Impact-generated pseudotachylitic breccia in drill core BH-5 Hättberg, Siljan impact structure, Sweden

WOLF UWE REIMOLD1,2, LUISE FISCHER1,3, JAN MÜLLER1,4, THOMAS KENKMANN5, RALF-THOMAS SCHMITT1, UWE ALTENBERGER3 and ASTRID KOWITZ1

Reimold, W. U., Fischer, L., Müller, J., Kenkmann, T., Schmitt, R.-T., Altenberger, U. & Kowitz, A., 2015: Impact-generated pseudotachylitic breccia in drill core BH-5 Hättberg, Siljan impact structure, Sweden. GFF, Vol. 137 (Pt. 2, June), pp. 141–162. © Geologiska Föreningen. doi: http://dx.doi.org/10.1080/11035897.2015.1015264.

Abstract: Pseudotachylitic breccia (PTB) in the form of cm-wide melt breccia veinlets locally occurs on the exposed central uplift of the 380 Ma Siljan impact structure. The host rock to the PTBs is the so-called Järna granite of quartz monzonitic to syenodioritic composition. The nearly 603 m long BH-5 drill core from Hättberg, near the centre of the Siljan central uplift, contains numerous veins and pods of PTB. In particular, two major zones of 60 m combined width contain extensive PTB network breccias (30% actual melt breccia component), with individual melt breccia occurrences up to >1 m in length. Core logging and petrographic and geochemical analysis of the core have been performed, and the data are interpreted to suggest the following. (1) The impact event caused low to moderate (at essentially <20 GPa) shock deformation in the host rock and in clasts of this lithology within the PTB. (2) Macroscopic deformation of the basement mainly comprises fracturing, with only localised cataclasis. (3) No evidence for shock melting (i.e. compression/decompression melting early in the cratering process) could be observed. (4) Optical and scanning electron microscopy showed that dark PTB contains a definite melt component. (5) Shearing has significantly affected this part of the central uplift, but its effects are limited to very short displacements and likely did not result in extensive melting. (6) A frictional heating component upon melt generation can, however, not be excluded, as many PTB samples contain clasts of a mafic (gabbroic) component, although only in one place along the entire core, a 1.2 cm-wide section through such material in direct contact to host rock was observed. Consequently, we suggest that, upon uplift in the central part of the impact structure, considerable melt volumes were generated locally, especially in areas that had been affected by extensive cataclasis and where grain size comminution favoured melt formation. Rapid decompression related to central uplift formation is the preferred process for the generation of the PTB melt breccias.

1Museum für Naturkunde Berlin, Invalidenstrasse 43, 10115 Berlin, Germany; ralf-thomas.schmitt@mfn-berlin.de, astrid.kowitz@mfn-berlin.de
2Humboldt Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany; uwe.reimold@mfn-berlin.de
3Institute of Earth and Environmental Sciences, University of Potsdam, Karl-Liebknecht-Strasse 24-25, 14476 Potsdam-Golm, Germany; Luisefischer.weimar@web.de, altenber@uni-potsdam.de
4Department of Earth Sciences, Freie Universität Berlin, Malteserstr. 74-100, 12249 Berlin, Germany; koenermann.j@gmail.com
5Institute of Earth and Environmental Sciences, University of Freiburg, Albertstrasse 23-B, 79104 Freiburg, Germany; Thomas.kenkmann@geologie.uni-freiburg.de

Manuscript received 12 August 2014. Revised manuscript accepted 22 January 2015.

Introduction
In the Earth Impact Database (last visited November 2014), 185 confirmed impact structures are listed. Of these, 39 are located in Europe, with 20 of these known in Scandinavia. One reason for this apparent plethora of Scandinavian impact structures is that the crystalline basement in this region is well exposed due to the widespread removal of younger supracrustals by extensive glaciations and long-term regional uplift. This has provided a long geological record – including an extensive record of impact events. This also includes the largest known impact structure in Europe, the Siljan structure centred at 61°2’N/14°52’E in south-central Sweden. The size of this structure has been variably estimated at 52 (Grieve 1988) to 65 km (e.g. Kenkmann & von Dalwijk 2000; Reimold et al. 2005, and references therein). One aspect of longstanding interest related to Siljan has been its age, with values between 361 and 377 Ma having been published (Reimold et al. 2005). To obtain reliable impact ages, it is required to analyse
materials that have either bona fide completely reset isotopic systematics, namely impact-melted phases derived from target rock or formed at the time of impact (i.e. either impact melt rock, melt-bearing pseudotachylitic breccia (PTB) or impact melted minerals; Jourdan et al. 2012). Siljan has so far been conspicuous by a dearth of such datable materials, with only a handful of melt rock exposures having been found on surface in the inner part of this structure (Reimold et al. 2005). Jourdan et al. (2012) recalibrated earlier dating results for Siljan according to revised data for age monitors and concluded that the currently best age for this impact was 380.9 ± 4.6 Ma (see also Jourdan & Reimold, 2012 for first results of work in progress).

The high-energy impact process generates a range of impact breccias that were defined by Stöffler & Grieve (2007). In particular, they emphasised monomict and polymictic lithic breccias (composed of target rock-derived clast components only), suevite (a mixture of clasts and particulate impact melt), and impact melt rock (that contains target rock-derived mineral and lithic clasts in a melt groundmass). In addition, they classified dyke rocks of the crater floor, central uplift, and crater rim. These dykes have also been the subject of earlier review publications including those by Lambert (1981) and Dressler & Reimold (2004). Lambert (1981) pointed out that different clast-dominated and melt-dominated breccia types occur as locally formed veins and dykes in the craters or were injected into fissures in the crater floor, during different stages of the impact process. Specifically, impact breccias are generated during both the early shock compression regime and the later decompression regime associated with collapse and modification stages of cratereing (e.g. Melosh 1989).

Besides coherent impact melt bodies, melt breccias or melt-bearing breccias of impact origin can occur in the form of veins, dykes and pods within the crater floor and central uplift (Dressler & Reimold 2004), and frequently appear similar to pseudotachylite – friction melt of tectonic origin that has been found worldwide in numerous shear and fault zones. Pseudotachylite is characterised by an aphanitic or microcrystalline matrix carrying variable amounts of clast material. It is actually quite unfortunate that Shand (1916) coined the term “pseudotachylite” (modern spelling “pseudotachylite”) for the voluminous, mostly black melt breccias of the Vredefort Dome. However, at that time this complex was still considered an endogenous structure. It was not until the 1990s confirmed (e.g. Leroux et al. 1994; Kamo et al. 1996; Koerber et al. 1996) as the deeply eroded central uplift of the world’s largest and oldest known impact structure (e.g. Gibson & Reimold 2008; Reimold & Koerber 2014).

Reimold et al. (1999) demonstrated in a detailed petrographic and chemical investigation of dyke breccias from the crater floor of the large Morokweng impact structure in South Africa (Reimold & Koebler 2014) that both melt-bearing impact breccias and impact-generated cataclasite (monomict lithic impact breccia) were present. This represents a typical example that a range of clast-based or melt-bearing breccias may occur in such settings and megascopically closely resemble friction melt. As summarised more recently by, e.g. Mohr-Westheide & Reimold (2011), cataclasite or ultracataclasite as well as pseudotachylite (friction melt) of pre-, syn- or even post-impact age, and impact melt injections may all be present in impact crater settings. This may even include occurrences in lithic clasts in polymict impact breccias such as suevite or lithic impact breccia in impact structures and their environs (Dressler & Reimold 2004). Consequently, Reimold (1995, 1998) and Reimold & Gibson (2006) recommended that such dyke breccias in impact settings should be termed “pseudotachylitic breccias” (abbreviated PTB) until such time that their true nature and place in the breccia classification, and consequently their mode of origin, have been identified.

Besides the Vredefort PTB and even more massive formations in the Sudbury impact structure (the so-called Sudbury Breccia; e.g. Dressler & Reimold 2004), smaller developments of PTB have been described from the Rochechouart (e.g. Reimold et al. 1987), Araguaı́nha (e.g. Machado et al. 2009; Preuss 2012), Charlevoix, Carswell (e.g. Grieve 1996, and references therein), and Dhala (Pati et al. 2013) impact structures. Only very small occurrences of such melt breccia have ever been observed in other impact structures.

