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SECTION IV.

REPORT OF THE PANEL ON VOLCANOLOGY

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SECTION IV.

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SUMMARY

Two primary goals are identified as focal to NASA's research efforts in volcanology during the 1990's. These goals are viewed as complimentary to those of other agencies, particularly in the fields of volcano monitoring, hazard assessment, and the investigation of the impact of eruptions on the atmosphere, climate and ecosphere. The two NASA objectives are: 1) To understand the eruption of lavas, gases and aerosols from volcanoes, the dispersal of these materials on the Earth's surface and through the atmosphere, and the effects of these eruptions on the climate and environment; and 2) To understand the physical processes that lead to the initiation of volcanic activity, that influence the styles of volcanic eruptions, and that dictate the morphology and evolution of volcanic landforms.

These objectives should be addressed by: 1) Satellite-borne thermal and gas observations of new eruptions, and repetitive volcano monitoring using existing instruments (e.g., Landsat TM, SPOT, TOMS and AVHRR), and instruments to be incorporated on the EOS spacecraft (e.g., MODIS, SAR, ITIR, GLRS, MISR and HIRIS); 2) The compilation of a global baseline data set of satellite images of active and dormant volcanoes, from which temporal changes (over time periods of a few months to a decade or more) could be detected and monitored; 3) The development and use of ground-based remote sensing systems to provide high temporal resolution ground truth data (seismicity, tilt, temperature and gases emissions) via satellite read-out for the calibration of orbital systems; 4) The development of new sensor systems to provide more sensitive and precise sulfur dioxide and temperature determinations. Such a capability would be offered by the proposed Orbiting Volcanological Observatory (OVO), which would permit frequent observations (perhaps as often as once/day) at a high (10's of meter) spatial resolution over the UV to thermal infrared portion of the spectrum.

1. INTRODUCTION

The study of volcanoes and volcanic provinces crosses many interdisciplinary boundaries, from geology and geodynamics to atmospheric chemistry, climatology and ecology. Programs such as the International Geosphere Biosphere Program (IGBP), the International Decade of Natural Hazard Reduction (IDNHR), and the National Academy of Science's Global Change Program provide strong international and inter-agency motivation for the study of volcanoes and their products. That large-scale volcanic eruptions can have considerable effects on the Earth's climate is also becoming widely recognized in the Earth sciences community. Such observations date back over two centuries when Benjamin Franklin correlated the decrease in temperatures in western Europe with the 1783 eruption of the Laki volcano in Iceland. A new term, "Volcanic Winter", has been coined to describe the effects of large eruptions on hemispheric temperature and climate (Rampino *et al.*, 1988), and it is evident that both explosive and lava-producing eruptions can have major impacts on climate and the ecosystem (Handler, 1989). These relationships were recognized as significant by the Earth Systems Science Committee, but essential questions still remain, however, concerning the bounds of these effects in terms of degree, duration and spatial extent. The Volcanology Panel thus advocates that NASA undertakes investigations of the nature and dynamics of active volcanic processes, and the role of volcanism as an expression of global geodynamic processes, in order to further understand volcanic processes and the direct and indirect effects of volcanism on the global environment.

As surface expressions of the Earth's internal physical and chemical evolution, volcanic eruptions present uniquely challenging science problems because they operate over geologically short time scales, are inherently dangerous to observe at close hand, and are frequently located in remote areas where there are no suitably trained and equipped observers. Furthermore, while many minor eruptions in the more remote regions of the world may be completely unobserved, it has been estimated that between 20% and 30% of all subaerial eruptions unreported to the science community each year because of difficulties in communications (Mouginis-Mark *et al.*, 1989). Even under favorable conditions, the sheer scale of both lava-producing and explosive eruptions can be so great as to make useful ground observations hard to achieve. It is rare that sufficient manpower is available to make the necessary field measurements of the development of an entire lava flow field, or to sample the entire spatial and temporal dispersal of an ash plume. Similarly, geologic field mapping of volcanic landforms over hundreds to thousands of square kilometers is impractical at anything except a reconnaissance level.

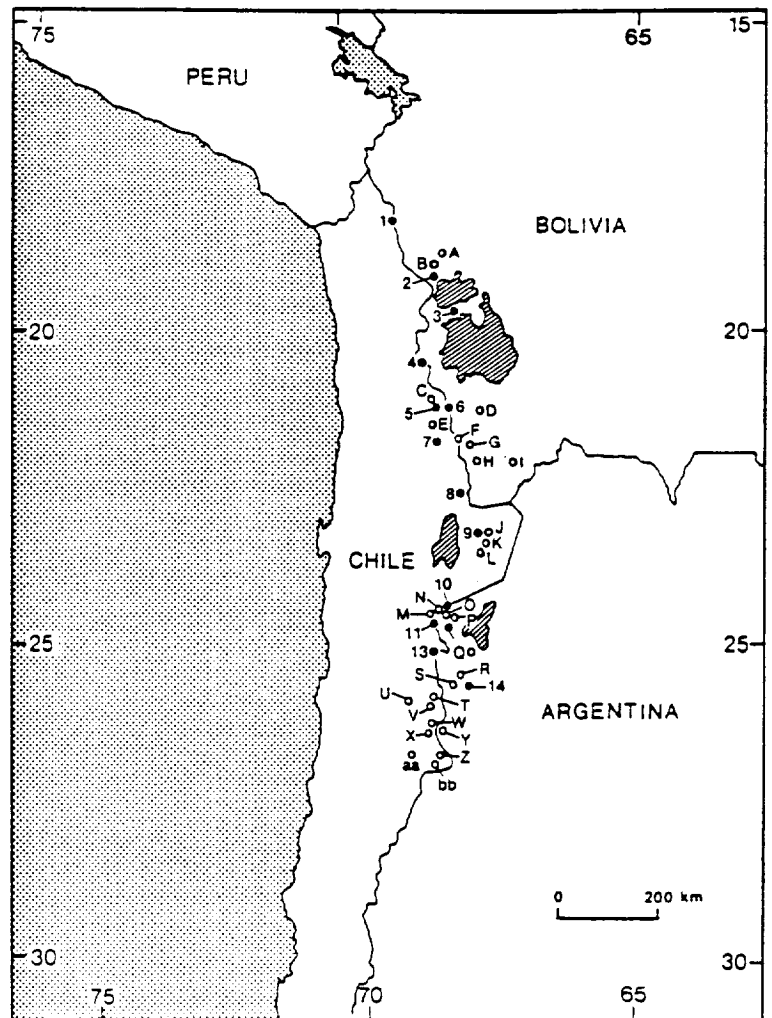
Within the United States, Europe and Japan, most active volcanoes and volcanic provinces have been mapped in detail, studied petrologically, and investigated with a variety of geophysical techniques. In sharp contrast, many of the most devastating eruptions of recent times, such as that of El Chichon, Mexico in 1982, have taken place in developing countries on poorly documented volcanoes which were thought to be either inactive or not to present major hazards. Prior to its lethal eruption in 1951, Mt. Lamington, New Guinea was not even known to be a volcano. For the central Andes, Francis and de Silva (1989) reported that preliminary Landsat Thematic Mapper (TM) studies revealed that 50 - 60 volcanoes should be regarded as potentially active, whereas previously only 16 had been identified (Figure 1). Synoptic satellite-borne instruments provide such a means of obtaining this new overview of the distribution of active volcanoes, and of making quantitative estimates of global budgets of magmatic, thermal and volatile emissions from volcanoes. Correlations between the distribution of volcanoes and their tectonic setting, as well as the consideration of the frequency of eruption and magma chemistry of each volcano, can also provide information on regional crustal and mantle processes.

