur mainly on the rimwalls of the Kärdla crater and in its immediate vicinity, as well as in the crater filling deposits. In single drill-core samples Zn and Pb concentrations are comparable with the respective concentrations in commercial ores. The mineralization is accompanied with intense calcitization and partial dolomitization of the host rock. These processes occur both in the sedimentary rocks overlying the impact structure and the brecciated crystalline basement rocks. More intense cross-cutting mineralization evidence have been recorded in the northeastern part of the rimwall on the outer slope of Paluküla uplift, and near Tubala in the southwestern part of the rimwall on its crest. In the Paluküla uplift area in drillhole F–374 in 6-m section the content of Zn in the overlying dolomitized limestones ranges from 1 to 10% and that of Pb from 0.01 to 0.4%. In Tubala area in the overlying sandy limestones according to 1-m long samples from drillhole F–178, in 8-m section the Zn and Pb content is up to 1.26% and 0.29%, respectively. For the mineralised sections, increased contents of Cd, Ag, Mo, In and Cu are characteristic. The described mineralized carbonaceous rocks have deposited some millions of years after the Kärdla event.

The distribution of sulphide mineralisation has not been investigated. In the Kärdla area the sedimentary bedrock is overlain by glacifluvial and glacial deposits, the latter in turn mainly by sand and silt deposited during different Baltic Sea stages. Therefore, the efficiency of surficial geochemical methods is low. The results of investigations carried out along single profiles using the method of geochemical sorbents have indicated considerable more extensive distribution of mineralization. Data about the till's heavy fraction mineralogical composition provide additional information. In three analysed till samples the content of sphalerite in heavy fraction reaches 0.3–0.6%.

Presently the age and genesis of sulphide mineralization have not been unambiguously established. The provisional stratiformal mineralization probably occurred simultaneously with the Dictyonema shale formation. The cross-cutting mineralization took place between the the Kärdla event in the Early Caradocian (~454 Ma) and the Silurian (~440 Ma).

The S isotope data ($d^{34}S$) of both cross-cutting and the provisional stratiform mineralization range from -3.8 to +2.9‰. These results show that the mineralization more likely originates from some deep-seated source.

Three-dimensional magnetic imaging of the Chicxulub crater

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Although few magnetization measurements are available for the structural elements of the Chicxulub impact crater, the three to four orders of magnitude greater magnetization intensities of the crater's melt sheet, upper breccia unit, and central uplift versus the 3 to 4 km-thick carbonate and evaporite stratigraphy covering the Yucatán block allow three-dimensional modelling of the crater's structure by inversion using a two-layer model. Two layers are separately inverted by dividing the crater's magnetic field expression into <40 km- and >40 km-wavelength components. The upper layer (average depth 2 km) models the distribution of highly-magnetized zones in the crater's melt sheet. The lower layer (average depth 5 km) represents relief on the Yucatán block's basement surface and effectively maps the crater's ~50 km-diameter central uplift and possibly the expression of the surrounding collapsed disruption cavity fill. The shallower magnetized zones consist of two generally concentric distributions, at radii of ~20 and ~45 km. These highly magnetized zones are thought to result from hydrothermal systems, localized at the edge of the central uplift and the collapsed disruption cavity, having produced magnetic phases during alteration of the melt sheet.

Geophysical studies at the Ilumetsa impact site

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The Ilumetsa impact crater field in SE Estonia (58°57'N; 27°24'E) consists of two well-preserved simple impact structures, named Põrguhaud ("Hell's Grave") and Sügavhaud ("The Deep Grave") with diameters of 75-80 m and 50 m, and depths of 12.5 m and 4.5 m, respectively. These were first reported in 1938, during regional geological mapping [1]. Both structures are surrounded with a few meters high rim, higher in the eastern parts of the craters.

In 1970, the post-impact infill of Põrguhaud (2.15 m of the organic material, composed of 2.00 m of peat and 0.15 m of gyttja in the lowermost part) was sampled by hand-drilling, and analysed by means of ^{14}C and palynology, yielding an age of ~6000 years [2]. In summer 1996, glassy spherules at the depth of 5.7 m in the Meenikunno Bog, 6 km to SW from Ilumetsa, were found [3]. The radiocarbon age of the layer with spherules is ~6600 years. However, the connection between these spherules, and the Ilumetsa impact is not proven yet.

The target for Ilumetsa consists of Middle Devonian brittle reddish or light-yellow silt- and sandstones of the Burtnieki Stage, overlied by a ~3 m of brown basal till, and ~1 m of glaciofluvial sand and peat. The Põrguhaud structure is filled by an up to 8 m thick lens of allogenic breccias (sand, mixed with brown basal till), post-impact organic sediments, and is usually waterfilled. Authigenic breccias are represented by impact-fractured and -bended silt- and sandstones, which interchange with loose sand. The zone of authigenic breccias may spread down to ~30 m [1]. In the rim area, the bedrock and Quaternary cover is uplifted, whereas the basal till has been pushed into the Devonian sandstone. An ejected layer of allogenic breccias, which are similar to those inside the structure, covers the rim.

In June 1999, geophysical investigations on the Põrguhaud structure were performed. These included 6 profiles with ground penetrating radar (GPR) and ten vertical electrical soundings (VES) with a Schlumberger array. The profilings and soundings were concentrated to the rim and the nearest surroundings of Põrguhaud. Profiling with GPR was made across the rim wall along 4 radial profiles. Two circular profiles were measured, along the rim and inside the structure along the water line, respectively. Four VES were located on the rim, one inside the structure at the water line, and five outside the rim.

The interpretation shows that the impact had a clear and observable influence on the electrical properties of sediments. VES-data show that the resistivity of sandstone is less (~1000 Ωm) under the rim, compared with the surroundings (~2000 Ωm). At the rim, the resistivity versus depth models show significant variation in the top few meters, probably due to the interposition of sand and clay in the allogenic breccia, and the location of the local water table. The proximity to the crater structure induces however spurious effects as the geometry differs significantly from an assumed horizontal layering.

