CAN LIGHTNING STRIKES PRODUCE SHOCKED QUARTZ? G. S. Collins[1], H. J. Melosh[2] and M. A. Pasek[3], [1]Impacts and Astromaterials Research Centre, Dept. Earth Science and Engineering, Imperial College London, SW7 2AZ, UK (g.collins@imperial.ac.uk); [2]Department of Earth and Atmospheric Science, Purdue University, Lafayette IN 47907, USA; [3]Department of Geology, University of South Florida, Tampa FL 33620, USA.

Introduction: Shock metamorphism of quartz generates several characteristic features [1-3], which are collectively attributed as shocked quartz and are considered diagnostic of a hypervelocity impact cratering event [1]. Indeed, several putative impacts have been proposed based on the presence of shocked quartz in glassy samples alone [4-6].

A critical assumption of these studies is that shocked quartz cannot be produced by endogenic processes. However, metamorphism of quartz observed in fulgurites (cylindrical glassy products of lightning strikes, sometimes hollow, surrounded by a rough outer surface of melted and unmelted grains), shows some similarity to shock metamorphism [7]. For example, the Edeowie glasses were suggested to be impact glasses [5] but are likely better classified as fulgurites [8]. This prompts the question: can lightning strikes produce shocked quartz?

Lightning strikes are very energetic—a typical strike may dissipate up to 1 GJ per flash [9], a small fraction of which (~1 MJ) reaches the ground. As well as raising the temperature of the soil in the lightning channel, the deposition of lightning energy raises the pressure in the channel, accelerating material in and around the channel radially outward. This outward motion is resisted by the strength of the soil. If enough energy is deposited in the channel, and if the energy is deposited sufficiently fast, the outward propagating pressure wave may accelerate the soil more rapidly than it can respond elastically, resulting in a shockwave that might cause permanent shock metamorphic effects.

Using the iSALE shock physics code we simulated the approximate P-T-t conditions in lightning strikes. We quantified the effect of channel diameter, total energy and approximate current duration (as well as soil strength and porosity) on the radial distribution of maximum pressure and temperature.

Methods: Fulgurite modeling used the iSALE shock physics code [10, 11], a two-dimensional multi-material, multi-rheology extension of the SALE hydrocode [12]. iSALE was used in Lagrangian mode and cylindrical geometry, the computational mesh representing a 5-mm thick horizontal slice through a vertical lightning channel and surrounding soil. Freeslip boundary conditions were used on all sides, implying that along-channel movement of material was ignored. The lightning channel of initial radius r_c was resolved by at least 10 cells in all simulations (minimum cell size 0.5 mm); the results presented were not sensitive to resolution. The total mesh dimensions were 350 x 10 cells.

The thermodynamic response of the soil material was modeled using an ANEOS-derived equation of state table for SiO_2 [13], combined with the epsilon-alpha porous compaction model [11]. An initial porosity of 5-20% was assumed for the soil, together with standard compaction model parameters for sandstone [14]. The response of the soil to deviatoric stress was modeled using a simple Drucker-Prager strength model, in which the yield strength Y is a linear function of pressure p; $Y = Y_0 + fp$, where Y_0 is the zero-pressure yield strength and f is a constant related to the soil's angle of internal friction. All models assumed $f = 0.7$. In some simulations this static strength was increased as a function of increasing strain rate.

The lightning strike was simulated by a prescribed increase in the internal energy of cells within the cylindrical lightning channel. The internal energy added to the channel each time step was prescribed using:

$$\frac{dE}{dt} = \begin{cases} E_p\left(\frac{t}{\tau_R}\right)^2 & \text{for } t < \tau_R \\ E_p \exp\left(-\ln 4\left(\frac{t-\tau_R}{\tau_D}\right)\right) & \text{for } t > \tau_R \end{cases}$$

where E_p is the internal energy at the time of peak current, τ_R is the rise time of the lightning current, τ_D is the half-life of the lightning current and t is time. In deriving this equation we assumed that the lightning current rises linearly from zero to its peak value at $t = \tau_R$ and then decays exponentially, with a characteristic time to half peak, τ_D. E_p was computed by equating the integral of Eq. (1) from $t = 0$ to infinity with an assumed total energy (per unit length) deposited by the lightning E_{tot}. A parabolic relationship between energy increment and radius was used to distribute the internal energy increment across the lightning channel, from a maximum energy increment at the center of the channel to zero at the channel wall.