It has been known for some time that a drill core (BH-5) extracted from the central uplift of the Siljan structure at Hätteberg (Fig. 1) intersected a dark breccia, but, with the exception of a single reference (Kenkmann et al. 2005), no detailed work regarding the breccia has been reported so far. Those authors concluded that the breccia exhibited evidence for melt and that its likely mode of origin was friction melting. They found that breccia veins were preferentially formed along the contact between the host rock and mafic dykes and sills during shock loading and subsequent movements. Strain localisation along interfaces resulted from impedance contrasts of these lithologies (Kenkmann et al. 2000). As part of a renewed dating study focused on the Hätteberg breccias (a first report: Jourdan et al. 2012), our group has investigated the drill core. Up to 10 cm-wide samples of dark and, as it turned out, melt-bearing breccia and Järna granite host rock from the BH-5 core were located in the impactite collection of the Museum für Naturkunde Berlin (MfN) and served as study material for two BSc theses (Müller 2012; Fischer 2014). These early interesting results, and information that became available from the Habilitation Thesis of T. Kenkmann (Kenkmann et al. 2005), prompted us to investigate the entire core in an attempt to contribute to the understanding of the formation of these melt breccias.

The Siljan impact structure

Already Torneqvist (1871) noted the circular structure in the Siljan area of south-central Sweden, corresponding to downfaulted Palaeozoic supracrustals and an annular arrangement of lakes (Fig. 1). However, only in the 1960s was an impact hypothesis first proposed by Wickman et al. (1963) and Fredriksson & Wickman (1963). This was backed up with findings of shatter cones and shock-deformed quartz during the following decade (Svensson 1971, 1973). As reported by Collini (1988), by the late 1980s the impact origin had been widely accepted. The size of the structure has been variably estimated at c. 50–65 km (Grieve 1988; Kenkmann & von Dalwijk 2000; Henkel & Aaro 2005). Kenkmann & von Dalwijk (2000) identified radial transpression ridges as a major structural feature at the periphery of the central uplift.

The Siljan structure is eroded by perhaps as much as 2 km, whereby the actual crater form and associated impact breccia fill have been completely removed. The central part comprises a low-elevation, c. 30 km-wide central complex of c. 1.8 Ga crystalline basement rocks, which, in its western part, is covered by younger Proterozoic, c. 1.7 Ga sedimentary and
volcanic rocks (e.g. Högström et al. 2010). This complex is considered the remnant of a central uplift or perhaps a central peak ring structure (Kenkmann et al. 2005). The ring basin around this central complex contains strongly deformed Ordovician and Silurian sedimentary strata (Lehnert et al. 2013). According to Kenkmann et al. (2005), the strata represent impact-downfaulted rocks and material slumped off the inner crater wall. Högström et al. (2010) cited seismic data originally reported by Collini (1988) that indicated a 350 m thickness of these rocks.

The crystalline basement of the central uplift comprises rocks of the Transscandinavian Igneous Belt (e.g. Högdahl

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**Fig. 1.** Inset: Location of the Siljan impact structure in central Sweden. Main figure: Schematic map of the geology of the Siljan impact structure. It covers the central uplift area made up of two different intrusives (the so-called Järna granite and Siljan granite) and the surrounding ring basin of supracrustal sequences, the latter of which is partially obscured by lakes. The location of the BH-5 Hätterg drilling in the north-central part of the central uplift is marked as well.
et al. 2004). The central part of the structure is made up of so-called Dala granites, which, in turn, comprise the 1.7 Ga Siljan and 1.8 Ga Järna granites (Juhlin 1991, for ages; also database of the Geological Survey of Sweden, www.sgu.se; Ahl et al. 1999, 2004; Högdahl et al. 2004; Stephens et al. 2009). Siljan granite is dominant in the outer part of the central uplift and is relatively more felsic (granite to quartz syenite) than the Järna granite (quartz monzonite, monzonite to syenodiorite) that dominates in the centre and south-eastern part (Ripa et al. 2012). There are also occurrences of dykes and sills composed of dolerite and porphyritic intermediate to basic rocks. Seismic data indicated that 5–60 m thick dolerite sheets could occur throughout the granitic basement – although the true nature of these seismic reflectors has remained unconfirmed. Dolerites from surface outcrops likely belong to either or both of two generations emplaced at c. 1.27 and 0.98 Ga (e.g. Söderlund 2006).

Impact breccia exposures are rare in the Siljan central uplift. Rondot (1975) reported small and narrow dykes of so-called (Stöffler & Grieve 2007) allochthonous impact breccia and some erratic boulders of melt breccia. Bottomley et al. (1978) referred to an outcrop with a “small dykelet of melt breccia”, and Aberg & Bollmark (1985) to a “shock melt” from another locality. Juhlin (1991) added a reference to a “granitic pseudotachylite” erratic boulders of melt breccia. Bottomley et al. (1978) referred (Stöffler & Grieve 2007) allochthonous impact breccia and some

**Methodology**

The entire length of core BH-5 Hättberg was logged noting lithological and structural (i.e. deformation) details. Samples were collected of all lithologies according to the need to analyse chemically the individual rock types. The samples, their respective depth intervals and lithological classification are listed in Table S1. Polished thin sections of most samples were prepared for optical polarising and electron microscopy at the MfN, where all analytical work was conducted. Scanning electron microscopy was done with a JEOL JSM-6610LV instrument equipped with a LaB6 cathode and an energy-dispersive X-ray (EDX) spectrometry detector. The SEM was operated at 20 kV and with a current of 20 nA on the sample surface. The QUANTAX Esprit 1.9.4 EDX analytical software was used.

The electron microprobe at MfN is a JEOL type 8500F field-emission-cathode instrument equipped with five wavelength-dispersive and one EDX detector. Measurements were done at 15 kV with a cup current of 15–20 mA. For precise spot analysis, the beam diameter was set to 1–2 μm. Peak counting time was 30 s for most elements with the exception of Na and Mg with counting times of 20 and 40 s, respectively. Background values were collected on both sides of a peak for 15 s each. For probe calibration the following international mineral standards (such as ASTMEX reference materials) were used: anorthite (for SiO2, Al2O3, Na2O), osmiumite (FeO, K2O), diopside (MgO, CaO), rutile (TiO2), apatite (P2O5) and bastamite (MnO). Analytical errors determined by repeated analysis of a basalt glass standard are (all in rel-%) for SiO2 0.2, Na2O 1.6, FeO 1.0, K2O 3.2, TiO2 2.0, Al2O3 0.4, MgO 0.7, CaO 0.2 and MnO 5.9. Average precision errors (3 sigma) determined by analysis of feldspar and amphibole are as follows: SiO2 0.14, Na2O 0.08, FeO 0.2, K2O 0.02, TiO2 0.09, Al2O3 0.08, MgO 0.16, P2O5 0.01, CaO 0.08 and MnO 0.02 wt%.

A large number of Järna granite samples, either the main phase in the following designated “Järna Granite Main Phase” (JGMP) or felsic to intermediate enclaves therein, and PTB samples were analysed for major and trace elements by X-ray fluorescence spectrometry using a BRUKER AXS S8 Tiger instrument. Standard XRf analytical procedures, information on reference materials, detection limits for the analysed major and trace elements, as well as the precision values were given recently by Raschke et al. (2013).

The results of chemical analysis were processed for harmonic least-squares (HMX) mixing calculations according to the concept and software of Stöckelmann & Reimold (1989).

**Results**

**Drill core BH-5 Hättberg**

The drill core is generally in good condition. The dm- to m-long sections are separated by fractures that are oriented mostly core-parallel or at high angles to the core axis. The main lithology in the core is a mostly porphyritic, feldspar-rich phase (JGMP) that has the chemical composition (discussed later) of quartz monzonite, monzonite or syenodiorite. It is characterised by highly variable grain size, ranging from medium- to coarse-grained, and even contains pegmatoidal parts (for a number of impressions of the core lithology, see Figs. 2 and 3). Megacrysts of K-feldspar vary in size from several mm to 2 cm, and larger crystals commonly show oscillatory growth zonation. Where the dominant mineral is K-feldspar and the rock is not bleached due to alteration, the lithology is of pinkish to locally even reddish colour, whereas sections comparatively enriched in plagioclase are pale whitish.