In recent years, much progress has been made in the use of both satellite and aircraft remote sensing techniques to collect data on volcanoes, and it is clear that many new aspects of volcanic eruptions, and the relationship between volcanoes and their tectonic setting, can now be studied by such methods. Indeed, the 1990's will see NASA play an increasing role in the monitoring and analysis of both lava-producing and explosive volcanic eruptions, and the deposits produced by these volcanoes. Although satellite and aircraft observations are limited at present by their infrequent

repeat coverage of volcanoes (one overpass every several hours to several weeks is typical), volcanological remote sensing offers a number of benefits. Satellite remote sensing observations allow: (1) all the world's volcanoes to be studied by the same techniques, thus providing a globally consistent data set which can be used to monitor temporal variations in volcanic activity, (2) collection of information on areas which are difficult to reach in other ways because of physical or political constraints, and (3) the utilization of a broad range of sensors working in wavelengths ranging from the ultraviolet to the microwave. These advantages apply to both airborne and orbital observations.

In order to gain a global perspective of both contemporary volcanism and the link between the distribution of volcanoes and the structure of the Earth's crust and lithosphere, NASA must play a major role in volcano monitoring, hazard assessment, and the environmental impact of volcanic eruptions on world climate. Apart from direct effects in the vicinity of volcanoes, global climatic and atmospheric perturbations caused by major eruptions have historically been sufficient to significantly affect agricultural production, leading to widespread food shortages and famine (Sigurdsson, 1982). In broad terms, it is known that the climatic effects of volcanism are due to the emission of sulfur dioxide (SO_2) (because it results in absorption of solar radiation), aerosols, and possibly other gases such as chlorine (Cl_2) and fluorine (F_2) (because of their effects on the ozone layer). The injection of these gases and particles into the stratosphere during very explosive eruptions (such as Tambora in 1815, Krakatoa in 1883, and El Chichon in 1982), and the possible links between major eruptions, anomalous sea level pressure, and the strength of El Nino events (Handler, 1989) warrants particular attention, and is an interdisciplinary investigation that NASA can address.

Figure 1 The locations of volcanoes in the Central Andes for which debris avalanches have been identified. Landsat TM data have revealed that 28 previously undescribed examples of breached volcanic cones, and 14 major volcanic debris avalanches, providing a new regional perspective of volcanism in this area. From Francis and Wells (1988).



There are two major goals that the Volcanology Panel has identified as key to NASA's research efforts in volcanology during the 1990's. These goals are viewed as complementary to other agency studies of volcanoes, wherein the U.S. Geological Survey may focus on volcano monitoring and hazard assessment, and the National Science Foundation may fund basic field and laboratory research. The two roles identified for NASA are: 1) To understand the eruption of lavas, gases and aerosols from volcanoes, the dispersal of these materials on the Earth's surface and through the atmosphere, and the effects of these eruptions on the climate and environment; and 2) To understand the physical processes that lead to the initiation of volcanic activity, that influence the style of volcanic eruptions, and that dictate the morphology and evolution of volcanic landforms. These goals are described in detail in the next two sections.

2. CONTEMPORARY VOLCANOLOGY

The primary goal of NASA research in contemporary volcanology should be to understand the eruption of lavas, gases and aerosols from volcanoes, the dispersal of these materials on the Earth's surface and through the atmosphere, and the effects of these eruptions on the climate and environment.

2.1: SPECIFIC QUESTIONS

The role of remote sensing in volcanology is a complementary one to measurements made in the field and laboratory. Remote sensing provides the regional overview of an eruption, permitting volcanic processes that extend over many tens to thousands of square kilometers to be studied at uniform spatial and spectral resolution, and to observe the temporal evolution of these phenomena (Figure 2). In certain instances, due to safety and/or geographic reasons, satellite or airborne data may be the only information available for certain volcanological parameters. The correlation of data for eruptions with measurements of temperature, rainfall, and biophysical processes can also best be achieved via satellite remote sensing techniques. Considerable emphasis will still be placed on field measurements of volcanic processes and landforms, because only in this way can high spatial and temporal resolution information (such as the thickness of a lava flow or ash deposit or the dynamics of an overturning lava lake) at a given locality be factored into the interpretation of the remotely sensed information. Meteorological and biophysical data will also be needed to assess the effects of eruptions on the entire Earth system. In this way, it is envisioned that the NASA Volcanology effort will interact closely with the research conducted by the U.S. Geological Survey, with NOAA for weather and climate data, with NSF-funded ecosystems research, and with efforts conducted by foreign scientists working on volcanoes in the field.

To reach our goal of understanding the dynamics of volcanic eruptions and their links with the lithosphere, atmosphere and climate, we have identified three specific questions that relate to the physical processes, eruption rates and dispersal of volcanic materials around the globe.

2.1.1. *How does the distribution of volcanic gases and particles in the troposphere and stratosphere relate to the physics and dynamics of explosive eruptions?*

- A) What are the thermal and velocity structures of eruption plumes as a function of altitude?
- B) How rapidly does an eruption plume lose its heat, and what is the temperature differential between the eruption cloud and the surrounding atmosphere?
- C) What is the mass and particle size distribution within an eruption plume as a function of distance from the vent?
- D) What is the rate of gas release from a volcano, and what is the relative proportion of one gas compared to another (e.g., mass of SO₂ vs. CO₂ or H₂O)?

- E) How can the dispersal of particles within an eruption plume be related to the deposits of ash measured in the field?

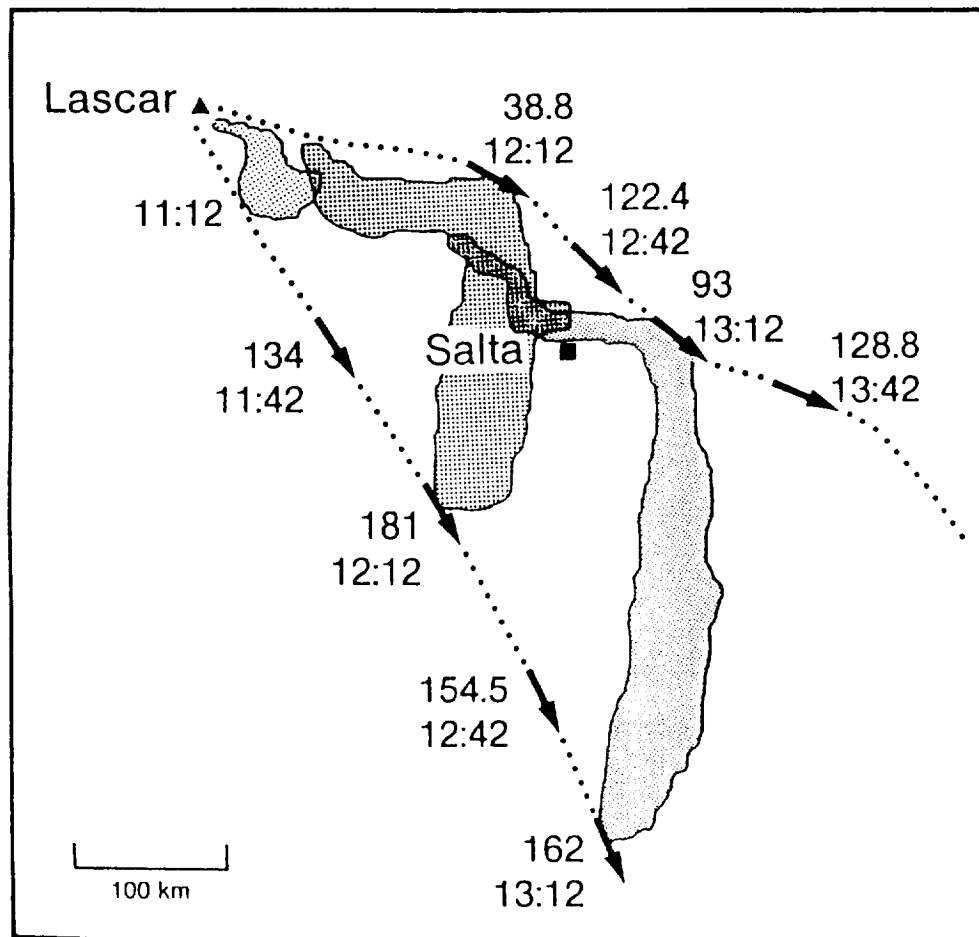


Figure 2. The changing structure of the eruption plume for the September 1986 eruption of Lascar Volcano was recorded by the GOES weather satellites. At each site the computed plume velocity (in km/hr) and time (UT) are given. From Glaze *et al.* (1989). The temporal evolution of future eruption plumes will be studied using the EOS platforms, and also represents one of the prime objectives of the Orbiting Volcano Observatory (OVO).

