VOLCANIC HAZARDS ASSESSMENT

Committee on Earth Observation Satellites (CEOS)
Disaster Management Support Project

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EXECUTIVE SUMMARY

Volcanoes pose a serious threat to persons on the ground near erupting volcanoes (due to proximal hazards such as lava flows, mud flows, ash fall, etc). Ash clouds from major eruptions endanger aircraft and airport operations over distances of thousands of kilometers. Remote sensing has become an indispensable part of the global system of detection and tracking of the airborne products of explosive volcanic eruptions via a network of Volcanic Ash Advisory Centers (VAACs) and Meteorological Watch Offices (MWOs). Visible and InfraRed (IR) satellite data provide critical information on current ash cloud coverage, height, movement, and mass as input to aviation SIGnificant METerological (SIGMET) advisories and forecast trajectory dispersion models. Recent research has also shown the potential of remote sensing for monitoring proximal hazards such as hot spots and lava flows using geostationary and polar InfraRed (IR) data. Also, Interferometric Synthetic Aperture Radar (InSAR) imagery has been used to document deformation and topographic changes at volcanoes. However, limited spatial and temporal resolution of available satellite data means that, for most proximal hazards, it is used mainly as supplemental information for current eruptions, and post-disaster assessment in mitigation and prevention of future disasters.

Spectral bands used in detection of volcanic ash and surface-based hazards are identified in this report. They include a variety of IR bands, especially those centered near 4, 7.3, 8.5, 11 and 12 microns. Visible (0.5 - 1.0 micron) and dual ultraviolet (UV) (0.3 - 0.4 micron) channels, although limited to daytime use, are valuable for qualitative assessment of ash and sulfur dioxide (SO_2) plume coverage, and quantitative estimation of ash optical depth, ash cloud top height (through parallax techniques) and total mass of silicate ash and SO_2. The minimum spectral channels needed for effective remote sensing of volcanic hazards are specified in the report and recommendations, as are threshold and optimum spatial resolutions and frequencies. Similar requirements are proposed for some important derived products (ash cloud height, ash column mass, and SO_2 concentration).

Despite the fact that most current meteorological satellite data are being used for an application for which they were not intended, and research into various channel and spacecraft combinations is fairly new, the current remote sensing systems work fairly well for ash cloud detection in some areas. The main limitations of the current systems are: (1) obscuration by clouds or ambient moisture, (2) reduced capability at night, and (3) limited ability to detect small-scale events. As for the detection of the onset of a volcanic eruption, the current system is inadequate in all parts of the world due to poor timeliness (satellite data frequency is typically 30 min to several hours depending on the platform) and precision (false alarm rates are high for existing techniques). While the spatial resolutions of some low earth orbit systems are sufficient for monitoring proximal hazards, timeliness and cost are important issues. For radar, there is an additional need for wider availability of stereo viewing, and for the addition of L-band radar, to expand InSAR applications in vegetated area.

Future geostationary and polar satellite systems will result in overall improvements in our ability to monitor volcanic ash and proximal hazards, except in the Western Hemisphere. The one major weakness in the near term will be the loss of the "split window" (12.0 micron) band, beginning with Geostationary Operational Environmental Satellite (GOES) spacecraft launched in July, 2001, extending to at least 2008. Alternative strategies are being addressed to alleviate this data gap, including research to utilize the remaining IR and visible bands on GOES, and better use of the GOES sounder and polar spacecraft.

CEOS Volcano Hazards Team Accomplishments: September 2000 - August 2001

(Listed chronologically)

- ***Participated in a special session on volcanic clouds at the American Geophysical Union (AGU) Fall Meeting in San Francisco (December 2000).***

- ***Responses from a remote sensing survey sent to volcano observatories were evaluated. The results were presented at the CEOS DMSG meeting in Brussels and are summarized in Appendix B (this report).***

- ***Participated in the CEOS Disaster Management Support Group meeting held in Brussels, Belgium, 26-28 June 2001:***
  - ***Developed a scenario for emergency actions during an ongoing major eruption. That and further scenarios are presented in Appendix C (this report).***
  - ***Provided NOAA / NESDIS responses to specific CEOS action items***
  - ***Briefed on a demonstration project to provide realtime fire and volcano products to Central American nations***

- ***Helped organize an international volcanic cloud workshop held at Michigan Technological University from 28 July - 3 August 2001 at Houghton, Michigan. As a result of the workshop:***
  - ***There will be increased collaboration on specifying "source terms" in eruption clouds***
  - ***A letter supporting various spectral channels on the future GOES will be drafted***
  - ***An effort will be initiated to allow more widespread access to MODIS data and derived products***
  - ***Another workshop is planned for July, 2003, with greater participation from VAACs desired***
  - ***Communications among participating scientists will be increased by means of a web-based "Volcanicclouds" discussion group***

GENERAL APPLICATION DESCRIPTION

Volcanic Ash Plumes

Volcanic ash poses a menace to persons on the ground near erupting volcanoes, and to aircraft over thousands of kilometers for major eruptions. Volcanic eruption clouds containing silicate ash particles, volcanic gases, and acid aerosols can do extensive damage to high altitude jet aircraft. When ingested into jet engines, melted volcanic ash can block air intakes, abrade turbine surfaces and blade tips, and generally cause loss of engine performance that could result in either emergency engine shutdowns or compressor stall failures (flameouts). Other hazards to aircraft includes pitting and corrosion of leading edge surfaces, abrasion of windshields, and electrical discharges (Casadevall, 1992). Because of their higher operating temperatures, the most modern, fuel-efficient "high bypass" engines are the most susceptible to ash ingestion hazards. Thus, as more and more aircraft are powered by this type of turbine, the consequences of ash ingestion are likely to get worse, rather than better, with time. Since volcanic aerosols (gases and particulates) can be injected at all altitudes from sea level to 150,000 ft (45,000 m) Above Sea Level (ASL) or more, from perennially erupting sources (e.g., Mt. Etna, Italy; Mt. Sakurajima, Japan) or from massive, explosive eruptions (e.g., Mt. Pinatubo 1991), aircraft can be affected at any operational altitude. Thus, ash ingestion and abrasion risks can be experienced by trans-continental and trans-oceanic aircraft at cruising altitudes in the upper troposphere and lower stratosphere, as well as by aircraft operating near the ground in regions affected by local plumes or ashfall. In addition to the hazards of ash to jet engines, the SO_2 and acid aerosols that normally accompany silicate ash pose a separate hazard, although not one that actually stops engines in mid-flight. These components of volcanic plumes etch acrylic windows quickly, and damage exposed metal, plastic and rubber components of aircraft. With the exception of damage to acrylic windows, the damage is difficult to recognize, so that appropriate cleaning and maintenance may not be performed in a timely manner (Casadevall, op. cit.)

The advent of two-engine passenger jet aircraft that are intended for long-distance travel will require (under current safety rules in the United States) that a greater number of airports be clear for emergency landings. For example, along the air routes in the northern Pacific, this means that proximal ash hazards that close an airport (e.g. Adak Island) may require delaying flights through the region, even though that airport would not normally be a destination. Eruptions near airports, as is the case for Popocatepetl near Mexico City, Mexico, or in heavily traveled areas such as the Carribean also pose a problem for arriving and departing jetliners, as well as smaller commuter aircraft.

Because of the worldwide hazard that airborne ash poses to aviation, remote sensing has now become an indispensable part of the global system of detection and tracking of the airborne products of explosive volcanic eruptions. Nine centers of expertise, known as Volcanic Ash Advisory Centers (VAAC), provide updated advisories hazardous ash clouds to Meteorological Watch Offices (MWO), who are responsible for forecasts and official warnings (SIGnificant METeorological (SIGMET) information). VAACs also provide reports of eruptions as received from local or federal geological or volcanological facilities. Areas of responsibility for the VAACs are shown by Figure 1. The Volcanic Ash Advisories (VAAs) are also sent to Area Control Centres (ACCs), who issue NOTices to AirMen (NOTAMs) that describe adverse effects of volcanic ash on air routes and airports. The VAACs are part of the International Airways Volcano Watch (IAVW) program, established by the International Civil Aviation Organization (ICAO). Government agencies that operate meteorological satellites such as NOAA/NESDIS in the United States, European Organisation for Exploitation of METeorological SATellites (EUMETSAT), and Japan Meteorological Agency (JMA), contribute their data to the VAACs and other volcano monitoring facilities such as the United States Geological Survey (USGS). Once initial conditions regarding the eruption are estimated, parameters are used to initialize a numerical dispersion forecast model that becomes a critical component of the air route planning process.

Proximal Volcanic Hazards

The hazards posed by airborne volcanic ash and acid aerosols to jet aircraft have attracted much attention from the remote sensing community, and understandably so, as the location of these plumes can be monitored by no other means. However, the effects of a volcanic eruption are most intense in the neighborhood of the volcano itself. If satellite-derived information is to make a larger contribution to volcanic hazards mitigation, we must find ways to monitor and quantify the proximal effects of volcanic activity, and to get that information to the locally-based communities that are responsible for volcano monitoring and emergency response.

There are two distinct circumstances in which volcanologists monitor activity at volcanoes: (1) unrest at a volcano that has been dormant, but which may be preparing to erupt and (2) activity at a volcano during an eruption, particularly a long-term eruption with spurts of accelerated activity or pauses (as at Kilauea, or Etna, or the slow dome-building eruptions of Montserrat or Unzen). In the first instance, the volcano will erupt only if there is renewed influx of magma from deep within the earth. Magma movement triggers earthquakes and tremor, hence the widespread use of seismic networks as the monitoring method of first resort. Satellite monitoring can come into play only when the magma is near enough to the surface to produce surface deformation, or enhanced heat flow or gas emissions. At this later stage of reawakening, volcanologists need all the information they can get to evaluate the probability of an eruption, and it is here that remote sensing may usefully contribute.

In the second instance, involving long-term eruptions, remote sensing can again be useful in surveying the active area, as it may be too hazardous to survey on the ground, or too time-consuming or expensive (after years or decades) to maintain extensive ground surveillance. In addition, remote sensing data can be used in volcano hazard assessment work at dormant or active volcanoes. Tables 5 and 6 (below) list the various methods for monitoring and assessing volcanic hazards, using both ground-based, and satellite techniques.

Before discussing the potential role of satellite information in detail, it is useful to lay out some differences between dealing with local volcanic hazards vs. the disseminated ash-plume. These differences include:

1. The magnitude of the proximal threat is much larger. There is the potential for many (perhaps thousands) of deaths and of extensive or total destruction of buildings, roads, dams, pipelines, or any other structures in the area. The surface drainage pattern may be disrupted, and arable land or forest temporarily or permanently destroyed.

2. As with the aircraft hazard, the basic means of hazard mitigation is avoidance. However, instead or diverting aircraft for comparatively brief periods, proximal hazards require evacuation of people, livestock, any other movable property, to appreciable distances from their homes, for uncertain lengths of time, often weeks or months.

3. Responsibility for most aspects of volcano monitoring is dispersed and usually quite local. The directory of volcano-monitoring entities issued by the World Organization of Volcano Observatories (WOVO) lists 61 separate observatories. Most of these focus on a single volcano, and the levels of staffing, instrumentation, computer support, and communications links with the outside vary greatly. Their strengths in the event of a volcanic crisis are (1) familiarity with the eruptive history and probable behavior of the local volcano(es), (2) previously established local credibility based on that knowledge, and (3) established connections with relevant local government officials and emergency responders.

By contrast there are only nine VAACs, all recently established, which are similarly equipped and staffed, and have been designed specifically to communicate with existing formal aviation and meteorological data networks (MWOs and ACCs), and each other. However, remote sensing capabilities vary from VAAC to VAAC (see the next section).

4. The audiences for ash vs. local hazard warnings are very different. For proximal hazards, the entire population is the audience. The experience of that local population with volcanic eruptions is usually limited, often non-existent, as most volcanoes have major eruptions less than once a century. (The best tool for public education found so far is videos of actual eruptions and their consequences.)

By contrast, the audience for warnings about ash clouds consists of dispatchers, flight planners and pilots, who are more technically aware than the general population, and for whom flight diversions (usually because of weather) are almost a daily occurrence.

5. Responsibility for ordering volcano-inspired response (decisions to limit access to, or require evacuation from, certain areas, and for how long) usually rests with local government officials and emergency managers or civil defense personnel. There are enormous social and economic costs to any measures taken, and great resistance from almost all components of the local community is the norm. Even one instance of evacuation that in hindsight comes to be viewed as a "false alarm" can damage the credibility of both the officials and the scientists whose information formed the basis for the action, for many years. (By contrast, a false alarm about a cloud that turns out not to contain ash is a nuisance of short duration, and poses little public safety hazard.)