A few up to 15 cm-wide intersections of enclaves of mostly intermediate composition are abundant and scattered throughout the entire core. We estimated for a number of m-long sections that the abundance of such enclave intersections ranges from <5 to rarely 20% (of core length). Total enclave content over the c. 600 m of core is of the order of 5% (see also Fig. 6 for a
Fig. 2. Selected macroscopic impressions of the occurrence of PTBs in the upper of two main development zones (compare Fig. 6). Note that in this and consecutive images, the depth values refer to the midpoint of sample cuts. A. Core box with c. 1 m long core sections. Alternating massive and vein-type PTB developments in Järna granite are quite obvious (black). B. An up to 4 cm thick vein of PTB cutting with rather discrete margins through coarse-grained, locally K-feldspar porphyritic Järna granite. Scale bar = 2 cm wide. C. 238.02 m depth. Another irregularly formed pocket of melt breccia with a distinct darker inclusion in normal-grey groundmass (upper left of melt breccia). Likely this is a fine-grained mafic clast, as discussed in the petrography section. The geometry of this entire pocket indicates that shearing was involved in melt breccia formation/emplacement: several slivers off the host rock have been partially separated from the wall rock. D. 186.80 m depth. A mm-wide veinlet of PTB (blue arrow, at left) as well as an up to half cm-wide subhorizontal vein that forms a distinct step up to the right, likely because of a pre-existing fracture (that was seemingly re-activated during drilling). On the far left, a light grey patch of completely altered PTB is noted. E. 546.85 m depth. Pegmatoid host rock with a pre-impact mylonitic band that obviously constituted a zone of weakness and was preferentially utilised for the formation of PTB. Slivers of this mylonite are incorporated into the PTB. F. 522.45 m depth. Network of fine hair-like veinlets of PTB. In thin section it has not been possible to establish whether such veinlets carry a melt phase, due to the complete alteration of their fillings.
frequency profile of enclave occurrences along core). These enclaves are fine- to medium-grained, feldspar and quartz rich rocks of syenodioritic to syenogabbroic compositions (compare Fig. 11) that mostly contain much enhanced amounts of mafic minerals in comparison to the JGMP. The contacts between enclaves and host rock are locally sharp but may also be diffuse. Two main litho-types (Fig. 3A,B) were noted for the enclaves: a fine-grained, granular-textured and compositionally mostly intermediate type with a significant amount of mafic minerals, and a porphyritic type with euhedral, up to 1 cm-sized, prismatic feldspar crystals set into a dark-grey, very fine-grained groundmass. In addition to obvious megacrysts, the core also shows a number of intersections of enclave material that contains clasts of K-feldspar or grain aggregates derived from the surrounding main phase.

Only one occurrence of *in situ* gabbro, in quasi-direct contact with JGMP, was observed in the core, in sample L35 from 231.05 m depth. This 1.2 cm wide intersection of fine-grained gabbro represents the same material described later in the Petrography section in the form of mafic clasts in PTB. The contact between the two lithologies (gabbro against JGMP) has been exploited by a sub-mm wide veinlet of PTB.

Overall, the syenitoid rocks of the core are rather fresh; however, there are some zones of dm to m extent that appear bleached to a whitish-grey colour or have been altered by iron-rich solutions and then appear tainted reddish. These zones are frequently strongly fractured and obviously represent pathways for solutions. There are also a large number of veinlets (up to several mm wide) of secondary mineralisation (mainly secondary quartz or calcite, and rare occurrences of epidote) scattered throughout the core.

Essentially, the entire core is fractured (Fig. 6), with quite varied intensity as estimated from the spacings between fractures (i.e. number of fractures per m). Fracture/joint orientations are quite variable from core metre to metre, although several orientations are dominant. This includes orthogonal fractures in subhorizontal and subvertical (parallel to the core axis) directions, and quite prominent jointing at 45–70° to the core axis. Some extended JGMP sections have wide spacings of fractures, in places as wide as 2 dm, whereas breccia zones (discussed later) have densities of fractures at mm to cm spacings. Displacement between joints is not frequent but can locally be up to 2 cm. Shear deformation is localised and was often observed to be transected by PTB. These locally mylonitic shear zones are oriented at highly variable angles to the core axis, from <45° to 80°. They have also been affected by alteration shown by a greenish colour due to the presence of chlorite and epidote.

Many joint surfaces are characterised by slickenside development. In addition, a number of fractures between core links exhibit the shatter cone phenomenon (Fig. 4A,B). The case shown in Fig. 4B even displays two opposed striated fractures sloping away towards either side of a pre-existing fracture.

Besides localised fracturing, strong cataclasis occurs in places at various depth levels. Cataclasites can occur as up to 2 cm wide zones that are oriented in many different directions with respect to the core axis. In the interval 404–421.5 m, a nice example of domino-texture caused by multiple parallel, stepped fractures was observed in coarse-grained main phase. In addition, several instances of complex microfaulting have been observed.

**Pseudotachylitic breccia**
Over the entire length of the drill core occur mm- to m-wide intersections of dark (black to dark-grey) or, when altered, light to medium grey or even reddish-tainted PTB. Thin veinlets,
contacts between PTB zones and host rock, or offshoots of thin PTB veinlets from comparatively larger PTB developments are commonly oriented parallel to the orientations of main fracture/joint developments (compare examples shown in Figs. 2 and 5). There are two major occurrences of PTB between 220 and 263 m (see the example core box of Fig. 2A) and from 544.3 to 558.7 m depth. Both zones have similar characteristics. Up to 1 m wide PTB occurrences alternate with dm- to m-wide JGMP sections. Unfortunately, especially contacts between wide PTB zones and host rock were sampled and removed from the core boxes during the 1980s, so that it is difficult to provide a thorough assessment of contact relationships.

Only the lower, sharp contact between the upper broad PTB zone and host rock is preserved at 263 m depth. The large JGMP clasts in these PTB zones do not appear to be more deformed than the host rock outside of these zones, but many smaller lithic clasts in PTB have been broken up and sometimes are clearly cataclastic (see also our microscopic results, later). Other clasts are well rounded, and it had to be checked microscopically whether these clasts had been thermally abraded or partially melted and assimilated into the groundmass (discussed later). Some PTB samples display fluidal textures at the macroscopic scale, sometimes exaggerated by schlieren of cataclastic debris. Contacts between veins and pods of PTB and host rock may show rip-off clasts (e.g. Fig. 2C), other PTB occurrences have sharp contacts to the wall rock (Fig. 2B). Where the contact to wall rock has embayments, it is presumed that these are former locations of ripped out clasts. Locally, sheared JGMP is cut by PTB, and it appears that pre-existing weaknesses in the precursor rock to melt breccia were exploited here (Fig. 2E). In other places, a network of finest veinlets with grey infill is observed (Fig. 2F) that was revealed as strongly altered cataclasite.

PTBs are not always preferentially developed at lithological contacts, such as between JGMP and enclaves, but such incidents do occur. Interestingly, PTB are in such cases generally developed on the enclave side, which is somewhat more mafic in composition than the JGMP. This is in keeping with what one can frequently observe, for example, in the granitoid basement of the Vredefort Dome, where PTB development is favoured on the amphibolite or diorite side of lithological changes to granitic gneiss bands (e.g. Reimold & Gibson 2006). The enclaves are comparatively enriched in volatile-bearing biotite and/or amphibole, breakdown of which clearly favoured melt formation.

Macroscopically no vesicles have been recorded in PTB. No contacts between PTB and a mafic host lithology can be reported, besides the one, narrow PTB veinlet along the contact of JGMP and gabbro already referred earlier. Macroscopic mafic clasts only occur rarely as up to 2 cm sized inclusions (Fig. 5A) in PTB. Macroscopically, obvious enclave-derived clasts in PTB are exceptions. Even where PTB was developed at the contact between an enclave and main host rock phase, the PTB only rarely contains obvious enclave-derived clasts. The example of such a configuration shown in Fig. 5B clearly illustrates a lateral displacement on a thin (2–3 mm, locally expanding to a pod of several cm thickness) veinlet. Displacements of a few mm to rarely 1 or 2 cm have only been observed a few times along the entire core – they are not the rule. Where locally the wall rock is enriched in amphibole, adjacent PTB may also be darker coloured than elsewhere – alluding to local generation from such more mafic material.

