Climatic Impact of Explosive Volcanism

Recommendations for Research

Tokyo, December 1-5, 1993

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PAGES Workshop Report, Series 96 - 3

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PREFACE

Paleo-records aim for and increasingly achieve high temporal resolution with confident ascription of calendrical age. Some of these records, from tree-rings, varves, many ice cores and corals for example, provide evidence which, when combined on a broad enough regional, or even global scale, points to brief periods of anomalous climate in the wake of major volcanic events.
Moreover, meteorological records over the last two decades link major volcanic eruptions to perturbations in world climate lasting for two to three years.
Both types of observation highlight the need to document and better understand the climatic impact of explosive volcanism.

The present Working Group Report seeks to develop and promote a research agenda that responds to this need.

1. INTRODUCTION

An international and interdisciplinary group of scientists met in Tokyo, Japan (December 1-5, 1993), to discuss the direction and opportunities for research on the climatic impacts of explosive volcanic eruptions. The Workshop on Climatic Impact of Explosive Volcanism was initiated and jointly sponsored by the Past Global Changes (PAGES) Core Project of the IGBP and the Commission on Tephrochronology of the International Union for Quaternary Research (COT/INQUA). The meeting was hosted by Meiji University, Tokyo.

After a series of review presentations which delineated the current state of understanding of the relationship between volcanism and climate, participants divided into four thematic working groups to consider priorities and recommendations for future research. Each working group prepared a brief set of recommendations for consideration by the research community and national agencies. The resulting documents have been edited for consistency and compiled here. Taken together, they highlight critical scientific problems and provide an overall plan for the future interdisciplinary research that must be undertaken to ensure an improvement in our understanding of the effects of explosive volcanism on global and regional climate.

1.1 Rationale for the Meeting

Large, explosive volcanic eruptions appear to cause transient climate changes on time scales from months to years. It has also been suggested that periods of enhanced volcanism or unusually large eruptions at times of climatic instability may trigger climate changes lasting decades or longer. The recent volcanic eruptions of El Chichón in 1982 and Pinatubo in 1991, both accompanied by El Niño climatic conditions, have been linked with global weather and climate disturbances lasting two to three years. Other large eruptions during the past 200 years that produced significant stratospheric aerosol layers include Tambora (1815), Krakatau (1883), Katmai (1912) and Agung (1963). These eruptions produced similar, but less well-documented effects. During the last century, global average climate warmed by more than 0.5°C, concomitant with anthropogenic increases in atmospheric CO_2 and other greenhouse gases. In order to understand this pattern of climatic change, it is necessary to understand the effects of volcanic eruptions on climate, since the forcing associated with each of the eruptions mentioned above produced a transient cooling effect larger than the opposite forcing effect of all the anthropogenic greenhouse gases in the atmosphere today. A more complete understanding of volcano-climate processes and interactions will be an essential part of any effort to model and predict the effects of large volcanic eruptions that occur in the future.

An important opportunity now exists to document both the frequency and intensity of past explosive volcanic eruptions and the climatic effects associated with these eruptions. In some cases, geologic environments that directly incorporate physical products of volcanic eruptions simultaneously record proxy climatic data. Studies of such records have the potential to reveal a detailed history of volcano-climate interactions on annual time scales during the last two millennia, through most of the last 10,000 years of the Holocene, and at coarser level of temporal resolution through the last 150,000 years of the most recent glacial-interglacial cycle. Of particular interest are those prehistoric eruptions that are larger than any seen during the last few hundred years, because the magnitude and duration of the climatic effects associated with such eruptions are very poorly documented.

Through a careful analysis of multiple varieties of high-resolution paleo-volcanoclimatic records and numerical modeling studies of the effects of volcanic aerosols on the climate system, it may be possible to reach a quantitative understanding of this mechanism of climate forcing. Although volcanic aerosols have a much shorter residence time in the atmosphere than greenhouse gases, well-characterized eruptions may provide valuable tests for climate models and atmospheric dynamics.

Progress is being made in understanding the volcanic-atmosphere interactions that result in climate perturbations. Also, new technological developments are expanding our ability to use volcanic ash deposits to directly correlate and precisely date proxy climate records from many natural archives. The PAGES/INQUA meeting in Tokyo was organized to identify these new developments and research opportunities, to encourage the development of collaborative research projects on these topics, and to initiate the development of a science and implementation plan to guide future research on climate forcing and feedback mechanisms within the PAGES Task on Volcanic Influences on Climate.

