Meteoritics & Planetary Science 44, Nr 8, 1107–1113 (2009)
Abstract available online at http://meteoritics.org

Shocked quartz grains in the polymict breccia of the Granby structure, Sweden—Verification of an impact

Carl ALWMARK

Department of Geology, University of Lund, Sölvegatan 12, Lund SE-22362, Sweden
*Corresponding author. E-mail: carl.alwmark@geol.lu.se

(Submitted 30 March 2009; revision accepted 14 June 2009)

Abstract–The Middle Ordovician Granby structure in Sweden is generally considered the result of an asteroidal or cometary collision with Earth, although no hard evidence, i.e., shock metamorphic features or traces of the impactor, have been presented to date. In this study, drill core samples of a sedimentary breccia from the Granby structure have been investigated for microscopic shock metamorphic evidence in an attempt to verify the impact genesis of the structure. The finding of multiple sets of decorated planar deformation features (PDFs) in quartz grains in these samples provides unambiguous evidence that the structure is impact derived. Furthermore, the orientation of the PDFs, e.g., ω $\{10\bar{1}3\}$, π $\{10\bar{1}2\}$ and *r*, *z* $\{10\bar{1}1\}$, is characteristic for impact deformation. The fact that a majority of the PDFs are decorated implies a water-bearing target. The shocked quartz grains can be divided into two groups; rounded grains found in the breccia matrix likely originated from mature sandstone, and angular grains in fragments from crystalline target rocks. The absence of melt particles provides an estimated maximum shock pressure for the sedimentary derived quartz of 15–20 GPa and the frequency distribution of PDF orientations in the bedrock quartz implies pressures of the order of 10 GPa.

INTRODUCTION

Impact geology is a growing discipline of geoscience and the number of known impact craters is increasing as well. About 175 impact structures are currently (as of 23 March 2009) recognized on Earth (Earth Impact Database 2009). The increase in popularity of impact geology is, however, not altogether positive, as it has triggered many claims of discovered impact craters without proper supporting evidence, thus making the impact record somewhat unreliable. Reimold (2007) suggested that the terms “possible” or “probable” should carefully be applied to crater structures lacking the widely accepted impact-diagnostic criteria of either shock metamorphism or traces, physical or chemical, of the projectile.

The Middle Ordovician Granby structure in Sweden is generally considered the result of an impact event and has been listed as a confirmed impact crater in the Earth Impact Database (2009). Although the structure’s bowl-shape form and the presence of both crystalline and sedimentary breccias suggest that the structure is the result of an impact of an extraterrestrial body, no hard evidence, i.e., shock metamorphic features or traces of the impactor, has been presented so far. Thus, the structure should have been labeled as a “possible impact structure.” In this study, four drill core samples taken at different depths from within the Granby structure have been investigated and searched for microscopic shock metamorphic features, with focus on the presence of planar deformation features (PDFs) in quartz. The aim is to confirm the impact origin of the structure and, if possible, to obtain an estimate of the shock peak pressure experienced by these materials, as well as to see if there are any variations in shock metamorphic features depending on lithology.

GEOLOGICAL SETTING

The subsurface Granby structure, located in the Östergötland province of southern Sweden (N 58°25′, E 14°55′; Fig. 1a), was formed in the Middle Ordovician, at about 467 Ma (Grahn et al. 1996). This age is revised compared to earlier literature based on the 2004 Geological Time Scale (Cooper and Sadler 2004). The structure is a bowl-shaped depression over 377 m deep, about two kilometers in diameter, and is limited on the sides by an up to 70 m elevated rim (Fig. 1b; Bruun and Dahlman 1982). The depression is surrounded by brecciated pre-Cambrian crystalline basement rocks and filled with various sedimentary rocks of Paleozoic age. The lowermost 70 meters

