THE FORMATION OF ORE MINERAL DEPOSITS ON THE MOON: A FEASIBILITY STUDY

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Most of the ore deposits on Earth are the direct result of formation by hydrothermal solutions. Analogous mineral concentrations do not occur on the Moon, however, because of the absence of water. Stratified ore deposits form in layered instrusives on Earth due to fractional crystallization of magma and crystal settling of high-density minerals, particularly chromium in the mineral chromite. We have evaluated the possibility of such mineral deposition on the Moon, based upon considerations of "particle settling velocities" in lunar vs. terrestrial magmas. A first approximation of Stoke's Law would seem to indicate that the lower lunar gravity (1/6 terrestrial) would result in slower crystal settling on the Moon. However, the viscosity of the silicate melt is the most important factor affecting the settling velocity. The viscosities of typical lunar basaltic melts are 10-100 times less than their terrestrial analogs. These lower viscosities result from two factors: (1) lunar basaltic melts are typically higher in FeO and lower in Al_2O_3, Na_2O, and K_2O than terrestrial melts; and (2) lunar igneous melts and phase equilibria tend to be $100-150°$ C higher than terrestrial, largely because of the general paucity of water and other volatile phases on the Moon. Therefore, particle settling velocities on the Moon are 5-10 times greater than those on Earth. It is highly probable that stratiform ore deposits similar to those on Earth exist on the Moon. The most likely ore minerals involved are chromite, ilmenite, and native FeNi metal. In addition, the greater settling velocities of periodotite in lunar magmas indicate that the buoyancy effects of the melt are less than on Earth. Consequently, the possibility is considerably less than on Earth of deep-seated volcanism transporting upper mantle/lower crustal xenoliths to the surface of the Moon, such as occurs in kimberlites on Earth.

INTRODUCTION

On Earth, minerals commonly occur in economically recoverable concentrations called ore deposits. The various mechanisms that bring about these mineral concentrations are largely the subject of the field of economic geology. Inherent in the usage of the term "ore deposit" is that one or more metals can be extracted from the ore "at a profit." At this stage in the development of lunar base concepts, it is difficult to foresee the exact needs or economics of any such lunar endeavor. It is probable that we will never mine ores on the Moon in order to bring the metals back to Earth. However, there are certain minerals known to be present on the Moon that will undoubtedly be used almost immediately by the early lunar settlements, minerals such as native FeNi for structural purposes, and ilmenite ($FeTiO_3$) for oxygen production. In addition, other oxide minerals such as chromite ($FeCr_2O_4$) and ulvöspinel (Fe_2TiO_4) may be used for their oxygen or metal contents.

Most of the ore minerals on Earth are sulfides and oxides and are called "opaque minerals" because they do not pass light even in thin section. These concentrations of ore minerals most commonly result from deposition by hydrothermal solutions (i.e., $100-300°$C watery solutions). The Moon does not possess appreciable amounts of water, if any; therefore, the presence of ore minerals deposited by hydrothermal solutions is improbable. However, there are other means of depositing ore minerals [e.g., chromite, ilmenite, Platinum Group Elements (PGE)] that are based on fractional crystallization and crystal settling.

Crystallizing minerals will settle within a melt if their densities are greater than the melt. On Earth such accumulations are commonly found in layered intrusions and are known as stratiform deposits. In fact, the mineral chromite ($FeCr_2O_4$), which constitutes the world's major source of the strategic metal, chromium, occurs in mafic strata of large layered igneous complexes often associated with PGE. However, only three layered intrusives—the Bushveld of Transvaal, the Great Dyke of Rhodesia, and the Stillwater Complex of Montana—are known to contain substantial amounts of chromite.

Layered complexes such as the Stillwater originate as large igneous intrusions where the slow cooling of the melt results in fractional crystallization leading to the settling of successive layers of crystals on the progressively rising floor of the intrusive sheet. Related silicate mineral assemblages embrace almost the complete range of mafic and ultramafic rocks: peridotite, dunite, pyroxenite, norite, and to a lesser extent, gabbro and anorthosite. In fact, the presence of such rocks is evidence that fractional crystallization and gravity-controlled crystal settling have been effective. On the Moon, anorthosites, gabbros, troctolites, etc. are common and point to fractional crystallization as a real process. Therefore, it is worth speculating on the possibility of stratiform ore deposits on the Moon.

