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SOME CHARACTERISTICS OF PELE'S HAIR

By WENDELL A. DUFFIELD, EVERETT K. GIBSON, Jr.,[1] and
GRANT H. HEIKEN,[2] Menlo Park, Calif., Houston, Tex., Los Alamos, New Mex.

Abstract.—Pele's hair is a filamentous variety of brown sideromelane glass that forms during eruption of basaltic lava. Strands of Pele's hair form from droplets of lava that are spun or stretched into filaments during quenching, and others may form as chilled streamers of lava. Common elongate vesicles, sometimes twisted, indicate extreme stretching and twisting during hair formation. Hair diameter ranges from about 1 to 300 micrometres. Refractive index of hairs decreases with hair diameter and is most probably a function of the process of formation rather than chemical composition. Masses of Pele's hair form natural spun-glass filters that trap small particles and serve as sites for sublimate deposition. Such deposition may begin even while hair is falling to the ground through an eruption fume cloud. Sublimates include carbonates, sulfates, sulfur, and less commonly hydrocarbons, thus complicating the interpretation of volatiles in Pele's hair in terms of original magmatic constituents. Vesicles, which provide the most nearly pure samples of magmatic volatiles, contain mostly H_2O and CO_2.

During vigorous gas-driven eruption of basaltic lava, a variety of pyroclastic materials may form, inincluding fine strands of brown sideromelane glass known as Pele's hair. Relatively little Pele's hair forms compared with the bulkier pyroclastic products, and much of this hair is quickly dispersed downwind during eruption. Masses of hair may collect around active vents, but these commonly are quickly covered by subsequent flows that may remelt the glass strands. Thus, there is little chance for the preservation of sizeable deposits of Pele's hair; such samples must be collected at the time of hair formation or shortly thereafter.

We collected several samples of Pele's hair that formed during eruptions of Kilauea Volcano in 1969–72. Most samples were only a few hours to several days old when collected; some were gathered while strands of Pele's hair, together with clots of spatter and scoria, fell on and around us downwind from lava fountains. Subsequent studies of hair morphology, refractive index, chemical composition, and sublimate coatings indicate that caution must be used in comparisons with bulkier though contemporaneous or closely allied eruption products.

HAIR FORMATION AND MORPHOLOGY

Near-surface acceleration due to expansion of gases (Shaw and Swanson, 1970) drives jets of basaltic lava that partly solidify in air to form droplets, irregularly shaped clots, and glass threads (Pele's hair). According to previous workers (Wentworth, 1938; Williams and McBirney, 1969; Heiken, 1972, 1974), Pele's hair forms from droplets that are stretched into threads. Hairs with attached droplets (fig. 1), known as Pele's tears, indicate that some strands form in this manner. Most strands are free of such droplets but have broken ends and thus may have formed from droplets or from chilled streamers of melt. Isard (1971) calculated that such streamers should break up into droplets only

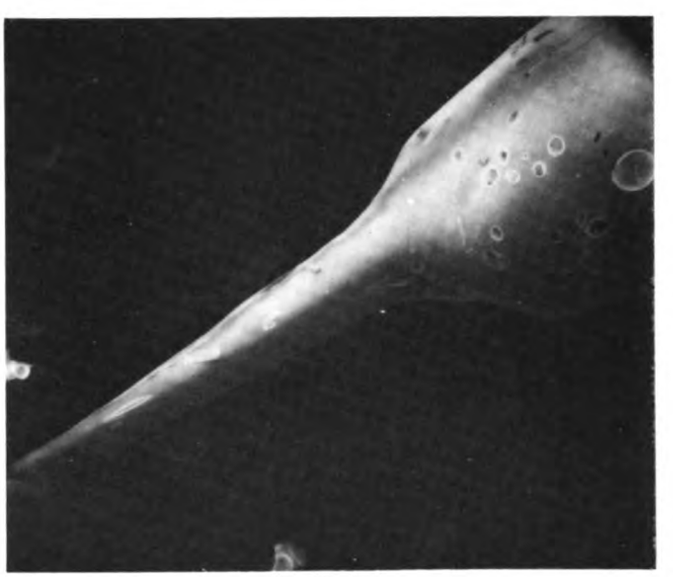

FIGURE 1.—Photomicrograph of hair attached to clot of spatter. Note roughly circular outline of exposed vesicles on clot and elongate outlines of those on hair, indicative of stretching during hair formation.

[1] National Aeronautics and Space Administration.
[2] Los Alamos Scientific Laboratory.