Fractures/joints are in many places cut by PTB veins and dykes, but the reverse does occur as well. It is conceivable that a brittle deformation phase took place prior to PTB formation and that later adjustment of the impact structure caused a second stage of brittle deformation of the breccias. In several places, PTB was observed to have intruded into older fractures. The upper breccia zone comprises mainly dark PTB, whereas the lower one has extended sections of grey and reddish-tainted breccia. Both breccia zones amount to about 60 m core length, of which we estimate that dark breccia accounts for 30%, with the remainder made up of Järna granite and minor mafic dyke-derived material. Over the core length, no further local accumulations of breccia can be reported. As shown schematically in Fig. 6, enclaves occur throughout the core length. There are a few intervals of core with enhanced abundance of such intersections, in particular in the upper part of the core. However, when comparing enclave occurrence with PTB abundance (see also Fig. 6), there is no coincidence. Enhanced
PTB development is constrained to the two noted breccia zones, and general PTB development at different vein widths is noted along the entire core. Finally, this figure also compares breccia development and fracture/joint density, and while the main breccia zones do coincide with some strong fracturing (in fact, even local cataclasism), there are other strongly fractured zones that have no relation to particular breccia developments.

**Petrography**
The JGMP is composed of K-feldspar, plagioclase, quartz, and minor amphibole and sphene, besides accessories including biotite and muscovite, and traces of pyroxene and zircon. K-feldspar can attain up to 2 cm size, with such megacrysts frequently being strongly zoned. Amphibole, and also sphene (Fig. 7C), may occur as disseminated single grains or as local aggregates (“clots”) of up to 0.5 cm size. Close to contacts with PTB, feldspars and, to a minor degree, quartz may be partially annealed, generally along fractures and intragranular micro-faults. Feldspar has been subject to widespread sericitisation, locally quite severely, and amphibole has been altered to chlorite and/or biotite. Plastic deformation may be found in the vicinity of PTB veins, with undulatory extinction and local shearing being prominent. However, only locally this shear-related deformation is associated with PTB occurrence. In other samples, sheared rock clearly already existed prior to PTB formation. In sheared areas, alteration may be enhanced compared with the surrounding rock, as for example in the form of stronger chloritisation and saussuritisation of feldspar.

Microfracturing affected all minerals – and is notably enhanced near PTB occurrences. Microscopic displacements at PTB contacts are observed along microscopic offshoots from main veins. These offshoots may or may not be developed preferentially on one side of a vein – suggestive of Riedel fractures that have been intruded by melt off the main vein. Local cataclasism does occur, and as discussed later, must be related to decompression. Interstices between clasts are filled with secondary sericite or chlorite.

Shock deformation is abundant. In a few places (and in partial grains only), transformation of quartz, and to an even lesser degree, feldspar, into diaplectic glass is noted. Single or multiple sets of planar deformation features (PDFs) are regularly observed in quartz (Fig. 8). Up to three sets of PDFs at different crystallographic orientations have been observed. PDFs are frequently decorated with fluid inclusion trails and sometimes have been the loci for annealing to trails of tiny mosaic quartz crystals (Fig. 8C). PDFs have only rarely been found in feldspar, but are likely to a large degree camouflaged by the significant alteration of these minerals. If this could be substantiated, this would be clear evidence for post-impact alteration. Sphene and also some zircon crystals display single or multiple sets of sub-planar or planar fractures. Amphibole sometimes displays cataclasis, sometimes mechanical twinning, of likely shock origin. In quite a few places quartz crystals were noted to display toasting (Ferrière et al. 2009).

Contacts between enclaves and JGMP at the microscopic scale are often sharp, and some contacts between PTB and JGMP or enclaves also (Fig. 7B). However, these contacts may also be highly irregular at the micro-scale, with abundant embayments, rip-off clasts and micro-offshoots. Fig. 7A shows such a situation. Often it is possible to connect clasts in PTB veins to the host rock along the contact, with contrasting outcomes regarding lateral movement of micro-clasts: the example in Fig. 7A shows movement of amphibole fragments away from the contact into the veinlet, whereas the tiny sphene clasts derived from the large, altered crystal in the wall rock shown in Fig. 7C have not been laterally displaced.
Fig. 7. Thin section and microphotographs: A and B taken with plane polarised light, C–F with cross-polarised light. 

A. Sample L35, 231.05 m depth. Fluidal-textured PTB veinlet cutting across a fine-grained mafic rock of the intersertal to ophitic texture typical for mafic clasts in PTB. The mafic rock was in direct contact with the JGMP host rock, but now the contact is the location for a sub-mm-wide PTB seam. Small clasts derived from the mafic lithology are incorporated into the adjacent melt breccia.

B. Sample L46, 264.35 m depth. Thin PTB veinlet cutting across a fine-grained enclave. Note the plethora of K-feldspar clasts derived from the main host rock phase.

C. Large sphene crystal in sample L33 (226.98 m depth) cut by PTB melt breccia vein. Note the obvious micro-clasts in the melt breccia that are derived from the adjacent sphene; while melt movement is indicated, it is only of minimal lateral extent.

D. Sample L33, 226.98 m depth. Sphene clast in PTB groundmass – partially digested.
Felsic to intermediate enclaves are composed mainly of plagioclase, alkali feldspar, quartz, amphibole and mica (biotite > muscovite). The latter two minerals comprise up to 30 vol.%, of which most is amphibole. Secondary chlorite is significant, at 5–15 vol.%. The mineral content designates these lithologies as granitic (rare) to granodioritic to dioritic. Granular rocks are mostly fine-grained but medium-grained varieties also exist. They do not contain any megacrysts. The porphyritic variety is also enriched with respect to amphibole (and minor biotite) in comparison to the JGMP, but this rock is significantly more heterogrnanular. The fine- to medium-grained groundmass carries clots of medium-grained, often subhedral to euhedral amphibole crystals up to 2–3 mm in width. In addition, there are euhedral feldspar megacrysts of both K-feldspar or plagioclase, with the former dominant, which are mostly a few mm in size but may attain 1 cm in length (compare Figs. 3A, B for these enclave textures).

Plastic deformation in intermediate enclaves is absent and significant fracturing is not observed either. Individual samples show some healed fractures that are filled with chlorite, secondary fine-grained aggregates of quartz, or in exceptional cases thin films of iron oxide/hydroxide, as also observed in the JGMP. Shock deformation in the enclaves is less prevalent than in the main lithology of the core. Single sets of decorated PDFs in quartz do occur occasionally.

The one occurrence of mafic rock referred earlier, in a thin section of sample L35 from 231.05 m depth, represents a very fine-grained, subophitic lithology composed of fine plagioclase laths and interstitial orthopyroxene. Traces of quartz (sometimes carrying rutile needles) occur. Former mesostasis is completely altered to secondary chlorite, and so is a small portion of the pyroxene. Plagioclase is commonly altered (sericitisation). A minor component is iron oxide (magnetite, partially converted to hematite lamellae) and there are traces of pyrite. The orthopyroxene in some places displays mechanical twinning as a likely manifestation of low-pressure shock metamorphism. The mm-wide PTB veinlet at the contact between this mafic lithology and JGMP contains micro-clasts derived from both wall rock types. The vein locally bifurcates with sub-mm-wide veinlets extending into both lithologies and also carrying micro-clasts of both lithologies. This illustrates that at least short lateral movement has taken place (discussed later). This thin veinlet ends in a cm-wide PTB zone that carries clasts and micro-clasts from both lithologies.

The PTBs (Fig. 7) are composed of a very fine-grained or aphanitic matrix, with minerals, when measurable optically, < 0.1 mm in size. The grain sizes of crystallites in melt matrix range from tiniest, skeletal crystals that occur in interstitial texture to some tens of μm in size in microphorpyritic varieties. Matrices carry highly varied (5–40 vol.%) amounts of clasts. In general, these PTB are matrix-supported. Matrix textures are either fine-grained interstitial (Fig. 9A) or fine-grained granular (Fig. 9B, C). In the case of aphanitic samples, it is not possible to resolve the groundmass optically. Electron microscopy then revealed that extremely fine-grained crystals make up much of these groundmasses. This groundmass material does include a component of partially melted micro-clasts of feldspars and amphibole. In addition, some mixed melt areas were detected with EMPA compositions that can only be explained as mixtures of feldspar (derived from the precursor rock) and ilmenite/sphene or rutile. Also remnants of partially melted amphibole were recognised. Fig. 9C shows a partially groundmass-assimilated mafic clast. Microscopically, fluidal textures are also observed in many instances by colour variation in schlieren and bands but are also enhanced by occasional extended schlieren of micro-clasts or accentuated by the orientations of microlites.

