Shock deformation in zircon grains from the Mien impact structure, Sweden

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Abstract—Recognition of impact-induced deformation of minerals is crucial for the identification and confirmation of impact structures as well as for the understanding of shock wave behavior and crater formation. Shock deformed mineral grains from impact structures can also serve as important geochronometers, precisely dating the impact event. We investigated zircon grains from the Mien impact structure in southern Sweden with the aim of characterizing shock deformation. The grains were found in two samples of impact melt rock with varying clast content, and in one sample of suevitic breccia. We report the first documentation of so-called “FRIGN zircon” (former reidite in granular neoblastic zircon) from Mien (pre-erosion diameter 9 km), which confirms that this is an important impact signature also in relatively small impact structures. Furthermore, the majority of investigated zircon grains contain other shock-related microtextures, most notably granular and microporous textures, that occur more frequently in grains found in the impact melt than in the suevitic breccia. Our findings show that zircon grains that are prime candidates for establishing a new and improved age refinement of the Mien impact structure are present in the impact melt.

INTRODUCTION

The identification of shock metamorphic features in minerals is crucial for confirming terrestrial impact structures, and has pushed the boundaries of our understanding of the impact cratering process (e.g., Osinski and Pierazzo [2012] and references therein). Studies have traditionally been focused around quartz, and while planar deformation features (PDFs) in quartz continue to be a robust impact signature, the mineral is generally absent in mafic rocks and thus rare on other planetary bodies. Alongside quartz, zircon can serve as an important indicator of hypervelocity impact, due to its ability to develop microstructures as a response to shock deformation (e.g., Bohor et al. 1993; Moser et al. 2011; Erickson et al. 2013; Schmieder et al. 2015; Cavosie et al. 2016). Zircon is also an important mineral for geochronological dating and has provided impact ages from a number of impact structures (e.g., Moser et al. 2011; Kenny et al. 2019; Montalvo et al. 2019; Schmieder et al. 2019; Schwarz et al. 2020). Furthermore, zircon has the advantage of being able to record both high pressures and temperatures (Timms et al. 2017) and its physical and chemical robustness means that textural features can persist for billions of years. Typical features in shock metamorphosed zircon include polycrystalline/granular textures (Bohor et al. 1993; Wittmann et al. 2006; Schmieder et al. 2015), {112} twin lamellae (Moser et al. 2011; Timms et al. 2012; Erickson et al. 2013; Thomson et al. 2014), {100}-parallel deformation bands (Erickson et al. 2013), microporosity (e.g., Wittmann et al. 2006; Schmieder et al. 2015; Singleton et al. 2015; McGregor et al. 2018, 2019), and decomposition of zircon to zirconia (ZrO₂) and SiO₂ (e.g., El Goresy 1965; Marvin and Kring 1992; Wittmann et al. 2006; Cavosie et al. 2018a, 2018b). Furthermore, the presence of the ZrSiO₄ high-pressure polymorph reidite is considered unambiguous evidence of hypervelocity impact (e.g., Glass et al. 2002; Wittmann et al. 2006; Erickson et al. 2017; Timms et al. 2021 The Authors. Meteoritics & Planetary Science published by Wiley Periodicals LLC on behalf of The Meteoritical Society (MET). This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.
defined in the landscape as a lake-filled depression. Sweden (56.41812° N, 14.85785° E; Fig. 1a) and is defined in the landscape as a lake-filled depression. Mien was first recognized in the late 19th century by Nils Olof Holst by its ring-shaped appearance, unusual rock types, and occurrence of ballen silica (Holst 1890). The primary theory was that the structure was a remnant of a Tertiary volcano (Holst 1890), which was more or less accepted until findings of shocked quartz containing PDFs (Engelhardt and Stöffler 1965) and coesite (Svensson and Wickman 1965) confirmed a hypervelocity origin of the structure.

The original rim-to-rim diameter of Mien has been estimated to be 9 km (Åström 1998) and the current topographic diameter is ~6.5 km. The structure is filled by a lake with a maximum depth of 42 m (Stanfors 1969), and is associated with a 5 mGal concentric negative gravity anomaly (Vogel 1973).

