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Controls of host rock mineralogy and H_2O content on the nature of pseudotachylyte melts: Evidence from Pan-African faulting in the foreland of the Gariep Belt, South Africa

S.H. Büttner [a,*], S. Sherlock [b], L. Fryer [a], J. Lodge [a], T. Diale [a], R. Kazondunge [a], P. Macey [c]

[a] Department of Geology, Rhodes University, Grahamstown, South Africa
[b] Centre for Earth, Planetary, Space & Astronomical Research (CEPSAR), Department of Earth and Environmental Sciences, The Open University, Milton Keynes, United Kingdom
[c] Council for Geoscience, P.O. Box 572, Bellville 7535, South Africa

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Late-orogenic Pan-African tectonics formed an 8 km long fault-fracture zone in the shallow foreland crust of the Gariep Orogen in Mesoproterozoic granitoid basement. Pseudotachylyte was locally formed during a single seismic event that caused brittle failure in cohesive quartz-diorite, granodiorite and granitic gneiss. $^{40}Ar/^{39}Ar$ laser spot analysis provides an age of 512.5 ± 7.5 Ma for this seismic event. The depth of the hypocentre between 1700 and 5300 m is inferred from the likely thickness of the overlying rock at that time. Abundant quartz melting in conjunction with low host rock temperature indicates a minimum seismic temperature rise exceeding 1030 °C but in some samples dry quartz melting at temperatures exceeding 1700 °C might have been possible. The abundance of hydrous phases in the host rock controlled the volume of melt produced in a given host rock type. Different types of primary melt were formed by the fusion of batches of host rock with different relative proportions of plagioclase, alkali feldspar, quartz, biotite, and, where present, amphibole or garnet. The chemical and physical interaction between these melts depended on contrasting melt mobility and viscosity. In quartz-diorite, glasses of variable composition are well preserved and show the distribution of primary melt species at the time of quenching. These different melt species had limited tendency of mixing, unless mixing was assisted by syn-seismic shearing. In granodiorite, which has a low proportion of hydrous phases, low-viscosity melt was formed at high temperatures, eliminating most host rock fragments and leading to extensive melting of quartz. The low melt viscosity, probably further decreased by the dissolution of free H_2O, permitted effective melt homogenisation in such veins. Still in the liquid state these melts segregated, effectively separating secondary melts of sodic–calcic and of K–Mg–Fe-rich composition. After quenching the solid state diffusion of cations in glass was comparatively insignificant.

1. Introduction

The investigation of tectonic pseudotachylytes provides a wide range of opportunities to study the nature of, and conditions prevailing during, seismic slip along fault zones (e.g., Maddock, 1983; Lin, 1994, 2008, and references therein). The kinematic analysis of brittle faults in conjunction with ^{40}Ar–^{39}Ar isotope analysis of pseudotachylyte as time constraints for seismic activity is an effective combination of tools to unravel the tectonic evolution of the seismogenic crust (e.g. Kohút and Sherlock, 2003; Sherlock and Hetzel, 2001; Sherlock et al., 2008, 2009; Tagami, 2012). The nature and composition of pseudotachylyte glass allows the investigation of a variety of physical parameters, such as the magnitude of frictional heat production and its post-seismic dissipation (e.g., Andersen and Austrheim, 2006; Ikesawa et al., 2003; Kirkpatrick et al., 2012; Lin, 2008) or the mechanical influence of melt on the slip process (e.g., Di Toro et al., 2006; Spray, 1993, 2005).

Heat, and subsequent melt production, generated by seismic friction along pre-existing or newly generated fault surfaces is controlled by physical and chemical factors. Important physical parameters are those controlling the shear strength of the faulted rock, which, in turn, control the amount of stress that can be built up before, and instantly released during, a seismic event. These are the rock type, the orientation of the regional stress tensor with respect to the slip plane, pre-seismic fluid pressure, and the depth of the hypocentre. If a sufficient amount of stress is released at a high rate of displacement, the amount of heat generated might be sufficient to fuse the rock. In addition to these physical parameters, the likelihood and extent of melting depend on the melting temperature of mineral phases that are heated, whereby hydrous phases have a considerably lower melting point compared to anhydrous phases (e.g. Spray, 2010).

