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Lunar Material Resources: An Overview*

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Abstract

The analysis of returned lunar samples and a comparison of the physical and chemical processes operating on the Moon and on the Earth provide a basis for predicting both the possible types of material resources (especially minerals and rocks) and the physical characteristics of ore deposits potentially available on the Moon. The lack of free water on the Moon eliminates the classes of ore deposits that are most exploitable on Earth; namely, (a) hydrothermal, (b) secondary mobilization and enrichment, (c) precipitation from a body of water, and (d) placer.

The types of lunar materials available for exploitation are whole rocks and their contained minerals, regolith, fumarolic and vapor deposits, and nonlunar materials, including solar wind implantations. Early exploitation of lunar material resources will be primarily the use of regolith materials for bulk shielding; the extraction from regolith fines of igneous minerals such as plagioclase feldspars and ilmenite for the production of oxygen, structural metals, and water; and possibly the separation from regolith fines of solar-wind-implanted volatiles. The only element, compound, or mineral that by itself has been identified as having the economic potential for mining, processing, and return to Earth is helium-3.

Introduction

To be economical, a lunar base operation requires the identification, characterization, development, and utilization of local resources (Flawn 1966, Dalton and Hohmann 1972, Criswell 1980, Haskin 1983, Carter 1985). Even though it is romantic to dream about exotic and fabulously rich mineral deposits, history has shown us repeatedly that in any area the natural resources that are exploited first are those that (a) are needed for basic survival, (b) are readily available, and (c) can be used with the least modification. Ore deposits that are remote, mineralogically complex, or low

grade (and therefore must be dealt with in large volume) are not exploited until after the infrastructure necessary for their exploitation can be constructed. Meeting the criteria for early exploitation is material from the lunar regolith, the layer of debris that covers the surface of the lunar bedrock. Such material can be used as is for bulk shielding to reduce cosmic ray exposure. And from the lunar regolith such desirable elements as oxygen and iron can be extracted without extensive processing such as crushing. The ideal situation ultimately will be to use the lunar regolith material as a feedstock and to separate from it numerous

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elements and products (Lindstrom and Haskin 1979), but this requires an extensive infrastructure of sophisticated and elaborate processing equipment (Williams et al. 1979).

In this paper I develop a general overview of what can be inferred from theoretical considerations of the physical and chemical processes operating on the Moon and what is known about possibly available types of lunar materials from analysis of samples returned by the Apollo and Luna missions. My overview will include an evaluation of lunar regolith fines (the less-than-1-mm fraction) as a source of volatile elements.

Physical and Chemical Processes

Comparison of physical and chemical processes operating on the Earth and on the Moon provides a basis for predicting both the possible types of material resources, especially minerals, and the physical characteristics of ore deposits potentially available for exploitation on the Moon.

Active Surface Agents

One approach to evaluating possible lunar material resources is to compare the active surface agents that affect the Earth and the

Moon. These are listed in table 1. The most striking feature described in table 1 is that the Moon has no atmosphere. Therefore, it has (a) no free water (and thus no freeze/thaw cycles and few, if any, water-bearing minerals such as clays), (b) no free oxygen (and thus no oxidation), and, most importantly, (c) no biological activity. The major physical (erosional) and chemical (weathering) agents—water and oxygen, respectively—and the resulting products we are familiar with on Earth play no role in shaping the surface of the Moon and thus they play no role in the formation of potential lunar ore deposits. The only indigenous lunar erosional agent is volcanic, especially basaltic, lava flows (Hulme 1973). The extremely low viscosities and thus the high extrusion rates of lunar basaltic lava flows (Moore and Schaber 1975) are conditions favorable for the formation of lava channels and tubes, which are very abundant on the lunar surface (Oberbeck et al. 1971). It may be possible to use the naturally sheltered environment of a large lava tube as housing for a lunar base (Hörz 1985). Moreover, some lava tubes may contain accumulations of volatiles.

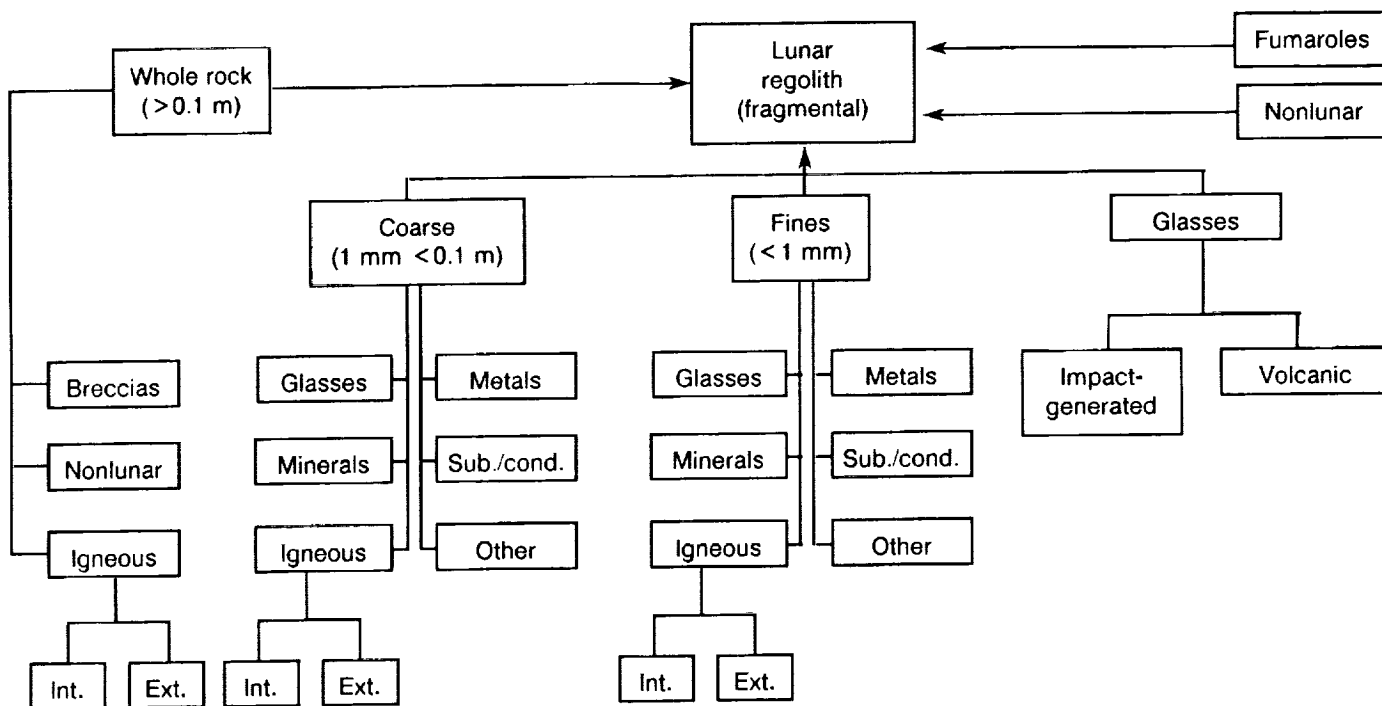
TABLE 1. Comparison of Active Surface Agents on the Earth and on the Moon