The island Ramsö, located in the western part of the lake (Fig. 1a), is suggested to be a remnant of the central uplift of the original complex impact crater (Åström 1998). The central area of the lake is also distinguished by the presence of a strong positive magnetic anomaly (Henkel 1982) which was assigned to the presence of an impact melt sheet (Henkel 1982). Due to the lack of exposed outcrops, impactite samples from Mien generally derive either from erratic boulders found in glaciofluvial sediments around the lake (Bottomley et al. 1978; Henkel 1982; Ekelund and Engström 1990; Schmidt et al. 1997; Berczi et al. 2001) or from sampled sections of two available drill cores obtained from Ramsö (e.g., Stanfors 1973). The drill cores consist of an ~20 m thick layer of impact melt rock (commonly referred to, although erroneously, as “Mien rhyolite”) with varying clast content, followed by an ~1 m thick horizon of suevitic breccia and brecciated target rock at the base of the cores (Stanfors 1973). The impactites have been subjected to extensive alteration; this is not seen in the unshocked country rock around the lake or in other Precambrian rocks in the area (Welin 1975).

The bedrock in the area is part of the Blekinge–Bornholm orogeny, and dominated by Precambrian (1.8–1.4 Ga) monzogranite and granite (Wahlgren and Stephens 2020), although rhyolite also occurs north of the lake (Claeson and Juhojuntti 2009). The granites are medium to coarse grained and consist of quartz, K-feldspar, and plagioclase, and titanite, zircon, and apatite as accessory minerals. Secondary constituents include chlorite, epidote, and sericite. The so-called “Mien rhyolite” is a commonly used name for the impact melt rock from Mien, which has caused confusion regarding the formation process of the rock, both in Swedish media (Tingsryd–Förbjuden försäljning av sten från Mien 2007) and even by the county government (Simonsson 2019). The name is a remnant from when the structure was thought to be volcanic.

Natural occurrences of reidite have been found in, for example, the Ries impact structure (Gucsik et al. 2004; Wittmann et al. 2006; Erickson et al. 2017), the Xiuyan crater (Chen et al. 2013), the Rock Elm impact crater (Cavosie et al. 2015), the Woodleigh impact structure (Cox et al. 2018), the Haughton impact structure (Singleton et al. 2015), distal ejecta from the Chesapeake Bay impact (Glass and Liu 2001; Wittmann et al. 2009; Malone et al. 2010; Cavosie et al. 2020), and the Stac Fada ejecta deposit (Reddy et al. 2015). Recently, electron backscatter diffraction (EBSD) analysis of zircon textures from two impactite lithologies (impact melt rock and suevitic breccia) from the Mien impact structure (Kenny et al. 2019), and has also been found in impact glass (Cavosie and Koeberl 2019).

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In this study, we have documented and compared zircon textures from two impactite lithologies (impact melt rock and suevitic breccia) from the Mien impact structure (Sweden), with the aim of investigating how zircon has responded to impact in this relatively small (9 km pre erosion) and heavily eroded structure. We also update the classification of the Mien impactites and establish suitable candidates for a new and improved age determination of the structure.

**GEOLOGICAL SETTING**

The Mien impact structure is located in southern Sweden (56.41812°N, 14.85785°E; Fig. 1a) and is defined in the landscape as a lake-filled depression. This high-pressure phase forms at ≥30 GPa in shock experiments (Kusaba et al. 1985; Leroux et al. 1999) and can revert to zircon at elevated temperatures (1200 °C; Kusaba et al. 1985).

Shock deformation in zircon grains 363
2. Rock clast Melt clasts Vesicles Alteration rim Mineral clasts Clastic matrix Melt matrix 5 cm Impact melt rock samples Suevitic breccia sample

b Impact melt rock samples

c Suevitic breccia sample

5 cm Sample 1702 Alteration rim Mineral clasts Melt matrix Sample 1703 Mineral clasts Vesicles Melt matrix

5 cm Sample 1707 Clastic matrix Rock clast

Granite sample (outside the topographic rim)
and should therefore be considered obsolete, also to avoid confusion with the much older, rhyolite bedrock north of the structure (Fig. 1a). Furthermore, the name “Mien suevite,” which is mostly used in older literature, remains somewhat disputed (see also discussion on this subject in Osinski et al. 2016; Osinski and Grieve 2017), which is why we use the term “suevitic breccia” for this lithology, following the last discussion on this subject in Osinski et al. 2016; Osinski and Grieve 2017), which is why we use the term “suevitic breccia” for this lithology.

