pact, or both, but the patterned ground is interpreted as fallout material which is draped over a minutely fractured basement. Although it seems reasonable that many of the undulations observed in the Tycho rim materials are due to fallout ejecta draped over basement lineaments, it seems more probable that the definitely wavelike forms were developed by base-surge flow. In contrast to Shoemaker's interpretation, Masursky *et al.* (*11*) indicate that extensive tracts of the "patterned ground" surrounding Tycho "is probably fine ejecta deposited by base surge. The dune features may be deceleration dunes localized at concentric fractures in the underlying material."

Certainly the pattern of these dune-like ridges from Tycho is not unlike the dunes we have observed around Earth maars, except in scale. Base surges would soften the outlines of small craters and other lunar landscape features and eventually cover and reduce them to ghostlike images. In any event, layered deposits of granular material and geomorphic features of the lunar landscape should be evaluated with the possibility that fragmental material may have been emplaced by flow, as well as by fallout, regardless of rock composition.

It is now widely accepted that the small lunar craters which are aligned along fissures and rills may be of volcanic origin. Many are similar in size and form to Earth maars. Thus, base-surge deposits similar in size and origin to those in Earth maars may also be present on the moon. If a permafrost layer occurs within permeable materials beneath the lunar surface as is postulated by some workers (*12*), conditions exist whereby phreatic base-surge flows could develop from lunar magma rising into ice-filled fractures. The presence of chilled sideromelane in cross-bedded antidunes might afford reliable indications of the presence of underground ice.

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13 June 1969; revised 30 July 1969

Lead: X-ray Diffraction Study of a High-Pressure Polymorph

Abstract. *An x-ray diffraction study of lead under pressure has shown that the face-centered cubic structure transforms to the hexagonal close-packed structure at room temperature and a pressure of 130 ± 10 kilobars. The volume change for the transformation is −0.18 ± 0.06 cubic centimeter per mole.*

On the basis of a 23 percent increase in electrical resistance, Balchan and Drickamer (*1*) have reported that a phase transformation in lead occurs at 160 kb and room temperature. However, the crystal structure of this high-pressure phase was not determined. A hexagonal close-packed structure was predicted for the high-pressure phase by Klement (*2*), who found a similar transition in bismuth-lead alloys. We have identified the crystal structure of the high-pressure phase in pure lead by means of an x-ray diffraction method with a polycrystalline sample compressed in a diamond-anvil high-pressure cell.

We used a high-pressure x-ray diffraction camera designed by Bassett *et al.* (*3*). The high-pressure cell of this camera consists of two ⅛-carat gem-quality diamond anvils driven by a piston screw assembly. When a polycrystalline sample is compressed between the anvil faces (~ 0.4 mm in diameter), a maximum pressure is produced at the center of the anvil area. A finely collimated x-ray beam, approximately 50 μm in diameter, of filtered MoKα radiation passes through one of the anvils and impinges on the central part of the anvil area where a maximum and a minimum pressure gradient exist. Diffracted rays pass out

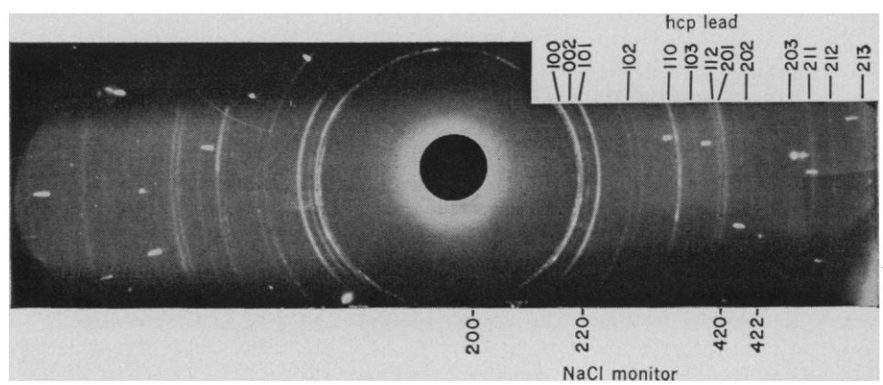

Fig. 1. X-ray diffraction pattern for the high-pressure phase of lead at 139 kb. All the diffraction lines for lead can be indexed as hexagonal close-packed. The pattern also shows the diffraction lines from the NaCl platelet placed in the x-ray beam on the back of the diamond facing the film for the purpose of monitoring the constancy of the camera geometry and film dimension. Many lines for the high-pressure phase of lead exhibit spottiness due to coarse crystallinity.

through the other anvil to a curved film with a radius of 50 mm that allows a dispersion equal to a maximum 2θ angle of 45°. The geometry of this camera is essentially that of the Debye-Scherrer camera. In order to monitor the constancy of camera geometry and film dimension during high-pressure experiments, a small polycrystalline platelet of NaCl was placed in the x-ray beam at the back of the diamond facing the cylindrical film. Thus the resulting x-ray diffraction pattern consists of the diffraction lines produced by the lead sample [samples of lead were shaved from an ingot of extra-high purity (99.999 percent Pb) (American Smelting and Refining Co.)] under pressure and by the NaCl platelet, as well as Laue spots from the diamond anvils.