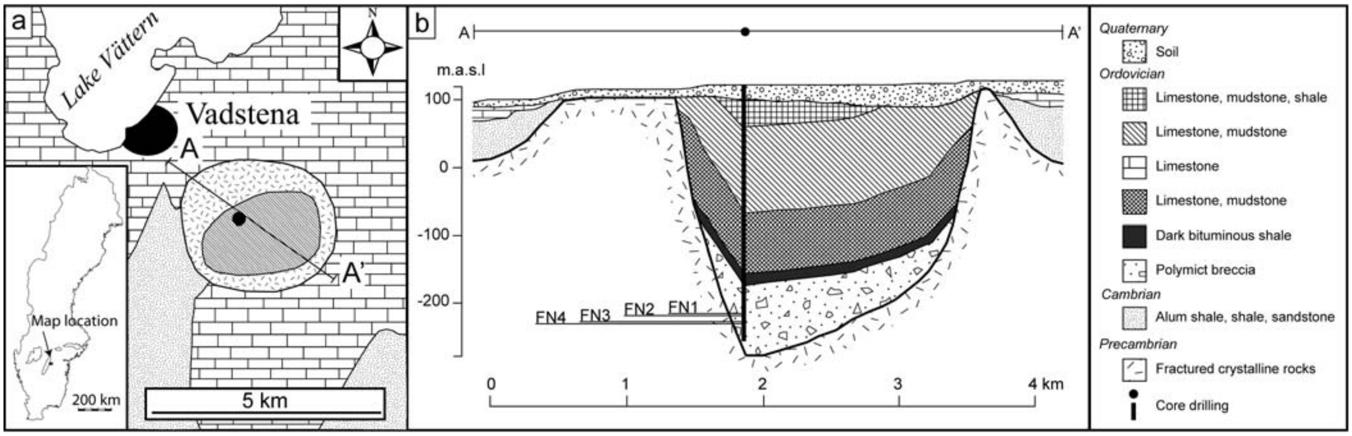

Fig. 1. a) Simplified geological map of the area around the Granby structure. b) Profile of the structure along A-A' of (a) with the location of the four samples (FN1-4) in drill core Fylla Norrgård. Both figures after Bruun and Dahlman (1982).

of the infill consist of a polymict sedimentary breccia with angular fragments of Cambrian and Ordovician sandstones, limestones, and shales, as well as pieces of the underlying crystalline bedrock (Bruun and Dahlman 1982). The fragments range in size from submillimeter to tens of centimeters in discontinuous intervals throughout the whole breccia sequence. The heterogeneous distribution of fragment sizes is most likely the result of slumping processes (Ormö and Lindström 2000). The fragments are embedded in a matrix of dark clay with a high amount of well-rounded quartz grains. The breccia is overlain by 20 meters of dark bituminous shale, similar to that of the matrix of the sedimentary breccia, but lacking both lithic fragments and quartz grains. A distinct boundary marks the bottom of the dark shale, implying a prominent change in the depositional environment. From this point upward, the infill of the depression is comprised of limestone and mudstones, resembling a more typical sedimentation sequence for the Ordovician period of the area (Bruun and Dahlman 1982).

MATERIAL AND METHODS

Four samples (FN1-4), from drill core Fylla Norrgård (N 58°25′49″, E 14°55′30″) from the northwestern part of the depression were chosen for this study (Fig. 1b). The samples are all from the upper part of the sedimentary breccia, covering the level of 48 to 64 meters above the brecciated crystalline basement. The four samples have a similar composition, exhibiting the typical features of the sedimentary breccia, with angular brecciated fragments of mainly limestones and claystones embedded in a matrix composed of dark clay and silt, as well as fine sand-sized, rounded quartz grains (Fig. 2). Bedrock fragments are present as a minor constituent in all the samples. The sizes of the breccia fragments vary between the individual samples, with the uppermost sample (FN1) being the coarsest, with clasts of up to 50 mm in size, and sample FN3 the finest, with fragments no larger than 2 mm. Samples FN2 and FN4 hold similar medium-sized fragments, generally between 1–10 mm (Fig. 2).

In total, 17 thin sections were prepared from the four samples and studied for shock metamorphic features with both optical and scanning electron microscopes. An estimate of the frequency of shocked quartz in each sample was obtained by point counting and comparing the number of quartz grains with and without PDFs. The crystallographic orientation of PDFs (planar fractures [PFs] excluded) were determined in individual shocked quartz grains using a Leitz 5-axes universal stage (U-stage; cf. Reinhard 1931; Emmons 1943). The orientation of the optic axis and the poles perpendicular to planes of PDF were measured and plotted in a stereographic Wulff net and then indexed with Miller-Bravais indices (*hkil*), using a stereographic projection template, displaying the possible pole orientations of common PDF planes within a 5° envelope of measurement error (e.g., Engelhardt and Bertsch 1969; Stöffler and Langenhorst 1994; Langenhorst 2002; Ferrière et al. 2009b). The stereographic projection template used in this study is an updated version from Ferrière et al. (2009b) including five additional known orientations. Note that, as recommended by Ferrière et al. (2009b), all measured orientations that fall into the overlapping zone between $\{10\bar{1}3\}$ and $\{10\bar{1}4\}$ have been treated as belonging to $\{10\bar{1}3\}$ orientations, because the $\{10\bar{1}4\}$ orientations are not considered to be a major orientation in comparison to $\{10\bar{1}3\}$.