To date, there have been several attempts to date the Mien impact structure (Storzer 1971; Welin 1975; Bottomley et al. 1978). The most commonly quoted age is based on $^{40}$Ar–$^{39}$Ar analysis of impactites that yielded a “pseudo plateau” of about 118 Ma (Bottomley et al. 1978). The age was later revised to 121 ± 2.3 Ma (Bottomley et al. 1990) and recently recalculated with a revised K decay constant to 122.4 ± 2.3 Ma (Schmieder and Kring 2020). The interpretation and quality of the argon data have, however, been questioned by Jourdan et al. (2009), who recommended that the Mien structure should be cited as formed at ~121 Ma.

**MATERIALS AND METHODS**

The samples used in this study consist of two cobbles and one boulder from glacial erratics. The cobble samples were collected at the southern shore of the lake (location 1 in Fig. 1; 56.392902°N 4.838016°E), and contained impact melt rock with varying clast content (Fig. 1b; samples 1702 and 1703). A boulder collected in a natural gravel pit (location 2 in Fig. 1a; 56.368815°N, 14.856186°E) south of the lake consists of suevitic breccia (Fig. 1c; sample 1701). A reference sample of the unshocked target rock was obtained from an outcrop ~2.5 km south of the lake but outside the topographic rim (56.368815°N 14.856186°E; Fig. 1d).

The impactites were crushed to a fine-grained powder and loaded onto a Willfrey-Holman 700 water shaking table in order to separate heavy minerals, following the procedure by Söderlund and Johansson (2002). A total of 288 zircon grains (between 75 and 125 grains per sample) were handpicked under a binocular microscope and mounted on carbon tape for scanning electron microscopy (SEM) imaging of grain surface textures. The grains were then cast in epoxy mounts and polished to midsection so that grain interiors could be examined. In some instances, this allowed correlation of interior and exterior surfaces of the same grain. In order to study zircon grains in situ, as well as other possible shocked phases, thin sections were manufactured from several small blocks of each impactite sample and from the reference sample. Both thin sections and the epoxy mounts were imaged with a Tescan Mira3 high-resolution Schottky field emission (FE)-SEM, equipped with secondary (SE) and backscatter electron detectors (BSE), an Oxford energy dispersive spectroscopy (EDS) system, an EBSD system, and a cathodoluminescence (CL) system, located at the Department of Geology, Lund University, Sweden.

Four fully granular grains and two grains with porous texture were selected from the impact melt rock samples for further EBSD analysis. Orthogonal grids of electron backscatter diffraction patterns (EBSPs) were acquired with an EBSD Nordlys Nano high-resolution detector, at an accelerating voltage of 15 kV, a working distance of 17 mm, and at a beam current of 10 nA. The mapping was performed at binning mode 4x4, at high gain, with band detection min/max of 6/8, a Hough resolution of 60, with step sizes ranging between 100 and 300 nm, and with match units for zircon (Hazen and Finger 1979; 1 atm), baddeleyite (monoclinic ZrO$_2$; Gualtieri et al. 1996), and reidite (Farnan et al. 2003). Before the analysis, the samples were polished with colloidal silica, coated with a 5 nm carbon layer to avoid charging effects, and mounted on a 70° pre-tilted specimen holder. Construction of orientation maps and pole figures was performed with Channel 5 software packages Tango and Mambo, respectively, from Oxford Instruments (v. 5.12). In order to remove misindexed data points, wild-spike noise reduction was undertaken on all EBSD maps. Pole figures were plotted as equal area, lower hemisphere projections, using an inverse pole figure coloring scheme to reveal misorientation between neoblasts.

