The hydrothermal breccia of Berglia-Glassberget, Trøndelag, Norway: Snapshot of a Triassic earthquake

Axel Müller[1,2*], Morgan Ganerød[3], Skule Olaus Svendsen Spjelkavik[4] &
Rune Selbekk[†]

[1]Natural History Museum, P.O. Box 1172 Blindern, N-0318 Oslo, Norway (a.b.mueller@nhm.uio.no)
[2] Natural History Museum of London, Cromwell Road, London SW7 5BD, United Kingdom
[3] Geological Survey of Norway, P.O. Box 6315 Torgard, 7491 Trondheim, Norway
[4] NTNU University Museum, Department of Archaeology and Cultural History, NO-7491 Trondheim, Norway
[†] Deceased 4 December 2017

Introduction

Breccias are fragmented rocks which are commonly found in the highest, most fluid-saturated part of the crust, where brittle deformation is dominant (*e.g.* Sibson 1977, 1986). They occur across a wide range of settings: sedimentary breccia, impact breccia, fault breccia (gouge, cataclasite, pseudotachylite), hydrothermal breccia, hydrothermal-magmatic breccia, and purely magmatic breccia. The study of mineralized hydrothermal and hydrothermal-magmatic breccias have been of major interest for ore deposit research due to their potential of hosting economic mineralization (*e.g.* Sillitoe 1985; Taylor & Pollard 1993; Fournier 1999; Landtwing *et al.* 2002) whereas studies of non-mineralized breccias are more scarce. However, understanding the nature and genesis of breccias is important not only economically but also in the context of regional tectonics and earthquake prediction. Brecciated fault zones, for example, preserve a rich historical record of seismic faulting; a record that is yet to be fully studied and understood (*e.g.* Sibson 1986, 1989; Roberts 1994; Cowan 1999; Micklethwaite & Cox 2004; Woodcock *et al.* 2007).

In this contribution, the quartz-K-feldspar-cemented, hydrothermal breccia of Berglia-Glassberget in Trøndelag, Norway, is studied. The Berglia-Glassberget breccia is barren in terms of economic commodities, but famous among mineral collectors for being a large and rich site of high-quality crystal quartz of various colours and habits found in open cavities (Ewensson 2000; Nordrum 2002b; Jørgensen 2003). The mineralization is rather unique in respect to its geological setting: It occurs within Late Palaeoproterozoic rocks of the Lower Allochthon of the Norwegian Caledonides regionally isolated from any other contemporaneous hydrothermal or magmatic activities. The breccia formation post-dates the Caledonian deformation and a hydrothermal mineralization of such young age (<390 Ma) has not been described from central Norway. The aims of this study are to better understand the formation of the Berglia-Glassberget breccia in terms of pressure-temperature-composition (P-T-X) conditions, the origin of breccia-cementing fluids, the age of breccia, and the circumstances which have led to the breccia formation. Finally, the results are discussed and evaluated to place the breccia-forming event in a regional context.

Geology and mineralogy of the Berglia-Glassberget breccia

Geographically the breccia of Berglia-Glassberget is situated in the Lierne municipality in the Trøndelag county of central east Norway. The breccia is hosted by Late Paleoproterozoic mylonitic (very fine-grained), greyish to pinkish metarhyolite of the Formofoss nappe complex. The breccia forms an appr. 250 × 500 m large, ellipsoid structure comprising a dense network of randomly orientated, breccia-filled, mainly quartz-cemented and subordinate K-feldspar-cemented fractures (3 cm to 4 m wide). Most of the area is covered with post-glacial soil, woods and swamps. The area of most intense brecciation is found in the SW of the structure which is named breccia center in the following. In the center the fragmented metarhyolite is strongly silicified and dark grey to black in colour instead of pinkish grey. The borders of the breccia structure are transitional: the fractures getting thinner and less common with increasing distance from the breccia center. The randomly orientated fractures hosting hydrothermal breccias are mainly matrix-supported except parts of the breccia center, with 0 to 75 vol.% clasts, 25 to 100 vol.% matrix, and 0 to 80 vol.% open space (cavities). The lithology of the breccia fragments is exclusively metarhyolitic (monomictic) corresponding to the closest wall rock. The size of clasts is highly variable ranging from millimeter-scale to meter-scale (Fig. 1A). The cavities contain quartz crystals of varying quality, mostly milky quartz with common crystal sizes of 0.5 to 5 cm (Fig. 1B). The deposit produced high quantities of collector quality crystal quartz specimen of different colour and habit over a period of about 100 years (Ewensson 2000; Nordrum 2001, 2002a, 2002b, 2003a, 2003b, 2005, 2007, 2008; Jørgensen 2003; Figs. 1C and D). Calcites of different shapes and colours have been found in some cavities. In addition, albite, galena, rutile, and laumontite have been recorded. The northeastern part of the mineralization has been known by local mineral collectors since its discovery. In the 1980s and 90s collectors as Inge Rolvsen, Egil Skaret and Harald Kvarsvik started to take out quartz crystals for the mineral collector market. In the late 1990s Lars Jørgensen leased the area for systematic collection of specimens. In 2005 large cavities (up to 3 × 3 × 4 m in size) with smoky quartz were discovered in the southwestern part of the breccia structure (breccia center; Fig. 1B). Despite the intense collection activities there is unfortunately very little documentation and literature about the mineralization (Jørgensen 2003).

