ROLLAND L. BLAKE
Bureau of Mines
Twin Cities Metallurgy Research Center
Minneapolis, Minn.

Ore Deposits in Volcanic Rocks on Earth With Lunar Extrapolation

A literature search was made on the origin of ore deposits in volcanic rocks on Earth. The close association between mineralization of the rocks in a region and the later stages of volcanism is well established. Also recognized is the prominent role of magmatic solutions composed mostly of juvenile water, but frequently supplemented with ground water, in the formation of mineral deposits by such processes as hydrothermal deposition and sublimation. Ten ore-forming processes were recognized, and eight of these form ore deposits in Earth volcanic rocks.

Effects of the inferred lunar environment on processes forming ore deposits were also studied. Mineral deposits thought to exist in volcanic rocks on the Moon, in order of decreasing amount and likelihood, are those formed by the following six processes: Hydrothermal deposition, sublimation, combined eruption and exhalation, volcanic eruption, and, rarely, contact metasomatism and evaporation. The Moon is viewed by the writer as a still-dynamic body with some volcanism likely.

Areas needing further work are summarized in the following suggested work plan: (1) Develop sensors for both remote and near-source detection of water in sublimates, rocks, and volcanic exhalations; (2) study volcanic sublimates, their properties and probable stability, in the lunar-surface environment; (3) investigate gases other than steam as a resource for life support; (4) assemble a space-geology nomenclature for efficient communication; (5) improve geophysical-geological techniques and equipment so that mineral deposits other than water can be located in volcanic rocks; and (6) compile information and stimulate research for answers to problems related to volcanism, meteorite impact, and formation of mineral deposits.

INTRODUCTION

Astronomical, geophysical, geochemical, and geological evidence and reasoning from lunar studies indicate that natural materials and processes similar to those on Earth should be expected on the Moon as changed by the modifying effects of the surface and near-surface environment. The role of volcanic activity in forming and modifying the lunar surface and crust is becoming apparent from study and interpretation of space-probe photographs by U.S. Geological Survey geologists and NASA scientists and by individuals such as Green (refs. 1 and 2) and Fielder (ref. 3). On Earth the close association of volcanic activity with mineralization of the adjacent country rock has been recognized for many years.

This study involves a literature search to: (1) study formation of Earth ore deposits in volcanic rocks; (2) study effects of the lunar environment on formation and occurrence of lunar mineral deposits; (3) summarize expected lunar mineral resources in volcanic rocks; and (4) recommend further Earth studies that will aid in the location and use of mineral resources in volcanic rocks on the Moon and perhaps on other extraterrestrial bodies.

Dr. Jack Green of the Douglas Advanced Research Laboratories prepared a survey report entitled "Calderas as Related to Lunar Exploration" (ref. 4). Green's report has greatly aided the preparation of the present report and together they constitute a summary of the funded work.

EARTH MODEL

Earth's Crust

The outer 16 kilometers (10 miles) of the Earth's crust is estimated to consist of 95 percent igneous and metaigneous rocks and 5 percent sedimentary and metasedimentary rocks (ref. 5). (The prefix "meta," or metamorphosed, means altered by pressure and/or heat.) No estimate of the amount of igneous rocks that are volcanic (extrusive) was found, but volcanic rocks are prominent. As an example, Waters estimates that basalts in the Eocene epoch in the Pacific Northwest (estimated as a 20-million-year time interval) covered an area of 155 000 km^2 (60 000 mi^2) and attained a volume of 170 000 km^3 (40 000 mi^3) (ref. 6). Thus, the Earth's crust contains a substantial proportion of volcanic rocks which may be host to mineralization that forms ore bodies both on the surface and within the crust.

The 12 most abundant elements constitute over 99 percent of the Earth's crust; of these, only 3 (Fe, Ti, Mn) form extensive metallic ore deposits. The remaining elements of the crust are present in small to trace amounts. The ore-forming processes must concentrate Pb about 1200 times, Zn 150 times, and Cu 70 times to form currently economic deposits.

