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Simulated Lunar Rocks

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The present paper describes the selection of rock materials for use by the Bureau of Mines in its extraterrestrial resource utilization studies which are designed to simulate the range of materials likely to be found on the Moon. It includes preliminary results of the measurement of the engineering properties of these materials.

INTRODUCTION

One of the first problems facing the Bureau of Mines in 1965 in its NASA-sponsored program of providing the basic scientific and engineering knowledge for extraterrestrial mining and processing was the selection of representative materials (refs. 1 and 2). Because we expect the first manned bases will be on the Moon, our immediate concern was with the nature of the lunar surface. Up until the successful chemical analysis of the lunar surface by Surveyor V, we knew nothing of its chemical composition. We supposed that the same elements might be available for rock-forming processes as are present on Earth because the relative abundance of the different elements is much the same throughout the universe. We also believed that if the Moon's composition was the result of differentiation like the Earth's, then certain elements like O, Si, Al, Na, Ca, Fe, Mg, and K would be concentrated in the crust. That the Moon's rocks were also likely to be silicates followed from what is known about the composition of the Earth and from what meteorites implied about other bodies in the solar system.

We still know very little about how the various dynamic processes such as mountain building, weathering, volcanism, and meteorite impact change the crustal rocks on other planets. These processes may affect the rocks in ways unfamiliar to us; they may operate to a different degree or not at all. A good example on the Moon would be the lack of weathering as we know it on the Earth. The absence of any atmosphere on the Moon suggests that the rounded boulders in the Surveyor pictures may be mostly a result of micrometeoroid erosion or thermal spalling.

Another example is that on the Moon we do not see any of the great linear mountain ranges which have originated on Earth through crustal activity and folding. If crustal activity in the form of mountain-building forces is limited and erosion of the rocks is minimal, it is unlikely that the deeper intrusive rocks, like granite, are widely exposed.

Most of the controversy about the Moon has focused on the problem of the origin of the craters and maria (ref. 3). Some experts say that impact by meteors and other bodies has been the principal surface-forming process. On the other hand, there are those who maintain endogenous volcanism was largely responsible. Although excellent arguments and examples can be offered supporting either concept of crater formation, it is not the purpose of this paper to discuss these theories. We are mainly interested in recognizing their implications in the selection of a range of materials suitable for use in developing a lunar mining technology.

Let us accept the fact that both impact and volcanism have been important factors in creating the Moon's surface. If this assumption is true, then the main types of material we are concerned with in the maria are the rubble

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produced by impact and rocks or fragmental material of volcanic origin. The rubble will probably consist of reworked volcanic and meteoritic material. In any case, volcanic rocks must receive considerable attention, not only because they appear to be quite widespread on the Moon, but also because a volcanic terrain is likely to provide more usable resources than does an impact terrain. Green, in reference 3, says:

> Volcanic terrain offers more shelter, more useful minerals and rocks, more subsurface heat, and more water than an impacted one. Therefore, to whatever degree the lunar surface is volcanic, we must seek out volcanic areas on the Moon because that is where the survival advantages lie.

We wish to thank the following individuals and organizations for their assistance in making the collection of this suite of simulated lunar materials possible: E. Groh, N. Peterson, L. Ramp, and H. Dole of the Oregon State Department of Geology and Mineral Industries; G. Oakeshott of the California State Division of Mines and Geology; R. Hogberg of the Minnesota State Geological Survey; J. Green of McDonnell Douglas Aircraft Co.; W. Kennedy, Superintendent, National Park Service, Lava Beds National Monument; W. Miller of the Central Oregon Pumice Co.; the U.S. Forest Service; the Oregon State Highway Department; the Hanna Nickel Mining Co.; and the Chamber of Commerce, Bend, Oreg.

Rock properties were measured by personnel of the Rock Physics, Thermal Fragmentation, Chemical Fragmentation, Hydraulic Fragmentation, and Mechanical Fragmentation Laboratories at the Bureau of Mines Twin Cities Mining Research Center. Petrographic and chemical analyses of the six rocks selected by Green were made by personnel of North American Aviation Co. The other rocks were analyzed by personnel of the Petrographic and Chemical Laboratories at the Bureau of Mines Twin Cities Metallurgy Research Center.

SELECTION OF SIMULATED LUNAR ROCKS

It is apparent that the volcanic rocks formed on Earth may be used to simulate such rocks on the Moon. Consequently, we have chosen these rocks for our research to assure that we cover the range of physical and chemical properties that are likely to be found on the lunar surface. As we learn more about the Moon, we can concentrate on those rocks which are more representative or are of particular interest. The recent chemical analyses of the lunar surface performed by Surveyor V and Surveyor VI, which indicated a composition similar to terrestrial basalts, provide additional confidence in using volcanic rocks in our studies.

In choosing a source for volcanic material, we turned to the large areas of volcanism in Oregon and northern California. Green had already selected six rocks from this region for lunar research, and his work has been of considerable value to our program (ref. 4). His criteria for selecting the specific rocks were: (1) they should be representative of possible lunar rocks; (2) they should have the specific characteristics needed for the particular research to be performed; (3) they should come from an outcrop uniform in composition and texture; and (4) samples should be convenient to collect in sufficient quantity for the research to be performed.

Using these criteria as a guide, Green selected these rocks: a tholeiitic basalt, to simulate rock from large basalt flows such as might be found in the maria (tholeiitic basalt was chosen because low-pressure environments might favor their evolution on the Moon); a semiwelded tuff, in case the maria are filled with ash flows; an obsidian, to simulate rock from a flow of quickly chilled rhyolitic lava; an altered rhyolite, to represent a hydrothermally altered material containing a high water concentration; and, finally, two intrusive igneous rocks, a serpentine (serpentinite) for its high water content and to allow for an ultramafic Moon or a Moon with considerable iron and magnesium in its composition, and a granodiorite, to represent a deep-seated rock exposed on the lunar surface. No meteoritic material was included because of the difficulty of obtaining bulk quantities.

In choosing our suite of simulated lunar materials, we decided to include all of the rocks selected by Green. Our research program, however, required a broader range of rocks to assure that our fundamental work on material properties and behavior will be adequate. For this reason we have added the following volcanic rocks: a rhyolite, as a fine-grained extrusive silicic rock; a dacite, to simulate an extrusive rock of composition intermediate between rhyolite and basalt; a pumice; and three vesicular basalts with different size vesicles, to allow for the very likely possibility of vesicular rocks on the Moon.

We have also included a gabbro, to simulate a coarse-grained basic intrusive, and a dunite, in the event that the Moon has a composition similar to chondritic meteorites or to the Earth's mantle. Like Green, we made no attempt to collect meteoritic material because of the need for large quantities. The 14 figures in appendix A are photographs of hand specimens and photomicrographs of all the rocks mentioned. Petrographic descriptions and chemical analyses are given in appendixes A and B, respectively. For completeness, Green's petrographic descriptions and chemical analyses have also been included (ref. 4).

Other rocks may later be added to our suite of simulated lunar materials. We intend to look at the problem of shock metamorphism in natural materials, such as that associated with impact craters (ref. 5). We also intend to look at the problem of obtaining larger and more uniform vesicles by artificially frothing basalts or obsidians (ref. 6). The Moon's lower gravity and lack of atmosphere suggests that nucleation of the gas bubbles within lunar lavas occurs at greater depths than on Earth. As the bubbles rise toward the surface, they expand at a rapidly increasing rate to form correspondingly larger vesicles as the lava cools. The effect of vesicle size on the engineering properties of the lunar rocks will be an important consideration.

PROPERTIES OF SIMULATED LUNAR ROCKS

The simulated lunar rocks are being used in their unfragmented form to represent a bedrock lunar surface, and in a fragmented and pulverized form, to represent rubble surface. Each of these situations raises particular problems with respect to extraction and processing of the rocks. In the former case, problems of rock fragmentation are paramount. In the latter, material-handling problems are more important. In both cases we are concerned with physical and chemical composition, surface properties, elastic properties, strength properties, thermal properties, electrical and magnetic properties, and explosive shock properties. In order to show the range of property values represented by the materials we have selected, average values for some of the properties that have been measured on core and block specimens of the rocks are given in table 1. These data are preliminary and may be modified by additional work which will take into account the anisotropy that is characteristic of most of the rocks as well as refinements in measurement and analysis. Final results and descriptions of experimental techniques will be reported by the individual researchers of the Bureau of Mines Twin Cities Mining Research Center.

All of the properties shown in the table other than the coefficient of rock strength were measured by common laboratory methods. This strength measurement is a simple test of the energy involved in breaking a unit volume of rock to a given size. It is performed by placing a specimen in a tube, dropping a standard weight from a standard height, and measuring the volume of material that is produced below a standard size. The table illustrates the broad range of property values covered by the simulated lunar materials. At the low-density, low-strength, and low-hardness end of the scale, this range extends beyond that usually encountered in mining problems on Earth.

