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IMPACT CRATERING RECORD OF FENNOSCANDIA.

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A compilation (Fig. 1) of circular topographic, morphological, or geophysical structures in Fennoscandia and adjacent areas reveals 62 craterform structures of which 15 (class A or a) appear to be of extraterrestrial origin due to meteorite impact. The majority of the structures are probable (class B, 9) and possible (class C, 34) impact craters for which there is not yet sufficient proof for impact origin.

Four of the proven impact craters (Lappäjarvi, No. 31, ~77 Ma old; Dellen, No. 5, ~90 Ma old; Mien, No. 20, ~120 Ma old; and Jänisjärvi, No. 36, ~700 Ma old) contain large volumes of impact melt and many other features of intense shock metamorphism. The age of the recognized impact craters vary from prehistoric (3500 B.C., No. 38, Kaali) to late Precambrian (~1210 Ma, No. 11, Björkö). The histogram of the ages (although the number of proven impact craters is still very small) shows two possible peaks (Fig. 1, inset): one group consisting of impact craters less than 150 Ma old and the second one with ages between 350 and 600 Ma. There is so far a deficiency of impact craters in Fennoscandia with ages between 200 and 350 Ma. The majority of the proven impact craters have rim diameters between 5 and 20 km; the largest meteorite impact crater in Fennoscandia, the Siljan (No. 6, age ~360 Ma), has a diameter of 55 km. The impact cratering rate for Fennoscandia in the region where craters occur is 2.4×10^{-14} km^{-2} a^{-1} and includes 12 proven impact craters with diameters from 3 to 55 km. This amounts to 2 events per every 100 Ma during the last 700 Ma.

There is increasing evidence that some (3, class E) of the large circular geological, morphological, or geophysical features [the Uppland (No. 45), the Nunjes (No. 46), and the Marras (No. 55) structures, Fig. 1] represent deeply eroded scars of Early Proterozoic impact craters, but impact-generated rocks or fall-out ejecta layers have not yet been identified with these structures.

No craterform structures of Archean age have so far been discovered in Fennoscandia although, statistically, remnants of Archean cratering events should be found in the Fennoscandian Shield. New ways of searching for these craters are proposed and discussed. In addition to changes in the petrophysical properties of rocks, such as density, magnetization, and electrical conductivity, redistribution of large volumes of rocks are associated with large impacts. Such changes in structures and rock properties may be identified by integrated interpretations of regional high-resolution geophysical data.

The Siljan impact case shows, however, that the impact overprinting can be very slight in comparison to geophysical anomalies caused by preimpact lithological and structural variations.

We review the Fennoscandian impact cratering record giving examples of geophysical signatures of impact craters.

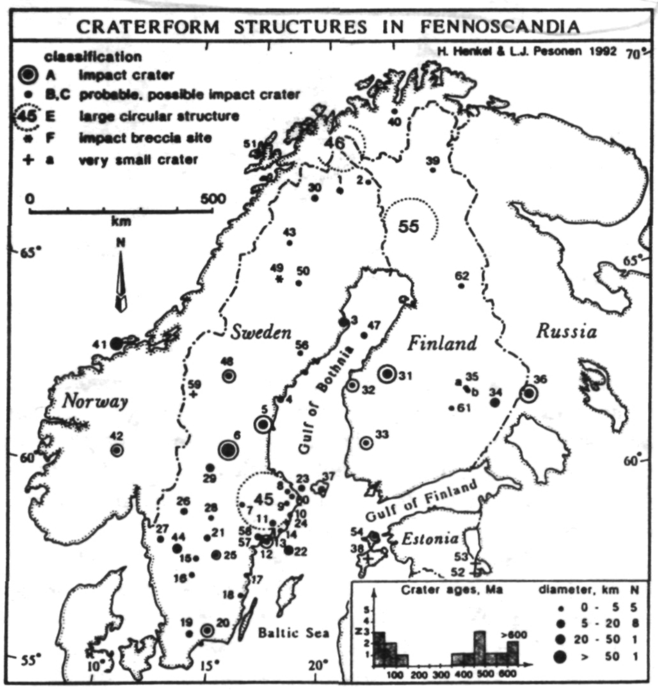

Fig. 1. Impact craters and other craterform structures in Fennoscandia and adjacent areas. Encircled structures refer to proven impact craters (class A); the others refer to class B (probable) and class C (possible) impact craters respectively. The very large circular patterns refer to class E structures for which impact origin is not yet proven. The class F sites represent locations of breccia occurrences without known crater structure. The very small Quaternary craters (class a) are denoted with a plus sign. (Inset) Ages and diameters of the proven (classes A and a) impact craters.