For all the difficulties involved, the volcanological community has experienced some major successes in working with decision-makers and the general public to mitigate the damage from volcanic eruptions. An excellent discussion of the complexity of the process, and the intrinsic difficulties, can be found in Newhall and Punongbayan (1996), who review the history of response to the 1980 Mt. St. Helens and 1991 Pinatubo eruptions.

In considering how to expand the use of remote sensing information in support of volcanic hazards response and mitigation, it is important to understand that, for volcanoes in populated areas, such information will likely be used only in addition to, not instead of, ground-based information. Attempts by outsiders (no matter how expert or well-intentioned) to preempt the role of the local observatories and local scientists has led to confusion and can delay effective action by decision-makers and the public.

The basic recommendations of this report therefore are (1) to take steps to enhance mutual awareness between the space agencies and the volcano observatory community, and (2) to facilitate the task of finding relevant imagery, especially for newcomers to the system, in the event of a major episode of volcanic unrest.

SPECIFIC APPLICATION DESCRIPTION: Volcanic Ash

Hazard Type: ***Volcanic Ash***
User Level: ***International***
Disaster Management Category: ***Mitigation/Preparedness***
Operational Status: ***Operational***

Current remote sensing techniques for detection and tracking of volcanic ash clouds vary from VAAC to VAAC, and are very dependent on the availability of satellite data streams and local processing capabilities. In the best case, polar and geostationary single and multi-spectral channel imagery, and polar ultraviolet spectrum data is available in a timely fashion and used together to extract the maximum information. At other VAAC's, only one satellite data stream may be available and that one source may not be adequate for detecting all volcanic ash plumes. In either situation, cloud cover, large amounts of moisture in both the ambient atmosphere and ash cloud, and nighttime conditions may limit the VAAC's ability to detect and track ash.

Current satellite-based data and products:

The following satellite data and products have been deemed useful in volcanic ash detection (spectral channels used in deriving these products are also shown, along with citations):

- o Ultraviolet (UV) Backscatter and Absorption (i.e., Total Ozone Mapping Spectrometer (TOMS) 0.3 - 0.4 micron)
  - Sulfur dioxide concentrations (Krueger et al, 1995)
  - Aerosol Index: Sensitive all absorbing aerosols, such as silicate ash, acid aerosols, silicate dust, and smoke (0.34-0.38 micron bands) (Seftor et al. 1997)
- o Visible band (0.5-1.0 micron) (Holasek and Self, 1995; Holasek et al. 1996)
- o Thermal IR band (11 micron) (Holasek and Self, 1995; Holasek et al. 1996)
- o “Split-Window” IR (11 micron minus 12 micron temperature difference) (Prata, 1989; Schneider et al. 1995)
- o Thermal IR mid-wave band (8.5 micron) (Realmuto et al. 1997)
- o Water vapor absorption band (6-7 micron) (Lunnon and McNair, 1999)
- o SO_2 absorption (7.3 micron) (Crisp, 1995)
- o Reflectivity product (3.9, 11 micron) (Ellrod and Connell, 1999)
- o Experimental, three channel IR products (3.9, 11, 12 micron) (Ellrod and Connell, 1999)
- o Passive microwave data (85 Ghz) (Delene et al. 1996)

The above images or products are derived from both geostationary (GOES, METEOSAT, GMS) and Polar orbiting satellites (NOAA Advanced Very High Resolution Radiometer (AVHRR), NASA’s Earth Probe TOMS). The use of some of the above data types or products is currently experimental, and is not available at all VAACs. The “split window” (11 minus 12 micron IR) technique is in widespread use at many VAACs, and is especially effective for “aged” ash plumes with low water vapor content. Thus, the technique does not always provide unambiguous identification of the ash cloud. An example of the capability of the split window product for a long-lived eruptive ash cloud is shown by Figure 2. Routine image product frequency is currently 30-60 minutes for geostationary satellites (except 15 minutes for GOES over the Continental United States), and 2-6 hours for polar products. Product or data resolutions range from 1-8 km. A multi-panel image showing GOES capabilities for an eruption of Popocatepetl near Mexico City (Figure 3) depicts the standard raw images in visible, thermal IR and shortwave IR, plus the split window product, a 3.9 - 11 micron difference image, and the experimental three-band product.

Detection of ash further depends on (a) estimating the amount of ambient water vapor assumed in the atmospheric column, and (b) knowing the amount of magmatic or phreatic (ground water source) water vapor in the eruption column. Given a relatively dry atmosphere and volcanic plume, current IR detection algorithms work well (e.g., 1992 Spurr eruption discussed in Schneider et al, 1995). Also, for eruptions where both TOMS and AVHRR data are available, they give similar results for ash retrievals (Krotkov et al., 1999), though the TOMS data is low-resolution and available only during daylight hours.

However, where an eruption incorporates much phreatic water, or under tropical conditions where the water vapor content in the atmospheric column is high, it is more difficult to distinguish volcanic from meteoric clouds (e.g. the 1994 eruption of Rabaul, discussed by Rose et al., 1995, and Prata and Grant, 2001. In regions where only one IR channel is available (i.e., Africa - METEOSAT at present), we cannot distinguish ash from meteorological clouds, except by cloud source and shape.

Detection of volcanic hazards at night is more difficult and thus, less adequate, due to the absence of visible band (0.6 micron) imagery or UV data, and the lower resolution of geostationary IR channels. Ash has a distinctive appearance in visible data, and can thus be used to qualitatively verify signatures observed in IR products.

Despite the fact that these meteorological satellite data are being used for an application for which they were not intended, and research into various channel and spacecraft combinations is fairly new, the current remote sensing systems work fairly well for some areas. As for detection of a volcanic eruption, the current system is inadequate for detecting eruptions with a high degree of timeliness in all parts of the world.

Parameters extracted from the satellite data:

An analysis of the horizontal extent of an ash cloud is determined from satellite images, either single channel visible, infrared (IR) or multi-spectral IR, at one of the regional VAACs. The height of the plume is estimated by means of IR satellite imagery, upper level temperatures and winds (derived from radiosondes, satellite cloud motion, or numerical prediction models), aircraft pilot reports, or ground-based observations. The plume location and height (along with eruption time and duration) are then used to initialize a numerical model that forecasts the trajectory of the ash cloud for use by MWOs in developing forecasts and warnings. Model output is also used for air route planning.

Volcanic aerosols and SO_2 are also detected using TOMS UV data, but the availability of TOMS is limited to a few passes per day at present. Figure 4 is an example of ash coverage depicted by TOMS UV on the Japanese ADEOS satellite for an eruption of Bezymianny on May 8, 1997.

PRODUCTS AND SERVICES: Volcanic Ash

Principal users of volcanic ash products (satellite data, derived products, warnings, advisories) at the international, national, and local levels are summarized in Table 1. Examples of volcanic ash text and graphic products issued to these users include:

- Volcanic Ash Advisory (VAA) issued by all VAACs
- Volcanic Ash graphic analysis (currently issued only by the Washington VAAC)
- Trajectory and dispersion forecast models:
  - Volcanic Ash Forecast Transport and Dispersion (VAFTAD, Washington VAAC)
  - PUFF dispersion model (Anchorage VAAC)
  - CANadian Emergency Response Model (CANERM, Montreal VAAC)
  - Modele Eulerian de DIspersion Atmospherique (MEDIA, Toulouse VAAC)
  - Nuclear Accident Model (NAME, London VAAC)
  - Hysplit Model (Darwin VAAC)
- SIGnificant METeorological information (SIGMET) issued by MWOs
- NOTices to AirMen (NOTAM) issued by ACCs
- Volcanic Eruption Information Release issued by USGS Volcano Observatories

An example of a dispersion forecast of a Mt. Spurr eruption cloud valid at 1200 UTC on 14 February 1996 from the CANERM model (Pudykiewicz, 1988) is shown in Figure 5. Validation of dispersion trajectory forecast models are usually conducted in-house and involve comparison of forecast ash cloud coverage with visible and IR satellite images. A study by Heffter and Stunder (1993) found that VAFTAD forecasts of several Mt. Spurr eruption clouds in 1992 agreed reasonably well with satellite imagery, considering the inability of satellite data to detect lower concentrations of ash. A recent inter-comparison of VAFTAD and the Alaska PUFF model by the Washington VAAC found that the forecasts from both models provided consistent results.

The ICAO requirement for updates of the VAA, and forecast products (SIGMETs) is a minimum of every six hours during a volcanic ash event. Planned capabilities of future satellite systems (see final section of report) will satisfy the ICAO requirements for remote sensing of volcanic ash, e.g. text messages and/or graphics containing a description of the ash cloud position and its movement every 6 hours, including accurate forecast positions. However, unless suggested research areas are supported and realized, there may be periods where the ash monitoring capability will be degraded, such as during the time frame when GOES will not be carrying the “split window” channel, at night, or in the critical first few hours of an eruption. It should be noted that this report reflects not only ICAO requirements, but the desires of the aviation community to have accurate ash cloud updates as frequently as possible, as well as the best possible forecast models.

TABLE 1.
Primary Users of Volcanic Ash Products

International	***National***	***State/province/local***
VAACs	Civil aviation agencies	Emergency managers
MWOs	Regional airlines, ACCs	Airport managers
ACCs	All airlines, Military	Police
Major airlines	Geophysical and meteorological agencies	Fire and rescue
International Relief Agencies (Red Cross)	Emergency management agencies	Medical facilities
Geophysical researchers	Medical/relief agencies	
	Volcano observatories	

An overview of the global volcanic hazard alerting system, showing responsible agencies and their products, primary users, and data used in the decision making process, is shown by Figure 6.

OBSERVATIONAL REQUIREMENTS: Volcanic Ash Plumes / Eruptions

Remote sensing requirements for adequate volcanic ash and SO_2 detection are listed in the following three tables that describe: (1) the resolutions of raw image data (Table 2), (2) derived product specifications (Table 3), and (3) data frequency (Table 4). The requirements were developed after consideration of: (1) the spatial and temporal scales of the phenomena, (2) current capabilities of the remote sensing system, (3) user needs, and (4) ongoing and prior research, including case study simulations with existing sensors. Data that were considered difficult to obtain or too costly were not considered in the analysis. Threshold requirements determined by current system capabilities and observed performance are listed. Optimum capabilities were those considered achievable in the near future (10-20 years) assuming conservative advances in technology.

The current remote sensing systems need to be augmented to improve existing capabilities. In particular, the resolution of geostationary data needs to approach the polar resolution of 1 km from AVHRR. All VAACs should have access to “split window” geostationary data at 30 minute intervals. An IR SO_2 absorption channel is required, and ideally, global UV data should be made available concurrently with high resolution thermal IR data. To achieve these capabilities, a timely “call up” capability for very high refresh rates is needed, or access to military assets should be provided. Minimum areal coverage of the satellite data is for each VAAC and surrounding VAACs. Optimally, each VAAC would eventually have global satellite data coverage for all VAAC regions.

TABLE 2.
Data Resolution Requirements

Phenomenon	**Data**	**Threshold**	**Optimum**
Ash Cloud	IR	5 km	1 km
" "	Visible	1 km	0.5 km
" "	Sounder	10 km	2 km
SO2 Cloud	UV	20 km	10 km
" "	IR	5 km	1 km
Thermal Anomaly *	IR	1 km	30 m

* Verified (with False Alarm Ratio < 5%)

TABLE 3.
Derived Product Specifications

Product	**Threshold**	**Optimum**
Ash Cloud Top Height	< 2 km	< 1 km
Ash Column Density	1 ton/km2	0.3 ton/km2
SO_2 Precision *	5 DU	0.5 DU

* (SO_2 range = 0 to 700 Dobson Units (DU))

TABLE 4.
Observational frequencies

Phenomenon	**Threshold**	**Optimum**
Ash Cloud	30 min	5 min
SO_2 Cloud	2 hr	5 min
Thermal Anomaly (Persistent)	2 hr	5 min
Thermal Anomaly (Transient)	30 sec	10 sec

RECOMMENDATIONS: Volcanic Ash

The CEOS Volcanic Hazards team makes the following recommendations regarding the remote sensing of volcanic ash and SO_2 clouds:

Space Agencies:

o Incorporate the following spectral channels in planning for all future satellite instruments:
- **Dual longwave (thermal) IR (11-12 micron)**
- **Dual shortwave thermal IR (2-4 micron)**
- **SO_2 / ash absorption IR (8.5 micron)**
- **SO_2 absorption IR (7.3 micron)**

o Include both IR and UV (0.3-0.4 micron) sensors on future geostationary satellites for a complementary volcano monitoring system.

o Develop a call up capability to obtain satellite data at the highest frequency possible for emergency situations, and assure transmission to the users.

o The minimum frequency of available multi-spectral data should be 30 minutes for geostationary satellites, with the optimum goal ~5 minutes. The minimum spatial resolution should be 5 km for IR, with an optimum goal of ~1 km.

o Allow VAACs, volcano observatories, and other qualified agencies to have access to multi-spectral satellite data and/or derived products at a frequency of at least 30 minutes. Each VAAC should have access to satellite data coverage for all neighboring VAACs in the event of "handoff" or backup situations.