RESULTS

Shock metamorphic features in the form of PDFs and PFs (Figs. 3a–b) in quartz are present to a varying degree in all investigated thin sections. No diaplectic glass, neither fresh nor recrystallized, or signs of melting were identified. Samples FN1 and FN2, from 64 and 60 m above basement display a low frequency (<0.05%) of quartz grains with PDFs. Only five and six grains, respectively, displaying PDFs were detected. No PDFs or PFs were observed in the breccia

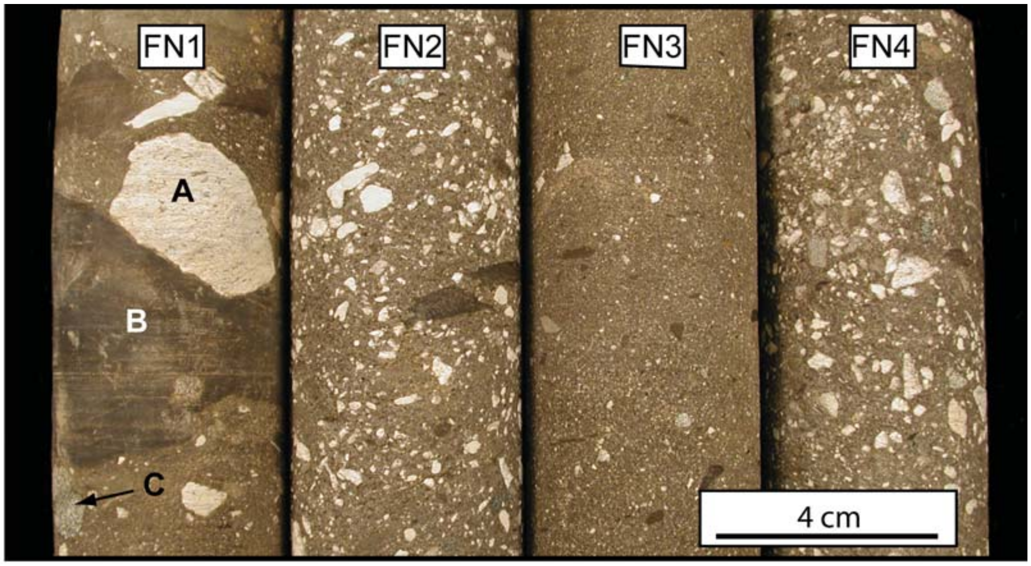

Fig. 2. Macrophotographs of the four drill core samples (FN1-4) investigated. Note the variation in size of the breccia fragments. A) Limestone clast. B) Claystone clast. C) Bedrock fragment.

