Cooling rates for lunar samples determined with a diffusion model for phosphide exsolution

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Abstract—A numerical model for diffusion-controlled phase growth has been applied to the exsolution of phosphide lamellae in lunar metal grains. Computer simulations reproduce observed composition profiles, and reveal the influence of cooling rate on dimensional and compositional parameters of phosphide and metal. At lower cooling rates, phosphide lamellae are larger and the concentration of P in the metal host close to the interface is lower. Cooling rates inferred for Apollo 16 samples, based on compositions and dimensions of the phosphide-metal grains, are mostly in the range 1–100°C/day. These rates correspond to burial depths of 5–0.5 m for melt rocks and 3–0.3 m for breccias. This is in good agreement with thicknesses of lunar cooling units determined by other techniques.

INTRODUCTION

Cooling rate is a factor which strongly influences the textures and mineralogical details of lunar rocks. Attempts have been made to determine cooling rates from crystal morphology (Lofgren et al., 1975) and opaque oxide compositions (Taylor et al., 1975). Some lunar rocks contain metallic grains consisting of lamellae of phosphide (schreibersite) exsolved from kamacite (alpha Fe–Ni). Since the Fe–Ni–P system is well known (Doan and Goldstein, 1970; Heyward and Goldstein, 1973; Norkiewicz and Goldstein, 1975), a mathematical model for diffusion-controlled phase growth can be used to simulate this exsolution. Calculations show that compositions and dimensions of phosphide lamellae and their host metal grains are strongly influenced by cooling rate. In this paper, cooling rates for lunar samples are obtained by matching measured phosphide data with calculated values.

Computer Simulation of Phosphide Exsolution

A numerical model for diffusion-controlled phosphide growth in kamacite in the ternary system Fe–Ni–P has been developed by Randich (1975a). The assumptions of this model and its application are further discussed by Randich and Goldstein (1975) and Goldstein and Randich (1977). The temperature variation of two- and three-phase boundaries of the Fe–Ni–P phase diagram (Doan and Goldstein, 1970) and of diffusion coefficients (Heyward and Goldstein, 1973; Norkiewicz and Goldstein, 1975) is incorporated in a computer simulation.
program. Exsolution of a phosphide lamella may be simulated by providing the computer program with data such as bulk composition, initial and final transformation temperature, and cooling rate. The program calculates a composition profile in a discontinuous fashion, as temperature decreases and time increases. Final interface compositions and lamella size are the important parameters for interpreting natural phosphides cooled at unknown rates.

The basic assumptions in the computer program HEX (Randich, 1975b) are that interface equilibrium is maintained at all times and that phase growth is controlled by diffusion. Plane front, one-dimensional growth is considered. The program was designed for an investigation of phosphide exsolution in hexahedrites (Randich, 1975a; Randich and Goldstein, 1977). These meteorites apparently formed at the very low cooling rates (~0.5–25°C/m.y.) associated with the interiors of asteroidal bodies. HEX therefore specifically assumes that bulk equilibrium is maintained in the metal-phosphide assemblage down to moderately low temperatures (~400°C). Clearly this assumption may not be valid for the higher cooling rates experienced near or on planetary surfaces. Therefore, for lunar samples, a modified version of HEX was written without the assumption of bulk equilibrium. In the modified program, a phosphide nucleus (halfwidth 0.01 μ) is assumed to form after a small amount of undercooling (~50°C). The fundamental assumptions of interface equilibrium and diffusion-controlled phase growth are maintained in the modified program.

The general characteristics of the exsolution process under lunar conditions can be illustrated using a bulk composition of 5.5 wt.% Ni, 0.5 wt.% P, and 94.0 wt.% Fe in the program. Figure 1 shows composition profiles for Ni and P for phosphide growing in kamacite as a function of cooling rate after cooling to 400°C. The effect of lowering the cooling rate is to increase the size (halfwidth) of the lamella. This lamella size is, potentially at least, a measure of cooling rate. Note that Ni and P are partitioned into the phosphide lamella and the metal phase is depleted in these elements close to the interface. As the cooling rate is lowered, the metal phase as a whole is more strongly depleted in P which goes to form the phosphide. In addition, at lower cooling rates the composition gradients become less steep, indicating lesser departure from equilibrium.

The influence of final growth temperature on composition profiles is shown in Fig. 2. At 500°C the composition gradients are very small, indicating very slight departures from equilibrium. Note that on cooling to lower temperatures, the additional growth of the lamella is negligible. However, the interface depletion of Ni and P in the metal is marked, as required by the phase diagram. On cooling from 400°C to 250°C, the diffusion rates are so low that the composition profile is changed only in the immediate vicinity of the interface.