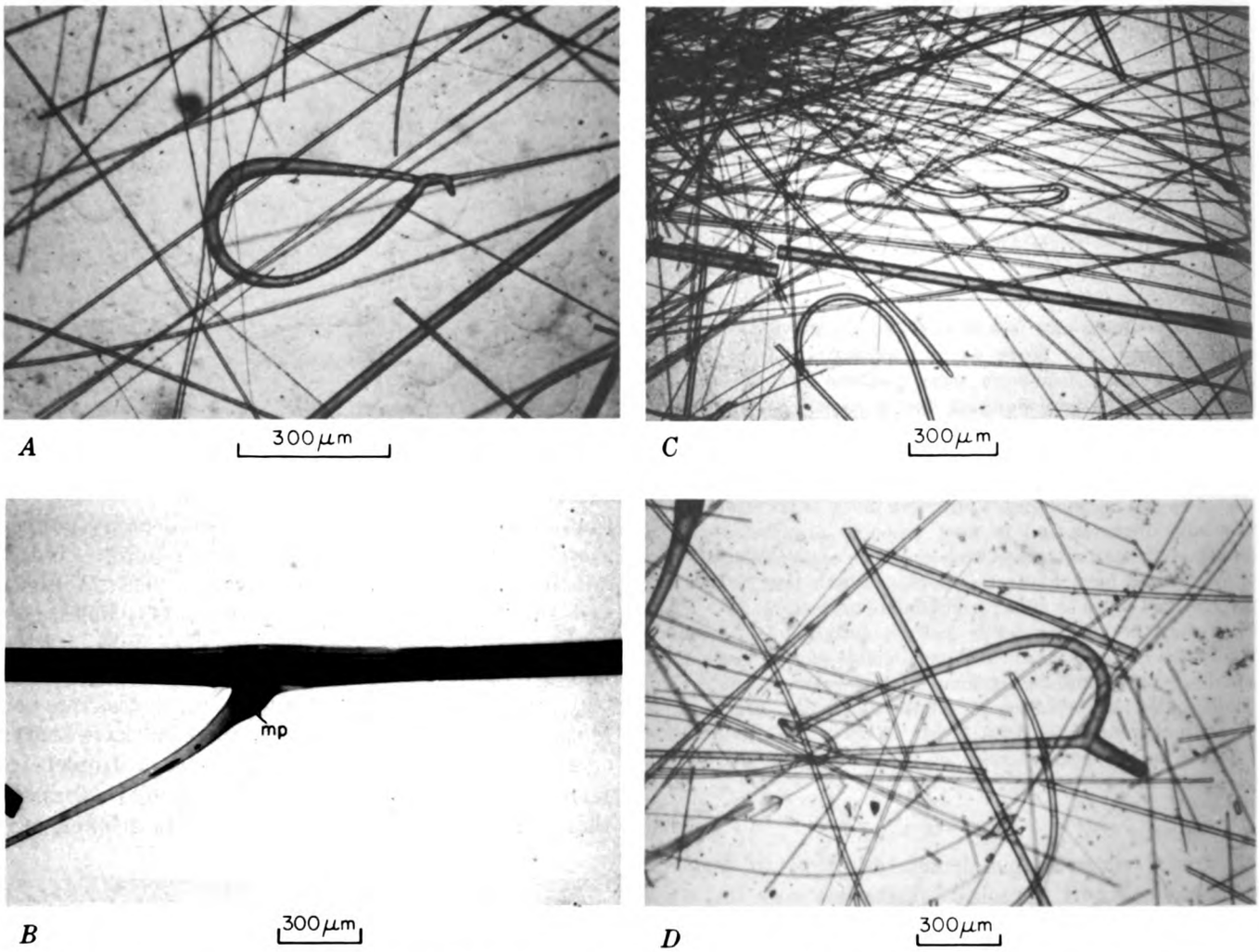

FIGURE 2.—Photomicrographs of Pele's hair showing common shapes. *A*, Closed loop. *B*. Branching. Note microphenocrysts (mp) where branch is attached to main hair, and small, nearly invisible branch between the two larger filaments. *C*, Mass of rods including S- and hook-shaped hairs. *D*, Tuning fork.

if the viscosity of the material is less than 10^3 poises, and the work of Shaw, Peck, Wright, and Okamura (1968) suggests that much of the lava at Kilauea has a viscosity of 10^3 poises or less during eruption. Observation of Kilauea lava fountains, however, typically indicates simultaneous formation of Pele's hair and droplets. The formation of all such particles probably is a complex process involving rapidly changing temperature (and therefore viscosity) in a turbulent, expanding eruption fountain that is not readily amenable to quantitative analysis.

We have also observed the formation of Pele's hair at a few-metres-high cascade in a lava river and at a lava falls plunging as much as 120 m through violent updrafts into a pit crater. Almost certainly, some Pele's hair forms wherever clots of low-viscosity lava are introduced into strong air currents, and because these conditions occur most frequently at erupting vents, most Pele's hair is formed there.

Pele's hair has been described by several earlier workers (for example, Krukenberg, 1877; Dana, 1891; Wentworth and Macdonald, 1953). Typically, Pele's hair is roughly circular in cross section with a diameter between about 1 and 300 micrometres. In detail, the basic cylindrical form exhibits numerous modifications, including bent, bifurcated, and pretzellike shapes, and changes in diameter as much as an order of magnitude either abruptly over lumps caused by microphenocrysts and vesicles or gradually from one end of a strand to another (fig. 2). The interiors of hairs are also varied. Solid glass cylinders occur, but spherical to elongate vesicles are common. Elongate vesicles form capillary-like tubes parallel to hair axes

