FROM REGOLITH TO ROCK BY SHOCK

SUSAN WERNER KIEFFER
Dept. of Geology, University of California, Los Angeles, Calif., U.S.A.

Abstract. A model for shock-lithification of terrestrial and lunar regolith is proposed that accounts for: (1) observed petrographic properties and densities of shock-lithified material from missile impact craters at White Sands, New Mexico and from Meteor Crater, Arizona; (2) observed petrographic textures of lunar soil and lunar soil analogues experimentally shocked to known pressures in laboratory experiments; (3) theoretical calculations of the behavior of air and water under shock compression; and (4) measured Hugoniot and release adiabat data on dry and wet terrestrial soils and lunar regolith. In this model it is proposed that air or an air-water mixture initially in the pores of terrestrial soil affects the behavior of the soil-air-water system under shock-loading. Shock-lithified rocks found at Meteor Crater are classified as 'strongly lithified' and 'weakly lithified' on the basis of their strength in hand specimen; only weakly lithified rocks are found at the missile impact craters. These qualitative strength properties are related to the mechanisms of bonding in the rocks. The densities of weakly lithified samples are directly related to the pressures to which they were shock-loaded. A comparison of the petrographic textures and densities of weakly lithified samples with textures and densities of 'regolith' shock-loaded to known pressures suggests that weakly lithified terrestrial samples formed at pressures well under 100 kb, probably under 50 kb. If terrestrial soils are shock-loaded to pressures between 100 and 200 kb by impact events of short duration, the pore pressure due to hot air or air-water mixtures exceeds the strength of the weak lithification mechanisms and fragmentation, rather than lithification, occurs. At pressures above 200 kb, lithification can occur because the formation of glass provides a lithification mechanism which has sufficient strength to withstand the pore pressure. During shock-lithification of lunar regolith at pressures below 50 kb, the material is compressed to intrinsic crystal density and remains at approximately that density upon release from the shocked state. It is proposed, however, that at pressures in excess of 50 kb, the release of trapped volatiles from lunar soil grains into fractures causes an expansion of the regolith during unloading from the shocked state.

1. Introduction

Many returned lunar samples contain evidence that they were formed by *construction* from smaller particles rather than by *destruction* of larger particles. Among these samples are the breccias (microbreccias, regolith breccias) and agglutinates. Textures of some of these samples such as the shocked breccias and microbreccias (Chao, 1971; Christie *et al.*, 1973) and the agglutinates (McKay *et al.*, 1972) suggest that the samples may have formed by lithification of regolith particles during impact events. The construction of larger particles from smaller ones during the passage of a shock wave is called *shock-lithification.* The purpose of this paper is to relate the various mechanisms by which material is shock-lithified in terrestrial analogs of the lunar regolith to specific conditions of cratering and, thereby, to make more specific the possible conditions of formation of 'rock' from 'regolith' by shock processes on the lunar surface.

Shock-lithified material is defined here as material which is formed by construction from preexisting individual grains *during the time* when the pressure in the regolith is above ambient due to an impact. During even very mild shock compressions grains are generally crushed, with the result that the shock-lithification process is a complex one and includes not only the aggregation of grains along preexisting surfaces but

The Moon **13** (1975) 301–320. *All Rights Reserved*

also the assemblage of small freshly crushed fragments. (According to this definition, bulk melting of regolith material is a shock-lithification process; however, vaporization of regolith grains with subsequent condensation of the vapor after pressure release is not considered to be a shock-lithification process.)

Shock-lithification processes are related to detailed shock histories of individual regolith particles around impact sites. In a porous regolith the detailed structure of a shock wave propagating radially away from an impact is controlled *primarily* by the pore structure of the regolith and only *secondarily* by compositional differences of regolith particles (Kieffer, 1970, 1971). Deformation occurs primarily around collapsing pores or along grain boundaries and lithification processes are generally initiated at grain boundaries. In order to demonstrate the effect of porosity on regolith lithification mechanisms, I will describe here mechanisms of lithification observed in shocked soils from missile impact craters at White Sands Missile Range, New Mexico and in shocked Coconino Sandstone, a quartzite with initial porosity of approximately 20%, from Meteor Crater, Arizona. The strength of the Coconino Sandstone is due to overgrowths of quartz on the original detrital grains and is negligible in shock processes at pressures above the Hugoniot elastic limit of about 10 kb, because, at these pressures the grains are crushed or otherwise metamorphosed before lithification occurs. Hence the Coconino Sandstone is a good *textural* analogue to lunar regolith material.

In hand specimen, shock-lithified Coconino Sandstone samples at Meteor Crater are of two types which are best characterized by a qualitative measure of their strength. The samples are called here simply by the terms ‘strong’ and ‘weak’ which refer to the strength of the material in hand specimen. These qualitative strength properties are related to the detailed mechanisms of lithification, as discussed in Sections 2 and 3 below.

The *strongly lithified* material, found in abundance on the flanks of the crater and in shaft dumps on the crater floor, typically cannot be broken with bare hands (unless along cleavage surfaces). Specimens of this material are always compositionally of Classes 2, 3, 4, and 5 of shocked Coconino Sandstone (Kieffer, 1971). The most weakly shocked fragments of strongly-lithified material (Class 2) formed at pressures of about 50 kb. The most strongly shocked fragments (Class 5, vesicular glass) formed at pressures near or in excess of 500 kb. The properties of strongly shock-lithified material are summarized in Section 2. A detailed model of the conditions of its formation can be found in Kieffer (1971) and Kieffer *et al.* (1975, in preparation).

The weakly-lithified Coconino Sandstone, found only in regions of Meteor Crater that have been protected from erosion (that is, mainly within the shaft dumps on the crater floor) is friable and is easily broken by hand or finger crushing. It is called Class 1b shocked Coconino Sandstone (Kieffer, 1971) and is believed to have formed at pressures between 10 and 50 kb.

Weakly shock-lithified material is also found in abundance around missile impact craters formed in soils at White Sands, New Mexico; however, strongly lithified material is absent. The absence of strongly lithified ejecta at the missile impact craters is puzzling, because the pressures inferred for the impacts are relatively high; for example, molten droplets of aluminum from the projectiles are found around some of the impact sites, indicating that pressures of several hundred kilobars were generated within the projectiles. Induced pressures can be estimated for one impact for which the velocity of the missile can be specified. This missile impacted into gypsum sand at 3.9 km s^{-1}. Although the Hugoniot curve of gypsum has not been measured, a reasonable estimate of the *minimum* pressure induced in the gypsum sand by the impact may be made by considering a one-dimensional impact into a dry soil with porosity and mineral density similar to the gypsum, e.g., NTS playa material with a density of 1.55 g cm^{-3} (Anderson *et al.*, 1966, p. 37). Since gypsum is a hydrated mineral ($CaSO_4 \cdot \cdot 2H_2O$), its Hugoniot actually may be more similar to wet, rather than dry, soil. In this case, higher pressures would be estimated. An aluminum projectile impacting dry NTS playa material with a velocity of 3.9 km s^{-1} will generate an initial pressure of 200 kb. At 200 kb, porous materials are compressed to densities greater than the intrinsic crystal density (e.g., Anderson *et al.*, 1966). Severe shock deformation is therefore expected and, as shown below, is not found in the missile impact ejecta. As will be discussed below, its absence appears to be related to the response of terrestrial soils, which contain air and, sometimes, water, to shock loading.