These micro-crystals include K, Na-feldspar as well as plagioclase needles. A more mafic phase was recognised but attempts to analyse it by field-emission cathode electron microscope failed, as consistently other groundmass material was also analysed.

Often micro-clasts can be related to larger clast remnants or are compositionally similar and, thus, derived from a mutual precursor. However, the lateral transport of these micro-clasts is limited and does rarely exceed a few mm. Evidence for lack of lateral movement is also abundant, such as the sphene example in Fig. 7C. Many quartz and feldspar clasts appear plastically deformed and some parts have even been absorbed into the matrix. Mineral clasts are derived from all three precursor lithologies. A pyroxene component is clearly derived from the mafic lithology. The matrix contains pyroxene, amphibole and plagioclase crystallites, besides fine sprays of tiny opaques, mostly magnetite and ilmenite, as well as minor pyrite. In cases of reddish altered samples, there are also haematite and some Fe- oxy-hydroxide present in the groundmass. Pyrite shows two textural types: a porous variety likely derived from precursor rocks, and a more massive variety that occurs as very fine-grained crystals that might be formed from the melt, as well as aggregates or single larger crystals that could also be derived from parental material.

Some samples have considerable numbers of vesicles in their groundmass, which are filled mainly by extremely fine-grained light-greenish material (some of it analysed as chlorite) and may be spotted with a dark-brown phase tentatively considered illite-montmorillonite. Calcite is a further phase often found to fill entire vesicles or occupy the central parts of some. In rare instances, tiny, euhedral (blade-shaped) crystals of low refractive index occur in vesicles. They are thought to represent zeolite minerals, and by their energy-dispersive spectrometric signatures, this phase could indeed be laumontite or chabazite. A zoned vesicle of several mm size contains a central zone of possible zeolite, which is surrounded by alkali feldspar and plagioclase. A few specks in this outer zone were analysed as fluorite, and some tiny pyrite crystals occur as well. It is sometimes rather difficult to decide whether such “inclusions” in PTB groundmass represent vesicles or whether they are actually remnants of melted and partially assimilated mafic minerals from precursor rocks – unless there is a distinct zonation with a narrow zone of a specific phase marking the inner margin of the subject.

Colour of PTB groundmass at the microscopic scale is varied, from dark-grey with or without reddish tint, to black. The darkest melt often contains remnants of mafic minerals such as amphibole, so that the variegated appearance likely relates to alteration as well as compositional differences of precursor.
Fig. 8. Examples of shock deformation in JGMP wall rock adjacent to several PTB veins. Cases in A and C photographed with crossed polarisers, B in plane polarised light. Crystallographic orientations (deformation features marked by thin black lines) determined by universal stage. A. Sample L36, 233.52 m depth. Quartz crystal transected by irregular fluid inclusion trails as well as two sets of planar deformation features. B. Sample L38, 233.71 m depth. A minimum of three differently oriented sets of PDFs (marked by thin black lines) in a locally recrystallised quartz grain. The features at bottom right and on the left side are oriented oblique to the thin section plane, so that they appear slightly wider than normal PDFs should. C. Sample L38, 233.72 m depth. Partially annealed quartz crystal with PDFs of two different orientations. Note that the annealing postdates PDF development (mosaic-textured trails along some PDFs), and thus ought to have taken place due to the thermal overprint from massive PTB development. Note that two equivalent planes related to a common zone are marked.
material. Our thin section collection comprises samples of individual veins or of vein networks, or individual veins with offshoots and with melt pods in their immediate environs. Locally, PTB seems to occur in two cross-cutting generations, in some places also enhanced by colour differences of cross-cutting veins, and small displacements along intersections. Overall, however, it appears more likely that such vein pairs are coeval.

Clasts in PTB are mainly derived from the main precursor phase. Mineral clasts cover the full range of minerals typically present in JGMP and enclaves. Lithic clasts, despite frequent cataclastic deformation, are mostly medium-grained and, thus, derived at least in their majority from JGMP. Individual mineral clasts can be as large as 1 cm, and are invariably derived from the main lithology. Mineral clasts are fractured, cataclased, partially melted, partially annealed or toasted. Chilled margins around clasts are abundantly noted. Quartz and feldspar clasts show PDFs in single or, rarely, two or even three sets per host crystal. As already reported from the host rocks, diaplectic glass in clasts is also very rare. Lithic clasts are in all samples mostly derived from directly adjacent wall lithology. Fracturing, microfaulting and also shearing are frequently noted. Such micro-shear zones are often characterised by strong chloritisation, so that it is not possible to state with confidence that this secondary mineralisation relates to pre- or post-PTB formation time. Not a single optical microscopic indication for the presence of high-pressure phases such as coesite or stishovite has been noted in connection with thin veinlets of PTB.

Alteration is widespread and mostly relates to sericitisation and saussuritisation of feldspars, chloritisation of mafic minerals (mostly amphibole and biotite), as well as secondary deposits of carbonate (as vein fillings and related to decomposition of feldspar). In addition, locally secondary sulphide (mostly pyrite) is noted. Besides syenitoid-derived clasts, PTB melt invariably contains fine-grained mafic clasts of the subophitic to interstitial type as shown in Fig. 7E. These clasts are mostly well rounded, but a few elongated clasts occur, too. These mafic clasts are composed of fine-grained plagioclase laths (up to 0.5 mm but mostly <0.2 mm long) intergrown with orthopyroxene and iron oxide. Textures of these fine-grained rocks suggest a volcanic or hypabyssal origin. It is thought that such clasts are related to the doleritic lithologies known to occur in the crystalline basement at and around Siljan. Fig. 7F demonstrates that the JGMP precursor to PTB contains an angular occurrence of this mafic lithology. This squarish cross-section of a mafic rock clast could represent either an enclave entrained in the host rock or a narrow, square-shaped mafic vein cutting across it.
In 44 thin sections covering the entire length of the BH-5 drill core, a detailed investigation of shock metamorphism was carried out. The occurrences of PDFs in quartz, alkali feldspar and plagioclase were evaluated by assessing the respective numbers of sets occurring in these minerals by optical microscopy. Additional observations (such as presence of planar fractures in specific minerals) were also recorded. Both wall rock and clasts in PTB were studied. The results are listed in the supplementary material (Table S2). In essence, it is not possible to identify a localised change of shock deformation degree along the drill core as expressed in relative abundance of single or multiple occurrences of PDFs. Specifically, the two major PTB zones are not characterised by a notable increase of such shock deformation. Throughout the core length, strongly deformed and less deformed samples alternate.

Electron microprobe analysis was employed to investigate the general groundmass composition of several selected samples (Müller 2012; Fischer 2014; Table 3). This included a thin PTB offshoot into a medium-grained plagioclase and amphibole setting (Fig. 10, Table 1), and the composition of mafic clasts (Table 2). Using a defocussed electron beam (DFB) of 20 μm diameter, groundmass spots in four PTB samples were analysed (compare Table 3). For three samples, bulk PTB and groundmass compositions can be compared (Fig. 11). There is

### Table 1. Average compositions and standard deviations for PTB [1–3] and host minerals for the PTB in areas 4 (plagioclase) and 5 (amphibole), as marked on the image in Figure 10 (sample L36B from 233.56 m depth).

