Pseudotachylites Generated in Shock Experiments: Implications for Impact Cratering Products and Processes

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Laboratory hypervelocity impact experiments in which quartz was shock-loaded from 42 to 56 gigapascals imply that type A pseudotachylites form by strain heating and contribute to the loss of strength of rocks in the central uplift of large impact structures. Shock impedance–matched aluminum sample containers, in contrast to steel containers, produced nearly single-wave pressure loading, and enhanced deformation, of silicate samples. Strain heating may act with shock heating to devolatilize planetary materials and destroy extraterrestrial organic material in an impact.

Meteorite impact is the most cataclysmic planetary geologic process operating in our solar system. During the formation of an impact crater, rocks are subjected to enormous transient pressure and deformation causing phase transitions, melting, and vaporization. Large impacts produce a transient cavity in the crust that immediately rebounds, forming a flat-floored crater with a central peak, or in the case of the largest impacts, a multi-ring basin.

Some impact-induced features that occur in rocks from both large and small craters have been synthesized in laboratory shock experiments (*1*). Other features found in abundance only in larger impact structures, such as shatter cones and pseudotachylites (a fine-grained, dark gray or black rock that resembles tachylite, a volcanic glass) (*2*), are difficult to reproduce in laboratory shock experiments, suggesting a significant dependence on scale. Although the pressures experienced by rocks in small and large impacts are comparable, the principal difference is in the amount of strain to which the rocks are subjected. Laboratory experiments have simulated the pressure but not the strain produced by impact. To investigate the origin of strain heating and the production of pseudotachylites, we have conducted a series of experiments using shock recovery systems that enable us to vary the strain experienced by the sample during shock loading. We produced glassy veins of black material in quartz that are analogous to pseudotachylites found in the central portion of large impact craters.

Pseudotachylites are bodies of melted and pulverized rock formed in situ by frictional melting and are found in large impact structures (*3*) and along some tectonic faults (*4*). Workers have identified two varieties of impact pseudotachylites that differ in size and timing of formation (*5*). Type B pseudotachylites are large dike- or sill-like masses (centimeters to several hundred meters in width and up to kilometers in length) and commonly occur along discrete faults. They are analogous to, though usually larger than, tectonic pseudotachylites and are formed by frictional heating as a result of large amounts of slip along a fault surface. Type B pseudotachylites have been produced experimentally with the use of friction-welding devices (*6*), demonstrating that friction melts in rock can be produced by high-speed slip along a fault surface. At the Sudbury impact structure, type B pseudotachylites (known as Sudbury Breccia) define the basin-bounding rings of the structure (*7*).

Type A pseudotachylites are smaller (<1 mm to several millimeters in width) and are found mainly in bedrock exposed in the central parts of large impact structures. They form a distinctive network of veins throughout the rock rather than occurring along discrete fault surfaces. In some cases, type A pseudotachylites are found along the surface of shatter cones (*8*). Martini reported that small type A pseudotachylites in quartzite from the Vredefort impact structure in South Africa contain coesite and stishovite (*9*). Disrupted clasts of rock containing type A pseudotachylite have also been observed in dikes of type B pseudotachylite (*5*). These features suggest that type A pseudotachylites form before type B pseudotachylites during the initial compression and excavation of the crater (*7*), but their exact mechanism of formation, and the implications for impact cratering, have not been well understood.

To achieve production of pseudotachylites, we used a sample capsule similar in geometry to those used in earlier studies (*10*) but made of aluminum instead of steel. The sample and capsule were contained by a large fixture made of a strong titanium alloy (*11*). Aluminum, with a density of 2.7 g/cm^3, has a shock impedance much closer to that of silicates (in this case quartz, density 2.65 g/cm^3) than to that of steel. The shock impedance match produces nearly a single loading pulse in the sample, rather than a reverberation or "ring-up" to high pressure, as for steel capsules. This single-wave loading produces a greater rise in temperature than the quasi-isentropic loading of a ring-up experiment and we believe more realistically approximates the single-shock pressure rise during meteorite impact. Lateral deformation of the sample takes place on release from high pressure, analogous to the deformation that occurs during the excavation stage of crater development. Despite being held in the strong Ti-alloy fixture, samples held in Al capsules undergo more than three times the radial strain of samples held in steel (*12*) and shocked to the same pressure.