The weakly shock-lithified material is described and estimates of the pressures to which it was shock-loaded are presented in Section 3. A model for the formation of shock-lithified material under terrestrial and lunar environments is given in Sections 4 and 5.

2. Strongly Shock-Lithified Material

Material becomes strongly lithified when contact between grains or grain fragments is created at an atomic scale over large surface areas by (1) the formation of glass, or (2) the growth of new crystalline phases. The pressures and temperatures under which strong shock-lithification can occur vary from conditions at which total melting of the regolith is produced (average pressures on the order of, or exceeding, 300 kb) to those at which new phases are produced only locally (average pressures as low as 50 kb). These conditions are summarized in Table I.

Bulk melting of regolith material is the highest pressure form of shock-lithification. Bulk melting results in mobilization and mixing of many individual regolith grains and is usually accompanied by ejection of the melt from the crater. Laboratory experiments with impacting spheres at velocities of 6 km s^{-1} (Gault *et al.*, 1963) demonstrate that melting may occur either in an initial jet, which emanates from the surface between the meteorite and regolith at the first moment of impact, or in a zone of high pressure (average pressure equal to or greater than $\sim$300 kb depending on the porosity of the regolith) surrounding the penetration path of the meteorite (e.g., Gault and Heitowit, 1963). The melt which is ejected from the crater may contain inclusions of shocked and unshocked lithic fragments incorporated either during ejection, or, if the melt is still liquid or plastic, upon landing. Lunar agglutinates are generally believed to have formed from melt generated in this way (McKay *et al.*, 1972).

TABLE I

Shock-lithification mechanisms at impact craters in regoliths

Crater zone			Possible lithification mechanisms
1. Complete melting	Decreasing pressure, increasing distance from center of crater, or less energetic event	Strong mechanisms	Bulk melting and mixing of regolith components; jetting at projectile-target interface; crystallization of melt possible.
2. Partial melting			Melting of compressible components or components with low melting temperatures; pressure melting; jetting into pores; crystallization of melt possible; (recrystallization possible).
3. High pressure phase formation.			
(a) with melting upon release adiabat.			Melt formed from high pressure phases; (recrystallization possible).
(b) w/o melting upon release adiabat.			High pressure phases formed and retained.
4. Mixed phases			High pressure phases formed and retained; thetomorphic glass formed.
5. Low pressure phases.			
(a) Incipient vaporization of noncondensible gases			In a regolith system with noncondensible gases, escape of gases may preclude shock lithification
(b) Fracturing		Weak mechanisms	Mechanical locking; electrostatic attraction; pressure welding; possibly, glass or new phase formation in very small regions.
Post-shock			Recrystallization and devitrification; recondensation of vaporized rock components.

Melting of local components of the regolith (individual grains or parts of grains) may occur at lesser pressures than required for bulk melting and may contribute to shock-lithification processes by binding together grains or grain fragments in contact with the melt. Local melting usually involves only minor transport and mixing of material and therefore lithifies material *in situ* in contrast to the bulk melting process. Local melt can be produced by any of the following mechanisms: (1) pressure melting (e.g., at point contacts or in regions of high shear, such as grain boundaries); (2) melting of compressible components (e.g., melting of framework silicates, such as plagioclase, at pressures where pyroxene grains are unmetamorphosed except for fracturing); (3) inversion and/or melting of high pressure phases (e.g., melting of coesite (Kieffer *et al.*, 1975)); (4) jetting upon collision of grains during pore collapse in the regolith (Kieffer, 1975). In addition, (5) the formation of thetomorphic glass lamellae within crystalline grains lithifies, or at least prevents the disruption of fractured fragments of regolith material which are confined between the lamellae.

New crystalline phases may be formed under a variety of shock conditions, none of which are well known. Stable high pressure phases, high pressure phases which have reverted to glass, recrystallized phases, and devitrified phases all have been observed in ejecta from impact craters. Some of these phases form during shock compression; others in the rarefaction. Recrystallization and devitrification may occur long after the shock has passed. All contribute to lithification of regolith, but for processes which occur after passage of the rarefaction, the term 'shock-lithification', as defined in this paper, is not correct. 'Thermal lithification' or 'post-shock-lithification' are more appropriate terms. Such post-shock lithification processes may destroy the record of shock processes leaving a record only of a thermal event.

The formation of strongly lithified Coconino Sandstone occurred under shock-loading to pressures as low as 50 kb (Kieffer, 1971) – well below the pressures induced at the missile impact craters, where no strongly lithified rocks were formed. In the Coconino Sandstone, lithification at pressures below 200 kb is largely due to the formation of high pressure crystalline phases, since at these pressures large amounts of melt were not generated. Since the growth of high pressure phases of quartz, and probably of other silicates, in a shock wave is sluggish, the formation of strongly lithified rocks below about 200 kb may be restricted to cratering events of long duration, i.e., to large cratering events. In impact events of short duration, the only strong lithifying mechanism possible in silicate materials may be the formation of glass, which generally requires pressures above about 200 kb. The duration of the shock generated by the missile impacts may have been too short to allow the growth of high pressure phases. The lack of strongly lithified material at the missile impact craters may therefore be accounted for by (a) pressures too low for the formation of melt, and (b) shock durations too short for the formation of crystalline high pressure phases.

3. Weakly Shock-Lithified Material

In weakly shock-lithified terrestrial 'regolith' samples glass or shock-induced crystalline phases are not detectable at the scale of petrographic observations. The samples all have some porosity.

The processes which create weakly shock-lithified material are less well-defined than those which create strongly shock-lithified material. In an effort to describe the conditions under which such material is formed and the mechanisms by which it is lithified, I have collected and examined weakly shock-lithified samples from four missile impact craters at White Sands, New Mexico and from Meteor Crater, Arizona.

The missiles formed craters (Figure 1) in unconsolidated soils which varied in composition (see Moore (1969) for a description of the soils and craters). Most soils are alluvial soils rich in quartz, feldspar, opaque minerals, and clay; some soils were locally interbedded with caliche layers. One impact crater was formed in slightly indurated gypsum sand. Initial soil densities ranged from 1.3 to 1.6 ± 0.1 g cm^{-3}. The

Fig. 1a.

Fig. 1b.

Fig. 1. (a) Missile impact crater formed in unconsolidated soil (visible in foreground). Weakly shock-lithified sheared and compressed ejecta fragments are visible in the throwout and in the interior wall of the crater, which is approximately 7.4 m in diam. (b) Weakly shock-lithified sheared and compressed ejecta in the wall of the crater. The scale is 16 cm in length. Photographs courtesy of U.S. Army.