This study describes features related to frictional fusion formed during an isolated and small seismic event at shallow crystal level. We provide

* Corresponding author. Tel.: +27 46 6038775.
E-mail address: s.buettner@ru.ac.za (S.H. Büttner).

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some estimates of the physical environment in which pseudotachylyte was generated, such as the approximate depth of the hypocentre, and the approximate stress magnitudes leading to seismic failure, for which the regional geological situation and ^{40}Ar–^{39}Ar age data provide important information. However, the main focus lies on the influence of the host rock composition on the nature and amount of melt generated, and on the physical and chemical behaviour and interaction of different liquids formed at high syn-seismic temperature.

The small, for the regional geological evolution insignificant, seismic event provided an environment of limited seismic displacement that supported the preservation of a variety of textural and compositional patterns in pseudotachylyte that large displacement magnitudes probably would have destroyed. We present data and observations that identify the impact of the abundance of phases with low melting points, such as biotite and amphibole (e.g., Lin, 1994; Spray, 2010), and of free H_2O, on the amount and nature of melt that could be generated in different granitoid host rocks.

Energy Dispersive Spectroscopy (EDS), Electron Probe Micro-Analysis (EPMA) and X-ray Fluorescence Spectroscopy (XRF) provide data for detailed geochemical modelling of the sources and the origin of different glasses, which shows that different primary melts form from host rock batches of different modal composition, varying at small scale. This information, in conjunction with textural observations, provides qualitative information about melt mobility and viscosity, and the interaction of different melts in the liquid state. Furthermore, geochemical modelling and textural observation allow identifying glasses that cannot have formed from primary melts but must be the result of melt dissociation.

Technical details of micro- and whole rock-chemical analysis, argon isotope analysis, and information on some aspects of data processing, are provided in the Appendix, where we also describe the criteria which we have used to identify glass in the investigated pseudotachylytes. Structural data are reported as dip direction/dip angles for planar fabrics and as trend/plunge values for linear structures and stress vectors. Symbols for rock forming minerals and endmembers of solid solutions are used according to Kretz (1983).

2. Regional geological setting

The Neoproterozoic Pan-African orogeny in south-western Africa reworked the western margin of the Namaqua Metamorphic Province (NMP), a medium- to high-grade metamorphic granite-gneiss terrain (Fig. 1a) which formed and consolidated during high-temperature orogenic events in the Palaeoproterozoic and the Mesoproterozoic (~1.8 Ga and ~1.3–1.0 Ga; e.g., Eglington, 2006). The Pan-African event was associated with an early and prolonged period of extensional tectonics, rifting and sedimentary and oceanic basin evolution (~770–580 Ma; Frimmel et al., 2001; Frimmel, 2008). Consumption of the Adamastor Ocean in the west led to back-arc extension and sediment deposition in the Gariep Basin, which was followed by the collision of the Rio de la Plata and the Kalahari cratons and long-lasting contractional tectonics (~600–495 Ma; Blanco et al., 2011; Frimmel, 2008; Frimmel and Frank, 1998; Gresse et al., 2006).

The late-Neoproterozoic Nama Group, having formed in a foreland basin related to the Pan-African orogen (e.g. Blanco et al., 2011; Frimmel et al., 2011; Gresse and Germs, 1993; Grotzinger and Miller, 2008), covers large areas east of the Gariep Belt in Namibia but has been largely eroded on South African territory. The seismic event discussed in this paper occurred in the Namaquan basement that at the time was overlain by the sedimentary rocks of the Nama Group.

