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A Brief Review on Behavior of Sandstone, Limestone and Shale Rocks under Laser Radiations

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ABSTRACT

The Laser devices convert one form of energy into photonic energy or photons which are electro-magnetic radiations. This photonic energy in the form of laser radiations has enough potential that rock destruction can be achieved by its interaction with rocks. This paper surveys research and experimentation performed in the past to study laser-rock interactions from the date laser was invented. The paper elaborates about mechanisms of rock destructions due to laser radiation interactions for sandstone, limestone and shale rocks. Laser radiations operate using three basic rock destruction mechanisms as thermal spalling or chipping at low laser power, melting or fusion at high laser power and vaporization at very high laser power for sandstone and shale rocks, whereas for limestone rocks dissociation is the mechanism of rock destruction. The paper also explains utilization of absorbed laser energy for primary processes and secondary effects in the rocks.

Key words: Laser-Rock Interactions, Rock Behavior under Laser Radiation, Laser Drilling and Perforation, Rock Destruction by Laser Radiations, Primary and Secondary Laser-Rock Interaction Processes.

1. INTRODUCTION

The term "laser" is an acronym for "light amplification by stimulated emission of radiations". A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. In 1917, Albert Einstein predicted the possibility of generation of photons via transitions between atomic or molecular energy levels [1]. Maiman invented the first working ruby laser in the year 1960 and was awarded the Nobel Prize for this invention [2]. Subsequently, many new laser systems including semiconductor lasers, Nd:YAG lasers, CO2 gas lasers, dye lasers and other types of gas, crystal and polymer drive lasers have been designed and fabricated with better reliability and durability [3].

The idea of rock destruction or rock drilling using laser radiations is not new, although there are still many technical hurdles remain to be cleared for field implementations. The earliest studies were focused on enhancing tunneling machines implemented in mining industry using lasers. Available lasers in early stage of studies were of very low power, large wavelengths producing and were unsafe for industrial implementations. Apparently, laser drilling was never considered feasible for the oil industry either.

In last few decades, the researchers have performed numerous research and experimentations to investigate behavior of different rocks under laser radiations time to time with advancement in laser systems. The effects and the extent of affected area due to interactions of laser radiations with rocks varies with the type of rocks. In other words, the absorbed laser energy for removing unit volume of rocks varies with types of rocks depending on processes happening in the rock and its effects on surroundings. The absorbed photonic energy in the rocks goes for primary processes and secondary processes in sandstone, shale and for dissociation reactions in limestone rocks during laser-rock interactions.

The amount of energy required to remove unit volume of rock can be given by specific energy (SE). For laser application SE is total energy exposed on the sample to volume of the material removed by the beam and expressed in the unit KJ/cm^3.
SE= Energy Input/ Volume removed.

2. LASER ROCK ITNERACTIONS

Three cells were prepared with different populations of the photonic energy of laser radiation goes for absorption, scattering and reflection when laser radiations interact with rocks or any other solid. The amount of energy goes in these processes depend on laser radiation properties, surface and inert physical properties of the rock and its composition. The reflection and scattering are loss of the radiation energy to environment whereas the absorbed energy determines the level of rock destruction that takes place. The small ratio of λ/d results in large fraction of scattered radiation. Where λ is wavelength of the incident laser radiation and d is the dimension of surface relief. The rock property of low reflectivity, high absorption and low thermal conductivity (compared to metal) are favourable for laser rock destruction [4]-[8].

2.1 Rock properties affecting laser rock destructions

The thermal and physical properties of the rock determine utilization of incident laser energy during laser rock interactions. The main properties are reflectivity, absorption, black body radiation, thermal conductivity, heat capacity and diffusivity.

2.1.1 Reflectivity (ρr)

Reflectivity of rocks depends on the rock composition, rock surface condition, rock colour, rock temperature, angle of incidence and wavelength of radiation. Rock surface condition includes dampness, dustiness, roughness, size of the grains, etc. Reflectivity is loss of the incident energy, therefore more refection results in less energy absorption or less rock destruction. The table shows reflectivity (ρr) of minerals when lased with a beam of visible spectrum which means wavelength (λ) range from 6.38 to 0.77 µm [9]

Table 1: Reflectivity (ρr) of minerals during lasing with visible spectrum beam (6.38 to 0.77 µm). [9], [10]