Interface compositions are commonly used to indicate final temperatures of equilibration. The spatial resolution of the conventional electron probe is such that, in the Fe–Ni system, analyses characteristic of a single phase can be obtained to within about 1 μ of a grain boundary (Miyake and Goldstein, 1974). When data are collected on a traverse with 1 μ steps, the analyses closest to the interface but still representative of only one grain are, in general, about 1.5 μ
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Fig. 1. Concentration profiles for Ni and P across the interface between a phosphide lamella and host metal grain, as a function of cooling rate.

Fig. 2. Concentration profiles for Ni and P across the interface between a phosphide lamella and host metal grain, as a function of final temperature.
from the interface. Thus the “interface” concentrations obtained by conventional microprobe analysis are actually concentrations about 1.5 μ from the interface. For measurements of P interface concentrations, spatial resolution is determined by the Fe–Ni matrix and there are no secondary fluorescence effects. Figure 2 shows that the best estimates of final temperature for this assemblage are obtained from the interface concentration of P in the metal phase, as indicated by Goldstein and Axon (1973). Since the true interface P concentrations cannot be measured with the microprobe, the appropriate calculated values must be used. For purposes of cooling rate calculations, P “interface” values were taken from the calculated profile 1.5 μ from the interface, in metal. These are the data plotted for interpretation of microprobe data. The “interface” concentrations calculated show significant changes down to final temperatures of 250°C. Further changes in composition close to the interface occur below 250°C and were calculated. However, such compositional changes can only be detected with high resolution equipment, such as electron microscope microanalyzer (EMMA) or scanning transmission electron microscope (STEM) down to distances of 100 nm from the interface.

**Simulation of Lunar Phosphide Lamellae**

The bulk composition of lunar metal-phosphide grains is variable. Published analyses of such two-phase grains concentrated from lunar soil provide a good indication of the range in bulk compositions. Bulk compositions for metal phosphide in soil 63501 determined by microprobe in the scanning mode (Goldstein and Axon, 1973) show a typical range and are plotted in Fig. 3. The sample is bimodal in terms of P. A large group of grains has less than 1% P and a smaller group contains several percent P. Most grains contain between 4% and 7% Ni. Two compositions have been chosen to represent these groups, 5.5% Ni with 0.5% P and 5.5% Ni with 2.0% P. Phosphide growth calculations using the low P composition have been discussed in the earlier section (Figs. 1 and 2).

In addition to bulk composition, cooling rate, initial temperature and final temperature, the diffusion field length is an important variable in the simulation program. The diffusion field length is the distance from which P is drawn into the growing lamella. In grains containing several lamellae, the field length is half the distance between growing phosphides. Figure 4 shows several photomicrographs of lamellae in metal-phosphide particles. In all of these, the diffusion field length is half the distance between lamellae. The field length will determine the amount of P available for growth, and will influence the size of the lamella that can be grown. Under some circumstances the diffusion field length will influence the composition gradients and therefore the “interface” compositions as measured with the electron microprobe. Values of field length (i.e., half lamellar spacing) observed in lunar samples range from 10 to 100 μ, while the full width of observed lamellae ranges from much less than 1 μ to at most 10 μ. These values may be confirmed from recorded observations (Fig. 4; Figs. 5 and 7 in Goldstein and Axon, 1973; Fig. 6 in Gooley et al., 1973; Fig. 4 in Misra and Taylor, 1975).
Fig. 3. Bulk compositions of all two-phase metal-phosphide particles separated from soil 63501 (Goldstein and Axon, 1973).

The influence of diffusion field length on lamella size (halfwidth) is illustrated in Fig. 5. The computer runs were made for a bulk composition of 0.5% P, a nucleation temperature of 600°C and field lengths of 10, 25, 50, 100 μ, and higher values. Although the sizes of lamellae are essentially fixed at high temperatures, as shown in the previous section, the halfwidths plotted were obtained from runs with a final temperature 250°C.

Figure 5 shows that lower diffusion field lengths give smaller lamellae, since the amount of P available influences the size to which the phosphide can grow. It also confirms the earlier observation that lower cooling rates give larger lamellae. Note that the curve for a cooling rate of 0.001°C/day falls quite close to the calculated line for infinitely low cooling rate. The case of an infinitely low cooling rate is attained when all the possible P has diffused into the phosphide. This condition yields the maximum possible lamella halfwidth.

