BRIDGING THE GAP: FORMATION OF VOLUMINOUS PSEUDOTACHYLITIC ROCKS IN TECTONIC AND IMPACT SETTINGS.

B. Vogt[1], Z. K. Shipton[1], and W. U. Reimold[2]. [1]Department of Civil and Environmental Engineering, University of Strathclyde, 75 Montrose Street, G1 1XJ, Glasgow, United Kingdom; [2]Museum für Naturkunde, Invalidenstrasse 43, 10115 Berlin, and Humboldt Universität, Unter den Linden 6, 10099 Berlin, Germany. Email address: brigitte.vogt@strath.ac.uk.

Introduction. In 1916, Shand proposed Vredefort, South Africa as the type locality for pseudotachylyte. The dark, aphanitic rock that resembles tachylite obtained its name from the Greek: *pseudo* “fake”, *tachos* “speedy” and *lithos* “rock”. The term’s roots suggest pseudotachylite to be spelled with “I”, however, some authors favour the traditional “Y” spelling coined by Shand.

Impactites. Only the two largest impact structures on Earth, Sudbury (Canada) and Vredefort (RSA), have developed voluminous pseudotachylitic rocks. The processes behind the formation especially of fracture and network widths >10 cm to over tens of metres, are an ongoing matter of debate [1]. Several formation processes have been proposed, such as shock compression melting, decompression melting, friction melting, injection of melt from the impact melt sheet, flash replacement melting, and acoustic fluidization.

Tectonites. The tectonic community uses pseudotachylite as a synonym for friction melt rock and trades it as "the only unequivocal evidence for paleo-earthquakes" [2]. After high velocity rock friction laboratory experiments have successfully reproduced structures and compositions resembling those of pseudotachylites in nature (e.g. [3]), these rocks gained much attention in the recent decades. Tectonic pseudotachylitic faults in nature (generally not exceeding 10cm in thickness) and micro-faults have been used to derive earthquake source parameters (e.g. [4, 5]). Much larger occurrences of pseudotachylitic rocks in tectonic settings have only been reported from three localities: the Woodroffe Thrust, Australia [6], the Ikertoq Shear Belt, Greenland [7], and the Outer Hebrides Fault Zone, Scotland, [e.g., 8]. The Outer Hebrides are commonly regarded as the type locality for tectonic pseudotachylites.

Pseudotachylites across the fields. The ambiguity of both usage and genetic implications of the term "pseudotachylite" between the two geology subcommunities hampers the advance of research in both fields. As proposed by Reimold [9] already two decades ago, we prefer a nomenclature without genetic implication and use “pseudotachylitic” solely as an adjective. The term “pseudotachylitic rocks” is used as the umbrella term for “fake tachylites” of any geometrical occurrence. “Pseudotachylitic breccias” (PTBs) feature a high matrix to clast ratio and range from cm to several tens of metres in size (no upper limit). “Pseudotachylitic micro-faults” bear thicknesses of mm to cm. They too contain clasts of the host rock, however, of much smaller size.

Based on fieldwork in the Outer Hebrides, Scotland, this paper outlines structural similarities of pseudotachylitic rocks in both geological settings, poses open questions relevant to both scientific fields, and advocates for closer interaction between the two communities. The focus lies on pseudotachylitic breccias of decimeter to meter scale (the breccia and quasi-conglomerate of Sibson [4]), which have gained little attention in the tectonic literature.

Results. In a one kilometre-squared area on the Northwest coast of Barra, Outer Hebrides, Scotland, about two thirds of the outcrops are characterized by PTBs, as shown in Figure 1. The PTBs generally occur in zones of decimeter(s) to several meters (up to at least 15 m) in thickness extending over several tens up to hundreds of meters in length, which are oriented parallel to the foliation of the host Archean gneiss. They contain up to over 1 m large, often rounded and fractured clasts of the host rock. The amount of displacement could not be established due to the lack of reliable markers. Between these zones, pseudotachylitic micro-faults dominate, often forming networks. Locally, the pseudotachylitic matrix constitutes as much as over 30% of rock in an outcrop. The estimate of total volume of pseudotachylitic matrix for the mapped area is as high as 14%.