Indexing of PDFs in quartz grains was performed with a Leitz five-axis universal stage (U-stage) at the Department of Geology, Lund University, Sweden, following the methods described by Engelhardt and
Bertsch (1969), Stöffler and Langenhorst (1994), and Ferrière et al. (2009b).

RESULTS

Petrographic Descriptions of Studied Impactite Lithologies

Impact Melt Rock

Both impact melt rock samples are characterized by their dark gray color and aphanitic matrix (Fig. 1b) but contain a varying degree of lithic clasts, with sample 1703 (Fig. 1b) being more clast rich than sample 1702. Petrographic studies of both samples reveal a devitrified, holohyaline matrix consisting mainly of randomly oriented lath-like microlites of plagioclase and K-feldspar (Figs. 2a–c), that frequently display quench textures. The mineral clasts consist of quartz fragments that have been recrystallized to a polycrystalline mosaic texture, rounded quartz clasts with reaction rims and a sometimes “toasted” appearance (Whitehead et al. 2002), scarce isolated rounded plagioclase grains with albite twinning, and Fe-Ti oxides. Some grains are identified as ballen silica that have been partly digested by the melt (see (Fig. 3b). Glassy fragments are usually a mixture of glass and small mineral fragments, generally with well-defined angular edges (Figs. 2d–f). The flow banding is defined by alternating dark and light streaks that contain a varying amount of small mineral fragments (e.g., Fig. 2e). A few melt clasts are less well defined, with irregular, rounded rims, and with turbulent flow textures. The lithic clast population consists of granitoid crystalline fragments (with biotite, feldspar, and quartz) and sandstone.

Reference Sample

The reference sample is part of the granite–monzogranite country rock in the area (Fig. 1d), and is dominated by fine-grained, angular shaped quartz, K-feldspar, more or less sericitic plagioclase, biotite that is occasionally altered to chlorite, and hornblende. No shock textures were found in quartz and feldspars.

SEM Imaging of Zircon Grains

SEM-SE-BSE imaging of 288 zircon grains from the impactite samples revealed that 36% of the zircon grains from the impact melt rock samples (1702 and 1703) display granular texture (Table 1). When the grains were polished to midsection, 27% contained granules visible on the interior surface. Sizes of the “host” zircon grains ranged between 30 and 80 µm, and the individual granules were, with a few exceptions, generally rounded, less than 1 µm, and relatively homogenous in size within the grain. Figure 4 shows two exceptions, where larger (~5 µm) and relatively euhedral neoblasts occurred together with smaller, rounded granules (Fig. 4a), and in where a “band” of small micrometer-sized granules cuts the longest axis of the grain, surrounded by larger, elongated granules and homogeneous regions (Fig. 4b). Furthermore, granules could occur in fractures, seemingly “underneath” the exterior of the grain (Fig. 4c). Granular textures were less common in the suevitic breccia, where 7% of grains displayed external granules, and only 3% of the polished surfaces contained neoblasts. The granules were generally smaller than in the impact melt rock and sandstone clast is visible in the lower left in the image. This clast is also visible in the lower part of the thin section in (d). f) BSE image of suevitic breccia (sample 1707) showing a hypocrystalline glass fragment in the center of the image, outlined by the dashed line, consisting of glassy streaks and occasional mineral fragments. The matrix consists of randomly dispersed, angular lithic fragments. (Color figure can be viewed at wileyonlinelibrary.com.)
Melt fragments
Lithic fragment
Impact melt rock #1703
Suevitic breccia #1707
400 µm
Mineral fragments
400 µm
500 µm
Granular zircon
Feldspar
Impact melt rock #1702
BSE
SiO₂
Granular zircon
Feldspar
Impact melt rock #1703
PPL
Melt fragments
Lithic fragment
500 µm
Impact melt rock #1702
Suevitic breccia #1707
PPL
Melt fragment
Lithic fragment
500 µm
Suevitic breccia #1707
BSE
SiO₂
zircon
Mineral fragments
Hypocrystalline glass fragment
were more sparsely distributed throughout the grain. Only one pervasive granular grain was observed from the suevitic breccia. The granules in this grain have a “sugary” appearance (Fig. 4d) and seem to only occur within a ∼20 µm sized area; when polished to midsection, the same area displays a spongy and porous interior texture, surrounded by a relatively homogeneous rim (Fig. 4e).