Process	Agents		Type	Earth	Moon	
ENDOGENIC	Atmosphere	H ₂ O	Free	Yes (major)	No? (transient)	
		O ₂	"	Yes (major)	No? (transient)	
		CO ₂	"	Yes	Yes? (transient)	
		H ₂	"	Yes (v. minor)	Yes (v. minor) (transient)	
		S	"	Yes?	Yes (v. minor) (transient)	
		Others	"	Yes	Yes? (transient)	
	Liquid water			Yes (major)	No	
	Solids			Yes (major)	Yes (minor?)	
	Volcanic Liquids			Yes (major)	Yes (major)	
	Gases			Yes (minor)	Yes (v. minor)	
Freeze/thaw			Yes (major)	No		
Thermal						
No water			Yes? (v. minor)	Yes (v. minor?)		
Biological			Yes (major)	No		
Gravity			Yes (major)	Yes (minor)		
EXOGENIC	Solar wind			No	Yes (major)	
	Impact-produced	Micro. met.		No?	Yes (major)	
		Solids				
		Macro. met.		Yes (v. minor)	Yes (major)	
		Micro. met.		No	Yes (major)	
		Liquids				
		Macro. met.		Yes (v. minor)	Yes (major)	
	Micro. met.		No?	Yes (minor)		
Gases						
Macro. met.		Yes (v. minor)	Yes (major)			

The lack of an atmosphere on the Moon allows meteorites, comets, micrometeorites, and the solar wind to bombard the lunar surface unimpeded. These are the most

important agents shaping the lunar surface. They also contribute to its material resources (table 2; see also Williams and Jadwick 1980).

TABLE 2. *Types of Lunar (Mare, Highland, Other) Materials Resources*



Cond. = condensates
 Ext. = extrusive
 Int. = intrusive
 Sub. = sublimates

The various types of materials that contribute to the lunar regolith are diagrammatically displayed in table 2. To reveal the exploitation potential of the contents of any box requires much additional information. Also of importance is the distribution of the various types of lunar materials. From the simplest point of view, the Moon has two basic types of physiographic provinces: light-colored lunar highlands and dark-colored lunar maria. The highlands are old crust (more than four billion years). The maria are relatively young (less than four billion years) and are large impact-produced craters that are flooded with basaltic rock types (Taylor 1975).

The chemistry of these two basic physiographic provinces is similar, except in aluminum, iron, calcium, and titanium (table 3), but their mineralogy is quite different. The highlands consist of rocks very rich in plagioclase and thus rich in aluminum and calcium; whereas, the maria consist of ilmenite-bearing basaltic rocks and thus are titanium- and iron-rich. The ideal early exploitation target would be situated where both types of materials are juxtaposed, such as near the margins of some mare (McKay and Williams 1979) or on a ray from a major impact that extends from the lunar highlands into a mare.

TABLE 3. *Average Major Element Chemistry for Mare and Highland Soil*
[From Turkevich 1973]

Element	Percent of atoms			Weight percent of oxides		
	Mare	Highland	Average surface	Mare	Highland	Average surface
O	60.3 ± 0.4	61.1 ± 0.9	60.9			
Na	0.4 ± 0.1	0.4 ± 0.1	0.4	0.6	0.6	0.6
Mg	5.1 ± 1.1	4.0 ± 0.8	4.2	9.2	7.5	7.8
Al	6.5 ± 0.6	10.1 ± 0.9	9.4	14.9	24.0	22.2
Si	16.9 ± 1.0	16.3 ± 1.0	16.4	45.4	45.5	45.5
Ca	4.7 ± 0.4	6.1 ± 0.6	5.8	11.8	15.9	15.0
Ti	1.1 ± 0.6	0.15 ± 0.08	0.3	3.9	0.6	1.3
Fe	4.4 ± 0.7	1.8 ± 0.3	2.3	14.1	5.9	7.5

Rock Cycle

Another approach to evaluating possible lunar material resources is to compare the rock cycle of the Moon (fig. 3) to that of the Earth (fig. 4). A rock cycle is a sequence of events leading to the formation, alteration, destruction, and reformation of rocks as a result of various physical and chemical

processes. Thus, it is a pictorial way of viewing the different processes that lead to natural material resources such as ore deposits and of predicting the types of deposits that result from the various physical and chemical processes. A comparison of the Moon's rock cycle with the Earth's (shown in figures 3 and 4, respectively) reveals the

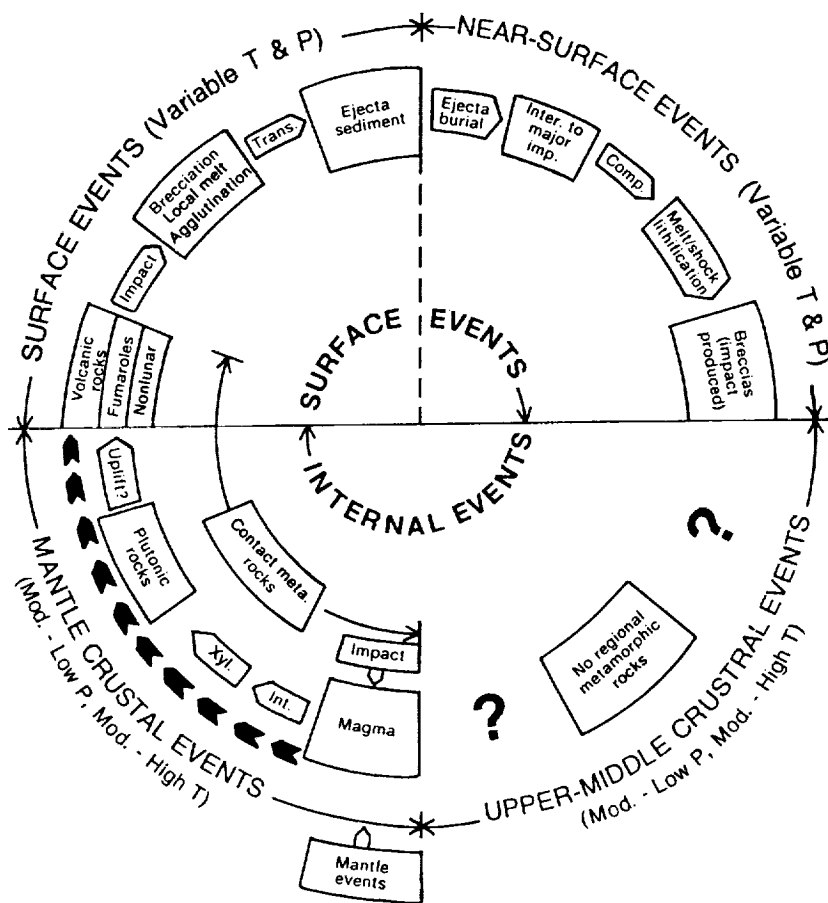


Figure 3

Moon Rock Cycle

- Comp. = compression
- Imp. = impact
- Int. = intrusion
- Inter. = intermediate
- Meta. = metamorphic
- Mod. = moderate
- Trans. = transport
- Xyl. = crystallization