CEOS:

o Support bi-annual international volcanic ash summits such as the one held at Houghton, Michigan in July, 2001.

o Create a standing Science Working Group on Volcanic Hazards Detection.

Operational Hazard Warning Agencies:

While not germane to the responsibilities of the CEOS volcano hazards team, the following recommendations would improve the operational volcanic ash alerting system, provide a better flow of products and services to users, and improve the utilization of remote sensing data:

o Streamline and periodically test the communications system in order to provide timely:
(1) initial notification of an eruption from VAACs to all interested agencies
(2) dissemination and display of volcanic ash products from warning agencies to users

o Develop new and/or improved remote sensing tools (i.e. to automatically detect eruptions, discriminate volcanic ash (every 30 minutes), determine height and base of ash clouds, and composition and particle size of ash).

o Increase collaboration and validation efforts between operational agencies and research community, perhaps through regional workshops, WMO, and the World Wide Web.

o Expand education, training, and utilization of remote sensing derived information for all components of the IAVW, through regional workshops, WMO, and the World Wide Web.

Areas for Further Research and Development:

- **o Develop techniques for automatic detection of volcanic eruptions with as low a false alarm rate as possible (optimally <5%).**
- **o Develop techniques for more accurate estimation of eruption column neutral buoyancy altitude and the top height of the resulting ash cloud (< ±1 km) (Alternate methods include cloud parallax techniques ~~and,~~ UV "ring effects" (Joiner and Bhartia, 1995) and "CO2 slicing" technique (Menzel et al 1983) for optically thin ash clouds)**
- **o Develop techniques for automatic edge detection of ash clouds every 30 minutes**
- **o Develop or improved existing techniques for determining ash column loading, particle size distributions, and total mass.**
- **o Develop alternative sources of 12.0 micron IR data or additional multi-spectral techniques to ameliorate loss of this channel on GOES from 2002 to 2010 or so (Viable alternatives include: the GOES sounder and AVHRR)**
- **o Initiate research on the minimum concentrations of volcanic ash detectable by satellites, and whether or not these concentrations are hazardous to jet aircraft**

In general, an increase in communications among the small group of active researchers in the remote detection of volcanic eruptions and resulting ash clouds, and between the research and operational communities, is fundamentally crucial to the continued success of this effort and the maintenance of safety margins with respect to volcanic ash hazards.

SPECIFIC APPLICATION DESCRIPTION : Proximal Hazards

Introduction

Many volcanic phenomena are detectable and partly quantifiable using remote sensing information. A review of the subject by Francis et al (1996) mentions long-term (baseline) monitoring of deformation or thermal emissions, monitoring of gas emissions, detection of the onset of eruptions, and monitoring of processes during eruptions (especially long eruptions), including topographic changes that influence where lava or pyroclastic flows, lahars, and other gravity-driven materials go during an eruption. Table 5 summarizes important ground-based methods in use vs. currently available satellite techniques.

TABLE 5.

Monitoring Methods for Volcanic Hazards

Ground-based and airborne methods	Satellite techniques
Seismic networks to monitor earthquakes, tremor, rockfall	--------
Deformation networks to monitor tilt, expansion or contraction --often in conjunction with GPS	GPS, in conjunction with ground-based networks Radar, particularly InSAR
Monitoring changes in microgravity to detect magma intrusion	----------
Observation of thermal emissions, measurements of temperature, airborne FLIR cameras	Thermal IR
Gas emissions (SO_2, CO_2 levels or changes in gas ratios) via COSPEC, LICOR, FTIR, direct sampling	UV, IR (8.5 micron) can detect SO_2; acid aerosols detectable by various UV, IR methods
Acoustic monitoring for debris flows and lahars	-----------
Mapping, photography to document stages of the eruption, distribution of eruptive products	high-resolution panchromatic or multispectral imagery
Mapping to document topographic changes caused by the eruption, and to determine thickness of eruptive products	high-resolution stereo panchromatic imagery, radar

The techniques are listed in roughly the order in which they can be used to detect movement of magma toward the surface and then in the near-surface environment. Seismicity, deformation and gravity changes provide the earliest assessments; however, volcano-related seismic signals can be quite variable and require much experience in interpretation, for best results. Thermal and gas emissions may also precede activity, but some techniques, such as acoustic flow monitoring require an actual eruption event in progress. Note that there are several types of ground-based monitoring that have no satellite equivalents. **However, satellite data provides unique information on (1) broad increases in thermal emissions, especially at temperatures below incandescence in the visible, and (2) broad patterns of deformation over areas, which cannot be done by ground-based networks.**

There are two key difficulties in trying to develop satellite systems for better volcano monitoring. The first is that volcanic eruptions are comparatively rare. Thus there are no satellite systems in place that were designed specifically for volcano monitoring: we are working with tools developed for other purposes. However sensors needed for detecting and evaluating other hazards (wildfire detection and tracking, detecting deformation fields associated with earthquakes, landslide imaging and assessment) would also serve to monitor volcanic phenomena.

A second problem is that the time-scale involved is highly variable. Explosive volcanic eruptions are quite brief, while other types can go on for decades. A related problem is that eruptions can happen at night, when many of the higher-resolution sensors do not function. Pieri et al (1995) gave a good summary of how the brevity of most volcanic eruptions works against using satellite systems for eruption monitoring, comparing two packages that are on the recently launched Terra (formerly EOS AM-1) system (characteristics summarized in Appendix A). The MODIS package has low spatial resolution, hence gives only a rough image of volcanic activity. The high-resolution ASTER system has a revisit time of 16 days at the longer wavelengths, which makes it difficult to capture any but the longest eruptions.

An example of success in capturing volcanic activity is shown in Figure 7. This Landsat 7 image of Shishaldin has captured not only an ash plume, but other relatively ephemeral features such as thin ash deposits and lahar tracks in snow, which can be difficult or impossible to map after the snow melts, or after another season's weather. The downside of such systems is that, with a 16-day repeat, short events are caught only by chance. Also, at present Landsat 7 and ASTER imagery are not readily available to the relevant volcano observatory in real time.

Data Acquisition Issues

The remotely sensed data used by the VAACs come from operational meteorological satellites, and the data delivery systems needed are already fairly well developed. This is not the case for remote sensing data needed by volcano observatories. The observatories generally need multiple data streams from several satellites, run by different agencies with different data policies, many of whom do not have an operational role. Even those observatories that make frequent use of remote sensing imagery acquire their data in an ad hoc fashion, which depends on the initiative of individuals. A considerable proportion of remote sensing work on volcanoes monitored by observatories is done by academic research groups who are often at some distance from the observatory effort. For better operational use of remote sensing in volcanology, we will need to get the data to observatories in a more timely and consistent manner. Two possible ways to achieve this would be through either (1) by establishing a global data clearing house system, or (2) by expanded facilities for local data reception.

The role of the clearing house or data center would be to provide a consistent stream of data. There is no "World Volcano Remote Sensing Data Center" that can play this role. However, data delivery could be accomplished via the internet, or by internet/communication satellite high-bandwidth routes. A big advantage to observatories of such a system would be to buffer the observatories from having to deal directly with the individual data providers. The recently established International Charter, cosponsored by CNES, ESA and CSA, constitutes an alternative approach, but will provide data only under specific, previously defined circumstances (see scenarios in Appendix C).

Local data reception has several aspects that would be attractive to observatories:

- In some locations it is the only way to acquire data (if the observatory is out of range of major ground receiving stations for satellites that do not have substantial on-board storage).
- It maximizes the chance of timely access to data.
- It engenders a sense of local commitment and ownership of the data (equivalent to running a seismic network).

A major inhibitor of local reception is the cost of hardware (e.g. steerable X-band dishes), though this should come down to within the range of observatory budgets in the future. Another factor is that the observatory would have the initial administrative overhead of negotiating bilateral deals with the data providers. Lastly local reception would in most cases require additional (permanent) staff at the observatory to deal with the data.

Specific monitoring activities:

Hazard Type 1:	***Thermal monitoring of volcanoes***
User level:	***Local/national***
Disaster management category:	***Preparedness/mitigation***
Operational status:	***Demonstrated to be useful in restricted circumstances but not in routine operational use.***

Volcanic activity introduces heat onto the earth's surface and into the earth's atmosphere, often at temperatures beyond those from other sources, such as wildfires or most human activities. Furthermore, increased surficial heat flow (new steaming cracks, or enhanced activity at existing hot springs and fumaroles) is a recognized precursor to volcanic eruptions. Accordingly, the potential of satellite-derived thermal imagery of volcanic and geothermal areas has been frequently evaluated (see e.g. Oppenheimer, 1998). Because thermal images, with appropriate color-coding of pixels, are more readily understood by non-specialists than (for example) most radar imagery, they lend themselves to public display and discussion. Such products are hence are more likely to be used in disaster response, if freely available, than most other types of satellite-based information currently available.

Volcanic features which have distinctive thermal characteristics include: fumarole fields, crater lakes, lava lakes, lava domes, lava flows and pyroclastic flow deposits. However, success in developing remote sensing tools for thermal monitoring of volcanoes has been limited either by inadequate spatial resolution or inadequate temporal resolution of the satellite systems. <u>Spatial resolution</u> problems arise because extremely hot regions on active volcanoes are usually sub-pixel size for most sensors, even in the visible and SWIR range, but are hot enough to saturate a pixel much larger than the emitting area. Two studies of thermal imagery of Kilauean lava fields illustrate the problem: Realmuto et al (1992) used airborne TIMS to delineate the thermal anatomy of a lava field at Kilauea, but their success was strongly dependent on the 6m resolution of the imagery, as can be seen by comparing their data with the Landsat image (resolution 30m) of the Kilauean lava field analyzed by Flynn et al (1994). As for <u>temporal resolution</u>, existing systems with moderate spatial resolution obtain repeat coverage only after many days, a repeat interval which does not permit monitoring of a rapidly developing lava flow or the emplacement of a pyroclastic deposit.

On a more positive note, changes in bulk heat production over large areas, or from a fumarolic field, can be monitored with relatively low resolution, low repeat time, IR imagery. Long-term and emergency monitoring of these targets is possible with AVHRR and the Along Track Scanning Radiometer (ATSR) sensors on the ERS platforms. For example, Wooster and Kaneko (1998) show that combined low (ATSR) and moderately high spatial resolution (TM) SWIR data permit us to monitor the gross heat flux at the surface of an erupting lava dome. The newly available Landsat 7 imagery (resolution 30m and 60m) and ASTER imagery (resolution 30 m and 90m) will be adequate for such broader monitoring, even with the 16-day return time; availability of this imagery may encourage the volcano monitoring community to begin to evaluate it on a more routine basis.

Recently Harris and others (1999) have sought to exploit the high temporal resolution of GOES thermal imagery to monitor rapid-onset hot spots at a selection of volcanoes within the Western Hemisphere. They use bands 1, 2 and 4 of GOES 8 and 10 data to define hot areas on Kilauea, Popcatepetl, Soufriere Hills (Montserrat), and other very active volcanoes. Updated every 15 minutes, the GOES data are processed to give 6 image products per volcano that are posted on the web (http://volcano1.pgd.hawaii.edu/goes/), where they can be picked up by the relevant volcano observatories (the Hawaiian Volcano Observatory for Kilauea; CENAPRED for Popocatepetl and the Montserrat Volcano Observatory for Sourfriere Hills) for detailed inspection, evaluation and use. Sources of noise or data gaps include cloud cover and solar reflection, and the 4 km spatial resolution is a major limitation. However, even with these limitations, the data are being used, either to help verify heightened eruptive activity or to disprove an erroneous report.