Figure 1. *Pseudotachylitic breccia (PTB) from the Outer Hebrides, Scotland. Length of Hammer 80cm.*

On meso- and micro-scales, the host rock shows a prevailing brittle behaviour, including curved fractures, dilational fractures, branching fractures, and fracture sets resembling indentation fracture systems. Curved fractures point to a dynamic or thermally induced stress field and may facilitate formation of primarily rounded clasts. Some of the pseudotachylitic fractures grade into (ultra)cataclasite. Dilational pseudotachylitic fractures were found as sets of en echelon fractures ("injection veins") and in perpendicular arrays, indicating (local) tensional stress regimes. Point indentation fractures suggest high point loads (high differential stresses), indicative of their formation after initial brecciation. The clasts show pervasive brittle deformation, with common fractures parallel to pseudotachylitic veins.

Flow structures resembling "magma mingling", clast rotation, and melting textures were also found, pointing to a fluid state of the pseudotachylitic matrix during formation. Flow structures are related to compositional differences in terms of abundance of clasts and mineralogy. Some of the single grain clasts show embayed grain boundaries, which is an indicator for melting. Both micro- and meso-scale clasts are rotated with respect to their host and to neighbouring clasts.

Radiometric isotope analyses (Sm-Nd and Rb-Sr) demonstrate that the pseudotachylitic matrix originates from their immediate host rock, and they are geochemically distinct from the similar looking and very abundant Tertiary dyke intrusions (results to be published elsewhere, B. Vogt).

Discussion. The high abundance of pseudotachylitic rock, the large lateral extent of PTBs and their thicknesses are uncommon for tectonic pseudotachylitic faults. The meso- and microstructures – the brittle behaviour of the host rock and clasts, the dilational fracturing, the rotation of clasts – are very similar to structures observed in impact PTBs.

The process of formation by frictional heat induced melting has been established for pseudotachylitic *micro*-faults (thicknesses in the mm-range). After the production of a continuous melt film, the interface friction coefficient drops and therefore further melt production is prevented. Sibson [4] suggests formation of PTB by progressive displacement from network forming pseudotachylitic micro-faults. This, however, requires significant displacement and continuous melt production on micro-faults feeding the PTBs. Continuous PTB layers extending over several hundred metres occur both in the investigated field area and in large impact structures. Typical displacements of the largest recorded earthquakes are up to 10 m [10]. Menke et al. [11] estimate that the maximum displacement during the 2004 Sumatra-Andaman M_w 9.1 earthquake locally exceeded 30 m with rupture velocities up to 2.8 km/s. Using the linear relationship $d=4h$ between displacement d and thickness h of pseudotachylitic faults elaborated by Wenk [5] (for pseudotachylitic micro-faults), a 30 m displacement corresponds to a pseudotachylite thickness of 7.5 m, which is half the thickness of several of the observed PTBs on the Outer Hebrides.

TEM analyses of PTBs from the Outer Hebrides by Wenk et al. [12] show intense brittle deformation, very high dislocation densities in quartz and feldspar, and microstructures closely resembling cold-worked material. The observations point to deformation under conditions of very high strain rates at relatively low temperatures. Non-equilibrium effective mineral melting temperatures can be lowered to approximately 0.4 of the bulk melting temperature by increase of vacancy concentration [13]. Efficient brittle comminution and crystal lattice distortion by high strain rate deformation may effectively lower the melting temperatures, especially of minerals with low fracture toughness, allowing for "low temperature melting".

Conclusions. The appearance of the PTB occurrences on Barra in terms of volume and structures more closely resemble the pseudotachylitic breccias documented from the terrestrial impact structures Vredefort and Sudbury [14] than tectonic pseudotachylitic rocks which have been used to derive earthquake source parameters.

The possibility that the Barra PTBs are related to an impact event should not be excluded, even though shock metamorphic evidence remains to be identified. However, and more importantly, the processes behind the formation of pseudotachylitic rocks need to be adressed more carefully. A distinction needs to be made between pseudotachylitic micro-faults, which are used as a synonym for produced by frictional melting, and pseudotachylitic breccias. For PTBs, additional processes are required to explain the formation of these considerable volumes of matrix. Both impact and tectonic communities will profit from a comprehensive and concertedly used terminology, and a collaborative discussion about the variety of processes involved in the formation of pseudotachylitic rocks.

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