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Satellite observations of active volcanoes: Prospects for the 1990s

Observations of volcanoes and volcanic eruptions worldwide are being made increasingly often by the use of sensors that are flown upon Earth-orbiting spacecraft. Particularly exciting are the new capabilities that enable remote measurements of the temperatures of lava flows and volcanic domes, the regional dispersal of eruption plumes, and the topography and structure of cloud-covered volcanoes in areas such as Indonesia, Central America, and the Aleutian Islands. These measurements will become an integral component of observations made by the National Aeronautics and Space Administration's Earth Observing System, due for launch in 1998, and will present new challenges in terms of data handling and the political aspects of volcano-hazard monitoring.

Introduction

The 1990s will see the use of many new remote sensing instruments in studies of volcanoes and volcanic eruptions. By providing access to a completely new range of observations, the instruments flown on satellites and aircraft will contribute significantly to our knowledge of both eruption processes and the impact of eruptions on the environment. By providing views of so many volcanoes so often, remote sensing techniques also provide entirely new means for monitoring volcanoes worldwide and thus of contributing to the mitigation of volcanic hazards. Space-based instruments provide a unique synoptic perspective on the massive perturbations to the atmosphere that are caused by large volcanic eruptions. Thus, in the decade ahead, the interaction between volcanism and the atmosphere will be one of several interdisciplinary studies that will draw geologists and other earth scientists into closer collaborations. Specifically, the monitoring of the dispersion of stratospheric aerosols from large eruptions will provide an important means of testing and refining the global circulation models that are critical to the current debates about atmospheric evolution and global climatic change.

This article reviews some of the satellite systems that are being used to study volcanoes, provides a summary of planned missions that will have a strong volcanology component, and discusses the implications of using remote sensing in order to identify and monitor volcanic hazards. A list of acronyms is provided in table 1.

Current capabilities

Mouginis-Mark and others (1989) reviewed the applications of many remote sensing techniques as they are applied to the analysis of volcanoes and volcanic terranes. Briefly, satellite and airborne sensors have been used already in the following types of volcanology investigations:

- (1) Mapping the distribution of volcanic lithologies in remote areas (for example, Landsat TM studies of the central Andes: Francis and de Silva, 1989; de Silva and Francis, 1990);
- (2) Identifying potentially active volcanoes and characterizing their styles of activity (de Silva and Francis, 1990);

Table 1.—Acronyms

Acronym	Full name
ADEOS	Advanced Earth Observing Satellite
ARGOS	Data storage and forward channel on European satellites
ASTER	Advanced Spaceborne Thermal Emission and Reflection radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVO	Alaskan Volcano Observatory
CVO	Cascades Volcano Observatory
EOS	Earth Observing System
EOSP	Earth Observing Scanning Polarimeter
ERS-1	European Remote Sensing satellite #1
GOES	Geostationary Operational Environmental Satellite
GSFC	Goddard Space Flight Center
GVN	Global Volcanism Network
HVO	Hawaiian Volcano Observatory
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior
IDNDR	International Decade for Natural Disaster Reduction
IGBP	International Geosphere-Biosphere Programme
JERS-1	Japanese Earth Resources Satellite #1
MISR	Multiangle Imaging SpectroRadiometer
MLS	Microwave Limb Sounder
MODIS	Moderate Resolution Imaging Spectrometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
RIDGE	Ridge InterDisciplinary Global Experiment
SAGE III	Stratospheric Aerosol and Gas Experiment #3
SAR	Synthetic Aperture Radar
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SIR-A	Shuttle Imaging Radar experiment A
SIR-B	Shuttle Imaging Radar experiment B
SIR-C	Shuttle Imaging Radar experiment C
SPOT	Système Probatoire d'Observation de la Terre
TES	Tropospheric Emission Spectrometer
TIMS	Thermal Infrared Multispectral Scanner
TM	Thematic Mapper (Landsat)
TOMS	Total Ozone Mapping Spectrometers

Figure 1.—Landsat 4 TM image of Lascar volcano, northern Chile, acquired March 11, 1985. TM bands 7, 5, and 2 are displayed in red, green, and blue, respectively. Active crater is at center of nested crater chain; thermal anomaly is observed in this image as a bright red spot. Prominent lava flow northwest of Lascar is thought to have erupted in the 19th century. Image width is equivalent to 15 km. Volcano on the right is Cerro Aguas Calientes (inactive).