1.2 Working Group Discussions

The following topics, dealing with different types of paleovolcanic and paleoclimatic records, were addressed by the ad hoc working groups:

• Modeling studies, ice cores, frozen ground, historic, non-biologic records;
• Tree-rings, palynology, corals (biologic records);
• Volcanology and climatic components;
• Tephrochronology;

Each of the working groups was asked to consider the following questions in their discussions:

• What significant contributions can this discipline make to high resolution paleoclimatic and paleovolcanological studies?
• What is the current status of research in the discipline?
• What strategy should be developed to promote research in this subject area?
• What obstacles (technical or administrative) preclude real progress being made on this topic?
• Who are the key community leaders and individuals not present at this meeting?
• What resources are required to make significant progress on this topic over the next five years?
• What are the high priority areas of research requiring immediate attention?

Some working groups adhered closely to the topics in these questions, while others addressed them in a more general fashion. The comments of each of the working groups have been edited for consistency and are outlined in the following sections.

2. MODELING STUDIES, ICE CORES AND FROZEN GROUND, HISTORIC RECORDS

Working Group Members:

Yoshiyuki Fujii
Takaaki Fukuoka
Masami Fukuda
Takehiko Mikami, Hideki Narita
Alan Robock (Co-Chairperson)
Gregory Zielinski (Co-Chairperson)

2.1 Introduction

Ice cores offer the great advantage of simultaneously recording past climatic conditions, atmospheric chemistry and paleovolcanic events. They contain direct physical evidence of episodes of volcanic aerosol loading from which the characteristics of past volcanic eruptions and the magnitude of coeval climatically-important forcing can be determined with seasonal or annual resolution. Spatial coverage may be increased with other natural archives of comparable resolution, such as: varved sediments which contain tephra, tree-rings showing climatic deterioration after volcanism and historical documents. With this base of information, modeling studies can explore the patterns of climatic response to volcanic eruptions and the relationship of volcanic events to past climate change.

2.2 Status of current research

The GRIP and GISP2 Projects recovered ice cores from central Greenland and represent a major advance in the retrieval of high resolution records of past climate and volcanism. Annual, and even seasonal, variation are recorded further back in time than in any previous ice cores. Major deep ice-coring projects in East and West Antarctica are presently being undertaken or will be undertaken in the near future by several national agencies (e.g. Japan, the European countries, Australia, and the United States). Following methods used in ice coring, studies of ground ice (permafrost) are just beginning and, in ideal cases it may be possible to obtain century-to-decadal resolution from frozen loess sequences.

For certain well-documented areas, historical analyses can contribute to the development of past climate records with daily resolution. The analyses of historical weather diaries which contain daily local weather records are ongoing, and represent an unusually detailed source of paleoclimatic information. By combining weather data from several diaries describing different areas, it is possible to reconstruct regional weather patterns. In some cases it is even possible to reconstruct daily weather maps. It is estimated that about 90% of Japanese diaries have been collected, but there are many more high quality records yet to be collected from China and other regions. These records may extend back more than 300 years in Japan and Europe, and much longer in China.

Climate model experiments of the effects of volcanic eruptions on climate are in their early stages of development and models have only recently incorporated the capability to include the effects of aerosols on climate. Model runs calibrated with instrumental estimates of aerosol loading produced during the Pinatubo and El Chichon eruptions are in general agreement with the magnitude of observed climate effects. Model experiments suggest that aerosols from equatorial eruptions are most easily globally distributed and these eruptions are most likely to have global effects.

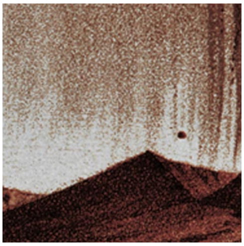
2.3 Obstacles and Resources

It is recognized that the logistics of ice core drilling are very expensive, and international agreements to share costs would be useful. Some technologies should be improved, including high resolution echo sounder and ground radar used for detecting tephra layers in ice sheets and methods to continuously measure ice core parameters while they are being melted for chemical analysis. The neutron activation technique and other sophisticated instrumental techniques should be adapted for the identification of source volcanoes from tephra in ice cores. The working group recognizes the logistical and financial difficulty of conducting permafrost studies in Siberia and recommends collaborative efforts to develop this archive.

2.4 Strategy and recommendations of high priority research requiring immediate attention

In climate modeling, a volcano-climate standardization experiment with existing climate models, i.e., a “Volcano Modeling Intercomparison Project” (VMIP) would be useful. The working group recommends an immediate focus on the well-documented eruptions of El Chichón and Pinatubo.

For ice coring, the working group encourages continued international cooperation on future cores and more intensive analyses of cores already collected. Establishment of a composite ice core chronology from all existing cores is a high priority. A drilling project in West Antarctica, comparable to the Greenland cores, will help to establish the long-range distribution pattern of major eruption events. Studies of intercalibrated tephra layers should be undertaken in both polar and low latitude ice caps. Low latitude ice caps, some of which have begun to rapidly ablate during the last century, may contain the detailed records of the critical equatorial eruptions that are most likely to have global impact.