The continental areas of the Earth's crust are fairly stable, but the oceanic-continental border areas are less stable and undergo large-scale, gradual deformation (tectonism) such as folding, faulting, and fracturing accompanied by igneous rock intrusions at various depths. Superimposed on these large-scale events are smaller scale volcanic eruptions caused by some of the intrusive magmas (molten rocks) reaching the surface. Also, on this smaller scale, and either during the late volcanic stage or afterward, the rocks in the region are usually mineralized. This mineralization is often aided by uplift or doming that produces fracturing of near-surface rocks on a large scale (refs. 7 and 8).

Cooling intrusive rocks give off fluids containing metals derived mostly from the intrusives and partly from the intruded rocks. The fluids are composed of water and compounds of B, F, Cl, P, S, C, As, and other rarer elements (ref. 9). Magmas are the original source of all mineral-deposit ingredients as is emphasized by Bateman (ref. 10).

Ore Deposits in Volcanic Rocks

Ore deposits are formed by the following processes:

(1) Magmatic concentration
(2) Contact metasomatism
(3) Hydrothermal deposition
(4) Sublimation
(5) Evaporation
(6) Sedimentation
(7) Residual and mechanical concentration
(8) Submarine volcanic exhalation
(9) Volcanic eruption
(10) Eruption-exhalation

This list is from the work of Lindgren (ref. 9) and Bateman (ref. 10). These authors have summarized much literature information and personal experience to present examples of ore deposits and concepts on their origin that are essentially valid today. Each process is briefly described below, and the extent to which it forms ore deposits in volcanic rocks is mentioned.

The process of magmatic concentration involves the differentiation (or separation and concentration) of certain elements and minerals within the cooling magma at considerable depths below the surface. The resulting deposits do not form in volcanic rocks. Contact metasomatic deposits are formed in intruded rocks by high-temperature gaseous emanations escaping from intruding igneous magmas. The rocks replaced by such ores are usually limestone and calcareous shales, and occasionally quartzites and older intrusive rocks. It is possible that such deposits could form in older volcanic rocks, but no such reference was found.

Hydrothermal solutions of deep origin are mixtures of high-temperature gases and liquids given off by a cooling intrusive mass. As they progress away from the magma source, they are, or become, liquids and gradually lose heat.

Deposition occurs by replacement or by filling, or a combination of these processes. Replacement, or metasomatic replacement, is defined as "a process of essentially simultaneous capillary solution and deposition by which a new mineral is substituted for one or more earlier formed minerals" essentially on a volume-for-volume basis (ref 10, p. 137).

Lindgren (ref. 9) recognized three groups of hydrothermal deposits based on distance outward from the intrusive, hypothermal, mesothermal, and epithermal, and to these has been added hot-spring deposits. The essential characteristics of each group are summarized in table 1. Hypothermal solutions are thought to be composed of water almost entirely of magmatic origin. Mesothermal solutions are diluted by ground water in degrees ranging from slight to great, and epithermal and hot-spring solutions are thought to be composed mostly of heated ground water.

A rather small number of hypothermal deposits occur in older volcanic rocks which were deeply buried at the time of mineralization. Mesothermal deposits in volcanic rocks are more numerous than hypothermal ones. Epithermal deposits are one of the most valuable classes of ores, having furnished much silver, gold, and mercury with lesser amounts of copper, lead, and zinc. These deposits are located in regions of comparatively recent volcanic activity. Hot-spring waters and their deposits are also nearly always found in areas of recent volcanic activity but are not so numerous in volcanic rocks as are epithermal deposits.

Small but important mineral concentrations are formed near and at the Earth's surface by the process of sublimation from vapors issuing quietly to violently at vents or fissures under atmospheric conditions. Rittmann recognizes two major types of gaseous emanations: solfataras and fumaroles (ref. 11, pp. 5–11). Solfataras are steam spouts at temperatures of 90° to 300° C with small amounts of CO_2 and H_2S that occur in all volcanic regions of the world. Free sulfur is deposited in crystals around the vents, sometimes in volumes large enough to be mined. A special type of solfatara-like steam spout occurs in Lardarello, Tuscany, Italy, where geothermal gases are exploited for generating electric power and for producing chemicals. Average composition of the vapor is as follows: H_2O, 95 percent; CO_2, 4.3 percent; H_2S, 0.9 percent; boric acid, 0.3 percent; NH_3, 0.3 percent; CH_4, 0.15 percent; and H_2, 0.04 percent. Each year 26 million tons of steam generate about 2 billion kilowatts of electricity (ref. 11). According to Bullard (ref. 12), the chemicals produced include Dry Ice (CO_2),