EDS mapping was conducted on a fully granular zircon grain in thin section from the clast-poor impact melt rock sample. This grain contained small, <1 µm, blebs (bright in BSE), identified as ZrO₂ (Fig. 4g).

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Table 1. Compilation of SEM-EBSD data of zircon grains from impact melt rock and suevitic breccia samples from the Mien impact structure.

| Sample                      | Number of grains | Manual picking—unpolished | Manual picking—polished | In thin section | % Granules on exterior surfaces | % Granules on interior surfaces | % Porous texture on exterior surfaces | % Porous texture on interior surfaces | Other shocked phases | Decomposed to ZrO₂ | Sample contains FRIGN zircon |
|-----------------------------|------------------|----------------------------|--------------------------|-----------------|--------------------------------|-------------------------------|-------------------------------------|-------------------------------------|---------------------|------------------|-----------------------------|
| Impact melt rocks (2)       | 200              | 94                         | 5                        | 36              | 27                             | 77                            | 88                                  | 39                                  | X                   | X                |                             |
| Suevitic breccia            | 88               | 37                         | 5                        | 7               | 3                              | 19                            | 70                                  | PDfs in quartz                      | Decomposed to ZrO₂ | –                |                             |

*aInterpreted to be porous (see discussion).
*bIn association with granular texture.

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Fig. 4. SEM images of representative grains with granular textures. a) A fully granular zircon grain. The close-up image shows three relatively euhedral granules, approximately 5 µm across, that sit adjacent to smaller, rounded granules. b) A zircon grain comprised of smooth, homogenous regions (left side), and a granular “tip,” with a band of small, rounded granules. c) A zircon fragment with a cluster of granules in the upper part (visible in the close-up). These granules appear to be located beneath a smooth top layer. Below the white box is a cluster of pores. d) One of few granular grains from the suevitic breccia, with small, <1 µm granules, forming a cluster with a “sugary” surface texture in the center of the grain. e) The same grain as in (d) but now exposing the interior of the grain, where triple junctions between neoblasts give the grain a porous appearance. f) A fully granular grain. Size of individual neoblasts is generally ∼1 µm, and these form several larger (∼5 µm) domains. The grain is dark in CL. g) A fully granular zircon grain from a thin section of the clast-rich impact melt rock. Granules containing ZrO₂ are visible in the close-up. ZrO₂ appears as small bright blebs (in BSE) enclosed in individual granules.
Grain exteriors - Granular texture

a. Impact melt rock (#1702)

b. Impact melt rock (#1702)

c. Impact melt rock (#1703)

d. Suevitic breccia (#1707)

Grain interiors - Granular texture

e. Suevitic breccia (#1707)

f. Impact melt rock (#1703)

BSE

CL

g. Impact melt rock (#1703)

ZrO₂
These were enclosed in individual zircon neoblasts, and mainly occurred in neoblasts adjacent to the groundmass, preferentially along the rims of a major fracture dividing the host grain into two parts.

Notably, 77% and 88% of the zircon grains from the impact melt rocks displayed exterior and interior pores, respectively (Table 1; Figs. 5a–d, 5f, and 5g). Pores were rounded and varied in size (Figs. 5a–d), from sub-μm to occasional larger ones, and could be both randomly dispersed or follow growth zonation, and sometimes appear in distinct patches (Figs. 5b and 5d). In the suevitic breccia, the difference between the exterior and interior was greater; only 19% of the unpolished grains contained pores, but when polished to midsection, pores were discernible in up to 70% of the grains. Porous texture on polished surfaces from both the impact melt rock and the suevitic breccia frequently followed interior zonation (e.g., Figs. 5e and 5f), and porous domains were dark when viewed in CL (Figs. 5e and 5f). In the suevitic breccia (sample 1707; Fig. 5e), the pore size of grains is relatively homogenous, while there is a gradual decrease/increase in pore size in grains of impact melt samples 1703 and 1702 (Figs. 5f and 5g).