2.1.2. *What are the dynamics of effusive volcanic processes and how do they relate to the evolution of volcanoes (how do volcanoes work)?*

- A) How does the eruption rate (volume per unit time) of lava erupted by a volcano vary over time scales of hours to weeks?
- B) How is the rate of lava eruption related to the size, depth, replenishment rate and geometry of the magma chamber and conduit system of a volcano?
- C) How does the surface deformation of a volcano during or prior to an eruption relate to the internal structure of the volcano?
- D) What is the velocity flow field of a moving lava flow?

- E) How fast does a moving lava lose its heat, and how does this cooling affect the rheological properties of the flow and the resultant surface features (pressure ridges, lava flow morphology, levee development)?

2.1.3. *What are the effects of volcanic eruptions on the Earth system (climate, ecosphere, and hydrosphere)?*

- A) What is the residence time and distribution of volcanic gases and particles within the atmosphere following eruptions of different magnitudes?
- B) What chemical reactions are associated with the eruption of volcanic gases on the local, regional and global scale, and how long do these effects persist?
- C) What are the effects of volcanic eruptions on local and regional temperatures and rainfall, and how long do these effects persist?
- D) What effects do major volcanic eruptions have on the ecosphere and hydrosphere, which areas of the globe are most sensitive to eruption-induced perturbations, and over what timeframe do these effects operate?

2.2: STRATEGY AND DATA REQUIREMENTS

In order to gain the required understanding of dynamic volcanic processes, their effects on the Earth system, and the hazards that they may represent, a concerted level of effort involving field and remote observations of volcanic processes is required. The most appropriate way to interpret remote observations is to develop "calibration sites" that are volcanoes for which considerable geophysical and field information already exists. Thus the remote sensing data can be placed in the context of both the historical eruptive history of the volcano and the geophysical and petrologic data, including seismics, gravity, magnetics, and trace-element geochemistry. Once the remote observations have been placed in the context of known characteristics of these volcanoes, it will be possible to more confidently extrapolate methods and interpretations to more geographically isolated volcanoes, or to volcanoes for which the supporting ground data sets are not available.

Three key requirements in understanding how volcanoes work, and their impact on the atmosphere, are: 1) the determination of the rate at which materials are erupted; 2) the assessment of the diversity (physical state, temperature, chemistry) of products erupted; and 3) where these materials are subsequently distributed. The ability to correlate these measurements with the short-term (hours to weeks) deformation history of the volcano also permits detailed numerical models to be developed regarding the internal structure of the volcano and the pre-eruptive history of the magma. Comparisons between the data for plume dispersal and information on air temperature, rainfall, and changes in plant productivity will also permit the effects of major eruptions on climate to be assessed.

Thus the NASA initiative to study dynamic volcanic phenomena should be orientated towards the development of a data base on volcanoes with good historic records and supporting geophysical and geochemical data, the interpretation of these data both in the context of the specific volcano under study and as a test for extrapolating these data types to other volcanoes, and the collection of remote data sets for other less well studied volcanoes around the world to permit inter-volcano comparisons. The specific research efforts needed to attain this objective are described in the next section.

2.3: RESEARCH EFFORTS

Six coordinated research efforts have been identified by the Volcanology Panel that enable NASA to make major contributions to our understanding of volcanic eruptions and the effects of this activity on the climate and environment.

2.3.1. Baseline Volcano Data Set:

Establishment of baseline satellite data sets (SAR and UV/vis/near IR) for ~120 of the world's most active volcanoes in order to determine initial conditions for rate of change studies.

Because many volcanoes erupt on a timescale of once every year to every decade, much can be learnt about the rate of change of the volcano (e.g., volume of lava erupted, rate of swelling of flanks due to inflation of magma chamber, removal of summit during an explosion) by comparing scenes of the volcano before and after an eruption. In order to conduct this temporal comparison, baseline data sets of the before eruption activity have to be collected. Approximately 50 Landsat TM scenes p.a. will be required for the first three years of the 1990's in order to assemble this baseline data set. SAR data from ERS-1, JERS-1 or SIR-C should be used to complement TM data in areas affected by frequent cloud cover.

The study of the rate of gas release from a volcano is also important for assessing the maturity of a magma body at depth. The frequent (daily to monthly) measurement of volcanic sulfur dioxide using an enhanced version of the TOMS instrument flown on NIMBUS 7 would provide an indication of new magma bodies being intruded at shallow depth or other changes in the shallow magma body. Thus initial gas flux value for each volcano must be established so that temporal changes over time periods of a few months to several years can be detected and monitored for their effects on the atmosphere.

Once the baseline data sets are collected, the plan would be to wait until an eruption has taken place and then collect a second set of satellite data, so that a "volcano difference map" at multiple wavelengths could be derived. These difference maps would then be interpreted in terms of volume of lava erupted, area and extent of vertical deformation, distribution of volcanic products (ash, pyroclastic flows etc.), and the rate of release of different gas species.

2.3.2 Field and Aircraft Studies:

Coordinated field and aircraft studies of well known type examples of volcanoes should be made in order to understand process-related phenomena: Hawaii (effusive) and Mt. St. Augustine (explosive). As stated earlier, these studies will be complementary to on-going programs currently funded by other agencies. NASA's role should be to develop new technologies and interpretation techniques that link field and airborne data to spaceborne measurements and interpretations. The availability of detailed field knowledge, as well as geophysical, petrologic and age data for volcanic phenomena studies, as well as the new remote sensing data collected by NASA, will be of mutual benefit to investigators from various agencies.

Kilauea Volcano, Hawaii has the best historic record for both geophysical (seismics, gravity, deformation) and geochemical (major and trace element) data. It is also easily accessible, erupts sufficiently frequently that the probability of monitoring an ongoing eruption is high, and is very safe to study at close hand. Detailed records of eruptions going back to the 19th century exist for Kilauea. It is also relevant that two other active volcanoes (Mauna Loa and Hualalai) could also be studied during a Hawaii deployment to provide inter-comparisons of basaltic shield development.

As presently envisaged, Mt. St. Augustine (Gulf of Alaska) appears to be a prime calibration site. It has erupted at least once each decade this century, producing large eruption plumes, pyroclastic flows and large variations in surface deformation. This is the most active "explosive" volcano in the United States, and while field logistics are more difficult than Hawaii (mainly weather and about 2 hour flight time from major airport) extensive ground work on deformation and

gas production have been done, along with several air/satellite comparisons during the 1986 eruption. Augustine is also located within the Alaska SAR Facility data mask, so that frequent coverage from ERS-1, JERS-1 and weather satellites is possible. Other calibration sites such as Mt. Etna or volcanoes in Central America are also possible, depending upon logistic, political and volcanic considerations.

Aircraft observations and ground studies (collection of calibration data for airborne sensors plus observations of field relationships and dynamic phenomena) of each of these sites to be made 3 - 5 times in ten years. The first deployment to each volcano should be in 1991 - 1992 timeframe, with site revisits occurring at intervals every 2 - 3 years. SAR data are required for regional lithologic mapping and structural studies, vis/near-IR plus thermal IR for analysis of thermal anomalies. Laser altimetry and radar interferometry data will be required for micro-topography and profiles of summit areas.

Satellite observations in UV to thermal IR, plus microwave measurements when available, to be made at least 4 times per year (more frequently on an as available basis during eruptions). Orbital SAR data will be required for interferometric studies of volcano growth.