fundamental differences resulting from the lack of free water and oxygen on the Moon. The comparison also shows that, while the Moon has been dominated by external processes, the Earth has been dominated by internal

processes. The various types of physical and chemical processes represented by the rock cycles, the resulting commercial types of mineral deposits on Earth, and the probable types of lunar deposits are shown in table 4.

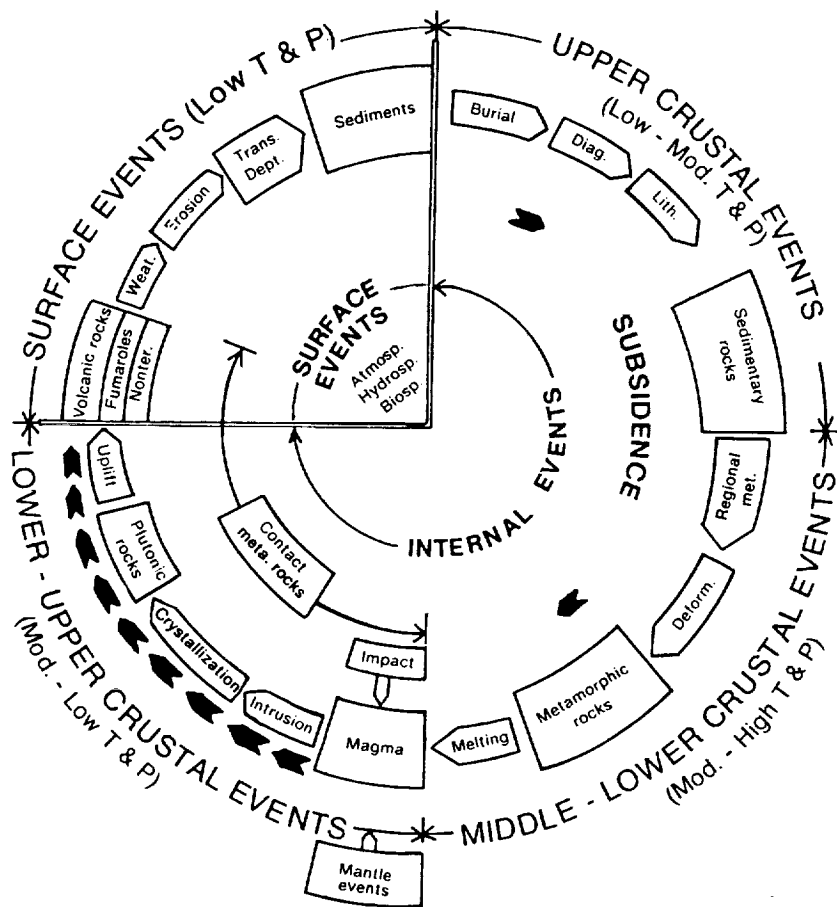


Figure 4

Earth Rock Cycle

- Atmosp. = atmospheric
- Biosp. = biospheric
- Deform. = deformation
- Dept. = deposition
- Diag. = diagenesis
- Hydrosp. = hydrospheric
- Lith. = lithification
- Met. = metamorphism
- Meta. = metamorphic
- Nonter. = nonterrestrial
- Trans. = transport
- Weat. = weathering

TABLE 4. *Various Processes in Mineral Deposit Formation*

Type	Probably occur on Moon	Commercial type Earth deposit	Probable type lunar deposit
I. Igneous			
A. Intrusive magmatic			
1. Early			
a. Dissemination	Yes	Diamonds, apatite, corundum	Ilmenite
b. Segregation	Yes	Chromite, Pt, anorthite, ilmenite, titanomagnetite	Ilmenite, anorthite, chromite?
c. Injection	Yes?	Magnetite	Oxides?
2. Late			
a. Gravitative liquid accumulation			
i. Seg.	Yes	Chromite, Pt, titanomagnetite	Ilmenite, titanomagnetite?
ii. Inject.	Yes?	Magnetite, apatite	Oxides?
b. Immiscible liquid			
i. Seg.	Yes	(Ni,Cu)S, Pt, Au	(Ni,Cu,Fe)S, Pt, Au?
ii. Inject.	Yes	(Ni,Cu)S, Pt	(Ni,Cu,Fe)S, Pt
c. Carbonatite	No?	Rare earths	?
d. Felsic pegmatite	No?	Feldspar, mica, rare earths, quartz, gemstones	?
B. Volcanic			
1. Glass	Yes	Perlite, pumice	Ti-, Al-rich
2. Submarine exhalative	No	Base metal	None
3. Sublimates; condensates	Yes	S, NaCl	S?, chlorides
II. Metamorphic/metasomatic			
A. Contact	Yes	W, Cu, Pb, Zn	?
B. Regional	No?	Abrasives, aluminosilicates	None?
C. Thick ejecta blanket	Yes	Meteoritic material	Phosphates, volatiles?
III. Surficial (sedimentation)			
A. Sedimentation	Yes	Sand, gravel, limestone	Regolith
B. Biochemical processes; organic accumulations	No	Petroleum	None
C. Oxidation; supergene enrichment	No	Base metal, Au, Ag, U	None
D. Residual/mechanical concentration	No?	Au, rare earths, Al, Fe, diamonds	None?
E. Evaporation	No?	Salts	None?
F. Groundwater	No?	U, Cu	None?
IV. Asteroid/comet impact	Yes	Ni, Fe, Pt?	Ni, Fe, Pt, C, H ₂ O, chlorides

The apparent lack of plate tectonics operating on the Moon (Taylor 1975) is also of importance in evaluating possible lunar material resources. Plate tectonics, which is characterized on Earth by a small number of large, broad crustal plates, each of which "floats" on a viscous underlayer (mantle) and moves more or less independently of the others, is fundamental to the development of most commercial type ore deposits and even petroleum deposits on Earth (Mitchell and Garson 1981, Hutchison 1983). One important aspect of plate tectonics on the Earth is the recycling and partial fusion of crustal materials to form granites and their related ore deposits and pegmatites (Mitchell and Garson 1981, Hutchison 1983). Even though a granite-like residual phase (mesostasis and "veinlets") and very small granitic clasts in breccias occur in rocks on the Moon (Rutherford et al. 1976, Warren et al. 1983a), there is no evidence that large-scale granitic bodies occur on the Moon (Taylor 1975). Moreover, unlike the majority of similar Earth rocks, the granite-like Moon rocks are completely devoid of hydrous phases (Warren et al. 1983a).

