

Impact melt rocks from the Paasselkä impact structure (SE Finland): Petrography and geochemistry

Martin SCHMIEDER^{1*}, Jarmo MOILANEN², and Elmar BUCHNER¹

¹Institut für Planetologie, Universität Stuttgart, Herdweg 51, D-70174 Stuttgart, Germany

²Vuolijoentie 2086, FIN-91760 Säräisniemi, Finland

*Corresponding author. E-mail: martin.schmieder@geologie.uni-stuttgart.de

(Received 06 March 2007; revision accepted 09 January 2008)

Abstract—Recently, samples of allochthonous melt rocks from the ~10 km and ≤ 1.9 Ga Paasselkä impact structure, SE Finland, were obtained. In this study, we present a first detailed petrographic and geochemical description of clast-rich Paasselkä impact melt rocks. Shock metamorphic features comprise shocked feldspar grains, intensely shocked and toasted quartz, marginally molten and recrystallized clasts thought to have been diaplectic quartz glass, largely fresh and recrystallized feldspar glasses, decomposed biotite flakes, recrystallized fluidal silica glass (originally probably lechatelierite) in partially molten sandstone clasts, all set into a glassy to cryptocrystalline melt matrix. The degree of shock metamorphism of clasts suggests initial whole-rock melting at peak shock pressures of ≥ 35 GPa and post-shock temperatures of up to ~ 1500 °C. Glass components vary in geochemical composition corresponding to the mixed character of the crystalline target rock (i.e., representing different monomineralic and mixed-mineral melts). Feldspar glasses and the fresh glassy to cryptocrystalline melt matrix indicate that the Paasselkä melt rocks are not intensely altered. The geochemical composition of the Paasselkä impact melt rocks is roughly consistent with the compositions of melt rocks from a number of impact structures located within the crystalline basement of the Baltic Shield.

INTRODUCTION, PREVIOUS WORK, AND GEOLOGICAL SETTING

The Paasselkä impact structure, located about 7 km ESE of the village of Savonranta in SE Finland (centered on $62^{\circ}09'N$, $29^{\circ}25'E$) (Fig. 1a), is entirely occupied by the oval-shaped Lake Paasselkä (also called Paasivesi in older literature) (Fig. 1b). Among the 11 impact structures confirmed to date in Finland (Pesonen et al. 2005), Paasselkä, with a diameter of ~ 10 km (Pesonen et al. 1999; Earth Impact Database 2007), is the third largest. The whole structure has been deeply eroded since its formation, especially by Pleistocene glaciation (see Puura and Plado 2005). A negative gravimetric anomaly associated with Lake Paasselkä was first noted and discussed by Elo (1979) and Elo et al. (1984). A possible impact origin of the structure was proposed by Henkel and Pesonen (1992) and Pesonen et al. (1999). Paasselkä was finally confirmed as of impact origin by the detection of shock deformation in brecciated bedrock (Pesonen et al. 1999; Kuivasaari et al. 2000). Impact-related geophysical anomalies (Abels et al. 2002) and probable impactor contamination in the form of Fe-Ni-Co sulfides in impactites from the Paasselkä impact structure were reported

by Öhman et al. (2003) and Badjukov and Raitala (2006). Target rocks at Paasselkä comprise ~ 1.9 Ga (Pesonen et al. 1999) mica schists, together with subordinate mafic intrusions, granitic and pegmatitic dikes, as well as some pre-impact sedimentary rocks of the Karelian Supergroup of the Baltic (Fennoscandian) Shield (see Korsman et al. 1997; Pesonen et al. 1999; Puura and Plado 2005). A general geological overview of the region is given by Nykänen (1975), Lavikainen (1986), and Korsman et al. (1997).

A drilling program carried out by the Geological Survey of Finland in 1999 recovered a ~ 200 m core of brecciated target rock material from the center of the Paasselkä impact structure, overlain by some Quaternary deposits (Pesonen et al. 1999). Öhman et al. (2003) suggested the occurrence of heavily altered impactites (referred to as possible former impact melt breccias) that lack a primary breccia matrix. Accordingly, no impact melt rocks have been reported from the Paasselkä impact structure so far (see also Puura and Plado 2005), and no radiometric dating of the Paasselkä impact structure has been done to date. Thus, only a maximum age for the Paasselkä impact event—the actual age of the Proterozoic ~ 1.9 Ga target rock—is mentioned in literature and terrestrial impact crater listings (e.g., Pesonen et al. 1999).

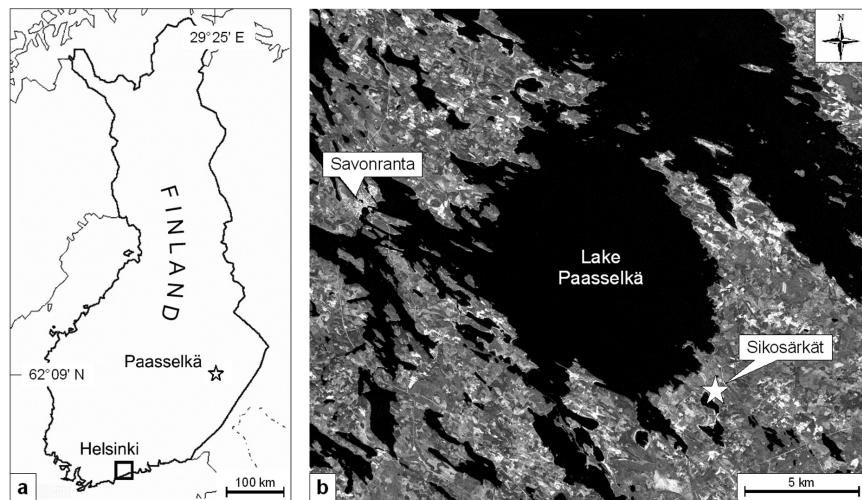


Fig. 1. a) Map of Finland and location of the Paasselkä impact structure. b) Satellite image of Lake Paasselkä (Landsat-7 ETM+ scene of path 187, row 016, acquired on May 16, 2000; panchromatic band 8 merged with visible color bands 3-2-1). Location of the till pit near Sikosärkät is marked by the star symbol.

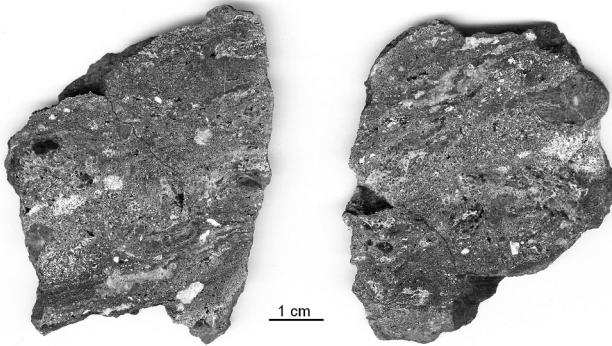


Fig. 2. Polished sections of a Paasselkä impact melt rock sample. A distinct overall flow structure and shocked target rock components are visible in the hand specimen.

Here, we present impact melt rocks from the Paasselkä impact structure collected by one of the authors (J.M.) in a till pit near Sikosärkät ($62^{\circ}06'17''\text{N}$, $29^{\circ}31'05''\text{E}$), about 1 km southeast of the southeastern shore of Lake Paasselkä, and give a detailed petrographic and geochemical description of these two melt rock samples. Northwest to southeast trending glacial striation on the bedrock around Lake Paasselkä (see Fig. 1b) indicates that impactite boulders and pebbles in the till pit are most likely derived from the Paasselkä crater.