The group of rocks we are using is primarily composed of volcanic rocks, although we have included some rocks which may be expected to form at depth. We have included intrusive, aside from allowing for the possibility of their being exposed on the Moon's surface, in order to provide a broader range of materials for the use of other research groups. Although in past years we have worked with many intrusive igneous rocks and also metamorphic and sedimentary rocks associated with mining and

TABLE 1.—*Properties of ~~Simulated~~ Lunar Rocks in Earth Environment*

Rock type	Bulk density, g/cc	Apparent porosity, percent	Permeability, darcys	Hardness, shore units	Pulse velocity, m/sec	Young's modulus, psi	Compressive strength, psi	Tensile strength, psi	Strength coefficient, ratio	Thermal expansion	Magnetic susceptibility, cgs units	Dielectric constant ratio	Dissipation factor ratio
Dunite	3.19	1	<<1	73	7500	18.7×10^{6}	27 000	2000	1.32	6.2×10^{-6}	400×10^{-6}	5.0	0.008
Gabbro	3.11	<1	<1	84	7100	16.6	30 000	2000	.96	3.9	6000	15.4	.081
Tholeiitic basalt	2.84	2	<<1	84	6000	16.3	53 000	3400	1.94	4.5	2000	11.1	.099
Granodiorite	2.58	1	<1	47	3000	6.1	21 000	950	.51	5.6	Negligible	5.5	.004
Serpentinite	2.56	3	<<1	68	6000	5.7	18 000	800	1.37	5.3	6000	(a)	(a)
Obsidian	2.30	1	<<1	103	5000	9.2	65 000	2200	.53	4.1	100	6.3	.010
Altered rhyolite	2.36	8	<1	59	3300	3.6	16 000	1100	.74	(a)	Negligible	4.8	.017
Rhyolite	2.35	8	<<1	70	4200	2.4	22 000	1200	.80	4.5	400	5.1	.003
Vesicular basalt 1	2.25	20	Varies	81	3800	2.8	10 006	1100	1.01	3.2	400	6.0	.012
Vesicular basalt 2	2.22	34	Varies	67	4500	2.5	5 500	590	.75	(a)	500	6.7	.036
Dacite	1.98	17	4	35	4500	2.0	6 000	620	.42	3.1	600	5.0	.006
Vesicular basalt 3	1.52	40	Varies	80	4800	2.7	5 600	810	.77	(a)	200	4.2	.005
Semiwelded tuff	1.15	50	.58	10	2500	.3	850	100	.10	3.3	400	2.0	.015
Pumice	.76	62	840	5	2500	.5	1 500	240	.06	4.5	Negligible	2.3	.006

(a) Not yet measured.

quarrying operations, we have done little research on volcanic rocks prior to the present program for NASA.

The present selection of rocks represents a range of lithologies and textures that we hope will appeal to other organizations requiring simulated lunar materials. We believe that it is very desirable for all groups doing research related to lunar resource utilization to use the same rocks in order to facilitate comparison of their results. A number of organizations are already using some of these rocks. The Bureau of Mines is providing samples of the rocks, on request, to any group doing research related to our program. We can provide quantities up to several pounds of any of the materials we have on hand, and we can usually provide the material in a form that will satisfy particular requirements.

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APPENDIX A—PETROGRAPHY OF SIMULATED LUNAR ROCKS

The petrography of the simulated lunar rocks is given in the following outline. Analyses of rocks I to VI were made by J. Kennedy. (See ref. 4.) Analyses of rocks VII to XIV were made by M. Boucher.

I. Basalt, Tholeiitic

A. Macroscopic:
   1. *Color.*—Black.
   2. *Texture.*—Aphanitic.
   3. *Structure.*—Massive columnar.
   4. *Field name.*—Basalt.

B. Microscopic:
   1. *Texture.*—Merocrystalline probably describes the texture best because both glass and crystals are present. However, the interstitial glass is charged with microlites of magnetite and plagioclase which impart a hyalopilitic texture to the matrix material. Only two large phenocrysts of plagioclase were found within the sections analyzed, but there are definitely two generations of plagioclase present. Most of the crystals are subhedral in form with the exception of the older generation plagioclase which have remnants and rounded corners which indicate partial resorption.
   2. *Structure.*—The spectrum of grain size is not wide except for that of the microlites found in the matrix glass. The older generation plagioclase are the largest crystals and average 0.15 millimeter in length and 0.05 millimeter in width. This does not include the phenocrysts mentioned above. The next largest crystals are the second-generation plagioclase which average 0.10 millimeter in length and 0.025 millimeter in width. The augite and olivine grains are approximately the same size with the former averaging 0.05 millimeter in diameter and the latter, 0.04 millimeter in diameter. The smaller microlites are less than 0.005 millimeter in diameter. The chlorite grains are variable with some being marginal alterations of the pyroxenes and some occurring as discrete entities.

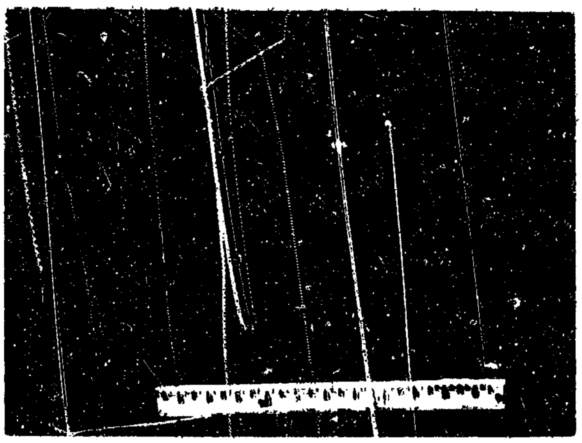
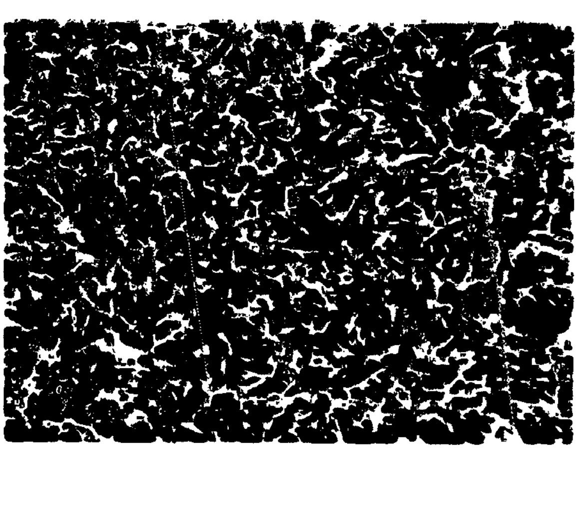


FIGURE 1.—Tholeiitic basalt; occurs northeast of Madras, Oreg. Above, hand specimen; below, photomicrograph, ×13.



C. Essential minerals:

	Content, percent
1. Plagioclase $An_{[illegible]}$ and $An_{[illegible]}$	30
2. Olivine	23.5
3. Augite	20.5

D. Accessory minerals and glass:

	Content, percent
1. Plagioclase microlites	12
2. Magnetite (titaniferous) and ilmenite	8
3. Glass	12
4. Chlorite	4
5. Quartz (very small inclusions in plagioclase)	1
6. Apatite	<1
7. Epidote	<1

E. Description of most commonly occurring minerals:
   1. *Plagioclase.*—$NaAlSi_3O_8$; $CaAl_2Si_2O_8$.
      (a) *General.*—Two generations of well-developed crystals of plagioclase are present along with needlelike plagioclase microlites, which occur in the groundmass glass. The older generation crystals appear to be brecciated phenocrysts. Large phenocrysts must have existed in the magma prior to flow. During the flow process these were broken and shattered and now appear only as fragments of former large crystals. A very few survived as discrete phenocrysts. These early crystals have retained only shadows of their former twinned planes, and zoning is pronounced. Zoning ranges from $An_{[illegible]}$, with most of the crystal being approximately $An_{[illegible]}$. Reverse zoning is prominently displayed, with the greatest Na molecule density occurring in the interior adjacent to the twin planes and

becoming more basic toward the margins of the crystal.

The later, or youngest, crystals show the reverse effect. Twin planes are sharp and distinct with a small amount of normal zoning present. The composition ranges from An[illegible] with the exterior margins being the more alkaline. Crystallization was much later in the magmatic history than in the earlier former plagioclase and orthoberceiation is not an important feature as it is with the older generation plagioclase.

(b) *Crystal development.*—Crystal faces of the older generation plagioclase are well developed but show rounding and corroded boundaries adjacent to matrix material. When other crystals such as olivine, pyroxene, and magnetite are found in contact with the older plagioclase, a well-developed sharp boundary is formed between the two minerals. Fractures, splintering, and separation along twin lamellae are common. Crystal boundaries of the younger generation plagioclase are well developed adjacent to all other crystals. The boundaries are sharp and well defined. Separation along twin lamellae and rounding of crystal corners is extremely rare.

(c) *Alteration.*—Small granules occur along twin lamellar separations in the older generation plagioclase. These have been tentatively identified as epidote and are probably an alteration product of the older plagioclase. The younger generation plagioclase does not show this feature or any other feature indicating alteration.

(d) *Inclusions.*—Several small inclusions are found within the plagioclase. These have tentatively been identified as epidote, quartz, or apatite. The inclusions occur as small round or slightly elongate globules, the largest being about 0.012 millimeter long and 0.007 millimeter wide. The inclusions are a primary feature of the plagioclase and are not an alteration product.

2. *Olivine.*—Fe_2SiO_4: Mg_2SiO_4.

(a) *General.*—Olivine occurs as small euhedral to subhedral crystals occupying the interstices between plagioclase laths along with augite, glass, and magnetite (ilmenite). In general, the crystals are smaller than those of augite but larger than the largest magnetite grains. Some crystals show broad twin lines, but these are relatively rare.

(b) *Crystal development.*—The crystals are partly euhedral and show typical olivine outline. Good face development against plagioclase, augite, and magnetite is common. In the section where it is found in subhedral form it is probably caused by separation along irregular fractures rather than poor development. It is colorless in thin section but stands out prominently because of its high relief and strong birefringence.

(c) *Alteration.*—In general, the olivine is unaltered, but in rare cases small patches of chlorite develop along some margins. A single instance was found of a euhedral crystal of olivine that was completely altered to chlorite.

(d) *Inclusions.*—Inclusions are practically absent in the olivine. However, occasionally it appears to contain small magnetic grains.

3. *Augite.*—$(Ca, Mg, Fe^{2+}, Fe^{3+}, Ti, Al)_2(Si, Al)_2O_6$.

(a) *General.*—Augite is distinguished from olivine by its lower birefringence and its cleavage. These features were used to identify or separate augite from olivine during the point-count procedure.