Zircon grains in two thin sections from the reference sample were documented with SEM imaging, revealing primarily anhedral grains consisting of distinct bright and dark domains (Fig. S1 in supporting information). Domains that were dark in BSE were also dark in CL, and appeared to be homogenous, as opposed to the fractured, bright domains. This is typical for metamict zircon, where internal volume increase of radiation damaged zones causes fracturing in non-metamict domains (e.g., Hay and Dempster 2009). No textures indicative of shock metamorphism, such as porosity, granules, or planar features, were found.

**EBSD Analysis of Zircon Grains**

In total, orientation mapping was conducted on six granular zircon grains from the impact melt rock samples (1702 and 1703). Four of these (grains labeled 1703_02–05) are shown in Fig. S2 in supporting information. In all analyzed grains, zircon was the only indexed phase. Pole figures for four of the analyzed granular grains (grains 1703_01–04) revealed that (1) the granules systematically occur in two or more clusters, oriented in 90° perpendicular angles to one another; (2) coincidence between {110} and (001); and (3) high-angle misorientations (85–95°) coinciding with poles for {110}. This systematic relationship has been described as indicative of the reversion from reidite to zircon, and thus indirectly confirms the former presence of the high-pressure polymorph. Grain 1703_01 is a rounded, fully granular grain with a length of approximately 80 μm. The pole figures show three distinct clusters that are rotated 90° around <110> (Fig. 6). The band contrast image (BC) provides the general quality of the mapping, where crystalline areas are brighter and vice versa. The IPFz colored image shows the relative orientation of neoblasts.

Orientation analysis was also conducted on two grains that were interpreted as having porous domains (1702_01 and 1703_05; Figs. 7 and S2d). Grain 1702_01 (Fig. 7) is a rounded grain with a size of approximately 60 μm that displays compositional growth zonation, evident in CL, apart from a dark porous rim. The porous rim consists of pores of varying sizes, with a grading with smaller pores toward the edge. The pole figures show that the grain has only one main orientation, with minor misorientation in the lower part of the grain.

**DISCUSSION**

**Granular Zircon and the Former Presence of Reidite**

The data obtained from this study represent a wide variation of microtextures in zircon grains from the Mien impactites, including the first documentation of former reidite from a Swedish impact structure. The suevitic breccia sample only contained one pervasive

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**Fig. 5. BSE-SEM images of zircon grains exhibiting porous texture.**
a) Rounded grain with porous texture, better resolved in the close-up. Pores are rounded and seem to be randomly dispersed. b) Relatively euhedral zircon grain from the clast-poor impact melt rock, with three major, cross-cutting fractures, and distinct, rounded pores of varying size, up to 1 μm in diameter. c) Zircon grain with porous texture in the upper part of the grain, possibly following a zonation pattern. Part of the interior is exposed, with clearly visible, rounded pores, up to 1 μm in size. d) Rounded grain, where the part facing the camera has a porous texture. An irregular rim divides the porous domain from a homogenous, smooth domain. e) Interior of a zircon grain from the suevitic breccia. Growth zonation is visible both in BSE and CL. The two close-ups show a porous texture that follows the zonation. The porous texture cuts radial fractures that are visible on both sides of the porous domain. f) Interior of a zircon grain from the impact melt rock. Porous domains are dark in CL and display sharp boundaries toward a homogenous core. Pores are rounded and become gradually smaller in size toward the outer rims. g) Zircon grain displaying three textural features: a homogenous domain; a porous domain with rounded pores of varying size; and a “vermicular” domain, possibly representing junctions between granules.
Grain exteriors - Porous texture

- Impact melt rock (#1703) 20 µm
- Impact melt rock (#1702) 20 µm
- Porous patches
- Part of the interior exposed

Grain interiors - Porous texture

- Suevitic breccia (#1707) BSE, CL
- Gradual decrease in pore size
- Porous/metamict domain
- Radial fractures
- No pores

