Analyses of *in-situ* airborne volcanic ash from the February 2000 eruption of Hekla Volcano, Iceland

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[1] A McDonnell-Douglas DC-8 NASA research aircraft inadvertently flew into an airborne volcanic ash plume from the 26 February 2000 eruption of Hekla Volcano. Filter samples from the aircraft were compared with "normal use" and "pristine clean" filters using SEM, energy-dispersive x-ray spectrometer, and Nicolet FTIR spectrophotometer analyses. These analyses confirm that the DC-8 encountered airborne volcanic ash from Hekla Volcano. This result is supported by independent onboard heated aerosol observations at the time of the encounter. The analyses further demonstrate the ambiguous nature of the dual band thermal IR ("split window") method for detecting volcanic ash from the point of view of aviation safety. They also highlight the utility of *in situ* aircraft filter-based observations of volcanic aerosols for scientific purposes. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0370 Atmospheric Composition and Structure: Volcanic effects (8409); 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 8404 Volcanology: Ash deposits; 8409 Volcanology: Atmospheric effects (0370); 3954 Mineral Physics: X ray, neutron, and electron spectroscopy and diffraction

1. Introduction

[2] *In situ* sampling of airborne volcanic ash at high altitude is an operationally difficult problem, but is of crucial scientific importance for understanding the dynamics and chemistry of volcanic plume aerosols, and for validation of existing ash plume detection algorithms. A recent airborne encounter provided just such a unique *in situ* opportunity, despite damage to the aircraft.

[3] A NASA DC-8 research aircraft studying arctic ozone during the Sage-3 Ozone Loss and Validation Experiment (SOLVE) inadvertently flew into an airborne volcanic ash plume from the 26 February 2000 eruption of Hekla Volcano, Iceland (64°N 19.7°W). The crew knew of the eruption and adjusted their flight plan to avoid the ash hazard, but plume position predictions were inaccurate [*Simpson et al.*, 2001]. At 76°N 00°W, about 700 nautical miles north of the northernmost predicted position of the ash plume (73°N 05°W at 27 Feb 0900Z), the aircraft penetrated it on 28 February at 0510Z at an altitude of 37,000 feet ASL. During the encounter, there were no visible exterior manifestations (e.g., St. Elmo's fire, windscreen abrasion). No apparent abrasive damage occurred to other exterior flight surfaces. On board instruments, however, registered increased SO_2 and decreased O_3 abundances [*Miller et al.*, 2000].

[4] Since volcanic ash can cause significant damage to turbine engines and compromise flight safety [e.g., *Miller and Casadevall*, 1999], upon arrival at Kiruna, Sweden, the engines were inspected, and, the engine oil and filters on all four engines were replaced. Oil and filter samples were saved for later analysis. Air conditioning filters that we analyzed were also replaced. When the DC-8 returned to Edwards AFB, California, (68 flight hours later), detailed analyses were undertaken. A spectral (SOAP) analysis was conducted on the retained samples, revealing elemental sulfur in the oil of all four engines at a concentration of about 500 ppm (normal range <1 ppm). Detailed engine bore-scope analyses indicated engine damage, including cooling holes plugged by melted ash, and erosion of leading edge coatings on turbine blades. A previous bore-scope analysis conducted in early December 1999 revealed no such phenomena. As the DC-8 flew only two post-bore-scope round trips to Sweden in December 1999 and January 2000, both without incident, the observed damage clearly occurred as a result of the February 2000 ash plume encounter. The degree of damage was severe enough that all four engines were sent to the General Electric (GE) Corporation facility in Kansas for refurbishment.

[5] This note describes our analyses of particulate samples recovered from the DC-8 air conditioning system, from the DC-8 engines during teardown by GE, and a comparison to airfall samples from the same eruption. Our goals are to determine the nature of the volcanic aerosols ingested by the DC-8 engine, to elaborate on the technique used to analyze these aerosols, and to provide an in-situ reality check on "split-window" retrievals [e.g., *Holasek and Rose*, 1991]. [Not shown is a preliminary SEM analysis of a single sample from the DC-8 Keddeg filter (*Simpson et al.*, 2001a). This paper extends and confirms the earlier preliminary result.]