We quantified the effect of channel diameter, total energy and current duration on the radial distribution of peak pressure and temperature in simulated lightning strikes. A range of channel diameters of 0.5-2 cm was investigated, based on typical fulgurite diameters of 0.5-8 cm [15]. Based on observations of fulgurite formation during arcing in high rupturing capacity fuses [16], an estimated ~2kJ is needed to produce each gram of fulgurite. As fulgurites exceeding ~20 kg have been documented [15], this would imply a maximum energy deposition of 10-50 MJ/m.

The duration of a lightning flash is highly variable and can span up to a second. However, flashes are composed of one or more strokes—very brief pulses of

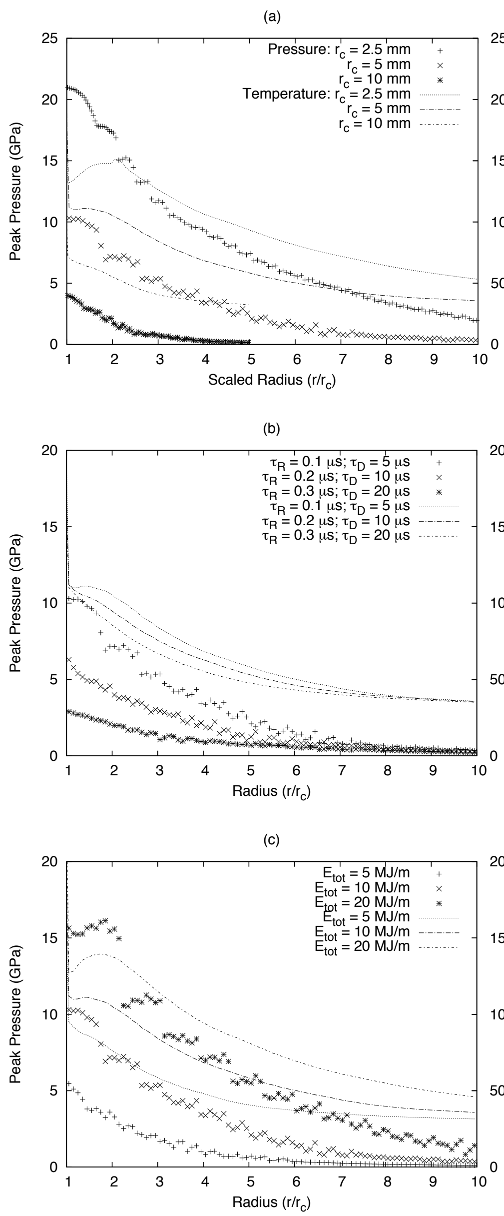

Figure 1 Results of iSALE simulations of lightning strikes in soil: (a) The effect of channel radius; (b) the effect of lightning current duration; (c) the effect of total lightning energy per unit length. Each plot shows maximum pressure (symbols) and temperature (lines) as a function of the initial radial location of the material (normalized by channel radius) for several simulated lightning strikes. Plotted in this way the results are independent of the soil yield strength, which controls only the final location of the material. In all cases the soil porosity was 20%. Unless stated, the lightning channel radius r_c = 5 mm; lightning current rise time τ_R = 0.1 μs; lightning current decay time τ_D = 5 μs; total energy deposited E_{tot} = 10 MJ/m.

high current—separated by (relatively) long periods of low current. In this work, we simulated a single lightning stroke. A typical stroke comprises a rapid rise in current, from zero to several kA in less than 1 μs, followed by a slower decline in current with a decay time of a few to a few tens of μs [18-20]. Decay times between 5 and 20 μs were considered.

Results: Figure 1 shows radial profiles of peak pressure and temperature in the soil surrounding the simulated lightning channel for a suite of different lightning conditions. Note that in these plots the radial distance is that of the original position of the material. The results illustrate that in most of the simulated cases maximum pressures outside the lightning channel do not exceed 10 GPa and shock heating alone appears insufficient to melt quartz. The fusing of quartz in "typical" fulgurite formation must instead be due to slower (but still rapid) heat transfer from the vaporized channel, which is neglected in our simple model. However, in very high-energy, short-duration, narrow-channel lightning strikes maximum pressures can exceed 10 GPa in a narrow zone outside the lightning channel. These pressures may be sufficient to cause shock metamorphism of quartz [1-3].

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