Hazard type 2: ***Volcano Topography and Deformation Monitoring with Radar***
User level: ***Local/national***
Disaster management Category: ***Preparedness/mitigation***
Operational status: ***Demonstrated to be useful but not in routine operational use***

Radar imagery has great potential for observation and measurement of volcanic activity because of its all-weather and day/night capabilities and its unique ability to measure detailed spatial patterns of surface deformation from space. The principal discouragements from a volcanologist's perspective are the difficulty of processing, expense, and low frequency of radar data. Topography can be supplied by two radar methods: radargrammetry and synthetic aperture radar interferometry (InSAR). Radargrammetry requires two distinctly separate viewpoints. Of the three main SAR satellites available during the 1990's (ERS, Radarsat, JERS) only Radarsat had a steerable angle of view. Unfortunately, the relatively low accuracy (20-30 m rms) and high cost of Radarsat data make this an unattractive option for repeat surveys. A possibility for the future is to use millimetric radar techniques for observing dynamic targets, such as lava domes. These give penetration through clouds to give quantitative ranging information, but can be used to measure temperature as well.

Recent and ongoing experience at trying to monitor the topography and deformation of the eruption at Soufriere Hills Volcano, Montserrat (1995-99) has shown some of the benefits and limits of the currently available data (Wadge et al. 2001) (Figure 8). The operational need for mapping the changing topography during dome growth is clear and a frequency of about once a week would be adequate. Equivalent deformation measurement intervals needed are a few weeks. As tested at Montserrat, InSAR proves to be very good at mapping the depth of pyroclastic flow deposits that fill the valleys of a stratovolcano. However, the topographic surface of the lava dome itself, which is a key observational target, is too dynamic to capture using the technique, even with the 1-day separation of ERS-1/-2 interferograms (Wadge et al, 2001).

Space borne differential INSAR has proved to be an excellent new source of deformation information on some volcanoes. Specifically, trans-eruption, hindcast studies of the deformation on basaltic volcanoes or volcanoes at high latitudes have yielded unique results. However, we have as yet no experience in using InSAR to predict anything about a pending eruption. Another difficulty is that the magnitude of the signal can be low, and noise high, particularly where vegetation is abundant. Volcanoes in the tropics are the greatest challenge in this regard. The longer wavelength of L-band radar relative to C-band allows better phase retrievals from forested areas (e.g. Rosen et al., 1996), but there is no L-band satellite currently available. A last problem is that, at present, there is a dearth of any kind of new SAR imagery: only the ERS-2 satellite is still operational, and it is near the end of its life. ENVISAT (to be launched in November 2001) will replace it, but not complement it, as the two have different C-bands.

The situation will improve as the next generation (2003 -2005) of space borne SAR satellites is launched. These will bring multi-frequency, polarization and angle data to bear on the problem. However, all of these platforms will have long (tens of days) repeat times, giving little direct improvement in the ability to respond rapidly to a new eruption. Also the problem of tropospheric noise from variable water vapor contents (Zebker et al., 1997) has no clear solution in sight. In the longer term (2005 -) the volcanological community should be arguing for (1) space borne single-pass interferometric radar to capture new topography, and (2) repeat-pass L-band radar, to generate a long time series of surface motion data, but with an event response mode with a tasking lead-time of hours to a day or two and complementary tropospheric water vapor mapping.

Hazard Type 3: *Gas Plumes*
User Level: *Local/national*
Disaster Management Category: *Preparedness/mitigation*
Operational status: *No appropriate sensors currently operational*

The Total Ozone Mapping Spectrometer (TOMS) instrument on Nimbus 7 and now on EarthProbe, even with their very coarse resolution (~40 km at nadir), can measure global scale and distal plume concentrations of SO_2, in conjunction with ozone determinations. At the local scale, many volcano observatories use ground-based remote spectrometry such as COSPEC to measure SO_2 flux, LICOR to measure CO2, and more experimental OP-FTIR instruments to measure other species such as HCl. Space borne measurements at high enough spatial resolution to monitor permanent and evolving SO_2 plumes near the source vents have not been possible, until recently. The value of near-vent monitoring is that (1) it measures primary volcanic flux before broader atmospheric processes complicate the signal, (2) it allows investigation of variations in magmatic gas flux as an eruption precursor, and (3) it documents the spatial and temporal extent of the local air pollution hazard.

The main channel needed for such SO_2 and sulfate mapping is the spectral band centred near 8.5 microns where there is a strong absorption doublet. The first satellite to demonstrate the capability of the 8.5 channel was the OCTS sensor on the short-lived ADEOS platform, which had a spatial resolution of about 700m at nadir. The new MODIS and ASTER sensors on Terra and EO-1 include the 8.5 micron IR band at 1 km (MODIS) and 90 m (ASTER) resolution. These should give us an unprecedented look at tropospheric SO_2 plumes, even at the ASTER revisit interval of 16 days, as data become available and are analyzed by the volcanological community. If these sensors do live up to expectations, they will provide a significant new capability for SO_2 monitoring, allowing evaluation of the effects of long-term (or short-term very high-level) volcanic emissions. These include increased respiratory disease, highly acid rain and vegetation damage from long-lived eruptions and SO2 emissions, such as those at for Kilauea (Sutton et al., 1997). Another strong SO_2 absorption band is centered at 7.3 microns. A 7.3 micron channel is available on MODIS and the GOES Sounder.

Hazard Type 4: *Mapping for Hazards Assessment*
User Level: *Local/National*
Disaster Management Category: *Prevention/preparedness/mitigation*
Operational status: *Some sensors newly available; older ones not consistently used*

Effective volcanic hazards monitoring and mitigation requires access to high quality topographic data, and easy updating of same. Much can be predicted about where lava or pyroclastic flows and lahars will go, if up-to-date topography can be obtained before an eruption and maintained during an eruption. In the past, topography was normally derived from aerial photography. As satellite systems mature, it may be possible to use stereo satellite imagery, as suggested in the discussion of radar systems above. Stereo viewing is also obtainable from SPOT, at visible wavelengths, and is part of the ASTER package.

Mapping of young volcanic deposits is essential to the evaluation of volcanic hazards at dormant volcanoes. It gives enormous insight into the style of recent activity (even if prehistoric) and offers the best, and often the only, basis for planning for future events. Table 6 summarizes some of the methodology involved, again contrasting ground-based and satellite methods. As with process monitoring, some kinds of information require ground-based studies and actual sampling. However satellite information can help speed the process of mapping the distribution of young volcanic products in rugged terrain.

TABLE 6.
Volcano Proximal Hazard Assessment Methods

Ground-based methods	Possible satellite sources
Topographic mapping, traditionally from aerial photography or other airborne sensors	Any high-resolution stereo imagery that can be georegistered accurately enough (SPOT, radar, ASTER panchromatic)
Geologic mapping to determine stratigraphy and character of eruptions, especially prehistoric eruptions	Multi-spectral (e.g. Landsat 7, ASTER) data, which can distinguish units, supplement field work
Radiometric and other dating of young eruptions to establish recent eruptive history of volcano (How young? How frequent?)	-----------

Early work by Kahle et al. (1988) documented that basalt flows of varying ages may be spectrally distinct, depending on the exact condition of the glassy chilled surface, even where there are no compositional differences, but this has not been widely applied to date. The improved resolution of newly available Landsat 7 TM imagery will be extremely important for mapping, and may bring multi-spectral mapping of volcanic rocks into wider use. Lastly, imagery from the experimental Hyperion sensor (resolution 30 m), currently operating on the EO-1 platform, offers an opportunity to evaluate the usefulness of hyperspectral data for mapping in volcanic terranes.

PRODUCTS AND SERVICES: Proximal Hazards

Products for monitoring of proximal volcanic hazards, and for responding to them, are under development in many government agencies and academic institutions. For thermal monitoring the best prototype products available so far are those on the Hawaii Institute of Geophysics (HIG) website. Specific products include images created by subtracting the T4 from T2 in GOES spectral channels (equivalent to T3-T4 for AVHRR data), which show thermally-emitting areas on a selected list of volcanoes. The HIG group also archives integrated radiance data for the hotspots they monitor, which is available by electronic mail to collaborators. The usefulness of the data is limited by the coarse (4km) pixel size of the GOES IR sensor. Other limitations are: (1) only the western hemisphere is covered, and (2) data are available only to volcano observatories that have access to the web or electronic mail. However, the simplicity and accessibility of the products has led to their expanding use. Also, the use of a university web site as a prototype public delivery system for volcanic hazards offers a model for distribution of other types of hazard-related satellite data.

Radar studies of dome growth or deformation at volcanoes are still by and large research projects rather than monitoring tools. This reflects limitations of the satellite systems, as well as the high level of computer analysis involved in working with the data. When improved data flow is achieved, however, it is unlikely that interferograms will be the product of choice for presentation to emergency managers and local officials. Shaded relief maps, with areas of inflation or subsidence highlighted in color might have more immediate impact than research-level images. In any case, there is research to be done on how best to communicate these valuable results in a crisis situation.

OBSERVATIONAL REQUIREMENTS: Proximal Hazards

For basic thermal monitoring, the needs in terms of temporal resolution and spatial coverage are well summarized by Harris et al (1999), who recommend:

(1) intervals of 15-30 minutes for image acquisition
(2) multiple IR bands, including the critical mid-IR 3.9 micron band for thermal emission monitoring
(3) more satellite coverage.

They state that five geostationary satellites with the appropriate bands could cover all volcanoes (and wildfire activity) within 55 degrees of the equator. Because several of the next generation geostationary satellites will include the appropriate bands, they anticipate that low-latitude coverage will be achieved. However, to provide equivalent temporal resolution for more northerly regions would require a large number (about 12) of AVHRR-type polar orbiters, which seems less likely to happen.

Beyond more extensive coverage, however, better thermal monitoring of volcanic activity will depend on obtaining better spatial resolution in the IR bands needed: the present 4 km pixel size is too coarse for all but roughest notices of activity. At this resolution we can't unequivocally distinguish between 100 C water and 1100 C lava. Nor can we distinguish between lava flows and wildfires, whether started by volcanic activity or other causes. To really see hot spots, glowing cracks, etc. we need spatial resolution of the order of 10 m, and to track events, we need temporal resolution of the order of 15-30 minutes, as opposed to hours or days. The observational requirements needed for effective monitoring of volcanic thermal signals are very similar to the needs for monitoring the outbreak of wildfires, so sensors that can serve the one hazard will support the other. Dense persistent cloud cover will still thwart our ability to acquire guaranteed regular time-series data.

For radar, the volcanological community should be arguing for (i) a spaceborne single-pass interferometric radar to capture new topography, and (ii) a repeat-pass L-band radar, to generate a long time series of surface motion data, but with a tasking lead-time of hours to a day or two and complementary tropospheric water vapor mapping. InSAR monitoring of deformation associated with earthquakes has much the same observational requirements as that for monitoring deformation at volcanoes, so, as with wildfires, improvements directed at one hazard will support monitoring of another.

RECOMMENDATIONS: Proximal Hazards

<u>**Space Agencies:**</u>

- **Provide information on types of products available, and how to obtain them, on web sites directed at volcano observatories and volcanology researchers. Language protocol as for ICAO.**
- **Establish mechanisms for expedited access to data and tasking authority for volcanic crises (especially for radar acquisitions), such as the new International Charter.**
- **Volcanic hotspot monitoring and (and wildfire detection) both need certain IR bands (2.2, 3.9, 11 microns) at high temporal and spatial resolution. These bands should be included on all future geostationary satellites.**
- **More SAR satellites, with higher resolution, design characteristics optimized for InSAR, plus L-band capability**
- **Improved SO_2 monitoring, especially SO_2 plumes at low elevations, requires the 7.3 and 8.5 micron band at high (~100 m) spatial resolution.**
- **Configure orbits for high resolution, low earth orbit (LEO) imaging satellites to reduce revisit**

times to less than 3 days.

CEOS:

o Assemble information on how to task various satellites and packages (e.g. GOES, ASTER) and post on the CEOS Volcanic Hazards web page, with layout organized for volcanologists.
o Expand education/training in the use of remote sensing information for all components of the volcanological community through workshops (e.g. at IAVCEI meetings).
o Create a standing committee on Volcanic Hazards Detection.
o Establish a liaison with the IAVCEI Remote Sensing Commission, following up on initial contact made at the July 2000 IAVCEI meeting in Bali.