Sr. No.	Mineral	Reflectivity (ρr) in %
1	Arsenopyrite	57
2	Cinnabar	27
3	Chalcopyrite	47
4	Chromite	14
5	Galenite	43
6	Graphite	26.5
7	Gypsum	85-95
8	Hematite	25
9	Magnetite	20
10	White Limestone	80-95

Reflectivity is higher for lighter coloured rocks e.g. white limestone and lesser in darker coloured rocks such as shale. Additionally, reflectivity shows 1.5 to 3 times lower as compared to dry sample [11]. When dust covered on a surface of a rock with different reflectivity than during lasing it shows same value that of dust. For example, if white limestone (ρr=80%) is covered with dust of chalcopyrite (ρr=47%), the limestone shows reflectivity same as chalcopyrite (ρr=47%) [12]. Researchers have observed reflectivity of different minerals at different wavelength of the laser beam. The wavelength range observed shows change in reflectivity of some minerals. However, some minerals showed same reflectivity at observed different wavelength values.

Table 2: Reflectivity of minerals as a function of different wavelength (λ) [11],[13]

Sr. No.	Rock/ Mineral	Reflectivity (ρr in %) at different wavelength (λ)		
		λ =0.478 µm	λ =0.541 µm	λ =0.633 µm
1	Granite	33	33	33
2	Marble gray	30	30	30
3	Marble white	77	77	77
4	Magnetite-hematite hornstone	18	19	20
5	Magnetite martite hornstone	23	24	26

2.1.2 Absorption

The rock utilizes absorbed energy for destruction of the rock. In other words, the destruction of rocks during lasing is a function of absorbed energy. The absorbed energy goes for heating the rock which lead to induce thermal stresses and fracturing, change in chemical and physical properties and eventually destruction of the rock occurs.

The absorption coefficient depends on the composition of the rock and wavelength of radiation and varies from 10 to 1000 (cm^{-1}) for rocks. It has been observed that rock infrared radiations penetrate deeper into rock than visible radiations during lasing [4]-[8].

2.1.3 Blackbody radiations from the rocks

Any substance when get heated or achieves higher temperature becomes source of radiation itself and referred to as blackbody radiation. Similarly, the rock temperature increases during lasing and rock radiates blackbody radiations. This causes the energy to be emitted back to the surface. The blackbody radiation represents the loss of energy in the process of laser rock destruction [14]. Therefore, the blackbody radiation from the rocks during lasing is a disadvantage for laser rock destruction. The flow of blackbody radiation energy ($E_{blackbody}$) can be calculated using stephane-boltzman law modified [8],[15]

$$\mathbf{E}_{\mathbf{blackbody}} = \varepsilon \ \square \ T^4 \quad (1)$$

Where ε is the blackness coefficient, □ is a constant and T is the temperature. The blackbody energy is a strong function of temperature. The following table shows value of blackness coefficient (ε) as function of temperature for different rocks and metals.

Table 3: Blackbody coefficient for some rocks, minerals and metals as function of temperature [11],[14]

Sr. No.	Rock/Mineral or metal	Temperature (K)	Blackbody coefficient (ε)
1	Clay	343	0.8
2	Coal	373-873	0.79-0.81
3	Limestone	293	0.8-0.9
4	White Marble	313	0.95
5	Quarts, Melted, Rough	293	0.93
6	Iron, Oxidized	373	0.74
7	Lead, gray, Oxidized	298	0.28

The blackbody coefficient determines extent of emission of blackbody radiations. The quartz shows higher value of coefficient, so it emits more energy back to the surface. The higher the value of blackbody coefficient the higher the loss of energy during lasing [16], [11].

2.1.4 Thermal Conductivity

The thermal conductivity (K_f) is defined as the quantity of heat energy transmitted through a unit volume in a unit time [17]. The thermal conductivity can be calculated as following:

$$Q_x = - K_f \ (\square T / \ \square x) \quad (2)$$

Where Q_x is the flow of heat in the x direction, K_f is the thermal conductivity and T is temperature. Thermal conductivity K_f can be represented as function of bulk density as followings:

$$K_f = \frac{\rho_b^4}{9.56 \text{ x } 10^{-3}} \quad (3)$$

Where ρ_b is bulk density (g/cc) and K_f is thermal conductivity (W/m-K). A higher thermal conductivity will lead to more temperature distribution in the surroundings.