2.3.3 Observations of New Eruptions and Volcano Monitoring:

The capability to deploy aircraft and obtain satellite images for any region of the world at short notice (a few days for satellite observations). Aircraft and satellite observations of active volcanoes, major new eruption sites, and the effects of eruptions on the atmosphere represent major research areas where NASA can contribute to our knowledge of volcanoes and their interaction with the atmosphere, climate and ecosystem. An additional 20 TM scenes p.a. for each of the 10 years of this program will also be needed for monitoring selected active volcanoes; it is expected that approximately 5 volcanoes will be imaged every three months to study the changes in thermal output of volcanic craters and fumaroles. It is fairly easy to select about 20 of the world's volcanoes that are quite likely to erupt between 1991 and 2000. Kilauea, Etna, Piton de la Fournaise, and several volcanoes in Indonesia and Central America have all erupted several times each decade throughout the 20th century.

It is highly likely that during the next decade, major eruptions (both lava-producing and explosive) will occur. The locations of this activity cannot be predicted, and so once an eruption is initiated the ability to obtain satellite data and, preferably, coordinated aircraft data, would permit dynamic processes (e.g., mass eruption rates, deformation rates, temperature and dispersal of a plume) to be investigated (Figure 3). With the advent of EOS platforms, this capability to identify new eruptions will be established, but the coordination of other satellite platforms and aircraft will still have to be implemented. It is implicit in the assumptions of the Volcanology Panel that EOS instruments, such as the SAR, ITIR, GLRS, and HIRIS will fly in the mid- to late- 1990's.

2.3.4: Effects of Volcanoes on Climate:

The study of the effects of volcanic eruptions on climate can be considered in three phases linked to the history of volcanic gases. The first phase concerns the origin of SO_2 , Cl_2 and F_2 , and their abundances as a function of magma type and the tectonic setting of the volcano. This knowledge will permit the extrapolation of data from one type of volcano/tectonic setting to the general population of volcanoes and geologic environments around the globe.

Secondly, gases and particles injected into the stratosphere can be transported around the globe, and can have residence times of months to a few years. The dispersal of these materials is almost impossible to monitor without spaceborne techniques, due to the scale and high altitude of the phenomena. Modeling the reaction of the SO_2 to H_2SO_4 (which represent the aerosols that attenuate the solar radiation) is very important in order to study changes in atmospheric chemistry and climate.

Finally, modeling of the climate effects of these constituents is also important. It is necessary to study the global dispersal of volcanic gases, model the hemispheric and global changes in

atmospheric chemistry, and correlate these observations with data on atmospheric temperature, sea surface temperature, vegetation productivity and annual rainfall. Major drops in temperature have been observed for several years after the largest volcanic eruptions, and it is likely that rainfall patterns and, hence, biological productivity, will also be affected. Recent analyses have also suggested that cooling of the land surface by volcanic aerosols will transfer air mass from the ocean anticyclones to the continents, and may provide a link between low-latitude eruptions and the strength of El Nino events (Handler, 1989). In this manner, data on volcanic eruptions provide a direct input into other aspects of Earth System Science and promote true interdisciplinary studies.

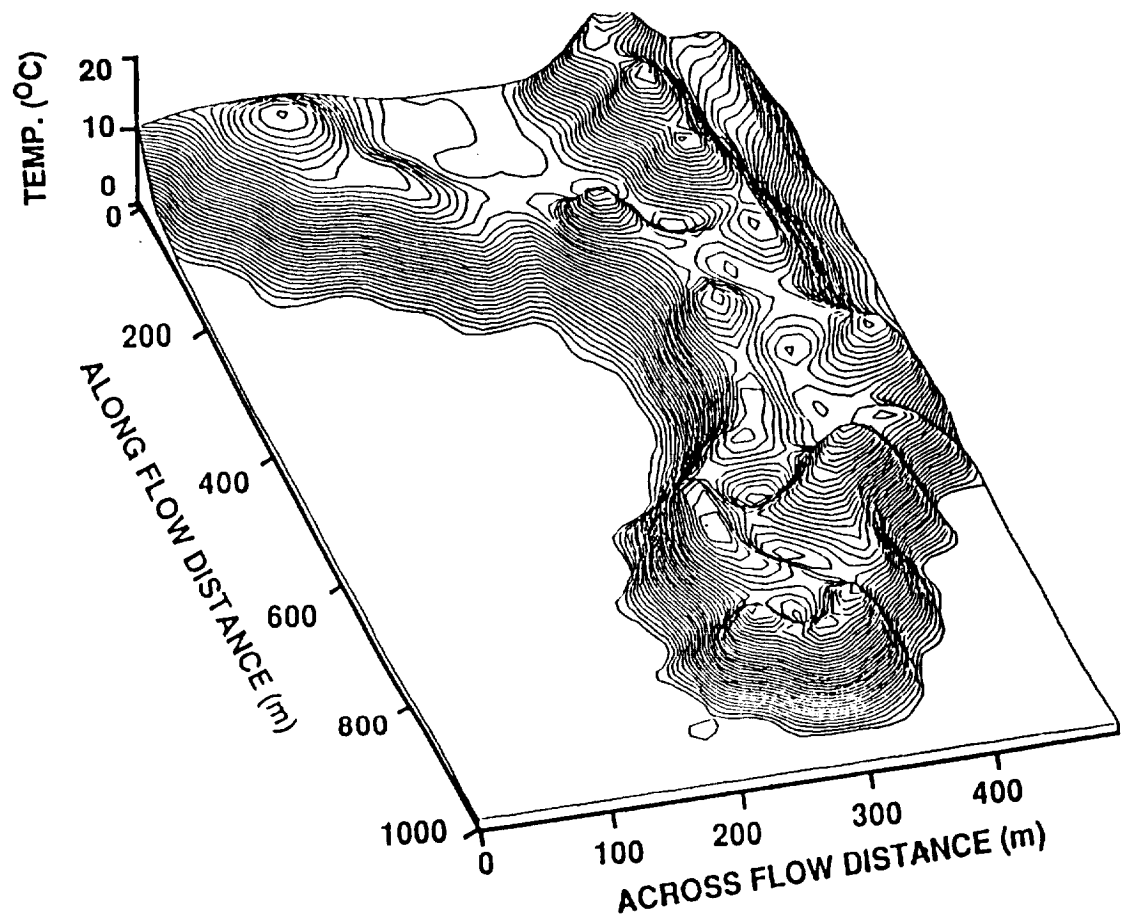


Figure 3. Thermal profile for the June 1984 lava flow erupted from Mt. Etna, Sicily, as derived from Landsat Thematic Mapper data. The flow direction of the lava flow is from top to bottom of the diagram. Vertical axis shows the decrease in temperature calculated for different parts of the flow; note the pronounced formation of "cool" edges to the flow. Data such as these permit the emplacement characteristics of the lava flow to be numerically modeled, thereby permitting the hazard potential of the eruption to be assessed. From Pieri (1989), unpublished data.

2.3.5. Automatic Field Monitoring of Volcanoes:

Field monitoring of remote active volcanoes using small automatic ground stations with direct satellite read-out capability should be carried out in concert with both space and airborne measurements. In this manner, field calibration and ground truth will be obtained for several volcanoes that may also be monitored by the U.S. Geological Survey or other agencies. Measurements made by these automatic field stations should include seismicity, tilt, temperature and released gas species. Approximately 1 - 3 stations required per volcano, for 5 - 10 volcanoes distributed globally.

Many changes on a volcano prior to an eruption are quite subtle, involving either cm-scale changes in relief (tilt), increasing seismicity (magnitude 2 - 4 earthquakes caused by subsurface movement of magma define conduit system), or temperature. These changes cannot be observed from space, nor is it feasible to have observers on the ground at many different sites. To overcome this limitation, remote measuring stations should be deployed on volcanoes known to be frequently active, thereby enabling their precursory activity to be more closely monitored.

In order to be used effectively, these field data should be transmitted back to a central data handling facility every day, using satellite relay capabilities. Similar technologies have already been used by NASA (and other agencies) in the study of ocean tides and currents, so that the methodology is already well proven.