Areas for Further Research and Development:

o Develop delivery systems for products based on remote sensing data that make information available to the volcano monitoring community. The GOES "hotspot" website of the University of Hawaii offers a possible prototype.
o Develop products that communicate information simply and effectively to non-specialists, and standardize those products (e.g. for radar imagery).
o Produce high-resolution DEM's for all active volcanoes in populated areas as data becomes available.
o Investigate, evaluate and link satellite observations for change detection (all kinds) at a volcano over the course of a cycle of volcanic activity.
o Identify means of evaluating edifice stability using remotely sensed data, including evaluation of data from the Hyperion sensor.
o Investigate the utility of new high resolution land surface imagers (e.g., ASTER, Landsat TM7) for providing information on eruption precursors (thermal anomalies), and supplemental information on the characteristics of eruption plumes (as anticipated by Pieri et al., 1995; Andres and Rose, 1995).
o Encourage the development of volcano observing sensors in the millimetric part of the spectrum, where combined topography and thermal signals can be retrieved.

Last but not least: the most difficult target of investigation, for ground-based observers and remote sensing techniques alike, is the eruption column, that is, the dense, usually opaque, vertical column of a large phreatic or major plinian eruption. Wen and Rose (1994) give an impressive list of aspects of volcanic columns (and plumes) for which further research and technique development (e.g. Doppler radar systems) is needed.

FUTURE SATELLITE SYSTEMS

Meteorological Satellites

Newly-launched and planned geostationary and polar satellite systems will result in overall improvements in our ability to monitor volcanic ash, except in the Western Hemisphere. A summary of these spacecraft, the sponsoring agencies, number of channels, and resolutions are shown in Appendix A.. The replacement for GMS (MTSAT) and the METEOSAT Second Generation (MSG) will both have shortwave IR (3.9 micron), and "split window" IR (12.0 micron) with a nadir resolution of 4 km and 5 km, respectively. MSG will also have 7.3 and 9.0 micron channels that could be useful for monitoring SO_2 concentrations. An advanced imager is being planned for GOES (circa 2008) that will have as many as twelve spectral bands (including 3.9, 12, and possibly 8.5 micron wavelengths) at higher temporal (5-15 min full disk) and spatial resolutions (2 km IR, 0.5 km visible).

Data from an Advanced Interferometric Radiometric Sounder (AIRS) and MODIS are now available from NASA's Earth Observation System (EOS). MODIS has 36 spectral channels, including the shortwave IR (3.9 micron) and thermal IR bands (7.3, 8.5, 11, 12 micron) needed for volcano monitoring, but will be available at a given location only every 1-2 days. Polar satellite coverage will be enhanced with the European ENVISAT (projected launch date June 2001), which has a near clone of the AVHRR, the European METOP (2002) with SO_2 detection capabilities, and Japan's sophisticated ADEOS-II, a thirty-nine channel, high resolution imager.

One major weakness of the future global satellite network with respect to volcano monitoring is the loss of the "split window" (12.0 micron) channel on all GOES spacecraft launched from 2001 until around 2008. That channel will be replaced by a 13.3 micron CO_2 absorption band at 8 km resolution, to be used for more accurate height assessment of wind vectors and cloud tops by means of a "CO_2 slicing" technique (Menzel et al 1983). Preliminary research has indicated that the 13.3 micron band could have some utility in discriminating volcanic ash from thin cirrus (Ellrod, 2001). The 13.3 µm IR band may also result in more accurate height estimates for thin ash clouds. GOES-11, the replacement for GOES-8, was launched in May, 2000, tested, and is being stored on orbit.

There is a possibility that UV data in several channels (10 km resolution, 15 minute frequency) could be included in a future GOES spacecraft as part of a "Coastal Zone Remote Sensing Instrument" that would also produce "ocean color" imagery for monitoring coastal eco-systems.

Alternative sources of appropriate IR data for the Western Hemisphere include the GOES sounder (available only at low and mid latitudes), and AVHRR and similar packages on polar-orbiting satellites (at 2-6 hour intervals depending on latitude). The GOES sounder has lower spatial resolution (10 km) and its temporal frequency is hourly at best, so this is considered a less desirable alternative. A recent study (Ellrod, 1999) describes this capability in more detail, and shows that the area coverage of volcanic ash will be underestimated in some situations.

Regardless of the alternative strategies derived, there will be some degradation of our ash monitoring capabilities in the Western Hemisphere during the period with the loss of the split window IR band on GOES.

Earth Observation Satellites

Monitoring of proximal volcanic hazards depends in part on the meteorological satellites, but also uses a broader range of low-earth-orbit imaging systems. New systems available now include Landsat 7, with 7 bands (resolution 30-60 m nadir) plus a higher-resolution panchromatic sensor. NASA's recently launched TERRA satellite has, in addition to MODIS (discussed above), the ASTER package, developed by Japan, which has 14 channels, including short wave IR (2.2, 3.9 micron) and longwave thermal IR bands (8.5, 11, 12 micron) needed for volcano monitoring. The ASTER package includes stereo panchromatic images for each frame, which can be used to generate a DEM if desired. A limitation of both Landsat and ASTER is that their revisit time is 16 days. The new EO-1 satellite also includes an experimental hyperspectral package (Hyperion).

Panchromatic data with 1-m resolution is currently available from the new IKONOS satellite, but cost and tasking of this commercial system remain problematical even for emergency response, much less monitoring, where a time series of images is usually desirable. Another relatively high resolution system would appear to be CSA's EROS-1.

Important research systems to be launched soon are: AQUA (to be launched in December 2001) as a companion to TERRA, and ENVISAT (projected launch date November 2001). ENVISAT capabilities include C-band radar and the MERIS multispectral package. More radar satellites are planned for somewhat farther in the future, including the Japanese ALOS satellite (L-band radar, to be launched in 2003) and Radarsat II (same C-band as Radarsat I, but intended to have characteristics that will allow production of images suitable for interferometric SAR) which has a planned launch date of April 2003. Additional multispectral packages of some interest include AMSR and GLI on ADEOS II. ALOS will also house a panchromatic stereo imager (PRISM) with a resolution of 2.5 m, and SPOT 5 will have a 3 m resolution pan capability. Lastly, CNES will launch the experimental DEMETER system, to monitor pulses in the earth's electromagnetic field, to see if such phenomena are associated with events such as earthquakes and volcanic activity.

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CEOS VOLCANIC HAZARDS TEAM MEMBERS

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Appendix A. Present and Future Satellites and Sensors Useful for Volcanic Hazards

I. Satellites currently in operation	Agency	Channels (µm)	Resolution (best)
<u>Geostationary meteorological satellites</u>			
GOES-8,10	NOAA	0.6, 3.9, 6.7,10.7, 12.0	4 km
GMS-5	NASDA	0.7, 6.9, 11.0, 12.0	5 km (1.25 vis)
MeteoSAT	EUMETSAT	0.7, 6.3, 11.5	5 km (2.5 vis)
<u>Polar-orbiting meterological satellites</u>			
NOAA-12, 14, 15, 16 (AVHRR)	NOAA	0.6, 0.9, 3.9, 10.5, 12.0	1 km
<u>Other polar-orbiting satellites</u>			
Earthprobe TOMS	NASA	6 uv bands	39 km
Landsat 7	NASA/USGS	8 vis/IR + pan	15, 30 m
TERRA (MODIS)	NASA (MODIS, MISR)	36 visible/IR bands	1 km
(ASTER)	METI (Japan)/NASA	14 visible/IR	15-90 m
EO-1 (MODIS)	NASA	Same as Terra	1 km
(Hyperion)	NASA	Hyperspectral	30 m
RADARSAT-1	CSA	C band	6-8 m
ERS-2	ESA/CNES	C band (+ ATSR)	30 m (1 km ATSR)
IRS-P4	ISRO	8 vis/NIR bands	250 m
SPOT 4	CNES	Visible, 0.9,1.6	10-20 m
IKONOS	Space Imaging	panchromatic, multi-spectral	1 m, 4 m
EROS-1	CSA	visible panchromatic	1.8 m

II. Satellites to be brought on line/ launched	**Agency (Launch date)**	**Channels**	**Resolution (best)**
<u>Geostationary meteorological satellites</u>			
GOES-11	NOAA (in orbit)	0.6, 3.9, 6.7, 10.7, 12.0	4 km (1 km vis)
GOES-M	NOAA (in orbit)	0.6, 3.9, 6.7, 10.7, 13	4-8 km (1 km vis)
MeteoSAT Second Generation (SEVIRI)	EUMETSAT (mid-2002)	12 vis/IR bands	5 km (1 km vis)
MTSat-1R	NASDA (early 2003)	0.7, 3.7, 6.7, 10.7,12	4 km (1 km vis)
<u>Polar-orbiting meteorological satellites</u>			
NOAA-M (AVHRR) and others	NOAA (March 2002)	same as NOAA-15, 16	1 km
<u>Other polar-orbiting satellites</u>			
QuikTOMS	NASA (Sept. 2001)	6 UV bands	42 km
AQUA (MODIS)	NASA (Dec. 2001)	36 vis/IR bands1 km	
ENVISAT (ASAR, AATSR)	ESA (Nov. 2001)	C band	30 m (1 km AATSR)
MERIS	“ ”	15 vis, NIR	300 m
RADARSAT-2	CSA (2003)	C band	3 m
ALOS (PALSAR)	NASDA (FY2003)	L band	10-100 m
(PRISM)		Stereo panchromatic	2.5 m
SPOT 5	CNES (March 2002)	6 vis/NIR + pan	5-10 m (3 m pan)
EROS 2-4	CSA	Panchromatic	1.8 m
ADEOS II (AMSR, GLI)	NASDA	39 vis/IR bands	250 m-1 km
DEMETER (electromagnetic pulses)	CNES (early 2003)	Non-imaging	

APPENDIX B: VOLCANIC HAZARDS QUESTIONNAIRE

In early 2000, the Volcanic Hazards group decided it might be informative to send a questionnaire to individual volcano observatories regarding their use of satellite imagery, in response to eruptive activity. The observatories chosen had all seen and responded to volcanic activity in the preceding 2 years, so there were actual, recent events in which satellite imagery or satellite-derived information could have been used. The table below shows the list of volcanoes and summarizes the types of activity they had exhibited.

The format of the questionnaire was as follows:

REMOTE SENSING SURVEY

The following questions concern your observatory's use of remotely sensed data from civilian or commercial sources only:

1. Has your observatory used remotely sensed (satellite/airborne) data to monitor volcanoes? If so, what type of data was used?

2. During the recent activity of (name) volcano, has remotely sensed data been used and if so, of what type (e.g. meteorological satellites, Landsat, radar, aerial photography) and for what purpose?

3. Is your use of remotely sensed data limited by:

Lack of knowledge/expertise

Scientific value of the available data/

Cost?

Timeliness of reception/processing?

4. What type of remotely sensed data would you like to obtain that you do not now?

5. Other comments:

In each case the questionnaire was sent, not simply to the observatory, but to an individual contact with responsibility either for the entire observatory or specifically for remote sensing. The questionnaire was accompanied by a covering letter introducing CEOS and the Volcanic Hazards group, and asking for their assistance. The letter and questionnaire were sent out in English or Spanish as seemed appropriate.

RESULTS OF THE SURVEY

The response rate, although not 100%, was very high, with responses received from all but three of the original observatories polled. A later followup to two observatories and the Indonesian Volcanological Survey netted some additional response.

The responses can be summarized as follows:

1. Most observatories (though not all) do use remotely sensed data. The exceptions are either extremely isolated physically or severely underfunded.

2. The data most commonly accessed and used are from the meteorological satellites (GOES, AVHRR, GMS). They are used to monitor ash clouds and thermal anomalies. In particular, the Hawaii Institute of Geophysics hotspot website is reaching at least part of its intended audience.

Other IR imagery (Landsat, SPOT) is used for thermal monitoring. TOMS is used for SO2, ash and aerosol monitoring. SAR imagery is used for topography and deformation monitoring, though not in real time. High-resolution optical (SPOT, Landsat) is used for topography, location of new lava, ash deposits, etc. Much of this activity occurs at a few observatories which have better access to imagery, the Web, and funding.

3. Most observatories do aspire to use more remotely sensed data if it could be arranged. There is widespread awareness of its potential.

4. Cost of data and lack of expertise are major inhibitors to wider use, and poor timeliness a significant factor for some.

5. Significant use of remotely sensed data of volcanic activity is made by the research community, "off-line" from operational use. Some of this activity is helpful to the observatories, and is shared with them. Some is conducted without communication with the observatories and hence is of relatively little use to them.

We anticipated that the responses would be bimodal, with some observatories making extensive use of satellite data, and others comparatively little. The most encouraging aspect of the responses is the widespread awareness of the existence and utility of satellite imagery, suggesting that the volcano observatories would be a receptive audience to data sharing programs such as the International Charter.