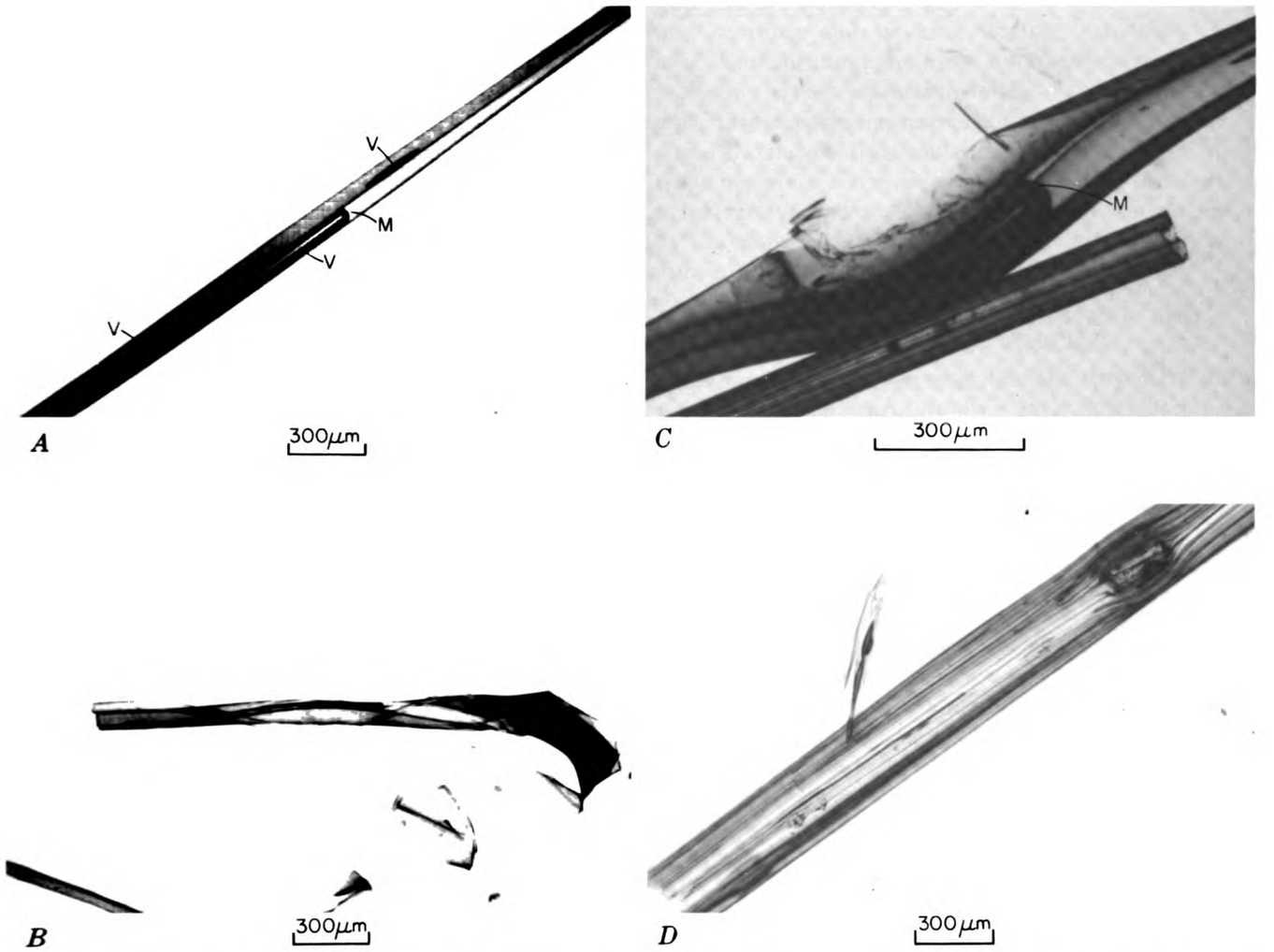

FIGURE 3.—Photomicrographs of Pele's hair with vesicles. *A*, Elongate vesicles (V) parallel to strand of hair. The longest vesicle was broken during sample preparation and partly filled with resin which formed a meniscus (M). *B*, Helical vesicle, indicative of twisting during hair formation. *C*, Thin-walled ovoid vesicle broken during mounting and longer vesicle with meniscus (M) in upper hair. End of lower hair shows pipelike shape caused by large near-axial vesicle. *D*, Highly ribbed surface caused by multiple, near-surface elongate vesicles. Vehicles curve around microphenocryst (mp) alined with long axis of hair.

and occur both singly and multiply, commonly producing a thin-walled tube or bundle of tubes (fig. 3).

At room temperature and pressure, vesicles contain a partial vacuum, but at higher temperatures vesicles burst and release mostly H_2O and CO_2. Abundant vesicles probably indicate initial high volatile content of the magma.

Some strands contain single crystals or clots of crystals as phenocrysts or microphenocrysts that commonly cause lumps in hair of otherwise rather uniform diameter. The longest dimension of a crystal generally is alined with the hair axis (fig. 3*D*). Both elongate vesicles and alined crystals attest to extreme stretching during the process of hair formation. The capillary vesicles suggest axial strain of several orders of magnitude relative to a presumably spherical gas bubble present in the lava before the stretching and solidification associated with hair formation. Helical vesicles also indicate some twisting (fig. 3*B*).

REFRACTIVE INDEX AND CHEMICAL COMPOSITION

The refractive indices of the glassy parts of about 90 samples of Pele's hair, spatter, pumice, and lava flows that formed during the 1969–71 Mauna Ulu eruption (Swanson and others, 1971) are summarized in figure 4. The range in refractive index shown by all types of materials is 0.031, although most values fall between 1.599 and 1.606, a range of only 0.007. Almost without exception, the refractive index of fine