(b) *Crystal development.*—Crystal faces are, in general, poorly developed, but euhedral crystals are present. In the case where glass is the surrounding medium, crystals are best developed. If augite is developed adjacent to olivine, the olivine deforms the augite to follow the shape of the olivine crystal. The same is true for some of the larger crystals of magnetite (ilmenite).

(c) *Alteration.*—In rare cases augite is seen to be slightly altered to serpentine(?). This is especially true when augite has come in close proximity to fragments of chlorite which contain plagioclase.

(d) *Inclusions.*—Small euhedral crystals of apatite are sometimes found in the larger augite crystals. This seems to be especially true when the augite occurs as a euhedral crystal of larger than average size. A few large augite crystals were observed. These were corroded to such a degree that only vestigial outlines were present.

4. *Magnetite (ilmenite or ore minerals).*—$Fe^{2+}Fe_2^{3+}O_4$; $FeTiO_3$.

(a) *Crystal development.*—Magnetite occurs in three forms: (1) fill for irregular voids, (2) euhedral crystals, and (3) microlites. The irregular masses occur most generally where there is the greatest concentration of other crystals. All crystals seem to deform magnetite, and its irregular nature indicates it emerged in the later cooling phase. However, some of the larger magnetite crystals form euhedral faces against augite. In general, the euhedral crystals and well-developed microlites occur in the glassy matrix material and do not contact other minerals. Because of the large microlites and the greenish tinge surrounding the grains of magnetite, the grains may be ilmenite in many cases, probably there is a mixture of both ilmenite and magnetite.

(b) *Alteration.*—None present. Hematite surrounding the ore minerals is conspicuous because of its absence. Lack of magnetite alteration indicates the rock is fresh.

(c) *Inclusions.*—None apparent.

5. *Chlorite.*—$Mg_3Si_2O_5(OH)_4$.

(a) *General.*—Most of the chlorite found in the sections of basalt occur as fragments rather than grains. These fragments consist of only chlorite and plagioclase.

(*b*) *Crystal development*.—The fragments are subhedral and the included chlorite portion is also anhedral. However, the included plagioclase is euhedral and has extremely well-developed faces, which stand out in sharp contrast to plagioclase belonging to the original magma.

(*c*) *Alteration*.—The chlorite itself is probably an alteration product.

(*d*) *Inclusions*.—Large plagioclase crystals described above.

6. Glass:

(*a*) *General*.—The glass occurs as a brown matrix material charged with microlites of magnetite and plagioclase. Also, euhedral crystals of magnetite are common throughout the matrix. Fracturing in the glass is uncommon and the microlites within the matrix have a random orientation. This gives the interstitial glass an extremely irregular appearance.

(*b*) *Alteration*.—The glass does not appear to be devitrified; however, its dark brown color may mask some devitrification. Microlites intimately mixed with the glass may cause some error in index determination. The index has been measured as approximately $n = 1.523$.

II. Semiwelded Tuff

A. Macroscopic:

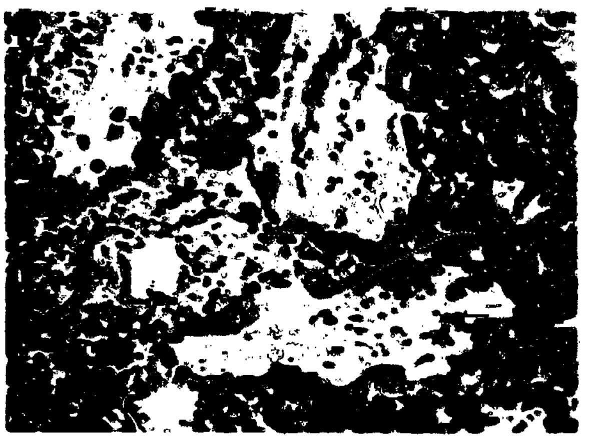
1. *Color*.—Light brown mottled with reddish-brown, brown, and black lapilli.
2. *Texture*.—Fragmental lapilli breccia consisting of pumice, dacite vitrophyre, and welded-tuff fragments in a volcanic dust and glass matrix.
3. *Structure*.—Generally massive with elongated fragments having a preferred orientation. These are subparallel but do not form definite bedding planes.
4. *Field name*.—Lapilli tuff.
5. *General observations*.—Fragments greater than 4 millimeters in diameter but less than 32 millimeters in diameter make up more than 25 percent of the total rock mass. Therefore, the prefix "lapilli" was assigned to the rock type. However, the rock is more consolidated than the usual tuff and has a semiwelded fabric.

B. Microscopic:

1. *Texture*.—The microscopic texture is divided into parts which depend on the portions of the thin section being examined. The divisions are: matrix, pumice lapilli, dacite vitrophyre lapilli, welded-tuff lapilli, and crystal fragments.

(*a*) *Matrix texture*.—The matrix consists of arcuate glass shards, rounded ash particles, occasional droplets of clear brown glass, and occasional perlites, all cemented together with an almost impalpable, slightly vesicular glass dust. "Vitroclastic," as used by Dr. H. Williams, is the term that most nearly describes the matrix texture.

FIGURE 2.—Semiwelded tuff. Brad. Obvg. Above, hand specimen; below, photomicrograph, × 13.



(*b*) *Pumice lapilli texture*.—The pumice fragments consist of a highly vesicular brown dust glass. The vesicles are variable in size and density both within a particular fragment and from fragment to fragment. In general, the vesicles are round or spherical, that is, typical of pumiceous texture, but irregular and ellipsoidal forms are not rare.

(*c*) *Dacite vitrophyre lapilli texture*.—The dacite vitrophyre fragments consist of lathlike microlites of andesine-labradorite plagioclase and interstitial pyroxene crystallites in a matrix of dark gray-green glass charged with ore mineral microlites. Occasional phenocrysts of plagioclase (An[illegible]) are found and small vesicles are common.

(*d*) *Welded-tuff lapilli texture*.—The welded-tuff lapilli has good lineation formed by thin discontinuous threads of brown dusty glass. Microscopic vesicles are numerous and are in general of two types: (1) long thin extended vesicles which occur within the threads and (2) almond-shaped vesicles which occur between threads. Flattening of ash particles is very evident in cases where they occur as discrete units. In general, ash particles have been completely fused and particle boundaries are not evident.

(c) *Included crystals.*—The included crystals occur as individual fragments making up part of the matrix material with the exception of the plagioclase phenocrysts which occur in the dacite vitrophyre. The crystal boundaries are clear and sharp and crystal faces are common. However, some rounding has taken place, especially where faces intersect to form corners. The edges have been eroded away, presumably by abrasive action of ash particles. This is suggested, rather than magmatic resorption, because each crystal fragment is surrounded by a clear glass rind which indicate very rapid cooling. The best overall textural term must also refer to the rock type, that is, a lapilli or lithic tuff.

2. *Structure.*—On a macroscopic scale the lapilli show fair lineation, which is more preferred orientation rather than lineation because actual continuous bedding does not exist. On a microscopic scale this preferred orientation is not apparent.

(a) *Matrix structure.*—No apparent structure exists in the matrix. All particles have a random orientation, and flattening of ash grains is not evident. The vesicles, which are ellipsoidal and somewhat flattened, do not possess a preferred orientation. The most impressive feature of the matrix material is the way the vitreous dust completely fills the interstices between glass shards, ash particles, and lapilli. No void spaces are present in the matrix, with the exception of vesicles. In a few widely scattered areas, some welding has taken place and microscopic sinuous lamellae are present and are very similar to those of a welded tuff.

(b) *Pumice lapilli structure.*—Each ash particle is slightly flattened against each adjacent grain. However, the grains maintain an almost spherical shape and the flattening effect does not have a preferred orientation. Lineation within the lapilli is not apparent.

(c) *Dacite vitrophyre structure.*—Small crystallites of plagioclase have a subparallel alinement that is deflected by included larger crystals such as hypersthene or plagioclase phenocrysts. A few reentrants around the margins and some included vesicles indicate the original rock was of a vesicular nature.

(d) *Welded-tuff lapilli structure.*—Good lineation is apparent in the welded-tuff lapilli even on a macroscopic scale. Thin discontinuous threads of brown dusty glass, which are slightly blocky on the ends, lie parallel to one another. These threads are deflected around vesicles and almond-shaped ash particles. This gives a gentle wavy appearance to the lineation. The structure as a whole is somewhat eutaxitic in nature.

(e) *Included crystals.*—The included crystals occur in all forms from euhedral to anhedral, but in general they have a euhedral outline with slightly rounded corners. These crystals have a completely random orientation and even the plagioclase laths, which would be expected to take on an orientation with their long dimension paralleling the surface, exhibit a random pattern.

C. General statement:

1. Many other fragments or lapilli of other rock types exist in the lapilli tuff, but in general these are variations of those listed above or are minor constituents. Two fragments of rhyolite (porphyritic), a few small fragments of obsidian, and one fragment of porphyritic basalt were observed, but because they are minor constituents they are not described in detail.

III. Obsidian

A. Macroscopic:

1. *Color.*—Dark gray with a slight brown tint.
2. *Texture.*—Glassy, macroscopically holohyaline.
3. *Structure.*—Massive with an oriented splintery fracture system. Fractures perpendicular to the splintery system are conchoidal.
4. *Minerals.*—None identifiable.
5. *Field name.*—Obsidian.

B. Microscopic:

1. *Texture.*—Glass matrix charged with glass shards, microlites, and crystallites. The microlites are of the longulite and belonite varieties. The glass shards have rounded resorption boundaries, and some are cloudy under crossed nicols indicating devitrification. A few widely scattered plagioclase grains also are present.
2. *Structure.*—The glass shards and microlites show a general preferred orientation with their long dimension parallel to the splinter-fracture pattern. Microlite density is variable; it occurs in streaks nearly parallel to the splinter-fracture system. Relic plagioclase laths occur as scattered unoriented grains.