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BOHEMIAN CIRCULAR STRUCTURE, CZECHOSLOVAKIA: SEARCH FOR THE IMPACT EVIDENCE.

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Test of the impact hypothesis [1] for the origin of the circular, 260-km-diameter structure of the Bohemian Massif (Fig. 1) led to the discovery of glasses and breccias in the Upper Proterozoic sequence that can be compared to autogeneous breccias [2] of larger craters. The black recrystallized glass contains small exsolution

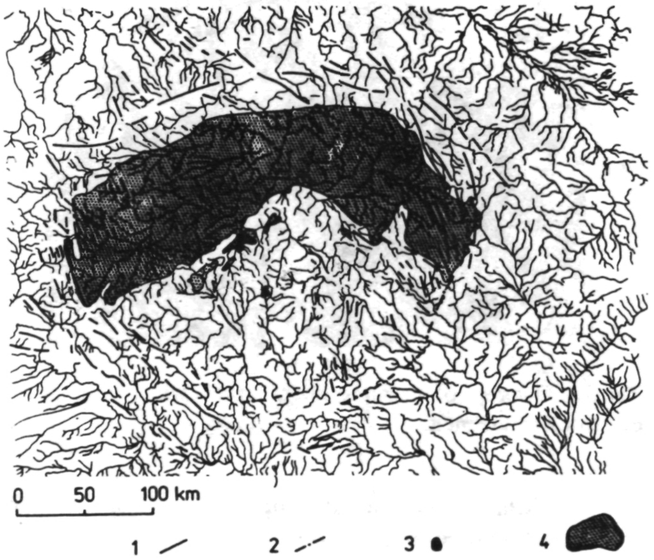

Fig. 1. Circular structure of the Bohemian Massif; 1—topographical features, 2—important faults with geological contacts of units differing in mobility in Variscan orogenesis, 3—outcrops of autogeneous breccias, 4—extent of the Upper Proterozoic series.

TABLE 1. Chemical composition of fragments and melt veins.

%	H_2O^+	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5
Melt	1.11	59.53	21.52	8.64	1.15	0.62	1.98	0.95	4.07	0.053	0.13
CR	1.45	57.76	23.60	8.41	1.19	0.21	1.86	0.61	4.47	0.050	0.12
Melt	1.06	60.61	21.42	8.32	1.09	0.50	1.91	0.71	3.91	0.058	0.14
Melt	0.99	60.92	21.34	8.37	1.08	0.46	1.89	0.62	3.89	0.053	0.14
C*R	1.36	60.73	18.84	8.34	0.84	1.20	3.04	2.54	2.40	0.310	0.11
ppm	Ba	Co	Cr	Nb	Ni	Rb	Sr	Y	Zn	Zr	
Melt	958	26	126	24	40	145	173	34	102	209	
CR	938	26	153	26	51	132	153	36	99	190	
Melt	877	25	117	22	43	150	150	33	92	194	
Melt	874	24	163	21	56	148	146	34	94	193	
C*R	392	29	146	13	54	90	95	29	96	126	

C*R—country rock from place more distant than other samples.

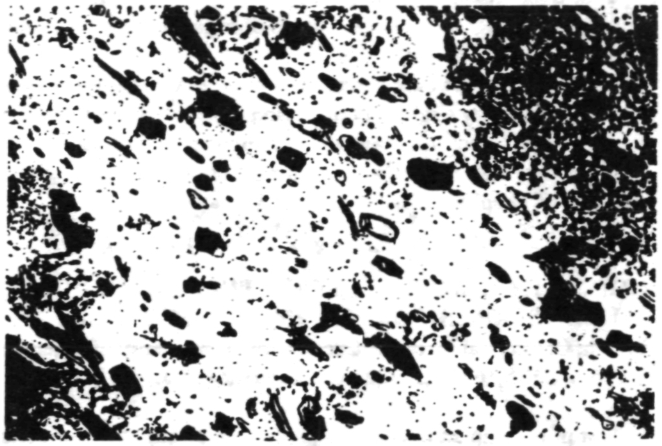

Fig. 2. Microphotograph of the recrystallized quartz glass with exsolutions of feldspar and biotite, × 100.