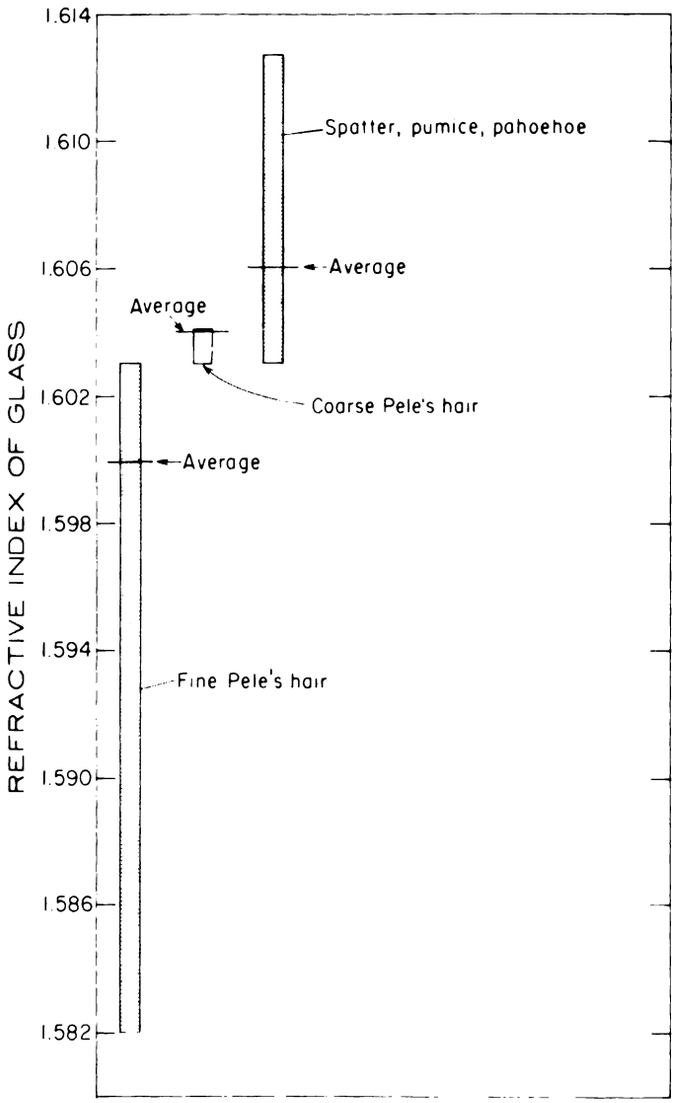

Figure 4.—Refractive indices of glassy parts of eruption products formed during 1969–71 eruption of Mauna Ulu, Kilauea Volcano, Hawaii. Indices were determined with sodium light in immersion oils that were checked periodically with an Abbey refractometer and corrected for temperature. Error of determination is estimated to be ±0.002. Samples were washed in distilled water to remove sublimate coating and then hand crushed. Only broken interior surfaces were used for refractive-index determinations.

hair (arbitrarily defined as less than about 75 μm in diameter) is less than that of coarse hair which in turn is less than that of most of the bulkier materials. These relations are further illustrated by examination of contemporaneous eruption products.

Thirteen sets of contemporaneous eruption products were obtained by hand sorting field-collected masses of Pele's hair into fine hair, coarse hair, and droplets that were attached to some strands of hair or clots of spatter caught in the mass of hair. Without exception, for each set of contemporaneous products, the finest material has the lowest refractive index (fig. 5). Furthermore, the hair of smallest diameter (sample PH–9) has the lowest refractive index of all studied material. In general, unambiguous intersample comparisons between refractive index and minimum dimension of particles are precluded by the estimated standard error (±0.002) in refractive-index determination and overlap in hair size caused by normal variation in diameter, even along individual hairs. Nonetheless, the consistency of the data (fig. 5) indicates that a direct relation between refractive index and the original minimum dimension of particles exists for all studied samples.

The refractive index of glass from fused or naturally glassy volcanic rock is commonly used to determine the silica content of the glass (George, 1924); silica increases as refractive index decreases. The refractive indices of a sample of Pele's hair (1.598) and droplets (1.604) broken from the ends of this hair suggest that the droplets are relatively poor in silica. However, chemical analyses (table 1) show that, within analytical precision, silica content is nearly the same for these two contemporaneous materials. Many electron microprobe analyses for silicon, iron, and magnesium were made along individual strands of Pele's hair that showed great axial variation of diameter. No measureable changes in these elements were found along these strands (B. A. Morgan, oral commun., 1973), thus suggesting variation in refractive index is caused by something other than major-element chemistry.

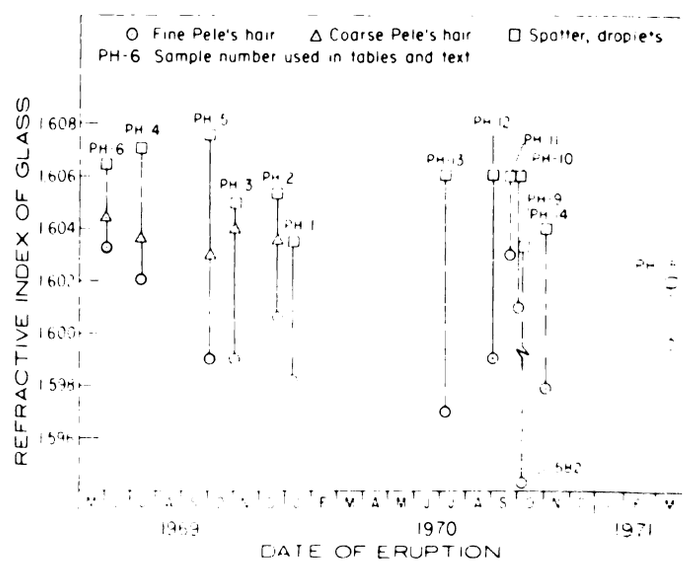

Figure 5.—Refractive indices of contemporaneous glassy eruption products of differing original dimension.

TABLE 1.—*Chemical analyses of Pele's hair (PH–1) and droplets (PH–18) broken from this hair*

[Analytical methods are described in Shapiro and Brannock (1962), supplemented by atomic absorption tests; analyst, P. L. D. Elmore]

	PH-1	PH-1S
SiO_2	50.6	50.7
Al_2O_3	13.7	13.0
Fe_2O_3	.60	.90
FeO	10.0	10.0
MgO	7.6	9.5
CaO	11.3	10.0
Na_2O	2.2	1.9
K_2O	.51	.41
H_2O^+	.27	.37
H_2O^-	.06	.00
TiO_2	2.3	2.1
P_2O_5	.30	.28
MnO	.18	.19
CO_2	.02	.01
	99.60	99.40

Ross and Smith (1955, 1961) have shown that the refractive index of volcanic glass is a function of water content and state of oxidation of iron, as well as silica content. The presence of hydrated minerals, as firmly attached sublimate coatings, and vesicles that contain water vapor precluded a test of possible control of refractive index by differences in water content of the glass itself. Change in refractive index related to oxidation state of iron is also untested, but it seems unlikely that oxidation state of iron in Pele's hair and attached droplets would differ much if at all. Well-known properties of manmade glass fibers suggest that the refractive index of Pele's hair is primarily a function of the manner in which the hair formed.

Manmade glass fibers have many properties that differ from bulk glass of the same composition (Weyl and Marboe, 1964). For example, tensile strength is higher, and the density and refractive index are lower (Slayter, 1952). These differences are attributed to marked contrasts in the cooling histories of fiber versus bulk glass, with solidification under stress (Weyl and Marboe, 1964) and relatively high rates of cooling (Slayter, 1952) as important factors in determining the properties of the fibers. The shapes of Pele's hair and its contained vesicles attest to extreme stretching, bending, and twisting during formation of the hair. Furthermore, the most finely attenuated strands have the lowest refractive index, which is consistent with the idea that rate of cooling as well as state of stress during cooling controls refractive index of the resulting glass. Thus we suggest that our observations of refractive index of Pele's hair are best explained by the manner in which hairs form, with only possible minor effects related to chemical composition.