In the radargrams, numerous small dislocations and a general increase in small scale reflectors can be observed in the whole volume under the elevated rim and under the crater floor down to about 30 m. Outside the structure, reflectors are observed at ~8 m and ~22 m depth. The upper reflector, which could correspond to the surface of the Devonian sandstones, is interrupted under the elevated part of the rim while the lower reflector can still be traced under the structure.

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Carbon-rich and magnetic spherules and particles from Kärdla ejecta, Estonia

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Recently, a variety of C-rich and magnetic spherules and particles were discovered in a ejecta layer of Kärdla impact crater. The layer of breccia and sandy material enriched with these particles was sampled in several drill-cores located on the crest of the crater NE rim wall and outside of the NE and SW rim walls. A single 0.1 mm spherule with a fractured surface was found inside the crater in allochthonous breccia matrix. Samples were classified using magnetic, grain size and heavy liquids' separation. Separated particles were studied by means of optical and scanning electron microscopy (ESEM) and wave-length-dispersive microanalysis (WDS) in the laboratory of the Department of Geology and Geochemistry, Stockholm University.

Preliminary classification considering morphology of particles is shown in Table 1.

Magnetic particles are particularly characterised by high content of iron, silica and carbon, whereas the content of nickel is low. A single spherule of 0.1 mm-size has a very well defined decorated surface composed of polygonal 5-15 micrometer-size platelets separated by a polygonal fracture system. Another spherule studied in cross section consists of Fe-Si-C homogeneous core coated with very fine-grained layer of the same composition, smooth at surface. Numerous 0.2-1 mm-size microbreccia platelets and sticklets are composed of highly magnetic, very fine-grained (1-10 micrometer-size) fragmental, poorly cemented material.

Crust fragments of 0.1-0.3 mm-size consist of a bed-plate, decorated with different crystallites of similar composition. Typically also drusy micro-aggregates of 10-20 micrometer or around 1 micrometer-size bladed crystals, 1 micrometer-size botryoidal aggregates of bladed (?) crystals, colloform coatings of about 0.1 mm-size area, *etc.*, occur. Decorated crusts may be covered with a C-rich coating. 0.1-0.3 mm-size quartz of other rounded mineral grains are covered with C-rich or, rarely, with Ca and P-rich coating. The coating is often multi-layered.

In optical microscope, around 0.5 mm-size rounded intensely fractured and milky quartz grains were found in the same layers. X-ray diffractometry study shows noticeable XRD line-broadening of quartz peaks, which indicates imperfect crystal structure with high frequency of structure defects. This quartz associates with coated mineral grains.

Table 1. Carbon-rich, magnetic and nonmagnetic particles in the Kärdla ejecta.

	Ejecta on the crest of the wall	Distal ejecta
Magnetic particles:		
	Sprerules	Spherules
	Microbreccia sticklets	Microbreccia sticklets
	Microbreccia platelets	
	Mineralised crusts	
Nonmagnetic particles:		
	Coated mineral grains	
	Large deformed quartz grains	Large deformed quartz grains

Dating of Ilumetsa impact craters, SE Estonia

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The Fennoscandian - Baltic region holds a number of impact craters of Holocene age. There are at least three groups of impact craters of Holocene age in Estonia: Kaali, Ilumetsa and Tsõõrikmäe. The Ilumetsa craters, a total of five hollows, were discovered in 1938 during geological mapping. Dr. Artur Luha identified these hollows as meteoritic craters, although meteoritic iron had not been found.

In the crater area, the Middle Devonian bedrock consists of reddish- or light-yellow weakly cemented silt- and sandstones of the Burtnieki Stage, which are overlain by a 1...2-m-thick layer of brown loamy till. On the basis of the Ilumetsa craters, Ago Aaloe distinguished in 1979 a new crater type – the so-called impact-explosion crater - where the explosion energy was not focused at the end point of the trajectory, but was distributed in the cylindrical zone of influence along the entire course of the meteorite body in the target rock.

The biggest crater, Põrguhaud, which has been studied in particular detail, has a diameter of 75...80 m at the top of the mound and is 12.5 m deep. The destruction zone is at least 50 m. The base of the crater is covered with a thin layer of gyttja and peat up to 2 m thick. The radiocarbon ages of 6030 ±100 (TA-130) and 5970 ±100 (TA-725) years BP from the lowermost organic layer and the palynological evidence suggested that the crater is about 6000 years old.

The Sügavhaud crater, next in size, is 4.5 m deep and has a diameter of 50 m at the top of the mound. The destruction zone of the bedrock is about 20 m. In both craters, the eastern part of the mound is higher which suggests the fall of the meteorite from the east.

In the middle of the 1990s, the first author of the abstract proposed a new method of geological correlation on the basis of the finds of impact spherules in loose Quaternary sediments around the crater field. Microscopic ferric and glassy impactites discovered in lake and bog deposits of Saaremaa and Hiiumaa islands have allowed to date precisely the impact event at Kaali and to find chronostratigraphical markers for geomorphological and stratigraphical studies. Later, the same method was used in the Ilumetsa area.

In the summer of 1996, we found glassy spherules of impact origin at a depth of 5.70 m in the Meenikunno Bog, ca 6 km southwest of the Ilumetsa crater in the layer dated at 6542 ± 50 (Tln-2214) in the depth interval 5.6 - 5.7 m, and 6697 ± 50 (Tln-2316) at the depth of 5.7 - 5.8 m by the ^{14}C method. Based on these ages, it may be concluded that the Ilumetsa craters were formed about 6600 years ago.

Preliminary mineralogical and geochemical studies of the impactites of the Dellen impact structure, Sweden

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The Dellen Impact Structure (61°55'N, 16°32'E) is situated about 300 km NNW of Stockholm, Sweden. It is a terrestrial, deeply eroded complex impact structure, the age of the impact was determined to 89 ± 2.7 Ma by means of Rb-Sr and Sm-Nd-dating [1].