SAMPLES AND ANALYTICAL TECHNIQUES

Two samples of allochthonous impact melt rocks from the Sikosärkät till pit (Figs. 1b and 2) were investigated by optical microscopy of polished thin sections. Geochemical analysis was carried out using a CamScan™ SC44 scanning electron microscope (SEM)—EDAX™ PV 9723/10 energy

dispersive X-Ray (EDX) system (Institut für Planetologie, Universität Stuttgart) and a CAMECA™ SX 100 electron microprobe equipped with five wavelength dispersive spectrometers (Institut für Mineralogie und Kristallchemie, Universität Stuttgart). Melt matrix composition was determined by in situ microprobe measurements on optically preselected areas of polished thin sections (the electron-beam diameter was $5\ \mu\text{m}$ at a current of $8\ \text{nA}$ and an acceleration voltage of $15\ \text{kV}$). Whole-rock composition was determined by analyzing polished thin sections (SEM-EDX measurements at low magnifications under defocused beam and an acceleration voltage of $15\ \text{kV}$) and additional EDX analyses of homogenized rock powder tablets. Microspec™ olivine, apatite, and kryolite (analyzed by the Oxford Instruments™ Microanalysis Group) were used as compound standards for EDX analyses. The accuracy of the analyses was better than 5% ($\sim 2\text{--}5\%$) for the main elements (SiO_2 , Al_2O_3 , FeO , MgO , CaO , Na_2O , and K_2O). Volatile content (water and CO_2) of the melt rocks was measured using a LECO™ RC-412 Multiphase Carbon Determinator facility (Institut für Mineralogie und Kristallchemie, Universität Stuttgart).

PETROGRAPHIC DESCRIPTION

Overall Appearance and Fabric

Uncut specimens of the Paasselkä impact melt rocks are surficially altered and have a coating of iron hydroxides; in fresh section, the melt rocks display a greenish-grey color. The rocks are rich in target rock inclusions and exhibit a distinct overall flow fabric, predominantly within domains rich in melt matrix, and reveal small vesicles as commonly observed in impact melt rocks (e.g., French 1998; Dressler

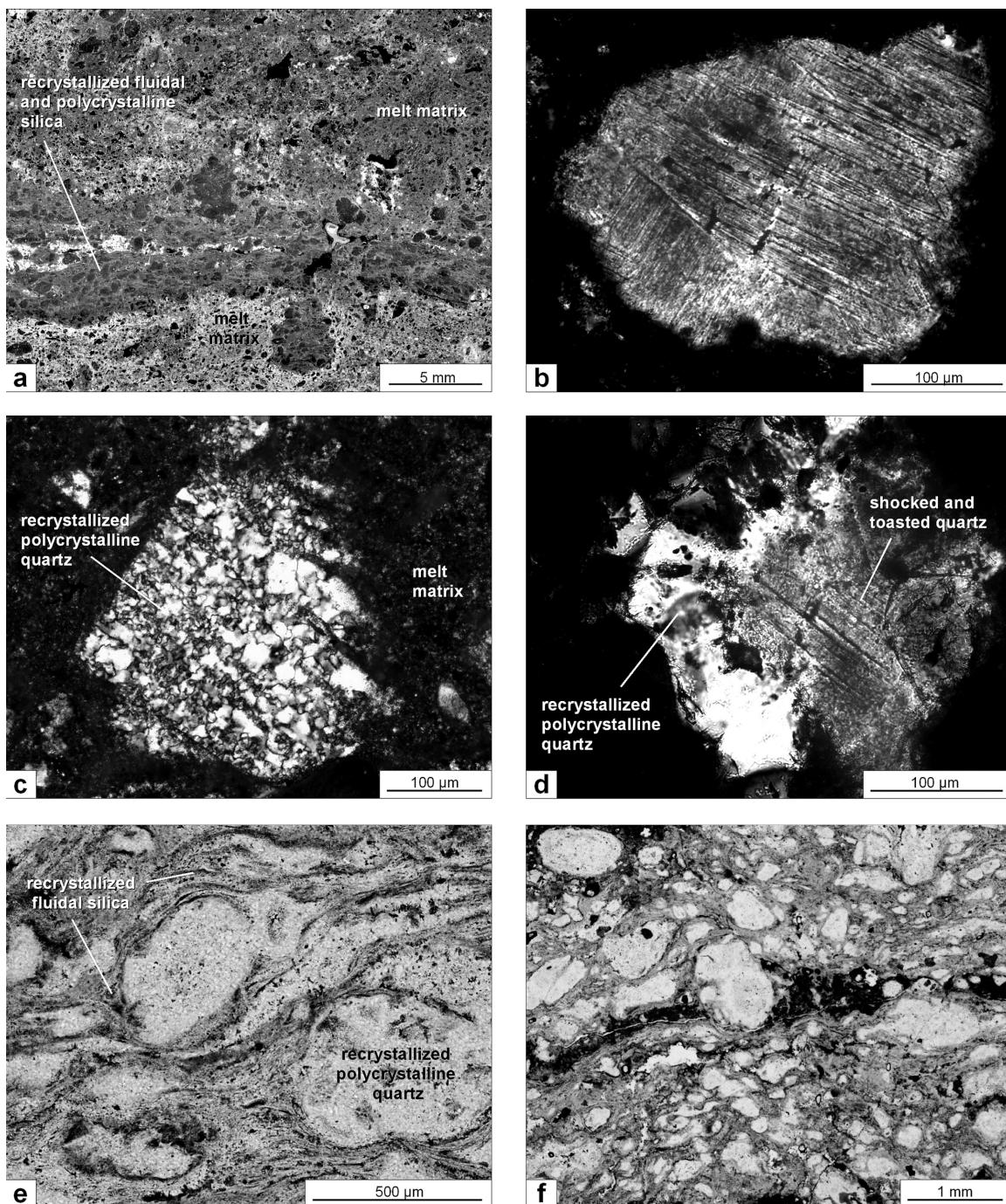


Fig. 3. a) Fluidal texture of Paasselkä impact melt rock with domain of recrystallized fluidal silica (probably partially molten sandstone); reflected light. b) Shocked and toasted quartz grain with planar fractures and three sets of PDFs in melt matrix; cross polarized light. c) Grain of polycrystalline silica (thought of recrystallized diaplectic quartz glass) with angular shape and relict (NW-SE-trending) planar fractures; cross polarized light. d) Shocked quartz partially transformed to polycrystalline silica (recrystallized diaplectic quartz glass) along grain rim; cross polarized light. e) Delta clasts of recrystallized polycrystalline silica domains surrounded by recrystallized fluidal silica; plane polarized light. f) Larger view of recrystallized silica glass domain with relict quartz sandstone fabric; plane polarized light.

and Reimold 2001; Stöffler and Grieve 2007) (Figs. 2 and 3a). Target rock inclusions comprise lithic clasts (predominantly impact-metamorphosed clasts of mica schist, granite, and

sandstone) and single mineral grains, most of which are quartz, feldspar, and decomposed mica flakes from the crystalline target rock.

