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Preliminary Geological Findings on the BP-1 Simulant

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LIST OF ACRONYMS

BP-1	Black Point 1
Ca	calcium
$CaSO_4 \cdot 0.5H_2O$	bassanite
CIPW	Cross, Iddings, Pirsson, and Washington
CO_2	carbon dioxide
Fe:Mg	iron:magnesium
Fe_2O_3	ferric oxide
FeO	ferrous oxide
HEPA	high-efficiency particulate air
IHO	Industrial Hygiene Office
JSC	Johnson Space Center
K_2O	potassium oxide
KSC	Kennedy Space Center
MSDS	Material Safety Data Sheet
Na_2O	sodium oxide
NaCl	halite (table salt)
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
RATS	Research and Technology Studies
SiO_2	silicon dioxide

LIST OF ACRONYMS (Continued)

TiO_2	titanium oxide
TM	Technical Memorandum
USGS	United States Geological Survey
XRD	x-ray diffraction
XRF	x-ray fluorescence

TECHNICAL MEMORANDUM

PRELIMINARY GEOLOGICAL FINDINGS ON THE BP-1 SIMULANT

1. INTRODUCTION

The following is a summation of information and discussion between Doug Stoeser of the USGS and Doug Rickman of NASA in February and March 2010 pertaining to the Black Point 1 (BP-1) simulant. The analytical results and the bulk of the text are from communications from Dr. Stoeser. Their form and final content, as presented in this Technical Memorandum (TM), are the responsibility of Doug Rickman. Information on particle size distribution provided by Laila A. Rahmatian and health recommendations from Greg Galloway of Kennedy Space Center's (KSC's) Industrial Hygiene Office (IHO) are also included.

The BP-1 simulant is made from the Black Point basalt flow, San Francisco Volcanic Field, in northern Arizona. The Black Point flow is about 60 miles (100 km) NNE of Flagstaff, AZ just east of state highway 89. It is over 40-km long and one of the younger flows of the San Francisco Volcanic Field (Pliocene age). In contrast, the Johnson Space Center (JSC)-1 and -1A simulants are made from Merriam Crater, an ash cone volcano in the San Francisco Field, and have a different composition.[1]

There is an aggregate (road metal) quarry on the northern margin of the flow towards the west end (fig. 1) that was used as a Desert Research and Technology Studies (Desert RATS) analog test site. The quarry site also contains piles of silt-sized washing waste that was included in the testing.[2] This silty material was also used in laboratory tests and found to have geotechnical properties similar to the NU-LHT-2M and Chenobi regolith simulants and is being proposed as a possible simulant for geotechnical use.[2] It currently has the designation of BP-1.

Figure 1. The Black Point basalt lava flow as seen with Google Earth. The location of an aggregate quarry and two USGS geochemical samples sites is also shown.

2. CHEMICAL COMPOSITION

The United States Geological Survey (USGS) National Geochemical Database contained two whole rock analyses of the Black Point flow (tables 1 and 2). The Black Point basalt is fairly alkaline (fig. 2) (i.e., it has high total alkalis ($Na_2O + K_2O$) and chemically is typical of continental basalts). The flow also has a high iron:magnesium (Fe:Mg) ratio relative to most basalts. As is the case with terrestrial alkaline basalts, it has a somewhat elevated titanium oxide (TiO_2) content of 2.2–2.3%. The high alkali content relative to lunar basalts possibly precludes the Black Point basalt from being appropriate for simulants where composition is a critical aspect, but the high Fe:Mg ratio is mare-like. These issues have nothing to do with BP-1 as a geotechnical material.

In figure 1, note that the flow distinctly changes color laterally from black to dark brown going eastwards and is distinctly brown at its east end (at its toe), suggesting oxidation of the basalt in that area. The eastern W172154 analysis seems to reflect a very high Fe_2O_3:FeO ratio relative to the W172158 western analysis. Fortunately, the quarry is located near the west end and thus in a good location to minimize oxidation in the simulant.