Several important conclusions can be drawn from Fig. 5. First, for grains of metal phosphide containing an average of 0.5% P, the lamella halfwidth and diffusion field length uniquely define the cooling rate. Second, if the lamellae attained a total width in excess of 1 μ, cooling rates of 0.1°C/day or lower were necessary. Smaller phosphides cooled more quickly and these phosphides cannot be investigated with the microprobe.

Figure 5 can also be used to illustrate the lamella sizes of metal-phosphide grains with 2% P. In the case of P-rich grains, exsolution begins at very high temperatures (Doan and Goldstein, 1970) and a close approach to equilibrium is maintained down to moderate temperatures for all, even high, cooling rates. Runs were made with an equilibrium version of the computer program to obtain
Fig. 4. Photomicrographs of Apollo 16 metal-phosphide particles. Arrows indicate position of microprobe traverse across phosphide lamellae. (a) 6F5-23, soil 63501. Field of view is 200 × 255 μm. Cooling rate is 0.001°C/day. The tiny phosphide precipitates in the matrix between the phosphide lamellae are produced during slow cooling. (b) 6S6-26, soil 68501. Field of view is 90 × 120 μm. Cooling rate is 1.0°C/day. (c) 6F4-21, soil 65701. Field of view is 220 × 220 μm. Cooling rate is 1–10°C/day. Note that a lamellar phosphide, not a bleb at a metal–metal grain boundary, has been analyzed. (d) 6S6-14, soil 68501. Field of view is 105 × 135 μm. Cooling rate is 1–10°C/day. Note Neumann lines in metal.
Table 1. Compositional and dimensional data for phosphide lamellae and host metal.

<table>
<thead>
<tr>
<th>Sample*</th>
<th>Particle #</th>
<th>Half-width microns</th>
<th>Field length microns</th>
<th>Bulk P wt.%</th>
<th>“Interface” P</th>
<th>Cooling rate °C/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>6F4</td>
<td>21</td>
<td>2.1</td>
<td>9</td>
<td>2.0</td>
<td>0.18</td>
<td>&gt;1.0, &lt;10.0</td>
</tr>
<tr>
<td>6F5</td>
<td>23</td>
<td>3.0</td>
<td>23</td>
<td>2.0</td>
<td>0.05</td>
<td>∼0.001</td>
</tr>
<tr>
<td>6S6</td>
<td>14</td>
<td>1.5</td>
<td>12</td>
<td>2.0</td>
<td>0.20</td>
<td>&gt;1.0, &lt;10.0</td>
</tr>
<tr>
<td>6S6</td>
<td>26</td>
<td>1.6</td>
<td>10</td>
<td>2.0</td>
<td>0.16</td>
<td>∼1.0</td>
</tr>
<tr>
<td>6F2</td>
<td>1</td>
<td>3.2</td>
<td>18</td>
<td>2.0</td>
<td>0.60</td>
<td>&gt;100.0</td>
</tr>
<tr>
<td>6F2</td>
<td>2</td>
<td>2.5</td>
<td>40</td>
<td>2.0</td>
<td>0.36</td>
<td>∼100.0</td>
</tr>
<tr>
<td>6F2</td>
<td>18</td>
<td>3.2</td>
<td>32</td>
<td>1.0</td>
<td>0.18</td>
<td>∼1.0</td>
</tr>
</tbody>
</table>

*6F4, soil 65701; 6S6, soil 68501; 6F2, soil 63501; 6F5, soil 63501 (as described in Goldstein and Axon, 1973).

![Fig. 5. Size (halfwidth) of phosphide lamellae grown in metal as a function of cooling rate and diffusion field length. These computer simulations were run for a bulk composition of 0.5 wt.% P and 5.5 wt.% Ni and a temperature of final equilibration of 250°C. For P contents of 2–3 wt.%, growth at high temperature is so extensive that lamella size for any cooling rate is given by the infinitely slow case.](image-url)
composition information. These runs confirm that, even for high cooling rates of 1.0°C/day, the lamella sizes plot essentially on the curve for infinitely low cooling rate. A curve showing lamella size for grains with 3% P at an infinitely low cooling rate is also plotted in Fig. 5. Note that for P-rich grains, no information about cooling rate can be gathered from the lamella size.