VOLCANIC PHENOMENA POTENTIALLY OBSERVABLE

Volcano	Date of eruption	Ash clouds	Lava flows, dome, etc.; erosion, deformation	Thermal emissions from lava, other	Gas emissions (SO2)
Guagua Pichincha	1999-2000	yes	dome, pyroclastic flows	yes	yes
Tungurahua	1999-2000	yes	ashfall, lahars	yes	very high
Pacaya	2000	yes	lava fountains, flows	yes	minor
Colima	1998-99	yes	dome, pyroclastic flows, ashfall	yes	yes
Popocatepetl	ongoing	yes	dome, minor ashfall	yes	yes
Soufriere Hills	ongoing	yes	dome, pyroclastic flows	yes	yes
Mayon	2000	yes	dome, pyroclastic+lava flow	yes	yes
Rabaul	2000	minor	ashfall	?	minor
Shishaldin	1999	yes	ashfall, bombs	yes	yes
Bezymianny	2000	yes	uncertain	yes	yes?
Piton de la Fournaise	1999-2000	no	lava fountains, flows	yes	minor
Etna	ongoing	yes	lava fountains, flows	yes	yes
Hekla	2000	yes	lava flows	yes	yes
Grimsvotn	1996, 1998	yes	ice cap melted, ashfall, tephra ring	yes?	yes?

Appendix C
Volcanic Hazards Scenarios Proposed for the International Charter

(Referred to in "Data Acquisition" section, Page 13)

Hazardous volcanic activity poses a threat to people and property. Unlike most other natural hazards, the damage inflicted by volcanoes can be significantly mitigated if volcanic behavior is assessed rapidly, as dangerous situations develop. Satellite imagery can provide useful information if available to the right people, and in a timely manner. Therefore we propose the following four scenarios to the committee that governs the International Charter. Each is slightly different, as follows:

Scenario #1

In this scenario, the trigger for a request for assistance under the Charter would be that **an eruption has been reported** at a volcano where there is some prospective danger to people and infrastructure on the ground. This scenario supposes that only the current assets of the Charter member agencies are available. It is further assumed that any danger posed by an ash cloud to aircraft or airport operations will be handled through the existing VAAC/MWO network.

Scenario #2

The trigger for this kind of request for assistance under the Charter would be that **there is major volcanic unrest reported at a volcano which is normally dormant**, and where an eruption would pose danger to people and infrastructure on the ground. It is assumed that any of the satellites listed in Appendix A will be available for tasking through the Charter at some point in the future.

Scenario #3

The trigger for this request for assistance under the Charter would be that, **at a volcano where a long-term eruption has been occurring, there is (1) evidence for a change in behavior to a more dangerous kind of eruption or (2) the build-up of unstable deposits on steep slopes has created a large-scale lahar/debris flow hazard**. Again, populated areas or significant infrastructure must be at risk; as in Scenario #2, we assume any satellite listed in Appendix A will be available.

Scenario #4: Volcanic Ash Scenario

The trigger for a request for assistance under the Charter would be that an eruption has occurred, and has produced a significant ash cloud, resulting in danger to aircraft in flight or in the vicinity of airports. Alerting will be handled through the existing VAAC/MWO network, and the imagery acquired would need to be directed accordingly.

Two other general recommendations for all four scenarios:

Value added processing of imagery or data for scenarios 1-3?

Desirable additional processing includes:
1. Feature labeling, north arrow on imagery desirable if user not the responsible volcano observatory, or if there is no observatory with prior experience for the particular volcano
2. DEM from stereo radar or other stereo imagery, if modern topography not available for the volcano
3. Temperature estimate(s) from IR data

Value added processing of imagery or data for scenario 4?

Desirable features include:
1. Feature labelling (e.g., edge of visible ash cloud, north arrow) on imagery desirable if user not the responsible volcano observatory or VAAC
2. Cloud top height estimates based on temperatures from IR data, cloud shadow length from visible data

Data delivery mechanism, all scenarios:

Project Manager under the Charter will need to ask the end user what will work (ftp, Internet, courier, etc). It may be that derived information FAXed to the observatory may be the fastest means of communication in the absence of adequate electronic connections.

Proposed Volcanic Hazard Emergency Scenario #1:

Obtain background information		Check if considered
1.	Name of volcano and its location (latitude, longitude)	
2.	Date(s) of the eruption(s) that have occurred so far	
3.	Responsible volcano observatory, if any; nature of ground-based monitoring being done for the particular volcano, if any	
4.	Location of nearby urban centres if any; otherwise an estimate of population near the volcano (within a radius of 20 km)	
5.	Location of major air routes near the volcano, identity of responsible VAAC	
6.	Location of roads, airports, factories, mines, etc.	
7.	Previous history of this volcano: frequent small eruptions vs. rare large eruptions? Explosive vs. non-explosive?	
8.	Potential role of water: Is there a lake in the crater or caldera? Is the volcano on the coast? Are there major rivers, lakes, reservoirs, etc nearby?	
	Obtain current and future status of volcanic eruption	
1.	Location of vent area, if not at summit location given above	
2.	Type of eruption(s) so far: ash column? Lava flow or dome? Ash or pyroclastic flow? Lahar or mudflow?	
3.	Seismicity: are there felt earthquakes? Is seismicity increasing?	
4.	Deformation/ground cracking observed?	
5.	New/enhanced steaming or sulfur emission or hot spring activity?	
6	Weather near the volcano (cloud cover, wind profile, etc)	
7	Potential/Expected/Future affected zone as eruption continues	
	Priorities for image planning	
1.	SPOT, standard product, plus especially IR data	
2.	Radarsat (fine mode, 4). Because of steep topography, need high graze angle to reduce shadowing and layover (> 35 degrees)	
3.	ERS, especially to try to duplicate earlier orbital parameters if archival imagery exists, for possible InSAR analysis (otherwise, parameters as for Radarsat)	
4.	Search archives all systems for possible pre-eruption imagery, for visual comparisons, and (for ERS) for potential InSAR	

Proposed Volcanic Hazard Emergency Scenario #2:

	Obtain background information	Check if considered
1.	Name of volcano and its location (latitude, longitude)	
2.	Date(s) of the beginning of unrest	
3.	Nature of unrest (seismic, ground cracking, increased fumarolic activity, etc.) and how much it deviates from normal (dormant) behavior	
4.	Responsible volcano observatory, if any; nature of ground-based monitoring being done for the particular volcano, if any	
5.	Location of nearby urban centres if any; otherwise an estimate of population near the volcano (within a radius of 20 km)	
6.	Location of major air routes near the volcano, identity of responsible VAAC	
7.	Location of roads, airports, factories, mines, etc.	
8.	Previous history of this volcano: frequent small eruptions vs. rare large eruptions? Explosive vs. non-explosive?	
9.	Potential role of water: Is there a lake in the crater or caldera? Is the volcano on the coast? Are there major rivers, lakes, reservoirs, etc nearby?	
	Obtain current status of volcanic unrest and potential for an eruption	
1.	Location of probable vent area, if not at summit location given above	
2.	Any small phreatic explosions? Dirty areas on snow even if no activity directly observed? Landslides or rockfall beyond what is normal?	
3.	Seismicity: are there felt earthquakes? Is seismicity increasing?	
4.	Deformation/ground cracking observed?	
5.	New/enhanced steaming or sulfur emission or hot spring activity? Areas of vegetation kill? Loss of usual snow cover?	
6	Weather near the volcano (cloud cover, wind profile, etc)	
7	Potential/Expected/Future affected zone if eruption occurs	
	Priorities for image planning	
1.	Moderate to high-resolution visible imagery, standard product, plus IR	
2.	Best-resolution C-band SAR imagery. both for visual analysis and for InSAR. If there is steep topography, will need high graze angle to reduce shadowing and layover (> 35 degrees) (ENVISAT, RADARSAT-2)	
3.	If areas of concern are vegetated (especially in tropics) L-band SAR, as available, for InSAR evaluation of deformation patterns	
4.	Search archives all systems for possible pre-eruption imagery, for visual comparisons, and for potential InSAR	

Proposed Volcanic Hazard Emergency Scenario #3:

	Obtain background information	Check if considered
1.	Name of volcano and its location (latitude, longitude)	
2.	Date(s) of the eruption(s) that have occurred so far	
3.	Responsible volcano observatory, if any; nature of ground-based monitoring being done for the particular volcano, if any	
4.	Location of nearby urban centres if any; otherwise an estimate of population near the volcano (within a radius of 20 km) . Towns built on lahars?	
5.	Location of major air routes near the volcano, identity of responsible VAAC	
6.	Location of roads, airports, factories, mines, etc.	
7.	Previous history of this volcano: Long eruptions, or multistage eruptions, that become more explosive in the later stages? Does it have deposits of large pyroclastic flows or lahars that have traveled long distances?	
8.	Potential role of water: Is there a lake in the crater or caldera? Is the volcano on the coast? Are there major rivers, lakes, reservoirs, etc nearby?	
	Obtain current and future status of volcanic eruption	
1.	Location of vent area, if not at summit location given above	
2.	Type of eruption(s) so far: Lava flow or dome? Any ash or pyroclastic flows? Thickness of accumulated ash? Any estimates of volume?	
3.	Seismicity: are there felt earthquakes? Is seismicity increasing?	
4.	Any new or increased deformation/ground cracking observed?	
5.	New/enhanced steaming or sulfur emission or hot spring activity?	
6	Weather near the volcano (cloud cover, wind profile, etc). Is there a predictable rainy season that is imminent?	
7	Potential/Expected/Future affected zone for severe eruption? Maximum possible lahar run-out distances?	
	Priorities for image planning	
1.	Moderate to high-resolution visible imagery, standard product, plus IR	
2.	Best-resolution C-band SAR imagery, both for visual analysis and for InSAR. Because of steep topography, need high graze angle to reduce shadowing and layover (> 35 degrees) (ENVISAT, RADARSAT-2)	
3.	If areas of concern are vegetated or covered by ash or other material unstable on a small scale, L-band SAR, as available, for possible InSAR	
4.	Search archives all systems for possible pre-eruption imagery, for visual comparisons, and for potential InSAR	

Proposed Volcanic Ash Cloud Scenario:

	Obtain background information	Check if considered
1.	Name of volcano and its location (latitude, longitude)	
2.	Date(s) and time(s) of the eruption(s) that have occurred so far	
3.	Responsible volcano observatory, if any; nature of ground-based monitoring being done for the particular volcano, if any	
4.	Locations of major air routes, identity of responsible VAAC	
5.	Locations of airports	
6.	Potential role of water: Is there a lake in the crater or caldera? Is the volcano on the coast? Are there major rivers, lakes, reservoirs, etc nearby?	
	Obtain current and future status of volcanic ash cloud	
1.	Type of eruption(s) so far: ash column? Lava flow or dome? Ash or pyroclastic flow? Lahar or mudflow? Suspected water/ice content of ash cloud?	
2.	Cloud coverage near the volcano	
3.	Predicted ash movement from trajectory models (VAFTAD, CANERM, PUFF, etc)	
4.	Strength and direction of winds aloft (from radiosonde, profiler, model or aircraft)	
	Priorities for image planning	
1.	Operational geostationary satellite images (visible, IR) and derived products (e.g. split window) (GOES, METEOSAT, GMS) at 30 minute intervals	
2.	Operational polar orbiting satellite images and derived products (AVHRR, FY1-C)	
3.	Research polar orbiting satellite images and derived products (EOS Terra, Aqua, EP-TOMS, etc)	
4.	High resolution images (visible, near-IR, IR) from land use satellites (Landsat, SPOT)	

APPENDIX D.