Under the direction of Robert Mueller, samples from five different 1-ton lots of BP-1 were taken. From each split, a <10-µm split was provided to the USGS. Table 3 compares the x-ray fluorescence (XRF) chemical analysis of the <10-µm splits of BP-1 versus the database values for the flow. The higher calcium (Ca), magnesium (Mg), and carbon dioxide (CO_2) values are compatible with secondary minerals as indicated by other observations.

Table 1. Whole rock major element geochemistry with normative mineralogy for the Black Point flow from the USGS National Geochemical Database <http://mrdata.usgs.gov/geochemistry/ngdbrock.html>.

Sample	W172158	W172154
Latitude	35.67	35.67
Longitude	–111.47	–111.35
SiO_2	47.2	46.9
Al_2O_3	16.7	16.4
TiO_2	2.3	2.2
Fe_2O_3	5.9	8.2
FeO	6.2	3.7
MgO	6.5	5.6
MnO	0.21	0.21
CaO	9.2	9.6
Na_2O	3.5	3.4
K_2O	1.1	1.1
P_2O_5	0.52	0.51
H_2O–	0.11	0.51
H_2O+	0.41	0.69
CO_2	0.05	0.26
Total	99.90	99.28
FeO_{total}	11.7	11.4
% An	47.1	46.7

Table 2. CIPW cation normative minerals.

Sample	W172158	W172154
orthoclase	6.6	6.7
albite	30.3	31
anorthite	27	27.1
nepheline	0.9	0.4
diopside	12.7	14.9
olivine	14.2	11.6
magnetite	4	4
ilmenite	3.2	3.2
apatite	1.1	1.1

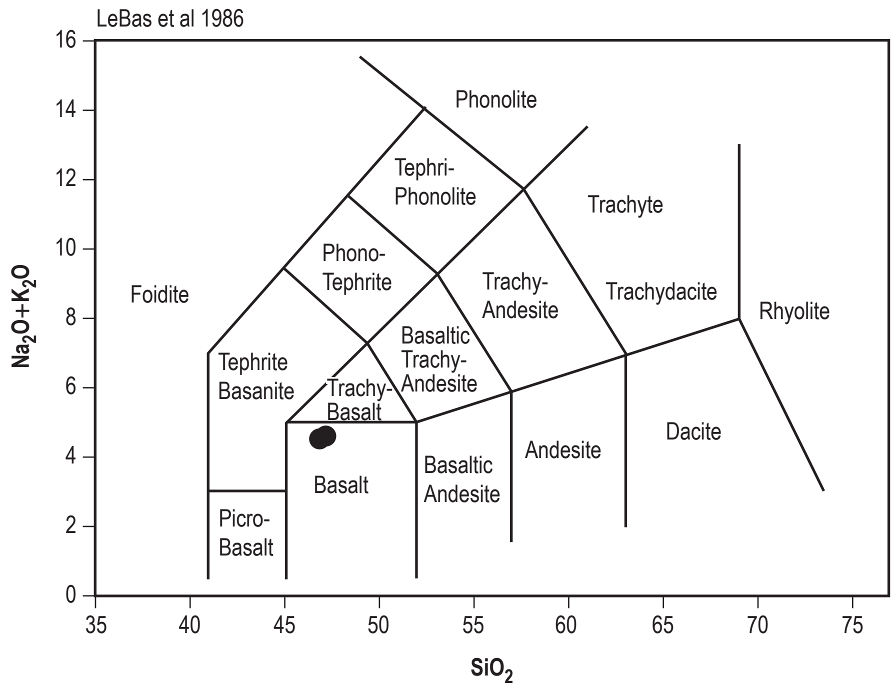

Figure 2. Total alkali versus SiO_2 rock type classification diagram.

Table 3. XRF analyses of BP-1 splits.