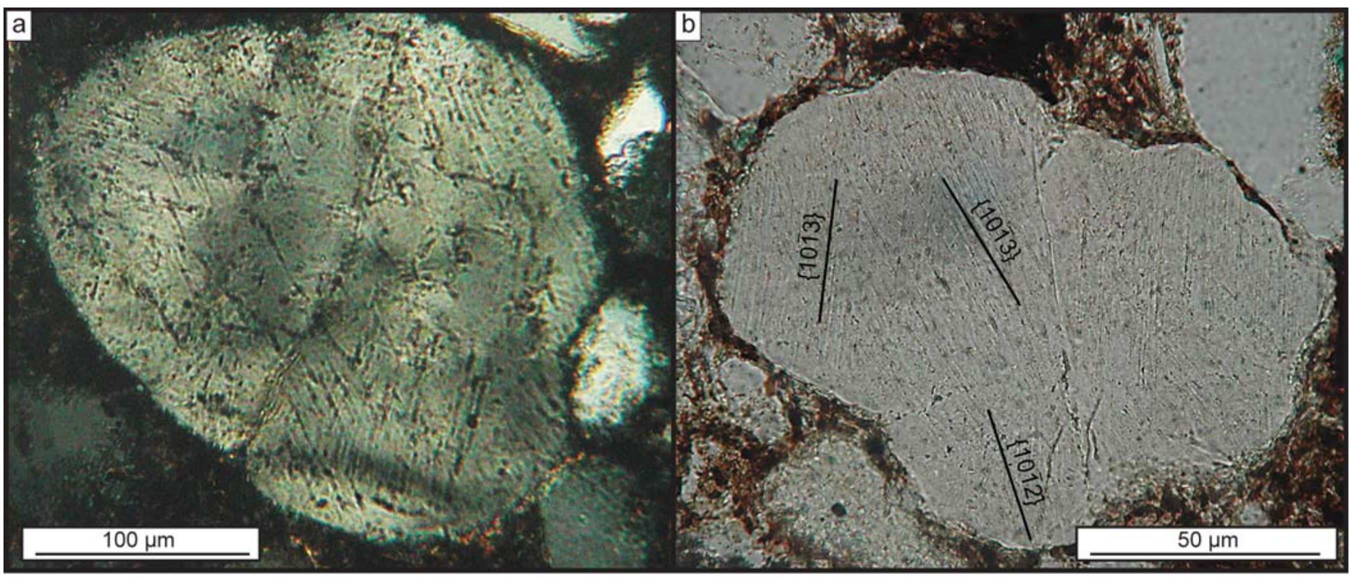

Fig. 3. Microphotographs of shocked quartz grains. a) Well rounded quartz grain from sample FN2 displaying PFs (cross-polarized light). b) Rounded quartz grain from sample FN3 exhibiting three sets of PDFs; two with ω $\{10\bar{1}3\}$ orientation and one with π $\{10\bar{1}2\}$ orientation (plane-polarized light).

fragments. The quartz grains with PDFs are subrounded to rounded and between 100–300 µm in size. Sample FN3, from 52 m above basement, is the sample richest in PDFs, with 31 quartz grains displaying one or more sets of PDFs, corresponding to a frequency of ~0.1%. The PDFs are all located in 50–300 µm rounded to sub-rounded quartz grains; no shocked grains were found in the breccia fragments. The only PDFs in quartz identified in the lowermost sample, FN4, taken 48 meters above basement, are located in a breccia fragment, i.e., no PDFs could be identified in individual quartz grains of the matrix. The matrix is, on the other hand, relatively rich in quartz displaying PFs. The breccia piece is a ~2 mm large angular fragment originating from the crystalline basement (Fig. 4a). The fragment consists of, apart from quartz, biotite and heavily altered feldspars. All the quartz grains, 23 in total, in the fragment display PDFs, but no PFs. The grains range in size from about 50 to 200 µm in size and are all angular in shape (Fig. 4b).

Although the frequency of PDFs in quartz grains varies substantially between the different samples, the PDFs themselves are alike, appearing in straight parallel sets with spacings between individual features of 1–5 µm, usually

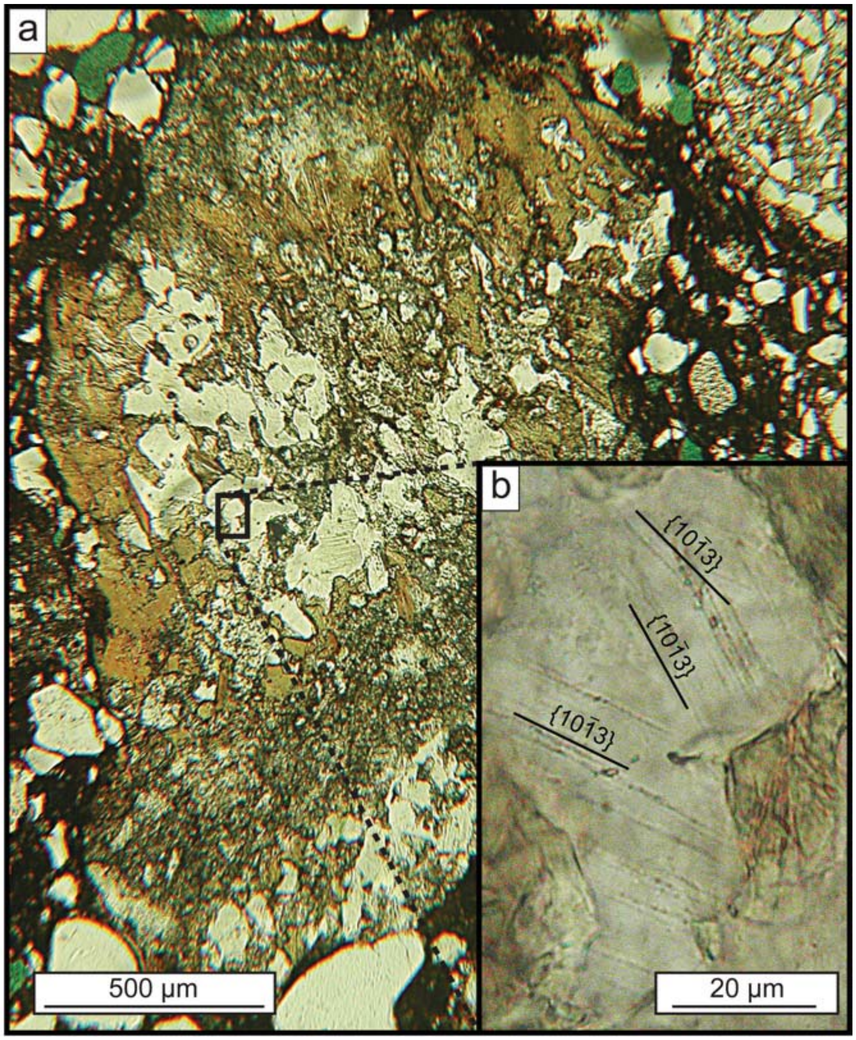

Fig. 4. a) Microphotographs in plane-polarized light. a) The crystalline fragment with quartz grains with PDFs from sample FN4. b) Close-up of small area in (a), showing three sets of partially decorated PDF sets, all of ω {10$1\bar{3}$} orientations, in an angular quartz grain.