We enclosed disks of synthetic high-purity cross-cut single crystal quartz [used in previous studies including (*10*)] in Al and steel capsules and shock-loaded the samples to 42 to 56 GPa (*13*) using the 6.5-m two-stage light gas gun at Lawrence Livermore National Laboratory. Samples recovered from Al capsules consisted of transparent amorphous SiO_2 cut by radial and concentric veins filled with a black glassy material (Fig. 1, A and B). The transparent regions of the sample show variable low birefringence under cross-polarized light indicating significant residual strain in the amorphous material. The regions with the highest birefringence have the densest spacing of veins. Overall, the density of veins increased with pressure. In contrast, a sample shock-loaded to 56 GPa in steel capsules was transparent throughout, showed no birefringence under cross-polarized light, and had only a few small, irregular fractures localized in the central portion of the sample (Fig. 1C). The total radial strain (*13*) of the 56-GPa sample held in Al was 60%, whereas it was only 20% for the sample held in steel and shock-loaded to the same pressure.

Analyses of the samples by x-ray diffraction and Raman spectroscopy showed that the black glass consists of a mixture of nanocrystalline Al (derived from the capsule) and Si and amorphous SiO_2. The amount of Si and Al increased with pressure, and the highest pressure sample contained 1 to 2% Si by weight (*14*). Transmission electron microscopy (TEM) images and electron diffraction patterns confirmed the presence of Si and Al crystallites, along with some crystalline Al_2O_3, and showed that the Si and Al occur as round clasts 10 to 400 nm in size in a matrix of amorphous

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SiO_2 (Fig. 2) (*15*). Raman spectra showed that the clear parts of the sample consist of diaplectic glass similar to that observed in studies of shocked quartz (*16*). The paucity of Al_2O_3 in the black glass and the absence of any detectable molecular oxygen indicates that much of the oxygen liberated by the dissociation of SiO_2 is unaccounted for. The melting of SiO_2 provides a lower limit on the temperature of the pseudotachylite in our experiments (2000 K at 1 bar), and these temperatures are similar to those required to reduce SiO_2 in soils struck by lightning (*17*).

The black glass veins made in our experiments are analogous to type A pseudotachylites found in large impact structures. Compression and development of a hemispherical transient crater cavity during meteorite impact involves bulk plastic deformation comparable to that created in these experiments but for much longer times (10^{-3} to 10^{0} s as compared with 10^{-6} s in these experiments). The rocks closest to ground zero undergo the largest amount of strain, which may explain why type A pseudotachylites are found principally in and around the central uplifts of large craters. Rebound of the crater floor and formation of the central peak or multiple rings involves significant displacement along faults rather than bulk plastic flow, explaining the production of type B pseudotachylites in discrete zones which postdate type A pseudotachylites (*7*).

Plastic deformation and the production of pseudotachylites may be an important process in meteorite impacts. Our highest pressure sample contained 1 to 2% crystalline Si by weight. TEM images suggest that the Si represents roughly 10 to 20% of the volume of black glass produced. Thus, 5 to 20% of the total sample consisted of pseudotachylite melt at a minimum temperature of 2000 K. This would substantially elevate the residual temperature of the entire sample. The formation of dense networks of type A pseudotachylites in the central portions of impact structures may similarly leave the rocks substantially hotter than predicted from Hugoniot data or postshock temperature measurements of bulk materials (*18*). If strain heating is important, as these experiments imply, the central portions of large impact structures may have a substantial static thermal metamorphic overprint. Such a feature has been reported in the rocks from the Vredefort impact structure in South Africa but has been attributed to endogenic processes (*19*). Friction-induced melting may also add to the total volume of impact melt in larger craters and may explain the reported increase in the proportion of impact melt with crater size (*20*).

Shock wave profile measurements show that when quartz is shock-loaded above the Hugoniot elastic limit (12 GPa), it is virtually strengthless on release from high pressure (*21*). The formation and persistence of melt veins may be a principal contributor to the loss of strength on pressure release (*21*). If so, the formation of type A pseudotachylites during compression and crater excavation may substantially weaken the basement rock in the center of the crater.

Finally, plastic flow and the formation of pseudotachylites might affect estimates of shock devolatilization of planetary materials on the basis of shock experiments. Experiments using steel capsules (*22*) may have prevented significant strain of the sample, thus producing lower temperatures and an underestimation of the amount of shock devolatilization with pressure. Similarly, numerical modeling of cometary impacts (*23*) may underestimate the role of strain heating in the projectile and thus may overestimate the potential for delivery of organic material by impact.