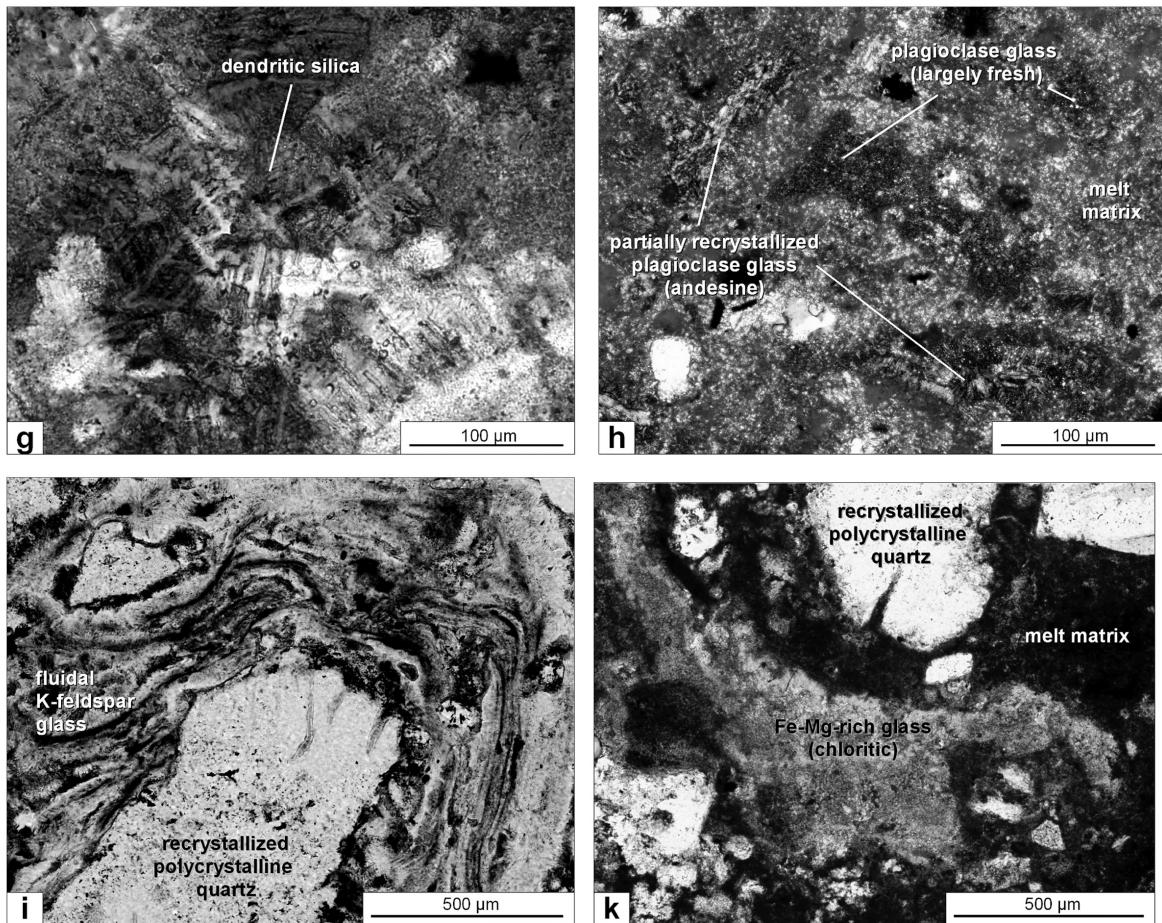


Fig. 3. *Continued.* g) Dendritic silica crystals within domain of recrystallized fluidal silica glass; cross polarized light. h) Largely fresh and partially recrystallized grains of plagioclase glass within melt matrix; cross polarized light. i) Fluidal K-feldspar glass entraining recrystallized polycrystalline quartz with relictic fractures; plane polarized light. k) Fluidal Fe-Mg-rich glass surrounded by melt matrix and grains of recrystallized polycrystalline quartz; plane polarized light.

Silica

Various types of silica can be distinguished in the impact melt rocks: (1) Shocked quartz with planar fractures together with single and multiple sets of decorated PDFs (up to 5 directions) as grains with original angular shapes. Shocked quartz grains are intensely toasted and exhibit a brownish hue due to a high content of minute fluid inclusions (see also Short and Gold 1993; Whitehead et al. 2002) (Fig. 3b). (2) Polycrystalline quartz aggregates do neither display PDFs nor fluidal texture and lack fluid inclusions. These aggregates commonly exhibit both angular and rounded grain shapes (Fig. 3c) and planar fracturing (see interpretation and discussion section). Transitional types between shocked quartz and polycrystalline quartz aggregates also occur (Fig. 3d). In some silica grains, spherulitic texture was observed. In larger silica domains, recrystallized polycrystalline silica grains are surrounded by (3) recrystallized fluidal silica glass rich in schlieren and fluid inclusions. Entrainment of recrystallized silica grains within fluidal silica glass causes a distinctive

“snowball” fabric (Figs. 3e–f). In places, fluidal silica domains exhibit dendritic (skeletal) crystal morphologies (Fig. 3g). (4) Some cavities are overgrown by idiomorphic quartz of yellow to brownish hue. In our Paasselkä melt rock samples, we did not observe unshocked or only fractured quartz grains.

Feldspar and Feldspar Glass

Shock feldspar grains with fractures and/or planar deformation features occasionally occur, whereas most of the protolith feldspar has been transformed into feldspar (plagioclase and K-feldspar) melt of both glassy and devitrified spherulitic appearance. Feldspar glass of plagioclase composition is abundant in the impact melt rocks (Fig. 3h) and displays angular and roundish shapes. Feldspar glass, in many cases, is partially recrystallized to minute plagioclase (andesine) laths. Fluidal plagioclase glass was also observed. K-feldspar domains generally exhibit a fluidal texture and may reach several millimeters in size; domains of fluidally shaped K-feldspar glass are commonly devitrified

(spherulitic) and entrain grains of recrystallized silica grains (Fig. 3i). Veinlets of normal K-feldspar glass are present within larger silica domains. In our samples, we did not detect unshocked feldspar grains.

Other Phases and Melt Matrix

Protolith-derived biotite flakes were completely decomposed into semi-opaque and opaque phases, iron oxides, and minute acicular Fe-Mg-Ti-crystallites (see also Schneider 1974; Feldman 2001), and have been partly replaced by chlorite. Semi-translucent Fe-Mg-rich phases occur as devitrified materials with spherulitic texture (Fig. 3k). The glassy to cryptocrystalline melt matrix (Fig. 4) is semi-translucent in thin section and partially altered to goethite. Vesicles within the melt matrix are commonly lined by chlorite and goethite.

GEOCHEMISTRY

Scanning electron microscope-EDX and electron microprobe measurements of the Paasselkä impact melt rocks revealed that the melt rocks are remarkably siliceous in bulk composition (>60 wt% SiO₂; local silica content, however, varies widely between ~62 and ~71 wt%; Table 1). This is in contrast to the melt matrix, which is relatively poorer in silica (~51–63 wt% SiO₂), but somewhat richer in Fe, Mg, and K (Table 1). Different compositional varieties of glass components can be distinguished within the impact melt rocks: 1) Na-Ca-rich plagioclase glasses of andesine composition, predominantly occurring as partially recrystallized grains (samples G-01-G-17) (Table 2); 2) K-feldspar glass predominantly builds up larger fluidal domains (samples G-18-G-26) (Table 2); and 3) glasses of mixed feldspathic composition, which plot in the actual miscibility gap of feldspars (samples G-27-G-33) (Fig. 5, Table 2). Incipient recrystallization of glass was observed in plagioclase glasses, where small laths of andesine feldspar (within a compositional range of Ab_{62–46}An_{31–40}Or_{4–17}) have formed. 4) Some glass components turned out to be of “mafic” (chloritic) composition, notably rich in Fe, Mg, Al, and volatiles (as inferred from electron microprobe analyses) but poor in silica (samples G-34-G-38) (Table 3). In addition, precursor biotite grains have been decomposed to various types of iron oxides and hydroxides, together with some subordinate Fe-K-Mg-Al-rich glasses and Fe-Mg-Ti-rich crystallites, which are restricted to decomposed protolith mica flakes. 5) Fluidal silica domains revealed an elevated content of Al (Al₂O₃ > 1.2 wt%) and other metals (CaO > 0.3 wt%; Na₂O > 0.2 wt%; FeO > 0.1 wt%) with respect to recrystallized polycrystalline silica. Additionally, dendritic silica crystals (Fig. 3g) are enriched in Al (Table 3). A summary of the various glass types and their geochemical composition is given in Tables 2 and 3 and plotted in Fig. 5.