LUNAR VS. TERRESTRIAL SILICATE MELTS

Introduction

The nonmare portions of the Moon, the highlands, consist of just the rock types that one would expect from fractional crystallization and crystal settling (or floating, in the case of plagioclase on the Moon). In fact, the concept of the Lunar Magma Ocean contends that the outer 200-400 km of the Moon

was molten during the first 100 m.y. after formation. As this magma slowly cooled, the plagioclase that crystallized floated to form "rockbergs" that ultimately coalesced to form the lunar crust. The mafic minerals (e.g., olivine and pyroxene) sank to form the mantle/lower crust, which later gave rise, by partial melting, to basaltic magmas. Such a scenario for lunar evolution implies that the same processes occurred in the igneous plutons of the Moon that occurred on the Earth.

Whether deposits of such minerals as chromite, formed by crystal settling, occur on the Moon is unknown because the Moon remains largely unexplored. Only a few of the nine sites (six from Apollo and three from Luna) visited have been sampled to any geographic extent, and the meager remote-sensing data we possess is of neither sufficient quality nor quantity to fully characterize the lunar surface. It would be unlikely that such data coverage of the surface of the Earth would reveal the presence of ore bodies; therefore, it is not surprising that ores have not been sampled on the Moon. However, the igneous activity of the early Moon suggests that accumulations of chromite, ilmenite, native FeNi metal, etc. are to be expected. Or are they?

Settling Velocities

With gravity on the Moon only one-sixth that of Earth, one would suppose that the effective settling velocities of phases in a lunar melt will be reduced. The settling velocity of a crystal in a melt can be approximated by considerations of Stoke's Law, an equation relating settling velocity to various parameters

$$V = \frac{2ga^2(d_1-d_2)}{9\eta}$$

where V is the velocity of crystal settling in cm/sec; g is the acceleration of gravity in cm/sec^2; a is the diameter of the particle in cm; d is the density of solid (1) or liquid (2) in gm/cm^3; and η is the viscosity of the liquid (dyne-sec/cm^2 or poise).

The most important factors to be considered here are (1) the acceleration of gravity, g, which directly affects settling rate; (2) the difference in density between the crystal and the melt; and (3) the viscosity, η, of the silicate melt, which inversely affects the velocity. As we know, the acceleration of gravity on the Moon's surface is about 160 cm/sec^2, compared to 980 cm/sec^2 on Earth. This factor will contribute sixfold less to the settling velocity for the lunar situation, all other factors being equal. The viscosity differences between silicate melts on the Moon and the Earth are related primarily to two parameters: (1) the average temperature of a lunar mare basalt liquidus and solidus is 100-150°C higher, caused by the paucity of water and other mineralizers that have a tendency to flux the melt; and (2) the typical lunar mare basalt is considerably higher in FeO and lower in Al$_2$O$_3$, Na$_2$O, and K$_2$O than its terrestrial counterpart.

We have performed an analysis of the various parameters that affect settling velocity for both terrestrial and lunar magmas. Representative types of terrestrial basalts, including one for the Stillwater magma and a Mg-rich basanite (Si-deficient olivine basalt), and selected mare basalts from various missions were selected for this analysis. Mare basalts were chosen for this study for two basic reasons:

1. Of the sampled rocks from the Moon, it is the mare basalts that contain the greatest concentrations of ilmenite, chromite, and native FeNi. These minerals commonly are early to crystallize during cooling of the magma, such that the effects of crystal settling would be least impaired by too much crystallization.

2. We have good knowledge of the nature of mare basins and their mare basalt fillings. It is probable that the basalts that we see at the surface came from magma chambers at shallow depths beneath the mare (e.g., 1-15 km). These chambers were supplied by basaltic melt from even greater depths. Schultz (1976) has presented various scenarios of basin formation and associated volcanism that depict the types of situations to which we are referring. It is the near-surface magmatic occurrences forming hypabyssal to shallow plutonic igneous regimes that are the subject of this study. They are close enough to the lunar surface to be potentially accessible and usable.

The densities and viscosities of the silicate melts (Tables 1 and 2) were calculated using the method and data of Bottinga and Weill (1970, 1972). The viscosities of the terrestrial melts were estimated at 1200°C, vs. 1300°C for lunar, because of the lack of fluxing components in the lunar melts, as mentioned above.

The settling velocities of various 1-cm spherical particles were calculated using Stoke's equation, given above, and are presented in Table 3 and Fig. 1. The values for the acceleration of gravity used were 160 and 980 cm/sec^2 for the Moon and Earth, respectively. This equation is for pure newtonian fluids. In reality, silicate melts can behave plastically once significant crystallization has occurred. However, for the purposes of this study, which is one of relative values, not absolutes, Stoke's Law should suffice.