- (3) Identifying large volcanic debris avalanche deposits and the factors rendering volcanoes prone to collapse (Francis and Wells, 1988);
- (4) Tracking the dispersal of major eruption plumes (AVHRR, TOMS: Matson, 1984; Krueger and others, 1990);
- (5) Monitoring the thermal characteristics of lava flows, lava tubes, and volcanic domes (Landsat TM, TIMS, and AVHRR: Glaze, Francis, and Rothery, 1989; Pieri and others, 1990; S.K. Rowland and others, unpublished data, 1991);
- (6) Investigating the spatial distribution of lava morphologies (SIR-B and aircraft radar) in order to aid rheological studies of the flows (Gaddis and others, 1990).

Volcanological applications of remote sensing techniques

Observations of Lascar volcano, northern Chile, provide instructive examples of volcanological applications of remote sensing techniques. Lascar is a 5,641-m-high volcano on the crest of the Andean chain in northern Chile (fig. 1). It has shown minor fumarolic activity throughout historic times, but no records of major eruptions exist. Because it is located at high altitude in a remote desert region, it has been difficult to obtain useful information on the condition of the volcano. When a powerful explosive eruption took place on September 16, 1986, the first reports reached the scientific commu-

Figure 2.—Subscenes from Landsat 4 TM images showing the temporal evolution of the thermal anomaly within Lascar crater. Width of each subscene is equivalent to 1 km. Dates of acquisition are March 11, 1985; July 21, 1985; October 27, 1986; and November 12, 1986. The major eruption took place 41 days before the October 27 scene was obtained.

nity not from the vicinity of the volcano but from Salta in Argentina, almost 300 km distant, where ash fall was recorded. Two aspects of Lascar's activity have been monitored by the use of satellite sensors that have quite different spectral, spatial, and temporal resolutions. We emphasize, however, that none of these sensors were designed specifically for the analysis of volcanoes; Landsat, for instance, has agriculture and land use as its primary investigations.

Landsat

Near-infrared Landsat TM images having a spatial resolution of 30 m have been used to monitor radiant thermal energy from Lascar volcano on a number of occasions over a period of 7 years. Evidence of previously unsuspected thermal activity at Lascar was discovered serendipitously during examination of a Landsat TM image of the

area for another purpose. At this time, an anomaly covering only about 20 pixels in TM bands 5 (1.55–1.75 μm) and 7 (2.08–2.35 μm) was revealed as a bright spot in the center of Lascar's active crater (Francis and Rothery, 1987). In a subsequent study, Rothery and others (1988) determined that the temperature of the anomaly was in the range 800–1,000 $^{\circ}\text{C}$, which is clearly consistent with magmatic temperatures and possibly was related to hot lava within the summit crater or to high-temperature fumaroles. In order to monitor the thermal flux from the volcano, retrospective and contemporary TM images have been acquired that span the date of the 1986 eruption from 1984 to the present day (fig. 2). Prior to the 1986 eruption, the radiant thermal energy flux showed a marked decrease. Immediately after the eruption, the anomaly, previously a single well-defined entity, appeared weak and fragmented into smaller centers. In subsequent months, radiant thermal energy flux increased

Figure 3.—GOES image collected at 12:12 UT (Chilean time = UT minus 4 hours), September 16, 1986, taken with the visible band, showing the eruption plume near the town of Salta approximately 93 minutes after the eruption. Lascar volcano is marked by the unlabeled arrow. North is to the top. Width of image is ~550 km.

dramatically, and it reached unprecedented high levels in 1988, which indicated that Lascar was in an unusually active state. Field investigations in 1987 and 1988 revealed a growing andesitic lava dome in the summit crater. This was the first record of lava extrusion in the central Andes and the first time that any such event had been detected exclusively by the use of remote sensing techniques. Thermal monitoring of Lascar and other volcanoes continues. An important research objective thus lies in characterizing the thermal signatures of different kinds of volcanic phenomena and in determining how thermal data can be used best in the assessment of likely future volcanic activity.