The calculated “interface” P concentrations have been plotted in Fig. 6 and following figures. Note that the P number used is the calculated P concentration at 1.5 μ from metal-phosphide interface. This value is that P concentration which can be measured with the microprobe. In Fig. 6, the “interface” composition is shown for a final temperature of 250°C, as a function of cooling rate and diffusion field length. The true interface P concentration is 0.005 wt.% P at 250°C and is independent of the cooling rate and field length. The calculated “interface” compositions plotted in Fig. 6 are seen to be strongly dependent on cooling rate. At lower cooling rates, there is a close approach to equilibrium and consequently the “interface” P concentration is lower. Calculations with 5.5 wt.% Ni, 2.0 wt.% P alloys show that the “interface” composition is essentially the same as for 0.5 wt.% P for the same cooling rate. As shown in Fig. 6, diffusion field length has a small influence on “interface” composition at field

Fig. 6. P concentration at 1.5 μ from the interface (the “interface” composition measurable by electron microprobe) at a final temperature of 250°C as a function of cooling rate. These curves were calculated for a bulk composition of 5.5 wt.% Ni and 0.5 wt.% P. The curves for a composition of 5.5 wt.% Ni and 2.0 wt.% P fall very close to these.
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lengths greater than 25 \( \mu \). Figure 6 shows that for all metal-phosphide grains (0.5–2.0 wt.% P) that had a singular cooling history to low temperature, the cooling rate can be obtained using measured "interface" compositions and diffusion field lengths. This cooling rate should also match, at the 0.5 wt.% P composition, the estimate of cooling rate obtained from lamella size (Fig. 5). If no match occurs, this may mean that the cooling pattern was interrupted by excavation. Ejection of material at moderate temperature by meteorite impact would have caused rapid quenching.

"Interface" P contents of the metal phase obtained at 400°C and 500°C are shown in Figs. 7 and 8 respectively. On comparing P concentrations for 250°C and 400°C (Figs. 6 and 7) two points become apparent. For low cooling rates, "interface" P concentrations are lower at the lower temperature because of greater approach to equilibrium. The true equilibrium interface composition at 400°C is 0.06 wt.% P. However, the "interface" P concentrations at the higher cooling rates (\( \geq 0.1 \text{°C/day} \)) do not change on going from 400°C to 250°C. This may be readily understood by reference to Fig. 2. At low temperatures, diffusion can modify compositions only immediately adjacent to the true interface. For a high cooling rate, little low temperature modification will occur. Thus for high cooling rates, the point at which the microprobe is measuring "interface" composition is too far from the true interface to detect the changes going on.

![Fig. 7. "Interface" P concentration of the metal phase at a final temperature of 400°C, as a function of cooling rate. Curves for bulk compositions of 0.5 wt.% P, 5.5 wt.% Ni (shown) and 2.0 wt.% P, 5.5 wt.% Ni are almost identical.](image)
Fig. 8. “Interface” P concentration for a bulk composition of 0.5 wt.% P, 5.5 wt.% Ni, and a final temperature of 500°C, as a function of cooling rate.

"Interface" compositions at 500°C are shown in Fig. 8. All the curves are significantly higher than the lower temperature curves, which is consistent with Fig. 2. Note that at 500°C, the compositions for rates of 0.01°C/day and 0.001°C/day virtually coincide. This indicates a very close approach to equilibrium is maintained down to 500°C, which again is consistent with the nearly flat profiles of Fig. 2. The true interface concentration is approximately 0.16 wt.% P at 500°C.

For a metal-phosphide grain containing 0.5 wt.% P, the cooling rate may be obtained from the lamella size (Fig. 5) and then the temperature of excavation or effective quenching may be estimated from “interface” composition (Figs. 6, 7, 8). For P-rich grains (>0.5 wt.% P) such unique solutions may not be possible. However, in most cases, constraints can be placed on the cooling rate and effective final temperature from the “interface” composition.

Cooling History of Lunar Phosphides

Metal-phosphide grains are found in a number of lunar rocks, particularly impact melts and breccias. In many cases, however, the phosphides occur as equant blebs at grain boundaries rather than as the lamellae for which this diffusion model was developed. Suitable lamellar phosphides are observed in
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Apollo 16 melt rocks and breccias (e.g., Misra and Taylor, 1975). Similar phosphides in large metal grains, presumably derived from similar rocks, have been magnetically concentrated from Apollo soils 63501, 65701 and 68501 (Goldstein and Axon, 1973). Compositions typical of these grains (0.5 wt.% P, 5.5 wt.% Ni and 2.0 wt.% P, 5.5 wt.% Ni) have been used in these simulations. Therefore, compositional and dimensional measurements can be taken from these grains to obtain cooling rate information, as long as composition profiles indicate growth during cooling. Grains with reversed P gradients indicating dissolution on reheating were rejected. The data for accepted grains are listed in Table 1, along with the calculated cooling rates based on the appropriate figures. Figure 4 illustrates four of the analyzed particles. Arrows indicate the position of the electron probe trace by which “interface” P was measured. All of the phosphides chosen are approximately lamellar in shape.