Thermal Conductivity depends on many factors which include grain contact, density, saturation, cementation, porosity and permeability of the rock sample [29] Thermal conductivity unitedly as a function of density, porosity, permeability and formation resistivity factor can be represented [29] as followings:

$$K_f = 0.60\text{x}10^{-3} \ \rho_b - 5.52\boldsymbol{\Phi} + 0.92k^{0.10} + 0.22F - 0.054 \quad (4)$$

$\boldsymbol{\Phi}$ is porosity, ρ_b is density(g/cc) and K_f is thermal conductivity (W/m-K). This equation is based on dry sample and the experimentation conducted at 20 and 100 degrees Celsius.

2.1.5 Heat Capacity

The heat capacity (C_p) is defined as the energy required for raising 1-degree kelvin temperature of one mole solid [17]. The heat capacity of sandstone and limestone are as follows [18]:

Heat capacity for Sandstone rock:

$$Cp_{sandstone \ rock} = 0.1812 + 1.452 \text{ X } 10^{-4} T - \frac{1.495 \ X10^3}{T^2} \quad (5)$$

Heat Capacity for Limestone rock:

$$Cp_{Limestone \ rock} = 0.1968 + 1.189 \text{ X } 10^{-4} T - \frac{3.076 \ X10^3}{T^2} \quad (6)$$

Where T is temperature in degree kelvin and C_p is heat capacity in kcal/kg-K. Heat capacity for any rock filled with fluid can be given as:

$$\rho Cp = (1 - \phi)\rho_{rock} Cp_{rock} + \phi \, \rho_{fluid} \, Cp_{fluid} \quad (7)$$

Where ρ_{rock}, ρ_{fluid} and ρ are density of rock, fluid and the rock-fluid system respectively.
$C\rho_{rock,}$ $C\rho_{fluid}$ and Cρ are heat capacity of rock, fluid and rock fluid system respectively, $\boldsymbol{\Phi}$ is porosity.

2.1.6 Diffusivity

Diffusivity (α) is the ability of a material to conduct thermal energy compared to its ability to store energy [17]. Thermal conductivity, heat capacity, diffusivity and bulk density can be related as:

(8)

$$K_f = \rho_b \, \alpha C_p$$

Or can be represented as

$$\alpha = \frac{K_f}{\rho_b \; Cp} \tag{9}$$

Therefore, the more heat diffusive rock will allow more heat to spread in the surrounding which lead to more laser affected region in the surrounding of lased hole. The rock with high heat capacity will absorb more energy which will result less extent of affected region.

2.2 Rock destruction mechanisms under laser radiations

When the laser radiations interact with rocks, they got reflected, scattered and absorbed. Reflected and scattered beams are the losses whilst the absorbed beams are responsible for transferring heat to rock which goes for rock destruction, physical and chemical changes in the rock and induced effects in the surrounding of lased hole [19]. The rock destruction mechanisms and physical and chemical changes in the rock depend on compositional and structural properties of rock such as rock composition, water saturation, porosity and crystalline lattice structure, rock mechanical properties such as hardness, tensile and compressive strength, elasticity and laser parameters laser power, wavelength, band absorption and laser pulse length. The destruction mechanisms and changes also depend on thermal properties of the rock such as reflectivity, thermal conductivity, diffusivity, absorption, heat capacity and thermal blackbody emissions.

Laser beams provides energy to rock and absorbed energy results in physical and chemical change in the rocks. At low power cracking and chipping of rock surface occurs which is termed as thermal spallation. Further with increasing power melting and vaporization occur [8],[14],[15],[19]. However, these are not the only processes which utilize absorbed energy, but many other processes occur such as sublimation, chemical decomposition, dissociation, crystal lattice reconstruction, shock wave formation and alteration of magnetic properties. These all processes depend on both laser radiation properties and rock surface and type of rock. Brian [20] performed linear track test on Berea gray sandstone samples, Ratcliff limestone samples and Frontier shale samples. Power density (Irradiance) was varied by defocusing the beam as the Sample was moved beneath it. Different zones of spallation, melting and mineral dissociation and vaporization have been identified with different rock samples.The power density was varied by defocusing the beam as the Berea gray sandstone Ratcliff limestone samples and Frontier shale samples were moved beneath it. Five different zones of spallation and melting found for sandstone (See in figure 1). For Ratcliff Limestone, three distinct zones of spallation, mineral disassociation or vaporization were observed, as described in the figure (See in figure 2). In the case of shale, three distinct zones of spallation and melting found with varying laser power (See in figure 3).

