# EXPERIMENTAL INVESTIGATION OF SHOCK EFFECTS IN A METAPELITIC GRANULITE.

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**Introduction:** Shock experiments were performed on a high-grade, migmatitic, garnet-cordierite metapelite from the Etivé aureole, Scotland, to (1) characterise shock effects in a complex polymineralic rock with a significant proportion of hydrous ferromagnesian minerals, both as a function of variable shock pressure and pre-shock temperature, and (2) explore the effects of shock impedance contrast between component minerals on the distribution of these features. Shock experiments were performed at 12, 25, 30 and 60 GPa at 25°C, and at 25 GPa at 400°C. Observations will be central to the characterisation of shock and post-shock metamorphic effects in the Steynskraal metapelites from the Vredefort dome, South Africa.

**Methodology:** Shock recovery experiments were conducted at the Ernst-Mach-Institute at Weil a. Rhein. Laboratory techniques have been described in detail elsewhere [1, 2]. Thin sections of the shocked material were then studied using optical and scanning electron microscopy to determine the shock metamorphic effects in component minerals (planar fractures - PFs, fracture arrays, planar deformation elements - PDFs, onset of isotropization, formation of diaplectic glass, and shock melting).

The unshocked sample comprises quartz (25 vol%), garnet (5 vol%), biotite (10 vol%), plagioclase (15 vol%), K-feldspar (15 vol%), cordierite (25 vol%), and orthopyroxene (5 vol%), with accessory hercynite, ilmenite and pyrite. Grain size typically varies from 0.1 to 1 mm. The sample exhibits a granoblastic texture characterised by polygonal grain boundaries and triple junctions. A weak foliation is defined by cordierite-rich bands alternating with quartz-feldspar bands. Biotite and orthopyroxene commonly occur as aggregates in the quartz-feldspar bands. Locally, orthopyroxene is replaced by a quartz-biotite symplectite. Feldspar is largely unaltered, whereas cordierite exhibits a negligible degree of pinitisation along grain boundaries. Pyrite has been partially altered to goethite along cleavage and, as such, exhibits a banded appearance. A weak parting parallel to dodecahedral crystal faces is present in some garnet grains. The sample contains a few widely-spaced and discontinuous grain-boundary fractures.

**Results:** At *12 GPa and 25°C*, irregular, shock-induced fractures were generated in all phases, with fewer PFs parallel to cleavage in K-feldspar. Rarely, single sets of PDFs occur in quartz and K-feldspar. Fracturing is most intense in K-feldspar, plagioclase and cordierite against garnet, with density increasing toward the garnet contacts. Biotite is kink-banded, and shows PFs parallel to the basal cleavage. Orthopyroxene exhibits irregular shock fractures. Fracture density in minerals increases in the order: quartz, garnet, orthopyroxene, spinel, ilmenite, pyrite, quartz-biotite symplectite, plagioclase, K-feldspar, cordierite.

At *25 GPa and 25°C*, cordierite is completely converted to diaplectic glass. Plagioclase, K-feldspar and, to a lesser extent, quartz are partially to completely transformed to diaplectic glass. Up to three sets of PDFs are present in all partially isotropized quartz grains. Biotite is kink-banded with PFs both parallel and normal to cleavage. Orthopyroxene exhibits random, irregular, open (>5 μm) shock fractures together with a fine network of fractures parallel to cleavage. Cordierite diaplectic glass is relatively unfractured; however, this mineral also exhibits evidence of plastic flow along lobate and diffuse grain boundaries, consistent with incipient fusion along grain margins. Spinel is characterised by irregular PFs.

At *30 GPa and 25°C*, cordierite is completely isotropic. Plagioclase, K-feldspar, and quartz have undergone complete transformation to diaplectic glass in more than 95 vol% of grains. Vesiculation and plastic flow of cordierite, biotite, plagioclase and K-feldspar along primary grain boundaries is common and indicates the onset of shock melting of these phases and subsequent mobilization of shock melts. The development of grain boundary shock melts, suggests that (1) shock pressures are distributed heterogeneously, with highest shock pressures accommodated preferentially along grain boundaries, and (2) the interaction between phases with contrasting shock impedances facilitates the onset of shock effects typically observed at higher diagnostic shock pressures in single crystal experiments [2].

Two distinct isotropic bands are evident:

1. Low relief cordierite melt and diaplectic glass bands, with highly irregular and lobate margins. Relict grain boundaries are marked by vesiculated cordierite shock melts.
2. Feldspar and quartz diaplectic glass bands. These have typically higher relief and original grain boundaries are undisturbed. Plagioclase and K-feldspar show evidence of incipient shock melting along grain boundaries, particularly adjacent to garnet, but to a far lesser extent than cordierite.