	Bag 1	Bag 2	Bag 3	Bag 4	Bag 5	Bag All	W172158	W172154
Fe_2O_3	11	11	11	13	9	11	11.7	11.4
CaO	13	13	13	12	14	14	9.2	9.6
K_2O	0	0	0	0	0	0	1.1	1.1
SO_2	0	0	0	2	1	0	–	–
SiO_2	45	44	44	43	45	44	47.2	46.9
Al_2O_3	16	18	18	16	17	17	16.7	16.4
MgO	10	7	7	9	9	8	6.5	5.6
Na_2O	3	4	4	4	2	3	3.5	3.4
CO_2	1	2	2	1	2	3	0.05	0.26
Total	99	99	99	100	99	100	95.95	94.66

3. MINERALOGY

A small hand sample of the source rock was provided to Dr. Stoeser. He visually characterized it as an amygdaloidal basaltic material. The amygdules are filled with secondary minerals containing opaline silica, calcium carbonate, and ferric iron minerals based on hand examination of a limited sample. The formal petrography of the Black Point basalt and the BP-1 quarry waste remains to be determined.

An x-ray diffraction (XRD) analysis of a bulk simulant sample provided to the USGS yielded the preliminary data presented in table 4.

Table 4. XRD of bulk BP-1 simulant.

Mineral	Weight %
Labradorite	60.7
Augite $FeCa_4Si_8Mg_{2.96}O_{24}$	23.7
Quartz	1.7
Magnetite	3
Calcite	2.7
Olivine	6.2
Hematite	2

Calcite and quartz and possibly some or all of the hematite are not primary minerals. They are derived from weathering or alteration of the original basalt.

From each of the <10-µm splits, an XRD analysis was done. The results of these analyses are given in table 5. For the most part, the mineralogy is typical for a basalt plus a small amount of quartz, calcite, and hematite. Depending on the mineral (i.e., well separated peaks in the XRD spectrum), the XRD results are good down to 2–3%, and thus the numbers for the minor phases are only approximate. The plagioclase composition fitted to the spectrum has the composition An_{65} (i.e., $Ca_{0.65}Na_{0.32}(Al_{1.62}Si_{2.38}O_8)$). The pyroxene augite spectrum matches the composition $(CaMg_{0.74}Fe_{0.25})Si_2O_6$.

That differences exist between the single bulk sample and the <10-µm splits is not surprising. Plagioclase is apparently much more abundant in the whole than the splits. Conversely, olivine is more abundant in the splits than in the whole sample. The source of the differences is unexplained. As the whole sample analysis is preliminary and unverified, conclusions on this topic should be withheld.

Table 5. XRD summary table for <10-µm splits of BP-1 in weight %.

Mineral	Bag 1	Bag 2	Bag 3	Bag 4	Bag 5	Bag All
Primary Minerals						
Plagioclase	50	53	48	49	48	48
Augite	17	13	11	15	15	14
Olivine	14	10	8	13	12	11
Nepheline	3	3	2	2	1	2
Magnetite	8	7	6	10	5	6
Total Primary	92	86	75	89	81	81
Secondary Minerals						
Quartz	3	3	0	3	3	3
Hematite	2	3	2	2	2	4
Calcite	3	5	9	1	–	7
Muscovite (sericite)	0	3	5	0	5	5
Halite	1	2	5	3	1	1
Bassanite	0	0	3	4	2	2
Total Secondary	9	16	24	13	8	22

There are apparently substantial variations in the mineralogy of the samples. The variation in calcite, from 9 wt. % to nil, and variation of olivine, from 14 to 8 wt. %, are probably real. Chemically, the basalt is such that it should not have any primary silica (quartz); note the presence of nepheline. So the quartz is almost certainly all secondary and coming primarily from vesicle fillings and possibly seams. The total secondary minerals in the <10-µm splits range from 9 to 24%, which is high. The secondary minerals may be concentrating in the fine fractions used to make the BP-1 simulant because of the how they occur in the source rock and the way the rock is processed.

Of special note are the bassanite $CaSO_4 \cdot 0.5H_2O$ and halite (NaCl). The halite, common table salt, was confirmed by washing the material with distilled water, which removed the salt. Halite is not a constituent of basalts, neither is bassanite. It is hypothesized that the wash water used at the quarry probably comes from a saline aquifer. With reuse of the water, the dissolved salts will concentrate and eventually start to precipitate minerals.