All of the Apollo 16 phosphide-metal grains for which analyses were made are P-rich (≥1 wt.% P). None of the large group containing about 0.5 wt.% P developed sufficiently wide phosphide lamellae to warrant microprobe analysis. This implies cooling at a rate of 0.1°C/day or higher, for all of the low P metal grains. Absolute cooling rates for the P-rich particles fall mainly in the range 1–100°C/day (Table 1). Cooling rates based on oxide compositions and crystal morphology have been applied only to basaltic rocks. Mare basalts and gabbros have inferred cooling rates of 5–24°C/day (Lofgren et al., 1975) and 3–7°C/day (Taylor et al., 1975). These cooling rates for the high temperature range are considered equivalent to a flow thickness of 2–3 m (Lofgren et al., 1975). Previous estimates of cooling rates of non-mare rocks, also using metallic minerals, were based on less precise cooling rate models than the present one. Brett (1975) has used available cooling rates as a basis for the important inference that breccia cooling units are very thin sheets (1–5 m). The determination of absolute cooling rates from phosphide exsolution is therefore a useful development for examining models of breccia formation.

Smith and Goldstein (1977) presented a rapid graphical method for converting cooling rates into burial depths. The phosphide data of Table 1 are consistent with depths of burial between 10 and 1 m, according to this method. The conversion technique is based on the calculations of Taylor and Heymann (1971) for the cooling of a chondritic composition cooling unit by radiation from both sides. However, as shown by Taylor and Heymann, this model deviates significantly at low temperatures from the actual case of a layer on the surface of a planet cooling by radiation from the top of the layer and conduction from the base. The cooling rates determined for phosphide exsolution are those effective at 600–500°C, where the maximum phosphide growth took place. Because this is in the low temperature range, the conversion method of Smith and Goldstein (1977) is not the most appropriate.

Equations for the cooling of a surface flow by radiation from the top and conduction from the base have been presented by Jaeger (1968) and have been used by Brett (1975) for lunar breccia cooling units. Cooling rates determined in this study have been converted to burial depths using the Jaeger model. The
equation used is

\[ T/T_0 = \phi(\xi, \tau) - \phi(2 - \xi, \tau), \]

(Jaeger, 1968) where \( T_0 \) is the initial temperature of the flow (°C) and \( T \) is the temperature at any point in the flow (°C). The terms \( \xi \) and \( \tau \) are dimensionless parameters and

\[ \phi(\xi, \tau) = \frac{1}{2} \left( \text{erf} \frac{\xi + 1}{\sqrt{2\tau}} - \text{erf} \frac{\xi - 1}{\sqrt{2\tau}} \right). \]

The flow has a thickness \( 2a \) and is assumed to have a surface temperature of 0°C. The term \( \xi \) is the ratio \( x/a \) where \( x \) is the distance from the center of the flow. In this problem we calculate the cooling rate at the center of the cooling unit, \( x = 0 \), where \( \xi = 0 \). The term \( \tau \) is given by:

\[ \tau = \frac{kt}{a^2}, \]

where \( t \) is the time after deposition (sec) and \( k \) is the thermal diffusivity (cm²/sec). The thermal diffusivity is assumed not to vary with temperature and is equal to \( K/\rho C \), where \( K \) is the thermal conductivity of the cooling unit and basement (cal/cm sec°K), \( \rho \) is the density of the cooling unit and basement (g/cm³), and \( C \) is the specific heat of cooling unit and basement (cal/g°K). The conversion of absolute cooling rates to burial depths is complicated by the fact that thermal conductivity is strongly influenced by the porosity of the rocks (Langseth et al., 1976). Thus a certain cooling rate would imply a greater thickness for a solid igneous rock than for breccia or regolith, because the latter have lower thermal conductivities. The exact nature of the host in which the analyzed Apollo 16 metal-phosphide particles cooled is actually unknown. Three