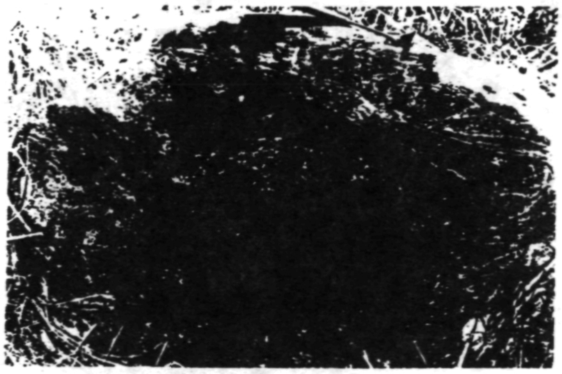

Fig. 3. Outcrops of the autogeneous breccia with rock fragments cemented by the melt.

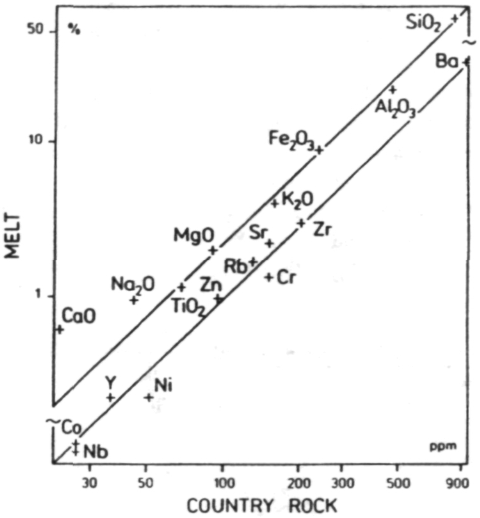

Fig. 4. Correlation graph of the chemical composition of country rock and melt.

crystals of albite-oligoclase and biotite, regularly dispersed in the matrix recrystallized to quartz (Fig. 2). The occurrence of these rocks is limited to a 1-km² area. It is directly underlain by the breccia (Fig. 3) of the pelitic and silty rocks cemented by the melted matrix, found on several tens of square kilometers. The melt has the same chemistry as rock fragments (Table 1, Fig. 4) in major and in trace elements. It is slightly impoverished in water. The proportion of melted rocks to fragments varies from 1:5 to 10:1 (Fig. 2). The mineralogy of melt veins is the function of later, mostly contact metamorphism. On the contact of granitic plutons it abounds on sillimanite, cordierite, and small bullets of ilmenite. Immediately on the contact with syenodiorites it contains garnets. The metamorphism of the impact rock melt seems the most probable explanation of the mineralogy and the dry total fusion of rocks accompanied by the strong fragmentation. The next rocks in the top of the sequence are larger bodies of tchermakitic metamelagabbros and conglomerates with the volcanic matrix. Crystalline rock fragments are frequently found here. Structurally they resemble orthogneisses and granites, but with a glassy appearance especially of feldspars. The very-fine-grained texture of rocks is explained tentatively as recrystallized shocked rocks. Some parts of the conglomerates can be suevites as well. The breccia formation and conglomerates are intercalated between the Moldanubian gneisses that transgrade the circular structure and between the Upper Proterozoic sequence, which on the map is crescent shaped, contouring the northern half of the circular structure (Fig. 1). The lower part of the Upper

Proterozoic sequence begins with pillow lavas and is terminated by the sedimentary sequence with shallow water fossils (from <10 m depth; Vavrdová, oral communication), indicating the successive filling of the hole. The total thickness of this formation is not known, though geophysical models indicate several kilometers. The restriction of breccias to the base of this formation provides age constraints that would indicate the age of the impact is 1.8–1.2 m.y.

The circular structure is defined by the topography, water courses, and geological contacts in the Tertiary through Upper Proterozoic sequences. It is visible also on the fault geometries in the brittle and in the ductile stages from later orogenies as featured by the half circular Permian and Cretaceous sedimentary basins. The rigid conservation of the circular form is tentatively explained by the later cooling of the upper mantle rocks under the structure after the impact, enabling them to behave rigidly. Several shearing phenomena encountered in crystalline rocks of the Moldanubian can be attributed to the excavation stage.

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THE VREDEFORT DOME—REVIEW OF GEOLOGY AND DEFORMATION PHENOMENA AND STATUS REPORT ON CURRENT KNOWLEDGE AND REMAINING PROBLEMATICS (FIVE YEARS AFTER THE CRYPTOEXPLOSION WORKSHOP).

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The Vredefort Structure located in the center of the Witwatersrand basin in South Africa and the Sudbury structure in Canada are widely considered the two oldest and largest impact structures still evident on Earth. Both structures are very similar in a number of geological aspects (e.g., association with major economic ore deposits, similar ages of ca. 2 Ga, abundant pseudotachylite as well as shatter cone occurrences, overturned collar), as summarized by [1]. However, whereas the geological community generally accepts an impact origin for the Sudbury structure, a number of researchers are still reluctant to accept this for the Vredefort Dome.

