drogen abstraction by activated CH_3 (*4*). The decay follows first-order kinetics (Fig. 2), and preliminary experiments indicate that the rate constant is dependent on surface coverage. This may be interpreted by assuming that the rate is determined by the release of the radical from the surface site, and that subsequent diffusion on the surface is fast and results in a low stationary concentration of mobile radicals.

At low coverage of CH_3I (a monolayer or less), it was noted that the intensity distribution of the EPR spectrum was markedly different from the binomial one; this is explained by the presence of a second type of CH_3 radical with the hyperfine constant $A_2 = 20.2 \pm 0.4$ gauss and *g*-factor $g_2 = 2.0016 \pm 0.0005$. This second type of CH_3 radical (Me′) is clearly noticeable in the spectrum at relatively early stages of irradiation (Fig. 3), but it is not very stable at 77°K and changes to another radical (X) exhibited by those extra lines shown in Fig. 4. The radical X has not yet been identified.

The intensity of the Me′ spectrum increased when the porous glass was first heated at higher temperatures (700° to 850°C) for longer periods of time than the normal outgassing procedure. The appreciable reduction in the hyperfine constant indicates a charge transfer from the CH_3 to the trapping site on the silicate surface. This trapping site could be the siloxane group. In this case radical X was not detected as the signal of Me′ disappeared.

These extra lines (Me′ and X) were only observed when the surface coverage was a monolayer or less, and may be informative to identify the trapping sites on the silicate surface. For this purpose, however, it is essential to define the surface more precisely chemically. Similar spectra were also obtained by the photolysis of CH_3Br on the porous glass surface, where, in addition, the intense hydrogen atom doublet was observed.

Thus porous glass is very useful as a host material for stabilization of the free radical and has an advantage over an inert gas matrix in that liquid helium temperatures are not required. Unfortunately, the interpretation of the kinetics on such a surface is not simple because of the presence of continuum of trapping potentials. However, it is because of this continuum that the stabilization can be achieved over a wide range of temperature.

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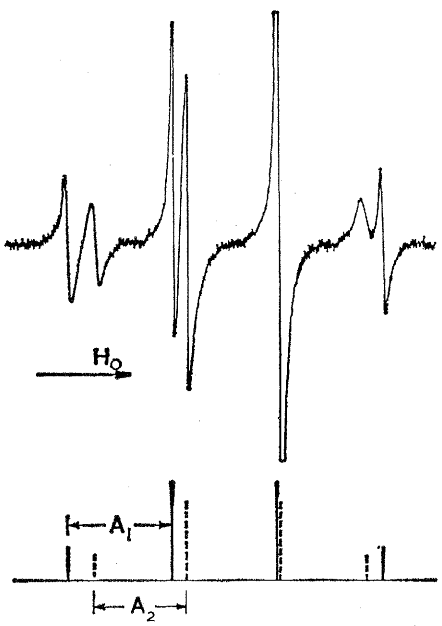

Fig. 3. The EPR spectrum of methyl radicals on the dry surface (first heated at 700°C for 48 hours), with coverage of 1 percent, observed after about 20 minutes of ultraviolet irradiation at 77°K. Extra lines and the apparent intensity anomaly of the main quartet are explained by the existence of another quartet as indicated.

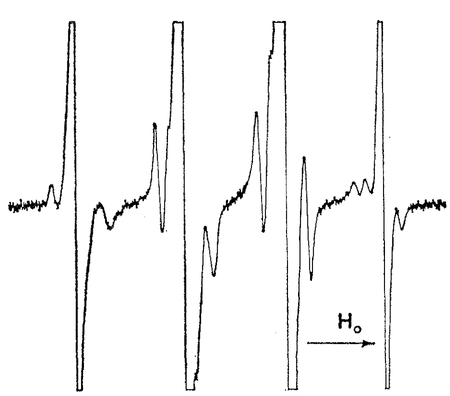

Fig. 4. The EPR spectrum of radicals on the surface, with coverage of 1 percent, stored at 77°K for more than 1 hour after irradiation.