Iraj A. Slehi, et. al. (2007), Larkina (1976a) and sobol (1983,1995) [8],[14],15],[19], investigated effect of thermal stresses, heat dissipation and temperature distribution in the surroundings of the rocks. Thermal stresses can be divided into thermos-elastic stress during laser heating which leads to cracking and chipping of rocks and residual stress takes place in the surrounding zone as non-homogenous plastic deformation of rock. Therefore, Thermal stresses can cause rock destruction in two ways: cracking and chipping on the surface of radiation incidence and rock weakening in the surrounding. Thermal weakening occurs after irradiating rocks with low laser power (500w from CO2 lasers) which can be described as non-elastic deformation and reduction in mechanical strength (30 to 50 times depending on rock type) in the surrounding of the lased hole.

Some researchers studied melting of rocks under laser radiations. The rock melting depends on refractory properties and melting temperature of the minerals. The refractory property of a melted material describes its ability to reflect the laser beam and being resistant to decomposition by heat. This phenomenon reduces the transfer of laser radiation energy to the rocks and makes destruction inefficient.

The chemical changes during lasing include rock decomposition, vaporization and sublimation. During lasing, the phenomena of thermal rock decomposition, dissociation and chemical transformation occur in the rocks depending on their composition [8],[15]. Lasing of marble and limestone rocks lead to dissociation of the rock and CO_2 produces as a product. Sobol et al. (1983, 1995) enlisted dissociation temperature of some minerals [8],[15].

Table 4: Decomposition/dissociation temperature of minerals [8],[11],[15]

S. No.	Mineral	Temperature in degree °C
1	Calcite	885
2	Dolomite	500
3	Magnesit e	373
4	Marble	850
5	Pyrite	690
6	Siderite	282

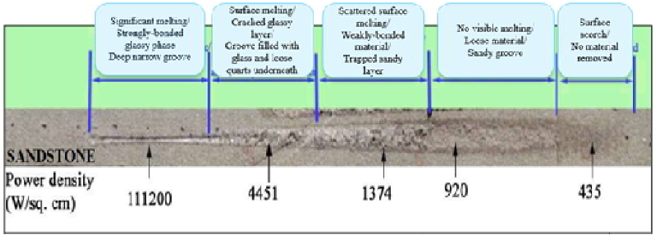

Figure 1: Linear track test of the Berea gray sandstone sample [20]

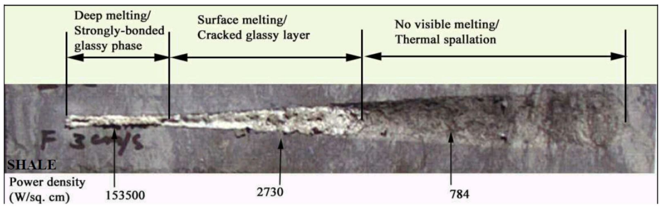

Figure 2: Linear track test of the shale sample [20]

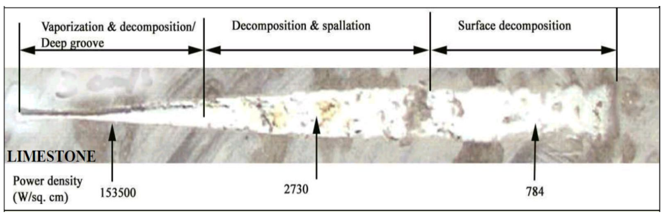

Figure 3: Linear track test of the Ratcliff limestone [20]

Some by-products resulted from rock dissociation of mineral in rocks like granite, sandstone and basalt are toxic such as volatile fluorine and chlorine and oxides of Si, AL, Pb, Fe and Mg [11]. Rock vaporization and sublimation consume more energy than melting [15]. The specific energy values for vaporization goes upto 20-40kJ/cm^3 whilst for melting SE value are generally 3-6kJ/cm^3.

Mukhamedgalieva et al. (1975, 1983, 2002) [24-26] demonstrated destruction by sublimation of minerals such as quartz, microline, nepheline, etc. Plasma and gas plumes were formed on the surface rock under laser radiations of very high power. The temperature of the outlying portion of the plasma was higher than the temperature of the area closer to the surface. It was noticed that the absorption of laser radiation energy by plasma and plume result in the decrease in rock destruction rate.