Five years ago an international workshop focusing on the Vredefort structure [2] scrutinized the evidence and attempted to resolve the differences between impact supporters and protagonists of internal genetic processes. Clearly, this goal was not achieved, but at least a number of important areas of further research were defined. Research in the Vredefort structure gained new momentum in 1991, partially in anticipation of the Sudbury '92 Conference, and because several mining houses realized how important full understanding of the structure and evolution of the Vredefort Dome is with regard to exploration and mining activities in the surrounding Witwatersrand basin.

Besides the long-established impact and gas explosion hypotheses, several other genetic processes have been discussed in recent years: rapid updoming, thrusting, combinations of several tectonic processes, and an impact event at 2 Ga ago followed by tectonic modification. Reviews of the geology and geophysics of the Vredefort structure were repeatedly presented in recent years (e.g., [3,4] and several papers in [2]). Therefore the aim of this review is to present new data, to highlight the most obvious shortcomings in the current database, and to summarize the major arguments in the genetic controversy.

Since 1987 important new results were provided by Hart et al. [3, and refs. therein] dealing with the geochemistry of the granitic core and aspects of dynamic metamorphism. Reimold [4] evaluated the geochemical database for Vredefort pseudotachylite, and new chronological data were contributed by [5] and [6]. Continued structural work had been demanded by the participants of the 1987 workshop. Colliston and Reimold [7] presented the results of a first detailed structural study in the southern part of the Dome and in areas of the northwestern sector. Minnitt et al. [8] mapped the Archean greenstone terrane in the southeastern quadrant and completed structural analysis of the granite-gneiss exposures in the southern part. Both studies resulted in similar findings, suggesting that deformation in the basement is mainly of Archean age and related to a stress field, in which the principal stresses operated in a near-horizontal plane (cf. Colliston and Reimold, this volume). Later macroscopic deformation is mainly restricted to local subvertical shear zones scattered throughout the granitic core. In the central part of the core deformation is very limited. New ^{40}Ar-^{39}Ar stepheating results [9] for mineral separates from host rocks to two pseudotachylite samples that were dated by [6] at ca. 1.4 Ga further supported the conclusion that these breccias were formed at post-2-Ga times.

Currently several structural projects in the collar are in progress, with preliminary reports indicating that several deformation events since deposition of the Witwatersrand Supergroup (ca. 2.75–3.05 Ga ago) could be recognized. Consequently, one aspect of utmost importance for future research must be to establish a complete chronological framework for the geological evolution in this region. The igneous rocks that intruded core and collar of the Dome at various times since Ventersdorp volcanism (ca. 2.7 Ga ago) are currently being studied as possible candidates for radiometric dating. ^{40}Ar-^{39}Ar stepheating and laser Ar dating of the various generations of pseudotachylite identified in both the structure and the Witwatersrand basin should be continued as well. A detailed metamorphic project, comparing the rocks of different metamorphic grades in the northwest/west (high) and northeast (low) sectors respectively with the metamorphic record for the whole Witwatersrand basin, has just been initiated. It is also still uncertain at what times the major metamorphic events took place and whether the enhanced metamorphism in the northwest/west is the result of contact metamorphism in the vicinity of alkali granitic intrusions or of regional metamorphism. The nature of the pseudotachylite-rich and charnockite-bearing transition zone between Outer Granite gneiss and Inlandsee Leucogranofels is still controversial: Does it represent a pre-Vredefort intracrustal lithological boundary, a thrust plane, or a decollement zone possibly linked to major pre-Vredefort gravity slides in the northern Witwatersrand basin? What is the significance of the charnockite occurrences that to date have not been studied in detail? New quarry exposures in and near this zone are being studied and could reveal the three-dimensional geometry of pseudotachylite breccia zones. Finally, (sub)planar microdeformations in Vredefort quartz have now become the object of TEM investigations.

At this point in time, the main arguments in favor and against an impact origin for the Vredefort structure can be summarized as follows.

Pro Impact: (1) The structure is regarded as being circular and (2) surrounded by ring faults. (3) The dome itself is considered to be the central uplift of a gigantic impact structure with (4) a "crust-on-edge" configuration of the structure, involving both overturned collar and basement. (5) The presence of shatter cones. (6) Pseudotachylite is regarded as an equivalent of impact breccia and (7) the