- Impact melt rock (#1703) BSE, CL
- Porous domain
- "Vermicular" domain

- Impact melt rock (#1702) BSE, CL
- Radial fractures
- No pores

Shock deformation in zircon grains
granular grain, and thus, all findings of FRIGN zircon were recovered from the impact melt rock samples. Natural reidite has previously been reported from, for example, suevitic breccias (Wittmann et al. 2006) and shock-metamorphosed gneiss (Chen et al. 2013; Cox et al. 2018), while FRIGN zircon has been documented in impact melt rocks (Cavosie et al. 2018b), tektites (Cavosie et al. 2018a), and impact glass (Cavosie and Koeberl 2019). Reidite formation takes place when zircon is subjected to pressures of approximately 30–52 GPa (Kusaba et al. 1985; Leroux et al. 1999), resulting in alignment of [001]zircon with <110>reidite. Reidite is known to revert back to zircon at temperatures above 1200° (Kusaba et al. 1985; Fiske 1999), following symmetrically equivalent paths, resulting in neoblasts with up to three orthogonal orientations where (001) planes are aligned with <110> directions.

Four grains from the impact melt rocks in Mien preserved evidence of reidite phase transformation; grain 1703_01 (Fig. 6) displayed three distinct clusters of 90°/<110> and grains 1703_02 and 1703_03 (Figs. S2a and S2b) displayed two dominant orientations. In both cases, (001) pole clusters were aligned with a {110} orientation. It is also noted that the orientation clusters of grains 1703_02 and 1703_04
are more widely dispersed than for the other two grains, similar to pole figures of zircon grains from impact melt rock from the Luizi impact structure, and Pantasma impact glass (Cavosie et al. 2018b). ZrO₂ was not indexed in any of the FRIGN zircon grains during EBSD analysis. However, EDS analysis confirmed that ZrO₂ occurs in the form of small, micrometer sized blebs in at least three granular zircon grains from the impact melt rocks. Thus, the granular texture formed at temperatures of >1,673 °C, which is when zircon begins to dissociate (experimentally constrained at 1 atm; Kaiser et al. 2008; Timms et al. 2017; Cavosie et al. 2018b). Impact-generated granular texture in zircon generally forms at high temperatures, during or subsequent to shock decompression, following shock pressures in excess of 30 GPa (e.g., Schmieder et al. 2015; Timms et al. 2017), and in some instances by the reversion from reidite to zircon if the zircon is subjected to post-shock conditions corresponding to shock stage IV (Erickson et al. 2017).

Previous pressure and temperature estimates of the Mien impact melt rocks have been based on the presence of ballen silica and α-cristobalite (Ferrière et al. 2010). Ballen silica is considered an impact characteristic feature as it forms during cooling, via back transformation from shock-induced states (Bischoff and Stöfler 1984; Ferrière et al. 2009a, 2010), requiring shock pressures in excess of 30–35 GPa, which is the pressure at which diaplectic glass can form (Stöfler and Langenhorst 1994). Furthermore, annealing experiments have shown that temperatures should exceed 1,200 °C to allow the formation of ballen silica (e.g., Short 1970). In

Fig. 7. A rounded grain from impact melt rock sample 1702 (grain 1702_01), with a homogenous interior and a porous rim. When viewed in CL, growth zonation is clearly visible in all parts but the rim. In the image is also the same grain with IPFx coloring and a band contrast image to show the relative quality of the EBSD data. Pole figures below only display one orientation domain (i.e., no internal misorientation). (Color figure can be viewed at wileyonlinelibrary.com.)
our study, ballen silica and quartz with PDFs were identified in thin sections from both lithologies.

There is a clear trend in our data with a higher percentage of granular zircon grains in the impact melt rock samples than in the suevitic breccia sample (Table 1). Impactites with larger fractions of melt are more likely to contain recrystallized zircon, as the zircon–melt contact facilitates such reactions (e.g., McGregor et al. 2018).

**Porous Zircon Textures**

There is no exact definition of the impact-induced “porous texture,” and descriptive terms that have been used for zircon grains with interior and exterior pores include, for example, micro- or nanoporous texture (Singleton et al. 2015; Timms et al. 2017), spongy texture (Nasdala et al. 2009), vesicular or microvesicular texture (Wittmann et al. 2006; Hauser et al. 2019), and degassing texture (Zhang et al. 2011). In this paper, we prefer to call it porous texture, as it does not imply a specific formation process.