Lunar Material Resources

The types of lunar materials available for exploitation (table 2) can be grouped into four basic categories: whole rocks and minerals, regolith, fumarolic and vapor deposits, and nonlunar materials. We have very little direct knowledge of whole rocks in situ, and we know virtually nothing about possible fumarolic deposits. The Apollo and Luna missions were designed to study the lunar regolith, with cores taken a maximum of 3 meters deep (Carrier 1974, Taylor 1975). Thus, in the subsequent sections, I will mainly discuss the potential of the near-surface lunar regolith as a source of materials, especially as a source of volatile elements.

Rocks and Minerals

Rocks: The major rock types in the maria are basalts, gabbros, pyroxene-rich peridotites, and breccias (Mason and Melson 1970, Levinson and Taylor 1971, Taylor 1975, Gillett 1983, Taylor 1984). The major rock types in the highlands are various types of anorthosites; anorthositic gabbros;

KREEP basalt enriched in potassium, rare earths, and associated elements; low-potassium basalt; norite; dunite; and breccias (Taylor 1975, Gillett 1983).

The mare rock types are composed primarily of plagioclase feldspars, clinopyroxenes, and ilmenite, with minor olivine, chromite/ulvöspinel, and tridymite/cristobalite (Taylor 1975). The highland rock types are composed primarily of plagioclase feldspars, orthopyroxenes, and olivine, along with minor ilmenite (Taylor 1975). The whole rocks represent a potential source of

these minerals and someday may be used as a feedstock because they would supply material of relatively uniform physical characteristics, but their use would require an extensive infrastructure for mining and processing. The regolith fines will probably be exploited first because they have already been pulverized by meteoritic and cometary bombardment. The ranges of modal abundances for the major lunar minerals in various rock types are shown in table 5. The ranges of chemical compositions for the major lunar minerals in various rock types are shown in table 6.

TABLE 5. *Ranges of Modal Abundances (Volume %) for the Major Lunar Minerals in Various Rock Types*
[Modified from Waldron, Erstfeld, and Criswell 1979]

	High-Ti mare basalts	Low-Ti mare basalts	Highland rocks
Pyroxene	42 - 60	42 - 60	5 - 35
Olivine	0 - 10	0 - 36	0 - 35
Plagioclase	15 - 33	17 - 33	45 - 95
Opaques (mostly ilmenite)	10 - 34	1 - 11	0 - 5

TABLE 6. *Ranges of Chemical Compositions for the Major Lunar Minerals in Various Rock Types*
 [Modified from Waldron, Erstfeld, and Criswell 1979]

Components (wt. %)	Pyroxene	Olivine	Plagioclase	Opaques (mostly ilmenite)
a. High-titanium mare basalts				
SiO ₂	44.1 - 53.8	29.2 - 38.6	46.9 - 53.3	< 1.0
Al ₂ O ₃	0.6 - 6.0		28.9 - 34.5	< 2.0
TiO ₂	0.7 - 6.0			52.1 - 74.0
Cr ₂ O ₃	< 0.7	0.1 - 0.2		0.4 - 2.2
FeO	8.1 - 45.8	25.4 - 28.8	0.3 - 1.4	14.9 - 45.7
MnO	< 0.7	0.2 - 0.3		< 1.0
MgO	1.7 - 22.8	33.5 - 36.5	< 0.3	0.7 - 8.6
CaO	3.7 - 20.7	0.2 - 0.3	14.3 - 18.6	< 1.0
Na ₂ O	< 0.2		0.7 - 2.7	
K ₂ O			< 0.4	
b. Low-titanium mare basalts				
SiO ₂	41.2 - 54.0	33.5 - 38.1	44.4 - 48.2	< 1.0
Al ₂ O ₃	0.6 - 11.9		32.0 - 35.2	0.1 - 1.2
TiO ₂	0.2 - 3.0			50.7 - 53.9
Cr ₂ O ₃	< 1.5	0.3 - 0.7		0.2 - 0.8
FeO	13.1 - 45.5	21.1 - 47.2	0.4 - 2.6	44.1 - 46.8
MnO	< 0.6	0.1 - 0.4		0.3 - 0.5
MgO	0.3 - 26.3	18.5 - 39.2	0.1 - 1.2	0.1 - 2.3
CaO	2.0 - 16.9	< 0.3	16.9 - 19.2	< 1.0
Na ₂ O	< 0.1		0.1 - 1.3	
K ₂ O			< 0.3	
c. Highland rocks				
SiO ₂	51.10 - 55.4	37.70 - 39.9	44.00 - 48.0	< 0.1
Al ₂ O ₃	1.00 - 2.5	< 0.1	32.00 - 36.0	0.80 - 65.0
TiO ₂	0.45 - 1.3	< 0.1	0.02 - 0.03	0.40 - 53.0
Cr ₂ O ₃	0.30 - 0.7	< 0.1	< 0.02	0.40 - 4.0
FeO	8.20 - 24.0	13.40 - 27.3	0.18 - 0.34	11.60 - 36.0
MgO	16.70 - 30.9	33.40 - 45.5	< 0.18	7.70 - 20.0
CaO	1.90 - 16.7	0.20 - 0.3	19.00 - 20.0	< 0.6
Na ₂ O			0.20 - 0.6	
K ₂ O			0.03 - 0.15	

Minerals: The number of mineral species positively identified on the Moon is 70, with 14 others tentatively identified (table 7) (Levinson and Taylor 1971, Frondel 1975, Warren et al. 1983b, Meyer and Yang 1988), which is less than 2 percent of the mineral species known on Earth (Fleischer 1987). However, less than 2 percent of the 3800 mineral species known on Earth makes up more than 95 percent of the commercially exploitable mineral deposits on