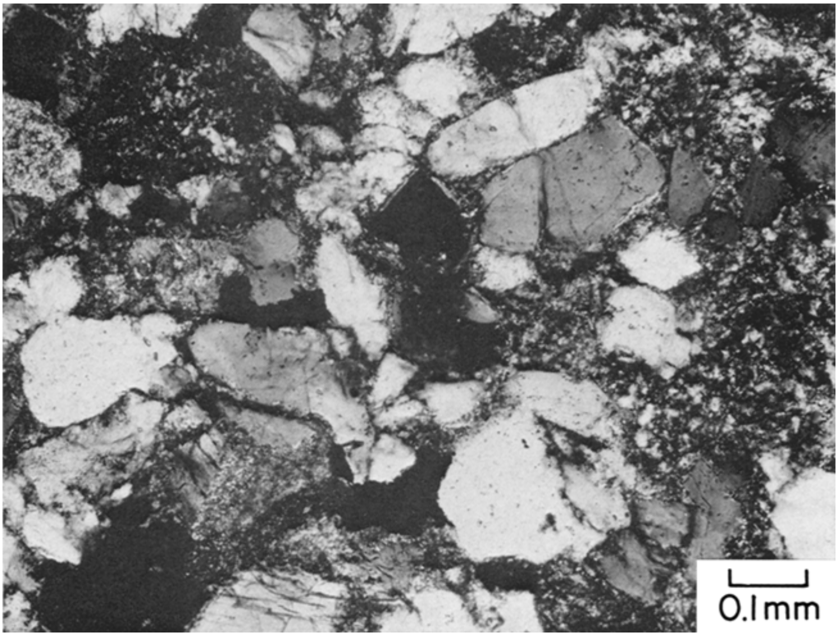

Fig. 2a.

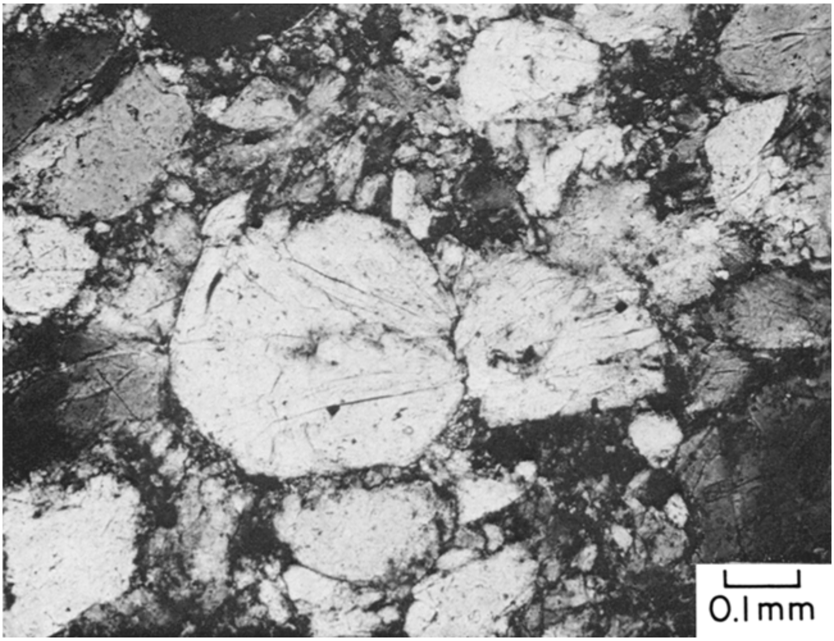

Fig. 2b.

Fig. 2. (a) Photomicrograph of a shock-lithified sheared and compressed sample from missile impact crater showing fractures in the larger grains. Much of the fine-grained material is clay which was present in the original soil. Crossed polarizers. (b) Photomicrographs of Class 1b shocked Coconino Sandstone from Meteor Crater, Arizona, showing shock-induced fracturing. Crossed polarizers.

initial unconfined compression strength of the soil was typically less than 2×10^{-3} kb. Initial water content varied from a few percent to saturated, but was typically about five percent. Particle sizes ranged from several millimeters to submicroscopic.

The soil around each impact site was sheared and compressed by the shock wave (Moore, 1969). Fragments of this sheared and compressed material are weakly shock-lithified. The ejecta fragments show variations in density and strength which reflect differences in the degree of compression to which the individual pieces were subjected. The least dense samples have densities near, but slightly exceeding, the density of the original soil; these fragments are easily crushed with one's fingers. The densest fragments are sufficiently strong that pieces of 15 to 25 cm diam and 3 cm thickness have been hurled 30 to 60 m from craters and survived secondary impact into the surrounding soil without fracturing. However, even the strongest fragments can be broken by hand. The color of the ejecta also varies with density: the densest samples are whitened by intragranular fracturing.

In thin sections of these weakly shock-lithified materials, fracturing is the only obvious result of the shock induced compaction. The most porous shock-lithified samples show essentially no recognizable shock damage. The least porous samples show fracturing in some of the larger grains (Figure 2a); the degree of fracturing is comparable to that observed in Class 1b samples of Coconino Sandstone from Meteor Crater (Figure 2b). It is possible that more intense shock deformation is present in the submicroscopic fine-grained fragments surrounding the larger fractured crystals, but severe deformation is not detectable with the resolution of the petrographic microscope (1–2 μm).

In an effort to determine the lithification mechanisms in the weakly shock-lithified rocks, some grains of original soil and some grains of the densest shock-lithified fragments from White Sands were examined with a scanning electron microscope (SEM). Typical results are shown in Figure 3. The surfaces of the original soil components were smooth, presumably due to abrasion during transport of the grains to the site of deposition (Figure 3a). In shocked samples, the grains have been pulverized and myriads of fresh fracture surfaces have been created. The shock-lithified rocks are complex three-dimensional aggregates of intersecting fragments (Figure 3b). It is possible that the strength of the material is accounted for simply by mechanical interlocking of the tiny fractured fragments (as suggested by Short (1966) to account for shock-lithification of unconsolidated soil materials around chemical explosion craters). It is also possible that some adhesion is provided by electrostatic attraction between the freshly exposed surfaces (e.g., as suggested by Arrhenius and Asunmaa (1973) to account for adhesion of grains to small particles of lunar soil).

The compaction attained in the weakly-lithified material was determined by measuring the density of individual ejecta fragments. Over 100 samples were selected as representative of the ejecta by criteria of apparent density, strength, and degree of shock-induced whitening of color. Individual fragments were coated in paraffin and weighed dry and in water; densities were calculated from Archimedes' principle. In order to facilitate comparison of the densities of the ejecta with experimental data on

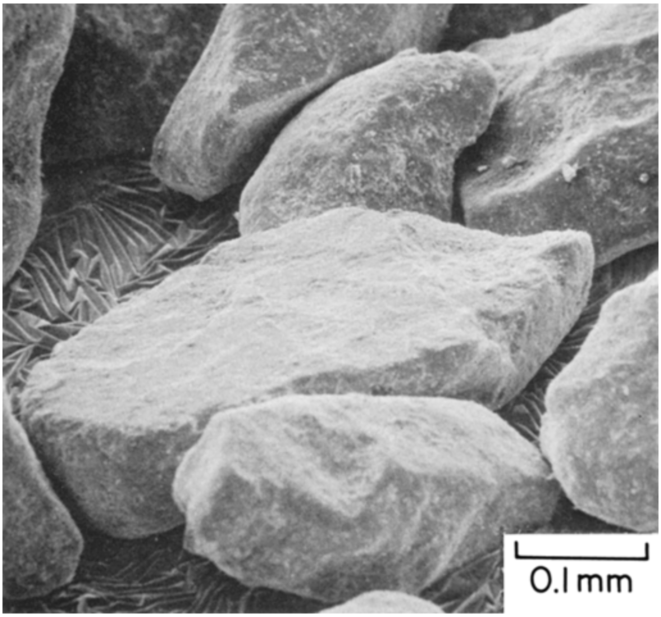

Fig. 3a.