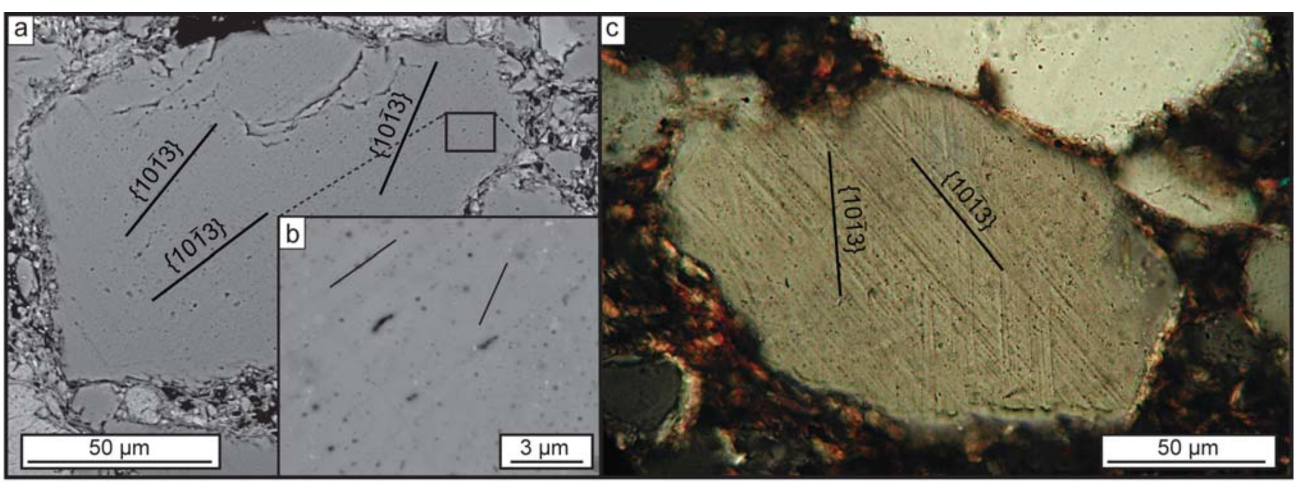

Fig. 5. a) Backscattered electron image of a quartz grain from sample FN3 displaying three sets of decorated PDFs, all with ω {10$1\bar{3}$} orientation. b) Close-up of (a) showing decorations by fluid inclusions. Note the small size of the inclusions. c) Microphotograph in cross-polarized light of slightly toasted quartz grain from sample FN3 with two sets of PDFs, both with ω {10$1\bar{3}$} orientation.

Table 1. Summary of PDF set abundance and indexed PDF crystallographic orientations in quartz grains from the various samples.

Sample	FN1	FN2	FN3	FN4	FN1-3 combined	FN1-4 combined
No. of sets	8	8	80	41	96	137
No. of grains	5	6	31	23	42	65
No. of PDF sets/grain	1.6	1.3	2.6	1.8	2.3	2.1
PDF sets; relative%						
1 set	40	67	13	35	24	28
2 sets	60	33	32	52	36	42
3 sets	0	0	39	13	29	23
4 sets	0	0	16	0	12	8
Total	100	100	100	100	100	100
Absolute frequency (%) of uniquely indexed PDFs						
Form						
c (0001)	n.d.	n.d.	2.5	n.d.	2.1	1.5
$\{10\bar{1}4\}$	n.d.	n.d.	1.3	n.d.	1.0	0.7
ω $\{10\bar{1}3\}$	87.5	75.0	55.0	92.7	59.4	69.3
π $\{10\bar{1}2\}$	n.d.	12.5	12.5	n.d.	11.5	8.0
ξ $\{11\bar{2}2\}$	n.d.	n.d.	2.5	n.d.	2.1	1.5
r/z $\{10\bar{1}1\}$	n.d.	n.d.	12.5	n.d.	10.4	7.3
ρ $\{21\bar{3}1\}$	n.d.	n.d.	1.3	n.d.	1.0	0.7
x $\{51\bar{6}1\}$	12.5	n.d.	2.5	n.d.	3.1	2.2
a $\{11\bar{2}0\}$	n.d.	n.d.	3.8	n.d.	3.1	2.2
m $\{10\bar{1}0\}$	n.d.	n.d.	1.3	n.d.	1.0	0.7
Unindexed	n.d.	12.5	5.0	7.3	5.2	5.8
Total	100	100	100	100	100	100

n.d. = none detected.