The topographical diameter of the structure is ~ 20 km and the depth of the present Dellen depression ~ 350 m. The impact origin of the structure was finally confirmed by identification of shocked quartz [2] and the existence of a coherent impact melt sheet [3]. Based on aeromagnetic measurements [3], the extent of the melt sheet has been interpreted to have a diameter of 9 km, with a thickness of 500 m.

Outcrops of impactites and impact-related rocks in the Dellen structure are scarce. This is due to severe erosion of the impact structure and a later superimposed thick Quaternary cover, additionally two lakes cover a large part of the crater depression.

Nevertheless, a wide assortment of the impactites and impact-related rocks from the various parts of the crater as well from boulders has been recovered. The impactites and impact related rocks include fractured basement rocks, authigenic breccia, allogenic breccia and at least three types of impact melt rocks: suevites, tagamites and buchites [4]. The shocked basement rocks situated at the margin of the crater depression display two different types of pseudotachylites: one caused by friction melting, the other is a result of shock melting. Following the terminology of [5] they are designated as E-type and S-type pseudotachylites. The first one is composed of extremely small mineral fragments in a glassy matrix and the second one appears as non- or weakly crystallised glassy veins up to few millimetres in wide.

In this study we intend to analyse the mineralogical features of the impact melt rocks together with the geochemical composition of both target rocks and impact melt rocks. The target rocks are represented by homogeneous intermediate, granodioritic granite with a minor amount of mafic dykes.

The petrographical studies show the different mineral composition of target rocks and impact melts that can be explained by non-eutectic crystallisation of the impact melt.

The presence of shock-metamorphic minerals in the impactites of the Dellen impact structure is not described in detail yet. The final diameter of the structure is poorly constrained as well, and mainly based on the topographic surface expression. A detailed structural and mineralogical investigation will help to unravel those questions.

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Meteoritic impact effects on Earth basement in large structures

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Impact craters on Earth are often named "deeply eroded" or astrobleme because weathering destroys the rim and elevated parts of the crater. However the lower parts are filled with allogenic breccia and some craters in lower parts of the Earth are later covered by sediments and preserved. Published geological information of 64 impact structures, from 200 km to 3 km diameter, allows us to outline a model of impact effects on the earth.

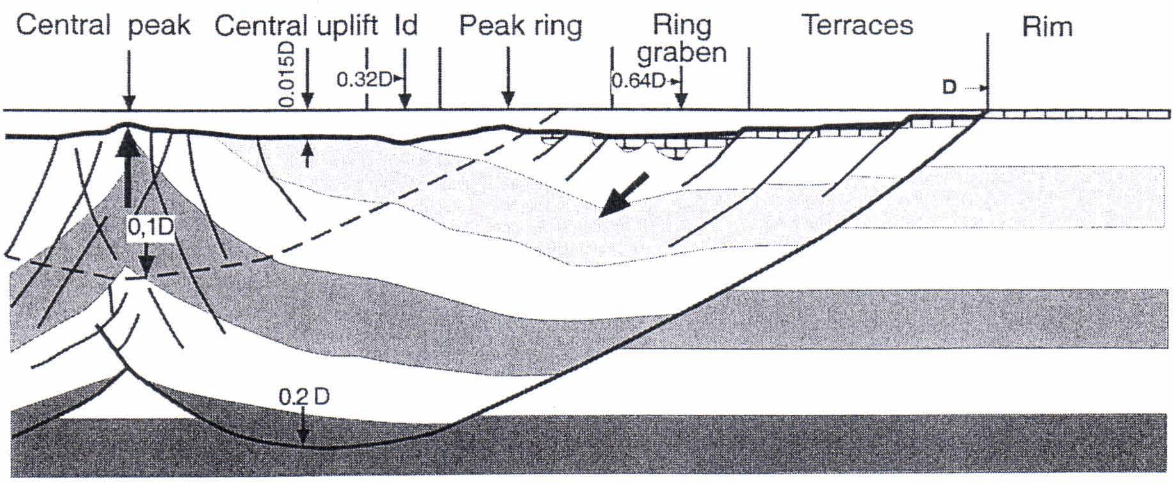

Figure 1. Schematic cross section of impact basement. Excavated crater in broken line.

Larger craters studied here have a irregular basement surface under allogenic breccia cover. Geological strata indicate that the basement has been uplifted in the center and collapsed around it. From the rim to the center we find the following features (Fig. 1): a) *apparent diameter*, D, from the first collapsed terrace. All other measurements are relative to the D value for each astrobleme. b) a *ring graben*, with the deepest collapsed ground. Structures larger than 30 km have a deep ring graben at 0,64 D. It is less marked in smaller structures. c) a *peak ring*, crown of small hills are visible in 14 structures. They are typically situated at about 0,44 D, but others are part of the central uplift and are probably attributed to the presence of hard rocks left by erosion. d) a *central uplift*, central uplift may be measured in structures where horizontal strata are affected. Measurements are from the diameter of the uplifted strata from the original level compared to the level outside the first collapsed strata. Eight measurements show it to be 0,46 D ± 10%. e) an *inner depression*, Id, deepest part of the bottom of the excavated crater, often with remnants of impact melt rock. Inner depression appeared in all structures at 0,32 D around the central peak of the small structures or forming a depressed ring in the larger structures. From the 64 impact structures studied, 44 retain some impact melt rock or allogenic breccia, *i.e.* erosion less than 0,03 D. Structures larger than 90 km generally have a central basin, but some smaller strucutres (Ries) may also have a central basin.

The proposed model [1] involves faults caused by kinematic pressure of the descending meteorite behind the shock wave. These faults act as listric faults during the modification stage due to the cohesionless fault breccia. Readjustments are only partly realized in structure with central basin due to the large size of the structure or the momentum or the inclination angle of the impact.