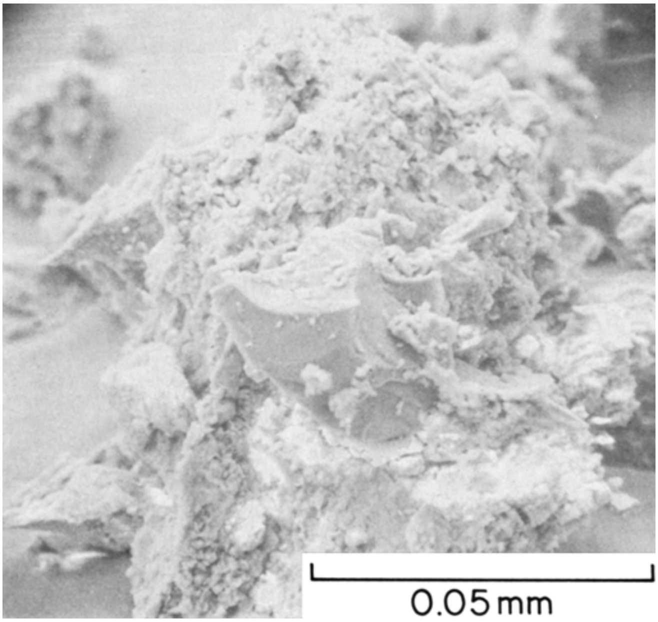

Fig. 3b.

Fig. 3. Scanning electron microscope photographs of (a) unshocked grain in original soils, and (b) fractured grain in weakly lithified soil from the missile impact craters.

Hugoniots and release adiabats, the densities were converted to specific volumes. The specific volumes of ejecta fragments from each crater are summarized in Figure 4. At each crater in alluvial soil, the density of the shock-lithified ejecta varied from values only a few percent greater than the initial soil value to a maximum value of 2.1 ± ±0.1 g cm^{-3}. A maximum density of 2.2 g cm^{-3} was reported by Moore (1969). The density of shock-lithified gypsum fragments did not exceed 2.1 g cm^{-3}. *The density of the shock-lithified material approached, but never equaled, the average density of the constituent minerals* (2.6 g cm^{-3} for a typical soil, 2.3 g cm^{-3} for gypsum). This observation imples that there is porosity in all of the weakly lithified samples. The SEM photos (Figure 3b) suggest that this porosity occurs in spaces created by the fine-scale fracturing.

The pressures to which the weakly lithified rocks were shock-loaded may be estimated in two ways: (1) by a comparison of the shock damage observed petrographical-

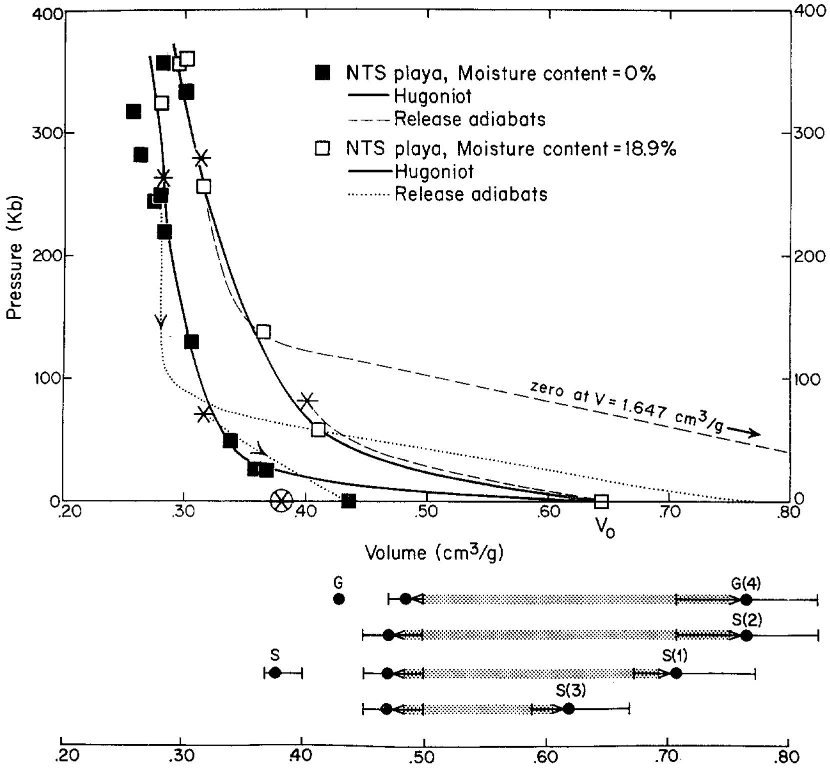

Fig. 4. A comparison of Hugoniot and release adiabat data on dry and wet NTS playa material (Anderson *et al.*, 1966) with data on specific volumes of shock ejecta from the missile impact craters. The initial volumes of the alluvial soils are indicated as $S1$, $S2$ and $S3$, and of the gypsum sand as $G(4)$ The bars show the estimated variation in initial soil volume at each crater. The broad bands extending to the left represent the range of volumes measured in ejecta fragments. The two points S and G show the intrinsic crystal volumes of the soil and gypsum. The circle on the volume axis of the Hugoniot data shows the intrinsic crystal volume of NTS playa.

ly with shock damage observed in specimens of similar material shocked to known pressures in laboratory experiments, and (2) by comparison of the measured specific volumes of the ejecta from the craters with measured specific volumes of laboratory samples upon release from high pressure. Such comparisons are only approximate because of differences in the composition, porosity, and water content of the soils and of the samples which have been shocked in the laboratory experiments, and because of differences in the duration of cratering events and laboratory experiments.

Shock recovery experiments on porous lunar regolith soils have been reported by Christie *et al.* (1973) and recovery experiments on porous plagioclase-pyroxene mixtures of nearly uniform grain size by Gibbons *et al.* (1975). Christie *et al.* (1973) have described the microscopic and submicroscopic texture of three porous lunar soils shocked to 50, 100 and 250 kb. In the sample recovered from 250 kb, nearly all of the plagioclase clasts had been converted to clear, homogeneous glass. A plagioclase-pyroxene powder of 38% preshock porosity shock-loaded to 205 kb showed a similar texture (Gibbons *et al.*, 1975). Lunar soil shocked to 100 kb was characterized by intense fracturing, undulatory extinction and the formation of some isotropic material in a few plagioclase crystals. Lunar soil shocked to 50 kb most nearly resembled the weakly shock-lithified material from White Sands in appearance. The main shock damage was fracturing, but many fragments were undeformed. (The 50 kb lunar sample was, however, more strongly lithified than the White Sands material, possibly because it was encapsulated in a strong metallic container which provided a lateral confining pressure during shock and release.) These experiments suggest that shock-loading to 50 kb could account for all of the observed deformation in the White Sands material and that shock loading to 100 kb is unlikely to have occurred in any of the weakly lithified samples. The apparent maximum pressure of less than 100 kb in the ejecta from the missile impact craters is inconsistent with expected pressures induced by the missile impacts, as mentioned in the introduction.