penetrating the better part of the host grain. The number of PDF sets within each individual grain varies from one to three (rarely four), with an average of 2.3 sets in the quartz grains in the matrix and 1.8 sets per grain in the crystalline fragment (Table 1). The PDFs are partially decorated to decorated, with numerous small fluid inclusions (Fig. 5a). The decoration is, however, not always visible at the level of the optical microscope, due to the submicrometer-size (often <100 nm) of the inclusions (Fig. 5b). Thus, in some cases, what appear to be fresh lamellae optically prove to be decorated features when viewed at higher resolution, i.e., at the scale of the SEM. Some of the shocked quartz grains are toasted, displaying, when viewed in plane-polarized light, a grayish-brown color (Fig. 5c). The discoloration is the result of small vesicles in the grains which enhance scattering of transmitted light. The vesicles are believed to have formed when trace elements and inclusions were removed from the quartz structure at high post-shock temperatures (Ferrière et al. 2009a).

The orientations of the poles of all identified PDFs (137 in total) in quartz grains from the four samples, were measured and those corresponding to rational crystallographic orientations of quartz, indexed. All indexed planes were plotted as the frequency of PDFs versus angle between c-axis and pole to PDF, in two separate charts, one for the shocked grains of the matrix (samples FN1–3), and one for the quartz grains of the crystalline fragment (FN4; Figs. 6a–b). Of all the measured and uniquely indexed PDF sets in the subrounded to rounded quartz grains (91 sets in 42 grains), i.e., from samples FN1–3, almost two-thirds (63%), are oriented parallel to crystallographic planes belonging to the ω $\{10\bar{1}3\}$ zone. PDFs having a polar angle of ~32° and ~52°, corresponding to π $\{10\bar{1}2\}$ and *r, z* $\{10\bar{1}1\}$, respectively, are second most common, comprising 12 and 11%, respectively, of the total. Only two PDF sets are oriented close to 0°, i.e., corresponding to the basal plane *c* (0001). Planes parallel to $\{10\bar{1}4\}$, $\{11\bar{2}2\}$, $\{21\bar{3}1\}$, $\{51\bar{6}1\}$, $\{11\bar{2}0\}$ and $\{10\bar{1}0\}$ orientations are also present, with a frequency of between 1 and 4%. Of the 96 measured PDFs, only five (~5%) did not correspond to any rational crystallographic orientation and, thus, remained unindexed. A total of 38 PDF sets in the 23 grains from the crystalline fragment were indexed. All of the planes have a polar angle within ±5° of ~23° of the c-axis, corresponding to the ω $\{10\bar{1}3\}$ zone. Three of the planes did not correspond to any rational crystallographic plane in quartz.

DISCUSSION

PDFs were found to be heterogeneously distributed, displaying a large variation over a relatively small depth