2. Analyses

[6] The McDonnell-Douglas DC-8 aircraft ingests air into its main cabin cooling system through two crescent-shaped ducts just below and about one meter rearward of its nose. Ducting then leads ram air to a Keddeg #22010 fiber filter (trapped particles typically $\sim$1–10 μm in size). We conducted electron microscopic imaging and energy-dispersive x-ray spectrometer (EDS) analyses on several pre- and post-encounter filter samples using a Camscan Series II Scanning Electron Microscope at the Analytical Facility of the Division of Geological and Planetary Sciences, the California Institute of Technology. The instrument, operated at 15 keV, has an Everhart-Thornley detector for secondary-electron imaging, a Robinson-type backscattered electron detector for atomic-number-contrast imaging (working resolution $\approx$100 nm), and a Link pentafet SiLi.

[7] Back-scattered electron micrographs of three Keddeg #22010 filters are reproduced at low and high magnifications (150X and 1500/2000X). These include a pristine unused filter (Figures 1a and 1d); a "normal use" filter (Figures 1b and 1e); and the "encounter filter" (Figures 1c and 1f). The relatively low-magnification electron micrograph (150X) of the "encounter filter" (Figure 1c) is typical of over 50 scans that were made on a variety of particles. Carbon was employed as the electron dispersive coating to enhance x-ray spectra transmission. Note the variety of aggregated small particulates ($\sim$1–10 μm) adhering to the larger fibers (10–30 μm). Aggregation in volcanic plumes occurs through collision, binding, and breakup of solid and liquid

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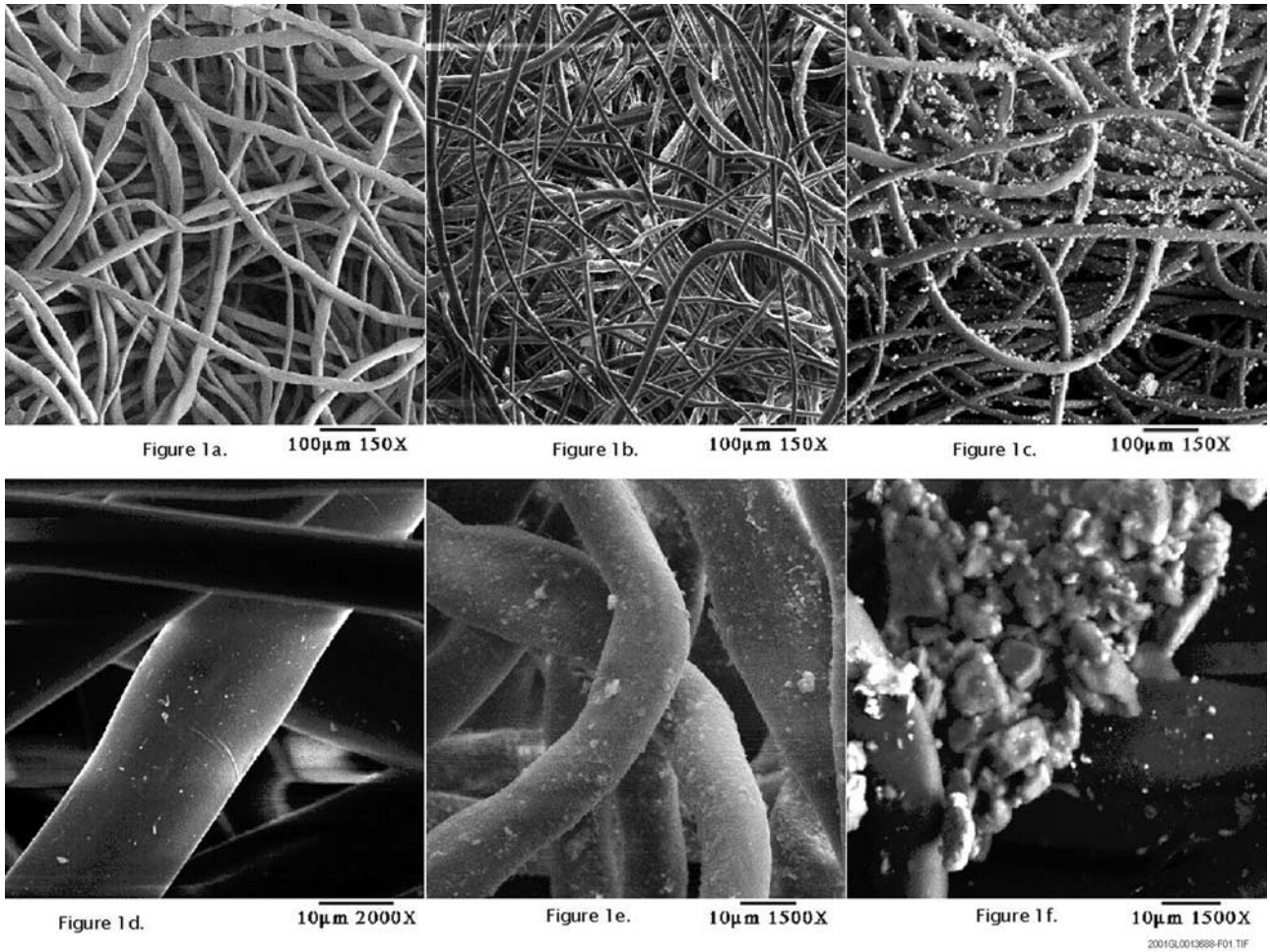