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Shock-Lithification of Unconsolidated Rock Materials

Abstract. *Loose quartz grains packed around chemical explosives are forced during cratering explosions into compacted, coherent masses resembling sandstone blocks found at certain meteorite craters. Sandstone-like lumps found at the Wabar (Arabia) meteorite craters are similar to these shock-lithified sands. Shock-lithification by impact may be effected on Moon as large meteorites strike surfaces covered with rubble from earlier collisions.*

Impacts of meteorites on indurated terrestrial and lunar rock surfaces should result in overall disaggregation and fragmentation of the target materials. However, aggregation of unconsolidated materials should be a less frequent but important process associated with shock events. Using explosive shocks, Fredrickkson and DeCarli (*1*) reindurated mechanically disaggregated fragments from the Bjurbole chondrite, closely simulating its original texture. Certain brecciated achondrites may represent lithified fragments considered by some to derive from Moon's surface (*2*). I suggest that a mechanism, termed shock-lithification, may operate during repeated impacts into lunar surface rubble, by which fragments from previous impacts are welded into coherent masses; and that some such masses receive sufficient velocity for escape earthward. I now present evidence of shock-lithification during explosion cratering and terrestrial impact in support of this hypothesis.

Shock-lithification of loose materials used to tamp explosives in holes is sometimes observed after detonation, by careful examination of the environment. In 1962 a series of row-charge cratering experiments at the Nevada Test Site entailed detonations of nitromethane, a liquid, in metal spheres buried 4.5 to 7.0 m under alluvium. Loose "Ottawa" sand was used to backfill space between the 1-m-diameter holes and the spheres. This sand consists mainly of spherical, well-rounded quartz grains ($\sim$ 1 mm in diameter) disaggregated from the St. Peter (Ordovician) orthoquartzite; both potash feldspars and sodic plagioclase make up 10 to 20 percent of all grains.

After several explosions, engineers noticed hundreds of lumps of white rock, ranging in size between 1 and 10 cm, scattered throughout the fallback and crater-lip rubble. These were unlike gravel or boulder fragments indigenous to the alluvium; they were exposed only in craters whose scaled depths of burial were near optimum for maximum excavation; some displayed prominent shear surfaces marked by slickensides.

The lumps have an average bulk density of 2.14, porosity up to 23 percent, sonic velocity of 3290 m/sec, and an unconfined compressive strength of 28 ± 3.5 kg/cm^2. The lumps resemble fragments of shocked sandstone collected at Meteor Crater, Arizona, Odessa Crater, Texas, and the Kentland structure, Indiana. The chalky white color resembles that of intensely shocked granodiorite recovered from the Hardhat nuclear explosion site (*3*); it results from extensive light-scattering caused by high fracture densities within individual crystals.

Petrographic-microscope examination reveals a characteristic rock texture (Fig. 1B); loose Ottawa-sand grains in mounts appear well-rounded, unfractured, and unstrained. In contrast, grains in the coherent lumps are fractured into fragments of varying sizes. Most quartz grains lose their original roundness and sphericity, developing instead irregular shapes, angular corners, and serrated, indented boundaries. Individual grains fit tightly against close-pressing neighbors. Many grains interpenetrate one another, adjusting their boundaries to accommodate the curvatures of the intruders. Nearly all grains are crisscrossed by numerous irregular fractures. Some fractures in the feldspars are subparallel and follow crystallographic planes; fractures opened to 0.5- to 5.0-μ widths break grains into polygonal mosaics of individual segments. Fault-like movements within grains are demonstrated by bending and offsets of albite twins in the plagioclase. Most larger quartz grains show, in polarized light, prominent patchy undulatory extinction. A matrix composed of grain fragments from 1 to 100 μ in diameter fills the voids between the larger angular grains; fine brownish "clay" and occasional shreds of mica help to bind these matrix fragments together.

Cohesion of the lumps of sand grains develops in several ways. (i) Interlocking of large angular fractured grains prevents movements by rotation. (ii) Nearly all available pore space is occupied by the finely granulated quartz and feldspar; thus slippage and rotations into voids are further restricted. (iii) This matrix material acts to "cement" the larger grains; the intermixed clay binder is probably alluvial material introduced into the loose grains before or, conceivably, during the explosion itself.