Earth. These may be divided into those that can be used in their natural state, either singularly or combined with others to form a rock, and those that must be refined. Of the known lunar minerals, a maximum of one-sixth have "early" exploitation potential. These are apatite, armalcolite, chromite, "goethite," ilmenite, iron-nickel, olivine, plagioclase feldspars, potassium feldspars, and whitlockite (table 7). But of these only ilmenite, plagioclase feldspars,

TABLE 7. *Lunar Minerals*

Common and abundant minerals		Important accessory minerals	
Clinopyroxenes	(Ca,Mg,Fe) ₂ Si ₂ O ₆	Apatite	Ca ₅ (PO ₄) ₃ (F,Cl)
Augite		Armalcolite	(Fe,Mg)Ti ₂ O ₅
Ferroaugite		Baddeleyite	ZrO ₂
Ferrohedenbergite		Cristobalite	SiO ₂
Ferropigeonite		Iron-nickel	FeNi
Pigeonite		Kamacite	
Salite		Taenite	
Subcalcic augite		Potassium feldspars	KAlSi ₃ O ₈
Titanaugite		Hyalophane	
Ilmenite	FeTiO ₃	Orthoclase	
Olivine	(Mg,Fe) ₂ SiO ₄	Sanadine	
Chrysolite		Pyroxferroite	CaFe ₆ (SiO ₃) ₇
Fayalite		Quartz	SiO ₂
Forsterite		Spinels	(Fe,Mg,Ti)(Al,Cr,Ti) ₂ O ₄
Orthopyroxenes	(Mg,Fe)SiO ₃	Chromite	
Bronzite		Picotite	
Enstatite		Pleonaste	
Hypersthene		Hercynite	
Plagioclase feldspars	(Ca,Na)Al ₂ Si ₂ O ₈	Spinel	
Andesine		Titanian chromite	
Anorthite		Tranquillityite	Fe ₈ (Zr,Y) ₂ Ti ₃ Si ₃ O ₂₄
Bytownite		Tridymite	SiO ₂
Labradorite		Troilite	FeS
		Ulvöspinel	Fe ₂ TiO ₄
		Whitlockite	Ca ₉ MgH(PO ₄) ₇
		Zirkelite	(Ca,Fe)(Zr,Ti) ₂ O ₇

TABLE 7 (concluded).

Rare minerals		Pyrochlore	
Aluminum carbide	Al_4C_3	Yttrobetafite	$(\text{Ca}, \text{Y}, \text{REE}, \text{Fe}, \text{Pb}, \text{Th}, \text{U})_2 (\text{Ti}, \text{Nb}, \text{Fe})_2 \text{O}_7$
Amphibole		Rutile	TiO_2
Hornblende		Schreibersite	$(\text{Fe}, \text{Ni}, \text{Co})_3 \text{P}$
$(\text{Ca}, \text{Na}, \text{K})_{2-3} (\text{Mg}, \text{Fe}, \text{Al})_5 ([\text{OH}]?, \text{F}, \text{Cl})_2 \text{Al}_2 \text{Si}_6 \text{O}_{22}$		Sphalerite	ZnS
Magnesioarfvedsonite		Thorite	ThSiO_4
$(\text{Na}, \text{K}, \text{Ca})_3 (\text{Mg}, \text{Mn}, \text{Fe})_5 ([\text{OH}]?, \text{F})_2 (\text{Si}, \text{Al}, \text{Ti})_8 \text{O}_{22}$		Tin	Sn
Bornite	$\text{Cu}_5 \text{FeS}_4$	Titanite	CaTiSiO_5
Brass	CuZn	Zircon	ZrSiO_4
Calcite (?)	CaCO_3	Tentative minerals	
Chalcocopyrite	CuFeS_2	Aragonite	CaCO_3
Cohenite	$(\text{Fe}, \text{Ni})_3 \text{C}$	Farringtonite	$(\text{Mg}, \text{Fe})_3 (\text{PO}_4)_2$
Copper	Cu	Garnet	
Corundum	$\text{Al}_2 \text{O}_3$	Spessartite	$\text{Mn}_3 \text{Al}_2 (\text{SiO}_4)_3$
Cubanite	$\text{CuFe}_2 \text{S}_3$	Hematite	$\text{Fe}_2 \text{O}_3$
Garnet		Magnetite	$\text{Fe}_3 \text{O}_4$
Almandine	$\text{Fe}_3 \text{Al}_2 (\text{SiO}_4)_3$	Melilite	$(\text{Ca}, \text{Na})_2 (\text{Mg}, \text{Fe}) (\text{Al}, \text{Si})_2 \text{O}_7$
"Goethite"	FeOOH	Moissanite	SiC
Akaganeite		Nickel	Ni
Lepidochrosite		"Nickel silver"	CuNiZnFe
Lawrencite	FeCl_2	Pentlandite	$(\text{Fe}, \text{Ni})_9 \text{S}_8$
Mackinawite	FeS	Perovskite	CaTiO_3
Mica		Sillimanite (or mullite)	$\text{Al}_2 \text{SiO}_5$
Biotite		Talnakhite	$\text{Cu}_9 (\text{Fe}, \text{Ni})_9 \text{S}_{18}$
$\text{K}_2 ([\text{OH}]?, \text{F})_4 (\text{Mg}, \text{Fe}, \text{Al})_6 (\text{Si}, \text{Al})_8 \text{O}_{20}$		Wüstite	FeO
Muscovite (?)			
$\text{KAl}_2 (\text{AlSi}_3) \text{O}_{10} ([\text{OH}]?, \text{F})_2$			
Monazite	$(\text{Ca}, \text{La}, \text{Y}, \text{Th}) \text{PO}_4$		
Ninningerite	MgS		

and possibly "goethite" are very likely to be exploited early (McKay and Williams 1979). These minerals could be used to produce oxygen, structural metals (aluminum, iron, and titanium), and water, and they seem to occur in concentrations high enough to

warrant exploitation. Apatite, potassium feldspars, and whitlockite are important raw materials in the production of fertilizers for growing plants on the Moon, but they may not be present in high enough concentrations to be easily exploited.

Regolith

The lunar regolith, especially the fraction called "fines" (the particles that are less than 1 mm in diameter), offers the opportunity to take advantage of two different physical processes operating on the lunar surface: (1) brecciation, including pulverization through meteoritic and cometary impact, and (2) solar wind implantation of volatile species. The longer the lunar regolith is exposed to bombardment, the greater the extent of pulverization and implantation of volatile species. However, two counterproductive processes are in operation. First, major impacts result in throw-out of large volumes of material that cover up older regolith. Second, micrometeorite bombardment results in production of agglutinates, which are lunar fines welded together with liquid silicate (glass) (McKay et al. 1971). Thus, there are both destructive and constructive processes operating on the lunar surface.