3. PRIMARY AND SECONDARY INTERACTION PROCESS-ES AND OPTIMIZED ROCK DESTRUCTION

In year 1997 Gas Research institute (Now GTI) assigned a project to group of scientists to find the feasibility of laser radiations to drill the rocks [20]. The project continued in further years sponsored by Department of energy (DOE) of USA to comprehensively understand and optimize rock destruction mechanisms by laser radiations for Sandstone, Limestone and Shale rocks [19].

3.1 Primary and Secondary laser-rock interaction processes for Sandstone, Limestone and Shale rocks

Application of high-power lasers on rocks enables the processes of spall, melt, vaporize and dissociation of the rocks during laser beam interaction. These processes of rock destruction which consumes laser energy to remove the rock are described as primary processes. The processes which consume the laser energy as an extravagance are considered as secondary processes [19].

Increase in the laser power, with a fixed beam diameter, results in phase changes and reactions in the rock, like dehydration of clays, releasing of gases and inducing thermal stresses. At a certain power, the rock will melt (fuse) and at higher power the rock will vaporize. It has been found that rock spallation is the most efficient and hence, the desirable mode for the rock destruction.

On other hand, the mechanism of laser rock interaction with limestone is different from sandstone and shale as it has different chemical composition. Thermal spallation and dissociation take place when limestone interacts with the laser radiations and produces carbon dioxide (CO2) as a byproduct. The rock gets dissociated at low power and the rate of decomposition of rock by dissociation increases with increase in laser power. The thermal dissociation process fastens with increasing laser power.

$CaCO3 \rightarrow CaO + CO2 \uparrow$

The secondary processes include loss of energy due to absorption and reflection by melt, plumes and plasma, energy dissipation in the surrounding of the lased hole etc. The raising of local temperature of the surrounding minerals to their melting points leads to form glassy melt. The amount of melt is a function of the mineralogy of the rock and inter-granular space of the rock matrix. For tightly packed grains, the heat conductivity could reach higher values dissipating the heat at a faster rate, reducing the amount of melted material. As the temperature increases, thermal energy accumulates in the grains. Grains in the matrix begin to expand (See in Figure 4) and the expansion results in developing micro-cracks within the grains [19].

Laser energy absorption by melt, plumes and plasma are type of secondary processes which can be controlled by keeping laser power lower and rock destruction can be performed by spallation mechanisms. Figure 5a, 5b and 5c are demonstrating lased hole by spallation of sandstone, limestone and shale respectively. The induced macro fractures clearly visible (5b and 5c) in sandstone and shale due to secondary effects.

Figure 4: Thin section of sandstone sample showing alteration of grains a) pre- lase b) post-lase) [19]

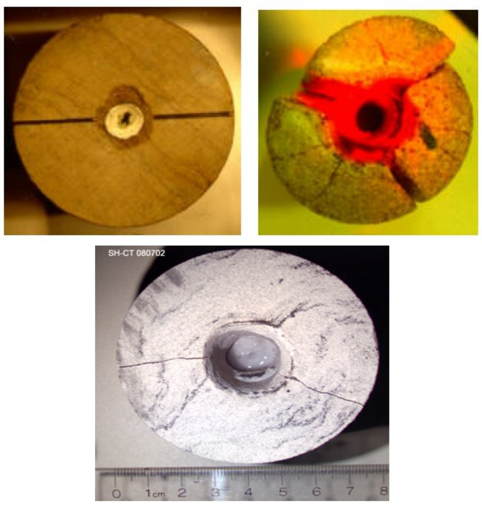

Figure 5: Laser Rock destruction by spallation mechanism a) Limestone [27] b) Sandstone [27] c) Shale [38]

The spalled rock fragments will start melting with time if not removed. Therefore, the spalled rock fragments need to be removed as they break on the rock surface. Purging system enables to do that by pressurized purge fluid nozzle. Purging fluid can be air, gas or any liquid which are transparent to laser radiation and do not absorb energy of laser radiations. The nozzle size, pressure and type of fluid are key parameters to consider optimized purging for each rock.