The settling velocities were calculated for (1) ilmenite, (2) chromite, and (3) a peridotite xenolith. The periodotite was included in order to evaluate the possibility of abundant upper mantle/lower crustal xenoliths in lunar basalts, such as those that occur in kimberlites and alkali basalts on Earth. The density of the chromite used in the calculations was different for the Earth and Moon situations (Table 3). On the Moon, chromites most commonly contain ulvöspinel (Fe$_2$TiO$_4$) in solid solution, with minor amounts of FeAl$_2$O$_4$ and MgAl$_2$O$_4$. On Earth chromite usually contains larger amounts of MgAl$_2$O$_4$ (spinel), with lesser amounts of FeFe$_2$O$_4$ (magnetite). Therefore, the density of the lunar chromites was judged to be about 5.0 gm/cm^3 vs. 4.5 gm/cm^3 for the terrestrial chromites. Lunar and terrestrial ilmenites have similar densities.

The thermal regime in which the magma chambers is located can be an important control on settling velocity. If there are sufficient vertical thermal gradients in the melt, classical upward and downward convection will be active. However, the lunar environment is one void of atmosphere (10^{-10} atm) and water. An important effect is that the lunar rocks are considerably less efficient in heat conduction. Therefore, a lunar magma will have better thermal insulation from heat loss than its terrestrial analog. Thus, temperature gradients and subsequent convection should be less. All other factors being equal, the net result is that crystal settling should be more effective on the Moon than on the Earth.

SUMMARY OF RESULTS

1. The viscosities of lunar basaltic melts (9.26 to 36.0 poises) are significantly less than those of terrestrial melts (260.2 to 1200 poises), a difference of 1-2 orders of magnitude.

2. The densities of lunar basaltic melts (2.89 to 3.34 g/cm^3) are greater than terrestrial magmas (2.65 to 2.8 g/cm^3), largely because of higher FeO and TiO$_2$, and lower Na$_2$O and K$_2$O contents for lunar magmas.

3. Viscosity of the silicate melt is the most important factor affecting the settling velocity. As shown in Fig. 1, differences in

TABLE 1.   Chemical composition, density, and viscosity of lunar basalts.

| | Apollo 11 [*] | | Apollo 12 | | | Apollo 14 | Apollo 15 | | Apollo 17 |
	Low K Avg (8)	High K Avg (6)	Ol Avg (9)	Pig Avg (4)	Ilm Avg (4)	VHA Avg (2)	Ol Avg (9)	Pig Avg (13)	Hi-Ti Avg (30)
SiO$_2$	40.67	40.37	44.32	46.46	44.47	45.80	44.98	47.98	38.84
TiO$_2$	10.18	11.77	2.65	3.35	4.63	1.89	2.41	1.82	12.35
Al$_2$O$_3$	10.40	8.84	8.03	10.38	9.76	13.20	8.81	9.46	8.84
FeO	18.68	19.28	21.11	19.72	20.78	17.70	22.37	20.13	18.94
MnO	0.27	0.24	0.28	0.27	0.27	0.24	0.30	0.28	0.27
MgO	6.92	7.56	14.07	7.94	8.52	9.70	10.42	8.74	8.52
CaO	11.70	10.59	8.61	11.03	10.78	10.30	9.79	10.54	10.80
Na$_2$O	0.41	0.52	0.22	0.28	0.32	0.51	0.28	0.31	0.32
K$_2$O	0.07	0.31	0.06	0.07	0.07	0.14	0.05	0.06	0.05
P$_2$O$_5$	0.09	0.17	0.08	0.11	0.10	—	0.08	0.07	0.06
S	0.16	0.22	0.06	0.07	0.08	—	0.07	0.06	0.17
Cr$_2$O$_3$	0.29	0.36	0.63	0.47	0.42	0.47	0.57	0.47	0.49
Total	99.84	100.23	100.12	100.15	100.20	99.95	100.13	99.92	99.65
Mg/Mg+Fe	0.40	0.41	0.54	0.42	0.42	0.49	0.45	0.44	0.44
Viscosity	25.62[1]	14.18	13.87	30.57	22.40	36.00	18.50	30.00	9.26
Density	3.22[2]	3.29	3.00	2.96	3.04	2.89	2.99	2.91	3.34

[*] Apollo 14 composition from *Neal and Taylor* (1988); all others are from *Papike et al.* (1976).
[1] Viscosity units = poise = dyne-sec/cm^2.
[2] Density units = gm/cm^3.

TABLE 2.   Chemical composition, density, and viscosity of terrestrial basalts.