In summary, a model for shock-lithification processes in terrestrial regolith material must take into account the following observations:

(1) Weakly lithified samples increase in density and in strength with increasing shock-loading up to a maximum inferred pressure of 100 kb.

(2) Weakly lithified samples are not crushed to the intrinsic crystal density, but have porosity in spaces associated with intense fracturing.

(3) In impact events of short duration, neither weakly nor strongly shock-lithified samples form at pressures in the range 100 to 200 kb. In events of long duration, the growth of crystalline high pressure phases allows strongly shock-lithified rocks to form at these and at higher pressures.

In the following section I will propose a model for shock compression of a porous regolith that accounts qualitatively for the observed differences in lithification mechanisms with increasing pressure. This discussion is necessarily somewhat qualitative because of the complexity of the ‘regoliths’ in which natural or missile impact craters are formed and the lack of experimental Hugoniot and release adiabat data on materials of the same composition, porosity and water content as the soils from which the ejecta were formed. It is, nevertheless, the first attempt to synthesize many different types of data and observations related to the problem of lithification mechanisms: (1) the observed densities and petrographic characteristics of shock-lithified terrestrial 'regolith' materials; (2) the observed petrographic characteristics of experimentally shocked and recovered porous terrestrial and lunar samples; (3) Hugoniot and release adiabat data on lunar soil and wet and dry terrestrial soils; and (4) theoretical models of the behavior of air and water under shock compression. All pressure estimates in the following sections are based on data for material of approximately 20% to 30% porosity. The pressures at which given shock phenomena (e.g., the formation of thetomorphic glass or of melt) occur depend on initial porosity and, therefore, would be different for materials of differing porosity.

4. A Model for Shock-Lithification of Terrestrial Regolith

In considering the shock-lithification of terrestrial regolith materials, it is necessary to consider the effects of not only mineral composition, but also the effects of air and water within pores in the regolith material. Since we cannot directly observe the formation of shock-lithified materials we must rely on laboratory and theoretical equation of state data to provide some insight regarding the behavior of air and water in porous materials under shock loading.

The measured compression curves (Hugoniots) of porous materials initially at one atmosphere pore pressure suggest that air within the pores is highly compressed under shock loading. The Hugoniot of dry Nevada Test Site (NTS) playa material shown in Figure 4 is typical of the Hugoniots of porous materials; the data are from Anderson *et al.* (1966). All data points were obtained for samples initially at one atmosphere pore pressure, except one point at 240 kb, for which the sample was initially evacuated. Within experimental error, the Hugoniot data point from the vacuum experiment did not differ from the data points obtained on samples initially at one atmosphere. The porous material was compressed to greater density than the intrinsic crystal density by shock-loading to pressures as low as 25 kb. Such large volume compressions during shock imply that air within the pores can contribute little to the compressed volume, and, hence, must be highly compressed. (The assumption is made that the air is confined within the pores during the shock experiment; the possibility that this is not so is discussed below.)

Air compressed within the pores must become extremely hot during shock because of its great compressibility. In Hugoniot experiments on porous NTS playa material shocked to approximately 140 kb, Murri and Smith (1970) noted that the records of two metallic stress gauges embedded in the playa material indicated that the material became electrically conductive. They believed that the conductivity was due to extreme heating (and, it is implied, partial dissociation) of air in the pores of the sample.

The temperature attained by air trapped in pores during shock depends upon the shock duration as well as upon the driving pressure in the shocked material because the final temperature is attained through a series of compressions and releases induced by reflected shock and rarefaction waves. A one-dimensional analysis of the process for porous tuff has been presented by Riney *et al.* (1971). In their model, an air-filled pore is assumed to be surrounded by an incompressible water/solid mixture. The air is treated as an ideal gas with an adiabatic exponent $\gamma = 1.4$. It is assumed that the boundary of the pore perpendicular to the oncoming shock is rigid. The thermodynamic problem is to calculate the increase in pressure and temperature due to reverberating shocks and rarefactions in air trapped between rigid walls and a rigid grain which is advancing across the pore at a constant velocity, W. Riney *et al.* (1971) chose the grain velocity W to be 0.4 km s^{-1} to correspond to the particle velocity of a tuff shocked to an average pressure of about 5 kb. For a pore size of 0.1 mm, it was found that the pore was 92% collapsed by the time that three shock reverberations had occurred in the air. The three compressive stages of the reverberations took the air to 4, 12 and 34 bars respectively. At 34 bars, the shock temperature was calculated to be 560 °C. Final compression to the equilibrium pressure of 5 kb requires further stepwise shocking and heating of the air. From this simple model it can be seen that the compression of the air within a porous sample is to some extent dependent upon the duration of the shock experiment, because of the stepwise approach of the air to final temperature. In short laboratory experiments, final air temperatures may not be as high as in longer cratering events due to natural or missile impacts. In addition there may be substantial escape of air laterally through free surfaces of laboratory samples, and, possibly, even in the forward direction through interconnected pores. Lateral escape is not likely under natural impact conditions because large masses of surrounding material provide lateral confinement. No analysis has been done of possible movement of air through pores in a forward direction during shock. It seems plausible that at low shock pressures, flow could occur through interconnected pores in a forward direction faster than the shock wave could propagate through the air-rock mixture.

The temperature of air confined in pores during shock compression may reach 10000K in a large impact event. For example, air shocked to 1 kb *via* a single shock reaches approximately 14000K (Davies, 1948). (Air shocked to the same pressure by the multiple shock process described above will be somewhat cooler however, because the process is more nearly isentropic.) In the pressure range from 30 bar to 1 kb, nitrogen and oxygen molecules within the air dissociate under shock conditions.

In considering the problem of shock-lithification of porous materials during impact, the behavior of the compressed air upon release from high pressures must be considered. Release adiabats of tuffs of varying porosities at pressures below 25 kb indicate that quasi-reversible to irreversible crush-up is attained in laboratory experiments at these pressures (Riney *et al.*, 1971). At 25 to 35 kb, the tuffs are compressed to densities greater than the intrinsic crystal density in the shock loaded state. During rarefaction, they release to densities very close to the intrinsic crystal density. These observations suggest that expansion of compressed air upon release from pressures of 25–35 kb does not cause significant expansion of porous tuffs or soils. At higher pressures the only release adiabat data available for dry porous material appear to be those of Anderson *et al.* (1966) shown in Figure 4. Upon release from 80 kb, the sample expands considerably beyond the intrinsic crystal density; from 280 kb, the expansion is even greater. Within the qualification that there are large uncertainties in the shapes of these release adiabats because of experimental techniques, Anderson *et al.* (1966) have interpreted the shape of the release adiabat as follows: The playa is 50% silica. It is known that silica collapses to a dense phase at pressures above 200 kb (Wackerle, 1962; Ahrens and Rosenberg, 1968). The steep part of the release adiabat is interpreted as the release behavior of the high pressure phase. The shallower part is interpreted as the release of a low pressure phase formed by inversion of the high pressure phase. The measurement of Murri and Smith (1970) which indicates that air in a sample shocked to 140 kb becomes hot enough to become electrically conductive suggests that some of the measured expansion of initially porous materials upon release from 80 kb and from 280 kb may be due to expansion of hot air trapped within the pores.