GOES

1.2 km resolution visible (0.55–0.75 μm) images acquired every 30 minutes from the GOES geostationary satellite were used to monitor the downwind dispersal of the September 16 eruption cloud from Lascar volcano (Glaze, Francis, Self, and Rothery, 1989). The eruption of Lascar, which took place at 10:39 UT (universal time) (+2 minutes) on September 16, 1986, lasted less than 5 minutes and produced a Vulcanian-type eruption column that rose to a height of

about 15 km and was borne downwind rapidly. Ground observations and GOES images showed that the eruption plume formed a discrete extended slug about 2 km thick at altitudes between about 10 and 14 km and passed over the city of Salta, Argentina, 285 km distant from Lascar, less than 2 hours after the eruption (fig. 3). The velocity of the leading edge of the cloud was derived from its position on successive GOES images, and its altitude was determined from shadow length measurements to be ~14.5 km (Glaze, Francis, Self, and Rothery, 1989). By 14:12 UT, the plume had diffused, having traveled 400 km in 3.5 hours, and covered an area greater than 100,000 km^2 . Thermal infrared GOES images were used to measure the plume temperature at different points along its track. The temperature at the top of the plume 1 hour after the eruption was -40.2°C , which corresponds with an altitude inferred from radiosonde data to be 10.6 km, significantly lower than that derived by shadow measurement. This unexpected discrepancy has focused research on various aspects of volcanic plume physics. Understanding of the ascent and dispersal of volcanic plumes will be of first importance not only for volcanological studies but also for broader problems of atmospheric circulation. Additionally, the Lascar study drew attention to a more immediate problem: the rapid downwind transport of the ash

Figure 4.—The dispersal of the sulfur dioxide cloud from the eruption of El Chichón volcano was mapped by the TOMS instrument on Nimbus 7, April 8, 1982. Abbreviation: MILLI ATM CM, milliatmosphere, in centimeters. Image provided by L. Walter, Goddard Space Flight Center, Greenbelt, Maryland, USA.

cloud could abruptly place at risk aircraft flying to and from cities such as Salta, far removed from the volcano. Incidents where large passenger aircraft have lost power in all engines after unexpectedly entering an ash cloud, such as that of Redoubt Volcano, Alaska, in 1990, demonstrate the major hazard that such plumes present and the urgent need to develop means of providing rapid warning of their location (Steenblik, 1990).

GOES (East) and GOES (West) geostationary satellites and the polar-orbiting NOAA 7 satellite also were used earlier to monitor the dispersal of a far larger eruption cloud, one that was injected into the stratosphere. An eruption of El Chichón volcano, southern Mexico, in April 1982 took the lives of many hundreds of people who were living on the flanks of the volcano (Rampino and Self, 1984). Just before the eruption of April 3, the wind in the stratosphere began to blow in its summer pattern from the east. A dense aerosol plume from the eruption, centered at about 20° N., reached Hawaii by April 9, Japan by April 16, and the Red Sea by April 20, and it encircled

the Earth completely by April 26. The cloud traveled westward at an average speed of about 20 m per second but expanded rather little to north and south and only covered about 25 degrees of latitude (Kent and McCormick, 1988).

TOMS

On board the Nimbus 7 satellite, the TOMS instrument normally is used to measure the level of ozone absorption in the upper atmosphere at ultraviolet wavelengths. Because sulfur dioxide also absorbs at two wavelengths near 0.3 μm , it too can be detected with the TOMS. TOMS data, for example, were used to map the distribution of sulfur dioxide from the El Chichón eruption (fig. 4). As much as 3.3 million tons of gaseous sulfur dioxide appear to have been injected into the stratosphere during this event (Krueger, 1983). Within 3 months of the El Chichón eruption, all of this sulfur dioxide appears to have been converted to sulfuric acid, which, in the form of

an aerosol, is the medium that mostly is responsible for the attenuation of solar radiation and consequent surface cooling and weather effects observed after large volcanic eruptions. (Ash particles fall out relatively rapidly). El Chichón's aerosol cloud may have caused a reduction in average monthly temperatures of about 0.2 °C in June 1982. Data from TOMS experiments also have been used to track the aerosols that were generated by several other major explosive eruptions, such as the 1985 eruption of Nevado del Ruiz, Colombia (Krueger and others, 1990).