Figure 1. SEM images of the NASA DC-8 Keddeg #22010 fiber filters: (a) unused, (b) ''normal use'' (c) recovered after the Hekla encounter. Panels (d, e, and f) correspond to panels (a, b, and c), respectively, except at higher magnification.

phases, binding by capillary forces, growth of secondary minerals and ice crystals, mechanical interlocking, Van der Waals forces at small spatial scales (<1 μm), and, by strong electrostatic forces on dry particles [*Sparks et al.*, 1997, p. 448–449]. The observed aggregates are characteristic of volcanic ash vigorously convected within a Plinian eruption column. The fine grain size is consistent with sorting after lofting to high altitude (e.g., 40Kft ASL) and transport over hundreds of km.

[8] Figure 1f is a high magnification image of two representative aggregated clumps on the ''encounter filter'' (Figure 1c). The polyphase aggregates are about 20 μm in diameter. An EDS spectrum from this cluster (Figure 2a) shows atomic abundances that are consistent with the composition of andesitic basalt and with values quoted for Hekla ash, in particular [*Ólafsdóttir and Sigmundsson*, 2001]. Importantly, the airborne ash elemental abundances also follow those that we measured for airfall ash samples from the same 26 February 2000 eruption of Hekla (Figure 2b).

[9] EDS spectra, acquired from other grains found on the ''encounter filter'' (Figures 2c and 2d), exhibit similar compositions. The spectrum in Figure 2c displays the characteristics of a silica-rich glass. It is characteristic of volcanic glass shards. A somewhat more diverse spectrum (Figure 2d), possibly of one or more micro-crystalline fragments, has strong K-alpha signatures for Si, Al, Fe, Ni, and Cr (other Hekla 26 February airfall eruption grains also exhibit noticeable Ni and Cr peaks).

[10] Note all three spectra from airborne ash show a strong S peak. Since a substantial SO_2 signature was observed for this eruption by the TOMS instrument, the presence of S is consistent with the hydrolysis of SO_2 within the volcanic column and plume, and the eventual deposition of a sulfate phase onto the airborne grains, thus further confirming the volcanic nature of these particulates.

[11] Two additional Keddeg #22010 fiber filters from the NASA DC-8 aircraft, one a pristine unused filter (Figures 1a and 1d), the other with 3000 flight hours of essentially ''normal use'' (Figures 1b and 1e), also were analyzed. The SEM image of the ''normal use'' filter (Figures 1b and 1e) indeed shows small particulates adhering to individual filter fibers. They are typically smaller (<1–5 μm) than the grains shown in Figures 1c and 1f, and their size distribution appears more uniform. Their EDS spectra indicate an atomic composition of Si, Al, Cr, Fe, Ni, with no appreciable sulfur signature, in contrast to the grains acquired during the plume encounter. The ''normal use'' grains show no evidence of aggregation. The ''unused filter'' (Figures 1a and 1d) has only a few tiny ($\ll$1 μm) particles of organic material adhering to the filter.