TABLE 1.—*Characteristics of Formation of the 4 Groups of Hydrothermal Deposits*

Deposits	Parameter					
	Temp, °C	Depth, km	Pressure, atm		Ores	
			Lithostatic	Hydrostatic	Common	Less common
Hypothermal	300 to 600	1.6 to 4.8	450 to 1350	150 to 450	Au, Cu, Fe, Pb, Sn, Zn	Mo, W
Mesothermal	175 to 300	1.6 to 3.2	450 to 900	150 to 300	Ag, As, Au, Cu, Pb, Sb, Te, Zn	Bi, Co, Mn, Ni, Pt
Epithermal	50 to 200	Surface to 0.8 or 1.6	1 to 112 or 225	1 to 37 or 75	Ag, Au, Hg, Pb, Zn	Cu, Pt, Sb
Hot spring	40 to 100	Surface	----------	1	Ag, As, Au, Cu, Hg, Pb, Sn	

liquid NH_3, $(NH_4)_2CO_3$ and NH_4Cl, sodium perborate, manganese borate, and boron carbide. Around 1940, 8000 tons of boric acid and 4500 tons of borax were produced each year.

Rittmann's fumarole types are as follows: (1) "cool" emanations (called moffete) producing water vapor and some CO_2, but not H_2S, at temperatures seldom exceeding 101° C; and (2) very hot fumaroles with temperatures up to 900° C found in craters or at fissures in active volcanoes. They always carry HCl, volatile chlorides and, especially, NaCl and $FeCl_3$ in addition to the constituents of solfataras.

The importance of calderas as sites of sublimate ore deposits has been stressed by Green (ref. 4), who has covered the recent Japanese literature contributions.

Extensive deposits of salts are formed by evaporation of water from lakes in closed basins in arid lands. Much smaller deposits are formed by evaporation at the surface of salt-containing waters ascending by capillary action, and just below the surface in caves and in smaller openings such as vesicles in lava flows and in loose volcanic aggregates. The amount of evaporite deposits in volcanic rocks is apparently very small.

Sedimentation in bodies of water by mechanical, chemical, or biochemical deposition has formed large ore deposits in sedimentary rocks, but only a few are interbedded with volcanic rocks and none are expected to form in such rocks.

Residual concentration may form an ore deposit by physical or chemical weathering involving air, water, acids (as H_2CO_3), and gravity; these agents remove the gangue material and leave behind the valuable ore mineral. Mechanical concentration takes place in moving water or air so that heavier minerals derived from various rock types and deposits are sorted to form placers. No ore deposits in volcanic rocks with origin recognized as residual or mechanical concentration have come to the author's attention.

Submarine volcanic exhalation is a process of simultaneous gaseous, hydrothermal, and solid/molten magma emanations, all ejected under a sea-water medium. The gases entrapped in the volcanic rocks may deposit native sulfur and iron sulfides with minor quantities of lead, zinc, and copper. Certain massive sulfide and sulfur ores in volcanic pillow lavas are thought to have such an origin (refs. 13 and 14). Hydrothermal deposition may account for other such deposits.

Volcanic eruptions normally do not produce mineral deposits. Several very interesting exceptions to this normal behavior are described in the literature, however, and they involve an actual extrusion or flow of the ore mineral itself. Watanabe describes molten sulfur flows (ref. 15), Dawson describes sodium carbonate flows (ref. 6), and Park describes a magnetite-hematite flow in Chile (ref. 17).

It is likely that a process similar to submarine volcanic exhalation could take place on land without the presence and pressure of a confining hydrosphere. The term "eruption-exhalation" in the list refers to this possible process in which much of the gases would be lost to the atmosphere, but some could be trapped within the cooling lava and pyroclastic deposits near the main vents. This type of deposit may be similar to one that Green briefly described (ref. 4, p. 40) and associated with Jenks (ref. 18).

The Earth model discussed previously emerges as a dynamic body undergoing gradual crustal changes which are mostly confined to certain areas. Ore deposits are formed in some older volcanic rocks buried within the crust and in more recent ones at the surface. Volcanic activity is closely related to some mineralization, but nonvolcanic agents may also produce ore deposits in volcanic rocks.