AVHRR

The NOAA AVHRR is operating today on three spacecraft, NOAA-9, 10, and 11. These meteorological satellites are designed primarily for synoptic mapping of clouds and ocean-surface temperatures measuring radiance at visible to near-infrared (0.55–1.10 μm), mid-infrared (3.55–3.93 μm), and thermal infrared (10.3–12.5 μm). The AVHRR sensor has a spatial resolution of ~ 1 km. Because each satellite can observe an area on the Earth's surface twice each day (once during the day and once at night), it is possible to compile a high temporal-resolution data base of dynamic phenomena. Several scenes of an area may be obtained each 24 hours (the exact number of images depending upon the latitude of the target), which permits the rate of dispersal of a volcanic plume or the advance of lava flows to be monitored (S.K. Rowland and others, unpublished data, 1991). Thermal anomalies due to ongoing volcanic eruptions, such as the Pu'u O'o and Kupaianaha eruptions on the southeast flank of Kilauea volcano in Hawaii (fig. 5), thus can be studied in order to determine the evolution of a lava flow field over a period of weeks to months. The locus of surface activity has been seen to move from the Pu'u O'o and Kupaianaha vents down to the midlevel break in slope, where compound lava flows occasionally break out to the surface, and on to the coast, where the individual lava flows reach the ocean. Although these Hawaii AVHRR measurements do not replace the more detailed local measurements of the movement of flows as determined on the ground, they do demonstrate the advantage of using daily satellite measurements to track the large-scale motion of lava flows should they be detected on volcanoes that are less well monitored than those in Hawaii.

SAR

Optical and infrared sensors such as the Landsat TM and AVHRR have the major disadvantage that they only can observe a volcano during cloud-free conditions. Microwave sensors such as SARs do not suffer from this limitation and offer complementary information to the optical sensors for monitoring volcanoes. In volcanology, SARs have been used only in an exploratory manner until now. Data collected during the space shuttle radar flights in 1981 (fig. 6) and 1984 have been used to map the distribution of lava flows, cinder cones, and fault zones (see, for example, Gaddis and others, 1989). Starting in September 1991 with the operation phase of ERS-1, SAR data for the volcanoes in the Aleutian Islands and on the Alaskan peninsula will be obtained every 35 days (the timing of the spacecraft's repeat orbit). Topographic and deformation maps of these volcanoes will be compiled by using radar interferometry techniques (Gabriel and Goldstein, 1988; Gabriel and others, 1989) in order to search for dome growth, the formation of new lava flows or cones, or changes in summit ice cover that might be related to the onset of volcanic activity.

Earth Observing System (EOS)

Over the next decade, a major effort in remote sensing in volcanology will be 1 of 28 interdisciplinary investigations for EOS, due to be launched by NASA starting in 1998 (Mouginis-Mark and others, 1991). EOS is an ambitious "Mission to Planet Earth" and is intended to deploy NASA's unrivaled expertise in the scientific exploration of remote planets to a broad range of problems that are related to global change on Earth. The volcanological investigation, which includes about 20 volcanologists and remote sensing specialists in the United States and United Kingdom, will include both long-term and short-term monitoring of selected volcanoes, the detection and analysis of precursor activity associated with eruptions, and the monitoring of ongoing eruptions.

The data collected by EOS will allow two aspects of volcanism to be addressed. First, it will further our knowledge about the distribution of volcanic landforms, their temporal evolution, and the nature of the potential hazards posed by individual volcanoes. Second, it will provide a means for documenting, both in the immediate vicinity of the volcano and on a hemispheric scale, the compositions, flux rates, and total atmospheric budgets of the gases, particulates, and aerosols that are injected into the atmosphere by volcanoes. This category of EOS interdisciplinary investigations also will address the links between the magnitude and style of specific eruptions and the other components of the Earth system, such as the distribution of sea-surface temperatures, weather, short-term climate, and different ecosystems.

A variety of instruments on the NASA EOS platforms, together with additional data from NOAA and Japanese platforms, will enable the study of local to regional scale thermal and topographic features of volcanoes, and these will complement ground-based studies. On a larger scale, the same instruments will permit the study of the chemical and structural features of volcanic eruption plumes and aerosols, a critically important area of investigation that can be addressed only by using the synoptic view that is provided by spacecraft. Studies of the composition of plumes are particularly important because, at the present time, little is known about the rates at which gases other than sulfur dioxide are transmitted to the atmosphere by volcanic activity. The determination of the fluxes of H_2O , HCl , CO_2 , and H_2S would be especially valuable.

The principal instruments on EOS that will be used for volcanology include the following:

- (1) MODIS will obtain daily synoptic visible to near-infrared data at 1-km resolution, will be used for the detection of new eruptions by the identification of thermal and SO_2 anomalies, and will track the dispersal of plumes.
- (2) The EOS SAR will not only provide images of ongoing eruptions under day and night and all weather conditions but will also permit (by the use of interferometry) the generation of topographic maps of volcanoes and the study of topographic change. This last attribute will detect the emplacement of a new lava flow or cone, will measure the swelling of a volcanic dome or rift zone, and will enable temporal studies of lava effusion. Imaging radar studies of volcanoes are now in their infancy, but given the facts that many volcanoes in tropical latitudes are frequently covered by clouds and that others at high latitudes are in darkness for long periods, imaging radars ultimately are likely to prove crucial to the successful development of routine volcano-monitoring techniques.