The heating of the fines associated with micrometeoritic events liberates some of the solar-wind-implanted volatile species (Carter 1985) and plays an important role in the distribution and redistribution of volatiles on the Moon (Wegmüller et al. 1980).

The formation of agglutinates also decreases the availability of minerals, such as plagioclase feldspars and to a lesser extent ilmenite, for concentration from lunar fines (tables 8 and 9; figure 5). But agglutination does produce a small amount of metallic iron (Morris 1980), which should be concentratable by magnetic means. There is, in any case, an upper limit for production of agglutinates (McKay and Basu 1983). The ideal situation would be to have lunar regolith old enough to allow maximum solar wind implantation but not so old as to allow extensive production of agglutinates.

TABLE 8. Grain Populations in Percent for Selected Particle Types of the 90-150 Micrometer Size Fraction in Some Apollo 16 Soils
[From McKay and Williams 1979]

	Sample	Plagioclase	Anorthosite	Light matrix breccia	Total	Normative anorthite	Agglutinates
Core	60009,455	47.0	6.8	3.8	57.6	82	12.5
	60009,457	76.2	3.8	0.8	80.8	---	2.2
	61161	14.7	4.7	13.6	33.0	72	37.0
STA 1	61181	5.3	4.3	7.3	16.9	74	59.6
	61221	17.0	13.6	10.0	40.6	77	6.3
	61241	12.3	5.0	18.3	35.6	74	27.1
STA 2	62281	16.0	5.6	11.3	32.9	73	40.0
	63321	9.6	11.2	14.0	34.8	79	32.6
STA 3	63341	12.6	5.9	14.9	33.4	79	40.0
	63501	10.3	3.0	16.7	30.0	76	44.6
STA 4	64501	20.3	3.0	6.6	29.9	75	51.6
STA 8	68501	12.3	1.9	29.3	43.5	73	38.6
	67481	15.0	10.9	20.3	45.2	79	23.0
	67601	14.0	3.6	24.0	41.6	79	36.0
STA 11	67701	21.0	3.3	34.0	58.3	78	15.6
	67711	41.0	4.6	36.6	82.2	80	1.6

TABLE 9. *Modal and Normative Ilmenite in Mare Basalts From the Apollo Missions*
 [From McKay and Williams 1979]

Sample	Modal ilmenite content, %	Normative ilmenite content, %
10003	14-18	21.5
10017	14-24	22.4
10044	6-12	17.1
10045	7-11	21.3
10049	16-17	21.5
10072	13-22	22.8
Apollo 11 mean	14.5	21.1
12202	8-11	4.9
12012	5-12	6.6
12022	9-23	9.3
12039	8-10	5.7
12051	8-11	8.9
12063	8-10	9.5
Apollo 12 mean	10	7.5
15016	6	4.4
15076	0.5	3.6
15475	1.0	3.4
15555	1-5	4.0
15556	2	5.1
Apollo 15 mean	2.6	4.1
75055	12-20	20.5
70215	13-37	24.7
70035	15-24	24.7
70017	19-23	24.7
Apollo 17 mean	20.4	23.7

Minerals: The constant meteoritic and cometary bombardment of the lunar surface results in comminution of whole rocks, with liberation of the mineral constituents. Most of the minerals listed in table 7 have been found as isolated grains or as composite particles in the lunar regolith fines. The available anorthite content in the Apollo 16 lunar highland regolith samples (90- to 150-micrometer size fraction) varies from just under 17 percent to just over 82 percent (see table 8) and averages 43.5 percent. The lower values result from the inverse

relationship between available anorthite content and agglutinate content (see figure 5). The ilmenite content of mare basalts from all Apollo missions varies from 0.5 percent to 37 percent (see table 9) and averages 11.5 percent. If the significantly lower Apollo 15 samples are omitted, the average is 14.4 percent. Electrostatic separation experiments in vacuum by Agosto (1985) suggest that grade and recovery percentages should be between the high 70s and the low 90s.

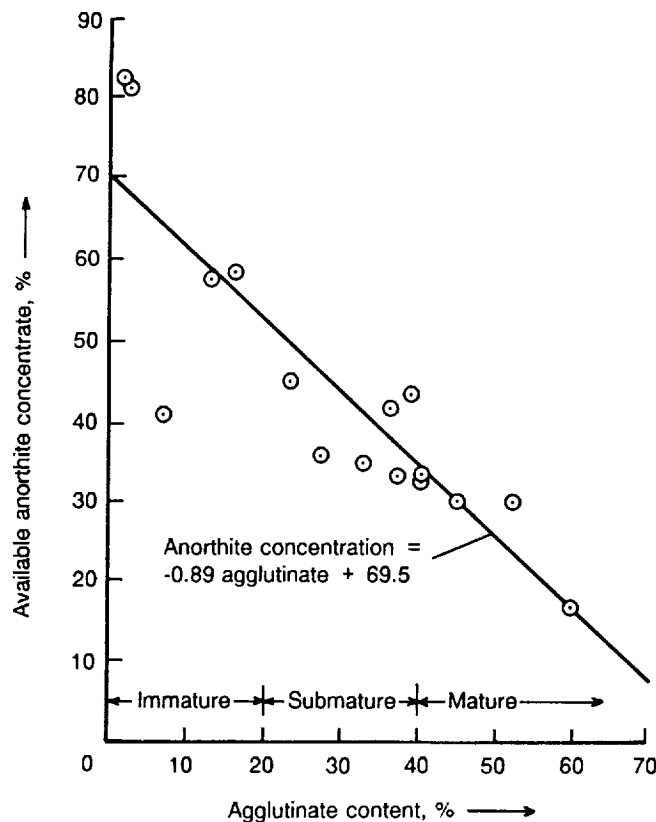


Figure 5

Relationship Between Available Anorthite and Maturity of Soil
From McKay and Williams 1979.

Glasses: There are two main types of glasses found in the lunar regolith—homogeneous and heterogeneous (Taylor 1975). The homogeneous glasses are "volcanic" in origin or produced by major impacts, and the heterogeneous glasses are produced by more minor impacts. Two chemically distinct homogeneous glasses have been found to be abundant in spots: green and orange (Taylor 1975). The green glasses are of the most primitive lunar composition yet found and are a possible source of aluminum. The orange glasses are a possible source of titanium. In addition, both have surface coatings that may offer chlorine, copper, lead, zinc, and other volatile elements and compounds (Jovanovic and Reed 1973, Rhodes 1973, Chou et al. 1975, Meyer et al. 1975). However, in order to utilize this material, we would have

to undertake extensive chemical processing. The heterogeneous glasses have a wide range of chemistries (Taylor 1975), and thus it would be difficult to separate them from the rest of the regolith.