C. Essential and accessory constituents or minerals:

	Content, percent
1. Glass	60
2. Microlites	30
3. Plagioclase	5
4. Augite	3
5. Ore minerals	2

D. Secondary minerals:

	Content, percent
1. Chlorite	1

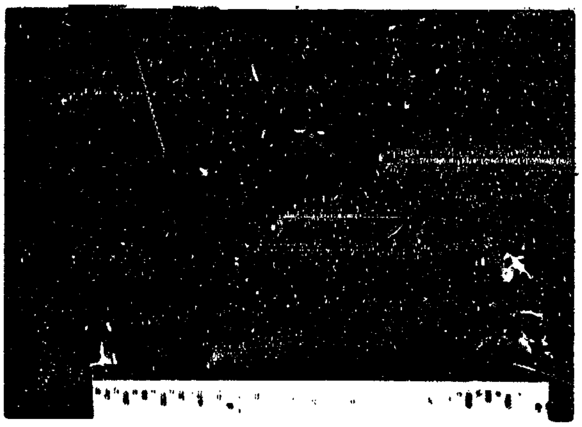


FIGURE 3.—Obsidian. Newberry Caldera, Oreg. Above, hand specimen; below, photomicrograph, × 13.

E. Essential constituents.

1. *Glass.*—Content, 65 percent (index of refraction n = 1.495). There is no crystalline form to the glass, but there are two varieties occurring in this obsidian: matrix glass and darker glass shards. The glass shards make up approximately 40 percent of the total glass content. The shards have conchoidal boundaries and rounded reentrants of matrix glass. Apparently, during cooling orthobrecciation was occurring along with resorption.

2. *Ore minerals.*—The ore minerals occur as very small spherical globules. In some cases, vestiges of face development can be seen.

   (a) *Inclusions.*—None.

   (b) *Alteration.*—None.

D. ALTERED RHYOLITE

A. Macroscopic:

1. *Color.*—Cream colored with streaks of brown limonite in fractured regions.

2. *Texture.*—Dense aphanitic, with scattered small vesicles. Some small (1 millimeter or less) crystals, probably sanidine.

3. *Structure.*—Numerous fractures with random orientation and small (1 millimeter in diameter) widely scattered vesicles.

4. *Field name.*—Altered rhyolite.

B. Microscopic:

1. *Texture.*—Minute lath-shaped crystals, principally feldspar with some interstitial glass in a matrix of felty crystallites and small microlites. Scattered random-oriented crystals 0.1 to 0.4 millimeter in diameter.

2. *Structure.*—The plagioclase laths occur in subparallel clusters, thereby imparting some lineation to the overall structure. Deflection of these crystals around knots of felted crystallites and vesicles gives a semiwavy pattern. The vesicles are not spherical but are irregular in shape and somewhat flattened and lined with small crystallites, which probably are quartz.

C. Essential minerals (percentages are visually estimated and should be considered only as approximations):

	Content, percent
1. Plagioclase (An[illegible])	25
2. Sanidine	10
3. Quartz	2
4. Felty groundmass and glass	60

D. Accessory minerals:

	Content, percent
1. Pyroxene(?) microlites	1

E. Secondary minerals:

	Content, percent
1. Hematite and clay	2

(a) *Inclusions.*—Glass is the matrix material. Therefore, all minerals are essentially included in the glass. However, the glass shards do not contain microlites or other crystalline material.

(b) *Alteration.*—Patches and widely scattered small spherical areas appear cloudy under crossed nicols (devitrification). These areas are generally around relic plagioclase or adjacent to a long fracture.

2. *Microlites.*—The microlites are oblong rectangles, in general, with some showing slightly bulbous ends. The outlines are clear and sharp, and they are mostly of the longulite class. Some of the larger microlites show extinction under crossed nicols. The extinction angle averages about 37°. If the orientation is considered as being normal to the (010) the microlites would be approximately An[illegible].

   (a) *Inclusions.*—None apparent.

   (b) *Alteration.*—None apparent.

3. *Plagioclase.*—Most of the plagioclase grains are highly fractured and very few crystal boundaries are well defined. The highly fractured nature and the angularity of the corners suggest orthobrecciation and partial resorption. Clouding of the glass adjacent to the plagioclase grains is common. No sharp twin planes are evident and

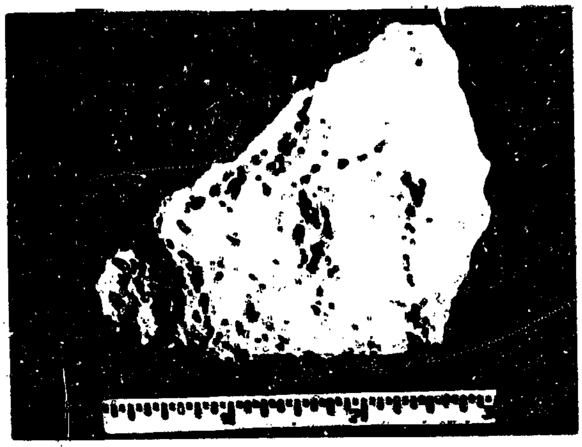
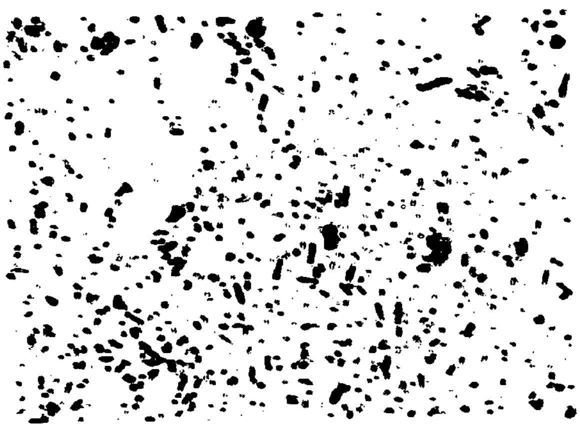


FIGURE 4.—Altered rhyolite: occurs east of P. .d, Oreg. Above, hand specimen; below, photomicrograph × 13.



the fragments are highly zoned. A few oriented grains show zoned extinction from An$_{..}$ to An$_{..}$.

(a) *Inclusions.*—None apparent.

(b) *Alteration.*—The cloudy area surrounding the plagioclase fragments indicates that resorption was taking place and enriching the surrounding glass. The alteration product has not been identified.

4. *Augite.*—Augite occurs as small semiglobular patches with serrate projections into the glass and microlite areas. No crystal faces are present and only in very widely scattered large grains is the cleavage visible. In general, the augite occurs as grains larger than those of the plagioclase. However, it is much more rare.

(a) *Inclusions.*—None apparent.

(b) *Alteration.*—In a few instances chlorite or a light green coloration surrounds the augite and projects a short distance into the glassy groundmass. In cases where microlites are adjacent to the augite the coloration surrounds the microlite.

F. Common minerals:

1. *Plagioclase* (An$_{..}$).—The plagioclase laths occur as discrete laths in the felty groundmass and are generally not twinned. However, occasional albite twins are present. In general, the crystals are poorly formed and are subhedral in outline.
2. *Sanidine.*—The sanidine crystals are anhedral with very poor crystal development. However, excellent interference figures are available and the 2V is approximately 4° and very nearly uniaxial in character. Some small glass shard inclusions are present. The irregular crystals are approximately 0.10 millimeter in diameter.
3. *Quartz.*—Quartz occurs in two phases: One mode very similar to that of the sanidine and the other as very small crystallites partially lining small vesicles.

V. SERPENTINE (SERPENTINITE)

A. Macroscopic:

1. *Color.*—Dark green mottled with apple green.
2. *Texture.*—Lineated with chrysotile phenocrysts and numerous randomly oriented hairline fractures filled with chlorite and ore minerals.
3. *Structure.*—Massive, with good subparallel lineation and some mammillary inclusions which interrupt lineation.
4. *Field name.*—Serpentine.

B. Microscopic:

1. *Texture.*—The texture is typical of serpentine. It consists of the typical mesh texture of antigorite with flakes of wavy fibrous chrysotile scattered at random. The apple-green lineations seen in the hand specimen are aggregates of crystals consisting of olivine, pyroxene, and amphibole.
2. *Structure.*—Grains as discrete entities are not evident except in the crystalline veinlets, where amphibole dominates with some crystals as large as 0.4 millimeter in diameter. Chainlike lineation of the ore minerals (magnetite and chromite) and also elongated masses are common. In some sections of the slide, especially in the massive antigorite regions, a poorly developed bastite structure is recognized.

C. *Essential minerals.*—Point-count procedures to determine the quantitative percentages of mineral composition of the serpentine are in progress; the following percentages are estimates based on visual thin-section examination.

	Content, percent
1. Antigorite	50
2. Chrysotile	20
3. Ore minerals	7

D. Accessory minerals:

	Content, percent
1. Enstatite	3

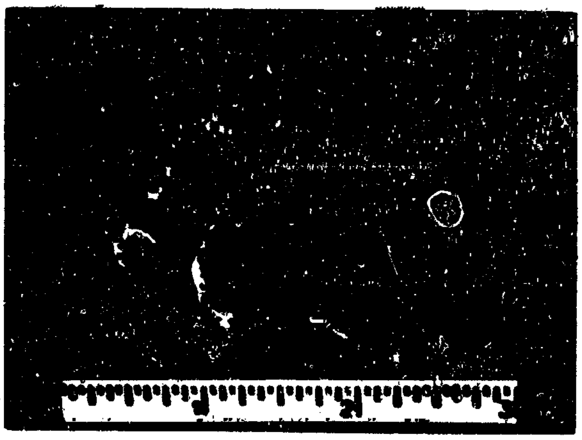


FIGURE 5.—Serpentinite; Rogue River, occurs northwest of Grants Pass, Oreg. Above, hand specimen; below, photomicrograph, × 13.