Soils which are partially saturated with water show a somewhat different behavior than dry soils during compression and release (Figure 4). Water reduces the compressibility of porous materials so that the shock states attained during compression are less dense than those of dry materials shocked to the same pressure. The final release states attained are also different from those of shock-loaded dry samples. At very low pressures ($P < 10$ kb) the only release adiabat data available are release adiabats of porous wet tuffs (Riney *et al.*, 1971). These data indicate that upon release from these low pressures some compaction is attained. Upon release from pressures near 100 kb, however, the final volumes attained by wet samples are approximately equal to, or slightly larger than, the initial volume of the porous material (see the 80 kb release adiabat of wet playa material shown in Figure 4). Theoretical calculations of the behavior of water under shock compression (Butkovich, 1971) demonstrate that upon release from pressures near or exceeding 100 kb, water is partially vaporized and steam is formed as the pressure decreases below 10 bar. The release adiabat from 280 kb shown in Figure 4 shows the extreme expansion caused by the formation of steam within pores upon release of samples from high pressure.

In summary, the equation of state data suggest that noncondensable gases within a shock-loaded system may strongly affect the shock-lithification mechanisms. The expansion of water converted to steam is the most pronounced effect. Steam may cause expansion of compressed soils upon release from pressures in excess of 100 kb. The equation of state data on dry soils and the theoretical models of the behavior of air under shock compression suggest that compressed soils *may* expand on release owing to the expansion of hot air initially in the pores. Under equilibrium conditions (that is, if the air were shocked to the average pressure attained in the mineral grains) such an expansion would occur upon release from a few kilobars pressure because the great compressibility of air causes extreme heating. Under nonequilibrium conditions created by laboratory or even missile impacts, air within pores may not attain pressure equilibrium before release and, hence, may remain relatively cool below average pressures on the order of 50 or 100 kb in surrounding minerals.

The potential of a terrestrial 'regolith' to lithify during a shock event is determined by the relative magnitudes of the induced pore pressure (P_{pore}) and the tensile strength of the rock due either to weak lithifying mechanisms (S_{weak}) or to strong lithifying mechanisms (S_{strong}) formed at a given pressure. Several lithification regimes are recognized in the rocks studied here.

Regime 1: Low pressures, $P_{\mathrm{pore}} < S_{\mathrm{weak}}$. At shock pressures below 100 kb where partial compaction is attained and no high pressure phases are formed, lithification by weak lithification mechanisms is possible *if* the pore pressure (P_{pore}) is less than the strength (S_{weak}) of the weak lithification mechanisms. Class 1a and 1b shocked Coconino Sandstone samples and all weakly lithified samples from White Sands are interpreted to have formed under these conditions. Pressures are inferred to be less than 100 kb, probably less than 50 kb. The data of Riney *et al.* (1971) indicate that the observed differences in compaction of recovered samples are directly related to differences in the pressure to which the samples were shock-loaded, that is, that the densest recovered samples were shocked to the highest pressures. Since no evidence of high temperatures was found in the weakly lithified rocks, it must be inferred that air in the pores either remained fairly cool at these pressures (perhaps because the equilibrium temperature was not attained) or escaped through interconnected pores. Theoretical calculations (Butkovich, 1971) of the equation of state of water suggest that water was not vaporized at these pressures. Air or water from the original pores may have traveled into the newly created fractures, resulting in the observed intragranular porosity. The inferred process of shock under these conditions is shown in Figure 5a.

Regime 2: Intermediate pressures, $S_{\mathrm{weak}} < P_{\mathrm{pore}} < S_{\mathrm{strong}}$: At intermediate pressures ($\sim$100 to $\sim$200 kb), the potential for lithification depends on the duration of the shock event. In long events, high pressure crystalline phases may nucleate and grow at relatively low pressures (on the order of 50 kb). These phases may provide the soils with strength, S_{strong}, due to strong lithification mechanisms. In short events, however, strong lithification mechanisms may not form unless the pressure is high enough to cause the formation of melt (on the order of 200–300 kb). In the absence of strong lithification mechanisms, lithification does not occur at pressures between $\sim$100 and $\sim$200 kb because the pore pressure due to expansion of hot air or formation of steam exceeds the strength of the weak lithification mechanisms. Soils shocked to these pressures in small impact events, such as the missile impacts, fragment and disperse. The inferred process is shown schematically in Figure 5b.

Regime 3: High pressures ,$P_{\mathrm{pore}} < S_{\mathrm{strong}}$: Lithification is possible at high pressures (above $\sim$ 200kb) if the strength of the strong lithification mechanisms, S_{strong}, exceeds the pore pressure, P_{pore}, due to hot air or to vaporized water. No samples of this regime were formed at the missile impact craters because the induced pressures were too low for silicate melt to form and the impact events were too short for abundant high pressure crystalline phases to form. At Meteor Crater, however, abundant samples are found which provide evidence that strong lithification mechanisms can withstand considerable pore pressure. The glassy (Class 4 and 5) samples contain abundant

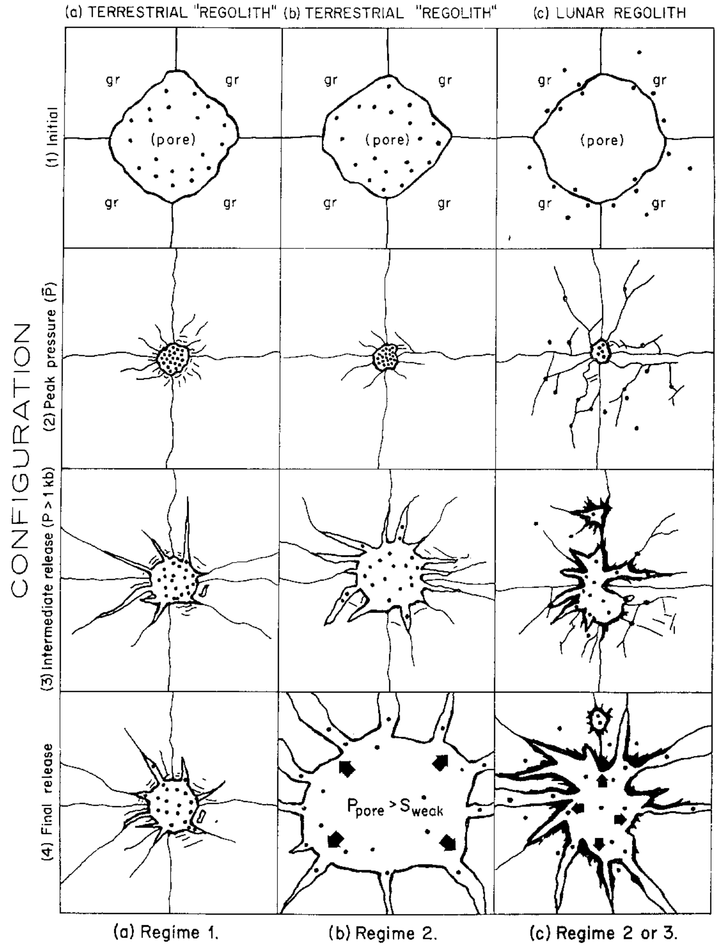

Fig. 5. Schematic shock configurations around pores in regolith materials.