Porous texture is frequently found in zircon grains both from impact and nonimpact settings. Pores confined to chemical growth zones within zircon have been documented by several authors (e.g., Wayne et al. 1992; Hay and Dempster 2009; Singleton et al. 2015), and the formation is often interpreted to be a response to a higher degree of metamictization in these zones (Geisler et al. 2007; Hay and Dempster 2009) as radiation damage has been shown to lower the chemical and physical stability, possibly promoting the formation of both porous and granular textures. Impact-induced porosity in association with radiation-damaged zones is supported by radial fractures that are crosscut by a porous domain (Fig. 5e). In this grain, the porosity follows a zonation that is dark when viewed in CL, and thus interpreted to represent a more metamict area.

Impact-associated porous texture has also been interpreted as the result of degassing in a ZrSiO$_4$ melt (Wittmann et al. 2006). Zhang et al. (2011) argue that the porous texture observed in granular zircon grains from the lunar meteorite Dhofar 458 is the result of melting and degassing processes, and thus prefer the name “degassing texture.”

When a granular grain is polished so that the interior is exposed, triple junctions between neoblasts will give the grain a porous appearance (e.g., Bohor et al. 1993; Hauser et al. 2019; McGregor et al. 2020). Hauser et al. (2019) conducted EBSD analysis of zircon grains that they had identified as porous through BSE imaging; EBSD data revealed that all porous grains consisted of neoblasts, and furthermore, the neoblasts preserved systematic orientations indicative of FRIGN zircon. In this study, we present EBSD analysis both of zircon grains with a pervasive granular texture (Figs. 6 and S2a–c) and of grain interiors with a porous texture (Figs. 7 and S2d). The granular grains were identified as being FRIGN (grains 1703_01-04), while the (solely) porous grains with pores confined to, for example, growth zonation displayed no distinct misorientation (grains 1702_01 and 1703_05). This shows that EBSD is a useful tool to distinguish between apparent porosity (granules polished to mid-section) and porous texture that formed, for example, through metasomatic alteration in metamict domains. In this study, all samples contained a substantial amount of porous grains on polished surfaces (70% and 88% of zircon grains from suevitic breccia and impact melt samples, respectively).

**Implications for Geochronology**

Altogether, the interpretation of the textures will have important implications when selecting grains for U-Pb dating. Although shock metamorphism does not guarantee resetting of the U-Pb isotopic system, it is an expected response in zircon grains with a FRIGN texture as these can be considered neocrystallized (Kenny et al. 2017, 2019; Hauser et al. 2019), making them prime candidates for U-Pb dating. However, recent U-Pb results from the Sääksjärvi impact structure (Kenny et al. 2020) revealed that the most promising grains for precise age determination derived from porous domains in zircon grains, and not from the granular domains as expected. This highlights that both granular and/or porous zircon grains from the impact melt rocks should be targeted for U-Pb dating.

**CONCLUSIONS**

The results of our study show that (1) the high-pressure polymorph reidite was present in zircon grains from impact melt samples from the Mien impact structure and (2) that a majority of the zircon grains in the impact melt contained microtextures such as granular and porous textures. We relate both of these textures to the impact event. Furthermore, a comparison between exterior and interior surfaces of individual zircon grains showed that porous texture seems to be more common on interior surfaces, both in suevitic breccia and impact melt rock, while granular texture was found more frequently on exterior surfaces, independent of lithology. These findings highlight the advantage of examining both grain exteriors as well as grains polished to midsection. The finding of “FRIGN” zircon in impact melt rock from
Mien is the first reported discovery of the former presence of reidite in a Swedish impact structure. Despite the fact that the Mien impact structure is heavily eroded and relatively small, and thus limited in the amount of preserved material, several granular zircon grains were found in the impact melt samples that exhibit a characteristic phase relationship between reidite and zircon.

There is to date no satisfactory age determination for the Mien impact event and since little work has been done previously on this structure in terms of mapping out and describing shock textures, this study lays the ground for future geochronological dating on selected samples.

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Additional supporting information may be found in the online version of this article.

**Fig. S1** SEM images of zircon grains from the reference sample.

**Fig. S2** EBSD orientation maps of four grains.