| Area   | 1 SD | 2 SD | 3 SD | 4 SD | Host mineral | 5 SD | Host mineral | SD |
|--------|------|------|------|------|--------------|------|--------------|----|
| SiO₂   | 46.22| 8.68 | 38.32| 2.64 | 41.90        | 3.90 | 45.33        | 7.50|
| TiO₂   | 1.74 | 0.85 | 6.17 | 0.35 | 3.52         | 0.14 | 1.49         | 0.29|
| Al₂O₃  | 15.30| 4.88 | 14.51| 2.42 | 15.84        | 3.51 | 18.10        | 7.89|
| Fe₂O₃  | 12.78| 1.94 | 13.36| 1.29 | 13.80        | 1.70 | 10.43        | 0.80|
| MnO    | 0.34 | 1.32 | 0.29 | 1.18 | 0.32         | 1.64 | 0.24         | 2.66|
| MgO    | 6.03 | 0.81 | 6.23 | 0.77 | 6.60         | 1.11 | 4.71         | 2.10|
| CaO    | 8.29 | 2.79 | 11.44| 1.29 | 8.78         | 1.99 | 10.19        | 3.88|
| Na₂O   | 1.82 | 0.00 | 0.91 | 0.00 | 1.23         | 0.00 | 0.59         | 0.00|
| K₂O    | 2.27 | 1.10 | 1.22 | 1.17 | 2.81         | 2.54 | 0.62         | 3.33|
| P₂O₅   | 0.00 | 0.08 | 0.00 | 0.06 | 0.00         | 0.10 | 0.00         | 0.18|
| Total  | 94.79| 1.84 | 92.45| 1.30 | 94.79        | 1.95 | 91.71        | 3.69|

Notes: Data are from electron microprobe analysis with a focused electron beam in plagioclase and amphibole, and in defocussed beam mode in PTB groundmass. Data are presented in wt %. NB: All standard deviations given in this paper are at the 1σ level.
no uniform trend of element enrichment or depletion with respect to bulk compositions for the groundmass compositions; groundmass may be more felsic or more mafic than corresponding bulk breccia. The grand average calculated from the individual average compositions of groundmass was then utilised for mixing calculations (discussed later).

The situation shown in Fig. 10 relates to a thin vein of PTB that bifurcates adjacent to a plagioclase crystal of the JGMP host rock. The thin offshoot first runs through plagioclase and then extends into amphibole. Microprobe analysis with DFB was conducted in the five areas marked on the figure, i.e. within the main vein, the offshoot and for comparison in the two host minerals (Table 1). It is obvious that the PTB composition in the narrow offshoot is generally comparable to that in the main vein – and not affected by, or even based on, host mineral compositions generally comparable to that in the main vein – and not affected by, or even based on, host mineral compositions. This demonstrates that PTB cannot have formed from the felsic to intermediate components of Järna granite alone but must have had a mafic precursor as well.

Bulk PTB and EMPA compositions of groundmass are reported for several samples and are emphasised by dashed lines connecting corresponding data points in Fig. 12A–G. With respect to Si, Fe, Ti and Ca, the mafic clast component could well represent this additional mafic precursor, when one considers the error limits at the 1 sigma level given in Table 3. However, with respect to Mg, Na and K this component cannot explain the entire variation of PTB compositions. Especially, the alkali elements are likely affected to some degree by alteration processes, despite the apparently limited alteration effect indicated by the CIA diagram (Fig. 12H).

Average abundances of some major and trace elements in the main lithologies have been plotted in the PTB/JGMP, Enclaves/JGMP and PTB/Enclaves ratio diagram of Fig. (13). This illustrates again that the major host rock components intersected in drill core BH-5 do not suffice to match the average PTB composition alone. Main differences in trace element abundances are noted for Ni, Rb and Ba. While Ni is obviously deficient in the felsic-intermediate precursors, Rb could have been strongly affected by alteration, and the strong Ba oversupply in PTB compared with the enclave component emphasises that the xenoliths cannot have been the prominent precursor to the melt breccia.

To further investigate possible contributions of JGMP, enclave, and mafic component observed as clasts in the PTB mixture, HMX mixing calculations (Stockelmann & Reimold 1989) were conducted. In Table 3, the average lithological compositions used for this suite of calculations are summarised. Note that this method involves consideration of errors on component parameters, which are also given in the table. Care was taken to consider which elements could be employed to characterise components and mixture, in order to provide elemental characteristics that would discriminate the components against each other, and to avoid elements, the abundances of which were likely disturbed by alteration. A selection of calculation results is shown in Table 4, where the allowed components, the mixture (PTB composition as listed in Table 3), the component and mixture parameters (elements) went into each calculation, and the results in terms of percent proportions of input components are

### Table 2. Electron microprobe analyses made in defocussed beam mode on mafic clasts in two PTB samples (L33 and L44).

| Sample | L33 | SD | L44 | SD | Grand average | SD |
|--------|-----|----|-----|----|---------------|----|
| N      | 14  | 71 |     |    | L33+44        |    |
| SiO₂   | 52.36 | 6.89 | 52.16 | 7.23 | 52.26 | 0.14 |
| TiO₂   | 1.76  | 2.18 | 2.42  | 3.44 | 2.09 | 0.07 |
| Al₂O₃  | 11.89 | 6.35 | 12.59 | 5.09 | 12.24 | 0.50 |
| CaO    | 10.66 | 6.60 | 9.78  | 7.67 | 10.21 | 0.63 |
| Na₂O   | 7.74  | 4.21 | 7.24  | 4.62 | 7.44 | 0.35 |
| MgO    | 3.21  | 3.68 | 4.98  | 5.89 | 4.25 | 0.30 |
| P₂O₅   | 0.03  | 0.10 | 0.02  | 0.09 | 0.02 | 0.00 |
| Total  | 100.52 | 1.02 | 100.00 | 0.93 | 100.26 | 0.37 |

Notes: A grand average composition for all these data is presented as well, as employed in mixing calculations. Data are presented in wt%.

### Geochemistry

**Chemical compositions** of bulk samples of the main host rock phase (JGMP), selected enclaves and PTB were determined by XRF spectrometry (Table S3). Major element results are illustrated in the De la Roche et al. (1980) R1–R2 diagram of Fig. 11, as well as in the Harker diagrams (e.g. Rollinson 1993) of Fig. 12A–G, where the analyses of Kenkmann et al. (2005) also have been plotted for comparison. The grand average composition derived from our EMPA DFB analyses of mafic clasts in PTB is also shown in Fig. 12. In Fig. 11H, the *Chemical Index of Alteration* (CIA) as defined by (Al₂O₃/[Al₂O₃ + CaO + Na₂O + K₂O]) × 100 ([in molecular proportions]; Rollinson 1993) was plotted against silica content for all these analyses. The CIA variation is very limited over the entire range of compositions – equally so for the various lithologies. This is a clear reflection of our a priori selection of optically least altered samples for analysis. Two analyses in Table S3, for samples L12 and L66, were not plotted, as the former is strongly iron-impregnated and the latter contains significant secondary carbonate. Thus, these two analyses were also excluded from the following considerations.

Fig. 10 demonstrates the quartz monzonite–monzodiorite character of the JGMP. Samples of enclaves in part also show syenodioritic affinity but others have syenogabbroic composition. PTB compositions cover the swathe from syenite to monzogabbro compositions. The Harker diagrams show that the JGMP analyses by our group and by Kenkmann et al. (2005) overlap with respect to all featured major elements (Fig. 12). They form a broad cluster of silica contents between c. 53 and 65 wt%. JGMP overall forms the high-silica end member component within the overall data trends. Enclave samples are intermediate along these trends; samples with the relatively highest silica contents overlap with the JGMP samples with lowest silica contents.

Comparing with the precursor rocks, the PTB samples cover a wide range of silica contents (up to c. 59 wt%) but also extend further down to 47 wt% SiO₂. Some PTB samples have elemental abundances comparable to those in the host rocks, but many others have lower (Al, Ca, Na) or higher (Fe, Ti, Mg, K) abundances. This demonstrates that PTB cannot have formed from the felsic to intermediate components of Järna granite alone but must have had a mafic precursor as well.

Bulk PTB and EMPA compositions of groundmass are reported for several samples and are emphasised by dashed lines connecting corresponding data points in Fig. 12A–G. With respect to Si, Fe, Ti and Ca, the mafic clast component could well represent this additional mafic precursor, when one considers the error limits at the 1 sigma level given in Table 3. However, with respect to Mg, Na and K this component cannot explain the entire variation of PTB compositions. Especially, the alkali elements are likely affected to some degree by alteration processes, despite the apparently limited alteration effect indicated by the CIA diagram (Fig. 12H).