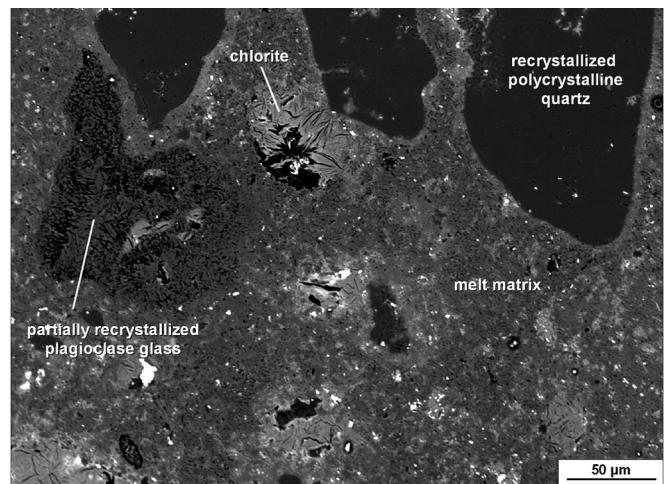


Fig. 4. Backscattered electron image of the glassy to cryptocrystalline melt matrix of the Paasselkä impact melt rocks. Note partially recrystallized feldspar glass (plagioclase), roundish grains of recrystallized polycrystalline quartz (dark grains), and melt vesicles filled by secondary chlorite.

INTERPRETATION AND DISCUSSION

Shock Metamorphic Conditions

From the petrographic observations, shock metamorphic conditions can be constrained for the Paasselkä impact melt rocks. Shocked quartz grains with multiple sets of PDFs (Fig. 3b) suggest shock pressures exceeding 20 GPa (e.g., Stöffler and Langenhorst 1994; French 1998). Polycrystalline silica grains commonly exhibit relictic angular grain shapes, relicts of planar fractures, and generally show no internal fluidal fabric (Fig. 3c). Thus, we interpret these silica grains as recrystallized diaplectic quartz glass. Transitional types most likely represent shocked quartz grains partially transformed into diaplectic glass (Fig. 3d). The frequency of recrystallized former diaplectic quartz glass implies that much of the clast component of the impact melt rocks experienced minimum shock pressures in excess of ~35 GPa (Engelhardt et al. 1967; Engelhardt 1972; Stöffler and Langenhorst 1994; French 1998; Langenhorst 2002). By the presence of roundish grains of recrystallized diaplectic quartz glass it can be assumed that these grains experienced marginal melting of silica (probably “secondary” melting of diaplectic quartz glass; see Grieve et al. 1996) at shock pressures ≥ 35 GPa and temperatures up to ~1500 °C (but obviously below the melting point of silica at 1713 °C; compare to French 1998). This also agrees with the temperatures required for the formation of glasses of mixed feldspar composition and spherulitic aggregates from feldspar glass at temperatures exceeding ~850 °C (Bischoff and Stöffler 1984).

The occurrence of sedimentary rock units in the Paasselkä area was reported by Puura and Plado (2005, p. 225). Highly shocked and molten sandstone clasts were

Table 1. Major element composition of the Paasselkä impact melt rock samples (electron microprobe data; values in wt%).

	#1	#2	#3	#4	#5	#6	#7	Melt matrix (electron microprobe)	#8	#9	#10	#11	#12	#13	#14	Average
SiO ₂	51.30	58.81	59.50	60.19	61.48	57.78	62.30	57.32	61.62	58.58	59.41	60.49	59.07	62.66	59.32	
TiO ₂	0.52	0.36	0.55	0.34	0.34	0.33	0.28	0.17	0.46	0.54	0.49	0.23	0.47	0.57	0.40	
Al ₂ O ₃	17.67	21.08	18.09	17.88	18.89	18.20	20.60	24.45	18.04	19.71	18.63	21.51	18.63	18.31	19.41	
FeO	9.98	1.40	3.46	3.43	1.75	3.35	0.24	0.40	1.48	3.28	3.62	0.67	2.76	1.39	2.66	
MnO	0.00	0.02	0.02	0.02	0.00	0.01	0.00	0.01	0.00	0.05	0.00	0.00	0.03	0.00	0.01	
MgO	6.42	0.65	0.25	1.58	0.36	1.97	0.02	0.02	0.59	0.81	1.17	0.05	1.09	0.46	1.10	
CaO	0.58	3.12	1.34	0.20	0.79	0.80	2.76	6.92	0.44	1.79	1.18	3.80	1.39	0.65	1.84	
Na ₂ O	1.95	5.19	3.60	1.70	2.91	2.95	5.29	6.92	2.13	3.60	3.52	6.52	4.30	3.93	3.89	
K ₂ O	6.12	5.81	8.83	11.40	10.21	8.64	6.63	0.59	11.55	8.09	8.55	4.17	6.52	9.21	7.59	
Total	94.54	96.44	95.65	96.74	96.72	94.01	98.11	96.78	96.31	96.44	96.57	97.43	94.26	97.18	96.23	

Electron probe microanalysis-EDX data; values in wt%)

	#1	#2	#3	#4	#5	#6	#7	Whole rock (SEM-EDX)	#8	#9	#10	#11	#12	#13	#14	Average
SiO ₂	66.84	70.61	63.93	65.52	64.46	62.31	66.37	62.28	66.37	62.31	66.37	62.28	65.29	62.28	65.29	
TiO ₂	0.91	0.68	1.17	0.88	0.67	1.23	0.66	0.90	0.90	0.66	0.66	0.90	0.89	0.89	0.89	
Al ₂ O ₃	14.31	12.05	14.83	14.73	15.67	16.41	14.68	14.68	14.68	16.41	14.68	16.41	14.95	14.95	14.95	
FeO	5.29	4.77	6.06	5.88	5.83	5.80	5.45	5.45	5.45	5.80	5.45	5.45	5.58	5.58	5.58	
MnO	0.24	0.14	0.57	0.47	0.14	0.39	0.24	0.24	0.24	0.14	0.24	0.24	0.41	0.33	0.33	
MgO	1.43	1.80	1.89	1.79	1.83	1.75	1.66	1.66	1.66	1.75	1.66	1.66	1.75	1.75	1.75	
CaO	1.60	1.17	2.12	1.74	1.78	1.92	1.47	1.47	1.47	1.78	1.92	1.47	1.92	1.72	1.72	
Na ₂ O	0.94	1.16	1.66	1.55	1.82	1.53	1.35	1.35	1.35	1.82	1.53	1.35	2.07	1.51	1.51	
K ₂ O	4.21	3.37	3.52	3.18	3.54	4.39	3.86	3.86	3.86	3.54	4.39	3.86	3.80	3.73	3.73	
Total ¹	95.75	95.75	95.75	95.75	95.75	95.75	95.75	95.75	95.75	95.75	95.75	95.75	95.75	95.75	95.75	

¹Total calculated from an average volatile content of 4.25 wt% (water + CO₂) of the whole rock as determined by the LECO RC-412 facility.

