EXPERIMENTAL INVESTIGATION OF SHOCK EFFECTS IN A METAPELITIC GRANULITE – NEW RESULTS, RAMAN SPECTROSCOPY AND MINERAL CHEMISTRY.

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Introduction: Shock experiments were performed on a high-grade, migmatitic, garnet-cordierite metapelite from the Etivé aureole, Scotland at 12, 25, 30 and 60 GPa at 25 ºC, and 25 GPa at 400 ºC. Shock effects in cordierite, orthopyroxene, garnet, biotite, plagioclase, K-feldspar and quartz have been described previously [1]. New experimental work involves shock deformation at 40 GPa and 25 °C and 17 GPa at 400 °C. Raman spectroscopy and scanning electron microscopy have been used to constrain structural and chemical phase changes with increasing shock pressures and attendant isotropization and shock melting in all experiments.

Methodology: Shock recovery experiments were conducted at the Ernst-Mach-Institute at Weil a. Rhein. Laboratory techniques have been described in detail elsewhere [2, 3]. Thin sections of the shocked material have been studied using optical microscopy, scanning electron microscopy and Raman spectroscopy to characterise the shock metamorphic effects in component minerals (planar fractures - PFs, fracture arrays, planar deformation features - PDFs, onset of isotropization, formation of diaplectic glass, and shock melting).

Summary of results: 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.

Shock effects in **biotite** with increasing shock pressure (25 ºC runs), include shock fractures parallel to basal cleavage, {001} and {010} and kink-banding. At 25 and 30 GPa, biotite birefringence is diminished and a patchy appearance both in plane and crossed polarised light is exhibited. Shock melting along grain boundaries is evident at 30 GPa and ubiquitous at 40 and 60 GPa.

Quartz invariably exhibits the lowest frequency of shock-induced fractures at all shock pressures. Shock fractures are irregular and continuous across an entire quartz grain. Quartz grains appear ‘dislocated’ from the enclosing assemblage by broad grain boundary shock fractures. Partial isotropization of quartz is achieved at 25 GPa, 25 ºC, with complete isotropization at 30 GPa, 25 ºC. At 40 GPa and 60 GPa, 25 ºC, biotite and cordierite shock melts penetrate shock fractures in the quartz. In extreme cases, quartz grains are retained as ‘islands’ within highly vesiculated shock melts.

At low shock pressures, feldspars exhibit irregular shock fractures, which locally trend parallel to cleavage orientations {001} and {010}. At 25 GPa, 25 ºC, **plagioclase** is characterised by partial isotropization in a band-like array. Non-isotropized bands are highly fractured. The frequency and density of shock fractures and degree of isotropization is commonly reduced where plagioclase is included in cordierite, suggesting suppression or ‘dampening’ of the shock pressure by the cordierite. At 30 GPa, 25 ºC, plagioclase displays complete isotropization. Grain boundary shock melting is observable and is most pronounced adjacent to quartz. At 40 GPa and 60 GPa, 25 ºC, plagioclase is completely converted to a diaplectic glass core, which grades into grain boundary shock melts. Grain boundary shock melts are more voluminous and vesiculated adjacent to either quartz or garnet.

At 25 GPa and 25 ºC, **K-feldspar** exhibits incipient isotropization along grain boundaries. Shock fracture arrays in K-feldspar cores at 25 GPa are denser than in plagioclase at the same shock pressure. At 30 GPa and 25 ºC K-feldspar displays complete isotropization. Local occurrences of grain boundary shock melting of K-feldspar are observed. Plagioclase may well be more susceptible to shock melting, as suggested by shock melting of plagioclase-rich myrmekite adjacent to K-feldspar diaplectic glass. At 40 GPa and 60 GPa, 25 ºC, K-feldspar is completely isotropized, locally grading into grain boundary shock melts (commonly against quartz).

Cordierite at 12 GPa and 25 ºC exhibits a mosaic extinction and diffuse grain boundaries indicative of incipient isotropization. Smooth, broad, continuous shock fractures perpendicular to the fabric, trend across cordierite-rich bands in the sample. Shock fracture density increases toward grain boundaries. At 25 GPa and 25 ºC, cordierite is completely isotropized with negligible shock fractures. At higher shock pressures, i.e., 30 GPa and 40 GPa, 25 °C, cordierite is completely isotropized, grading commonly into vesiculated grain boundary shock melts. Shock melting is typically more marked adjacent to quartz. At 60 GPa and 25 ºC, cordierite mineral grains have undergone complete shock melting. Cordierite shock melts are highly vesiculated. These melts appear less mobile and more viscous than biotite melts, but nevertheless exhibit flow structures.