The cohesive masses of "sandstone" are formed by compaction and lithification directly induced by the nitromethane explosion. Shock waves passing through the sand and driving forces

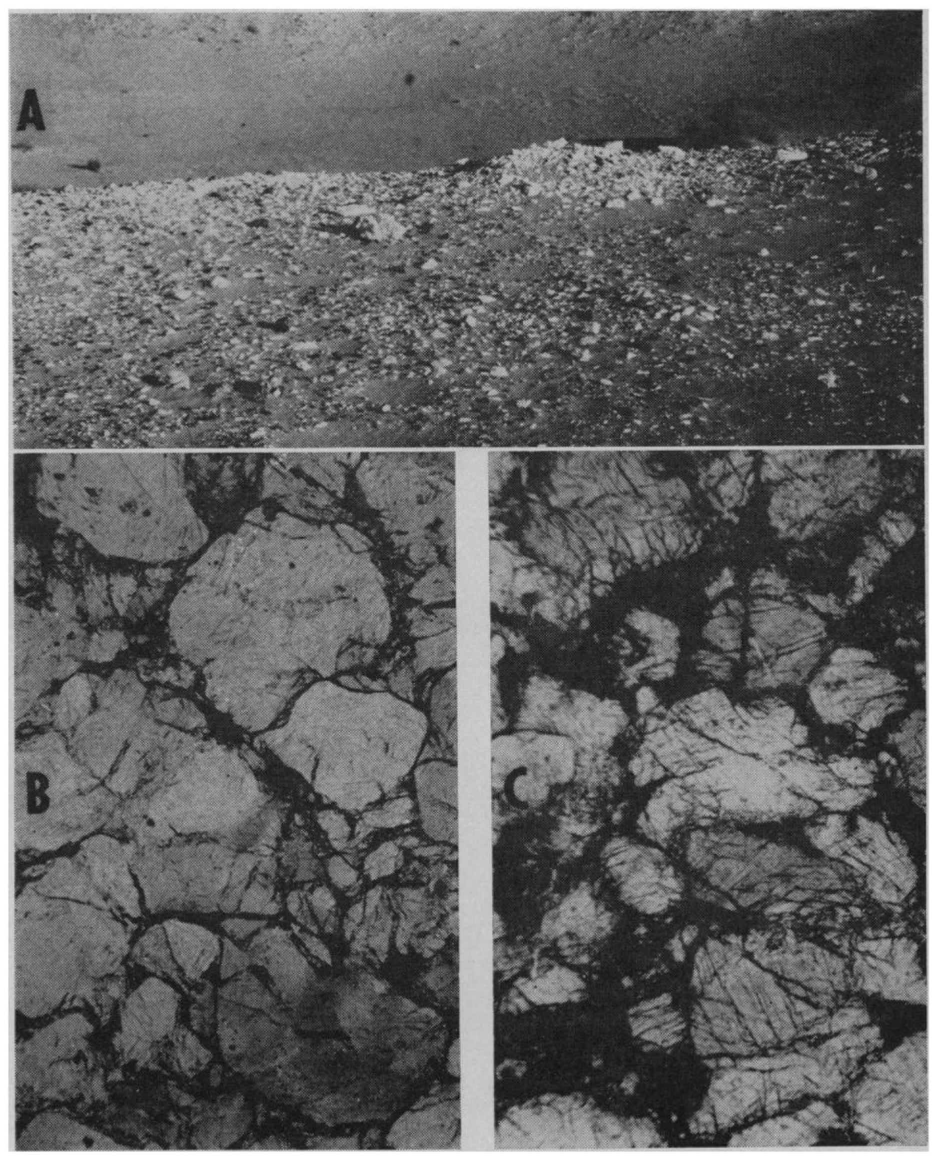

Fig. 1. (A) The larger of the two Wabar craters, showing the sand-covered depression and the crater rim. "Sandstone" fragments are scattered about the crater lip in the foreground; large blocks make up pseudo-bedding below the rim. [V. E. Barnes, NSF grant G10236] (B) Texture typical of shock-lithified Ottawa sand from chemical-explosion craters, Nevada Test Site $\times$ 35; plain light). (C) Texture typical of "sandstone" fragments from the Wabar craters. Note distinctive rhombohedral cleavage in quartz. Dark areas are partly glass mixed with iron stain ($\times$ 35; plain transmitted light).

from expanding gases released by detonation combine to accelerate rapidly grain particles away from the container. Simultaneously these grains are subjected to compressive and tensile stresses. At slightly later times the alluvium beyond the sand experiences less shock loading, and thus its compression and outward motions are delayed relative to the moving sand; the sand is thus driven against still-resistant barriers being displaced ahead at slower rates. The grains fracture and fragment as they are forced to squeeze into a rapidly changing volume. This compression occurs before the overlying medium is disrupted by reflected tensile shock waves. The sandstone thus formed between the spherical metal container and the alluvium walls of the hole is then disrupted en masse by "hoop" stresses generated in the expanding materials surrounding the explosion point or by later tensile shock waves returning to the explosion cavity, or by both.