Table 2. Major element composition of fresh and recrystallized feldspar glasses in the Paasselkä impact melt rock samples (electron microprobe data; values in wt%)

	G-01	G-02	G-03	G-04	G-05	G-06	G-07	G-08	G-09	G-10	G-11	G-12	G-13	G-14	G-15	G-16	G-17
	Plagioclase glasses																
SiO ₂	60.10	61.20	59.38	59.22	58.78	59.32	60.19	59.81	59.68	60.10	60.23	58.63	58.96	61.92	61.03	59.97	
TiO ₂	0.12	0.00	0.00	0.03	0.05	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.21	0.00	0.00	0.00	
Al ₂ O ₃	21.98	22.14	23.46	23.01	23.31	22.87	22.68	23.14	23.38	22.90	22.24	21.39	24.42	22.56	23.15	21.68	
FeO	1.15	0.11	0.21	0.33	0.52	0.35	0.50	0.42	0.17	0.29	0.36	0.07	0.47	2.20	0.08	0.16	
MnO	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	
MgO	0.02	0.02	0.05	0.02	0.06	0.11	0.10	0.13	0.00	0.07	0.15	0.02	0.14	0.92	0.01	0.05	
CaO	4.26	4.38	5.36	5.35	5.54	5.63	4.70	5.49	6.05	5.65	5.23	4.88	4.16	4.94	4.74	5.72	
Na ₂ O	8.37	7.97	7.01	7.17	7.61	7.38	7.37	7.57	7.00	8.03	7.52	7.69	8.13	7.34	8.81	7.93	
K ₂ O	0.84	1.56	2.14	2.32	1.29	1.48	2.55	1.45	2.07	0.87	1.57	1.88	1.30	1.02	0.57	1.67	
Total	96.83	97.36	97.61	97.47	97.15	97.14	98.08	98.00	98.79	97.97	97.85	97.02	94.24	100.00	99.32	99.45	
	K-feldspar glasses																
	G-18	G-19	G-20	G-21	G-22	G-23	G-24	G-25	G-26	G-27	G-28	G-29	G-30	G-31	G-32	G-33	
SiO ₂	64.23	53.18	64.20	61.13	64.38	62.56	60.47	64.47	55.82	59.40	61.59	62.24	61.27	62.76	61.62	65.07	
TiO ₂	0.02	0.04	0.02	0.10	0.01	0.49	0.03	0.04	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.02	
Al ₂ O ₃	17.42	31.36	18.69	18.47	18.42	19.23	18.06	18.77	28.71	20.34	21.40	20.24	21.70	20.91	20.72	19.92	
FeO	0.00	0.43	0.15	1.85	0.11	0.63	1.74	0.27	1.04	0.36	0.06	0.18	0.08	0.09	0.42	0.37	
MnO	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.00	0.00	0.00	
MgO	0.04	0.11	0.02	0.37	0.00	0.18	1.61	0.06	0.74	0.03	0.00	0.02	0.00	0.02	0.00	0.13	
CaO	0.05	0.04	0.04	0.09	0.12	0.15	0.11	0.10	0.10	3.33	3.97	2.69	4.21	3.00	2.95	0.72	
Na ₂ O	3.12	1.91	2.44	1.38	2.42	1.85	1.43	2.73	0.39	4.69	7.23	5.63	6.57	7.47	5.04	6.86	
K ₂ O	10.73	8.22	12.23	13.35	11.96	11.75	12.34	11.27	7.74	6.32	3.01	6.45	3.43	3.90	6.46	5.07	
Total	95.60	95.28	97.79	96.74	97.42	96.35	96.24	97.71	94.59	94.49	97.28	97.48	97.26	98.14	97.23	98.16	

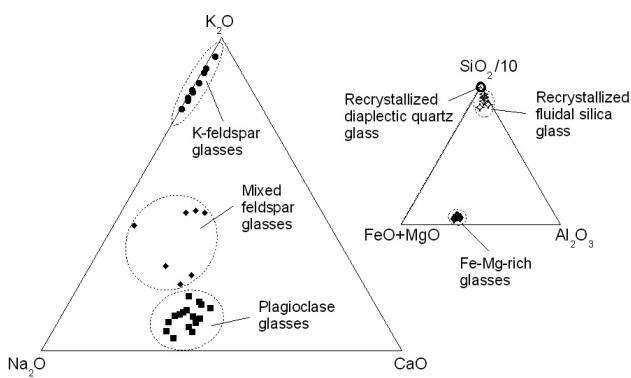


Fig. 5. Chemical composition of fresh and recrystallized glasses ($\text{Na}-\text{Ca}$ -rich plagioclase glasses; K-feldspar glasses; mixed feldspathic glasses; Fe-Mg-rich mafic glasses; recrystallized dialeptic and fluidal silica glasses) in the Paasselkä impact melt rocks. Note the scaling factor of 1/10 for SiO_2 in the small triangular diagram.

also described by Öhman et al. (2003). Domains of fluidal silica and recrystallized dialeptic quartz glass in our melt rock samples most likely derive from preferentially molten quartz sandstones of the target rock (i.e., initially porous target rock units). Accordingly, the arrangement of recrystallized dialeptic quartz glass grains together with fluidal silica glass might be interpreted as a relict sandstone fabric, and internal ductile deformation (due to flow in the viscous melt) may be inferred from the geometry of silica delta clasts (Figs. 3e–f). With respect to the shock behavior of dense crystalline rocks, more heat will be generated in porous sedimentary rocks, and melting of sandstone may occur at comparatively low shock pressures (e.g., French 1998). Recrystallized fluidal, schlieren-rich silica glass domains enriched in Al (Figs. 3e–f) are restricted to partially molten sandstone clasts and suggest the formation of normal silica glass (lechatelierite) at shock pressures of ~ 13 – 30 GPa and post-shock temperatures of ≥ 950 °C (Kieffer 1971; Stöffler 1972, 1984; Kieffer et al. 1976; Grieve et al. 1996; French 1998; Stöffler and Grieve 2007). Dendritic silica crystals within the fluidal silica domains indicate rapid crystal growth upon cooling of the local silica melt.

The high degree of shock metamorphism of the Paasselkä impact melt rocks and incipient whole-rock melting at peak shock pressures of ≥ 35 GPa and post-shock temperatures of probably up to ~ 1500 °C suggests the shock stages III–IV according to Stöffler (1971, 1984) and Stöffler and Grieve (2007). The presence of subordinate non-molten feldspar grains may be explained by the incorporation of cooler, less shocked target rock clasts and mineral grains upon melt movement during the excavation stage (see French 1998, p. 81). Crystallization of post-impact secondary phases, such as vesicle-lining chlorite and idiomorphic goethite-bearing quartz, can be ascribed to post-shock processes at low temperatures. Due to the lack of a representative mineralogical data set of Paasselkä impactites, it remains unresolved whether these phases formed by impact-induced

hydrothermal activity (e.g., Newsom 1980; Naumov 2005; Osinski 2005; Versh et al. 2005) or by regional hydrothermal overprint not related to the Paasselkä impact event.

Melt Rock Composition

Target rock clasts, mineral grains, and glasses of variable size and composition are irregularly distributed within the Paasselkä impact melt rocks and, therefore, are the cause of a rather inhomogeneous whole-rock composition (average values are given in Table 1). SiO_2 enrichment of the whole-rock with respect to the glassy to cryptocrystalline melt matrix (see Fig. 6) corresponds to a large number of silica grains (shocked quartz, recrystallized dialeptic quartz glass, and recrystallized fluidal silica) embedded within the melt matrix; Fe- and Mg-rich phases (such as decomposed biotite flakes, opaque iron oxides, Fe-Mg-rich glasses, and secondary vesicle-lining chlorite and goethite) are responsible for locally occurring higher Fe values. The intermediate SiO_2 content of the melt matrix and higher Al, Na, and K values with respect to the whole-rock probably reflect the preferential and selective melting of hydrous mica, amphiboles, and feldspars of the target rock (compare to Table 1). The rather inhomogeneous distribution of Fe, Mg, Ca, and alkali elements in the melt might point to incipient and/or irregular melt matrix alteration. Linings of secondary chlorite and goethite in melt matrix vesicles indicate the mobilization of iron and magnesium during post-shock cooling and alteration processes; however, chlorite is largely restricted to vesicles (Fig. 4) and domains of decomposed biotite flakes. The compositional variance within the melt matrix (see Table 1) and glasses (Tables 2 and 3) strongly suggests that (1) the Paasselkä impact melt—at least at the scale of the melt rock samples available—was not affected by complete homogenization. (2) The different glass components of the impact melt rocks (i.e., discrete domains of different monomineralic and mixed-mineral melts) reflect the mixed composition of the crystalline target rock.