[12] Three additional particulate grab samples were also subjected to SEM analyses: (1) a black glassy particulate sample scraped from the interior of one of the NASA DC-8 engines that had ingested material from the Hekla plume; (2) a brown particulate sample that also originated from one of the contaminated engines; and (3) a light brown particulate sample from a random GE jet engine, typifying the material that is extracted by GE in a ''normal use'' engine teardown. EDS spectra revealed potential volcanic signatures in both the black glassy material and the dark brown material, but no volcanic signature in the ''normal use'' sample.

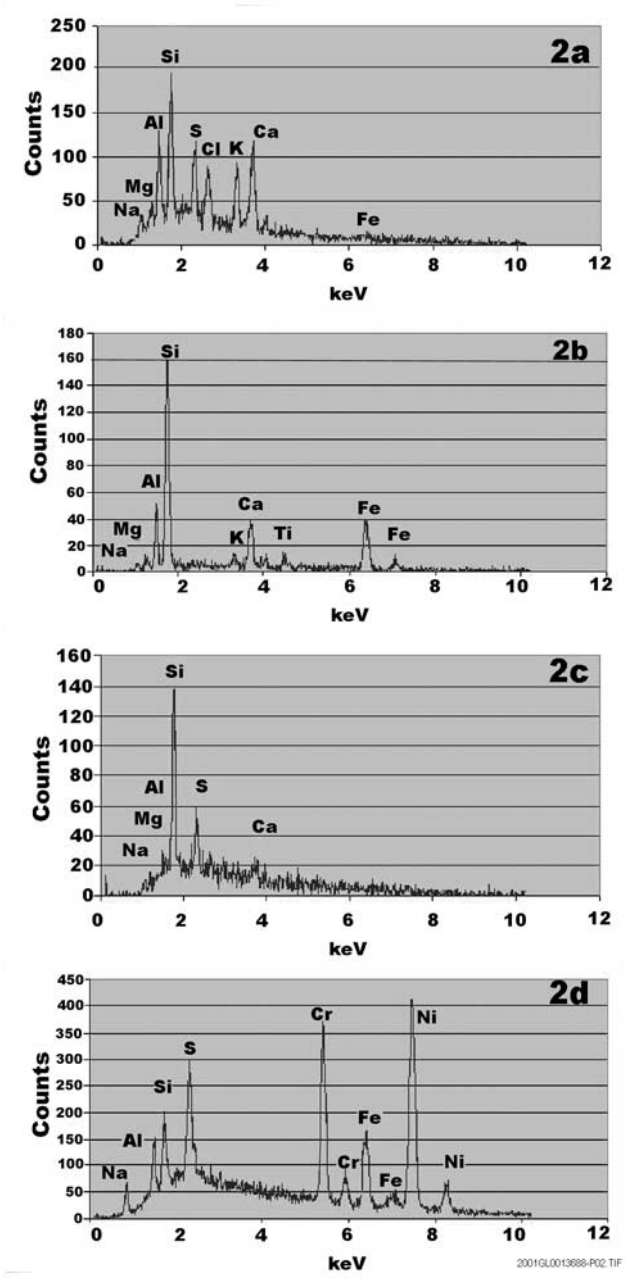

Figure 2. EDS spectra (a) corresponds to aggregate clumps in Figure 1f. Panel (b) is the spectrum from the Hekla airfall ground sample. Panels (c) and (d) are analogous to panel (a), except for different samples.

[13] We also measured the hemispherical reflectance of all filter samples between 2.08 and 15 μm using a Nicolet FTIR spectrophotometer. A residual spectrum due to a visually obvious dark contaminant was extracted using a linear spectral mixing model and compared to spectra from the "normal use" and pristine filter. Results from this analysis are broadly consistent with a 48–50% areal coverage of the Keddeg filter by predominately andesitic basalt particles <75 μm in characteristic dimension.