2.3.6. Volcano Deformation Studies:

When magma is moving along a conduit system close to the surface of a volcano (top 1 km), the change in volume of the volcano is recognized as a swelling of the surface (vertical as well as horizontal displacements of a few centimeters to decameters). These changes in volcano shape provide key information on the rate of magma flow at depth, which can then be correlated with conduit geometry, the rheology of the magma, and the rate of flow of magma from the parent magma chamber to the surface.

We recommend the deployment of networks of GPS transponders or GLRS laser ranging retro-reflectors on limited number (~3) volcanoes to observe intrusive events and lava dome growth on active volcanoes and recently active volcanoes. Alternative technologies, such as the tracking of transponders placed on volcanoes via the TOPEX altimeter, may also be a method by which to study volcanoes close to the coast. Kilauea (Hawaii), Hualalai (Hawaii), Krafla (Iceland), and Piton de la Fournaise (Reunion Island), Mt. St. Helens dome and St. Augustine are options, although cloud cover over targets at certain times of year may become a problem. In many of these cases, international cooperation in the deployment and maintenance of the GPS networks will be essential for the efficient collection of the data and their correlation with other geophysical data sets.

In addition to monitoring the magnitude and style of deformation of a volcano during an intrusive event, much information about the dissipation of strain energy and the association between dike emplacement, earthquakes and subsidence of a volcano's flanks can be learnt by monitoring the deformation and relaxation rates of a volcano for several years after a major intrusive event. In both Hawaii and Iceland, several meters of vertical displacement may occur over a time period of a decade or more following the intrusion of a near surface dike that may have a horizontal extent of several tens of kilometers. Remeasuring the subsidence rates of the unsupported flank of Kilauea Volcano, and the central graben at Krafla in Iceland, would provide significant information on magma intrusion processes and the internal structure of each volcano. Due to the time scale involved, site revisit frequencies could be of the order of once per month to twice per year, with ranging conducted each time to about 15 - 20 targets.

In order to derive these deformation data, relative horizontal displacements on the order of 1 - 5 cm need to be measurable from six - ten sites located along the rift zones of each volcano. Each network should extend for horizontal distance of 10 - 30 km. Vertical resolution of ~1 cm is needed to measure inflation/deflation rates of volcanoes due to changes in volume and pressurization of magma chamber. The ability to remeasure line-of-sight distances to each of the retro-reflectors once every day to once every week would be required.

Lava dome growth can also be studied in this manner, with the placing of 3 - 5 GPS receivers or GLRS reflectors on or around the dome. Growth rates of several hundred meters per year have been observed at Mt. St. Helens in the early 1980's, and such a process is related to the solidification of magma within the conduit, and its subsequent slow extrusion at the surface as the magma chamber pressure returns to its pre-eruption value.

2.4: INSTRUMENT DEVELOPMENT

While many of the volcanological investigations can be conducted via the use of current or approved new instruments, several of the proposed research efforts can only be realized with the development and deployment of new remote sensing instruments designed specifically for volcanologic (or geologic) investigations. Several such instruments have been identified by the Volcanology Panel. These instruments permit improvements in our ability to measure volcanic gases, thermal anomalies of surface features, sub-kilometer scale topography, and the ability to deploy mobile ground receiving stations for receipt of SAR data from remote locations.

2.4.1. Measurement of SO₂

The optimization of orbital UV spectrometers in order to improve the detection of sulfur dioxide in volcanic plumes is strongly encouraged, due to the established ties between volcanic eruptions and short-term climate change (Rampino *et al.*, 1988). Eruption rates of ~100 tonnes per day need to be detectable.

A key problem is the development of an instrument that would enable the measurement of gas released into the troposphere, since many effusive eruptions (e.g., Etna) do not inject sulfur dioxide into stratosphere. Higher spatial (~30 - 100 m/pixel) and, perhaps, spectral resolution (including IR) may be solutions. In the first instance, an augmentation to the TOMS instrument due to fly in the early 1990's would be the matching of band selection to more precisely discriminate the sulfur dioxide absorption bands. For the higher spatial resolution data sets, a new space platform, such as the Orbiting Volcano Observatory with new instrumentation (see section 2.5.1), will be required. These high spatial resolution data are required to enable smaller tropospheric plumes (low sulfur dioxide mass fluxes) to be investigated, and to study the sub-kilometer structure of large plumes. This new sensor must have off-nadir pointing capability in order to observe transient plumes (a few days to a month).

2.4.2. Automatic Ground Stations

The develop techniques for the detection and measurement of volcanic SO₂, CO₂, HCl and H₂O in the troposphere and stratosphere requires that techniques be developed for automatic field stations, then integrated into airborne and then spaceborne measurements. The goal will be to calibrate the spaceborne data. The key parameter to measure is either the ratio of SO₂/CO₂, or SO₂/H₂O, because these provide indications of depth of magma degassing and residence time of specific batches of magma at shallow depth beneath the surface. Kilauea, Stromboli and Mt. Etna are candidate targets. The mass flux of HCl is of great interest because it is known to vary considerably with tectonic setting, but few data currently exist to compare setting of volcano to production rate. Mt. St. Augustine and White Island (North Island New Zealand) are prime study areas.

Achieving this remote measurement of gas species and other volcanologically useful parameters requires the development of small automatic ground stations with direct satellite read-out capability. Daily read-out of seismicity, tilt, temperature and released gas species required from a network of approximately 1 - 5 stations per volcano, with up to 5 - 10 volcanoes so instrumented. These instrument packages should be sufficiently cheap that the loss of one (or several) during an eruption would not have a major impact. They should also be sufficiently small that they can be installed by volcanologists working on foot in rugged terrain, and consume sufficiently small amounts of power that they can run on batteries for about a year. In order to be used effectively, these field data should be transmitted back to a central data handling facility every day, using satellite relay capabilities.

2.4.3. SAR Algorithm Upgrades for Topography Determination

Small-scale topographic changes, due to the growth of volcanic domes or the intrusion of magma at shallow (< 1 km) depth can be sensitive indicators of intrusive activity. New lava flows or parasitic cones, or the removal of material during explosive eruptions, can also produce changes

of several to tens of meters in the topography of volcano flanks, which can then be related to the mass eruption rate of the volcano. While preliminary work has been done to demonstrate the feasibility of radar interferometry for topographic mapping (Gabriel *et al.*, 1989), additional algorithm development is required to derive these topographic measurements at the scale of ~3 - 5 m vertical and a spatial resolution of ~10 m (in order to study relief of individual lava flows). Routine application of these algorithms is required if the optimum use of radar interferometry and ERS-1 or JERS-1 data is to be achieved.

2.4.4. Mobile SAR Receiving Station

The deployment of a mobile orbital-SAR receiving station to Central America and Indonesia is advocated to collect ERS-1 and JERS-1 data of cloud-covered volcanoes and conduct regional tectonic mapping. These radar data are required to perform regional mapping of these very active volcanic regions at a spatial resolution of ~30 m over areas in excess of 10^6 km². It is expected that such deployments would be one-time events, and would be of sufficient duration to completely map each of these area.

There is a need to collect synoptic SAR data via this method prior to the deployment of the EOS SAR (currently scheduled for 1998 on N-POP-2), primarily because these data would be used to establish the long time-line data archive, and would be used to collect the radar-derived topography. The fixed geometry and single frequency/polarization capability of ERS-1 and JERS-1 make these spacecraft more appropriate than the EOS SAR for this task.