SUBLIMATES ON HAIR SURFACES AND VOLATILES IN VESICLES

Masses of Pele's hair that line the throats of fumaroles or rest on warm fuming lava flows become encrusted with sublimates. Generally, hair collected only minutes after its formation shows some surficial crusts, presumably deposited from the fume cloud through which the hair drifted to the surface. After a few hours in percolating fume, hairs may become completely coated (fig. 6*A*, 6*B*). Such sublimates may cement masses of hair together and may also cement tiny basaltic spheres to strands of hair (fig. 6*C*). We studied the volatile constituents in these sublimate coatings using the methods of Gibson (1973; 1974). Briefly, we heated samples to about 1,400°C at a rate of 6°C per minute in a vacuum of 2×10^{-6} torr and routed all evolved volatiles into a mass spectrometer for identification during heating. Near the melting temperature, vesicles burst, releasing additional volatiles that also were analyzed by the spectrometer. The weight of all samples was recorded continuously during heating. Most of the weight lost below 800°C represents the release of volatiles from sublimate minerals, whereas that lost above 800°C represents mostly degassing of the basaltic glass. Typical gas release profiles are shown in figure 7. These profiles differ depending principally upon the amount and variety of sublimate material present.

Microscopic examination of sample PH–10 shows that almost no sublimate material coats these hairs. During heating, only traces of volatiles were evolved below the melting point (fig. 7*A*). About 300 parts per million of adsorbed water was released around 100°C (see H_2O spike of fig. 7*A* and percentage weight lost in table 2), and a continuous diffusional loss of water occurred between 150° and 500°C. The release of CO_2 (30–60 ppm CO_2) between 400° and 600°C suggests traces of carbonates on hair surfaces. At the melting point of the glass (1130°±10°C), CO_2 and traces of CO were released suddenly, indicating the rupture of one or more gas-filled vesicles. Total weight loss was 2.31 percent after heating to 1400°C (table 2), with only 0.57 percent lost during heating to 800°C.

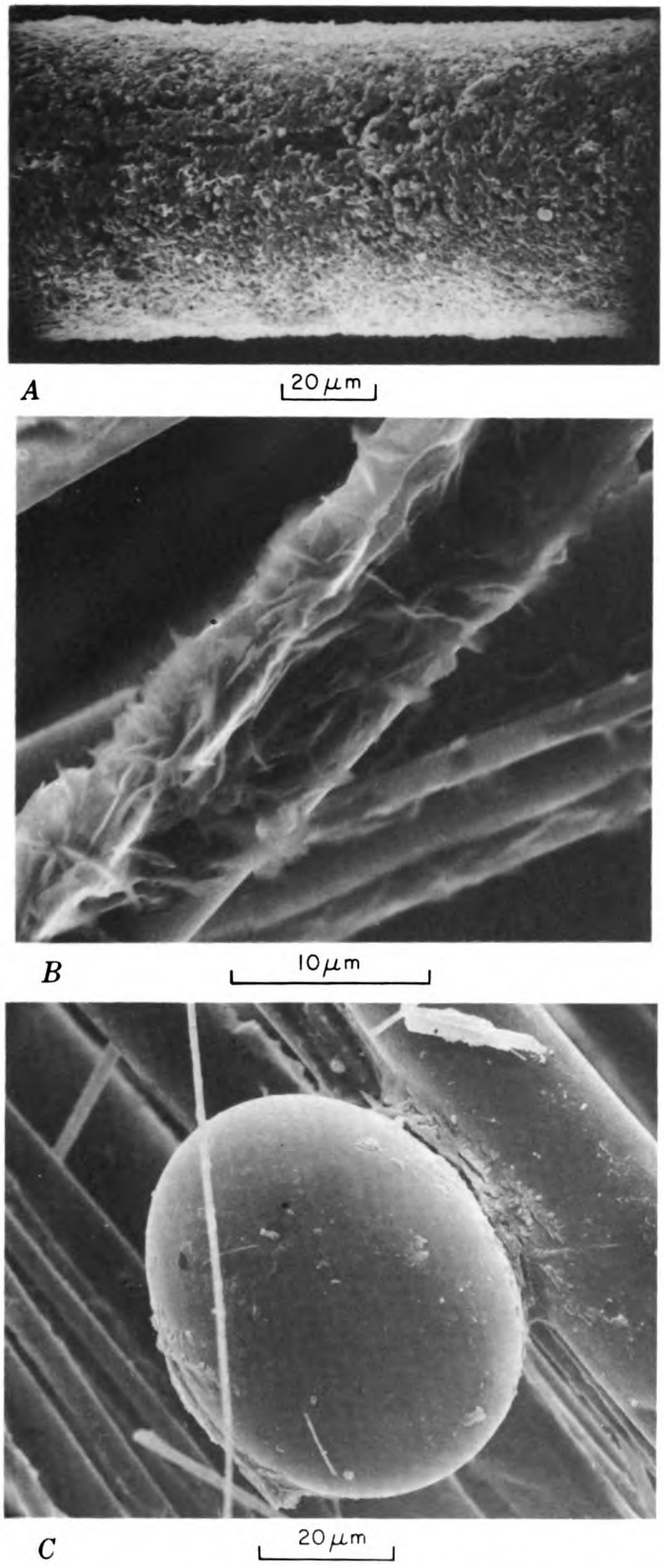

FIGURE 6.—Scanning electron micrographs of Pele's hair. *A*, Strand of hair almost completely coated with sublimate crust. *B*, Hair with feathery sublimate deposit (sulfur?) *C*, Small basaltic sphere cemented to Pele's hair by sublimate. Photomicrographs *B* and *C* by R. B. Finkelman.