Figure 5.—AVHRR image of Kilauea volcano, Hawaii, obtained by the University of Hawaii on September 1, 1990. This nighttime thermal infrared scene ($11.5\text{--}12.5\ \mu\text{m}$), obtained at 2:42 a.m. local time (HST, Hawaiian standard time), has been processed to show surface temperatures between 0 and 48 °C (see temperature bar at bottom). The active lava flow (east side of island) and a brush fire (extreme southern tip of island) were both detected in these data

that have 1-km spatial resolution. The Big Island of Hawaii is ~130 km in an east-west direction. Mauna Loa and Mauna Kea volcanoes appear yellow in this rendition because of their height and resultant cold temperatures. A large cloud (green) is indicated off the west coast at Kona. Image provided by P. Flament and H. Garbeil, University of Hawaii, Honolulu, Hawaii, USA.

Figure 6.—Nemnut Dagi caldera (center) and Lake Van (black area at left) in southeastern Turkey were imaged by the SIR-A radar experiment, flown on the space shuttle in November 1981. The caldera is 5×9 km in diameter and shows several radar-bright flows within its interior. Several parasitic lava domes and cones are also visible in this image. Radar look direction is from the top. SIR-A data take 35/36.

- (3) The ASTER instrument is a set of three sensors that will operate in the visible to near-infrared and thermal infrared, and it will obtain 15 m/pixel stereo images in the visible part of the spectrum. ASTER will be used to study lava flow and eruption plume temperatures and the topography of volcanic cones and plumes, and it will be the principal instrument for monitoring volcanoes for changes in fumarole distribution and temperature (at relatively low temperatures, that is, <100 °C), which may be precursors of new activity.
- (4) Several EOS instruments also will be used extensively to study volcanic gases. MISR, SAGE III, and EOSP will be used for distribution studies of volcanic aerosols. Particularly in the case of MISR, high-resolution (~250 m/pixel) stereo images of volcanic plumes will be obtainable, and the distribution of tropospheric aerosols will be determined from their light-scattering properties at multiple viewing angles. TES will be able to measure tropospheric SO₂, CO, COS, H₂S, and HCl and qualitative amounts of H₂O and CO₂. Vertical profiles of SO₂ (between 15 and 30 km in altitude) and HCl (15–60 km) will be obtainable from MLS.

Other satellite missions

Prior to the launch of EOS, existing polar-orbiting remote sensing satellites, such as Landsat 5, SPOT, and meteorological satellites, will continue to provide valuable data. It will also be possible to use experiments flown on the space shuttle and other satellites to collect data on volcanoes. Three radar systems (JERS-1, ERS-1, and

Radarsat) will be flown in the 1991–1994 timeframe, and the space shuttle will carry the third Shuttle Imaging Radar (SIR-C) experiment in 1993 and 1994. From the shuttle, volcanoes in Hawaii, the Galapagos Islands, the Indian Ocean, and the Andes will be imaged. From ERS-1, the topography and morphology of volcanoes in the Aleutian Islands also will be investigated.

Atmospheric studies will continue to be an important part of volcanology investigations from satellites even before EOS is launched. Although the primary objective of the TOMS instrument is the measurement of ozone, this instrument has been used successfully since 1978 on the Nimbus-7 spacecraft to study the SO₂ released into the stratosphere by major eruptions. A series of TOMS instruments is planned for launch starting with the Soviet Meteor-3 spacecraft in 1991 and is to be followed by a dedicated Earth Probe satellite in 1993 and the Japanese ADEOS satellite in 1995. SAGE III, which will measure the stratospheric aerosol concentration, either will fly on an Earth Probe-class satellite in the middle 1990s or will be part of an EOS platform.

The SeaWiFS, which is an 8-band visible to near-infrared radiometer, is scheduled for launch in late 1993 and may provide the first opportunity to search for shallow marine eruptions on the basis of the resultant discoloration of the sea surface.

Issues related to satellite monitoring of volcanoes

The advent of satellite investigations of volcanoes and volcanic eruptions anywhere in the world, sometimes in near real-time, raises

several important administrative and political issues. The geological remote sensing community rarely has had to face these issues, but they are encountered commonly by volcanologists in the field (Tilling, 1989). Some of these issues follow.