2.5: SPACECRAFT DEVELOPMENT

Several of the required measurements remain unobtainable even if the appropriate new instruments are developed; the orbital platforms and missions are currently not in the long-term planning of NASA. In order to change this situation, and to enable the data sets that are required to complete both the proposed volcanological science investigations and assess the effects of eruptions on the atmosphere and climate, we recommend four new spacecraft initiatives. These range in scale from a single instrument of use to a wide segment of the geophysical community to measure topography, to a low-cost volcanology free-flyer (an "Earth Probe" mission), to the installation of volcanology specific instruments on board a geostationary platform. These four spacecraft developments are as follows:

2.5.1. The Orbiting Volcano Observatory (OVO)

Develop the concept for a low-altitude (~330 - 500 km) volcanological "Earth Probe" mission. The Orbiting Volcano Observatory (OVO) would be used to study at high spatial resolution the distribution and rate of eruption of volcanic gases (SO₂, CO₂, HCl, H₂O) and the thermal characteristics (~20°C temperature resolution, 10 - 30 m spatial, ~10 - 30 km² areal coverage) of lava flows and volcanic craters at least once per week. Spatial resolution to be matched either with the capability of SPOT-1/2 panchromatic capability or HIRIS from EOS, depending upon the frequency of site revisits from EOS at this resolution. A key aspect of the OVO mission would be the ability to obtain high spatial resolution data with a frequent repeat cycle (perhaps once per day), thereby enabling short-term variations in temperature and gas flux to be studied.

2.5.2: Upgrades for TOMS Sensor

The opportunity exists to develop the TOMS instrument (due to fly on an early Earth Probe mission) for optimum measurement of volcanic sulfur dioxide, which will be particularly important for studies of the global effects of eruptions on atmospheric chemistry. Optimization of band selection in the 0.3 - 0.37 μm wavelength region will permit a better estimation of the mass flux of sulfur dioxide beyond what is currently possible with the existing TOMS instrument which has successfully been used to detect eruption plumes and to estimate the total mass of sulfur dioxide injected into the stratosphere (Table 1). It is also likely that the optimization of TOMS will enable tropospheric volcanic plumes to be studied, thereby opening up a new set of eruptions for investigation.

2.5.3: Medium Resolution Topographic Mapping

The lack of medium resolution topography for many of the areas of the world is a critical gap in our ability to interpret the geology and geomorphology of volcanoes (and other landforms). The Volcanology Panel supports the development of the capability to obtain digital topographic models of large (~100 - 5000 km²) volcanic landforms at a spatial scale of ~30 m horizontal and ~10 m vertical. Resolution requirements are set at a scale attainable by orbital SAR interferometry or a scanning radar altimeter, which are likely to be the only global topographic data base that could be derived. In areas where cloud cover permits, either stereo SPOT scenes or laser altimetry should be used to provide 10 m horizontal and about 5 m vertical accuracy.

**TABLE 1: VOLCANIC ERUPTIONS DETECTED BY TOMS
(Mouginis-Mark *et al.*, 1989)**

<u>VOLCANO</u>	<u>ERUPTION DATE</u>	<u>CLOUD TRACKED</u> (DAYS)	<u>TOTAL SO₂</u> (KTONNES)
SIERRA NEGRA	13th November, 1979	3	
ST. HELENS	19th May, 1980	4	340
ALAUD	27th April, 1981	22	
AMBRYM	8th May, 1981	2	
PAGAN	15th May, 1981	2	
"MYSTERY"	26th December, 1981	+12	1000
EL CHICHON	29th March, 1981	+64	5000
GALUNGGUNG	5th April, 25th June, July 14th 1982	1, 1, 2	275
SOPUTAN	27th August, 1982	1	
COLO., UNA UNA	24th July, 1983	1	
MAUNA LOA	25th March, 1984	1	190
FERNANDINA	31st March, 1984	11	
SOPUTAN	25th May, 1984	2	
KRAFLA	5th, 10th, 18th September, 1984	3, 1, 1	35
RUIZ	12 September, 1984	1	
RUIZ	13th November, 1985	7	660

2.5.4: Volcano Deformation from Laser-Ranging

Develop the capability to detect topographic change on a volcano due to swelling (~1 cm vertical accuracy for installed monuments) and the eruption of lava flows (~1-5 m vertical for areas of 1 - 20 km² at a spatial resolution of ~30 m). This capability will most likely require the use of GLRS, but it may also be possible to collect the data with GPS or from measurements by TOPEX of transponders placed on the flanks of the volcano.

Space-borne laser ranging capability using to determine topography on a scale of 5 m (horizontal) and a few cm (vertical). Needed to study deformation of summit craters (e.g., Kilauea) and the slow growth of lava domes (e.g., Mt. St. Helens). The laser altimeter of GLRS is also required to profile newly erupted lava flows in order to estimate volume of lava erupted.

2.6 DATA ARCHIVES

As the volume and diversity of satellite and airborne data sets on volcanoes and volcanic eruptions increases during the 1990's it will become necessary to develop, either as a separate entity (the SES DIS) or as part of a larger EosDIS or inter-agency volcano investigation, a volcano data

archive. The links between SES DIS and the broader volcanology community will have to be established, and it is here that a strong inter-agency and international component has to be developed. The Smithsonian Environmental Alert Network (SEAN) should also be incorporated into this data system.

There are three aspects of data collection that the Volcanology Panel has identified that warrant implementation by NASA's Geology Program:

2.6.1. Synoptic Satellite Data

The development of a baseline data set of ~150 Landsat TM scenes is a key aspect of understanding the current structure of volcanoes. In addition, the acquisition of TM scenes for ~5 volcanoes known to be active every 3 months is proposed as a method for monitoring on-going activity. Together with other sets of data (TOMS, AVHRR, SPOT and GOES) for areas of explosive and effusive volcanism, these scenes will form a crucial component of the volcanological data set in preparation for EOS data. Synoptic data to include temporal coverage sufficient to track dispersal of eruption plumes around the globe. Provide mechanism wherein new orbital data (ERS-1, JERS-1, SIR-C, EOS etc.) can be added to this archive.

2.6.2. Supplemental Data

Supplementary aircraft, field and climatic data for the observed eruptions. These data to include geophysical measurements of volcanic constructs, digital terrain models of volcanoes and their surroundings, airborne thermal measurements of activity, and ground observations of eruption rates and dimensions. It will also be necessary for the volcanology community to gain easy access to data on vegetation productivity (such as the AVHRR measurements) and sea surface temperatures in order for the effects of eruptions on the global environment to be assessed.

2.6.3. Real-Time Data for New Eruptions

Ensure data availability for new eruptions in close-to-real time. These data to include TOMS, AVHRR, TM, SPOT, and GOES, but should also include future space missions such as ERS-1, JERS-1, SIR-C, and MOS-1/2. An interface between the volcanological community and the Earth Observing System Data and Information System (EosDIS) must also be developed.

3. VOLCANOES IN EARTH EVOLUTION

The primary goal of NASA research in the volcanic aspects of tectonics should be to understand the physical processes that lead to the initiation of volcanic activity, that influence the style of volcanic eruptions, and that dictate the morphology and evolution of volcanic landforms.

3.1: SPECIFIC QUESTIONS

In order to reach our goal of understanding the connections between the chronology, structure and geochemistry of volcanoes in different tectonic settings, we have identified three specific questions that relate to the distribution of volcanoes and their tectonic settings.

3.1.1. *What material and energy transfer processes within the crust and upper mantle give rise to volcanoes?*

- A) What can the density, tomography and stress relationships under volcanic regions tell us about the temperature profiles and energy transfer processes of these regions? What is the distribution and diversity of volcanism as a function of regional tectonics?
- B) How does magma composition vary as a function of tectonic setting? Are there spatial variations in magma type within a single tectonic zone (e.g., intra-arc variations)? What is the gross morphology of volcanoes; what can it reveal with respect to types of volcanoes, their eruptive histories and subsequent changes due to subsidence or erosion?

- C) What is the history of magma before it erupts as a volcano? Where are the sources of this magma? How does magma migrate to the surface?