	Content, percent
2. Angite	5
3. Olivine	8

E. Secondary minerals:

	Content, percent
1. Chlorite	2
2. Talc	1
3. Tremolite	1
4. Dolomite or magnesite	1

F. Description of commonly occurring minerals:

1. *Antigorite* ($Mg_6(OH)_6Si_4O_{11}$).—Antigorite is the dominant mineral and it surrounds all minerals, veinlets, and other features. The structure is a combination beam-and-mesh type with the beam structure being predominate. Antigorite is also found as a minor secondary mineral within the apple-green veinlets of amphibole and pyroxene. Small groups of irregular carbonate minerals (dolomite or magnesite) are found between antigorite plates in some cases. However, tremolite crystals are rather common and show good crystalline form.
2. *Chrysotile* ($Mg_3(OH)_4Si_2O_5$).—Chrysotile crystals have an apparent random orientation with little or no relation to veinlets or fracture patterns. The crystals are irregular in shape and very finely fibrous. In some cases small crystals of tremolite are found within the chrysotile phenocrysts.
3. *Ore minerals*.—The ore minerals (magnetite or chromite) occur both as lineated stringers and irregular masses. However, the irregular masses also show some lineation. Almost all the chrysotile crystals have some ore minerals surrounding the crystal as a partial, discontinuous rim. Inclusion of ore minerals within the chrysotile is rare.

VI. GRANODIORITE

A. Macroscopic:

1. *Color*.—Light gray to white mottled with black minerals.
2. *Texture*.—Crystalline.
3. *Structure*.—Massive unfractured.
4. *Field name*.—Granite.

B. Microscopic:

1. *Texture*.—A number of randomly oriented grains are completely enclosed in optically continuous crystals of different composition (poikilitic texture). Some fingerlike intergrowths of quartz are found penetrating plagioclase crystals (myrmekitic intergrowths). However, this condition is a rare rather than a general characteristic.
2. *Structure*.—There is a wide spectrum of grain size, but in general the rock is medium grained with hypidiomorphic structure. Small grain or crystal inclusions in the larger grains consist of zircon, sphene, apatite, and opaque ore minerals.

C. Essential minerals:

	Content, percent
1. Plagioclase (zoned $An_{[illegible]}$)	40
2. Quartz	39
3. Orthoclase (untwinned)	8
4. Microcline (twinned)	2

D. Accessory minerals:

	Content, percent
1. Biotite	7
2. Muscovite	1
3. Zircon	1
4. Apatite	1
5. Ore mineral	1
6. Sphene	1

E. Secondary minerals:

	Content, percent
1. Chlorite	1
2. Epidote	1
Rock type, biotite granodiorite	

F. Description of most commonly occurring minerals:

1. *Plagioclase* ($NaAlSi_3O_8$; $CaAl_2Si_2O_8$).—Crystal faces are well developed against orthoclase and

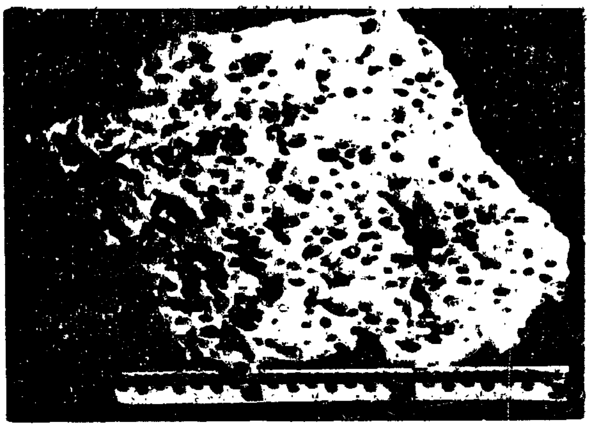


FIGURE 6.—Granodiorite; Bates Station, occurs east of Madera, Calif. Above, hand specimen; below, photomicrograph, × 13.

microline crystals, except where myrmekitic texture exists. Crystal faces are generally but, not always well developed against quartz crystals. The crystals are zoned from An[illegible] to An[illegible]. However, the rims extinguish at the same time as the core does and, in general, are of about the same composition. Three types of twinning are apparent: (1) albite, (2) carlsbad, and (3) pericline.

(a) *Alteration.*—White mica is found as small crystals along cleavage planes or as larger crystals in the core. The boundary between plagioclase and biotite contains both white mica and epidote.

(b) *Inclusions.*—Euhedral zircon, euhedral and subhedral biotite, anhedral ore minerals, and euhedral apatite.

2. *Quartz* (SiO_2).—Crystal faces are, in general, well developed against orthoclase, microcline, and quartz but are anhedral against other major minerals.

(a) *Alteration.*—None apparent.

(b) *Inclusions.*—Subhedral and euhedral biotite and plagioclase, euhedral zircon and apatite, subhedral muscovite, and anhedral opaque ore minerals.

3. *Orthoclase* ($KAlSi_3O_8$).—Very few crystal faces are developed, but some are found adjacent to quartz grains and other K feldspar.

(a) *Alteration.*—Myrmekite is fairly common and either may be a replacement phenomenon or may represent the final stages of crystallization.

(b) *Inclusions.*—Euhedral plagioclase both twinned and zoned and anhedral plagioclase with myrmekitic patches. Zircon and apatite occur as poikilitic anhedral crystals with inclusions of plagioclase, quartz, and biotite.

4. *Microcline* ($KAlSi_3O_8$; $NaAlSi_3O_8$).—Microcline crystals show a typical quadrille structure and are easily identified thereby. The crystals are, in general, anhedral with crystal faces being rare. The grains are poikilitic with numerous inclusions of euhedral plagioclase, quartz, and biotite.

(a) *Alteration.*—Myrmekite is found in some crystals, but it does not occur as often as in the case of orthoclase.

(b) *Inclusions.*—Euhedral plagioclase both twinned and zoned. Quartz, biotite, zircon, and apatite are common.

5. *Biotite* ($K_2(Mg, Fe)_{6-4}$ $(Fe, Al, Ti)_{0-2}Si_{6-5}Al_{2-3}O_{20-22}$ $(OH, F)_{4-2}$).—Crystals occur as large grains with no apparent original face boundary, but this is difficult to detect because of the excellent cleavage parallel to (001). Numerous elongate grains occur oriented with the (001) in the plane of the thin section. These show serrated edges that are slightly bent. This characteristic also is true of the elongate crystals near the ends where cleavage separation is more apparent.

(a) *Inclusions.*—Euhedral zircon, apatite, and ore minerals are common. There are some anhedral ore minerals and rare anhedral quartz crystals.

(b) *Alteration.*—Some grains are wholly altered to chlorite and most show chlorite alterations around the edges. Sphene and epidote also occur as alterations where biotite is in contact with plagioclase crystals.

6. *Muscovite* ($K_2Al_4(Si_6Al_2)O_{20}$ $(OH, F)_4$).—The (001) faces are well developed, but other faces are not. Ore-mineral inclusions are common and occur most often between the (001) cleavages.

(a) *Inclusions.*—Mostly free of inclusions except for the above-mentioned ore minerals.

(b) *Alteration.*—None apparent.

VII. PORPHYRITIC RHYOLITE VITROPHYRE

A. Macroscopic:

1. *Color.*—Gray.
2. *Texture.*—Aphanitic with feldspar microphenocrysts.

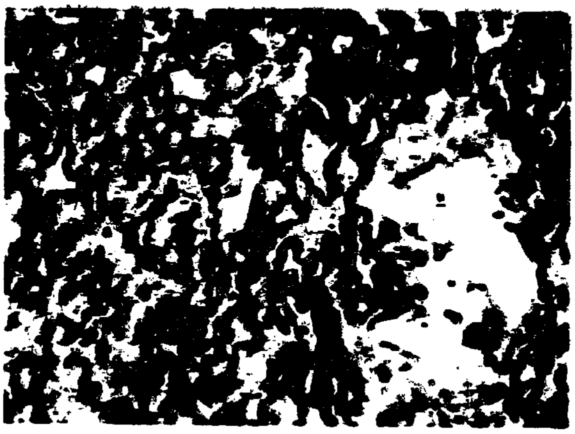


FIGURE 7.—Rhyolite; Newberry Caldera, Oreg. Above, hand specimen; below, photomicrograph, × 13.

3. *Structure.*—Massive.
4. *Field name.*—Porphyritic felsite.

B. Microscopic:

1. *Texture.*—This rock is hyaline and microporphyritic. The glassy matrix is filled with acicular crystallites which cannot be identified. Use of the term rhyolite is based mainly on the strength of the high SiO_2 percentage of rock. Tiny vesicles occur within the rock, and iron-stained alteration halos surround them.
2. *Structure.*—The plagioclase microphenocrysts range in size from 0.1 to 1.5 millimeters in length. The pyroxene grains range from 0.2 to 1 millimeter in length, and the magnetite grains range from 0.001 to 0.2 millimeter on an edge.

C. Composition:

(Visual estimates only)	*Content, percent*
1. Glass and crystallites	95
2. Plagioclase microphenocrysts (albite or oligoclase)	4
3. Pyroxene (augite)	<1
4. Magnetite	<1
5. Hematite	<<1

D. Mineral description:

1. *Plagioclase* ($CaAl_2Si_2O_8$: $NaAlSi_3O_8$).
   (*a*) *General.*—The plagioclase occurs as zoned crystals with carlsbad and albite twinning. The composition of the plagioclase indicated by its optical properties is in the high-temperature albite or oligoclase range.
   (*b*) *Crystal development.*—Most crystals are euhedral with sharp boundaries, but some are broken and show rounding.
   (*c*) *Alteration.*—None observed.
   (*d*) *Inclusions.*—Glass and crystallites are included in the plagioclase grains.
2. *Pyroxene* ($Ca(Mg, Fe_2, Al)(Si, Al)_2O_6$).
   (*a*) *General.*—The pyroxene is light green in color and augite in composition.
   (*b*) *Crystal development.*—The pyroxene occurs in euhedral prisms, with some grains broken and rounded.
   (*c*) *Alteration.*—A fibrous brown reaction rim (?) was noted on one pyroxene.
   (*d*) *Inclusions.*—Magnetite occurs in the pyroxenes with some glass and crystallites.