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Shock metamorphism and melting of the Jänisjärvi astrobleme target rocks (Karelia, Russia) - comparison of natural and experimental data

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With a view to research of regularities of Jänisjärvi (Karelia, Russia) astrobleme impactites formation two explosive experiments on loading by converging spherical shock-isentropic waves of muscovite-biotite-quartz slates containing garnet and amphibole porphyroblastes and predominating among the target rocks of this astrobleme were conducted. The experiments were performed by the method and technique described in [1]. In the experiments the samples of the rock had the form of a spheres with there initial diameter equal to 48.49 and 39.98 mm. The spheres were welded up in vacuum into the hermetic jackets of astenite steel and were subjected to the spherical explosive compression at the detonation of the layer of high explosive composition. The second sample has undergone a more intensive loading. Five ellipse zones prolongated along the initial rock foliated structure were observed in the first sample after its shock-isentropic loading. On a long axis of an ellipse these zones range in width from edge to centre: I – 14 mm; II - 3 mm; III - 6 mm; IV - 2 mm; V - cavity 1 × 1.5 mm.

I zone (σ_{xx} = 20 - 30 GPa, postshock temperatures, T_{ps} – 300 - 700°C) is an area of fracturing.

II zone (σ_{xx} = 30 - 37 GPa, T_{ps} = 700 - 1000°C) is characterized by decomposition of dark-colored minerals with the formation glass and olivine, in some places ilmenite appears. The newly formed phases are of micron sizes. The feature of olivine composition is impurity of Al_2O_3, (up to 8.5%). It has been revealed, that the process of dark-colored minerals decomposition is allochemical.

III zone (σ_{xx} = 40 - 80 GPa, T_{ps} = 1200°C and higher) is the zone almost full melting of all rock minerals, however a melt homogenization does not take place. In the separate sections of this zone crystallization of melts is noted with the formation of the dendritic spots of olivines, orthopyroxenes, spinellides and petals of biotites. Orthopyroxene contains up to 17% Al_2O_3, that testifies to its crystallization at 1100 - 1300°C.

IV zone (σ_{xx} = 80 - 180 GPa, T_{ps} >20,000°C) corresponds to the complete melting, but the full homogenization of melts formed on different grains of initial rock, is observed only at the boundary with an inner cavity.

Zones being analogous to those described for the first sample have been also registered in the second sample undergone the more intensive loading. However, their boundaries are located at higher radii, and the volume of the completely homogenized melt was essentially increased. The results of the experiment agree well with data obtained earlier when investigating impactites of the Jänisjärvi astrobleme [2]. The main difference of results of experimental results from the impact rock transformations in natural conditions consists in the appearance of olivine instead of pyroxene at crystallization impact melts and decomposition of dark-coloured minerals.

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Studies on the applicability of remote sensing data on geomorphological questions concerning impact structures; demonstrated by the Roter Kamm impact crater (Namibia)

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The Roter Kamm crater is located in the restricted diamond area of the southern Namib desert (Namibia). The centre of the crater lies at 27°46'S and 16°18'E. The rim to rim diameter of this simple, bowl-shaped structure is about 2.5 km. An impact origin for the crater was proposed and later confirmed on the basis of morphologic, geophysical, petrologic and geochemical evidence [1]. The Roter Kamm crater was formed approximately 3.7 Ma before present [2] in Precambrian granitic rock, and is partly covered by active windblown sand [3]. After magnetic analyses as well as gravimetric investigations [4], a GPR study has been done as an attempt to solve the degradation history of the crater.

Satellite data being used at this moment are images of the European remote sensing satellite ERS-1, which was launched in July 1991 in Kourou (French Guyana). The technical equipment of the ERS-1 consists of an Active Microwave Instrument (AMI), which operates in the C-band of the electromagnetic spectrum as a synthetic aperture radar (SAR). Furthermore, a radar altimeter as well as a microwave and an infrared radiometer are integrated. The radar remote sensing data hold the advantage of penetrating sand mantles and allowing the detection of otherwise concealed ejecta blankets and drainage patterns.

On the one hand, satellite data as well as aerial photographs are applied to get information about the geomorphology, geology and the soil of impact craters, in particular about degradation processes, the retrograde erosion of the crater rim and the limits of the ejecta blankets. On the other hand, geological and topographical maps as well as specific literature are used to verify the results of the remote sensing analyses.

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Structure of apographitic impact diamonds from Lappajärvi crater

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Studying the structure of impact diamonds, it should be to distinguish external morphology, which determines the appearance of impact diamonds, and internal morphology, which concern of thin structure of these composite polycrystalline objects. The external morphology describes the shape of overgrowths, twins, paracrystals, simple forms, macrorelief, (printrelief, induction, steps of growth, lamellae, bands), that is, macrostructure of impact diamonds. The internal morphology takes into account the size, form, structure, and texture of crystallites, that is, microstructure of impact diamonds. Besides, it should be to allocate nanometrical level of study, which allows considering subcrystalline structure of impact diamonds.

Impact diamonds found recently in suevites of Lappajärvi crater are products of solid-phase transition of graphite to diamond. Their description was given before [1]. In this paper, the results of study of micro-level structure of both crystallites and subcrystallites of impact diamonds are considered in detail. The display of oxidation is especially characteristic for allothigenic type of impact diamonds from suevites of the Lappajärvi. The morphology of papuls etching on the basal surface is well visible under electronic microscope [2]. Hexagonal outlines of intensely flatted plates repeat in general the contours of paracrystals, their sizes on the average make 1,54 - 0,26 microns. In consequence of strong corrosion, the basal surface of such crystallites exposes a finer relief. Revealed hexagonal plates (subcrystallites) are very lengthened and have orientation like crystallites. Their sizes on the average make 0,18 - 0,02 microns. The surface of subcrystallites is complicated by thin unidirectional shading conterminous usually to their lengthening. Nanolevel structure of impact diamonds is not considered in this paper because of it is partly described earlier [2] and requires separate consideration and specification.