Volatile species: Because the Moon has no atmosphere, the lunar regolith fines are a potential source of solar-wind-implanted ions such as H, N, C (table 10; see also, for example, Eberhardt et al. 1972 and Gibson, Bustin, and McKay 1988), and ^3He . Wittenberg, Santarius, and Kulcinski (1986) calculated that the Moon's surface materials contain approximately 10^9 kg of ^3He . If ^3He can be developed as an energy source, the energy payback for extracting and transporting ^3He to Earth is approximately 250, which is better than 10 times the payback for conventional energy sources on Earth.

TABLE 10. Concentration of H, C, and N in Lunar Regolith Fines
[Modified from Taylor 1975]

Site	Concentration, ppm		
	H	C	N
Apollo 11	46 - 54	142 - 226	102 - 153
Apollo 12	38 - 80	23 - 180	40 - 130
Apollo 14	36 - 70	42 - 186	80 - 164
Apollo 15	13 - 120	21 - 186	25 - 113
Apollo 16	8 - 79	31 - 280	30 - 155
Apollo 17	42 - 211	4 - 200	7 - 130
Luna 16			134 - 2100
Luna 20			80 - 800

Wittenberg, Santarius, and Kulcinski (1986) further calculated that, even if the U.S. electrical demand doubled every 25 years until the 22nd century and deuterium/helium-3 fusion provided all the electrical energy required after the year 2020, only 3 percent of the Moon's ^3He resources would be used. In addition, they concluded that "It should also be possible to use the lunar surface as a source of fuel for power plants in earth orbit, on the moon or on other planets. This lunar source of ^3He is sufficiently large to provide for a century or more of space research to exploit the extremely large ^3He reserves on Jupiter. Thus, the lunar ^3He can help deliver the 'clean' energy source that fusion scientists have been promising for over 30 years."

Fumaroles and Vapor Deposits

As I have stated previously, there is little direct evidence that fumaroles exist or ever existed on the lunar surface. The observation of gaseous emanations from the crater Alphonsus by Kozyrev (1962) and the probable fire-fountaining origin of the orange glass spheres (McKay and Heiken 1973) suggest that volcanic gases occur on the Moon. The crystallization of subsurface magma should release dissolved volatiles and, if these volatiles accumulate, then fumarolic activity should occur

(Sato 1979), with possible deposition of volatile species. Another source of volatiles is emanations from the lunar interior (Gorenstein, Golub, and Bjorkholm 1974; Hodges and Hoffman 1974; Geake and Mills 1977; Middlehurst 1977; Runcorn 1977). Fumarolic-like activity may also occur through the remobilization of material from the heating associated with major meteoritic or cometary impacts (McKay et al. 1972, Jovanovic and Reed 1975, Cirlin and Housley 1980). The discovery by McKay et al. (1972) of vapor-deposited apatite, ilmenite, metallic iron, plagioclase, pyroxene, and troilite in recrystallized Apollo 14 breccias is an example of remobilization of elements by a major impact event.

The permanently dark and cold areas of the lunar polar regions may be a source of cryotrapped volatiles (Watson, Murray, and Brown 1961; Arnold 1979; Lanzerotti, Brown, and Johnson 1981). Temperatures possibly as low as 40 K suggest the possibility of both surface and subsurface ices that could survive for billions of years. However, until exploration of the polar regions occurs, we can only speculate as to the possible presence and nature of ices (Staehle 1983). If they occur in useful quantities, they will provide an overwhelming reason for locating at least some part of a base complex near a pole (Burke 1985).

Nonlunar Materials

There are two basic types of nonlunar inputs: (1) meteoritic, including cometary, and (2) solar wind. The rocks from which the lunar regolith is formed are fragmented by meteoritic and cometary impacts. This process results in the input of material of nonlunar sources (Ganapathy et al. 1970, Baedecker, Chou, and Wasson 1972; Zook 1975). The fragmented material, with its included nonlunar material, is a potential resource. For example, if large masses or concentratable fragments of chondritic materials can be located, they will be a source of volatile elements (Taylor 1975). Meteoritic debris is also a source of metallic iron, nickel, and cobalt (Dalton and Hohmann 1972; Goldstein and Axon 1973; Goldstein, Hewins, and Axon 1974; Wänke, Dreibus, and Palme 1978; Mehta and Goldstein 1980) and a potential source of the platinum group elements and gold (Ganapathy et al. 1970, Wlotzka et al. 1972, Hertogen et al. 1977).

Discussion

The surface of the Earth is dominated by water-related erosional processes, oxidation, and biological activity, whereas the surface of the Moon is dominated by bombardment processes (table 1). Internal crustal processes for both the Earth and

the Moon are dominated by metamorphic reactions in which water plays an important role on Earth (figs. 3 and 4). There is no evidence of free water on the Moon. The lack of free water on the Moon significantly affects the nature of possible ore deposits on the Moon and eliminates the classes of ore deposits that are most exploitable on Earth; namely, (a) hydrothermal, which includes all base metal sulfide and precious metal vein deposits; (b) secondary mobilization and enrichment, which includes all ground-water-related ore deposits; (c) direct precipitation from a body of water, which includes evaporite deposits such as gypsum and salt; and (d) placer, which includes heavy mineral deposits such as diamond, gold, ilmenite, monazite, rutile, and zircon. These types of ore deposits have made up a significant percentage of the ores mined on Earth, because these processes concentrate the elements and the heavy minerals into exploitable deposits.

The data in tables 1 and 2 and the evaluation of figures 3 and 4 offer no evidence, direct or theoretical, for significant base metal sulfide or precious metal vein deposits on the Moon. However, we must be somewhat cautious about making categorical statements, because only nine lunar landing sites (six manned Apollo and three unmanned Luna) have been sampled and these were not chosen at random. Even though

meteoritic processes result in throw-out of materials and thus a potentially wide distribution of fragmented rock types, there could be small, localized, but very concentrated sources of desirable elements or compounds that would go unrecognized in studies of particles among the returned lunar regolith fines. If concentrations of desirable elements or compounds do occur, they should be found in igneous rocks, meteoritic and cometary debris, and regolith fines that have been affected by solar wind implantation (table 2; figure 3).

In 1985 I made a pioneering effort to evaluate quantitatively the lunar regolith fines as a primary source of hydrogen. The theoretical foundation laid in that paper can be used to evaluate quantitatively any solar-wind-implanted species or any species found on or near the surface of a particle, no matter what its origin.