3. Discussion

[14] The February 28th encounter raises obvious air safety questions and highlights the opportunity for *in-situ* ash data acquisition to verify existing volcanic plume trajectory models (e.g., Puff, VAFTAD, CANERM) and orbital thermal IR image-based ash plume detection algorithms [e.g., *Holasek and Rose*, 1991]. Some outstanding questions are: (1) what caused the discrepancy between the predicted plume position and the actual plume position at the time of the encounter in one of the most heavily trafficked air corridors in the world; (2) does this encounter reveal an inherent weakness of the current warning system; (3) to what degree was the ash spectral signature (and thus the airborne hazard) identified by AVHRR split-window detection algorithms; (4) was the damage sustained by the aircraft caused by ash ingestion or pre-existing and thus moot; and (5) if ash caused the damage, how do the engine damage and in-situ samples validate plume position and aerosol loading estimates and interpretations based on remote sensing? *Rose et al.* [2000], for example, claim that an observed positive "split-window" thermal anomaly in AVHRR data indicates that the NASA DC-8 probably encountered only water ice crystals and not volcanic ash, while *Miller et al.* [2000] report that a solid aerosol residuum was recovered from in-situ heated aerosol recovery experiments onboard the DC-8. The residuum was identified by them as volcanic ash. It is also worth noting that a bore-scope examination of the DC-8 engines in December 1999 revealed no foreign material, and that there were only two incident-free intervening flights after that examination and before the Hekla encounter.

[15] Accurate prediction of ash plume trajectories depends ultimately on a variety of volcanological and meteorological factors (e.g., the Canadian Emergency Response Model [CANERM], *Pudykiewicz* [1989]). It is crucial that ash trajectory models be accurately initialized in order to work properly, especially with respect to ash vertical and horizontal extent. Incorrect altitude initialization can introduce gross errors whenever altitude-dependent wind shears (common in the Arctic and sub-Arctic) are present [*Simpson et al.*, 2002]. Incorrect altitude initiation was also the culprit here [*Simpson et al.*, 2001].

[16] Recognizing the incorrect prediction of plume position (a theoretical issue), one might try to detect the presence of airborne ash using the established AVHRR/GOES-based "split-window" ash detection algorithm (an empirical observation). Unfortunately, in this case, an observed positive thermal anomaly implied that no threat existed because positive "split window" anomalies are associated with meteorological clouds and/or ice crystals [*Yamanouchi et al.*, 1987].

[17] Our data and analyses confirm that the DC-8 did ingest volcanic ash. Our SEM filter analyses demonstrate the presence of intensely aggregated shard-like particulates predominately in the range of 1–10 μm, typical for ash lofted distally to high altitude. The intense aggregation is consistent with high electrostatic charging of the particles typical for intense convective disturbances, such as occur in eruption plumes. The strong presence of S in the EDS spectra, along with strong peaks for Si, Al, Mg, Fe, K, Ca, and other elements typically present in mafic minerals found in volcanic rocks confirms a volcanic provenance for the observed grains.

[18] The presence of sulfur is especially important because the normal natural background level for this element is quite low, except in the volcanic context. Other non-volcanic silicate and non-silicate particulates were also detected on the "encounter filter," as would be expected from normal usage. In contrast, the "normal use" (non-encounter) Keddeg filter shows only very fine (<1 μm) single particles adhering to the filter. There is no observed aggregation, implying that these particles are probably electrostatically neutral. Chemically, there is nearly no indication of sulfur. Thus, we interpret these particles to be essentially non-volcanic particulates, resident as dilute aerosols at high altitude (>10,000 m) for periods long enough to have dissipated any significant electrostatic charge.

[19] The Nicolet infrared spectral analyses of the "encounter filter" surface supports the SEM analysis. The weaker volcanic

ash chemical signature in the engine grab samples almost certainly reflects the intense heat-treatment and melting and mixing with pre-volcanic particulates that occurred within the DC-8 engines. Nevertheless, one glassy black shard-like particulate residue from the affected engines strongly resembles obsidian.