Relics of the Nama Group are preserved as 600–700 m thick sub-horizontal strata in a narrow belt west of Springbok (Marais et al., 2001; Fig. 1a) that overlie discordantly the Namaquan basement at topographic altitudes between ~840 m a.s.l. in the south and ~1000 m a.s.l. in the north. In southern Namibia, sub-horizontally layered sedimentary rocks of the Nama Group are exposed ca. 40 km north and northeast of the study area (Fig. 1a). This sequence comprises the Kuibis, Schwarzrand and Fishriver Subgroups with a total thickness of ca. 1450 m in south-eastern Namibia (Grotzinger and Miller, 2008) and nearby on South African territory. Here, the unconformity between basement and Nama sedimentary rocks lies at about 850 m a.s.l.

The Nama Group's deposition started with the earliest Kuibis sediments at about 555 Ma and ended with the youngest members of the basin infill, the Fishriver Subgroup at 535 Ma (Grotzinger and Miller, 2008). The sediment provenance is dominantly the Pan-African orogen, in the late stages of deposition particularly exhumed volcanic arcs that were situated west of the Gariep Belt. These are now attached to the Rio de la Plata Craton (Blanco et al., 2011). The distribution of the Nama Group in South Africa and Namibia leaves little doubt that in the Early Cambrian these rocks also covered the basement in the study area (cf. Frimmel et al., 2011).

The Pan-African belts along the west coast of southern Africa have been affected by major Neoproterozoic tectonics forming ductile shearing and medium-grade metamorphism. Crustal contraction in the collisional stage was achieved along brittle, typically N–S striking thrust and reverse faults with top-to-the-east kinematics (Frimmel and Frank, 1998). Extensional tectonics during Mesozoic Gondwana breakup reactivated Pan-African contractional faults (Macey et al., 2011). Further N–S striking faults are common between the coast and Springbok, and occasionally are present further to the east (Agenbacht, 2007; Marais et al., 2001), but these have not been investigated as to their kinematics or their age. They may be either late-Pan-African faults, or be related to the Mesozoic Gondwana breakup. The latter is the case for normal faults in the Loeriesfontein area, where also occasional E–W striking faults of possible Pan-African age occur (Macey et al., 2011). However, some faults intersect the Phanerozoic Karoo sedimentary sequence. The eastern boundary of abundant Pan-African brittle tectonics, with abundant north–south striking faults, can be placed west of Springbok (Fig. 1a), ~200 km west of the fault-bound pseudotachylyte that is the object of the present study. Little is known about Pan-African, or any other post-Namaquan tectonics east of this Pan-African tectonic front.

3. Geological setting of faults and pseudotachylyte characteristics

The dominant lithostratigraphic unit that is transected by the pseudotachylyte-bearing fault zone is the Twakputs Gneiss (Moen and Toogood, 2007), an alkali feldspar megacrystic garnet- and sillimanite-bearing S-type granite that underwent regional syn-magmatic and localised post-magmatic shearing. The Twakputs Gneiss contains some biotite and minor cordierite, but its main mafic phase is almandine-rich garnet that forms up to 1.5 cm large crystals. The Twakputs Gneiss shows internally some variation and may range from granitic to syenitic in composition. Associated with the Twakputs Gneiss are lenses of biotite-rich and amphibole-bearing quartz-diorite, leucogranites and granodiorite bodies of tens to several hundred metres in size (Fig. 1b). The quartz-diorite can be distinguished on the satellite image as a markedly darker lens compared to the surrounding Twakputs Gneiss (Fig. 1b). Minor phases in all granitoids in the study area are magnetite, apatite and ilmenite.

This basement is overprinted by ~N–S and NW–SE trending ductile shear zones and mylonites that show synkinematic sillimanite but no white mica, suggesting upper amphibolite facies minimum conditions of deformation, which indicate their formation during the late Mesoproterozoic Namaquan event. One of these is the Hartebees River shear zone (Fig. 1a) which forms a regional-scale curving structure that is cut-off by the ~1104 Ma Naros Granite (Mdze et al., 2011) about 4 km NW of the study area. Shear zone 1 (Fig. 1a, b) essentially shows dextral strike-slip kinematics with variably but always shallow-plunging transport lineations in southwest dipping shear planes. Shear zone 1 is offset along shear zone 2 which shows east-down normal displacement.