3.1.2. *How can we improve our understanding of the structure, composition, physical properties and processes occurring within the lithosphere in order to determine how the spatial distribution of volcanic materials relates to their local and regional tectonic setting?*

- A) How can the spatial and temporal distribution of volcanic cones and erupted materials be related to the spreading and subduction rates of tectonic plates?
- B) What is the relationship between the volume and chemistry of released volcanic gases and the geochemistry of the underlying crust and lithosphere?
- C) How do magma production rates for intraplate hotspot volcanoes relate to mantle processes, and what is the origin of mantle plumes?
- D) What do the loading due to volcanic materials, strain release due to its erosion, and temperature alterations due to the presence of magma chambers reveal about the mechanical behavior and nature of the lithosphere?
- E) How does the frequency of volcanic eruptions of the scale of 10^3 - 10^4 years relate to that of tectonic movements? What is the influence of volcanic activity of the generation of seismicity and tectonic faults?
- F) How is the dissipation of volcanic energy related to long-term crustal movements?

3.1.3. *Has the global character of volcanism changed through geologic time? If so, what geodynamic factors have been involved, and what have been the consequences?*

- A) How has the character of volcanic activity evolved through time in contrasting tectonic environments, and how has this character been expressed in petrological and morphological parameters?
- B) What are the current rates of volcanic activity in contrasted tectonic settings, and how do these relate to spreading and subduction rates? Can eruption rates be inferred from ancient volcanic environments and inverted to infer geodynamic parameters?
- C) How do patterns of volcanic activity relate to variations in remotely-sensed gravity and magnetic fields?
- D) What have been the effects of catastrophic volcanic eruptions on the global environment as preserved in the geologic record?

3.2: STRATEGY AND DATA REQUIREMENTS

The approach to the interpretation of volcanoes and their products in the context of regional tectonics and crustal structure involves both the regional lithologic and topography mapping of volcanic terrains, and the integration of this spatial information into crustal models using regional geophysical models. At the scale of an island arc or a hot spot trace, orbital data are required not only to provide the necessary area of coverage, but also the uniform quality of geophysical data (e.g., gravity, magnetics, topography).

The key aspect of this research involves regional mapping using satellite measuring systems

to produce baseline data sets on the distribution of volcanic phenomena, their topographic form, and their three-dimensional structure from potential field data. Such measurements will be correlated with crustal dynamics information, such as plate convergence rates, depth to Benioff Zone, gravity and magnetic anomalies. Geochemistry will also be included, because several topics of magma chemistry, such as the rate and species of volcanic gases exsolved along an arc have to date not been studied, and yet such information would provide crucial information on the geochemistry of the recycled subducted plate along a zone of convergence.

3.3: RESEARCH EFFORTS

The strategy for this task will be implemented via a series of coordinated remote sensing and field studies of selected key volcanic regions:

3.3.1 Regional Volcanic Landform Assessment:

It will be necessary to conduct a systematic regional assessment of volcanic landforms using satellite systems. Orbital SAR and/or SPOT/TM/HIRIS data sets should be used to identify and relate volcanic landforms to tectonic setting and the geochemistry of parent rocks. Early in the 1990's, a vigorous program of data acquisition using the Landsat TM (~50 scenes p.a. for three years) is proposed, which will be augmented by EOS, SIR-C and ERS-1 data in future years. The Circum-Pacific "Ring of Fire" is the most important area to study, but other volcanic areas, such as East Africa, are also important.

3.3.2. Derivation of Digital Terrain Models and Visualization of Volcanoes and Volcanic Provinces

Satellite altimeter observations can yield major advances in our knowledge of the structure and evolution of the lithosphere upon which volcanoes are constructed. Other Panel Reports (e.g. the Global Plate Motions and Landforms Panels) have also identified the need for continental- to global-scale topographic information that is referenced to a common datum (see also Topographic Science Working Group, 1988), and the Volcanology Panel strongly supports this topographic mission. Coupled with this need for altimetric profiles, the Volcanology Panel recognizes the need for the derivation of digital terrain models for volcanic constructs in order for volume and slope studies related to eruptive mechanisms to be conducted.

The Volcanology Panel recommends that aircraft and orbital sensors (SAR/GLRS/SPOT) should be used to derive digital terrain models for volcanoes and their surroundings. Some of the key problems in the interpretation of volcanic landforms is the determination of slopes and volumes for lava flows and pyroclastic materials. In many instances, such as in the Andes, even the absolute elevation of a volcano summit is not known to an accuracy of a few hundred meters.

3.3.3. Measurement of Regional Deformation Rates

With the use of GPS receivers dedicated to for use in active volcanic areas, establish line-of-sight baselines across regions of volcanic extension (fault zones and rift zones). These data will be required to compare the activity (frequency and style) of an individual volcano with the current deformation/tectonic history of the area. Plate boundaries (e.g., Caribbean, Aleutians, Indonesian arc and the Andes) are prime study areas for this type of investigation. It is believed that the existing effort by NASA's Geodynamics Program to develop and deploy GPS receivers will directly compliment this volcanology effort.

3.3.4. Identification of Thermally-Active Volcanoes

Currently, it is not known how many of the world's volcanoes are in the early stages of precursive thermal activity (e.g., warm summit lakes, fumaroles, warm lava domes), and yet such phenomena provide a significant insight into which volcanoes may become active in the next few years. An inventory of these volcanoes needs to be made, in part to provide input into the "Contemporary Volcanology" research effort (Section 2), but also to assess the distribution and rate of loss of heat from the Earth's crust with respect to tectonic setting, magnetic and geochemistry (gas flux). It is proposed that NASA determine the distribution of thermally active volcanoes

around the world, utilizing near-IR (e.g. Landsat TM) and thermal IR (e.g., TIMS and TIGER/ITR) instruments. Each volcano that is found to be thermally-active should then be monitored at least several times per year.

Development of spaceborne thermal infrared technology is also required to monitor thermally-active volcanoes. The ITIR instrument on EOS, and the potential OVO Earth Probe mission will both require developments in technology beyond the current airborne capabilities provided by the TIMS instrument.

3.4 FIELD GEOLOGY

Although much of this task can be completed via the use of orbital sensors, specific field work will be needed to support this effort. The installation and maintenance of field equipment related to the measurement of tectonic deformation rates, field observations of geological processes, and the collection of field samples will all be required. Specifics are as follows:

3.4.1: Installation of GPS Receiver Stations

Establish network of ~20 GPS stations in conjunction with Geodynamics investigators to assess rate of plate movement in areas such as the Andes, Aluetians, Indonesia.

3.4.2: Calibration of Satellite Observations

Collect field samples to calibrate remote spectral observations and to provide absolute dates for erupted materials. Observe field relationships to help interpret Quaternary eruptive processes. These observations should be conducted in conjunction with airborne campaigns that will bridge the gap between field observations and satellite measurements.

3.5 LABORATORY RESEARCH

Appropriate petrographic and trace element/isotopic studies to support the field and remote sensing effort. Dating of Quaternary surfaces to provide crucial temporal context of frequency of eruptions and rates at which tectonic deformation has taken place. Laboratory spectral measurements of volcanic materials and gases are also required for the UV to thermal infrared.

3.6 INSTRUMENT DEVELOPMENTS

None specifically for this effort but requires support from MODIS, HIRIS, TIGER (or equivalent ITIR), GLRS, GPS as well as satellite gravity and crustal magnetic measurements. Also relies on the continuation of data availability from improved Landsat and SPOT or equivalent aircraft data in order to develop regional data base of volcano/tectonic settings.

Requires deployment of mobile SAR receiving stations to Indonesia and Central America in order to capture orbital SAR data for these cloud covered regions. The stations are required because until the turn of the next century, it is unlikely that satellite radar data for geographically remote areas of the world could be obtained. The SAR data rates are so high that tape recorders cannot be used and, unless direct line-of-sight data transmission is possible, then no data can be collected.

3.7 SPACECRAFT DEVELOPMENT

In order to complete the planned regional investigation, support for obtaining data from the EOS platforms is required. These data will be required to map, at ~30 m resolution, large (10^5 - 10^7 km²) areas of the world and will be used to assemble a basic inventory of volcanic landscapes.