[20] Given that the DC-8 did ingest ash from the Hekla plume, what caused the misleading positive "split-window" anomaly? It appears that rapid entrainment of advected moisture (either ambient water vapor from below the tropopause or magmatic/phreatic water) caused the formation of ice coatings on volcanic particles as they entered the stratosphere over Iceland during the eruption [*Simpson et al.*, 2001]. Given the low Moh-scale hardness of ice relative to that of silicates, ice coatings on ash particles markedly reduce their abrasive impact damage to aircraft exteriors. The silicate cores of such poly-phase particles, however, still present a severe ingestion hazard to turbine engines, as evidenced by this encounter [also see *Simpson et al.*, 2002].

4. Conclusions

1. Damage suffered by the NASA DC-8 aircraft was caused by the ingestion of andesitic basaltic ash lofted by the 26 February 2001 eruption of the Hekla Volcano, which contradicts results from other investigators [e.g., *Rose et al.*, 2000].

2. The positive "split-window" thermal anomaly seen in AVHRR data was most likely caused by the masking of the ash spectral signature by volume dilution or by direct coating of ice on volcanic particulates.

3. Points (1) and (2) emphasize that the split window ash detection algorithm does not detect all airborne ash which can be dangerous from the point of view of aviation safety. In this case, the large positive brightness temperature differential implied the airspace was safe when indeed the airspace was dangerous.

4. SEM analyses of aircraft filters recovered after volcanic plume encounters can provide valuable information about the nature of airborne volcanic materials, and thus an additional source of *in-situ* data.

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References

Holasek, R. E., and W. I. Rose, Anatomy of 1986 Augustine Volcano eruptions as recorded by multispectral images processing of digital AVHRR weather satellite data, *Bull. Volc.*, *53*, 420–435, 1991.

Miller, T. M., D. E. Hunton, J. O. Ballenthin, and A. A. Viggiano, In-Situ CIMS Measurements of SO_2, H_2SO_4, HNO_3, HF, HCl, and HCN in a Lower Stratospheric Volcano Plume, *Eos Trans. AGU*, *81*(48), *Abs. V61B-12*, 2000.

Miller, T. P., and T. J. Casadevall, Volcanic ash hazards to aviation, in *Encyclopedia of Volcanoes*, edited by H. Sigurdsson, B. Houghton, S. R. McNutt, H. Ryman, and J. Stix, Academic Press, San Diego, pp. 915–930, 1999.

Ólafsdóttir, R., and F. Sigmundsson, The Nordic Volcanological Institute, Reykjavik, Iceland, http://www.norvol.hi.is/hekla.html, 2001.

Pudykiewicz, J., Simulation of the Chernobyl dispersion with a 3-D hemisphere tracer model, *Tellus*, *41B*, 391–412, 1989.

Rose, W. I., G. J. Bluth, C. M. Riley, I. M. Watson, T. Yu, and G. J. Ernst, Potential Mitigation of Volcanic Cloud Hazards using Satellite Data—a Case Study of the February 2000 Hekla Event and an Unexpected NASA DC8 encounter, *Eos Trans. AGU*, *81*(48), *Abst. V61B-09*, 2000.

Simpson, J. J., G. L. Hufford, D. Pieri, and J. Berg, Failures in detecting volcanic ash from a satellite-based technique, *Rem. Sens. Environ.*, *72*, 191–217, 2000.

Simpson, J. J., G. L. Hufford, D. Pieri, and J. Berg, Response to Comments on 'Failures in detecting volcanic ash from a satellite-based technique', *Rem. Sens. Environ.*, *78*, 347–357, 2001.

Simpson, J. J., G. L. Hufford, D. Pieri, R. Severanchx, J. Berg, and C. Bauer, The February, 2001 Eruption of Mt. Cleveland, Alaska: Case Study of an Aviation Hazard, in press, *Weather and Forecasting*, 2002.

Sparks, R. S. J., M. I. Bursik, S. N. Carey, J. S. Gilbert, L. S. Glaze, H. Sigurdsson, and A. W. Woods, *Volcanic Plumes*, John Wiley & Sons, New York, 574 pp., 1997.

Yamanouchi, T. K., K. Suzuki, and S. Kawaguchi, Detection of clouds in Antarctica from infrared multispectral data of AVHRR, *J. Met. Soc. Japan*, *65*, 949–961, 1987.

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