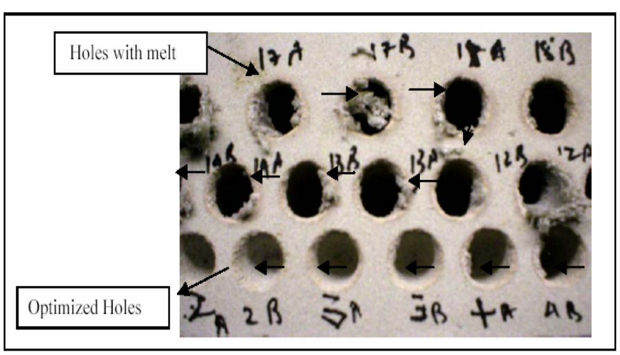

Figure 6: Holes created by changing purge type and parameters [19]

3.2 Change in petrophysical properties in the surroundings of the optimized lased hole due to secondary effects.

At low laser power, rock destruction occurs in two ways first chipping and cracking of the rock on the spot of interaction and rock weakening in the surroundings. The rock weakening depends on composition, thermal properties and structure of the rock. Lasing increases local temperature which lead to accumulation or dissipation of thermal energy in the surrounding grains which further lead to form micro and macro cracks or fractures.

The micro and macro fracture formation due to lasing depends on factors such as mineralogy, thermal properties of the rock, volume of void space, dimensions of the rock (experimental sample size) and amount of stress applied. For tight fitted grains, the grains in the matrix begin to expand and the expansion results in developing micro-cracks within the grains because of less void space to expand. Mineralogy effect on fracture formation can be described as the presence of clays in the rock. Clay contain water that, when subjected to high temperatures, will try to escape in the form of vapour. This increases the volume and pressure in the pore and can cause fractures. Sandstones and shale rocks have high thermal conductivity and contain clays. On the other hand, the limestone has low thermal conductivity and has low amounts of clay and quartz. Therefore, fractures can be expected more in sandstone and shale, and less in limestone.

Therefore, depending on thermal properties of the rock, presence of clay or water and evaporation or alteration of cementation minerals, the micro and macro fractures forming occur in rocks which consequently result in alteration of petro-physical properties in the surrounding of rocks

Table 5: Comparison of Change in petrophysical properties before and after lasing [27]

Sr. No.	Sample	Permeability (md)		Porosity (%)	
		Before Lasing	After Lasing	Before Lasing	After Lasing
1	Berea Yellow Sandstone	7754	7914	0.25	0.4
2	Berea Gray Sandstone	554	674	0.18	0.35
3	Sandstone Reservoir	11.1	30.1	0.18	0.4
4	Limestone Reservoir	0.02	0.02	0.02	0.02
5	Shale	0.43	0.55	0.01	0.03

The sandstone and shale rocks represent significant changes in petro-physical properties due to laser interactions. Shale contains less quartz, high clay and other temperature sensitive mineralogy, which lead to high increase in porosity and permeability with compare to other rocks.

4. CONCLUSIONS

The rock destruction by laser radiation includes various physio- chemical reactions and changes depending on rock composition and laser power. The laser energy expenses depend on thermodynamic properties thermal conductivity, reflectivity, heat capacity, absorption and black body radiations. It also depends on melting and vaporization point of associated minerals to the rock. The key parameter specific energy helps to understand the expense of energy for primary and secondary processes. The amount of energy required to remove unit volume of rock can be given by specific energy (SE). For laser application on rocks, SE is total energy exposed on the sample to volume of the rock material removed by the beam and expressed in the unit KJ/cm^3.

SE= Energy Input/ Volume removed

Based on discussion made in this paper and literature reviewed on laser-rock interactions or laser drilling/perforation, the following conclusion can be given

•The measured SE increases very quickly with the beam exposure time indicating the effects of energy consuming secondary processes.

•Shale samples recorded the lowest specific energy values as compared with limestone and sandstone samples.

•Two rock removal zones, spallation and melting, were identified in the shale sample data with the least required SE occurring at the point prior to melting.

•Each rock type has a set of optimal laser parameters to minimize SE as observed in the linear track tests.

•Rates of heat diffusion in rocks are easily and quickly overrun by absorbed energy transfer rates from the laser beam to the rock.

•As absorbed energy outpaces heat diffusion by the rock matrix, local temperatures rise to the minerals' melting points and quickly increase SE values.

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