<table>
<thead>
<tr>
<th>Model</th>
<th>Model II (breccia)</th>
<th>Model III (regolith)</th>
<th>Brett (1975) (ejecta blanket)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity K (cal/cm sec°K)</td>
<td>4.8 x 10^{-3}*</td>
<td>1.4 x 10^{-3}*</td>
<td>2.4 x 10^{-3}*</td>
</tr>
<tr>
<td>( T_0 ), deposition temperature (°C)</td>
<td>1250</td>
<td>1000</td>
<td>750</td>
</tr>
<tr>
<td>( \rho ) (g/cm³)</td>
<td>2.9†</td>
<td>2.9†</td>
<td>2.9†</td>
</tr>
<tr>
<td>( C ) (cal/g deg)</td>
<td>0.4†</td>
<td>0.4†</td>
<td>0.4†</td>
</tr>
<tr>
<td>( \tau_1 ), ( \tau_2 )</td>
<td>( \tau_1 = 0.4 ) ( \tau_2 = 1.0 )</td>
<td>( \tau_1 = 0.2 ) ( \tau_2 = 1.0 )</td>
<td>( \tau_1 = 0.4 ) ( \tau_2 = 0.4 )</td>
</tr>
<tr>
<td>( T/T_0 )</td>
<td>0.605</td>
<td>0.298</td>
<td>0.885</td>
</tr>
<tr>
<td>( T_1 ), ( T_2 ) (°C)</td>
<td>( T_1 = 756 )</td>
<td>( T_2 = 372 )</td>
<td>( T_1 = 885 )</td>
</tr>
<tr>
<td>Rate (°C/day)</td>
<td>1</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>( a ) (m)</td>
<td>4.8</td>
<td>0.48</td>
<td>2.8</td>
</tr>
</tbody>
</table>

*Langseth et al. (1976).
†Brett (1975).
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alternative conversions of rate to depth were therefore made, assuming the thermal conductivity and temperature of deposition of igneous rock, breccia and regolith, respectively. The adopted initial temperatures $T_0$ were chosen to represent temperature above the solidus, temperature between solidus and sintering point, and temperature below that at which sintering can occur. Details of these calculations, which follow the Jaeger method, are given briefly below.

Equation (1) was solved for $T$, using values of $\tau$ for which values of the function $\phi$ were tabulated by Jaeger (1968). The time $t$ (sec) to reach a temperature can be calculated, assuming various values for $a$, using Eq. (3). Cooling rates may be calculated by considering the difference in $\tau$ values, $\tau_1$ and $\tau_2$, between successive $T$ values, $T_1$ and $T_2$, in the temperature range of interest, 600–500°C. The depth $a$ was calculated for the observed phosphide cooling rates (C.R.), 1–100°C/day, using the expression

$$a = \sqrt{\frac{k(T_1 - T_2)}{(\tau_2 - \tau_1)(C.R.)}}$$

(4)

Results are given in Table 2. A calculation using the data of Brett (1975) is also given in Table 2. Note that the highest calculated depth of burial is about 5 m for an impact melt sheet and about 3 m for porous impact breccia for the 1°C/day cooling rate. For the one slow cooled soil particle (~0.001°C/day, Table 1) the depth of burial is ~100 m. The above calculations support the conclusion of Brett (1975) that in general lunar impact rocks are derived from local craters rather than from basin-forming events.

**General Applicability of Technique**

Cooling rates for lunar samples can thus be obtained from simple composition and dimension data for metal-phosphide particles. There are several limitations to the application of this method, not the least of which is that not all lunar rocks contain metal grains with phosphides. Furthermore, the phosphides must be lamellae, not blebs formed at metal–metal grain boundaries. The composition profiles must be consistent with growth during cooling. With dissolution or reheating, the P gradients are reversed and then the method is not applicable. Given a suitable phosphide, the interface P concentration, the size of the lamella (halfwidth) and the diffusion field length must be determined accurately for determination of cooling rate. The determinative curves used here were drawn so that the apparent “interface” compositions resolved by electron microprobe could be used with confidence. However, halfwidth and field length may not be easy to determine, because the phosphide lamellae may be distributed irregularly, oriented at angles to one another and inclined to the plane of the section. These problems must be overcome by judicious choice of the traverses across the lamellae.

One important finding is that bulk composition is not a significant variable, so long as the Ni content is not so high that taenite is present. Thus the figures presented here can be used for cooling rate determination for the majority of
lunar phosphides. The agreement between the burial depths obtained here and by other techniques indicates that further application of the phosphide method for cooling rate determination of lunar rocks is warranted.

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**References**