LUNAR MODEL

Environmental Effects

The writer believes that the Moon was formed at the same time as was the Earth and is of similar materials. That the proportion of these materials and their possible distribution are not identical to those of the Earth is suggested by the density difference.

Green (ref. 4) suggests that the lunar body tides that might be induced by Earth's mass and proximity may have the following effects: (1) they may create major fracture systems in the lunar crust; (2) they may generate heat by crustal flexing; and (3) they may provide periodic pressure release under crustal blocks to cause (or favor) the start of magma formation.

The Moon's crust is believed to be made up of almost 100 percent igneous and meta-igneous rocks with small amounts of meteoritic and shocked rock debris. The ratio of intrusive to volcanic rock would be difficult to surmise. No significant amounts of sedimentary rocks or their metamorphosed products would be present. On Earth, crustal and subcrustal forces can form mountains and ocean basins. Water and sediments collect in the basins and may reinforce or attenuate these forces. The same kind of forces acting in the absence of a hydrosphere and an atmosphere might be expected on a planetary body the size of our Moon. The resulting tectonism could provide openings and release fluids toward the surface, bury surface rocks at depths, and expose intrusive rocks at the surface. Burial and exposure would be considerably less than on Earth because of the lack of erosion and sedimentation effects of a hydrosphere and atmosphere. The extent of lunar tectonism and defluidization cannot be reasonably speculated upon at this time.

The generation at depth of different magma compositions by any of the several types of differentiation processes may occur on the Moon. On Earth the record shows that more mineralization is associated with magmas of acidic than with those of basic or intermediate composition (ref. 9). Estimates of the amount of lunar differentiation range from none at all, because the Moon always has been cold and lacked enough radiogenic heat to melt rock and form magma, to the other extreme of a small body giving off its contained heat so rapidly and early in its history that its later history is devoid of melting and possible differentiation and defluidization. The theory favored here is that of a cooling history rather like that of Earth, with gradual differentiation and volcanic activity throughout the Moon's history; this theory suggests a still-dynamic body rather than a now-dead Moon.

In lunar magma chambers the reduced gravity is believed to cause nucleation and coalescence of gas bubbles at greater depths than in the Earth analog (ref. 4, p. 22). This early removal of disseminated volatiles could provide a more viscous magma and a greater volume of fluids expelled during eruptions or available for mineralization. During mineralization the reduced gravity, and therefore lower lithostatic pressure, would favor earlier release of the more volatile substances which would be expelled ahead of the less volatile ones. This behavior might tend to deposit minerals at greater depths from the less volatile fluids and at shallower depths from the more volatile fluids. The results could be formation of deeper hypothermal deposits than on Earth, stretching out of mesothermal deposits in a greater vertical interval, and formation of smaller epithermal deposits. It would be difficult to predict on a temperature basis whether lunar hydrothermal deposits would have formed shallower or deeper than on Earth.

Close to the surface, the reduced gravity effect, especially where coupled with the lunar vacuum effect, is expected to cause greater vesiculation of outpouring lava, involve several times as much volume of explosive ejectamenta (ref. 1), and probably cause greater loss of volatiles in a volcanic area on the Moon than occurs on Earth.

Lunar surface temperatures vary from night to day in the approximate range of −150° to over 100° C. The highest vacuum measured by remote means of the lunavac (a word that can be defined as the lunar atmosphere which is a high vacuum with traces of gases and particulate matter) is about 10^{-13} atmosphere. The warmest temperatures in direct sunlight would have the effect of boiling off water as vapor from fumarole or solfatara vents and perhaps from any concentration in the upper part of the "soil." At lower temperatures, in the shadows or during the lunar night, water being expelled in magmatic fluids might freeze in the outer layers of soil or in rock cavities such as lava vesicles or lava caves. The lunavac would contain little or no oxygen, so that there would be negligible oxidation of compounds or gases. As Green points out (ref. 19), the sublimates expected would be those not requiring oxygen from the lunar atmosphere; if they exist in sunlight, they must not photodecompose.