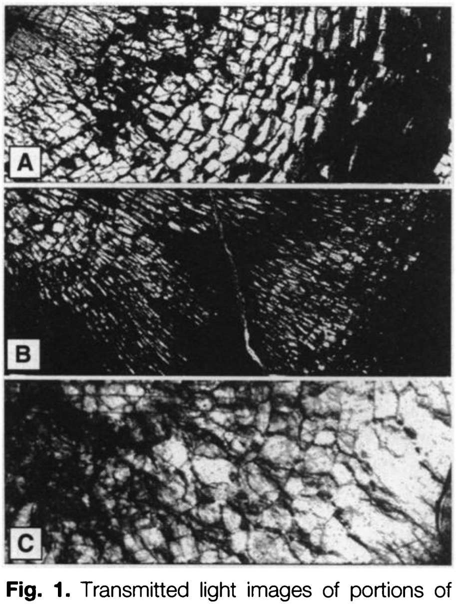

Fig. 1. Transmitted light images of portions of three disks of shock-loaded x-cut quartz viewed in the direction of shock wave propagation. Images are 7 by 2 mm. The center of each disk is in the upper left corner, and the edge is in the lower right corner. (**A**) Shock-loaded to 42 GPa in Al. The sample consists of clear regions of amorphous SiO_2 cut by radial and concentric veins filled with black glass. (**B**) Shock-loaded to 56 GPa in Al. The density of veins and the amount of crystalline Si increase with pressure. This sample contains 1 to 2% Si by weight. (**C**) Shock-loaded to 56 GPa in steel. Sample is optically clear with a few irregular fractures in the center of the disk. No Si was detected in this sample.

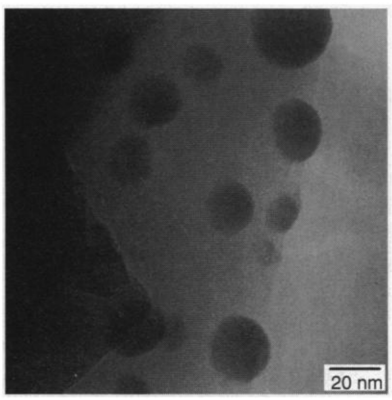

Fig. 2. Transmission electron microscope image of the black glass formed in quartz shock-loaded to 46 GPa in Al. The black glass consists of spheres of crystalline Si and Al (which appear darker) in a matrix of SiO_2 glass. Crystallites observed by TEM range in size from 20 to 400 nm.

REFERENCES AND NOTES

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11. The alloy Ti-6%Al-4%V is 45% lighter than 304 steel and has a tensile strength 40% greater. Some of these experiments were done by chilling the sample fixture to 100 K, which caused brittle failure of the outer Ti alloy fixture during release thereby producing an effective momentum trap. See P. Cordier *et al.* [*Phys. Chem Min.* **21**, 133 (1994)] for details.
12. The total strain was determined by measuring the initial and final diameter (D) of each sample. Strain was calculated as [(final D − initial D)/initial D)].
13. Shock pressures were generated by the impact of a 2- or 3-mm-thick Cu or Al impactor at velocities up to 4 km/s. Peak shock pressures were calculated by the impedance match method for the projectiles and the sample capsules. Samples were removed, mounted in epoxy, and polished. The entire sample was recovered in every experiment. Fifteen experiments were done for this study.
14. Concentrations of Si, Al, and Al_2O_3 were estimated from x-ray diffraction scans by comparisons to standards made from quartz glass with various amounts of Si, Al, and Al_2O_3. These experiments showed that the detection limit for Al_2O_3 was 1% by weight.
15. The formation of Si has been reported in a few other shock experiments in which the chemical reaction of SiO_2 with a reducing metal was involved. C. Jammes *et al.* [*Lunar Planet. Sci.* **14**, 347 (1983)] report the presence of Si and Al_2O_3 in the products of impact experiments with Al spheres and a quartz sand target. The presence of Si and Ta_2O_5 in an 800-nm reaction layer at the interface of quartz held in Ta capsules and shocked above 67 GPa was reported by M. Kikuchi *et al.* [*J. Mat. Sci. Lett.* **6**, 97 (1987)].
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Role of Transcriptional Activation of IκBα in Mediation of Immunosuppression by Glucocorticoids

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Glucocorticoids are potent immunosuppressive drugs, but their mechanism is poorly understood. Nuclear factor kappa B (NF-κB), a regulator of immune system and inflammation genes, may be a target for glucocorticoid-mediated immunosuppression. The activation of NF-κB involves the targeted degradation of its cytoplasmic inhibitor, IκBα, and the translocation of NF-κB to the nucleus. Here it is shown that the synthetic glucocorticoid dexamethasone induces the transcription of the IκBα gene, which results in an increased rate of IκBα protein synthesis. Stimulation by tumor necrosis factor causes the release of NF-κB from IκBα. However, in the presence of dexamethasone this newly released NF-κB quickly reassociates with newly synthesized IκBα, thus markedly reducing the amount of NF-κB that translocates to the nucleus. This decrease in nuclear NF-κB is predicted to markedly decrease cytokine secretion and thus effectively block the activation of the immune system.