4. PARTICLE SIZE

Rahmatian and Metzger provide particle size and several geotechnical measures of the BP-1 material.[2] Figure 3 is provided courtesy of these authors.

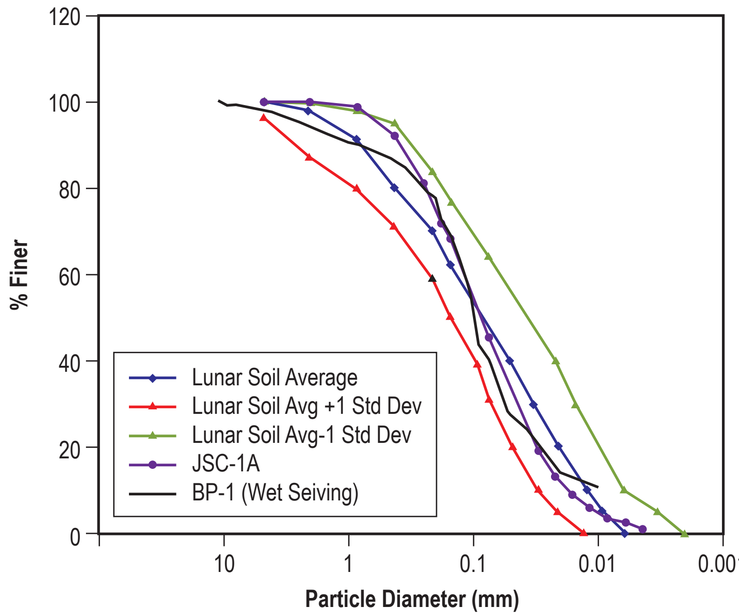

Figure 3. Cumulative frequency less than a given particle size for BP-1 and JSC-1A compared to lunar values. Reproduced with permission from work done by Laila A. Rahmatian and Philip T. Metzger.

An alternative plot of the same data is given in figure 4. To make this plot the first derivative of the source data behind figure 3, abundance versus particle size was computed. BP-1 has an unusual distribution. It has a large percentage in a narrow range while it also contains relatively high amounts of fine and coarse particles. The significance of such a distribution for any application of the simulant is unknown. In some respects, when compared to other simulants, it is likely that this broad distribution will yield a superior performance for some mechanical or geotechnical applications. The abundance of fine particles is certainly a concern for health applications should they become airborne.

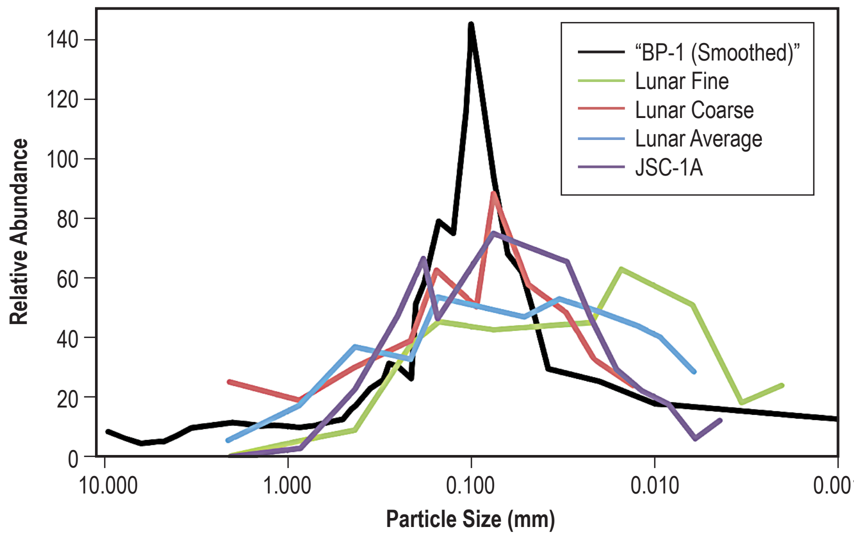

Figure 4. Abundance versus particle size for BP-1 and JSC-1A compared to lunar values.