As a result of research, multi-level character of the structure of impact diamonds is revealed. Forms of crystallites and subcrystallites coincide with contours of paracrystals of impact diamonds. So, the symmetry of similarity on both macro- and micro-levels is observed. It shows inherited character of martensite transition of graphite to diamond.

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Drilling in the Popigai crater: Status of the drill core and further exploration goals

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The Popigai impact crater (100 km in diameter), situated in the Taymyr Region, North Siberia, Russia [1, 2] is one of the best available objects for multiple explorations concerning to impact cratering. Besides of both, good preservation from erosion and vast expansion and diversity of different impact-derived and shocked rocks, the favourable conditions for it are provided by wide drilling program combined with geological and geophysical investigations carried out by the Polar Geological Prospecting Enterprise (PGPE) and Karpinsky Geological Research Institute (VSEGEI) on the crater area in 70-80's. With the purpose of both, establishing of inner structure of the crater, and complete consequences of impact melt rocks in different parts of the crater, and the prospecting, more than 700 boreholes were drilled (the total length of core obtained exceeds 130,000 meters) including near 200 boreholes stopped at 200 m and more, and 45 boreholes stopped at 400-1520 m.

The core obtained was described in detail and sampled for diverse petrographic-mineralogical, geochemical, petrophysical investigations and for the estimation of economic potential of impact rocks. In particular, based on drilling data, veritable 3D models of both the inner constitution of different structural elements of the crater (*i.e.,* the peak ring, the annular trough, the outer rim) and separate bodies of impact melt rocks were constructed [3].

At present, the core is situated in two temporary storages in the interior of the Popigai crater. Despite of some unfavourable influences, about 70% of core samples are still in good state. Inferred from unique character of core collection from the Popigai crater, the Committee of Natural Resources of the Taymyr District together with the PGPE and the VSEGEI initiate the efforts being aimed at preserving of both the core and data of its former documentation for further investigations. These works include: redocumentation of core at the storage points; transportation of core of 15 principal boreholes (including the core of all the 6 boreholes stopped at 800-1520 m) from Popigai to Khatanga or Norilsk; creation of presentable collection of shocked and impact rocks; formation of database on drilling data; generalization of geological and other data from the Popigai crater. As a result of these works, the core will be available to a considerable extent for study by investigators concerned. In the first place, the geochemical and isotopic studies as well as precise structural examinations of shocked and melted rocks could be of importance.

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The Zapadnaya impact crater: Shock metamorphism of rocks and minerals

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The Zapadnaya impact structure is a complex crater, about 3 km in diameter, located in the western part of the Ukrainian shield. The crater was formed in garnet-biotite granites and biotite gneisses. Presence of graphite in target rocks of the crater caused appearance of impact diamonds in suevites and impact melt rocks.

All impact rock types of the Zapadnaya crater contain shock-metamorphic effects. Degree of shock metamorphism of minerals rises from authigenic breccias of the crater basement to allogenic breccias and further to suevites. In the same time alteration processes in suevites sometimes destroyed some shock metamorphic effects of the highly shocked minerals [1].

Quartz from breccias and suevites contains abundant PDF's up to ten sets per grain. The sets parallel to $\{10\bar{1}3\}$, $\{10\bar{1}4\}$ and$\{0001\}$ predominate in quartz from autochthonous breccias, while sets parallel to $\{10\bar{1}3\}$ and $\{10\bar{1}2\}$ are the most abundant in shocked quartz from allogenic breccias and suevites. Refractive indices of quartz are dropped down to 1.511-1.520 and birefringence to 0.006 in some grains form allogenous breccias. In the same time diaplectic quartz glass and leshatelierite never occur in impact rocks of the Zapadnaya crater due to the processes of autohydrothermal alteration. Coesite was determined in shocked quartz. Feldspars contain PDF's, their refractive indices are reduced in some grains. Full and partial transition into diaplectic glass occurs in highly shocked plagioclase from suevites. Kink bands and PDF's occur in shocked biotite [1, 2].

Impact diamonds occur in suevites and impact melt rocks of the Zapadnaya crater. Impact diamonds are high-pressure paramorphs of initial graphite crystals from crystalline target rocks [3]. Tabular shape and size of diamond grains are similar to these properties of initial graphite crystals but are reduced in volume to about 37%.

Impact diamond is complex cryptoaggregate intergrowth of lonsdaleite and cubic diamond phases. Cryptocrystalline lamellar structure of impact diamond is visible on the TEM images of grain surface that corresponds to $\{0001\}$ surface of initial graphite crystals. Parallel oriented lamellae, about 0.5 μm in diameter and 0.05 μm thick, are high-pressure carbon phases, predominantly lonsdaleite [2].

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The mineral resources related to the Kärdla impact structure (Hiiumaa Island, Estonia)

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The 4-km-wide Kärdla impact crater (located on Hiiumaa Island, Estonia, and centered at 58°59'N and 21°47'E) formed 455 Ma ago (Upper Ordovician, Caradoc period) in a shallow (no more than 50 m) epicontinental sea. A small (12–15 km in diameter) atoll-like island, the oldest Proto-Hiiumaa, formed after the impact into the shallow sea. Numerous mineral resources and their appearances are found concerning the Kärdla impact crater and its post-impact sediments:

1. Section of notably pure organodetritial (cystoid) limestones of the Vasalemma Formation is formed around the northeastern part of the crater rim. These limestones are pure by it chemical characteristics, and correspond to demands of chemical and metallurgical industry.

2. On the highest part of the rimwall (outskirts of village Paluküla), on an area of few square kilometers, more than 10 m thick layer of the pure micritic (aphanic) limestones of the Rägavere and Saunja formations crops out under the thin (~1m) layer of soil. These limestones are not chemically so pure as limestones of the Vasalemma Formation, but their properties are more sustained and mining conditions are better.