We can be reasonably certain that both volcanism and impact have occurred on the lunar surface. Proponents of both processes have by now presented enough evidence to confirm this statement. Future efforts should be directed toward recognizing rock products of each process and determining product ratios in the lunar crust. The suggestion by Beals (ref. 20) to establish criteria for each type of rock product seems necessary; and excellent starts on this, slanted toward impact, are French's search for criteria of shock metamorphism (ref. 21) and the papers presented in the 1966 Conference on Shock Metamorphism of Natural Materials (ref. 22). More work of this nature should be done on suspected volcanic explosion structures.

Weathering of lunar-surface materials is expected to be mostly physical, such as: temperature-extreme spalling; alteration and disintegration by solar ultraviolet and X-rays, protons, alpha particles, and cosmic rays; and meteorite damage ranging from slight to extreme. Fracturing of solid rock from moonquakes could trigger landslides, and, because of the reduced gravity and friction, some workers have proposed extreme gliding that would tend to level the loose soil. However, the lack of an air cushion between very fine particles should partially compensate for the gravity effect.

Lunar Mineral Deposits in Volcanic Rocks

Volcanic rocks and related mineral resources on the Moon's surface would be accessible to early lunar explorers. The nature and utilization of such resources have been reviewed by several authors including Lowman (ref. 23) and Penn (ref. 24). While surface deposits are most accessible, subsurface deposits may be important in the future. Minerals and elements expected in lunar deposits are in general those found in corresponding Earth deposits, although sublimate minerals on the Moon's surface may differ somewhat in amount, stability, and composition.

Table 2 lists the 10 processes described earlier that form ore deposits on Earth. The known occurrences of such ore deposits in Earth volcanic rocks are indicated, and their likelihood in volcanic rocks on the Moon are suggested.

TABLE 2.—*Ore Deposits in Volcanic Rocks Known on Earth and Likely on the Moon*

Process of formation	Occurrence of deposits	
	Earth (known)	Lunar (likelihood)
Magmatic concentration	None	None
Contact metasomatism	Rare	Rare
Hydrothermal deposition:		
Hypothermal	Few	Few
Mesothermal	Some	Some
Epithermal	Many	Some
Hot springs	Some	Few
Sublimation	Some	Some
Evaporation	Small	Rare
Sedimentation	Few	None
Residual and mechanical concentration.	None	None
Submarine volcanic exhalation	Many	None
Volcanic eruption	Few	Few
Eruption-exhalation	Some	Some

Contact metasomatic deposits conceivably could form in deeply buried lunar volcanic rocks. Hydrothermal deposits formed by ascending magmatic fluids are very likely present. A few of the deep-seated hypothermal deposits are expected. However, they may occur at much greater depths than on Earth if lunar environmental effects suggested previously are correct. Less erosion is expected on the Moon; thus fewer deep-seated deposits would be exposed than on Earth. Mesothermal deposits are expected, but they may extend a longer vertical interval, be at deeper levels, and be less extensive than on Earth where some of them are believed to form from a mixture of magmatic and ground waters. Epithermal and hot-spring deposits are expected to be fewer and smaller on the Moon because of the expected scarcity of ground water.

Sublimates and their associated gaseous emanations are believed to be the most easily accessible deposits. Processes forming submarine volcanic exhalative deposits on Earth operate beneath a hydrosphere which is not expected on the Moon. It is possible that a combined gaseous/molten-magma/solidified-magma complex on the Moon could have some deposits of massive sulfide ores formed within it during and shortly after an eruption. Evaporation might conceivably operate near or at the lunar surface to extract water from depressions near volcanic activity where magmatic waters approached the surface, dissolved substances, and carried them into these depressions. No sedimentation or residual and mechanical concentration processes are envisioned to operate on the Moon that could form ore deposits in volcanic rocks because such concentrations are effected on Earth by air and/or water agents of weathering. Volcanic eruptions that on Earth furnish only a few flows of mineral concentrates such as sulfur, magnetite, or sodium carbonate represent an unusual concentration not expected to be any more widespread on the Moon than on Earth.

The sublimate deposits would be found near and at the surface in volcanic areas and probably predominantly in calderas. In early stages of lunar basing, the sublimates offer two advantages over other sources: (1) they offer a surface deposit not requiring much mining equipment; and (2) they are usually a highly concentrated mineral supply not requiring complicated processing treatment. Volcanic areas, especially those with sublimates, would be likely targets for future exploration at depths for hydrothermal deposits.