Average abundances of some major and trace elements in the main lithologies have been plotted in the PTB/JGMP, Enclaves/JGMP and PTB/Enclaves ratio diagram of Fig. (13). This illustrates again that the major host rock components intersected in drill core BH-5 do not suffice to match the average PTB composition alone. Main differences in trace element abundances are noted for Ni, Rb and Ba. While Ni is obviously deficient in the felsic-intermediate precursors, Rb could have been strongly affected by alteration, and the strong Ba oversupply in PTB compared with the enclave component emphasises that the xenoliths cannot have been the prominent precursor to the melt breccia.

To further investigate possible contributions of JGMP, enclave, and mafic component observed as clasts in the PTB mixture, HMX mixing calculations (Stockelmann & Reimold 1989) were conducted. In Table 3, the average lithological compositions used for this suite of calculations are summarised. Note that this method involves consideration of errors on component parameters, which are also given in the table. Care was taken to consider which elements could be employed to characterise components and mixture, in order to provide elemental characteristics that would discriminate the components against each other, and to avoid elements, the abundances of which were likely disturbed by alteration. A selection of calculation results is shown in Table 4, where the allowed components, the mixture (PTB composition as listed in Table 3), the component and mixture parameters (elements) went into each calculation, and the results in terms of percent proportions of input components are
Table 3. Average compositions and standard deviations, for the component and PTB mixture compositions as utilised in HMX mixing calculations.

| Component | JGMP (n = 22) | Enclaves (n = 16) | Mafic clasts (N = 85) | PTB (n = 18) |
|-----------|---------------|------------------|-----------------------|-------------|
| [wt %]    | Mean          | SD               | Minimum               | Maximum     | Mean          | SD               | Minimum               | Maximum     | Mean          | SD               | Minimum               | Maximum     |
| SiO₂      | 59.38         | 2.61             | 53.80                 | 65.10       | 52.94         | 1.63             | 50.10                 | 55.30       | 52.26         | 0.14             | 47.50                 | 59.10       |
| TiO₂      | 0.59          | 0.12             | 0.38                  | 0.84        | 0.89          | 0.14             | 0.64                  | 1.12        | 2.09          | 0.47             | 1.18                  | 0.38        |
| Al₂O₃     | 18.00         | 0.58             | 16.80                 | 18.90       | 17.53         | 0.80             | 15.80                 | 18.80       | 12.24         | 0.50             | 16.50                 | 0.91        |
| Fe₂O₃     | 5.23          | 1.06             | 3.60                  | 7.58        | 9.08          | 1.24             | 7.47                  | 10.60       | 11.85         | 0.92             | 9.51                  | 2.31        |
| MnO       | 0.13          | 0.04             | 0.08                  | 0.23        | 0.29          | 0.05             | 0.22                  | 0.39        | 0.21          | 0.01             | 0.19                  | 0.05        |
| MgO       | 1.61          | 0.45             | 0.96                  | 2.87        | 3.69          | 0.56             | 2.82                  | 4.63        | 5.00          | 0.86             | 3.70                  | 1.20        |
| CaO       | 4.02          | 0.99             | 2.82                  | 6.20        | 6.86          | 0.94             | 4.89                  | 8.17        | 10.21         | 0.63             | 4.56                  | 1.61        |
| Na₂O      | 4.02          | 0.99             | 2.82                  | 6.20        | 6.86          | 0.94             | 4.89                  | 8.17        | 10.21         | 0.63             | 4.56                  | 1.61        |
| K₂O       | 4.94          | 0.44             | 4.13                  | 5.58        | 5.20          | 0.71             | 4.15                  | 7.05        | 2.03          | 0.39             | 2.76                  | 1.13        |
| P₂O₅      | 0.27          | 0.09             | 0.15                  | 0.58        | 0.35          | 0.07             | 0.23                  | 0.49        | 0.02          | 0.00             | 0.28                  | 0.04        |
| Total     | 99.39         | 0.51             | 98.26                 | 100.30      | 99.75         | 0.41             | 99.19                 | 100.35      | 100.26        | 0.37             | 99.41                  | 0.57        |

| [ppm]     | Ni            | 11               | 3                     | 8          | 16           | 21               | 7                     | 11           | 35           |
| Zn        | 89            | 28               | 50                    | 161        | 163          | 42               | 116                   | 279          | 164          |
| Rb        | 91            | 24               | 55                    | 144        | 46           | 23               | 8                     | 95           | 233          |
| Zr        | 300           | 70               | 186                   | 428        | 151          | 61               | 28                    | 243          | 288          |

PTB matrix: L44C (258.25 – 258.31 m, N = 37) L48 (267.11 – 267.15 m, N = 64) 190.10 (190.10 m, N = 117) Grand average

| [wt %]    | Mean          | SD               | Minimum               | Maximum     | Mean          | SD               | Minimum               | Maximum     |
|-----------|---------------|------------------|-----------------------|-------------|---------------|------------------|-----------------------|-------------|
| SiO₂      | 50.84         | 3.19             | 42.99                 | 56.09       | 48.63         | 2.33             | 42.38                 | 54.11       |
| TiO₂      | 0.69          | 0.57             | 0.20                  | 3.26        | 1.29          | 1.01             | 0.25                  | 4.96        |
| Al₂O₃     | 16.27         | 0.94             | 13.82                 | 17.98       | 15.59         | 1.08             | 10.52                 | 17.40       |
| Fe₂O₃     | 13.03         | 3.47             | 7.65                  | 18.60       | 13.63         | 2.04             | 8.99                  | 18.05       |
| MnO       | 0.22          | 0.04             | 0.15                  | 0.31        | 0.29          | 0.05             | 0.18                  | 0.40        |
| MgO       | 5.41          | 1.18             | 3.73                  | 8.05        | 5.53          | 0.98             | 3.31                  | 7.32        |
| CaO       | 4.09          | 1.27             | 2.44                  | 7.64        | 5.45          | 1.86             | 2.06                  | 12.74       |
| Na₂O      | 2.62          | 1.09             | 1.22                  | 4.32        | 1.39          | 0.34             | 0.79                  | 2.26        |
| K₂O       | 5.47          | 1.01             | 3.38                  | 7.69        | 5.92          | 1.44             | 2.91                  | 9.19        |
| P₂O₅      | 0.09          | 0.08             | 0.00                  | 0.27        | 0.07          | 0.08             | 0.00                  | 0.31        |
| Total     | 98.72         | 0.56             | 98.01                 | 100.22      | 97.79         | 0.54             | 97.00                 | 99.29       |

Notes: Data in wt%. n = number of analyses by XRF; N = number of analyses by EMPA (defocussed beam).
listed. Also given is a discrepancy factor as a measure of best-fit (i.e., correspondence of input and calculated output mixture compositions). Discrepancy factors should be as low as possible and at $< 1$ signify an excellent fit (Stöckelmann & Reimold 1989).

The results for calculations with JGMP and enclave components indicate that for major element parameters a good fit can be obtained, whereby JGMP proportions are very much larger than the calculated enclave component (only 5–15%, within error limits). However, equally good fits can be achieved with either JGMP + mafic components or enclave + mafic components. As discussed in the previous section, JGMP and enclave components overlap strongly in composition. The best fit obtained for all calculations, represented in Table 4 by Run No. Si24, resulted in a mix of 70% JGMP + Enclaves and 30% mafic component. Müller (2012) also carried out HMX mixing calculations with Järna granite and dolerite (average epidiorite from Vredefort as given by Pybus 1995) components, and obtained a best fit for a mixture of 30% Järna granite (not differentiating between main phase and enclave components) and 70% dolerite. For comparison with these results, Kenkmann et al. (2005) obtained HMX mixing calculation proportions of c. 41.5% Järna granite (undifferentiated as well) and 58.5% mafic component. A close comparison of the component and mixture compositions in this and their studies is not possible, as Kenkmann et al. (2005) did not provide standard deviations on their average Järna granite, mafic component and PTB compositions.

In summary, within the constraints from available compositional data and the compositional variations within the lithologies, good correspondence between mixtures of about equal proportions of felsic-intermediate and mafic precursor components can be achieved, although the strong variations of the litho-compositions do not allow to pinpoint the actual proportions, at which the individual endmembers entered the mixture. The results do, however, imply that no additional litho-component has remained undetected.