3. Polymetallic (galenite, sphalerite) mineralization observed on the outer slopes of the rimwall is economically perspective. The mineralization occurs at the contact of the disturbed (brecciated) Cambrian terrigeneous target rocks (mainly sandstones) and strongly dolomitized Ordovician limestones of the covering complex. In the latter, content of lead and zinc in up to 4 – 5 m thick lode may rise to 10%. The spatial extent of the lodes is unknown. Thereby up to three phases of the hydrothermal mineralization can be observed.

4. In the crater proper, in the layer of slumped breccias (at the depth 300 m and deeper) mineral water is discovered. The content of sodium-calcium chloridic mineral matter in this water is 14 - 16 grams per litre, but it also contains bioactive elements as iodine and bromine. The resources of the mineral water (~120,000 m^3), which are practically non-recurrent, have been took into account. This mineral water with a trademark "Kärdla" has been bottled from well K-18 drilled in the central part of the crater proper.

5. The Ordovician artesian groundwater basin around and inside the crater is connected directly with the structures of the buried impact crater. The high-quality (content of a mineral matter ~0.2 grams per litre) artesian groundwater is distributed in areas where the bedrocks are covered with a thick layer (5-10 m) of the Quaternary glacilacustrial varved clays. On the outflow area, there are many wellsprings of a natural and artificial origin.

6. Thick layer (up to 12m) of the Quaternary glacilacustrial clays above the crater proper is connected with the buried crater proper in a certain way. These clays are taken into account as the potential mineral resources for ceramic industry.

7. On the southeaster slope of the buried structure, there are noticeable resources of gravel deposits formed in the Quaternary time by Litorina transgression. This gravel pit supplies almost all needs of Hiiumaa Island.

8. Extensive appearances of natural bitumens (oil, asphalt, asphaltite) are found above the rimwall and outer slopes of the Kärdla structure. However, these natural bitumens have migrational origin, whereas the structure acted as a trap. The thin (< 50m) collector and absence of the screen did not make it possible to form considerable beds of oil.

The Neugrund impact structure (Gulf of Finland, Estonia) on the geological and geophysical maps

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In 1996–1999 the Geological Survey of Estonia carried out marine geological mapping of the Neugrund impact structure and its surroundings on the area of 625 km^2 on the southern side to the entrance of the Gulf of Finland. The boundary of the Gulf of Finland lies between Osmussaar Island (Estonia) and Hanko Cape (Finland). On the basis of the above-said mapping results and information collected earlier, four geological and geophysical maps (bedrock, Quaternary deposits, bottom sediments, and aeromagnetometrical) at a scale of 1:50 000, and joint explanatory note, were compiled. Influence of the ancient (Early Cambrian) impact can be identified on all the cited maps.

The Neugrund Bank is situated on the southern side of the entrance of the Gulf of Finland (59°20'N; 23°33'E) some miles eastward of Osmussaar Island. It is a shoal of a very peculiar multiring shape. In the coastal and offshore area of western and northwestern Estonia as well as on Osmussaar, Vormsi, Muhu islands and the eastern part of the Saaremaa Island numerous erratic boulders consisting of rocks resembling impact breccias have been found. The investigations initiated in 1995 proved that under Neugrund Bank a buried and partially newly exposed well-preserved meteorite crater is located. The geophysical studies have revealed general morphology of the structure. In summer 1998, the submarine impact structure was investigated in detail by diving and sidescan sonar profiling. As a result, the impact hypothesis indirectly proved by remote sensing was finally verified.

The Neugrund impact crater was formed ~540 Ma ago in shallow epicontinental sea because of the impact of an extraterrestrial body ~400 m in diameter. Because of the impact, a crater with the rim-to-rim diameter of 7 km was formed. The depth of the crater proper (~5.5 km in diameter) has not been determined yet, but it is supposed to range over 500 m. At the distance of about 10 km around the structure, the target rocks are strongly disturbed. After the impact the crater deep was filled with clastic deposits and buried in a rather short time (during few millions of years). The sedimentation conditions in the crater deep differed from those of the surrounding area until the Middle Ordovician. Since then up to the Tertiary, the crater remained buried, and was partially uncovered in the Neogene. The epicentre of the Osmussaar earthquake (25 October 1976), historically the most powerful earthquake of the discussed region (magnitude 4.7 and intensity up to 7, depth of the focus ~10 km) was located within the limits of the Neugrund structure. To date the possible connection between this earthquake and the Neugrund impact structure has not been identified.

In the impact-influenced rocks (impact breccias) of the Neugrund crater the shock metamorphism evidence have been observed, such as mosaicism of quartz and feldspar, planar fractures and planar deformation features in quartz, kink bands in biotite, *etc.* The meteorite origin of the Neugrund structure can be considered verified. In the impact-influenced Precambrian basement rocks of the Neugrund structure potassium phenomena (enrichment of rocks with potassium and decrease in sodium content) similar to analogous rocks of the Kärdla and some other impact craters have been recorded.

Impact-hydrothermal origin of the Witwatersrand ores: The possible sources of fluid and gold

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1. Origin of the Witwatersrand ores is still a matter of debates, and a number of genetic conceptions was proposed for this unique deposit; "modified placer hypothesis" and "hydrothermal hypothesis" are the most known among them. Little by little, an important role of the Vredefort impact event in origin of the ores becomes evident in past decade, but both the hypotheses are still present and are divided by irreconcilable contradictions. Recently proposed impact-hydrothermal hypothesis [1] allows explaining the main arguments of both the competing opinions and considers that origin of the Witwatersrand ores was entirely related to the Vredefort impact event. This hypothesis opens a new perspective in forecasting and search for the deposits of so kind. Features of target rocks, evidences of hydrothermal origin of the ores, their localization in the Vredefort astrobleme, and impact-related classic pre-conditions for large-scale hydrothermal process (adiabatic decompression; spasmodic increase of fluid temperature and pressure; total development of high permeability) are among the main arguments of our hypothesis. Fluid and gold sources for the deposit were discussed recently [2]. Joining to the discussion, we present below our vision of the problem.