Enrichment in Al (containing up to 1.28 wt% of Al_2O_3) (see Fig. 3g, Table 3) and other ions (Fe, Mg, and Ca) (Table 3) in the fluidal silica domains of the Paasselkä impact melt rocks could be related to the crystallization of cristobalite or tridymite. Stevens et al. (1997) and Osinski (2004, p. 533) stated that Al and other metals may be preferably incorporated into the open cristobalite structure. The formation of cristobalite from silica glass indicates temperatures of ≥ 1100 °C (Rehfeldt-Oskierski et al. 1986; Shoval et al. 1997). Elevated Al contents are restricted to fluidally shaped silica domains and were not noted in recrystallized dialeptic quartz glass (see Table 3). Feldspars and mica of the target rock are unstable at the post-shock melt temperatures estimated (compare to Schneider 1974; Bischoff and Stöffler 1984, p. B648, Table 1; Feldman 2001) and might be regarded as the source for Al.

Table 3. Major element compositions of Fe-Mg-rich mafic and silica glasses in the Paasselkä impact melt rock samples (electron microprobe data; values in wt%)

	Fe-Mg-rich “chloritic” glasses [†]					Fluidal silica domains and dendritic silica					Recrystallized diaplectic quartz glass			
	G-34	G-35	G-36	G-37	G-38	G-39	G-40	G-41	G-42	G-43	G-44	G-45	G-46	G-47
SiO ₂	29.92	32.53	26.76	32.14	32.81	96.97	96.59	97.13	97.72	97.18	98.83	98.65	99.80	99.95
TiO ₂	0.07	0.05	0.04	0.74	0.77	0.07	0.11	0.07	0.12	0.00	0.04	0.00	0.00	0.03
Al ₂ O ₃	20.80	18.18	19.66	18.09	18.71	0.69	1.28	0.83	0.69	0.82	0.52	0.12	0.02	0.04
FeO	23.89	21.06	27.95	21.97	21.30	0.22	0.23	0.77	0.17	0.29	0.12	0.02	0.02	0.07
MnO	0.16	0.19	0.08	0.17	0.16	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.05	0.00
MgO	12.13	14.37	12.63	13.65	13.34	0.04	0.02	0.19	0.02	0.14	0.01	0.00	0.00	0.00
CaO	0.15	0.16	0.13	0.21	0.16	0.20	0.38	0.03	0.12	0.11	0.09	0.02	0.00	0.01
Na ₂ O	0.10	0.03	0.01	0.04	0.06	0.02	0.26	0.00	0.08	0.09	0.04	0.02	0.05	0.00
K ₂ O	0.72	0.48	0.06	1.16	1.21	0.02	0.03	0.07	0.02	0.04	0.03	0.01	0.01	0.00
Total	87.93	87.04	87.31	88.17	88.52	98.23	98.89	99.08	98.93	98.66	99.74	98.84	99.95	100.09

[†]Fe-Mg-rich glasses contain an average of ~12 wt% of volatiles.

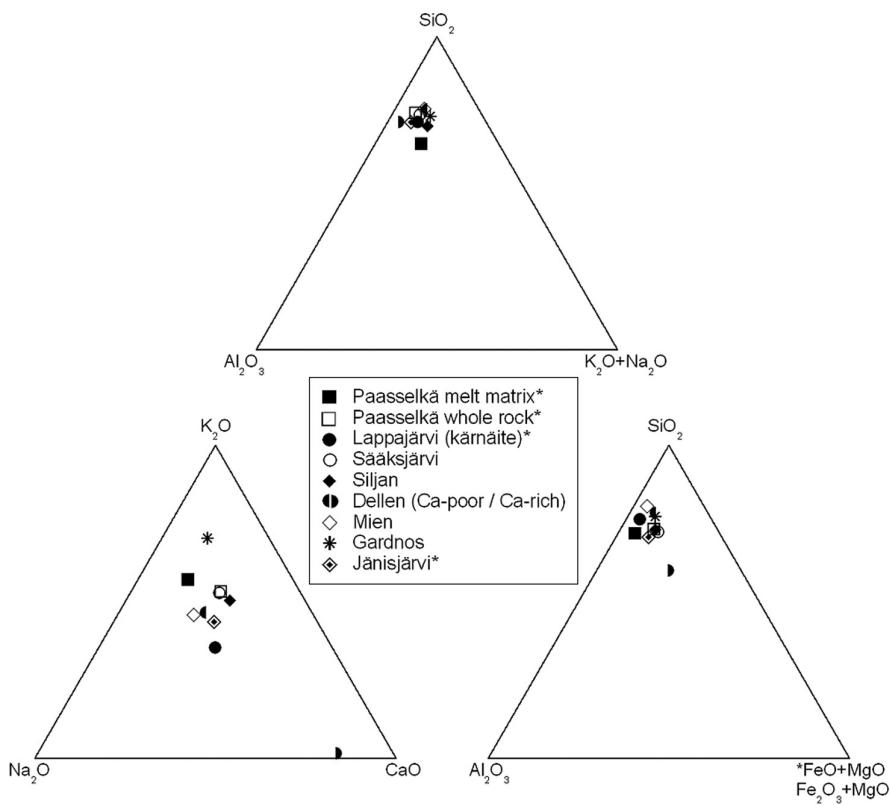


Fig. 6. Chemical composition of the Paasselkä impact melt rocks in comparison to impact melt rocks from some impact structures of the Baltic Shield. Plot based on geochemical data from Reimold (1980; Lappajärvi); Bischoff and Stöffler (1984; Lappajärvi); French et al. (1997; Gardnos); Schmidt et al. (1997; Dellen, Mien, Sääksjärvi); Badjukov and Raitala (1998; Jänisjärvi); Reimold et al. (2005; Siljan); *iron oxide content measured as FeO in the case of Paasselkä, Lappajärvi, and Jänisjärvi; note that the chemical data were determined by different methods.

Our geochemical observations are in good agreement with the mixed character of the target rock (mica schists, granitic and pegmatitic dikes, mafic intrusions, as well as sandstones). We refer to Engelhardt et al. (1969), Engelhardt and Graup (1984), and Osinski (2003), who distinguished different textural and compositional types of glasses in suevite of the Ries crater, Germany, corresponding to the mixed crystalline-sedimentary target rock sequence. Fe-Mg-rich volatile-rich glasses of chlorite composition (Fig. 3k) probably represent local melts from biotite schists. Lavikainen (1986), furthermore, noted amphibolites and mafic clinopyroxene-olivine-rich hornblendites west of Lake Paasselkä, which provide high concentrations of Fe and Mg, and which might represent protoliths for Fe-Mg-rich glasses as well. The hydrous and semi-translucent nature of Fe-Mg-rich glasses suggests enhanced local glass devitrification and alteration.