**Discussion**

Drill core BH-5 Hätterg presents a long vertical cross-section through the crystalline basement of the central uplift of the Siljan structure. It is composed primarily of so-called Järna granite, which contains some 5% of enclave material. Both lithologies have been affected by the impact event as demonstrated by widespread shock deformation of the main felsic minerals and their cross-cutting relationships with impact-related PTB. In addition, abundant clasts of a gabbroic lithology occur in PTB and signify that such a component does represent a further, definite precursor for PTB. Mafic rocks are, however, hardly in evidence along core – only one definite mafic rock/JGMP composite sample was collected, and a single JGMP clast with a possible mafic vein-derived inclusion was noted in a PTB sample. Macroscopic fracturing – likely to a large extent impact-induced – has affected the entire core but is not enhanced in PTB-rich sections, in contrast to some enhanced micro-fracturing noted in the direct environs of some PTB occurrences. Some fractures carry striations and show close resemblance to shatter cone surfaces. Plastic deformation of core (shearing, rare mylonite occurrences) seems to be of pre-impact age, as such narrow shear zones are commonly cut by PTB veins.

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**Fig. 11.** R1–R2 plot after De la Roche et al. (1980), representing the compositional variation of the Järna granite phases (JGMP and enclaves) and PTB. $R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$; $R2 = 6Ca + 2Mg + Al$. 

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PTB occurs throughout the drill core but particularly in two zones of 60 m aggregate length. In these, the dark matrix breccias are unusually abundant compared with the rest of the core. Melt matrix comprises in total some 20 m core length. Clast sizes in these breccia zones vary from less than a cm to m length, and the zones are best described as network breccias as they are also known from other impact structures. Outside of these zones PTB developments are well-constrained veins with or without offshoots or irregularly shaped pods (at least in some cases, likely cross-sections of veins oriented at high angles to the core axis). Evidence for displacement along vein margins is overall limited, but in rare instances displacements by as little as 2 cm have been observed. There is evidence of rip-off clasts and fracturing at high angles to veins, indicative of some local shear movements on some veins. Fluidal textures in PTB matrix attest to lateral movement along veins. The widespread occurrence of mafic clasts in PTB – in the face of near absence of such material in the drill core – further attests to lateral movement of melt. Consequently, shear movement and associated friction melting may well have been involved in the formation of at least some of these melt breccias. The groundmass of PTB is partially aphanitic, partially microcrystalline. The latter variety clearly requires a melt phase from which crystallisation could have proceeded. In all cases investigated by electron microscopy, the vein fillings contain a large amount of micro-clasts, in addition to a melt component (i.e. microcrystalline component after melt).

After PTB emplacement, fracturing continued. The core material was also subject to alteration, which affected the entire 600 m of
rock intersected in BH-5. Alteration intensity is variable and could have benefited from locally enhanced fracturing in the basement. PTB have been extensively affected by alteration as well.

Remarkably, both macroscopic core study and microscopic analysis did not reveal a strong component of clasts derived from mafic precursor material. However, the majority of PTB samples analysed by optical microscopy carries mafic clasts of a gabbroic lithology that was only once recognised in PTB. This component is also clearly responsible for the more mafic composition of many PTB samples in comparison to the mafic-intermediate and the mafic component to combine to PTB composition. However, it was not possible to define precise proportions of felsic and mafic precursors. PTB are also characterised by similar levels of shock deformation as the host rocks to PTB. No shock, or other deformation, enhancement at, or in clasts within, PTB can be reported. This constitutes strong evidence against a local formation of PTB melt by shock compression. The level of shock deformation does, generally, not change along the entire core.

Electron microprobe analysis of PTB groundmass (melt matrix) showed, in comparison to bulk PTB data from XRF analysis, that groundmass may be more mafic than corresponding bulk breccia. This could be related to local melt formation from specific precursor minerals, as known also from tectonic pseudotachylite occurrences, and/or varied contributions from the mafic precursor(s) assimilated into the melt phase. Microchemical analysis of a thin offshoot into plagioclase and then amphibole demonstrated that the melt was not formed in situ but injected into a fracture off a main melt vein.

Finally, chemical analyses of the three main core lithologies and additional defocussed beam electron microprobe analyses of mafic clasts illustrate that PTB compositions can be regarded as mixtures of the felsic-intermediate material with varied contributions from a mafic source. This is confirmed by HMX mixing calculations that demonstrated a major contribution from the felsic-intermediate and the mafic component to combine to PTB composition. However, it was not possible to define precise proportions of felsic and mafic precursors.

### Implications for PTB genesis at Siljan

Based on these findings, the various possibilities for the formation of melt-bearing PTB intersected in this drill core can be...
discussed. The processes concerned are as follows: (1) so-called compression melting (actually melting upon decompression from the original shock compression stage), also known as shock melting; (2) decompression melting upon central uplift formation (modification phase of cratering); (3) friction melting (also coincident with either [1] or [2]) and (4) intrusion of melt.

Process (1) can be excluded for the Siljan PTB due to the observation that not even at thin melt breccia developments, shocked deformation (or, for that matter, any deformation) is locally enhanced. No high-pressure mineral polymorphs have been detected. Only direct limited evidence exists for friction melting (process 3) being involved, at least locally, upon melt vein formation. No evidence was found to support that the bulk of the melt phase was formed by friction along extensive shears or faults and then intruded into the present setting. The fact that clearly a considerable amount of the material is derived locally and that the range of shock deformation in clasts is similar to that of the host rocks mitigates against formation/emplacement of Siljan PTB by injection of impact melt. In that case, one would also expect to find the complete range of shock effects from planar fracturing to mineral and bulk melting represented in the clast content.

This leaves process (2), whereby melt is generated at considerable volumes during the rapid decompression from the shock compression stage to equilibrated pressure/temperature conditions after rapid uplift related to the modification stage of cratering (i.e. collapse of the transient cavity and concomitant uplift in the central crater). This process has been promoted by Mohr-Westheide & Reimold (2011) for the massive Vredefort PTBs. Melt forms over an extended volume of rock and then, upon collapse of the central uplift, is pushed into extensional sites, thereby picking up local material. This would allow the formation of PTBs. Melt forms over an extended volume of rock and then, upon collapse of the central uplift, is pushed into extensional sites, thereby picking up local material. This would allow the Siljan PTB to contain a mafic clast component exotic to the immediate drill core environment and, at the same time, show little material (clast) movement in certain samples.

Once the melt phase has settled, the solidifying vein and dyke system is still subject to later deformation caused by the tectonic settling of the crater facies in the aftermath of the actual cratering event. This explains the fracturing cross-cutting PTB. And at this late stage, widespread alteration by hydrothermal solutions heated and set into motion by the impact event affects the crater floor rocks.

Conclusion

Detailed core logging and petrographic and geochemical analysis of the three core lithologies (JGMP, enclaves and PTB) in BH-5 Hättbergs resulted in the recognition of the following scenario for PTB development and emplacement:

1. The impact event results in low to moderate (10–20 GPa) shock deformation overprint on the sampled basement interval and the clastic component of the PTB.
2. The basement is extensively fractured and locally cataclased.
3. Upon uplift in the central part of the impact structure, considerable melt volumes are generated locally, especially in catastrophic areas where grain size comminution favours melt formation. These melts may carry a mafic clast component generated in the melt formation zone.
4. The uplift structure collapses and melt is injected into dilation areas and zones where the melt and carried clast component are mixed extensively with locally derived material.

5. Post-PTB emplacement, brittle deformation may continue until the crater has reached tectonic equilibrium. The crater floor is permeated by hot solutions that cause widespread hydrothermal overprint and alteration.

Supplementary data

Supplemental data for this article can be accessed doi: http://dx.doi.org/10.11035/897.2015.1015264.

Acknowledgements — Much of the results used for this paper originate from the BSc theses by Fischer (2013) and Müller (2012). We are grateful to Mr. Jere Hyttinen of the Malå offices of the SGU for making the investigation and sampling of the BH-5 core possible and also for his support during the ‘field’ visit. The technical staff of the MN supported us expertly during sample preparation and analytical work, in particular Kirsten Born, Peter Czaia, Hans-Rudolf Knöferl and Kathrin Kralin. Lutz Hecht provided expert input during electron microprobe analysis, and Marie Hoffmann excellent graphic support. An anonymous reviewer and Carl Alwmark provided much appreciated comments on an earlier version of the manuscript, and the comprehensive editorial input from Magnus Ripa ensured further upgrading of the manuscript.

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