Results

The structural characteristics classify the Berglia-Glassberget mineralization genetically as fault-related, fluid-assisted hydraulic breccia formed by a single pulse stress typically for the upper crust levels (*e.g.* Sibson 1977; Jébrak 1997). Such fault rocks represent implosion breccias, formed by the 'sudden creation of void space and fluid pressure differentials at dilational fault jogs during earthquake rupture propagation' (Sibson 1986, p. 159). The influx of fluids into fault zones can trigger short-term weakening mechanism that facilitate fault movement and earthquake nucleation by reducing the shear stress or frictional resistance to slip (*e.g.* Collettini *et al.* 2008). The development of fluid overpressures at the base of the fault zone can help to facilitate fault slip, which was likely the cause for the Berglia-Glassberget breccia formation. The seismic energy released by brittle failure lead to rapid, seconds-long, fragmentation and dilation of at least 30 million m^3 of metarhyolitic rock at Berglia-Glassberget. Hydraulic fracturing was mainly responsible for the rock fragmentation.

The influx of an aqueous CO_2-rich fluid coupled with a minor NaCl-KCl-bearing brine and NH_4 fraction (data are derived from microthermometric and petrographic studies of fluid inclusions) into the fault zone triggered the sudden fault movement. The initial temperature of the breccia-cementing fluid was in the range of 247 to 329°C. The origin of the CO_2-rich, fluid may have partially metamorphic origin due to decarbonation reactions (T >200 °C) of limestones of the underlying Olden nappe, but also deep sources, probably from mantle rocks implying that the breccia is situated on a deep-seated structure. The breccia fragments were sealed by K-feldspar-quartz cement. High percentage of open space in the breccia fractures with cavities up 3 × 3 × 4 m in size, fluid inclusion microthermometry, and trace element chemistry of quartz suggests that the breccia was formed at depths between 4 and 0.5 km (1.1 to 0.1 kbar).