Pele's hair in sample PH–14 is moderately crusted with sublimates. About 0.35 percent by weight of adsorbed water was released below 200°C (fig. 7*B*). The release of CO_2 between 400° and 550°C indicates a carbonate phase(s) in the sublimate crust. Similarly, the presence of a sulfate phase(s) is indicated by the release of SO_2 between 400° and 550°C (gypsum?). Elemental sulfur was released between 650° and 900°C. Total weight loss was 3.44 percent upon heating to 1400°C, and melting occurred at 1130° ± 10°C (table 2).

Pele's hair in sample PH–9 is completely coated with sublimates (fig. 6*A*). Below 300°C nearly 0.65 percent water was released (table 2 and fig. 7*C*). Methane and other hydrocarbons were released between 150° and 250°C. As with PH–14, the release of CO_2 and SO_2 between 400° and 550°C indicates the presence of carbonate and sulfate phases in the sublimate crust. A second release of CO_2 between 600° and 700°C suggests the presence of another carbonate phase, and additional CO_2 at about the melting temperature suggests gas release from vesicles. Microscopic sulfur crystals were melted and released as S_2 gas between 750° and 1000°C. Total weight loss was 7.03 percent after heating to 1400°C, with melting at 1120° ± 10°C.

DISCUSSION

Descriptions of the gas-release profiles for all studied samples are listed in table 3. The most extensively crusted samples give complex gas-release profiles that indicate the presence of sulfur, carbonates, sulfates, and in two samples, hydrocarbons in this crust, whereas hair with virtually no sublimates releases mostly H_2O and CO_2.

Gases released from such fresh uncrusted hair should represent a reasonably pure sample of the gases escaping from the lava at the time of eruption. Muenow (1973), reporting on gas-release studies of Pele's tears from eruptions of Kilauea in 1970–71, noted that the typical gas released from Pele's tears contained about 95 percent H_2O, 3.5 percent CO_2, 1 percent SO_2 (mole percent compositions), and traces of organic constituents. The gas release profiles for Pele's hair with sublimate coating are most similar to the profiles reported by Muenow (1973), suggesting that his samples included sublimates. In particular, samples of fresh Pele's hair did not evolve CO_2 as did Muenow's samples for the temperature interval 700°–800°C, and methane and other hydrocarbons were present only in Pele's hair that was heavily crusted with sublimates. Apparently the surfaces of small particles of volcanic glass are sites for the condensation and deposition of a wide variety of low-temperature minerals, even as

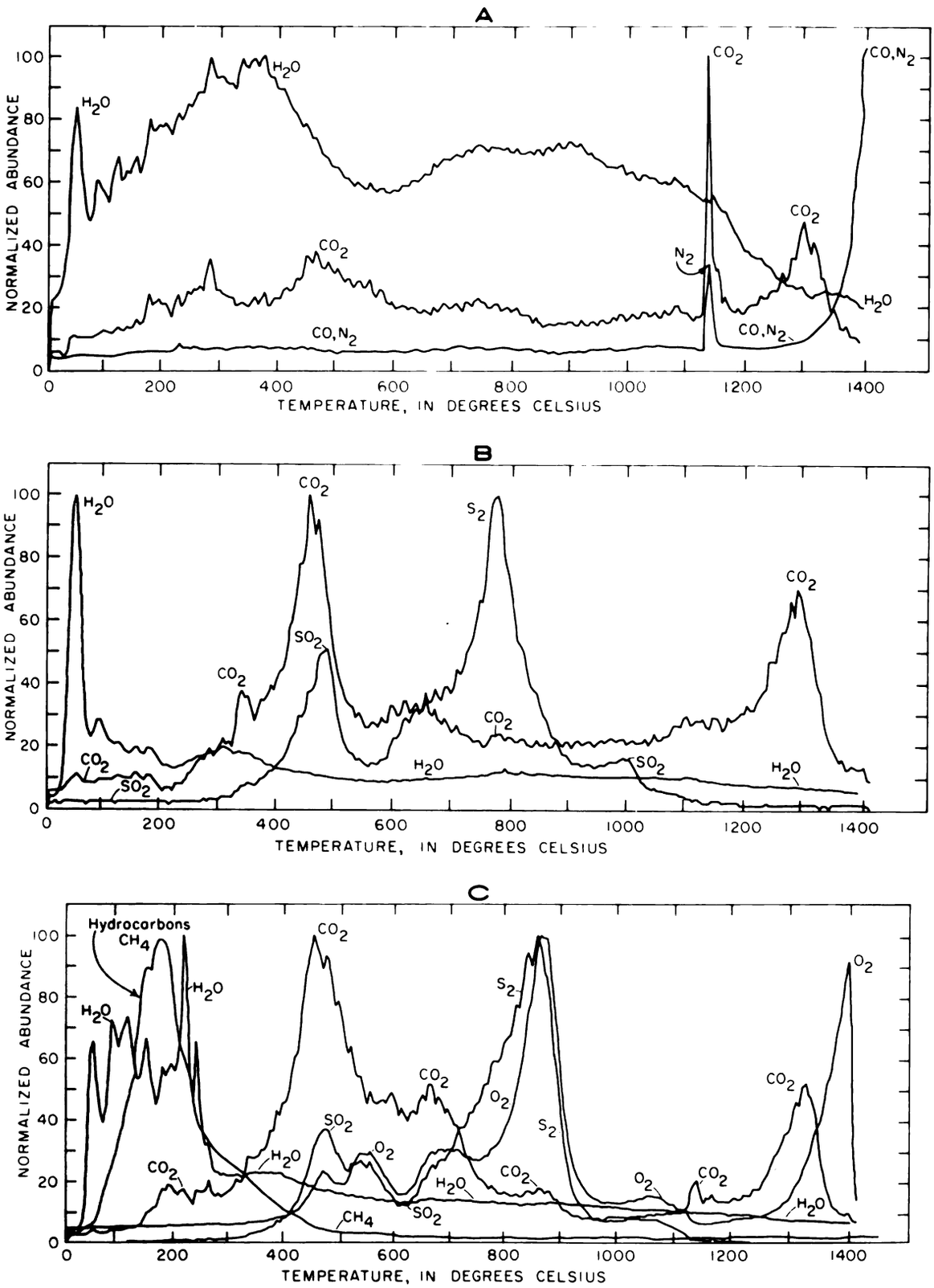

Figure 7.—Gas-release profiles of Pele's hair. See table 3 for further discussion. *A*, PH–10, virtually no sublimates. *B* PH–14, moderately coated with sublimates. *C*, PH–9, extensively coated with sublimates.