VIII. DACITE

A. Macroscopic:

1. *Color.*—Dark gray.
2. *Texture.*—Glassy, with feldspar microphenocrysts.
3. *Structure.*—Massive.
4. *Field name.*—Dacite(?).

B. Microscopic:

1. *Texture.*—This rock is hypocrystalline, with a microporphyritic, hyalopilitic texture. Some plagioclase microphenocrysts tend to be clustered together in small groups. The name dacite is based on the high percentage of silica and the composition of the plagioclase.
2. *Structure.*—The plagioclase microphenocrysts range in size from 0.2 to 2 millimeters in length. The matrix plagioclase averages 0.05 millimeter in length. The pyroxene ranges from 0.2 to 0.8 millimeter in length and the few oxyhornblende crossections seen are 0.2 millimeter in the longer direction. The magnetite occurs in cubes with edges as large as 0.2 millimeter.

C. Essential minerals and glass: (Visual estimates only)

	Content, percent
1. Plagioclase (microlites) (labradorite)	40
2. Glass	36
3. Plagioclase (microphenocrysts) (labradorite)	15

D. Accessory minerals:

	Content, percent
1. Pyroxene (pseudomorph of hornblende after augite?)	5
2. Magnetite	3
3. Oxyhornblende	<1

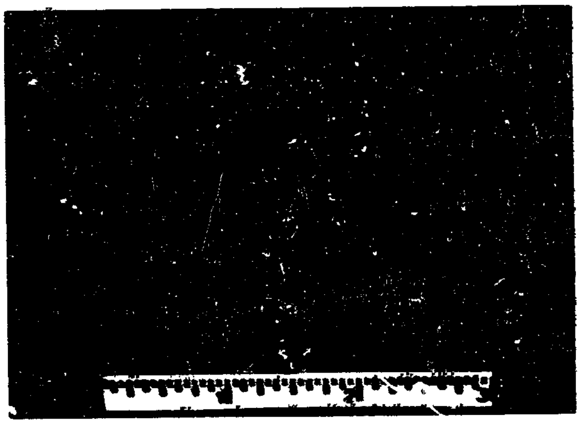


FIGURE 8.—Dacite; west of Bend, Oreg. Above, hand specimen; below, photomicrograph, × 13.

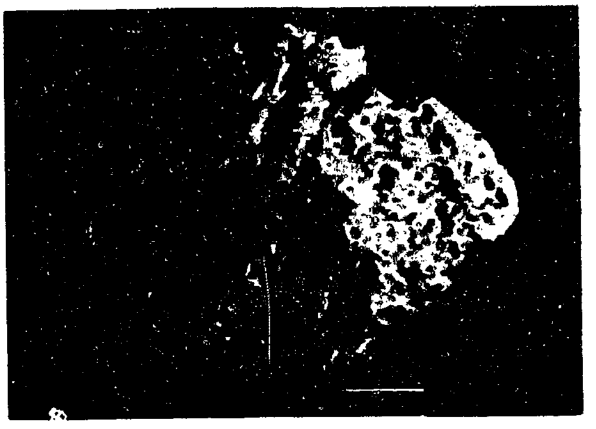


FIGURE 9.—Pumice; Newberry Caldera, Oreg. Above, hand specimen; below, photomicrograph, × 13.

E. Description of essential minerals:
1. *Plagioclase* ($CaAl_2Si_2O_8$; $NaAlSi_3O_8$).
(*a*) *General.*—The microphenocrysts are high-temperature, zoned crystals with both albite and carlsbad twinning. The microlites are unzoned with some carlsbad twinning in the larger grains. The composition of the plagioclase is labradorite.
(*b*) *Crystal development.*—The microphenocrysts range from good euhedral crystals to broken, skeletal, spongy, corroded remnants. The matrix grains are somewhat euhedral and range in shape from laths to blocky grains.
(*c*) *Alteration.*—None, other than corrosion of microphenocrysts.
(*d*) *Inclusions.*—Glass and euhedral magnetite occur as inclusions in the microphenocrysts.

IX. Pumice

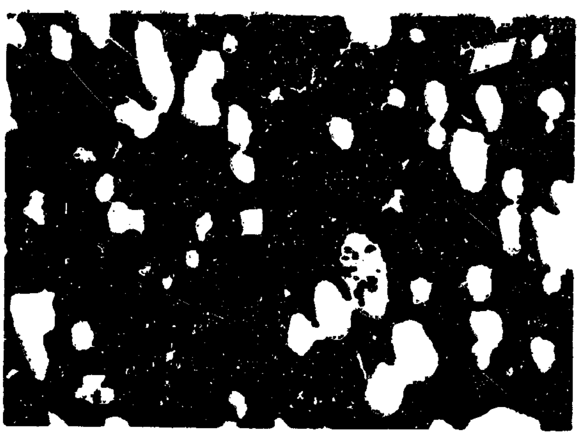
A. Macroscopic:
1. *Color.*—Light tan.
2. *Texture.*—Porous, glassy.
3. *Structure.*—Massive.
4. *Field name.*—Pumice.

B. Microscopic:
1. *Texture and structure.*—This rock is vitreous and is macrovesicular to microvesicular. Microscopic spherulites are present, and there is a definite lineation to the rock imparted by the ellipsoidal shape of the spherulites and vesicles and the flow lines. Some devitrification of the glass has taken place, and a few feldspar crystallites can be seen in the less glassy areas. The average vesicle size is about 0.2 millimeter at its longest ellipse axis. The glass is clear to cloudy (devitrifying) with an index of refraction of about 1.49. The spherulites make up an estimated 20 percent of the rock and the vesicles, about 40 percent. No alteration other than devitrification was observed.

X. Vesicular Basalt 1

A. Macroscopic:
1. *Color.*—Gray.

FIGURE 10.—Vesicular basalt 1; occurs south of Bend, Oreg. Above, hand specimen; below, photomicrograph, × 4.6.



2. *Texture.*—Vesicular, with microphenocrysts and aphanitic matrix.
3. *Structure.*—Massive.
4. *Field name.*—Vesicular basalt.

B. Microscopic:

1. *Texture.*—The texture of this rock may be described as hypocrystalline, vesicular, microporphyritic, and hyalopilitic. The plagioclase has a fairly continuous size range from microphenocrysts to matrix; this imparts a seriate texture for that mineral. This case exists similarly for the pyroxene and olivine.
2. *Structure.*—The vesicles are somewhat elongate in one direction, range in size from 0.1 to 0.5 millimeter long, and represent almost 35 percent of the total area of the section. The plagioclase laths vary from 0.01 to 0.5 millimeter in length. The pyroxene and olivine occur mainly as matrix minerals and occasionally as microphenocrysts. They range in size from 0.01 to 0.7 millimeter in diameter. Magnetite occurs as subhedral to euhedral grains about 0.01 millimeter in diameter.

C. Essential minerals and glass:

(Visual estimates only)	Content, percent
1. Plagioclase (matrix) (labradorite)	50
2. Pyroxene (augite)	20
3. Glass	15
4. Plagioclase (microphenocrysts) (labradorite or bytownite)	10

D. Accessory minerals:

	Content, percent
1. Olivine (forsterite, Fo[illegible]–Fo[illegible])	<3
2. Magnetite	2
3. Hematite	<1

E. Description of essential minerals:

1. *Plagioclase* ($NaAlSi_3O_8$; $CaAl_2Si_2O_8$).

(*a*) *General.*—The euhedral plagioclase microphenocrysts are zoned both continuously and discontinuously. Many crystals are "stuffed" zonally with dust, glass, and small nonpolarizing crystallites. Albite twinning is common for both the matrix and phenocrystic sizes. The smaller matrix laths are subhedral to euhedral, are unzoned, and have no particular orientation within the matrix. The composition of the plagioclase is at least labradorite or more calcic.

(*b*) *Crystal development.*—The crystal development becomes poorer as the plagioclase size decreases; therefore the microphenocrysts have the better crystal development and the matrix plagioclase microlites the least.

(*c*) *Alteration.*—None observed.

(*d*) *Inclusions.*—Dusty glass and crystallites of olivine(?) and pyroxene(?) occur zonally within the larger plagioclase crystals.

2. *Pyroxene* ($Ca(Mg, Fe_2, Al)(Si, Al)_2O_6$).

(*a*) *General.*—The pyroxene occurs as subhedral to euhedral grains of both matrix and microphenocryst size. No zoning or twinning is apparent, and the composition is probably augite.

(*b*) *Crystal development.*—Most grains have good crystal development, with the matrix-size grains being the more euhedral.

(*c*) *Alteration.*—None observed.

(*d*) *Inclusions.*—Some very small crystallites are included within the pyroxene grains.

XI. VESICULAR OLIVINE BASALT 2

A. Macroscopic:

1. *Color.*—Dark gray to black.
2. *Texture.*—Vesicular, aphanitic.
3. *Structure.*—Massive.
4. *Field name.*—Vesicular basalt.