Panel a: Terrestrial 'regolith' shocked to pressures below 100 kb, Regime 1. (a1) Pore containing air or air and water. (a2) Pore under shock compression. Fracturing is shown schematically in adjacent grains, but the complex interlocking of fractured fragments which gives rise to weak lithification is not shown in detail. (a3) Pore volume is partially regained during release due to expansion of air or air and water. (a4) If the pore pressure does not exceed the strength of the weak-shock lithification mechanisms, the rock is shock-lithified. Some porosity is generally retained (quasi-reversible compaction).

Panel b: Terrestrial 'regolith' shocked to pressures in the range 100 to 200 kb, Regime 2. (b1) Same as (a1). (b2) Same as (a2) except that the pore is more compressed and the gas is hotter. (b3) Gas expands upon release and exerts pore pressure. As long as the material surrounding the pore is under a net confining pressure greater than the pore pressure during release, fragmentation does not occur. (b4) If the pore pressure exceeds the strength of the rock and the confining pressure is released at the end of the rarefaction, the rock fragments.

Panel c: Lunar regolith shocked to pressures above 50 kb, Regimes 2 and 3. (c1) Unless pores in the lunar regolith are within breccia fragments, they do not contain gas molecules. Gas is shown schematically implanted within grains, primarily near surfaces. (c2) Gas molecules are released by thetomorphic glass formation, local melting or crushing at grain boundaries. (Regions where these transformations occur are indicated by heavier black lines.) (c3) Gases are released into an expanding fracture system. (c4) If the pore pressure is less than the rock strength, shock-lithification will occur; some volume expansion will occur because of the gas which has entered the pores created by fracturing.

vesicles ranging from submicroscopic dimensions to several millimeters in diameter. These vesicles are due to the exsolution of water from a water-rich silica melt at the time when pressures in the rarefaction decreased below 10 kb (Kieffer, 1971). Although the samples are extremely vesicular, they are strongly lithified. The stishovite-bearing samples (Class 3) of Coconino Sandstone contain a submicroscopic froth which is due to water-silica interaction at elevated temperatures (Kieffer *et al.*, 1975). Thus, although the water was vaporized, the rock is strongly lithified, indicating the rock strength exceeded the pore pressure. This evidence from the textures of the strongly lithified samples suggests that the strong lithification mechanisms can withstand considerable steam pressure.

5. A Model for Shock-Lithification of Lunar Regolith

The lunar regolith is similar to terrestrial 'regolith' in density and porosity, but differs from terrestrial 'regolith' in several important respects. Within the upper few centimeters, the average density of the lunar regolith is about 1.6 g cm^{-3}. However, the average specific gravity of the minerals in the regolith is 3.1, which is considerably higher than the typical value of 2.7 of terrestrial soil. The lunar minerals are denser than the terrestrial minerals because the major minerals are basic igneous minerals – plagioclase, olivine and pyroxene – with a relatively large amount of titanium and iron oxides.

The lunar regolith is a complex mixture of breccia, rock, mineral and glass fragments, and agglutinates. Typical mean grain sizes vary from 100 to 300 μm. The lunar regolith samples returned by Apollo missions have shown a surprisingly high gas content (Hintenberger *et al.*, 1970). The main constituents of the gas are hydrogen, helium, nitrogen, carbon and noble gases. Each gram of regolith material contains up to 3 cm^3 STP g^{-1} of gas, i.e., the ratio of gas molecules to regolith soil atoms is roughly 1:500. (In comparison, in a terrestrial soil which contains 10 weight percent water, the ratio of water molecules to soil atoms is approximately 1:10.)

There is a substantial difference between terrestrial and lunar soils in the distribution of volatiles and in the potential of these volatiles for pore activity. In terrestrial soils, the water is generally within the pores or adhering to grain surfaces; a notable exception is water bound in the mineral structures, as in clay or gypsum. In lunar soils the volatiles have been implanted within the *grains* rather than in the *pores* by the solar wind. Although there is a marked tendency for the volatile atoms to be concentrated near grain surfaces (e.g., Heymann *et al.*, 1970), the atoms are nonetheless implanted within the mineral structures. In preexisting breccia fragments incorporated into the soil, however, a substantial fraction of the volatiles may exist in pores within the breccia (Heymann and Yaniv, 1971). Thus, differences in the amount of volatiles and in their distribution between lunar and terrestrial regoliths preclude detailed comparison of shock compression properties and lithification mechanisms. Nevertheless, the observations on the terrestrial samples suggest a model for lunar shock-lithification processes that is consistent with the observations of Christie *et al.* (1973) and Gibbons *et al.* (1975) on experimentally shocked and recovered samples and the observations of Ahrens and Cole (1974) on lunar soil Hugoniot and release behavior.

By analogy with the model proposed in the previous section for terrestrial shock-lithification processes, I propose that shock-lithification processes in the lunar regolith may be divided into three regimes similar, but not identical, to the three regimes proposed for terrestrial shock-lithification processes. Pressures appropriate to these regimes are discussed below.

Regime 1: Low pressures, $P_{\text{pore}} < S_{\text{weak}}$: At low pressures partial to total compaction may be attained, with the degree of compaction being directly proportional to the pressure of shock-loading. Since there is no pore gas in the soil, except within breccia fragments, compaction at given pressure under lunar conditions should be more complete than in a terrestrial soil. Irreversible compaction and weak lithification will occur if: (a) negligible glass or high pressure phases are formed, and (b) little gas is released.

Regime 2: Intermediate pressures, $P_{\text{pore}} < S_{\text{weak or strong}}$: At intermediate pressures complete compaction will be attained during crush-up, and some glass may be formed within the fine-grained parts of the soil. At the present time there are not sufficient data to determine whether lithification in lunar soils shocked to intermediate pressures is due to weak or to strong mechanisms. The more complete crush-up expected under lunar conditions may account for the relatively large amounts of glass observed in lunar soils (shocked to ~100 kb) compared to soils shocked from one-atmosphere initial pressure. Grain contact must be more complete and shearing more extensive under evacuated shock-loading conditions than in the presence of air or water, even though differences in compressed volume are not measurable in Hugoniot experiments (Anderson *et al.*, 1966) because of the great compressibility of air. Some gas may be released from the regolith grains by crushing and the formation of thetomorphic glass. This gas may enter the extensive intragranular fracture network and cause some expansion of the shocked regolith upon release from high pressure, but probably will not cause fragmentation of the shock-lithified regolith fragments.

Regime 3: High pressures, $P_{\text{pore}} < S_{\text{strong}}$: At high pressures, strong lithification occurs. In lunar soils strong lithification is due mainly to glass formation; shock-induced high pressure phases are absent in lunar minerals. Dissolved gas released by melting may form small vesicles in the melt. The lithification process for Regimes 2 and 3 is shown schematically in Figure 5c.