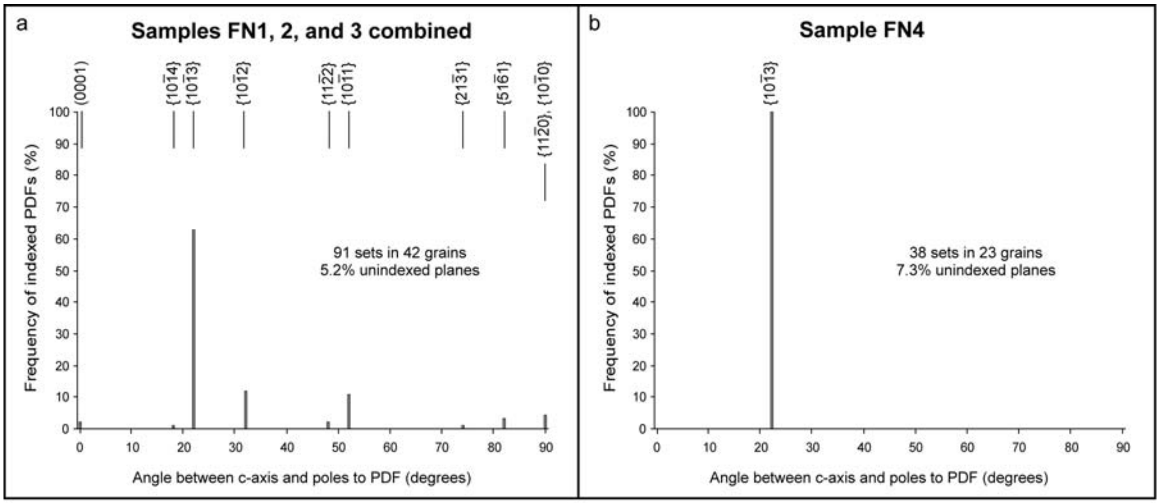

Fig. 6. Histograms of absolute frequency percent of only indexed PDFs in quartz grains from (a) samples FN1-3 and (b) sample FN4. Note that the total number of values was recalculated to 100% without unindexed PDF orientations.

interval, with a marked peak in sample FN3 at 52 meters above basement. That multiple sets of decorated planar deformation features are present in quartz from the in-fill breccia of the Granby structure, both in the sedimentary matrix and in a crystalline fragment originating from the basement bedrock, provides unambiguous evidence that the structure is impact derived. Furthermore, the pattern of the PDFs, with a sharp peak at ω {101$\bar{3}$}, followed by π {101$\bar{2}$} and *r*, *z* {101$\bar{1}$}, is characteristic for impact deformation and in marked contrast to the broader, bell-shaped distribution of deformation lamellae (Böhm lamellae) produced by normal metamorphism (e.g., French 1998). The consistent decorated nature of the PDFs, generally considered to be a secondary feature due to the effect of water-assisted recrystallization (e.g., Grieve et al. 1996; Leroux 2005), implies a water-bearing target. This is in accordance with the general notion that Baltoscandia was covered by an epicontinental sea at the time of the impact. The sea was probably relatively shallow in the Granby area, because no proper resurge deposit was formed; instead the sedimentary breccia has features pointing to the influence of slumping (Ormö and Lindström 2000). The reason for the low frequency of indexed basal PDFs could be that they can be difficult to identify optically if not decorated (Grieve et al. 1996; Leroux 2005). Thus, in this case where the decoration is not always visible in an optical microscope, owing to the small nature of the inclusions, some basal PDFs are likely to have been missed.

The generally semi-round to rounded morphology of the shocked quartz in the matrix, in marked contrast to the angular quartz in the crystalline fragment (Figs. 3b and 4b), implies that the majority of shocked grains originate from mature sedimentary rocks, probably a sandstone. The difference in lithology is most likely also the reason for the discrepancy in frequency distribution of PDF orientations, since sedimentary (porous) rocks react differently to shock compression compared to non-porous crystalline rocks (e.g., Grieve et al. 1996). The porosity of the sedimentary target, in this case sandstone, can cause highly variable shock deformation at the grain scale. Furthermore, studies on sedimentary target rocks at various other impact structures point to a larger abundance of high-angle PDF orientations (>45°) compared to analogous non-porous rocks (Grieve and Therriault 1995; Grieve et al. 1996; Gostin and Therriault 1997). Another factor that can have influenced the observed variation in frequency of PDF orientations is that the investigated bedrock fragment was originally located deeper (further away) from the shock wave source than the sedimentary target rocks and thus experienced lower shock pressures.

The reaction of porous rocks to shock pressures of various degrees is generally not so well constrained; generally, shock pressure calibration is based on shock effects for crystalline rocks (e.g., Stöffler 1966, 1971, 1984; Stöffler and Langenhorst 1994; Grieve et al. 1996), which may not be applicable to sedimentary rocks. This together with the heterogeneous distribution of shock effects makes a shock estimation for the matrix quartz tentative. However, according to Stöffler (1972, 1984) and French (1998), extensive melting will occur in porous rocks at shock pressures above 15–20 GPa, compared to a 50–60 GPa threshold for crystalline rocks. The reason for this is said to be due to when a shock wave passes through a porous rock more heat will be generated because more energy is absorbed by grain interfaces and pore spaces (Kieffer 1971; Kieffer and Simmonds 1980; Stöffler 1984). Thus, the lack of melt fragments or recrystallized glass in the samples indicates that the maximum pressure experienced by the studied materials was likely below 15–20 GPa. The quartz of the crystalline fragment displays PDFs exclusively oriented parallel to ω {$10\bar{1}3$} planes, although basal PDFs could be present but missed (see above), which is consistent with shock pressures of at least 10 GPa.