The known concentration range of hydrogen, nitrogen, and carbon in the lunar regolith fines is shown in table 10. Such values are often used as evidence that the Moon is devoid of water, even though 100 ppm of hydrogen is equivalent to 0.09 percent by weight of water. In addition to water, other elements necessary for the growth of plants—nitrogen and carbon (carbon dioxide)—are also present on the Moon. However, because these three elements together total

less than 0.3 percent of the lunar regolith (table 10), they must be beneficiated (concentrated) before they can be economically extracted. Beneficiation of lunar regolith fines can only occur under the following conditions: (1) A relatively small portion of the fine material must contain a significant amount of the element sought. (2) That material must be separable; that is, it must have unique physical and chemical properties. (3) The separation process must be economical; that is, not labor intensive or technically complex.

In my 1985 paper I demonstrated that the lunar regolith fines meet the basic requirement for beneficiation because a major portion (a minimum of two-thirds) of the hydrogen, and probably other solar-wind-implanted elements, occurs in the less-than-20-micrometer size fraction—a relatively small part of the fines. A comparison of the lunar data of Bustin et al. (1984) with the results of my theoretical calculations (table 11) reveals excellent similarity, except for a slight but significant increase of hydrogen in the size fractions that are greater than 120 micrometers. This enrichment of the lunar samples is due to the presence of constructional particles (McKay et al. 1971, Carter 1971); namely, agglutinates (DesMarais, Hayes, and Meinschien 1974) and other types of dust-welded particles.

One aspect of the question of economics is how difficult and expensive it is to extract the solar-wind-implanted elements from the beneficiated lunar regolith fines. In 1985 I recalculated the hydrogen thermal release pattern for a sample of Apollo 11 regolith fines (10086) (Gibson and Johnson 1971) and found that approximately 81 percent of the hydrogen is released below 600°C. This calculation means that only a moderate amount of thermal energy should be required to extract a significant portion of the hydrogen, especially if advantage can be taken of daytime temperature on the lunar

surface and if heat can be recycled to preheat the beneficiated fines. However, I also demonstrated that the amount of material that would have to be processed to supply 1 metric ton of hydrogen is significant, even when all efforts have been made to enhance the production. I found that, for the 63 percent of the hydrogen that occurs in the less-than-20-micrometer size fraction of Apollo 15 sample 15021 (Bustin et al. 1984), a minimum of 19 596 metric tons of lunar regolith fines would have to be processed, with 4507 metric tons of concentrate heated, yielding a recovery of 51 percent of the

TABLE 11. Comparison of Calculated Percentages (by Volume) of Coatings (200 Å Thick) on Particles of Various Size Fractions With Measured Percentages (by Volume) of Hydrogen in Such Particles [From Carter 1985]

Average particle diameter, μm	Percentage of total volume of fraction that is coating	Percentage of total coating in fraction	Percentage of total hydrogen in fraction*
10.0	1.195	56.46	51.34
32.5	0.369	17.42	17.11
60.0	0.200	9.44	9.73
82.5	0.145	6.87	6.38
120.0	0.100	4.72	5.03
200.0	0.060	2.83	4.36
375.5	0.032	1.51	4.03
750.0	0.016	0.76	2.01
Total	2.117	100.01	99.99

*Calculated from g/g data by Bustin et al. (1984) for Apollo regolith fines sample 15021.

hydrogen. Although these tonnages are not high by terrestrial standards, they will probably limit production of hydrogen in the early exploitation of the lunar regolith fines to that obtained as a byproduct or coproduct from the mining and processing of other materials. The production of two or more products at the same time may be the best way to reduce costs to economical levels (Criswell 1980, Simon 1985).

It is also interesting to speculate on bringing back to Earth valuable elements, compounds, or minerals. However, the only element, compound, or mineral that by itself has economic potential for mining, processing, and return to Earth is ^3He (Wittenberg, Santarius, and Kulcinski 1986). It is very expensive to transport materials from Earth and put together an infrastructure on the lunar surface (Simon 1985). It takes at least \$25 000 in 1987 dollars to deliver a pound of material to the lunar surface, which is approximately 5 times the value of a pound of gold on Earth!

In 1966, before a man walked on the Moon, Peter Flawn was insightful when he wrote,

Because of the acceleration of change in the last half-century, this writer is not inclined to

state categorically that mineral materials will never be transported through space from an extra-terrestrial source to earth. It is, however, difficult to conceive of the system under which such an enterprise could take place. Mining of local materials around extra-terrestrial bases, however, is something entirely different and makes good sense. The pioneers on earth found that where transportation facilities were nonexistent or where they were prohibitively expensive, they had to make do with local materials. Space pioneers will be in the same situation. Use of local minerals for sources of oxygen, for energy, and for materials will undoubtedly be more economical than large-scale transport from earth. Thus although extra-terrestrial minerals are not likely to be a source for augmenting earth supplies, they are a source which will reduce by minute amounts the export of earth minerals.

These thoughts still apply. Moreover, the comments on transportation of nonterrestrial mineral materials to Earth should remain valid at least until a significant infrastructure is in place on the lunar surface.

Conclusions

1. The type and range of lunar material resources are defined to a first approximation on the basis of analysis of samples returned, remote sensing, and theoretical considerations. Major uncertainties remain as to the presence of cryotrapped volatiles in the permanently dark and thus cold areas of the lunar polar regions and the presence of fumarolic deposits containing material rich in volatile elements or compounds.
2. Early exploitation of lunar material resources will be for shielding purposes and for local use of phases or elements that do not require extensive processing. Present knowledge suggests that this activity will be confined primarily to the minerals (plagioclase feldspars and ilmenite) and rock types that result from igneous processes, to meteoritic and cometary debris, and to regolith fines that are significantly affected by solar wind implantation.
3. Lunar regolith fines are an important source of (a) silicate minerals such as plagioclase feldspars, olivines, and pyroxenes; (b) oxide minerals such as ilmenite and spinels; (c) metallic iron-nickel-cobalt alloys; and (d) solar-wind-implanted elements such as H, N, C, and ^3He .
4. Lunar regolith fines meet the basic requirement for beneficiation because a major portion of the elements implanted by the solar wind occurs in the less-than-20-micrometer size fraction, which is a relatively small part of the lunar regolith fines.
5. Early exploitation of the lunar regolith fines for hydrogen probably will be limited to hydrogen obtained as a byproduct or coproduct from the mining and processing of other materials, because it takes at least 20 000 metric tons of typical lunar regolith fines to produce 1 metric ton of hydrogen.
6. There is no evidence, direct or theoretical, for significant base metal sulfide or precious metal vein deposits on the Moon.
7. Lack of free water on the Moon eliminates the classes of ore deposits that are most exploitable on Earth; namely, (a) hydrothermal, (b) secondary mobilization and enrichment, (c) direct precipitation from a body of water, and (d) placer.

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