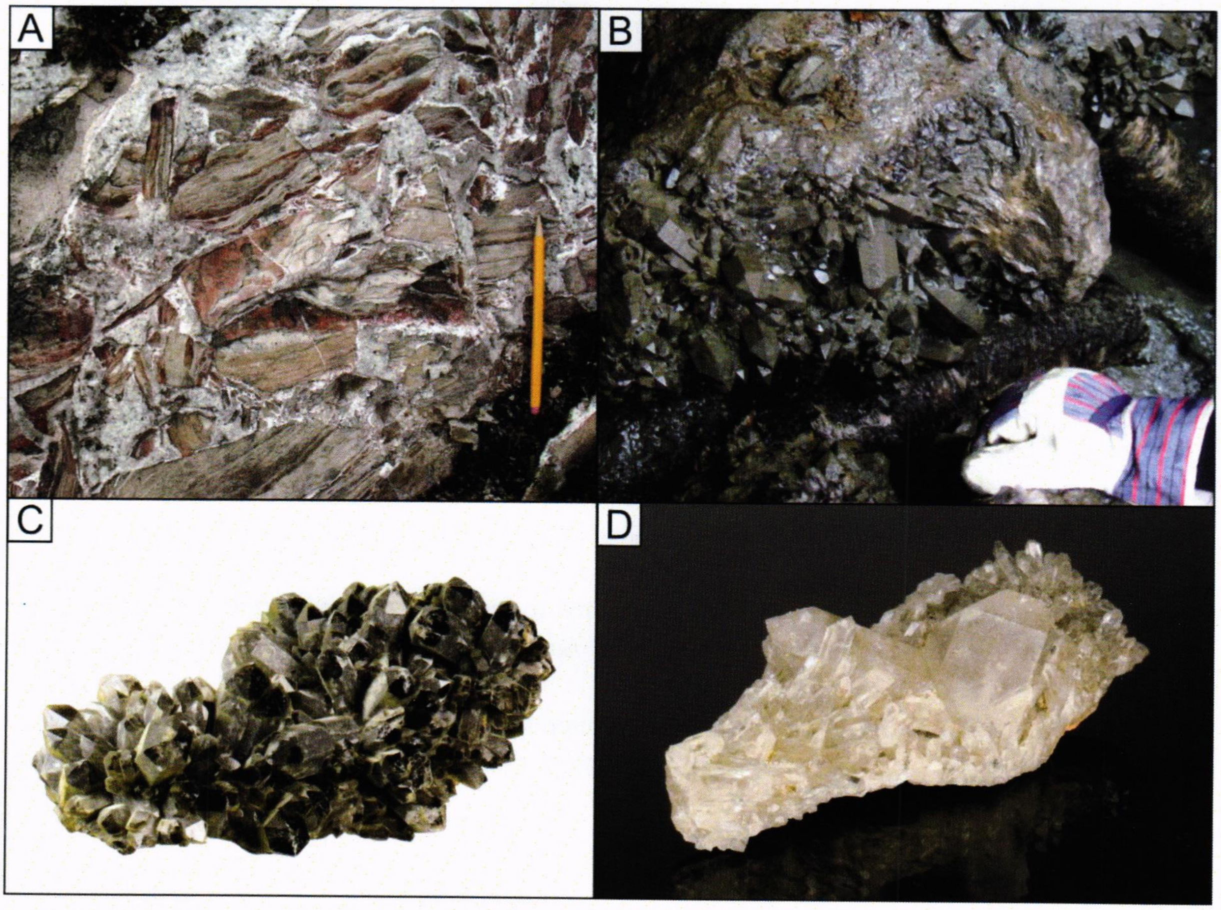

Fig. 1. Photographs of the Berglia-Glassberget breccia. ***A*** *– Outcrop in the center of the Berglia-Glassberget breccia.* ***B*** *– Recovering of a large cluster of smoky quartz crystals from the 3 × 3 × 4 m cavity discovered in 2005.* ***C*** *– Cluster of smoky quartz crystals. The length of the specimen, which was donated by Arne Jostein Devik to the Natural History Museum of Oslo, is 30 cm (NHM collection no. 41919). Photograph by Øivind Thorensen.* ***D*** *– Cluster of clear quartz crystals with a Japanese twin in the center donated by Egil Hollund to the Natural History Museum of Oslo (NHM collection no. 42418). Length of specimen 12 cm. Photograph by Øivind Thorensen.*

^{40}Ar-^{39}Ar dating of the K-feldspar cement revealed a middle Triassic age (240.3 ± 0.4 Ma) of this seismic event. However, tectonic, hydrothermal or magmatic activities of middle Triassic age have not been recorded in the vicinity of the Berglia-Glassberget mineralization which could be directly related to the breccia formation. On a global scale, the middle/late Triassic boundary (230±5 Ma) marks the incipient dispersal of Pangea by the onset of continental rifting (Veevers 1989). In NW Europe including Norway the Triassic was a period of major rifting and faulting (*e.g.* Ziegler 1981), involving many long-lived fault zones, such as the Møre Trøndelag Fault Complex (MTFC) (*e.g.* Gabrielsen & Ramberg 1979), the Lærdal-Gjende fault system (*e.g.* Andersen *et al.* 1999) and the Kollstraumen detachment (*e.g.* Nordgulen *et al.* 2002) in central Norway. Due to its regional setting it is concluded that the Berglia-Glassberget occurs at a supposed triple junction of long-lived fault zones belonging to the Møre-Trøndelag, Lærdal-Gjende and the Kollstraumen fault complexes. These fault systems and the associated Berglia-Glassberget earthquake are the expression of rifting and faulting in northern Europe during middle/late Triassic.

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