CONCLUSIONS

The presence of multiple sets of decorated PDFs in quartz grains oriented parallel to, for impact deformed materials typical crystallographic planes in the infill breccia of the Granby structure provides unambiguous evidence that the structure is impact derived. The decorated nature of the PDFs implies a water-bearing target. The shocked quartz grains can be divided into two groups; rounded grains found in the breccia matrix originating from mature sandstone and angular grains in fragments derived from crystalline basement rocks. The rounded quartz grains display a heterogeneous distribution of shock effects and several high-index PDF orientations. The PDFs in quartz grains from the basement rock are exclusively oriented along crystallographic planes belonging to the zone ω {$10\bar{1}3$}. The difference in frequency of PDF orientations is most likely a reflection of the different behavior under shock pressure of the two different target lithologies, rather than variation in shock pressure per se.

The absence of melt particles gives an estimated maximum shock pressure for the sedimentary derived quartz grains of <15–20 GPa. The frequency distribution of PDF orientations in quartz grains from the bedrock corresponds to pressures of about 10 GPa.

Acknowledgments—I would like to thank M. Lindström and A. M. Therriault for doing the pilot study which laid ground for this article. I am grateful to L. Ferrière for help with the universal stage. Detailed reviews by L. Ferrière and one anonymous reviewer, and editorial comments by W. U. Reimold are gratefully acknowledged.

Editorial Handling—Dr. Uwe Reimold

REFERENCES

Bruun Å. and Dahlman B. 1982. Den palaeozoiska berggrunden. In *Beskrivning till berggrundskartan Hjo NO*, edited by Wikman H., Bruun Å., Dahlman B., and Vidal G. Sveriges Geologiska Undersökning Af120. pp. 76–109. In Swedish.

Cooper R. A. and Sadler P. M. 2004. The Ordovician Period. In *A geologic time scale 2004*, edited by Gradstein F., Ogg J., and Smith A. Cambridge: Cambridge University Press. pp. 165–187.

Earth Impact Database 2009. http://www.unb.ca/passc/ImpactDatabase. Accessed 23 March 2009.

Emmons R. C. 1943. *The universal stage (with five axes of rotation)*. Geological Society of America Memoir #8. New York: Geological Society of America. 205 p.

Engelhardt W. von and Bertsch W. 1969. Shock-induced planar deformation structures in quartz from the Ries crater, Germany. *Contributions to Mineralogy and Petrology* 20: 203–234.

Ferrière L., Koeberl C., Reimold W. U., Hecht L., and Bartosova K. 2009a. The origin of “toasted” quartz in impactites revisited (abstract #1751). 40th Lunar and Planetary Science Conference. CD-ROM.

Ferrière L., Morrow J. R., Amgaa T., and Koeberl C. 2009b. Systematic study of universal-stage measurements of planar deformation features in shocked quartz: Implications for statistical significance and representation of results. *Meteoritics & Planetary Science* 44:925–940.

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.

Gostin V. A. and Therriault A. M. 1997. Tookoonooka, a large buried Early Cretaceous impact structure in the Eromanga Basin of southwestern Queensland, Australia. *Meteoritics & Planetary Science* 32:593–599.

Grahn Y., Nõlvak J., and Paris F. 1996. Precise chitinozoan dating of Ordovician impact events in Baltoscandia. *Journal of Micropaleontology* 15:21–35.

Grieve R. A. F. and Therriault A. M. 1995. Planar deformation features in quartz: Target effects (abstract). 26th Lunar and Planetary Science Conference. pp. 515–516.

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.

Kieffer S. W. 1971. Shock metamorphism of the Coconino Sandstone at Meteor Crater, Arizona. *Journal of Geophysical Research* 76: 5449–5473.

Kieffer S. W. and Simmonds C. H. 1980. The role of volatiles and lithology in the impact cratering process. *Reviews of Geophysics and Space Physics* 18:143–181.

Langenhorst F. 2002. Shock metamorphism of some minerals: Basic introduction and microstructural observations. *Bulletin of the Czech Geological Survey* 77:265–282.

Leroux H. 2005. Weathering features in shocked quartz from the Ries impact crater, Germany. *Meteoritics & Planetary Science* 40: 1347–1352.

Ormö J. and Lindström M. 2000. When a cosmic impact strikes the sea bed. *Geological Magazine* 137:67–80.

Reimold W. U. 2007. The Impact Crater Bandwagon: (Some problems with the terrestrial impact cratering record). *Meteoritics & Planetary Science* 42:1467–1472.

Reinhard M. 1931 *Universaldrehtischmethoden*. Basel, Switzerland: Birkhäuser. 118 p.

Stöffler D. 1966. Zones of impact metamorphism in the crystalline rocks at the Nördlinger Ries crater. *Contributions to Mineralogy and Petrology* 12:15–24.

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: 1. 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 observations and theory. *Meteoritics* 29:155–181.