Comparison to Other Terrestrial Impact Structures

A geochemical comparison of the Paasselkä impact melt rock samples with a representative data set for melt rocks from selected impact structures of the Baltic Shield (Lappajärvi, Finland; Sääksjärvi, Finland; Siljan, Sweden; Dellen, Sweden; Mien, Sweden; Gardnos, Norway;

Jänisjärvi, Russia) reveals that all these impact melt rocks are of generally similar composition (Fig. 6). SiO₂ contents slightly lower than those of the above-mentioned impact melt rocks might reflect the predominance of biotite-rich mica schists over granitic rocks (and the lack of quartz-rich gneisses) in the Paasselkä area. Alkali contents are widely consistent with the Fennoscandian impact melt rocks; there is no obvious indication of emphasized alkali metasomatism, such as notable K enrichment and stronger Na depletion (see Tables 1 and 2) as typical for post-shock hydrothermal alteration and weathering (e.g., Grieve 1978; Newsom 1980; Reimold and Oskierski 1987; Koeberl et al. 1996; Gurov et al. 1998; Hecht et al. 2004; Naumov 2005; Osinski 2005; Versch et al. 2005).

CONCLUSIONS

In this work, we present a first detailed petrographic and geochemical description of impact melt rocks from the ≤ 1.9 Ga and ~ 10 km Paasselkä impact structure, Finland. The clast-rich impact melt rock samples exhibit a distinct overall flow fabric and mainly consist of intensely shocked and toasted quartz grains, recrystallized and peripherally molten diaplectic silica glass grains, recrystallized fluidal silica glass

(lechatelierite), largely fresh to recrystallized feldspar glass, opaque and semi-opaque iron oxide phases, and some secondary minerals within a glassy to cryptocrystalline melt matrix. Glasses may be divided into Na-Ca-rich and K-rich feldspathic, mixed feldspathic, Fe-Mg rich mafic, and essentially pure siliceous varieties and correspond to local melts formed from the mixed crystalline target rock of the Fennoscandian basement. The shock metamorphic observations on the impact melt rocks correspond to shock stage III–IV (according to Stöffler 1971, 1984; French 1998) with initial whole-rock melting at peak shock pressures of ≥ 35 GPa and post-shock temperatures of up to ~ 1500 °C. The Paasselkä impact melt rocks reflect the general geochemical character of melt rocks from impact structures of the Baltic Shield. The presence of largely fresh feldspar glasses and the glassy to cryptocrystalline melt matrix suggests that the Paasselkä melt rock samples are less altered than probable melt rocks reported before by Öhman et al. (2003). In conclusion, largely fresh and recrystallized feldspar glasses of the Paasselkä impact melt rocks might be suitable for radioisotopic dating of the ≤ 1.9 Ga Paasselkä impact structure.

Acknowledgments—We are grateful to Uwe Reimold (Museum für Naturkunde, Institut für Mineralogie, Humboldt-Universität Berlin) for thorough reviews of our manuscript; Gordon Osinski (Canadian Space Agency, St-Hubert, Québec, Canada) and an anonymous reviewer for detailed comments; our Stuttgart colleague Thomas Theye (Institut für Mineralogie und Kristallchemie, Universität Stuttgart) for microprobe measurements; Christoph Wimmer-Pfeil for thin section preparation; Jörg Kröchert (Institut für Geologie und Paläontologie, Universität Stuttgart) and Anita Czambor (Institut für Mineralogie und Kristallchemie, Universität Stuttgart) for volatile measurements; Harald Stehlik (Vienna, Austria) for additional melt rock samples. The source for the Landsat-7 ETM+ scene used in Fig. 1b was the Global Land Cover Facility (available online at www.landcover.org), which is kindly acknowledged. Finally, we kindly thank our London colleague Hilary Randall, who proofread our manuscript.

Editorial Handling—Dr. Uwe Reimold

REFERENCES

- Abels A., Plado J., Pesonen L. J., and Lehtinen M. 2002. The impact cratering record of Fennoscandia—A close look at the database. In *Impacts in Precambrian shields*, edited by Plado J. and Pesonen L. J. Berlin, Heidelberg: Springer-Verlag. pp. 1–58.
- Badjukov D. D. and Raitala J. 1998. The impact melt of the Jänisjärvi crater (abstract #1609). 29th Lunar and Planetary Science Conference. CD-ROM.
- Badjukov D. D. and Raitala J. 2006. Ni in impactite sulphides in the Lappajärvi, Sääksjärvi, Suvasvesi S, and Paasselkä impact craters in Finland (abstract #1676). 37th Lunar and Planetary Science Conference. CD-ROM.
- Bischoff A. and Stöffler D. 1984. Chemical and structural changes induced by thermal annealing of shocked feldspar inclusions in impact melt rocks from Lappajärvi crater, Finland. *Journal of Geophysical Research* 89:B645-B656.
- Dressler B. O. and Reimold W. U. 2001. Terrestrial impact melt rocks and glasses. *Earth Science Reviews* 56:205–284.
- Earth Impact Database 2007. Available online at <http://www.unb.ca/passc/ImpactDatabase> (accessed December 14, 2007). Maintained by Hines J. (data manager), University of New Brunswick, Fredericton, New Brunswick, Canada.
- Elo S. 1979. *Paasiveden gravimetrisen minimi (Gravimetric minimum of Paasivesi)*. Espoo: Geological Survey of Finland, Report Q20/21/1979/3, Espoo, Finland, (in Finnish). 14 p.
- Elo S., Lauerma R., Lavikainen S., and Winterhalter B. 1984. *Geologisia ja geofysikaalisia havaintoja Paasivedeltä ja sen ympäristöstä Kaakkos-Suomesta—Summary: Geological and geophysical observations on Lake Paasivesi and its surroundings, southeastern Finland*. Espoo: Geological Survey of Finland, Espoo, Finland, Report of Investigation 64. 24 p. Partly in Finnish.
- Engelhardt W., von Engelhardt W., von Graup G. 1984. Suevite of the Ries crater, Germany: Source rocks and implications for cratering mechanics. *Geologische Rundschau* 73:447–481.
- Engelhardt W., von Arndt J., Stöffler D., Müller W. F., Jeziorkowski H., and Gubser R. A. 1967. Diaplectische Gläser in den Breccien des Ries von Nördlingen als Anzeichen für Stoßwellenmetamorphose. *Contributions to Mineralogy and Petrology* 15:93–102.
- Engelhardt W., von Stöffler D., and Schneider W. 1969. Petrologische Untersuchungen im Ries. *Geologica Bavaria* 61: 229–295. In German.
- Feldman V. I. 2001. Shock-thermal decomposition of minerals as one of the main diagnostic features of shock metamorphism. *Solar System Research* 35:90–94.
- French B. M. 1998. *Traces of Catastrophe. A handbook of shock-metamorphic effects in terrestrial meteorite impact structures*. LPI Contribution 954. Houston: Lunar and Planetary Institute. 120 p.
- French B. M., Koeberl C., Gilmour I., Shirey S. B., Dons J. A., and Naterstad J. 1997. The Gardnos impact structure, Norway: Petrology and geochemistry of target rocks and impactites. *Geochimica et Cosmochimica Acta* 61:873–904.
- Grieve R. A. F. 1978. The melt rocks at Brent crater, Ontario, Canada. Proceedings, 9th Lunar and Planetary Science Conference. pp. 2579–2608.
- Grieve R. A. F., Langenhorst F., and Stöffler D. 1996. Shock metamorphism of quartz in nature and experiment: II. Significance in geoscience. *Meteoritics & Planetary Science* 31: 6–35.
- Gurov E. P., Koeberl C., and Reimold W. U. 1998. Petrography and geochemistry of target rocks and impactites from the Ilyintsi Crater, Ukraine. *Meteoritics & Planetary Science* 33:1317–1333.
- Hecht L., Wittmann A., Schmitt R. T., and Stöffler D. 2004. Composition of impact melt particles and the effects of post-impact alteration in suevitic rocks at the Yaxcopoil-1 drill core, Chicxulub crater, Mexico. *Meteoritics & Planetary Science* 39: 1169–1186.
- Henkel H. and Pesonen L. J. 1992. Impact craters and craterform structures in Fennoscandia. *Tectonophysics* 216:31–40.