Water is a most valuable mineral resource of any extraterrestrial body, and its location and extraction from the body's natural minerals is important to future space exploration. Therefore its occurrence in Earth volcanic rocks has been summarized by Green (ref. 25) and its extraction studied by Wechsler et al. (ref. 26) and, extensively, by Green (ref. 25). The most likely sources of lunar-surface water, in order of decreasing concentration and ease of extraction, seem to be: (1) solfataras and fumaroles in volcanic areas, and especially in calderas; (2) mineral sublimates, especially in calderas; and (3) volcanic rocks exposed at the surface, such as tuffs and lavas, and hydrothermally altered rocks. Somewhat less likely because of special conditions necessary, but still very possible, are the following sources: (1) steam-spout areas; (2) water or ice in caves or other openings; and (3) water or ice (as permafrost) in the lower part of soils, especially near exhalation vents.

Expected lunar rocks as a resource have not been elaborated on in this report except as a source of water. Other uses for such rocks have been considered by Bensko and Shotts (ref. 27) for extraction of propellant substances such as water, hydrocarbons, carbon (graphite), oxygen, fluorine, and chlorine, and metals such as beryllium, boron, magnesium, aluminum, iron, and calcium. Green has considered the use of cast basalt for pipes and structural components based on the Czechoslovakian industry (ref. 4). Rosenberg et al. investigated extraction of oxygen from magnesium silicate (ref. 28).

Gases other than steam are often reported from volcanic exhalations; these include N_2 or NH_3, O_2, CO_2, CH_4, H_2S, SO_2, H_2, Ar, HCl, and HF. Most of these are of considerable interest as possible sources of life-support gases. Helium would also be of interest if present. Astronauts are to be provided atmospheres either entirely of oxygen (which strongly supports combustion) or of some artificial air mixture. Large volumes of air are required for permanent lunar stations or shelters. Man is searching for a source of oxygen on the Moon to save efforts required to transport it from Earth to Moon for an air mixture, and he should also be interested in finding a lunar source for the inert gases required to complete the air mixture. A possible source of these gases is volcanic exhalation, but more research is needed in detecting and measuring gases which occur in small amounts. Probably the required amounts could be collected from large volumes of such exhalations by an efficient collector.

SUMMARY AND RECOMMENDATIONS

A literature search was made on the origin of ore deposits in volcanic rocks on Earth. Ten ore-forming processes were recognized and eight of these form ore deposits in Earth volcanic rocks. After considering the lunar environmental effects on ore formation, it was suggested that six of the eight processes could form ore deposits in volcanic rocks on the Moon. These are, in order of decreasing amount and likelihood: hydrothermal deposition, sublimation, combined eruption-exhalation, volcanic eruption, and, rarely, contact metasomatism and evaporation. The possibility of finding fumaroles, solfataras, and steam spouts suggests a plentiful source of water, gases, sublimate minerals, and energy in the form of heat and dynamic fluids.

Areas recommended for further work as a result of this study are given in the following work plan.

Location and Use of Lunar Mineral Resources in Volcanic Rocks.

The objective is to develop a body of knowledge on mineral resources in Earth volcanic rocks that will be needed to locate and utilize similar resources likely to occur on the Moon and other extraterrestrial bodies. The information gathered (from the literature, field studies, and laboratory research) and its interpretation would have a twofold benefit:

(1) It would provide a single source of information which is now either scattered in the literature or nonexistent.

(2) It would reveal gaps in our knowledge of these mineral resources and thereby guide future research in the fields of geophysics, geology, mining, and metallurgy to provide this information.

Work Plan

The following work plan is recommended:

A. Locate possible sources of water on the Moon:
   1. Locate lunar landing areas:
      Examine lunar orbiter photographs to find desirable landing areas near locations showing evidence of recent volcanism so that early lunar exploration can emphasize search for water sources.
   2. Develop water sensors:
      a. Determine the feasibility of developing water sensor(s) for remote- and near-source detection and, if possible, measurement of water content of rocks and of mineral concentrations.
      b. If feasibility study is positive, start development of sensor(s), and plan to test them on Earth, both remote-source (Eros satellite), near-source (hovering vehicle, roving vehicle, and on-foot exploration), and in the laboratory under simulated lunar, near-source conditions.
      c. Guide lunar testing of the sensor(s) by insuring its inclusion in mission planning and follow its lunar application.
      d. Use A2*a* and A2*b* information to develop sensor(s) to locate and measure water-bearing (steam) fumaroles, solfataras, and steam spouts. A heat sensor might be coupled with another type of sensor.
   3. Collect, separate, and analyze volcanic exhalations:
      Develop mechanical apparatus for lunar application to confine and collect very hot, high-velocity, vapor exhalations together with the auxiliary apparatus to separate and analyze the water and the vapor-transported compounds. Start with existing technology from geothermal installations. Develop apparatus to utilize heat and velocity of exhalations to supply heat and power to lunar basing needs.
   4. Study volcanic sublimates:
      a. Study sublimate deposition on Earth to determine if the hydrated minerals reported have derived their water from the exhalative steam or from rain and ground water.
      b. Compile reliable physical and chemical data on sublimates and their vapors to assemble enough information so that, together with existing understanding of the theory of vapor-collection, vapor-transport, and vapor-deposition, a reasonable prediction can be made of what minerals will be precipitated, and in what order, at the lunar surface. Encourage and support laboratory research to furnish reliable information that is missing in the compilation.

      This information should be useful in studies of A2*d*, A3, B2, B3, and B4.

5. Study calderas:

   Carry out systematic caldera studies to determine fully their lunar basing potentialities and to aid the plans of A1 through A4.

B. Investigate gases (other than steam) on the Moon:

   1. Determine potential need for life-support "artificial air" gas components.
   2. If a lunar source is desired, study literature and collect and analyze Earth volcanic gases to determine how much atmospheric contamination is present. Establish whether the gases sought might be found in lunar exhalations of only magmatic origin.
   3. Start development of sensors to detect and possibly measure these gases in volcanic gas streams and chambers.
   4. Develop apparatus to collect and purify the gases for use; couple work with A3 and A4.

C. Assemble nomenclature for space geology communication:

   Work out a short, but useful, geological nomenclature for space exploration communication as proposed by Green (ref. 4). This nomenclature could be an example for the other sciences, such as geophysics and mining, to follow.

D. Locate lunar mineral deposits other than water in volcanic rocks:

   Improve geophysical techniques and equipment to detect and locate materials (both surface and subsurface) selected on a needs priority for lunar basing operations. Consider both remote- and near-source sensing. Both geology and geophysics would be needed to improve upon and test techniques and equipment.

E. Compile information on volcanism and ore deposits:

   Stimulate research by industry, universities, and Government agencies on some of the problems outlined previously by providing the information and the gaps in it as the body of knowledge in the objective is developed. Some interesting geological areas of study would be:

   1. Can volcanic explosions form shatter cones in rocks? Shatter cones are structures that some investigators regard as positive criteria for meteorite impact.
   2. Examine rocks for evidence of volcanic explosion effects. Compare these effects with those caused by meteorite impacts. Try to determine criteria unique to volcanic explosions and to meteorite impacts.
   3. Can impact trigger volcanism?
   4. Can impact trigger formation of ore deposits?
   5. Are rare-earth materials or other valuable mineral resources ever associated with the volcanic carbonatites? What is the likelihood of their lunar existence? Can carbonatite activity be triggered by meteorite impact? (On Earth, carbonatites are formed mostly by intrusive activity, although a small number are formed by extrusive volcanic activity.)

REFERENCES

1. Green, Jack: Tidal and Gravity Effects Intensifying Lunar Defluidization and Volcanism. Proc. N.Y. Acad. Sci., vol. 123, no. 2, 1965a, pp. 403-469.
2. Green, Jack: The Moon's Surface. Int. Sci. Tech., Sept. 1966, pp. 59-67, 82, 84.
3. Fielder, Gilbert: Lunar Geology. DuFour Editions (Chester Springs, Pa.), 1965.
4. Green, Jack: Calderas as Related to Lunar Exploration. Rept. DAC 61305, U.S. Bur. Mines, Apr. 1967.
5. Clarke, F. W.; and Washington, H. S.: The Composition of the Earth's Crust. Prof. Paper 127, U.S. Geol. Surv., 1924.
6. Dawson, J. B.: Sodium Carbonate Lavas From Oldoinyo Lengai, Tanganyika. Nature, vol. 195, 1962, pp. 1075-1076.
7. Wisser, E.: Relation of Ore Deposition to Doming in the North American Cordillera. Memoir 77, Bull. Geol. Soc. Amer., 1960, p. 117.
8. Goodwin, A. M.: Mineralized Volcanic Complexes in the Porcupine-Kirkland Lake-Noranda Region, Canada. Econ. Geol., vol. 60, no. 5, 1965, pp. 955-971.
9. Lindgren, Waldemar: Mineral Deposits. McGraw-Hill Book Co., Inc., 1933.
10. Bateman, Alan M.: Economic Mineral Deposits. John Wiley & Sons, Inc., 1950.
11. Rittmann, A.: Volcanoes and Their Activity. Transl. from the 1960 2d German ed. by E. A. Vincent. Interscience Publishers, 1962.