An estimate of the pressures appropriate to these three regimes may be obtained if release adiabat data of Ahrens and Cole (1974) on lunar soil are interpreted in terms of this model. The soils were shocked in a moderate vacuum (50 to 100μ Hg). Those samples shock-loaded to pressures in the range 20 to 50 kb were crushed to intrinsic density, 3.1 g cm^{-3}, and remained near intrinsic density upon pressure release (Regime 1). Upon adiabatic release from successively *higher* pressures up to 120 kb, successively *lower* release densities were produced. The density of material released from 120 kb was approximately 2.5 g cm^{-3}, a 20% *increase* in sample volume over the intrinsic crystal volume. Ahrens and Cole suggest that this density decrease was caused by the formation of increasing quantities of glassy phases. Since silicate glasses are generally about 10% less dense than their crystalline counterparts, a complete conversion of the crystalline material to glass and some vesiculation of the glass would be required to explain the observed large volume increase. However, the recovery experiments of both Gibbons *et al.* (1975) and Christie *et al.* (1973) suggest that the glass which is formed at 50 and 100 kb is thetomorphic glass, which is generally non-vesicular, and that the amount of glass which is formed could not account for the 20% volume increase. It seems plausible that the decrease in release density measured by Ahrens and Cole is due to pore pressure caused by volatile release from soil grains. Since vesicular glass was not observed in either the 50 or 100 kb experimentally shocked lunar soil (Christie *et al.*, 1973), it is necessary to assume that the gas is released either by crushing of the soil grains and included breccia fragments, or by the formation of thetomorphic glass.

6. Conclusions

Shock compression of porous terrestrial 'regolith' by relatively small impact events gives rise to three pressure regimes: Regime 1: at pressures below ~100 kb material is compacted and weakly shock-lithified; Regime 2: at pressures between ~100 and ~200 kb, material may be fragmented if the induced pore pressure exceeds the strength of the weak lithification mechanisms; and, Regime 3: at pressures above ~200 kb material is strongly lithified, but may be considerably expanded in volume due to the pressure of pore gases. Shock compression of lunar regolith gives rise to three analogous regimes: Regime 1: at pressures below ~50 kb material is compacted and weakly shock-lithified; Regime 2: at pressures between ~50 and ~100 kb thetomorphic glass is formed and material is probably lithified but shows some volume expansion (it is not possible to say whether it is weakly or strongly lithified); and Regime 3: at pressures above ~100 kb material is strongly lithified by the formation of melted glass and may have considerably expanded volume due to gases released by melting.

Acknowledgments

This work was sponsored by NASA grant PO A-8209-A to Dr R. P. Sharp, Dr E. M. Shoemaker and S. W. Kieffer, California Institute of Technology and NASA grant NSG 7052, UCLA. I thank Henry Moore (U.S. Geological Survey), Donald Gault (NASA Ames Research Center) and Thomas Ahrens (California Institute of Technology) for their continued interest in this problem, and Ron Scott (California Institute of Technology) for providing laboratory space. The Command of White Sands Missile Range were most helpful in allowing access to the missile impact craters and providing field support. Soil analysis from one crater was provided by Dr F. D. Nielson, Las Cruces, New Mexico. I thank the Barringer Crater Company for allowing the studies at Meteor Crater.

References

Ahrens, T. J. and Cole, D. M.: 1974, *Proc. Fifth Lunar Sci. Conf.,* 2333–2345.

Ahrens, T. J. and Rosenberg, J. T.: 1968, in B. French and N. Short (eds.), *Shock Metamorphism of Natural Minerals,* Mono Book Corp, pp. 59–81.

Arrhenius, G. and Asunmaa, S. K.: 1973, *The Moon* **8**, 368–391.

Anderson, G. D., Duvall, G. E., Erkman, J. O., Fowles, G. R., and Peltzer, C. P.: 1966, *Investigation of Equation of State of Porous Earth Media,* Air Force Weapons Lab. Rept. AFL-TR-65-146.

Butkovich, T. R.: 1971, *J. Geophys. Res.* **76**, 1993–2011.

Chao, E. C. T.: 1971, *Proc. Second Lunar Sci. Conf.,* 797–816.

Christie, J. M., Griggs, D. T., Heuer, A. H., Nord, G. L., Radcliffe, S. V., Lally, J. S., and Fisher, R. M.: 1973, *Proc. Fourth Lunar Sci. Conf.,* 365–382.

Davies, D. R.: 1948, *Proc. Phys. Soc.* **61**, 105–118.

Gault, D. E. and Heitowit, E. D.: 1963, *The Partition of Energy for Hypervelocity Impact Craters Formed in Rock,* Sixth Hypervelocity Impact Symposium, Cleveland, Ohio.

Gault, D. E., Shoemaker, E. M., and Moore, H. J.: 1963, NASA Publication TN D-1767, 39 p.

Gibbons, R. V., Morris, R. V., Hörz, F., and Thompson, T. D.: 1975, 'Petrographic and Ferromagnetic Resonance Studies of Experimentally-Shocked Regolith Analogues,' to be published in *Proc. Sixth Lunar Sci. Conf.*

Heymann, D. and Yaniv, A.: 1971, *Proc. Second Lunar Sci. Conf.,* 1681–1692.

Heymann, D., Yaniv, A., and Adams, J. A. S.: 1970, *Science* **167**, 555–558.

Hintenberger, H., Weber, H. W., Voshage, H., Wänke, H., Begemann, F., and Wlotzka, F.: 1970, *Proc. Apollo 11 Lunar Conf.,* 1269–1282.

Kieffer, S. W.: 1970, (1) Shock Metamorphism of the Coconino Sandstone at Meteor Crater, Arizona; (2) The Specific Heat of Solids of Geophysical Interest, Ph. D. thesis, Calif. Inst. of Tech., Pasadena, 252 p.

Kieffer, S. W.: 1971, *J. Geophys. Res.* **76**, 5449–5473.

Kieffer, S. W.: 1975, *Droplet Chondrules: Formation by Jetting,* in preparation.

Kieffer, S. W., Phakey, P. P., and Christie, J. M.: 1975, *Shock Processes in Porous Quartzite,* in preparation.

McKay, D. S., Heiken, G. H., Taylor, R. M., Clanton, U. S., Morrison, D. A., and Ladle, G. H.: 1972, *Proc. Third Lunar Sci. Conf.,* 983–944.

Moore, H. J.: 1969, *U.S. Geol. Surv. Prof. Paper* **650-B**, B107–B112.

Murri, W. J. and Smith, C. W.: 1970, *Equation of State of Rocks,* Stanford Research Inst. Report PGU 6618.

Riney, T. D., Garg, S. K., Dirsch, J. W., Hastings, J. W., and Hamilton, K. G.: 1971, *Systems, Science and Software,* Report DNA 2725 I, La Jolla, Calif, 339 pp.

Short, N. M.: 1966, *Science* **154**, 382–384.

Wackerle, J.: 1962, *J. Appl. Phys.* **33**, 922–937.