3.8 DATA ARCHIVES

In order to investigate the relationship between the distribution of volcanoes and their tectonic settings, it will be necessary to establish three different pieces of the data archive, and to link these to other data systems such as EosDIS:

- A) Establishment of a GIS archive for one-off data set at visible/IR/microwave frequencies for regions of Quaternary volcanism. Pacific Ring of Fire is top priority, but Italian volcanics and East African Rift Zone are also important.
- B) Data reduction of laser altimetry/orbital SAR/visible stereo images to produce digital terrain maps of volcanic selected regions.
- C) Access to geophysical data (magnetics, gravity, seismics and topography) necessary in digital form in order to correlate visible/IR/microwave data with regional features of tectonic setting.

4. INTERNATIONAL PROGRAMS

Volcanic studies require that many of the data to be collected as part of the NASA Volcanology Program are derived from volcanoes and eruptions outside the United States. Participation and collaboration of foreign geologists, meteorologists and ecologists will be critical for the overall success of this research effort during the 1990's. Several international programs are planned for the 1990's, and volcanology provides an important link between the solid Earth, the atmosphere and the biosphere. The International Geosphere Biosphere Program, the International Decade of Natural Hazard Reduction, and the Global Change Program are three such examples.

Currently there are a number of individual collaborations between NASA volcanologists and scientists in other countries that are likely to grow into important international efforts in volcanology. The following lists some of these ties identified by the Volcanology Panel, but it is likely that other individual or team efforts may also be currently underway:

4.1 U.S. - Italian Projects

NASA's C-130 aircraft has already flown over several of the Italian volcanoes, including Mt. Etna, Vulcano, Stromboli and the Rome Volcanic Field. These investigations include analysis of TIMS and TMS data for monitoring thermal characteristics of the volcanoes.

Strong interest has been expressed by the Italian volcanology community in the return of the NASA aircraft to Italy to measure temporal variations in these volcanoes. In addition, joint U.S. and Italian participation in the Orbiting Volcano Observatory Mission (see Section 2.5.1) has also been discussed.

4.2 U.S. - Soviet Projects

There are numerous explosive and effusive volcanoes in the Kamchatka Peninsula of the Soviet Union that are ideal candidates for comparison to Hawaii-style (e.g. Tolbachik) and explosive-style volcanism (e.g., Bezmianny and Kliuchevskoy volcanoes). While difficult to study in the field due to both their geographic isolation and political issues, two collaborative efforts between U.S. teams and the Soviet Eastern Academy are currently planned. At least one U.S. visit to Kamchatka is under discussion for 1990. Deployments of U.S. aircraft and the acquisition of U.S. and Soviet satellite data are currently being discussed.

4.3 U.S. - Chilean Projects

One of the key areas of the world where satellite volcanology has been developed has been in the Central Andes of Chile, Bolivia and Peru. Joint projects, based on the analysis of satellite

images (primarily Landsat), have been carried out by U.S., English, and Chilean geologists since the late 1970's. These joint projects will continue, particularly in the field of linking the distribution of volcanic landforms to the regional tectonics and crustal processes associated with the formation and evolution of the Andes.

4.4 U.S. - Ecuadorian Projects

The Galapagos Islands off the west coast of Ecuador are a prime area for the investigation of basaltic shield volcanoes that have formed in a tectonic setting different from the Hawaiian shields. Due to the greater spacing between the six active volcanoes, the shields in Galapagos have failed to produce the rift zones that are typical of Kilauea and Mauna Loa in Hawaii. Thus the Galapagos shield permit structural details of the way in which volcanoes grow (relative importance of intrusives vs. extrusives, size and location of the magma chamber) to be compared to the Hawaiian examples.

Two Space Shuttle Radar (SIR-C) experiments involve collaborations with volcanologists in Ecuador, and joint field visits to the Galapagos are planned starting in 1990.

4.5 U.S. - Icelandic Projects

NASA's P-3 aircraft has been flown over volcanoes in Iceland in 1988 and 1989, in order to test the utility of airborne laser altimeters in studying the deformation history of rift zones around Krafla Volcano, and to measure the erosional history of Surtsey Volcano. Collaboration between NASA, the U.S.G.S. and the Icelandic volcanology community is continuing.

5. STRAW-MAN TIME-LINE

In order to conduct the volcanological research necessary to support the investigation of contemporary volcanology and the role of volcanoes in Earth evolution, specific activities have to be phased for the ten year time period considered here. Manpower resources, both in the field and that available for data analysis also have to be budgeted for in addition to dollars spent. Thus the Volcanology Panel has attempted to define a ten year time line that includes instrument development, aircraft deployments, field instrument and satellite deployments that is both necessary to perform the science investigations and appropriate for the expected level of fiscal support and current NASA mission planning. The Volcanology Panel's recommendation for a ten year time line is as follows:

- 1991. Initiate development of the Data Archive, and its links to EosDIS.
- 1991. Initiate upgrades to TOMS sensor to enable better mapping of sulfur dioxide.
- 1991. Plan for first aircraft deployments to Kilauea and St. Augustine.
- 1991. Workshop to discuss New Start for Orbiting Volcano Observatory (OVO).
- 1991. Initiate routine Landsat and SPOT data acquisitions of known very active volcanoes (Kilauea, Augustine, Etna, Sakarajima (Japan), Stromboli, Fournaise (Reunion Island, Indian Ocean).
- 1991 - 1993. Build baseline data base of Landsat TM scenes of volcanoes that may be active within next decade.
- 1991 - 1992. First aircraft deployments to Kilauea and Mt. St Augustine. Conduct concurrent field studies.
- 1992. Deployment of SAR receiving station to Indonesia to capture ERS-1 and

- JERS-1 data. Use these data to exercise data archive.
- 1992. Phase A studies for OVO.
 - 1992. First flight of SIR-C radar. Conduct experiments of radar derived topography for Hawaii or other volcano (e.g., Galapagos, Reunion, Etna).
 - 1992 - 1993. Install first GPS receivers on Kilauea (top priority due to known geophysical and eruption characteristics). Timing depends on flight schedule of orbital laser ranging system.
 - 1993. Second flight of SIR-C radar. Perform radar interferometry experiment to test for temporal changes in volcano structure.
 - 1993. Phase B studies for OVO.
 - 1993. Data archive "user friendly" and operational, and contains growing volume of TOMS, SAR, TM, and SPOT data.
 - 1993. Deployment of SAR receiving station to Central America to capture ERS-1 and JERS-1 data. Note this is time-limited based on projected lifetimes of these free-flyers.
 - 1993 - 1994. Second set of aircraft deployments to Kilauea, Mt. St. Augustine or an as yet to be identified volcano. Target depends on level of activity since last flight. Conduct concurrent field studies.
 - 1994 - 1995. Install GPS receiver grid on Fournaise or Icelandic volcano (next priority, again based on known geophysical and eruption characteristics).
 - 1995. Potential New Start for OVO. Needed to complement EOS in 1997 - 2000 timeframe.
 - 1995 - 1996. Third set of aircraft deployments to Kilauea, Mt. St. Augustine or an as yet to be identified volcano. Target depends on level of activity since last flight. Conduct concurrent field studies.
 - 1995 - 1996. Install GLRS laser retro-reflector grid on Fournaise or Icelandic volcano (next priority, again based on known geophysical and eruption characteristics).
 - 1996. First EOS platform (N-POP-1) launch. Initiate collection of regional data sets to conduct volcano-tectonic studies. Use deployed laser ranging system to develop initial conditions for volcano stress analysis. Initiate volcano thermal survey.
 - 1997 - 1998. Fourth set of aircraft deployments to Kilauea, Mt. St. Augustine or an as yet to be identified volcano. Target depends on level of activity since last flight. Conduct concurrent field and EOS studies. Note this will be the first full-up comparison between EOS data sets and the higher spatial resolution data obtainable from aircraft and ground measurements.
 - 1998. Second EOS platform (N-POP-2) launch. Initiate global mapping of volcanoes with SAR for areas not previously visible to free-flyers and field receiving stations.
 - 1999 - 2000. Continue EOS-related investigations and plan for next ten years of NASA volcanology research.

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