12. BULLARD, F. M.: Volcanoes in History, in Theory, in Eruption. Univ. Texas Press, 1962.
13. RIDGE, J. D.: Suggested Volcanic Syngenetic Origin for Certain European Massive Sulphide Deposits. Trans. Soc. Min. Eng., AIME, vol 226, pp. 28–41.
14. KINKEL, A. R., JR.: Massive Pyritic Deposits Related to Volcanism, and Possible Methods of Emplacement. Econ. Geol., vol. 61, no. 4, 1966, pp. 673–694.
15. WATANABE, T.: Eruptions of Molten Sulphur From Siretoko-Iôsan Volcano, Japan. Jap. J. Geol. Geog., vol. 17, 1940, pp. 289–310.
16. WATERS, A. C.: Volcanic Rocks and the Tectonic Cycle. Spec. Paper 62, Geol. Soc. Amer., 1955, pp. 703–722.
17. PARK, C. F.: A Magnetite "Flow" in Northern Chile. Econ. Geol., vol. 56, 1961, pp. 431–436.
18. JENKS, W. F.: Some Relations Between Cenozoic Volcanism and Ore Deposits in Northern Japan. Trans. N.Y. Acad. Sci., vol. 28, 1966, pp. 463–747.
19. GREEN, JACK: The Geosciences Applied to Lunar Exploration. The Moon, Z. Kopal and Z. Mikhailov, eds., Academic Press Inc. (New York), 1962, pp. 169–237. Proc. 14th Symp. Int. Astron. Union (Leningrad, Dec. 1960).
20. BEALS, C. S.: The Identification of Ancient Craters. Ann. N.Y. Acad. Sci., vol. 123, art. 2, 1965, pp. 904–914.
21. FRENCH, BEVAN M.: Sudbury Structure, Ontario Some Petrographic Evidence for an Origin by Meteorite Impact. NASA TM X-55789, 1967.
22. Proc. 1966 Conf. of Shock Metamorphism of Natural Materials, Goddard Space Flight Center (Greenbelt, Md., Apr. 14–19, 1966).
23. LOWMAN, P. D., JR.: Lunar Resources Their Value in Lunar and Planetary Exploration. Astronaut. Acta, vol. 12, nos. 5–6, 1966, pp. 384–393.
24. PENN, S. H.: A Preliminary Look at Lunar Natural Resources. Trans. Soc. Min. Eng., vol. 235, Mar. 1966, pp. 66–70.
25. GREEN, JACK: A Study of the Feasibility of Using Nuclear Versus Solar Power in Water Extraction From Rocks. Final Rept., Contract no. AF 19(628)-3292, Proj. No. 000, Task No. 000011, North American Aviation, Inc. (Downey, Calif.), Sept. 30, 1965.
26. WECHSLER, A. E.; GLASER, P. E.; AND GERMELES, A. E.: Investigation of Water Extraction Processes for Use on the Moon. Ann. N.Y. Acad. Sci., vol. 123, art. 2, 1965, pp. 1148–1159.
27. BENSKO, JOHN; AND SHOTTS, REYNOLD Q.: Lunar Resources. Advances in Space Science and Technology, vol. 7, ch. 2, Academic Press Inc. (New York), 1965, pp. 147–214.
28. ROSENBERG, S. D.; GUTER, G. A.; AND MILLER, F. E.: Manufacture of Oxygen From Lunar Materials. Ann. N.Y. Acad. Sci., vol. 123, art. 2, 1965, pp. 1106–1122.