Lead in a face-centered cubic structure is thermodynamically stable at low pressures and room temperature. The effect of pressure on the volume of the face-centered cubic phase of lead was studied by Bridgman (*4*) at room temperature and pressures up to 100 kb. Using pure iron intimately mixed with lead as an internal standard for pressure, we have redetermined the effect of pressure on the volume by means of x-ray diffraction. The pressure-volume relation for iron determined by Takahashi *et al.* (*5*) at room temperature was used to obtain the pressure values based upon the lattice parameter. The seven diffraction lines, (111), (200), (220), (311), (222), (331), and (420), were used to calculate the lattice parameter of the face-centered cubic phase of lead. Our value for the pressure-volume relation for lead agrees with that of Bridgman (*4*) to within 0.5 percent or better. Once the compression curve for the face-centered cubic phase of lead was established, the lattice parameter of this phase could be used for the pressure measurements without an internal standard.

At a pressure of 130 kb, a new spotty line emerged between the (111) and (200) lines of the face-centered cubic lead structure, an indication of the onset of a phase transformation. As the intensities of this and other new spotty lines in a pure lead sample became stronger with increasing pressure, the diffraction lines for the face-centered cubic lead structure faded away, and at 145 kb these lines disappeared entirely, thus indicating that the phase transformation was complete.

The *d*-values and relative intensities for this high-pressure polymorph of lead at 139 ± 10 kb are compared with the corresponding calculated values in Table 1. All of the 13 diffraction lines observed can be indexed as hexagonal close-packed with a c/a ratio of 1.650. We computed the lattice parameters from these *d*-values by means of a least-squares method that minimizes the sum of the squares of the differences $[(1/d_{cal})^2 - (1/d_{obs})^2]$ (Table 1). The values obtained are $a = 3.265 \pm 0.004$ Å, $c = 5.387 \pm 0.007$ Å, and $c/a = 1.650$; the uncertainty values indicate the probable error at the 50 percent confidence level. The observed intensities were compared with those of a simulated powder pattern calculated by a computer program (*6*) for a hexagonal close-packed structure of lead. The calculated intensity values are in good agreement with the observed ones with the exception of the (100) and (110) reflections. Intensity distributions along diffraction lines (Fig. 1) indicate that there is an effect due to preferential orientation of crystallites in the high-pressure phase. In order to minimize the effect of the irregular intensities of the diffraction lines, we measured the relative intensities along ten different radial traverses and calculated the mean intensity for each line. Therefore, the intensity values for the spotty lines are rather unreliable.

Table 1. X-ray diffraction data obtained with MoKα radiation (0.7107 Å) for the high-pressure ploymorph of lead at 139 ± 10 kb and room temperature. The diffraction lines are indexed as hexagonal close-packed.

(*hkl*)	d_{obs} (Å)	d_{cal} (Å)	$(1/d_{cal})^2 - (1/d_{obs})^2$	$(I/I_o)_{obs}$	$(I/I_o)_{cal}$
100	2.82	2.827	-6.8×10^{-4}	75	23
002	2.69	2.694	−8.7	32	27
101	2.51	2.504	4.8	100	100
102	1.95	1.951	−9.4	12	17
110	1.633	1.632	2.3	71	21
103	1.514	1.516	−11.9	22	25
112	1.397	1.396	9.3	33	26
201	1.367	1.367	−2.8	36	18
202	1.254	1.252	24.6	5	5
203	1.110	1.111	−17.6	17	9
211	1.047	1.048	−21.8	18	16
212	0.9927	0.9933	−12.4	9	6
213	0.9195	0.9183	30.2	15	14

The volume change for the phase transformation from the face-centered cubic structure to the hexagonal close-packed structure has also been determined from several x-ray diffraction patterns that exhibit these two phases coexisting in the high-pressure cell. The volume change for this phase transformation, based on 12 measurements, is -0.18 ± 0.06 cm³/mole, or 0.99 percent in $-\Delta V_{tr}/V_o$, where V_o, the volume of the face-centered cubic phase at room temperature and a pressure of 1 bar, is 18.269 cm³/mole. The observed volume change associated with the phase transformation is one of the smallest values for a first-order phase transformation in metals.

The pressure-density relation in lead has been investigated by Al'tshuler *et al.* (*7*) up to 3.8 Mb and by McQueen and Marsh (*8*) up to 1.4 Mb by means of shock-wave techniques. However, no density discontinuity that would indicate a phase transformation was reported by these investigators. This failure to detect the volume change for the phase transformation from the face-centered cubic structure to the hexagonal close-packed structure is probably due to the small value of the volume change.

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22 May 1969