TABLE 2.—*Percentage weight lost from Pele's hair during heating at 6°C per minute under a vacuum of about 2×10^{-4} torr*

Sample No.	PH-5	PH-6	PH-9	PH-10	PH-14	PH-15	PH-23	PH-87	PH-87
Initial weight (milligrams)	112.43	124.38	105.02	121.68	111.76	86.28	153.76	157.69	159.07
Sublimate coating	Heavy	Virtually none	Heavy	Virtually none	Moderate	Moderate	Moderate	Heavy	Moderate
100°C	0.044		0.200	0.0329	0.231	0.336	0.026	0.044	0.006
200°C	0.133	0.008	0.646	0.107	0.351	0.406	0.052	0.082	0.013
300°C	0.276	0.016	0.932	0.230	0.411	0.533	0.098	0.127	0.019
400°C	0.480	0.040	1.179	0.296	0.642	0.684	0.124	0.165	0.019
500°C	0.720	0.048	2.053	0.403	0.899	1.159	0.150	0.203	0.031
600°C	0.872	0.064	2.595	0.452	0.976	1.298	0.156	0.228	0.044
700°C	0.960	0.096	3.013	0.510	1.122	1.425	0.228	0.247	0.063
800°C	1.085	0.129	3.412	0.567	1.259	1.553	0.280	0.292	0.088
900°C	1.218	0.169	4.230	0.608	1.404	1.669	0.306	0.336	0.126
1000°C	1.352	0.209	4.620	0.641	1.482	1.820	0.325	0.387	0.157
1100°C	1.565	0.346	4.857	0.740	1.610	2.121	0.442	0.476	0.258
1200°C	1.717	0.474	5.066	0.896	1.756	2.295	0.559	0.615	0.427
1300°C	2.144	0.981	5.504	1.282	2.175	2.747	0.891	0.964	0.780
1400°C	3.184	2.484	7.034	2.309	3.442	4.080	1.840	1.915	1.854
Melting point, ±10°C	1130°C	1120°C	1120°C	1130°C	1130°C	1120°C	1120°C	1120°C	1120°C

those particles are cooling and solidifying during eruption. Thus, interpretation of the origin of gases released on later examination is difficult.

CONCLUSIONS

Pele's hair forms by extreme stretching and twisting of lava as it cools and solidifies. This process of formation affects the refractive index of the resulting glassy strands in such a way that the refractive index decreases with diameter of the hair.

Masses of Pele's hair have a high ratio of surface area to weight and serve as natural spun-glass filters that trap small particles and provide sites for deposition of sublimate materials. Such deposition begins during initial descent of hair through its eruption fume cloud and may eventually account for as much as several percent of the total weight of a hair sample. The volatile constituents released on heating indicate that carbonates, sulfates and elemental sulfur are the most common sublimates. Water vapor and carbon dioxide are the most common volatiles released from hair with little or no sublimate coating.

Katsura (1967) believed that Pele's hair is the only material that represents a quenched sample of Hawaiian basaltic magma. It is true that Pele's hair is probably the most rapidly quenched subaerial eruption product, but the property that allows such rapid quenching (extremely small particle size) promotes similarly rapid contamination of the material; within days or hours weathering and contamination may advance to the stage at which it is virtually impossible to expose fresh interior. Bulkier glassy eruption products, such a lapilli-sized spatter, provide far better material for sampling quenched magma.

REFERENCES CITED

Dana, J. D., 1891, Characteristics of volcanoes: Dodd, Mead, and Co., New York, 399 p.

George, W. O., 1924, The relation of the physical properties of natural glasses to their chemical composition: Jour. Geology, v. 32, p. 353–372.

Gibson, E. K., Jr., 1973, Thermal analysis–mass spectrometer computer system and its application to the evolved gas analysis of Green River shale and lunar soil samples: Thermochim. Acta, v. 5, no. 3, p. 243–255.

——— 1974, Gas release study of selected volcanic ashes, *in* Heiken, G. H., An atlas of volcanic ash: Smithsonian Contr. Earth Sci., no. 12, p. 15–35.

Heiken, G. H., 1972, Morphology and petrology of volcanic ashes: Geol. Soc. America Bull., v. 83, p. 1961–1988.

——— 1974, An atlas of volcanic ash: Smithsonian Contr. Earth Sci., no. 12, 101 p.