- Kieffer S. W. 1971. Shock metamorphism of the Coconino Sandstone at Meteor Crater, Arizona. *Journal of Geophysical Research* 76: 5449–5473.
- Kieffer S. W., Schaal R., Gibbons R., Hörz F., Milton D., and Duba A. 1976. Shocked basalt from Lunar impact crater, India, and experimental analogues. Proceedings, 7th Lunar Science Conference. pp. 1391–1412.
- Koeberl C., Reimold W. U., and Gurov E. 1996. Petrology and geochemistry of target rocks, breccias, and impact melt rocks from the Ilyinets crater, Ukraine. LPI Contribution #27. Houston, Texas: Lunar and Planetary Institute. pp. 681–682.
- Korsman K., Koistinen T., Kohonen J., Wennerström M., Ekdahl E., Honkamo M., Idman H., and Pekkala Y., eds. 1997. *Suomen kallioperäkartta—Berggrundskarta över Finland—Bedrock map of Finland 1:1 000 000*. Espoo: Geological Survey of Finland.
- Kuivasaari T., Pesonen L. J., Elo S., Plado J., and Lehtinen M. 2000. Paasselkä—The ninth meteorite impact structure in Finland. 4th European Science Foundation Workshop, Programme and Abstracts, 79.
- Langenhorst F. 2002. Shock metamorphism of some minerals: Basic introduction and microstructural observations. *Bulletin of the Czech Geological Survey* 77:265–282.
- Lavikainen S. 1986. *Rääkkylän kartta-alueen kallioperä—Summary: Pre-Quaternary rocks of the Rääkkylä map-sheet area. Explanation to the geological map of Finland 1:100 000, sheet 4214*. Espoo: Geological Survey of Finland. 50 p. Partly in Finnish.
- Naumov M. V. 2005. Principal features of impact-generated hydrothermal circulation systems: Mineralogical and geochemical evidence. *Geofluids* 5:165–184.
- Newsom H. E. 1980. Hydrothermal alteration of impact melt sheets with implications for Mars. *Icarus* 44:207–216.
- Nykänen O. 1975. *Kerimäen ja Kiteen kartta-alueen kallioperä. Suomen geologinen kartta 1:100 000, kallioperäkartan selitykset, lehdet 4213 ja 4231—Summary: Precambrian rocks of the Kerimäki and Kitee map-sheet areas*. Espoo: Geological Survey of Finland. 46 p. Partly in Finnish.
- Öhman T., Badjukov D. D., Raitala J., Petrova T. L., and Stehlík H. 2003. Impactites of the Paasselkä and Suvasvesi South craters, Finland (abstract #1571). 34th Lunar and Planetary Science Conference. CD-ROM.
- Osinski G. R. 2003. Impact glasses in fallout suevites from the Ries impact structure, Germany: An analytical SEM study. *Meteoritics & Planetary Science* 38:1551–1707.
- Osinski G. R. 2004. Impact melt rocks from the Ries structure, Germany: An origin as impact melt flows? *Earth and Planetary Science Letters* 226:529–543.
- Osinski G. R. 2005. Hydrothermal activity associated with the Ries impact event, Germany. *Geofluids* 5:202–220.
- Pesonen L. J., Kuivasaari T., Lehtinen M., and Elo S. 1999. Paasselkä: A new meteorite impact structure in eastern Finland (abstract). *Meteoritics & Planetary Science* 34:A90.
- Pesonen L. J., Hietala S., Poutanen M., Moilanen J., Lehtinen M., and Ruotsalainen H. E. 2005. The Keurusselkä meteorite impact structure, central Finland: geophysical data. XXII *Geofysikaan päävät—Proceedings of the 22nd Geophysical Days*, May 19–20, 2005, Helsinki, Finland. pp. 165–170.
- Puura V. and Plado J. 2005. Settings of meteorite impact structures in the Svecofennian crustal domain. In *Impact tectonics*, edited by Koeberl C. and Henkel H. Berlin, Heidelberg: Springer-Verlag. pp. 211–246.
- Rehfeldt-Oskierski A., Stöffler D., and Hornemann U. 1986. Deformation, transformation, and thermal annealing of experimentally shocked single crystal quartz (abstract). 17th Lunar and Planetary Science Conference. pp. 697–698.
- Reimold W. U. 1980. Isotopen-, Haupt- und SpurenelementGeochemie und Petrographie der Impaktschmelzen des Lappajärvi-Kraters, Finnland. Ph.D. thesis, Westfälische Wilhelms-Universität, Münster, Germany.
- Reimold W. U. and Oskierski W. 1987. The Rb-Sr-age of the Rochecouart impact structure, France, and geochemical constraints on impact melt-target rock-meteorite compositions. In *Research in terrestrial impact structures*, edited by Pohl J. Braunschweig, Wiesbaden: Verlag Vieweg & Sohn. pp. 94–114.
- Reimold W. U., Kelley S. P., Sherlock S. C., Henkel H., and Koeberl C. 2005. Laser argon dating of melt breccias from the Siljan impact structure, Sweden: Implications for a possible relationship to Late Devonian extinction events. *Meteoritics & Planetary Science* 40:591–607.
- Schmidt G., Palme H., and Kratz K.-L. 1997. Highly siderophile elements (Re, Os, Ir, Ru, Rh, Pd, Au) in impact melts from three European impact craters (Sääksjärvi, Mien, and Dellen): Clues to the nature of the impacting bodies. *Geochimica et Cosmochimica Acta* 61:2977–2987.
- Schneider H. 1974. Shock-induced thermal transformations of Ries-biotites. *Contributions to Mineralogy and Petrology* 43:233–243.
- Short N. M. and Gold D. P. 1993. Petrographic analysis of selected core materials from the Manson (Iowa) impact structure. *Meteoritics* 28:436–437.
- Shoval S., Champagnon B., and Panczer G. 1997. The quartz-cristobalite transformation in heated chert rock composed of micro and crypto-quartz by micro-Raman and FT-IR spectroscopy methods. *Journal of Thermal Analysis* 50:203–213.
- Stevens S. D., Hand R. J., and Sharp J. H. 1997. Polymorphism of silica. *Journal of Materials Science* 32:2929–2935.
- Stöffler D. 1971. Progressive metamorphism and classification of shocked and brecciated crystalline rocks at impact craters. *Journal of Geophysical Research* 76:5541–5551.
- Stöffler D. 1972. Deformation and transformation of rock-forming minerals by natural and experimental shock processes: I. Behavior of minerals under shock compression. *Fortschritte der Mineralogie* 49:50–113.
- Stöffler D. 1984. Glasses formed by hypervelocity impact. *Journal of Non-Crystalline Solids* 67:465–502.
- Stöffler D. and Langenhorst F. 1994. Shock metamorphism of quartz in nature and experiment: I. Basic observation and theory. *Meteoritics* 29:155–181.
- Stöffler D. and Grieve R. A. F. 2007. Impactites. In: *Towards a unified nomenclature of metamorphic petrology*, Chapter 11: Impactites. A proposal on behalf of the IUGS Subcommission on the Systematics of Metamorphic Rocks. Blackwell Publishers.
- Versh E., Kirsimäe K., Jõeleht A., and Plado J. 2005. Cooling of the Kärdla impact crater: I. The mineral paragenetic sequence observation. *Meteoritics & Planetary Science* 40:3–19.
- Whitehead J., Spray J. G., and Grieve R. A. F. 2002. Origin of “toasted” quartz in terrestrial impact structures. *Geology* 30:431–434.