Glucocorticoids (GCs) have been used for decades as clinical tools to suppress both the immune response and the processes of inflammation (*1*), yet the immunosuppressive mechanism by which these drugs act is poorly understood. GCs bind to a cytoplasmic glucocorticoid receptor (GR), a member of the steroid hormone receptor superfamily, which then translocates to the nucleus as a transcription factor (*2*). Transcriptional activation of cytokine and cell adhesion genes is critical in the activation of the immune and inflammation systems and is repressed by GCs (*3*). GC repressive elements, however, have not been found in cytokine promoters. In addition, the GR is able to repress the transcription factor AP-1 through a cross-coupling mechanism (*4*), yet AP-1 regulates only a small number of GC-sensitive cytokine promoters. GCs can also repress members of the NF-κB–Rel transcription factor family (*5, 6*). NF-κB–responsive elements are required for the function of many cytokine promoters (*7*), and NF-κB–responsive elements in the interleukin-6 (IL-6) and IL-8 promoters have been implicated in GC-mediated suppression (*5*). A major form of NF-κB is composed of a dimer of p50 and p65 (RelA) subunits, and this complex is retained in the cytoplasm by repressor molecules that contain ankyrin repeat motifs (*7*). These inhibitory molecules include the IκB family: IκBα, β, and γ, as well as the NF-κB precursor molecules p105 (NF-κB1) and p100 (NF-κB2) (*7–9*). Although a cross-coupling mechanism of inhibition exists between NF-κB and the GR (*5, 6*), it cannot fully explain the ability of GCs to inhibit NF-κB. Here it is shown that GCs induce the transcription of the gene encoding IκBα. The increase in IκBα mRNA results in increased IκBα protein synthesis, which effectively inhibits NF-κB activation.

We initiated this study by extending our analysis of the ability of the synthetic GC dexamethasone (DEX) to block the induction of NF-κB–like DNA binding activities in several cell types and by several different inducers. As shown previously (*6*), DEX blocks the induction of NF-κB by tumor necrosis factor α (TNF-α) in HeLa cells (Fig. 1A, left panel) as well as induction by IL-1 (*10*). The identity of this complex as NF-κB was determined by supershift experiments (*10*). DEX inhibited the induction of NF-κB in the monocytic cell line THP-1, mediated by TNF-α (Fig. 1A, middle panel) and by lipopolysaccharide (LPS) (*10*). DEX also inhibited the TNF-α–mediated induction of NF-κB in the murine T cell hybridoma 2B4 (Fig. 1A, right panel). In addition, thymocytes and lymph nodes derived from mice treated with monoclonal antibody (mAb) to CD3 in combination with DEX no longer express NF-κB activity as compared with mice treated with CD3 mAb alone (*11*). This effect of DEX requires protein synthesis, as it is blocked by cycloheximide (CHX) (Fig. 1A, right panel). DEX treatment results in a reduction in NF-κB–mediated gene expression as measured by transfected reporter constructs (*5, 6, 11*). Previous work indicated that the inhibition of NF-κB was the result in part of a decrease in nuclear translocation after stimulation with TNF-α.

We wanted to determine if the DEX-mediated reduction of nuclear p65 translocation, after TNF-α stimulation, correlated with an increase in IκBα. IκBα is rapidly degraded after TNF-α addition (*7, 12*) (Fig. 1B, top left panel) and this loss correlates with the appearance of nuclear p65 (Fig. 1B, bottom left panel). After 1 hour in the presence of TNF-α, IκBα protein begins to reappear as a result of the induction of gene transcription by NF-κB (Fig. 1B, top panel, lane 5). After pretreating HeLa cultures with DEX, we observed a small but measurable increase in IκBα protein (Fig. 1B, top panels; compare lanes 1 and 6). The average increase in IκBα protein was measured as 1.5-fold ($n = 10$). DEX pretreatment had no effect on cytoplasmic p65 amounts (*10*). In addition, DEX pretreatment slowed the disappearance of IκBα mediated by TNF-α. After 1 hour of TNF-α treatment, the amount of translocated nuclear p65 was reduced approximately 50% in DEX-treated cultures as compared with untreated cultures (Fig. 1B, bottom panels; compare lanes 5 and 10). THP-1 cultures induced with TNF or LPS gave similar results (*10*). We then considered whether DEX might induce other NF-κB–sequestering molecules such as the recently cloned IκBβ (*13*). HeLa cells cultured with DEX for 5 hours were compared with untreated HeLa cultures, and no differences were found in amounts of IκBβ (*10*). Whereas IκBβ is insensitive to TNF treatment, LPS induction for 2 hours is sufficient to induce release of NF-κB and IκBβ degradation (*13*). Pretreatment with DEX had no effect on either IκBβ amounts or LPS-induced IκBβ

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