	Basanite[*]	Olivine Basalt	Stillwater Mafic Rock	Tholeiite
SiO$_2$	44.30	49.61	49.41	51.13
TiO$_2$	2.51	3.54	1.20	2.48
Al$_2$O$_3$	14.70	11.28	15.78	14.54
Fe$_2$O$_3$	3.94	2.13	2.11	3.51
FeO	7.50	10.11	10.25	10.19
MnO	0.16	0.18	0.20	0.47
MgO	8.54	7.67	7.36	3.81
CaO	10.19	9.66	10.88	9.50
Na$_2$O	3.55	2.37	2.19	2.71
K$_2$O	1.96	1.83	0.16	1.19
H$_2$O+	1.20	0.80	0.23	0.31
H$_2$O-	0.42	0.42	0.07	0.12
P$_2$O$_5$	0.74	0.52	0.11	1.03
CO$_2$	0.18	—	—	—
Total	99.89	100.12	99.95	100.99
Mg/Mg+Fe	0.64	0.55	0.54	0.37
Viscosity	260.19[†]	302.60	736.80	1200.00
Density	2.80[‡]	2.81	2.76	2.76

[*] Basanite and tholeiite compositions are from *McBirney* (1984); olivine basalt is from *BVSP* (1981); Stillwater mafic rock is from *Helz* (1985).
[†] Viscosity units = poise = dyne-sec/cm^2.
[‡] Density units = gm/cm^3.

TABLE 3.   Particle settling velocities (cm/sec) in basalt melts.

	Periodotite (3.42 g/cm^3)	Ilmenite (4.72 g/cm^3)	Chromite[*] (4.5-5.0 g/cm^3)
Earth			
Basanite	0.52	1.60	1.42
Olivine Basalt	0.44	1.37	1.21
Stillwater Basic Rock	0.19	0.58	0.51
Tholeiite	0.12	0.35	0.32
Moon			
Apollo 11			
Low K	0.28	2.08	2.47
High K	0.31	3.44	4.29
Apollo 12			
Ol Basalt	1.07	4.41	5.13
Pig Basalt	0.53	2.04	2.37
Ilm Basalt	0.60	2.67	3.11
Apollo 14			
VHA	0.52	1.80	2.08
Apollo 15			
Ol Basalt	0.82	3.31	3.85
Pig Basalt	0.60	2.14	2.48
Apollo 17			
Hi-Ti Basalt	0.31	5.30	6.37

[*] The densities of 4.5 and 5.0 gm/cm^3 were used for terrestrial and lunar chromites, respectively.

densities between the various terrestrial basaltic melts are small (i.e., 0.15 gm/cm^3), such that a best-fit linear relationship of viscosity and velocity is possible. The data are more scatttered for the lunar estimates.

4. When the difference between the densities of the melt and particle is small, the density becomes a major factor affecting the settling velocity. For example, the densities of the Apollo 11 and 17 high-Ti basalts are >3.2 gm/cm^3 (3.22 and 3.34 gm/cm^3, respectively), and the density contrasts between these melts and the peridotite particle is down to 0.08 gm/cm^3. In this case, the settling velocities are low, even lower than those for terrestrial

basanite and olivine basalt. These are the three symbols in the lower left of Fig. 1. Magma density has little effect on settling velocities for lunar ilmenite and chromite.

It is interesting to speculate upon the fate of olivine crystallizing from a high-Ti basaltic melt. With a density of about 3.1 gm/cm^3, it is entirely probable that olivine should float within a lunar high-Ti magma.