2. There are a lot of conceptions regarding to the sources of ore-forming fluids in the Witwatersrand Basin: regional metamorphic, igneous, meteoric, fluvial sources, and so on. Ignoring of the porosity of the rocks, and of the scale of the process is a common feature of all these speculations. Meanwhile, the porosity of up to several vol. % (and a corresponding number of liquid water with temperature of ~200 to 400°C and density of ~0.9 – 1.0 g/cm^3, following to its phase diagram) was a constant feature of the rocks regardless the stages of geologic history. Due to porosity, no one of igneous events was able to provide a complete expelling of the fluids. Moreover, every new impulse of geologic activity led to changes in porosity and to quantitative/qualitative changes in the entrapped fluid systems. So, there is no contradiction between various source models named above. From place to place of the Basin, there were a number of various sources for the entrapped fluids, and all of them might be able to take part in gold mobilization after the impact. The Vredefort impact event served as a trigger for hydrothermal activity of this multi-source fluid. In addition, the fluid (proton) flow from mantle was also possible, being a specific response of deep-seated interior to the impact.

3. The source of gold on the deposit is still debatable: the ores are considered either result of re-mobilization from ancient placers or the gold was introduced into the Basin by post-sedimentary hydrothermal fluids. "Placer" source is not supported by rare findings of clearly detrital gold particles. "Introducing" source requires too much long distance of transportation. Following to impact-hydrothermal hypothesis, gold might be extracted from the ordinary rocks of the Basin. This conclusion is based upon the theoretical speculations, general data on the gold geochemistry, and on the minimal initial estimations (an average gold content in the rocks was accepted to be ~5 t/km^3 and a rate of gold extraction: ~0.5 t/km^3). The source area of the Basin was limited by a ring zone of the present goldfields (70 km < R < 120 km). Average thickness of the producing strata was accepted to be ~10 km. Our estimations show, that the Vredefort impact event was able to provide a fluid mobilization and re-deposition of ~150,000 t of gold by means of hydrothermal solutions with low near-Clarke content of the noble metal (~10 mg/t).

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The Popigai impact event: Numerical simulation of initial stages of the cratering

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1. The 100-km well-exposed and well-preserved Popigai impact crater of ~35 Ma age in Arctic Siberia (Russia) is one of the most unique impact sites of the World. Its target is made up of a crystalline basement (Archean gneisses with density ~2.9 g/cm^3) and a sedimentary cover of up to 1.5 km in thickness (various Proterozoic to Mesozoic rocks, including loose sediments with density ~1.5 to 2.0 g/cm^3). With a total energy of impact ~6.24×10^{22} J, this crater is considered to be one of the possible causes responsible for Terminal Eocene mass extinction. Numerical simulation of the early stages of the Popigai impact event may have a definite interest in discussing its imprint in global-scale processes and its importance as a possible cause of the extinction.

2. Laboratory model of the process was based upon a number of physical parameters, which are important for the cratering after [1], and which were applied to the Popigai impact event. With the help of similarity criteria following to π-theorem by [2] these parameters were re-calculated for the laboratory-scale process. Vertical impact was modeled. The numerical simulation of the process was carried out by means of "Stereo-PC" program elaborated by Dr. B.P. Krukov, using 2-dimentional approach. Equations for non-viscous compressible liquid, "method of individual particles" by [3], and Tillotson Equations of State for the projectile (modeling by gabbroid anorthosite) and for the target (modeling of the sedimentary cover + basement by halite + granite, correspondingly) were also used.

3. The results of the simulation show that:

1) there was a clear axial cumulative effect of the ejection due to intensive vaporization of projectile, with a maximal axial ejection velocity ~14.6 km/s at 3.8 s after impact;
2) at 3.8 s after impact, vaporized and ejected projectile matter had densities in range from 0.0009 to 0.39 g/cm^3; at this moment, mass vs. ejection velocity distribution for the projectile was the next (% of projectile mass/ejection velocity): ~1.2 % (2.4×10^9 t)/>11.2 km/s; ~8.3 % (1.7×10^{10} t)/2 – 11.1 km/s; ~27.7 % (5.6×10^{10} t)/0.7 – 2 km/s;
3) at 3.8 s after impact, ~1.5×10^{12} t of vaporized target matter, with densities in range from 0.033 to 1.2 g/cm^3, was ejected with the velocities ranging from 2 to 5.4 km/s.

These data may be used in various estimations concerning to impact hypothesis of the Terminal Eocene mass extinction (response of the atmosphere to the ejecta plume, a rate of global dissemination of impact material, its imprint in the global sedimentary record, and so on).

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Impact glasses and tektites of ZH-facies: Some features of the rocks and models of their origin

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1. Fine-banded quenched impact glasses are known in the Popigai, Zhamanshin and El'gygytgyn impact craters. Vietnam Muong Nong-type tektites have a similar structure. Based upon results of a complex investigation, new data are presented below for the samples from the impact craters; data for the tektites, previously reported by other authors, are also confirmed.