Pressures and resultant stress states acting to form these lumps cannot be precisely specified. Pressure waves developed during detonation of nitromethane do not exceed 150 kb, but localized stress concentrations within grains or at boundaries may be higher at some stage of compaction. In consolidated samples subjected to shock loading, from one to seven sets of closely spaced, planar-parallel microfractures, many of which orient along the $\{10\bar{1}3\}$, $\{10\bar{1}1\}$, and $\{10\bar{1}0\}$ crystallographic planes, form in quartz at peak pressures above 60 to 75 kb (*3*). These diagnostic features are absent in grains from the sandstone lumps (*4*); I interpret this absence to mean that pressure levels of this intensity probably did not persist after the initial compaction.

On Earth, natural shock-lithification is probably restricted to meteorite-impact structures. In most of more than 40 such structures found on the continents (*5*) the target materials had been consolidated rocks which were intensely fractured, brecciated, melted, or even vaporized. Lithification of shock breccias occurs, essentially after impact, by some such process as cementation, devitrification, or recrystallization. Several recent crater groups, such as Campo del Cielo and Henbury, are formed in unconsolidated soil cover from which indurated lumps have been recovered.

I recently learned of one impact structure in which lithified "sandstone," analogous to the lumps produced by chemical cratering, appears to have formed. The al-Halida (Wabar) pair of craters in the Rub'al-Khali desert of southeastern Arabia (see cover), from which meteorite material and coesite have been reported (*6*), have maximum diameters of 97 and 55 m. Barnes (*7*), Baldwin (*8*), and others state that only deposits of desert sand, whose thickness extends below the floor of the deeper crater, occur at the site (*9*).

Scattered within the craters, around the lips, and beyond are lumps of white sandstone-like material and blackish, vesiculated, slag-like glasses (Fig. 1A); some blocks are several meters long. The smaller lumps, displaying varying degrees of crushing, are usually coated by a thin-to-thick veneer of glass. The lumps are most conspicuous around the rims of both craters where they simulate outcrops.

Except for closer association of fracturing with crystallographic direction (*10*), the presence of isotropic materials (mainly glass), and the greater proportion of iron-bearing clay binder, a typical Wabar lump is strikingly similar in texture (Fig. 1C) to lumps from chemical-explosive craters.

From this similarity I conclude that the Wabar lumps were produced by shock-lithification during meteorite impact. Maximum shock pressures on samples were probably around 400 kb. Less than 10 percent of the target sands were thus lithified (another fraction was converted to fused silica glass) because peak pressures fell off rapidly beyond the line of impact; during the cratering action most of the lithified materials were dispersed over wide areas both within and beyond the craters.

The Wabar observations point to a general impact process capable of transforming loose materials into larger fragments by shock-lithification. On the surface of Moon, impacts would initially comminute consolidated rocks, producing the rubble that many assume covers parts of Moon. By analogy with Wabar, additional impacts could convert some fraction of this target debris into larger lithified fragments and glasses. Densification and enlargement of particles by aggregation would increase the overall size distribution—lead to poorer sorting even though comminution continues with each major impact. Lithification would affect only the limited volume near the line of impact that experiences high shock pressures. The transfer of considerable energy in that vicinity would probably melt some of the target, to be ejected as splash (tektites?) capable of escaping the lunar gravitational field. Workers disagree as to whether other parts of the target material also would receive velocities sufficient for escape.

Both Surveyor-1 and Luna-9 television pictures of Moon's surface show rock fragments, from gravel to boulder in size, lying on a firm pavement, but the textural details needed for identification of the fragments were not revealed; several interpreters have compared them to "soil-like clods." I believe that some of these fragments may be shock-lithified rubble aggregates, even though the landing sites were in maria distant from large craters. Probably only collection of such samples during manned exploration will answer this postulate.

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1 August 1966