5. *Hess* (1960) considered 30,000 and 300 poises to be the upper and lower viscosity limits for the Stillwater magma. These same values were also used by *Wager and Brown* (1967) as the viscosity for the Stillwater complex (737 poises) near this lower
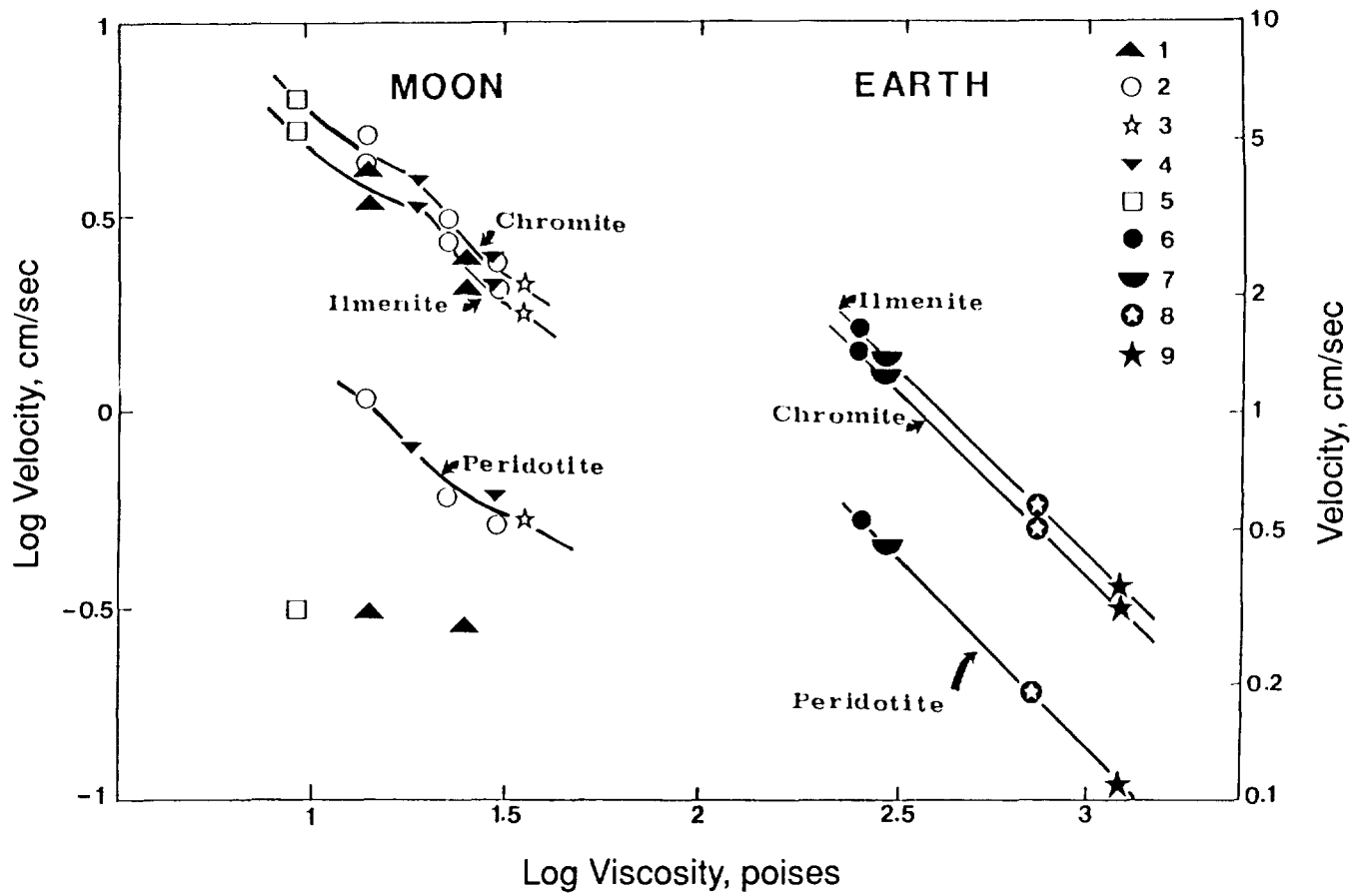
Fig. 1. Calculated viscosities vs. particle settling velocities for chromite, ilmenite, and peridotite in silicate basaltic melts on the Moon and the Earth. See the text for discussion of conditions. *Symbol notation:* 1. Apollo 11; 2. Apollo 12; 3. Apollo 14; 4. Apollo 15; 5. Apollo 17; 6. Basanite; 7. Olivine Basalt; 8. Stillwater Basic Rock; 9. Tholeiite. References: 1-5 from *Papike et al.* (1976); 6 and 9 from *McBirney* (1984); 7 from *BVSP* (1981); 8 from *Helz* (1985).

limit (Table 2). We suggest that this value of 300 poises is a lower limit for most terrestrial basaltic magmas. In contrast, the upper viscosity found on the Moon is still <36 poises. However, the densities of the terrestrial and most lunar basaltic magmas are within the range of 2.7-3.0 gm/cm^3.

6. In general, the particle settling velocities for oxide minerals on the Moon are greater by 5-10 times than those on Earth.

CONCLUSIONS

We conclude that oxide crystals will have greater settling velocities in lunar magmas than in terrestrial magmas. It is highly probable that stratiform ore deposits similar to or even larger than those on Earth exist on the Moon. The most likely ore minerals occurring in lunar intrusive bodies are chromite, ilmenite, and native FeNi metal.

On Earth, magmas from as deep as 200 km bring xenoliths to the surface because of their buoyancy ability, a direct function of melt viscosity. The greater settling velocity of peridotite in lunar melts indicates that the buoyancy effect of the melt is less. Therefore, the probability of finding upper mantle/lower crustal xenoliths brought to the surface of the Moon by deep-seated volcanism is less than on Earth.

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