5. HEALTH

The following information is abstracted from a report done by the IHO at KSC.[3] The IHO was asked to evaluate the BP-1 material for possible use in a “sandbox” trial, a use that would involve students. The office performed bulk sampling of 10 1-ton bags. Using a certified laboratory, the samples were evaluated according to the National Institute for Occupational Safety and Health (NIOSH) 7500 standard method using XRD. The purpose of the evaluation is to measure the abundance of three polymorphs of SiO_2, cristobalite, quartz, and tridymite. These minerals are causative agents for the disease called silicosis. The report states that all 10 sample results contain between 0.57 and 2.9 wt. % cristobalite and up to 2.3 wt. % quartz.

Geologically, the cristobalite values are highly improbable for two reasons. First, the source rock is a nepheline basalt, which means the melt was undersaturated with respect to SiO_2. Had more SiO_2 been available in the liquid, more plagioclase would have been formed. Only with substantially more dissolved SiO_2 than occurs in this source rock will a discrete SiO_2 phase form. Second, cristobalite is a high temperature polymorph. In this rock, it would have to be a primary mineral (i.e., formed before the molten rock solidified completely). At Earth surface pressure, cristobalite’s stability field does not begin until approximately 1,470 °C, which is hotter than most lavas. Tridymite, which was not detected, forms in the range between approximately 900 and 1,470 °C. Thus, the NIOSH test is reporting the presence of a very high temperature phase without the intermediate temperature phase in a rock that is originally undersaturated with respect to SiO_2. The total amount of cristobalite plus quartz reported in the IHO report does correspond with the total quartz seen in the analyses by the USGS. As noted previously, the quartz in the BP-1 feedstock is a secondary mineral.

As a result of the mineralogical analyses and the particle size data for BP-1, the IHO recommended that personal protective equipment and controls be used. The measures recommended should be used until measurements of potential exposure could be obtained. Recommended controls exclude nonessential personnel from the area, provide a decontamination area with a high-efficiency particle air (HEPA) vacuum for equipment, a hand-wash area that can be utilized when exiting the box, and an eye-wash station was to be available. Recommendations for personnel protective equipment are presented in table 6, which is taken from the Galloway IHO report.[2]

The report states:

“The use of respiratory protection for judges must comply with OSHA Respiratory Standard 1910.134 to include medical certification, fit testing, and training. There is a duty under the OSHA Hazard Communication standard to communicate the potential hazards to all individuals who will be entering the lunar sandbox. Prior to entrance into the sandbox, each individual should receive a pretask briefing and an MSDS should be provided for review.”

Table 6. Personal protective equipment recommendations for Lunabotics preparation and competition.

Exposure Group	Estimated Exposure Frequency/Duration	Recommended Personal Protective Equipment
Students	Short term, as required estimated to be <45 min per day.	Filtering facepiece with N95, Tyvek suits and booties (or equivalent), dust goggles.
NASA	Several times per day. Additional exposure possible through continued work with sandbox.	Half-face respirator with P100 cartridge, Tyvek suits and booties (or equivalent), dust goggles.

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14. ABSTRACT

A waste material from an aggregate producing quarry has been used to make an inexpensive lunar simulant called BP-1. The feedstock is the Black Point lava flow in northern Arizona. Although this is part of the San Francisco volcanic field, which is also the source of the JSC-1 series feedstock, BP-1 and JSC-1 are distinct. Chemically, the Black Point flow is an amygdaloidal nepheline-bearing basalt. The amygdules are filled with secondary minerals containing opaline silica, calcium carbonate, and ferric iron minerals. X-ray diffraction (XRD) detected approximately 3% quartz, which is in line with tests done by the Kennedy Space Center Industrial Hygiene Office. Users of this material should use appropriate protective equipment. XRD also showed the presence of significant halite and some bassanite. Both are interpreted to be evaporative residues due to recycling of wash water at the quarry. The size distribution of BP-1 may be superior to some other simulants for some applications.

15. SUBJECT TERMS

lunar simulant, BP-1, source, chemistry, mineralogy, particle size, health

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