LIST OF ACRONYMS/ABBREVIATIONS

ACC - Area Control Centre

ADEOS - ADvanced Earth Observing Satellite (Japan)

AIRS - Advanced Interferometric Radiometric Sounder (United States)

ASL - Above Sea Level

ASTER - Advanced Spaceborne Thermal Emissive Radiometer

ATSR - Along Track Scanning Radiometer

AVHRR - Advanced Very High Resolution Radiometer

CANERM - CANadian Emergency Response Model

CENAPRED - El Centro Nacional de Prevencion de Desastres, the geophysical agency of Mexico

COSPEC - Correlation Spectrometer

DEM - Digital Elevation Model

DU - Dobson Units

ENVISAT - ENVironmental SATellite (Europe)

EOS - Earth Observation System (United States)

ERS - Earth Resources Satellite (Europe)

EUMETSAT - European Organisation for the Exploitation of METeorological SATellite date

GOES - Geostationary Operational Environmental Satellite (United States)

GMS - Geostationary Meteorological Satellite (Japan)

IAVCEI - International Association of Volcanology and Chemistry of the Earth's Interior

IAVW - International Airways Volcano Watch

ICAO - International Civil Aviation Organization

InSAR - Interferometric Synthetic Aperture Radar

JMA - Japan Meteorological Agency

JERS - Japanese Earth Resources Satellite

LEO - Low Earth Orbit

MEDIA - Modele Eulerian de DIspersion Atmospherique (France)

METEOSAT - METeorological SATellite (Europe)

METOP - Meteorological Operational satellite (Europe)

MODIS - Moderate Resolution Infrared Spectrometer (United States)

MSG - Meteosat Second Generation (Europe)

MTSAT - Ministry of Transportation SATellite (Japan)

MWO - Meteorological Watch Office

NAME - Nuclear Accident Model (Great Britain)

NASA - National Aeronautics and Space Administration (United States)

NASDA - NAtional Space Development Agency (Japan)

NESDIS - National Environmental Satellite, Data and Information Service (United States)

NOAA - National Oceanographic and Atmospheric Administration (United States)

NOTAM - NOTices to AirMen

OCTS - Ocean Color and Temperature Scanner

OP-FTIR - Open Path Fourier Transform Infra Red Spectrometer

SAR - Synthetic Aperture Radar

SIGMET - SIGnificant METeorological information

SPOT - high resolution land use satellite (France)

SWIR - Short Wave InfraRed

TIMS - Thermal Infrared Mapping Spectrometer

TIR - Thermal InfraRed

TM - Thematic Mapper

TOMS - Total Ozone Mapping Spectrometer

USGS - United States Geological Survey

UV - Ultra-Violet

VAAC - Volcanic Ash Advisory Center

VAA - Volcanic Ash Advisory

VAFTAD - Volcanic Ash Forecast Transport and Dispersion (United States)

VOLCAM - VOLCanic Ash Mapping (United States)

WMO - World Meteorological Organization

WOVO - World Organization of Volcano Observatories

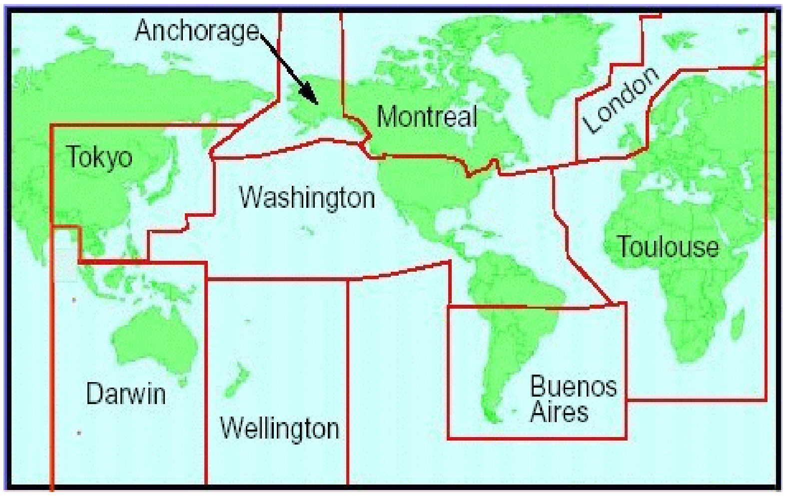

Figure 1. Areas of monitoring responsibility for the Volcanic Ash Advisory Centers (VAAC) established by ICAO. Shaded areas are unmonitored. (Courtesy of D. Schneider, Alaska Volcano Observatory)

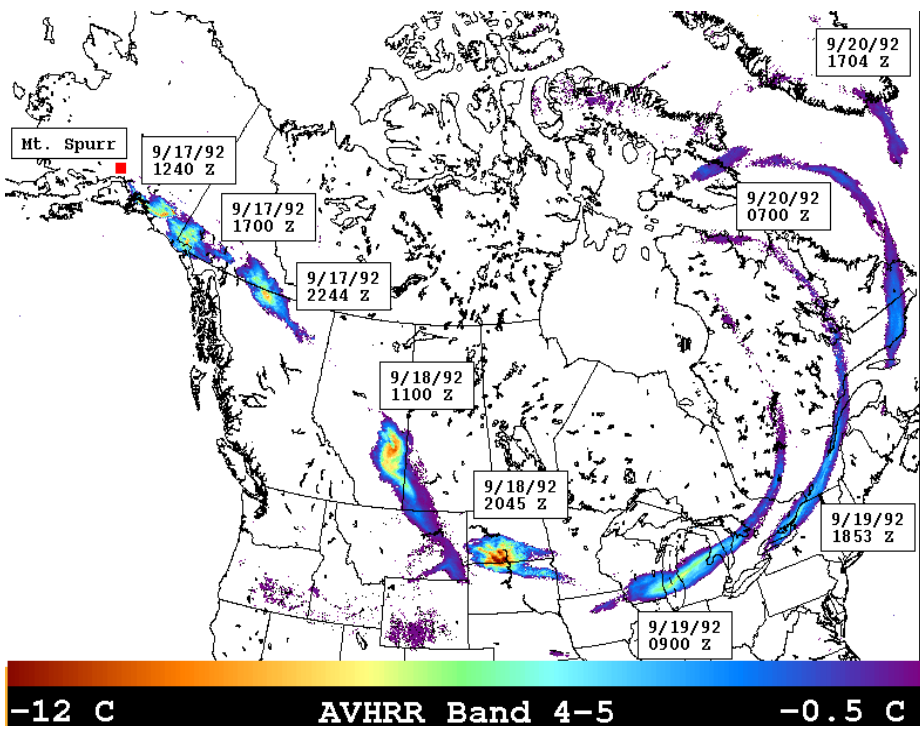

Figure 2. Path of eruption cloud from Mount Spurr eruption of 17 September 1992 from NOAA AVHRR band 4-5 (split window) over a three day period (Schneider et al. 1995)

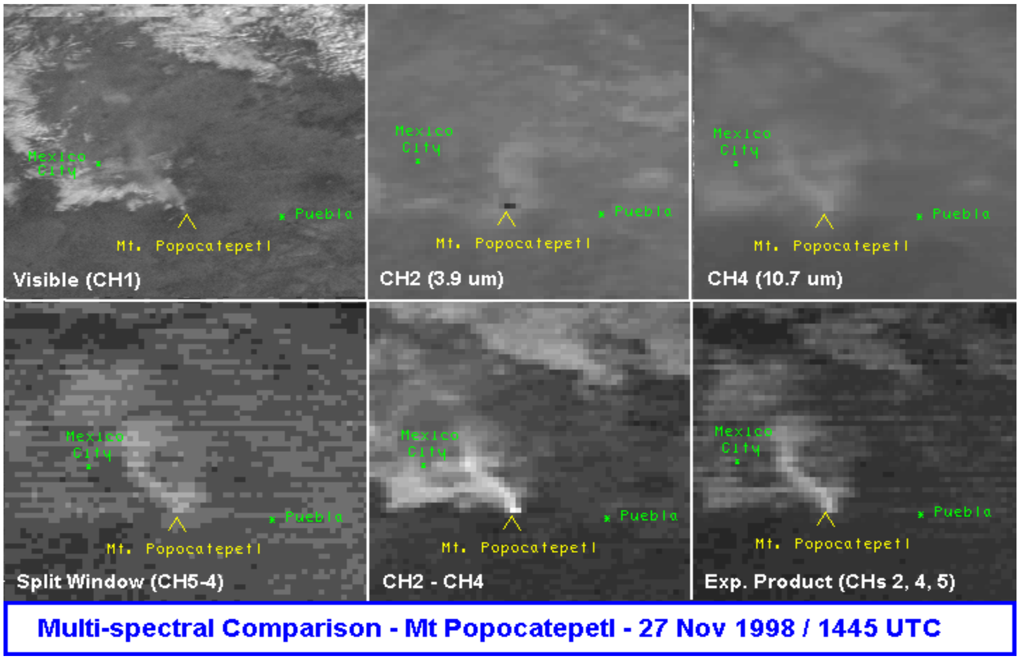

Figure 3. Multi-spectral comparison of GOES-8 data for an eruption of Popocatepetl on 27 November 1998.

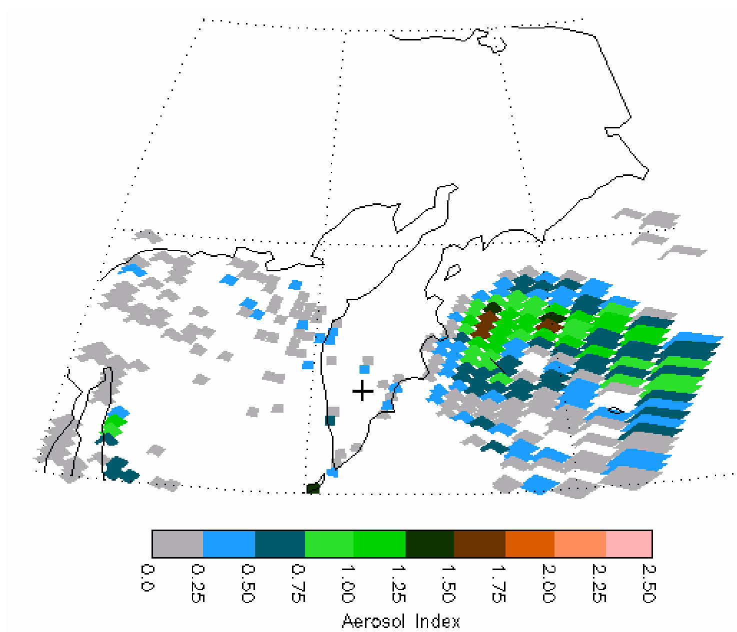

Figure 4. TOMS UV Aerosol Index from the ADEOS satellite on May 8, 1997 showing extent of volcanic ash from an eruption of Bezymianny (at location shown by +). The resolution of TOMS UV is about 40 km at nadir. (NASA)

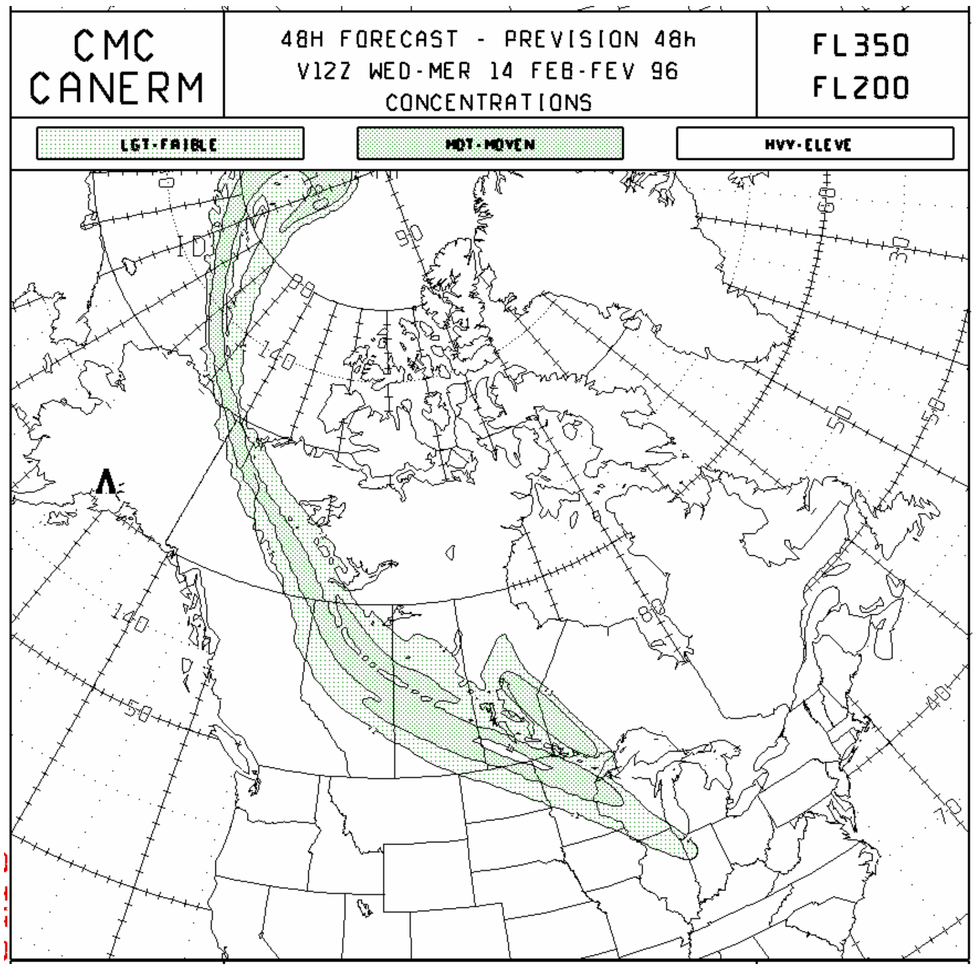

Figure 5. Canada Emergency Response Model (CANERM) 48 hour forecast output valid on 14 February 1996 at 1200 UTC for an eruption of the Mt. Spurr volcano in Alaska (from Servranckx et al. 1996). Ash concentrations are color coded for the altitude range from 20,000 ft (Flight Level 200) to 35,000 ft (FL350) above Mean Sea Level (MSL).