B. Microscopic:

1. *Texture.*—This rock may be described as hypo-

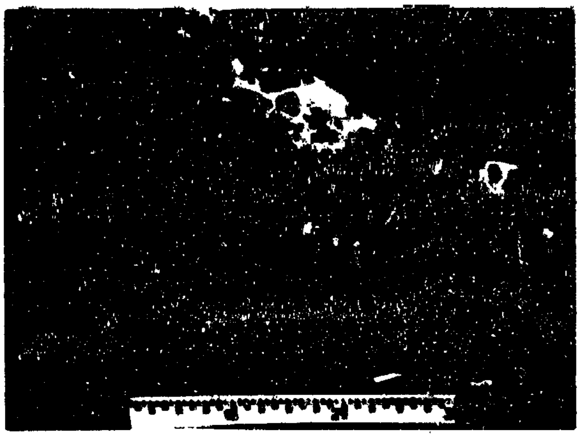
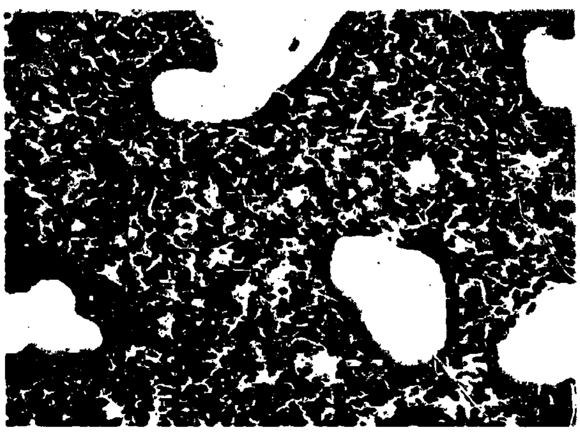


FIGURE 11.—Vesicular basalt 2; occurs south of Bend, Oreg. Above, hand specimen; below, photomicrograph, X 4.6.



crystalline and as having a vesicular, hyalopilitic texture. The plagioclase and pyroxene have no specific orientation.

2. *Structure.*—The plagioclase laths range in size from 0.1 to 1.5 millimeters long and average about 0.7 millimeter. The olivine grains are rounded and range from about 0.05 to 0.5 millimeter in diameter. The pyroxene grains are elongated prisms averaging about 0.3 to 0.5 millimeter in length, and they are the main constituents of the vesicle walls. The vesicles represent about 40 percent of the area of the section. They are somewhat elongate and range from 2 to 15 millimeters in the longest dimension. The magnetite occurs in anhedral to euhedral grains ranging from 0.01 to 0.30 millimeter in diameter. Some alteration of magnetite to hematite has occurred.

C. Essential minerals:

(Visual estimates only)	Content, percent
1. Plagioclase (labradorite, $An_{[illegible]}$)	50
2. Olivine ($Fo_{[illegible]}$–$Fo_{[illegible]}$)	25
3. Pyroxene (augite)	15

D. Accessory minerals and glass:

	Content, percent
1. Magnetite	5
2. Glass	5
3. Hematite	<1

E. *Description of essential minerals:*

1. *Plagioclase* ($CaAl_2Si_2O_8$; $NaAlSi_3O_8$).
   (a) *General.*—The plagioclase occurs as laths with polysynthetic twinning, with compositional zoning apparent in some more equant (older?) grains. The composition indicated by the Michel-Levy method for the twinned laths is about $An_{[illegible]}$ in the labradorite range.
   (b) *Crystal development.*—The laths are subhedral with splintered, broken ends. Twin planes and intergranular boundaries are sharp.
   (c) *Alteration.*—None observed.
   (d) *Inclusions.*—A few inclusions occur in the plagioclase and are probably olivine (?).
2. *Olivine* ($(Mg, Fe)_2SiO_4$).
   (a) *General.*—The olivine grains are indicated to be in the $Fo_{[illegible]}$–$Fo_{[illegible]}$ range.
   (b) *Crystal development.*—The grains are rounded to euhedral, with the small grains being the most euhedral. Some resorption may have occurred, thereby causing the rounding of the (older?) larger grains.
   (c) *Alteration.*—None observed.
   (d) *Inclusions.*—A few inclusions of undetermined composition occur in the olivine grains.
3. *Pyroxene* ($Ca(Mg, Fe, Al)(Si, Al)_2O_6$).
   (a) *General.*—The pyroxene is brown in color and probably augite.
   (b) *Crystal development.*—The grains forming the vesicle walls are elongate, somewhat radiating, and poorly developed. Pyroxene also occurs in the matrix as interstitial and more euhedral grains.
   (c) *Alteration.*—None observed.
   (d) *Inclusions.*—Most magnetite occurs as inclusions within the augite.

XII. VESICULAR OLIVINE BASALT 3

A. Macroscopic:
   1. *Color.*—Dark gray.
   2. *Texture.*—Vesicular, aphanitic.
   3. *Structure.*—Massive.
   4. *Field name.*—Vesicular basalt.

B. Microscopic:
   1. *Texture.*—The rock is hypocrystalline with a vesicular, microporphyritic, hyalopilitic texture. The plagioclase laths have no specific orientation in either section (perpendicular or parallel).
   2. *Structure.*—The plagioclase microphenocrysts range in size from 0.2 to 1.3 millimeters long. The plagioclase microlites range from 0.01 to 0.3 millimeter long. The olivine grains are from 0.01 to 0.4 millimeter in diameter. The mag-

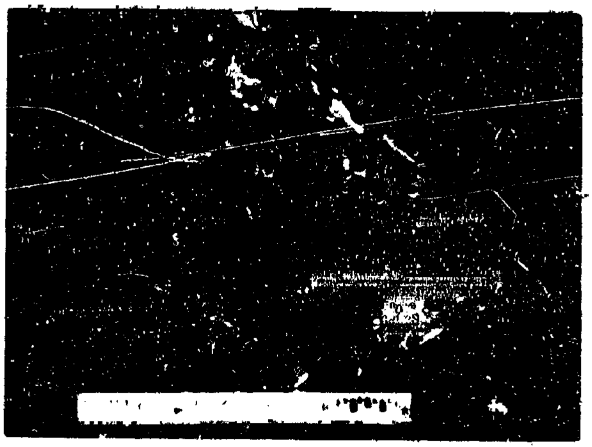
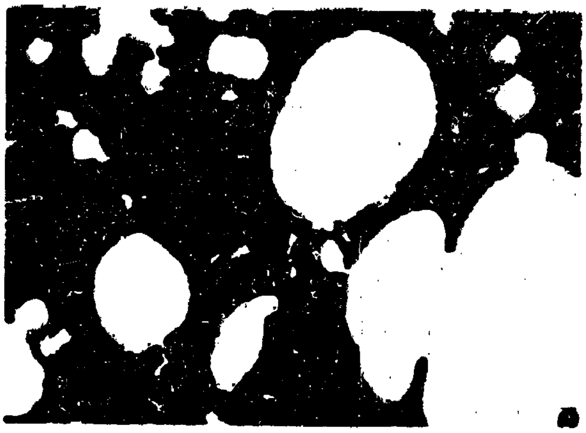


FIGURE 12.—Vesicular basalt 3: Lava Beds National Monument, Calif. Above, hand specimen; below, photomicrograph, × 4.6.



B

netite grains are very small and average 0.002 millimeter in diameter. The vesicles represent about 35 percent of the area of the section, are ovoid in shape, and range from 2 to 10 millimeters in diameter. Some of the vesicle walls have colloform opal linings. The glass, although cloudy, is not particularly altered.

C. Essential minerals and glass:

(Visual estimates only)	Content, percent
1. Plagioclase (matrix) (labradorite, An[illegible])	45
2. Olivine forsterite (Fo[illegible]–Fo[illegible])	20
3. Plagioclase (microphenocrysts) (bytownite)	10
4. Glass	20

D. Accessory minerals:

	Content, percent
1. Magnetite	5

E. Description of essential minerals:

1. *Plagioclase* ($CaAl_2Si_2O_8$; $NaAlSi_3O_8$).

(a) *General.*—The microphenocrysts are zoned and have a compositional range averaging about sodic bytownite. Carlsbad twinning is common, with some albite twinning. The matrix plagioclase displays albite twinning and is in the labradorite (An[illegible]) range; this is determined by using the Michel-Levy technique.

(b) *Crystal development.*—The microphenocrysts are corroded remnants of euhedral, twinned crystals, but they still retain much of their original outline. The matrix crystals are subhedral laths with splintery ends, and are not well crystallized.

(c) *Alteration.*—None observed.

(d) *Inclusions.*—Dust and glass are zonally included in the plagioclase microphenocrysts in the center or middle zones.

2. *Olivine* ($(Mg, Fe)_2SiO_4$).

(a) *General.*—The olivine is mostly matrix size with a few larger grains. The composition is indicated to be in the forsterite range (Fo[illegible]–Fo[illegible]).

(b) *Crystal development.*—The matrix grains are very crystalline and euhedral. Some larger (older ?) grains tend to be somewhat rounded.

(c) *Alteration.*—None observed.

(d) *Inclusions.*—A few unidentified inclusions are scattered through the grains.

XIII. GABBRO

A. Macroscopic:

1. *Color.*—Dark brown, mottled.
2. *Texture.*—Medium-grained feldspar has some orientation.
3. *Structure.*—Dense, massive.
4. *Field name.*—Gabbro.

B. Microscopic:

1. *Texture.*—The rock has a phaneritic, holocrystalline, anhedral-interstitial texture. The plagioclase laths do not appear well oriented in this section. The subhedral plagioclase laths are surrounded by anhedral grains of pyroxene, olivine, and magnetite which impart the anhedral—interstitial texture.
2. *Structure.*—The grain size is fairly uniform for all species except plagioclase, which has laths that average 10 to 15 millimeters long and 1 millimeter wide but range from 0.3 millimeter long. The pyroxene grains range from 1 to 2 millimeters and the olivines from 0.5 to 1.5 millimeters in diameter. Most olivines show some incipient alteration to fibrous serpentine along fractures and grain boundaries. The magnetite grains vary in size from 0.1 to 1.5 millimeters in diameter, although most grains are at the larger end of the range.