2. Banded structures of the rocks are either related to their irregular re-crystallization (Popigai, El'gygytgyn) or irregular coloration (Zhamanshin, Muong Nong-type tektites). Glass bands of the samples are either similar to each other in terms of the bulk geochemistry or have insignificant distinctions between, small enough to explain an origin of the banded structures. Banding of Popigai glasses correlates with water content: pure glass bands (0.226 – 0.897 wt. % of H_2O) are of 2.1 to 4.33 times poor in water than re-crystallized ones are (0.525 – 2.246 wt. % of H_2O). Zhamanshin glasses are much poor in water (0.001 – 0.059 wt. %), and water distribution is random. The tektites are very poor in water (0.0008 – 0.016 wt. %). Elgygytgyn glasses were not studied. Following to ESR data, a part of Fe^{+3} ions in the Popigai and Zhamanshin glasses is present as isolated atoms (g = 4.3), but a dominating portion of Fe^{+3} is related to mineral phase (g = 2.0). At this, a number of the Fe^{+3} ion of mineral phase is higher in the Popigai re-crystallized glasses (2 – 10 times) and in the Zhamansin intensively colored glasses (2 – 66 times). Mossbauer data show the next bulk features (Fe^{+2}I/Fe^{+2}II/Fe^{+2}III/Fe^{+3}, in wt. %,): 43.1 – 54.4/13.8 – 38.3/9.6 – 38.9/4 – 4.3 (Popigai); 40.3 – 45.5/23.1 – 27.2/24.7 – 30.4/2.1 – 6.2 (Zhamanshin); 45.1 – 49.6/12.1 – 30.0/17.6 – 36.3/2.0 – 7.3 (Vietnam tektites).

3. Origin of the Popigai banded glasses is attributed to water, which had provided a selective re-crystallization. Two models of such a process are possible, including intensive mixing and quenching of the impact melt during flight: A) irregular distribution of water was inherited from the target rocks; B) irregular capture of water had taken place during flight of the melt in the explosion cloud. Origin of the Zhamanshin banded glasses is attributed to irregular distribution of Fe^{+3} ion of the mineral phase; supposedly, iron was oxidized by atmospheric oxygen during flight and mixing of the melt. Origin of the banded tektites might follow to a similar model (ejection –irregular oxidation by atmospheric oxygen – mixing – quenching – flight – landing). Origin of the El'gygytgyn banded glasses is still an open question.

4. Archean target rocks were a source of the Popigai banded glasses. A source of the Zhamanshin banded glasses is still unknown (supposedly, sedimentary cover and weathering crust of the target, of ~200 to ~20 Ma-age). A close similarity between the Zhamanshin banded glasses and the Vietnam Muong Nong-type tektites seems to be not a casual fact. Therefore, a known source of the Zhamanshin glasses may help in solving the origin of the tektites. Due to its size (13 km in diameter) and target features, the Zhamansin crater may be a source of the tektites

5. The banded glasses described may be considered as rocks of the special "Zhamanshinite facies", or "ZH-facies" (after the Zhamanshin crater, where they are broadly widespread). Bands of ZH-glasses have similar bulk geochemistry, but are very heterogeneous in water content or in a state of iron oxidation. ZH-glasses are quenched products of high-speed ejecta of impact melt deposited uppermost of suevites in impact craters or globally disseminated in form of the tektites. As the supposed "water" or "oxygen" models of origin for ZH-glasses should be very common, one can expect their broad presence in various impact structures and within various tektites' strewn fields. This conclusion is supported by the Muong Nong-type tektite occurrences known in North America, Europe and in oceanic sediments (DSDP Site 612).

Experimental data on impact-vapor differentiation

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The impact experiments (5.0-6.5 km/s) which we carried out using the two-stage hypervelocity launch facility (the experimental technique is described in [1]) showed that the impact vaporization (IMPVAP) is selective that is the impact melt and vapor have different compositions. Some typical data of the impact vapor (≡condensate) and initial rock compositions are presented in Table 1.

Table 1.

	Ultramafic target		Mafic target		Acid target	
wt.%	*harzburgite*	*condensate*	*basalt*	*condensate*	*granite*	*Condensate*
SiO_2	45.2	52.6	51.8	61.7	70.2	50.8
Al_2O_3	1.7	2.7	15.4	16.7	16.0	19.2
FeO	7.8	9.6	9.9	1.7	2.3	1.1
MgO	43.6	25.1	8.2	3.7	-	-
CaO	1.5	4.3	11.7	8.2	1.1	3.5
Na_2O	0.1	3.8(?)	2.8	7.0	3.8	22.7
K_2O	0.1	1.9(?)	0.2	1.0	6.6	2.7

At least 5 conclusions follows from the experiments: 1) The IMPVAP of ultramafic rocks tends to more SiO_2 and less MgO contents in the vapor. A comparison between target rocks and vapors shows that the SiO_2 /MgO ratio is as a rule higher a 1.5-2 times in vapor phase; 2) The IMPVAP of a basalt gives rise the more silica- and alkalies-rich vapors. The total apobasaltic vapor compositions are formally similar to granodiorite ones; 3) The IMPVAP of acid rocs tends to silica decrease in the vapor. The total apogranitic vapor compositions are formally similar to nepheline-syenite ones; 4) It was detected the systematic increase of a number low volatile lithophile elements (U, Th, Hf, REE) in the vapor phase; 5) It was measured and estimated that at the impact velocity ~6 km/s the total mass of silicate vapor reached amounts comparable to ~10% of the projectile mass.

The behaviour of the elements during IMPVAP does not obey the classic row of volatility. This is result of specific cluster mechanism of IMPVAP under conditions of impulse high temperature heating. Molecular cluster can join together elements with different individual volatility that is responsible for joint vaporization, transport and condensation. The main detected clusters had enstatite (Mg:Si=1:1) [2] and nepheline (Na:Al:Si=1:1:1) [3] types.

If we take into account that all the planet mass is just a sum of former projectiles, the portion of the planet material which was involved in IMPVAP and possible differentiation is ≥10%. Hence, the obtained data permit to suggest that the impact proto-Earth accretion was accompanied by profound changes of the planetary substance as a result of IMPVAP and later vapor condensation. Through all accretionary time the main petrochemical tendency of the surface rocks was increase of silica contents due to cyclic impact vaporization-condensation process and increasingly more admixture of condensate materials into surface regolith. It is not difficult to imagine that the impact differentiation could lead (or promote) to the formation of primary basalt crust and even zones with primitive granitic-like rocks.

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