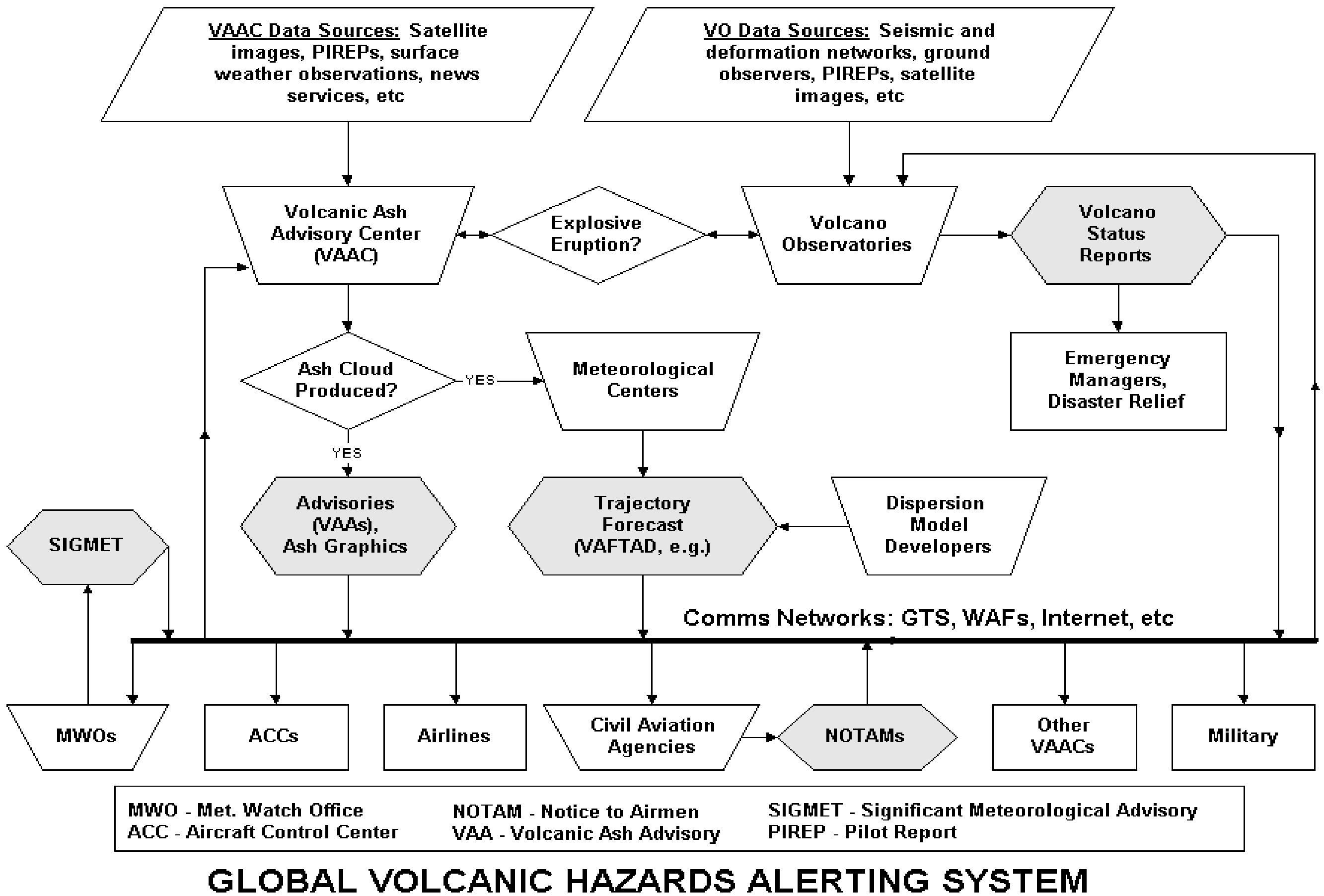

Figure 6. Generic flow chart showing the global volcano hazard alerting system. Products are shaded. Users are shown within rectangles, agencies responsible for products are shown by trapezoids.

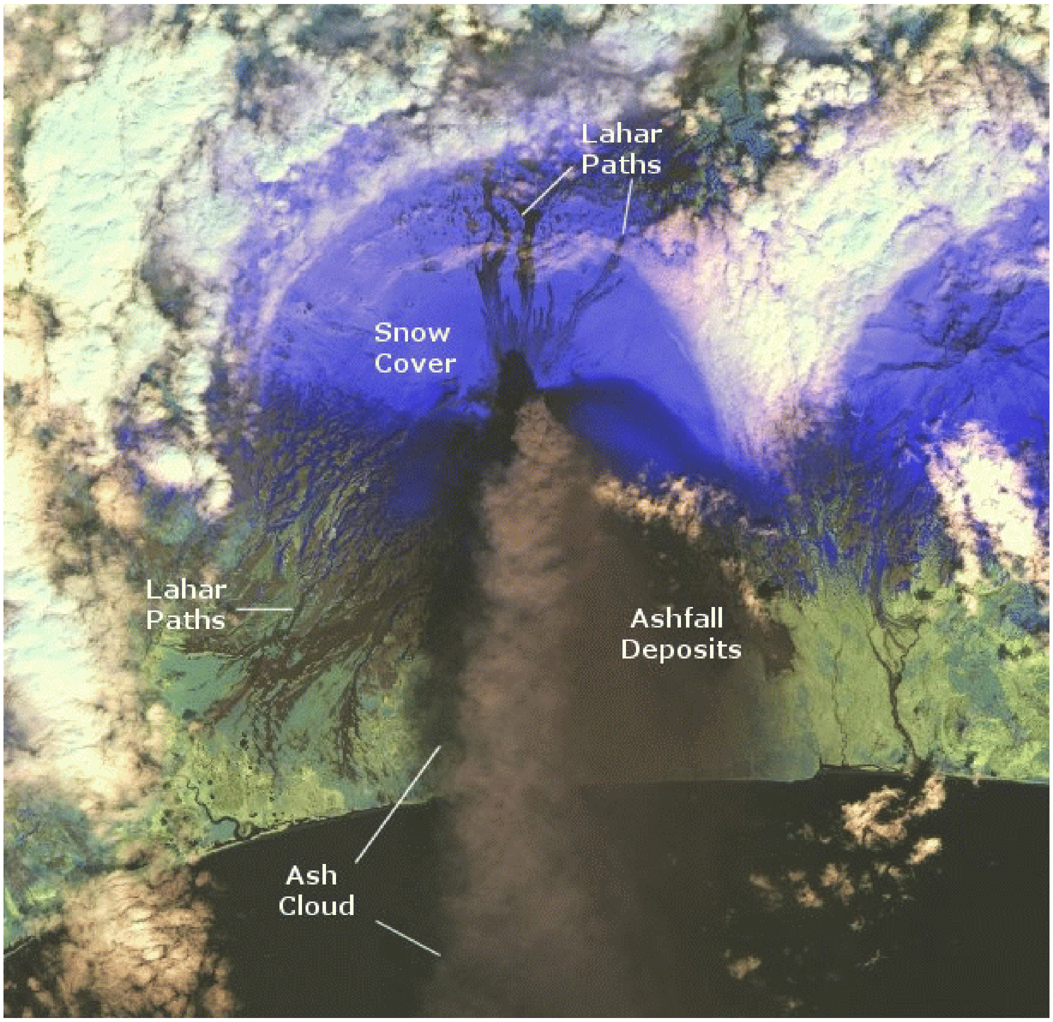

Figure 7. Multi-spectral Landsat image of Shishaldin volcano on May 25, 1999, showing ash-bearing eruption cloud (gray plume at bottom center) and an area of ashfall deposits to the south of the volcano (dark area under gray plume). Lahar pathways in the snow are also visible through light cloud on the north side of the volcano (top center) and to the southwest (lower left). Blue areas indicate snow cover. Image processed and interpreted by D. J. Schneider, USGS. Satellite source: Landsat-7 (false-color image, using bands 7 (2.2 µm), 5 (1.6 µm) and 4 (0.8 µm). North is up.

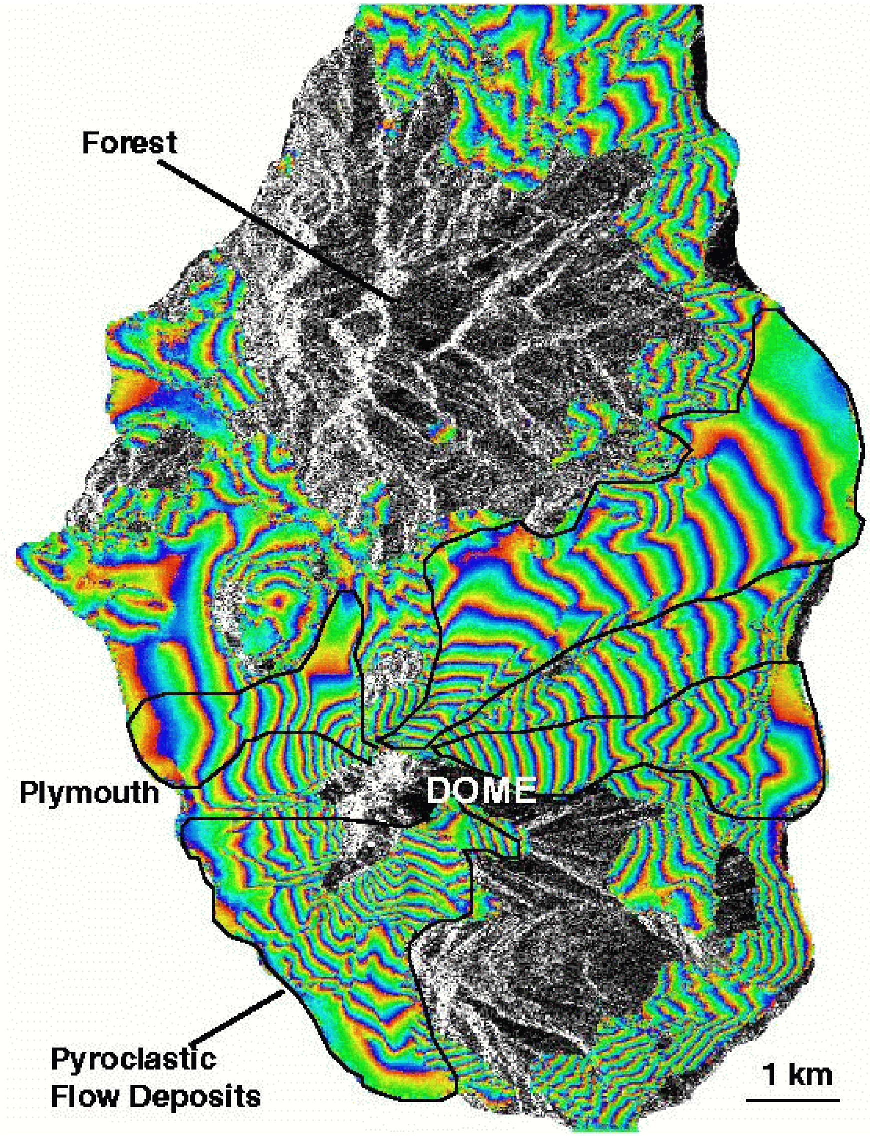

Figure 8. SAR image (in slant range) of Montserrat during the ongoing eruption of Soufriere Hills Volcano (1995-). The grey tones are amplitude data and the colour is interferometric phase data. In this case the phase has not been corrected for topography so we see the effects of topography as fringes representing about 45m of relief per fringe (blue-green-yellow-red closer to the satellite). The data are from the ERS-1 and -2 C-band SARs (copyright ESA) acquired on 4 and 5 March 1999 respectively. The phase data are lost over this 24 hour period in areas of forest and from part of the growing lava dome. The pyroclastic flow deposits, some of which destroyed Plymouth the main town of Montserrat, are shown in outline. (from Wadge et al 2001)