At lowest shock pressures (<25 GPa, 25°C) **garnet** exhibits irregular shock fractures only. At 30 GPa and 25ºC, broad, continuous, sub-parallel fractures are present with an intricate, subordinate, dense network of fine, irregular fractures, which locally form a polygonal array on {112}. At 60 GPa, shock fracturing is more intense and garnet exhibits an unusual birefringence.

Orthopyroxene appears to be the most robust of all phases and exhibits only cleavage-parallel shock fractures at all shock pressures. The highest density of shock fractures is observed at 60 GPa and 25 ºC. No shock melting is observed.

In the 17 GPa sample preheated to 400 ºC, shock effects in all phases resemble those developed in the samples shocked at 25-30 GPa and 25 °C. Shock effects include partial isotropization of quartz and, to a lesser extent, feldspars. Biotite is kink-banded with shock fractures generated parallel to {001}. Cordierite is completely converted to diaplectic glass with grain boundary shock melting in places. In the sample preheated to 400 ºC 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. 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. Orthopyroxene exhibits a greater degree of irregular shock-induced fractures than at higher shock pressures and ambient temperature.

Raman spectroscopy: Raman spectra were obtained at core and rim locations for all major phases shocked at 30 GPa and 60 GPa at 25°C, and at 25 GPa preheated to 400°C. Reference core and rim spectra of unshocked material were obtained for comparison. One of the most notable findings was the marked luminescence of all phases in the shocked samples. This phenomenon requires further investigation, but may prove diagnostic of shock. At 30 GPa and 25 ºC, all phases exhibit a broadening and dampening of peaks. Plagioclase, quartz and cordierite have lost all peaks in both core and rim spectra consistent with the pervasive isotropization of these phases at this shock pressure. K-feldspar preserves a minor peak in the core spectra at 517 cm^{-1}. Biotite and orthopyroxene have retained most peaks in grain cores, however, peaks in the grain margin spectra for these phases are either entirely absent or broadened and intensity is markedly suppressed, consistent with enhanced isotropization along grain boundaries. Garnet has retained only major peaks from the unshocked state, but lost minor peaks. At 60 GPa, the feldspars, quartz, cordierite and biotite have lost all peaks, indicative of shock melting and or complete isotropization. Only garnet and orthopyroxene retain major reference peaks, albeit they are markedly suppressed and broadened. Raman spectra for the 25GPa, 400 °C sample reveal an unexpected degree of relict order. Rim and core spectra for all phases except biotite and cordierite feature more robust peaks than the 30 GPa spectra. Thus, despite the earlier onset of diagnostic shock effects in the preheated sample, higher post-shock temperatures apparently facilitate a degree of annealing.

Mineral chemistry: Representative core and rim compositions of major phases in all samples were determined using a defocused beam on a Leo 1430VP scanning electron microscope with Link EDS. At highest shock pressures (>40 GPa), major component cation totals exhibit progressively increasing variance, consistent with loss of stoichiometry with shock melting and associated mechanical mixing and potentially intracrystalline/intercrystalline diffusion of components down chemical potential gradients. Evidence for diffusion in shock melts

Conclusions: Shock metamorphic effects have been characterized in a variety of common crust-forming minerals. The experiments at 400 °C, which simulate mid-crustal temperature condtions, indicate a significant decrease of between 5 and 10 GPa in the onset pressures of shock metamorphic effects in all major phases. This temperature effect needs to be taken into consideration when using shock metamorphic effects to estimate shock pressures in large impact structures that penetrated mid- to lower crustal levels (e.g., Vredefort).

References: [1] Ogilvie, P. et al. (2004) LPSC 35, #1242. [2] Langenhorst, F., et al. (2002). *MAPS*, 37, 1541-1544. [3] Langenhorst, F., Deutsch, A. (1994) *EPSL* 125, 407-420.