Biotite, particularly adjacent to cordierite, has melted along grain boundaries. Biotite and cordierite shock melts may be injected up to 100 μm away from generation sites into irregular shock fractures in enclosing phases. Garnet exhibits dense, irregular, shock-induced fractures, with a markedly higher density than at lower shock pressures. Phases adjacent to garnet are intensely fractured and plagioclase and K-feldspar are characterised by preferential shock melting. Limited mixing of these melts is indicated by progressive changes in melt composition between biotite, plagioclase and K-feldspar. Orthopyroxene exhibits dense, irregular shock fractures and a fine array of planar fractures parallel to cleavage. Pyrite is brecciated and locally shock melted. Fe-S shock melts may be injected up to 50 μm into the surrounding assemblage. Ilmenite exhibits shock-induced fractures parallel to cleavage ($10\bar{1}1$), but no evidence for shock melting. In places, ilmenite breccia fragments may be welded together adjacent to relict, crystalline biotite in a biotite shock melt.

At *60 GPa and 25°C*, significant melting occurs in biotite, cordierite, plagioclase, K-feldspar and pyrite, particularly adjacent to garnet where shock impedance contrast is greatest. The degree of vesiculation in phases allows determination of the extent of shock melting in specific phases. Cordierite and biotite are melted entirely, whereas plagioclase and K-feldspar diaplectic glass cores are retained and grade into vesiculated shock melt that formed from the grain margin inward. Energy dispersive microanalysis of the compositions of the shock melts suggests an exceptional degree of mixing, hybridization and melt mobility.

In the sample *preheated to 400°C* and shocked to *25 GPa*, shock effects resemble those attained at 30 to 60 GPa, namely, complete to partial isotropization of plagioclase, K-feldspar and cordierite. Cordierite exhibits evidence of shock melting along grain boundaries, particularly adjacent to garnet. Plagioclase and K-feldspar exhibit diffuse and lobate grain boundaries, indicating incipient grain boundary shock melting. PDFs are commonly developed in quartz in up to three different orientations. Quartz is partially isotropized. Unusual flow features in quartz and plagioclase may be related to plastic deformation facilitated by combination of locally enhanced shock and pre-shock temperatures. Biotite is kink-banded with incipient shock melting internally but particularly along grain margins. Biotite shock melts are injected along intragranular and intergranular shock fractures up to 50 μm from their sites of generation. Ilmenite only exhibits cleavage-parallel shock-induced fractures. Pyrite is variably fractured depending on the adjacent phases, i.e., it is intensely fractured adjacent to garnet, while markedly less fractured where included in garnet, quartz and plagioclase. Pyrite shock melts may be injected up to 50 μm from sites of generation. Orthopyroxene exhibits a greater degree of irregular shock-induced fractures than at lower shock pressures and ambient temperature.

The most obvious effect of an increase in pre-shock temperature in metapelites is the decrease in onset pressures of isotropization in quartz, plagioclase and K feldspar, and shock melting in cordierite and biotite. In samples shocked at room temperature, the latter features developed only in the 30 and 60 GPa experiments. These observations agree with [3]. The occurrence of very dense arrays of PDFs in partially to completely isotropized quartz concurs with the contention of [3] that dense PDF arrays form prior to complete isotropization during the shock transition or compressed state in preheated samples.

**Conclusions:** Shock features in cordierite, biotite, quartz, garnet, plagioclase, K-feldspar, orthopyroxene, ilmenite, and pyrite have been characterised in a polycrystalline sample with respect to shock pressure and pre-shock temperature. The polycrystalline nature of the experimental material more closely approximates reality than single crystal experiments and reveals highly heterogeneous shock effects in specific minerals as a function of shock impedance contrast with adjacent minerals. Where shock impedance contrast is greatest, shock effects typically observed at higher shock pressures and pre-shock temperatures may be anomalously developed at lower shock pressures. Shock metamorphic effects are thus constrained by: the magnitude of shock pressure, pre-shock temperature and spatial association of minerals with attendant local shock impedance contrast.

These shock experiments may be used to constrain and distinguish shock and post-shock metamorphic effects in the Steynskraal metapelites from the Vredefort dome, South Africa. The heterogeneity of shock effects observed in the experiments, as a function of shock impedance contrast, as well as mobilization of biotite shock melts, have enabled us to tentatively accommodate pseudotachylitic breccia genesis and the occurrence of K-feldspar moats enclosing plagioclase, noted by [4], via fusion and subsequent mobilization of shock melts.

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