C. Essential minerals:

(Visual estimates only)	Content, percent
1. Plagioclase (labradorite, An[illegible])	50
2. Pyroxene (pigeonite)	25

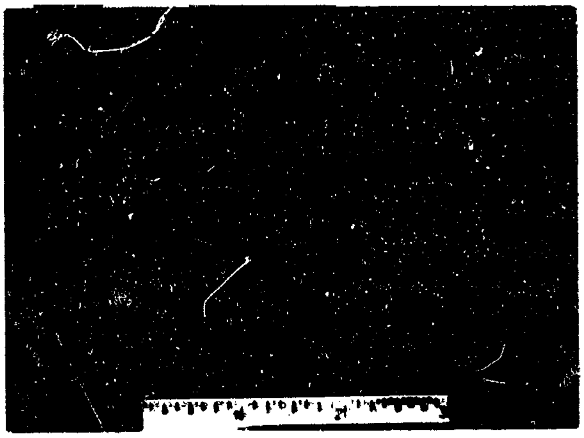


FIGURE 13.—Gabbro; occurs north of Duluth, Minn. Above, hand specimen; below, photomicrograph, × 13.

D. Accessory minerals:

	Content, percent
1. Magnetite	10
2. Olivine (forsterite (Fo[illegible]–Fo[illegible]))	5
3. Serpentine	<1
4. Pyrite	<<1

E. Description of essential minerals:

1. *Plagioclase* ($NaAlSi_3O_8$; $CaAl_2Si_2O_8$).

(*a*) *General.*—The laths are unzoned, with both albite and carlsbad twinning present. The composition is indicated as about An[illegible] (labradorite) by using the Michel-Levy technique.

(*b*) *Crystal development.*—Outlines are irregular with no good faces developed, but the twin and intergranular boundaries are sharp.

(*c*) *Alteration.*—Some apparent sericitic (?) alteration was observed on several grains.

(*d*) *Inclusions.*—Tiny, nonpolarizing crystallites occur scattered evenly throughout the plagioclase grains, and these probably are primary inclusions.

2. *Pyroxene* (Ca(Mg, Fe, Al)(Si, Al)$_2O_6$).

(*a*) *General.*—The pyroxene grains are anhedral, unzoned pigeonite.

(*b*) *Crystal development.*—There are no crystal outlines, but grain boundaries are sharp.

(*c*) *Alteration.*—None observed.

(*d*) *Inclusions.*—Some (exsolved ?) crystallites were noted along two or more crystal directions and these may be another pyroxene phase.

XIV. DUNITE (HARZBURGITE)

A. Macroscopic:

1. *Color.*—Green-black.
2. *Texture.*—Fine-grained, some surface alteration.
3. *Structure.*—Dense, highly fractured.
4. *Field name.*—Dunite.

B. Microscopic:

1. *Texture.*—This rock is phaneritic and holocrystalline with a mosaic texture. The grains are anhedral and equant to elongate.
2. *Structure.*—The larger, more elongate grains of olivine and pyroxene give a layered appearance to the rock. Many olivines have undulatory extinction, and many pyroxenes are sheared along cleavage directions. The rock is highly fractured but healed by serpentine. The fractures are long, are closely spaced, and occur in several directions. The olivine grains range in size from 0.2 millimeter in diameter to 6 millimeters long and 2 millimeters wide. The pyroxenes range from 0.2 to 4 millimeters long. The spinel is yellow-brown, varies in size from 0.02 millimeter to 1 millimeter in diameter, and occurs as irregular interstitial grains.

C. Essential minerals:

(Visual estimates only)	Content, percent
1. Olivine (forsterite)	60
2. Orthopyroxene (enstatite)	35

D. Accessory minerals:

	Content, percent
1. Spinel (chromite)	3
2. Serpentine	1
3. Magnetite	<<1

E. Mineral descriptions:

1. *Olivine* ((Mg, Fe)$_2SiO_4$).

(*a*) *General.*—The olivine grains are unzoned, but they are strained and show wavy extinction. The composition is in the forsterite range.

(*b*) *Crystal development.*—None, but grain boundaries are well defined.

(*c*) *Alteration.*—Some alteration of olivine to fibrous serpentine has occurred along fractures.

(*d*) *Inclusions.*—Some very small crystallites are present in the olivine grains.

2. *Orthopyroxene* ((Mg, Fe)SiO_3).

(*a*) *General.*—The larger grains show a zoning parallel to the cleavage which may be due to an exsolved pyroxene phase, twinning, or a shearing effect. The lamellar zones are continuous and very closely spaced. The pyroxene is enstatite

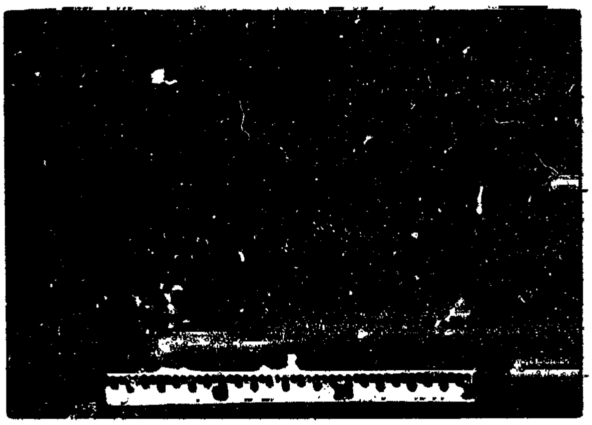
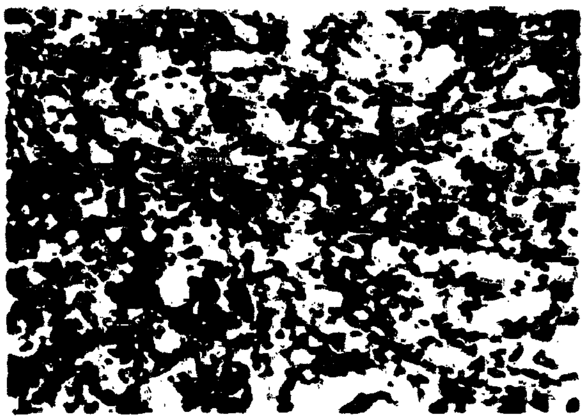


FIGURE 14.—Dunite; Riddle, Oreg. Above, hand specimen; below, photomicrograph, × 13



and occurs in local concentrations rather than in even distributions throughout the rock.

(b) *Crystal development*.—None, but boundaries are sharp.

(c) *Alteration*.—Some serpentine and sericite occur along fractures in the pyroxene.

(d) *Inclusions*.—Very tiny crystallites occur scattered throughout the grains.

APPENDIX B—CHEMICAL ANALYSES OF SIMULATED LUNAR ROCKS

Chemical analyses of the simulated lunar rocks are given in table B1. Analyses of rocks I to VI were made by T. Cook. (See ref. 4.) Analyses of rocks VII to XIV were made by R. Jefferson.

TABLE B1. *Chemical Analyses of Simulated Lunar Rocks*

Constituent	Content, percent, in—					
	I	II	III	IV	V	VI
	Tholeiitic basalt	Semiwelded tuff	Obsidian	Altered rhyolite	Serpentine	Granodiorite
SiO_2	51.0	71.2	72.8	72.5	40.0	70.0
TiO_2	2.7	.23	.21	.33	.04	.34
Al_2O_3	14.0	14.0	14.4	15.7	1.8	16.0
Fe_2O_3	3.4	1.4	.34	.75	6.4	.07
FeO	8.8	.59	1.5	0	1.8	2.1
MnO	.23	.08	.07	.02	.11	.04
MgO	4.4	.34	.04	.26	37.2	.64
CaO	8.0	.93	.84	.65	.9	3.2
Na_2O	2.4	5.0	4.9	3.7	.08	4.4
K_2O	1.7	3.0	4.0	5.0	.04	2.2
P_2O_5	1.4	.08	.03	.03	.02	.1
H_2O+	.76	2.3	.2	1.4	12.3	.47
H_2O-	.1	.15	.1	.2	.3	.2
Total H_2O	.86	2.45	.3	1.6	12.8	.67
CO_2	.03	.16	0	0	.04	.05
S	.004	Nil	Nil	.043	.022	Nil
Total	100.0	99.7	99.7	100.6	101.2	99.6

Constituent	Content, percent, in—							
	VII	VIII	IX	X	XI	XII	XIII	XIV
	Rhyolite	Dacite	Pumice	Vesicular basalt 1	Vesicular basalt 2	Vesicular basalt 3	Gabbro	Dunite
SiO_2	70.1	71.5	71.8	54.4	47.6	53.0	43.3	42.2
TiO_2	.26	.33	.23	1.13	1.62	.77	3.97	Nil
Al_2O_3	14.9	14.5	13.6	16.8	17.0	16.2	13.1	1.60
Fe_2O_3	2.77	.61	1.10	3.17	3.56	3.28	6.46	1.67
FeO	.44	1.92	1.03	5.39	6.33	5.19	9.97	6.31
MnO	.18	.15	.13	.23	.18	.17	.22	.22
MgO	.30	.35	.20	4.94	8.00	6.74	7.33	45.71
CaO	1.33	2.05	1.30	7.67	10.90	8.56	11.50	.63
Na_2O	5.74	4.35	4.34	2.43	2.70	3.01	1.70	.01
K_2O	2.60	2.81	3.86	.92	.20	1.00	.12	Nil
P_2O_5	.050	.11	.05	.28	.23	.13	.02	.005
H_2O+	.13	.09	.08	.66	.36	.31	.12	.25
H_2O-	.48	.40	1.07	.15	.23	.09	.16	2.28
Total H_2O	.61	.49	1.15	.81	.59	.40	.22	2.53
CO_2	< .10	< .10	< .10	.20	< .10	.40	.26	< .10
S	.011	.005	Nil	.003	.005	.010	.056	.004
Total	99.3	99.6	99.3	98.5	98.7	99.0	100.3	101.1