Involvement of local scientists and government authorities

How do we involve local scientists and government authorities? Access to satellite data does not make an investigator in a laboratory an immediate expert on a remote volcano. Given the volume and breadth of remote sensing data that EOS will provide, it should be possible to monitor remote volcanoes, to detect changes in volcanic activity, and when experience has been accumulated over many years, to detect precursors of some kinds of eruption. But understanding or even predicting the eruptive behavior of a volcano is a separate issue from assessing the hazard that an eruption might present because a volcanic hazard involves many more complex issues, such as timing and topography. Remote sensing techniques may be able to show, for example, that temperatures on a previously dormant volcano have increased significantly and that an eruption may take place within days or weeks. But predicting eruptions is only part of the problem. Several of the worst volcanic disasters in history have taken place on volcanoes that already were very obviously active, such as Mt. Pelée in Martinique in 1902. In such instances, the volcanic hazard arises from very sudden, short-lived events, such as the eruption of nuées ardentes.

Thus, the unique perspective given by spacecraft observations cannot necessarily provide the remote sensing volcanologist with the range of measurements and local knowledge that are required to interpret the behavior of an individual volcano and then provide useful advice to local authorities on potential volcanic hazards. Indeed, local geologists will continue to provide essential information from firsthand observations and the details of the eruptive history of a volcano. Previous volcanic crises have demonstrated that casual interactions with local authorities, the usual *modus operandi* of scientists, can lead to serious misunderstandings. Investigators working with remote sensing data will find it essential, therefore, to focus on specific areas of investigation that will be carried out in collaboration with local scientific institutions and officials and will be formalized through appropriate protocols. Within the framework of EOS investigations, the lack of real-time data will constrain most investigations to basic research and data gathering, rather than hazard assessment and prediction.

Coordination with similar programs

The EOS volcanology project is not synonymous with NASA's efforts in volcanology, nor is it the only program that will study volcanoes in remote parts of the world. Coordination with the Smithsonian Institution's GVN (Washington, D.C., USA) and the U.S. Geological Survey's volcano observatories (HVO, AVO, CVO) will be essential if the broader U.S. community is to take full advantage of the modern sensors. Similarly, cooperation between the U.S. programs and international groups that are interested in volcanic hazards would benefit from a formal definition of roles, data exchanges, and collaborative research.

Cooperation with international programs

Several international programs could interface with the U.S. satellite volcanology experiments. For example, the potential use of the existing French ARGOS system in order to monitor volcanoes and provide "early warning" of anomalous behavior of selected volcanoes

on a global basis could provide the early information that is necessary for retargeting the spacecraft sensors.

Linkage with other disciplines

The EOS volcanology investigation fits well within the overall goal of the EOS project, which is to study the regional and global interrelationships among components of the Earth system, because it specifically investigates the links among volcanism, atmospheric chemistry, and short-term (1–3 year) climate change. Linkage between these EOS studies and other international programs is also a possibility, but the precise mechanism for coordination remains unclear. For example, many volcanoes around the world could be monitored in detail by using the EOS satellite sensors. An obvious group of volcanoes to be studied could be those selected specially as "Decade Volcanoes" by the IAVCEI for the IDNDR. The IGBP and RIDGE could interface with the NASA studies of volcanism and volcano-climate interactions. However, interagency planning and, probably, joint funding of research programs most likely would be required in order to develop these interdisciplinary ties substantially.

Conclusions

Remote sensing offers the potential for significantly increasing our knowledge of volcanoes around the world, as well as for collecting data of uniform quality over sufficiently large areas that will allow us to interpret volcanic processes such as eruption plume dynamics and the growth of lava flow fields. Certain measurements, such as the ones that give us the ability to use SAR to map the distribution of topographic change over areas of several hundred square kilometers on cloud-covered volcanoes, also offer the promise (as yet unproven by actual measurements on volcanoes) of significant new types of measurements. A crucial issue presented by this unprecedented volume of data is the ability of earth scientists to access and interpret the information in a timely manner. We hope that the whole scientific community will have free access to the EOS data set, but in many instances, the ability to locate the appropriate information within the data archive, obtain the calibrated data sets, and make timely use of the data will be a challenge for the foreseeable future. In addition, particularly in the case of volcanic hazard monitoring, the strong links between the remote sensing expert on one hand and the volcanologists and local civil defense experts on the other have to be developed with care and respect for the roles and abilities of the respective groups. Remote sensing of volcanoes will make the greatest contribution to the earth sciences if the resulting information is used in conjunction with the detailed knowledge of the region that is derived by volcanologists in the field.

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