TABLE 3.—*Descriptions of Pele's hair studied in heating experiments*

Sample Number	Site of formation	Type of activity	Date of collection	Maximum time between formation and collection	Volatiles released during heating
PH-5	Mauna Ulu	degassing lake	Sept. 29, 1969	21 hours	Water was the major gaseous phase released below 200°C and amounted to 1100-1300 ppm. Between 250 and 400 C sample lost 0.35% by weight, mostly CO_2 with traces of CO, O_2, and H_2O. Between 350° and 600°C, CO_2 from a carbonate and SO_2 from decomposition of a sulfate were released and amounted to 0.39% weight loss. After loss of low-temperature condensates sample was essentially depleted of volatiles other than reaction products formed at high temperatures. Large amounts of hydrocarbons with fragments of mass 41 were released between 250° and 400°C.
PH-6	do.	active fountain	May 27, 1969	Several hours	Sample contained a trace (less than 10-20 ppm) of H_2O adsorbed on surface, but had no surface condensates as indicated by lack of volatiles released below 800°C. Only 0.13 weight percent was lost upon heating to 800°C and only 2.48% after heating to 1400°C (with 1.5% being lost between 1300 and 1400°C).
PH-9	1/2 km S.E. of Mauna Ulu	cascading stream	Oct. 1, 1970	24 hours	Below 300°C, H_2O was the major gas phase released (around 0.65 weight percent). Between 150° and 250°C, methane was released. Release of CO_2 and SO_2 between 400° and 550°C indicates decomposition of carbonate and sulfate. A second release of CO_2 occurred between 600° and 700°C. Between 750° and 1000°C S_2 was evolved whereas SO_2 evolved at lower temperatures. The sulfur results from melting of sulfur crystals observed on surfaces of hair.
PH-10	Mauna Ulu	active fountain	Oct. 1, 1970	24 hours	Trace quantities of water (less than 20 ppm H_2O) were evolved around 100°C. A diffusion controlled loss of H_2O occurred between 150° and 500°C. Traces of sublimate carbonate are indicated by release of small amounts of CO_2 between 400° and 600°C. At melting point of glass (1130°C) CO_2 and a trace of CO were released suddenly, suggesting rupture of gas-filled vesicles.
PH-14	do.	do.	Oct. 29, 1970	24 hours	Unusually large amounts of water (0.35 weight percent) were released below 200°C. CO_2 from decomposition of carbonate was evolved between 400° and 550°C. Sulfate minerals decomposed between 440°c and 550°C and between 650° and 900°C. Both SO_2 and S_2 were evolved at higher temperatures.
PH-15	do.	degassing lake	June 16, 1971	3 months	Gas release profile is almost identical to that of PH-14. Below 200°C sample lost 0.41% water. Decomposition of sublimate carbonate and sulfate occurred between 400° and 750°C. Loss of S_2 and traces of SO_2 occurred between 850° and 1100°C. Near melting, sudden release of CO_2 and traces of CO indicated vesicle rupture.
PH-23	Kilauea Caldera	active fountain	Aug. 14, 1971	None-immediate collection	Trace of adsorbed water was released below 150°C. Sudden release of H_2O at 200°C suggests rupture of vesicles. Between 200° and 300°C vesicles containing H_2O and CO_2 ruptured causing "spikes" on gas release profiles. Evolution of SO_2 between 500° and 800°C suggests traces of sublimate sulfates, and traces of CS_2, probably a reaction product, were evolved between 700° and 1000°C. At melting point of glass (near 1120°C), CO_2 with traces of CO was released suddenly, indicating vesicle rupture.
PH-87	Rim of Makaopuhi Crater	120-m lava falls into crater	June 11, 1972	1 day	Traces of adsorbed H_2O, CO_2, CO and/or N_2 were evolved at low temperatures, and about 130 ppm H_2O was released by diffusion between 240° and 450°C. Traces of SO were evolved between 400° and 900°C and traces of CS_2 between 700° and 900°C. Additional SO_2 was evolved between 1000° and 1120°C and probably was a product of reaction between sulfur-bearing phases and silicates of the glass.

Isard, J. O., 1971, The formation of spherical glass particles on the lunar surface: Second Lunar Sci. Conf. Proc., Geochim et Cosmochim. Acta Suppl., 3, v. 3, p. 2003–2008.

Katsura, Takashi, 1967, Pele's hair as a liquid of Hawaiian tholeiitic basalts: Geochem. Jour., v. 1, p. 157–168.

Krukenberg, C. F. W., 1877, Mikographie der Glasbasalte von Hawaii [Micrography of basaltic glass from Hawaii]: Tubingen, 38 p.

Muenow D. W., 1973, High temperature mass spectrometric gas-release studies of Hawaiian volcanic glass: Pele's tears: Geochim. et Cosmochim. Acta, v. 37, no. 6, p. 1551–1561.

Ross, C. S., and Smith, R. L., 1955, Water and other volatiles in volcanic glasses: Am. Mineralogist, v. 40, p. 1071–1089.

——— 1961, Ash-flow tuffs: Their origin, geologic relations, and identification: U.S. Geol. Survey Prof. Paper 366, 81 p.

Shapiro, Leonard ,and Brannock, W. W., 1962. Rapid analysis of silicate, carbonate, and phosphate rocks: U.S. Geol. Survey Bull. 1144–A, p. A1–A56.

Shaw, H. R., Peck, D. L., Wright, T. L,. and Okamura, R., 1968, The viscosity of basaltic magma: An analysis of field measurements in Makaopuhi lava lake, Hawaii: Am. Jour. Sci., v. 266, p. 225–264.

Shaw, H. R., and Swanson, D. A., 1970, Eruption and flow rates of flood basalts: Second Columbia River Basalt Symp. Proc., Eastern Washington State College, Cheney, Wash., Mar. 21–23, 1969, Eastern Washington State College Press, p. 271–299.

Slayter, Games, 1952, Strength of glass: Am. Ceramic Soc. Bull., v. 31, no. 8, p. 276–278.

Swanson, D. A., Jackson, D. B., Duffield, W. A., and Peterson, D. W., 1971, Mauna Ulu eruption, Kilauea Volcano: Geotimes, v. 16, no. 5, p. 12–16.

Wentworth, C. K., 1938, Ash formations of the Island of Hawaii: Hawaiian Volcano Observatory, 3rd Spec. Rept., 183 p.

Wentworth, C. K., and Macdonald, G. A., 1953, Structures and forms of basaltic rocks in Hawaii: U.S. Geol. Survey Bull. 994, 98 p.

Weyl, W. A., and Marboe, E. C., 1964, The constitution of glasses: A dynamic interpretation: Vol. 2, Part 1 *of* Constitution and properties of some representative glasses: John Wiley and Sons, New York, p. 429–892.

Williams, Howel, and McBirney, A. R., 1969, An investigation of volcanic depressions, Pt. I, Airfall and intrusve pyroclastic deposits, and Pt. II, Subaerial pyroclastic flows and their deposits: U.S. Natl. Aeronautics and Space Adm. Research Grant NGR–38–003–012, prog. rept., 100 p.

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