A major program should be undertaken to identify tephras and aerosol/acid peaks in ice cores and correlate them with specific eruptions at source volcanoes. Historic eruptions (Katmai, Laki, Tambora, Krakatua) should be targeted, together with major prehistoric events through the Holocene and Late Pleistocene time span covered by ice cores. Such a program would produce estimates of global aerosol loading, and possibly produce major breakthroughs in ice core chronology and global tephrochronology.

3. HIGH RESOLUTION BIOLOGIC-PROXY CLIMATIC RECORDS

Working Group Members:

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Susanne Leroy
Janice Lough
Tatsuo Sweda
Yuji Tazawa

3.1 Introduction

High resolution paleoclimatic data sets, such as tree-rings, coral, pollen, micropaleontology, and other proxies, contribute to the characterization of climate events and their relationship to volcanic eruptions. In some cases they may also provide a means of dating the eruptions themselves. These studies typically require interpretation of an indirect response (i.e., vegetation impacted by a severe freeze, extended precipitation/drought events, etc.).

3.2 Status of current research

Studies of tree rings represent one of the most mature areas of biologic-proxy climate records. As a general rule, comparable and compatible techniques are used by dendrochronologists throughout the world. Dendrochronologists are encouraged to use the International Tree-Ring Data Bank (ITRDB), held at the World Data Center for Paleoclimatology, as a repository for their data sets. This practice facilitates the comparison of multiple tree ring records, and also allows intercomparisons of tree-rings with other proxy climate records, including ice cores.

Palynologists are just beginning to examine the climatic impact of volcanism as recorded in pollen profiles. Although most pollen records from bogs or lakes do not have annual resolution, decadal resolution may be attainable with careful work. Consequently, the sensitivity of pollen records to short-term climate events associated with volcanic eruptions is not well known.

Proxy climatic records from corals may be long-term and of annual resolution, as they have relatively rapid growth rates (ca. 10 mm a-1), and may have life spans of several centuries. However, the development of coral records is in its early stages, and it is not known at the present time if they might incorporate geochemical tracers associated with volcanic eruptions, or whether they are sensitive to transient climate events associated with distant explosive eruptions.

3.3 Obstacles and Resources

Communication between scientists at the international level needs to be improved. Scientists focused on biologic-proxies need to be alerted to volcano-climatic issues. Communication might be enhanced through newsletters (NGDC Newsletter, pollen newsletter, etc.), the widening use of electronic mail, and also through topical workshops.

A major problem in dendrochronologic and other types of paleoclimatic studies is the existence of large geographic gaps in the available data. It is essential to identify and encourage work in data-sparse areas (such as Japan, equatorial areas, Africa, etc.)

Although there is considerable potential for increasing the resolution of pollen data, the approach has been limited by the lack of high precision dating techniques that could be applied to pollen sequences. Recent advances in AMS and conventional (benzine synthesis) radiocarbon dating have brought standard counting errors down to approximately 1-2% of reported ages; this still will yield only decadal to century scale resolution at most sites.

The development of methods for obtaining paleoclimatic data from coral faces a unique problem. Rapid global degradation leading to widespread mortality of coral colonies may be occurring and resulting in the loss of the source of data in some areas. A widespread "rescue sampling" project may be necessary in the near future to ensure access to this data source.

The coordination of these types of studies needs support from global scientific administrative bodies (such as PAGES/IGBP) to encourage the recognition and delineation of volcano-climate forcing.

3.4 Strategy and high priority research requiring immediate attention

It is highly desirable to make multiproxy comparisons of different types of high resolution proxy climate data sets. Each proxy-focused community, however, has priority items that will contribute to the global change effort.

The working group recommends that the tree-ring research community:
• continue to add new dendro-records to the ITRDB and focus on climate-volcanism reconstructions;
• develop binary chronologies of frost-ring occurrences in local areas and a global frost-ring compilation. This will be especially useful in identifying eruptions during both PAGES Streams I and II.
• explore isotope and trace element signatures related to eruptions, or their climatic impact, in the high resolution tree-ring data sets.

The working group recommends that the palynology research community:
• investigate the response of vegetation to nearby eruptions with emphasis on site location with respect to the volcanic plume;
• assess the volcano-climatic potential for pollen sites with annual resolution;
• encourage the recovery of long pollen sequences in key terrestrial areas, perhaps through the International Continental Drilling Program (ICDP).

The working group recommends that the coral research community:
• continue to produce detailed climate reconstructions from coral cores;
• determine if corals capture volcanic fallout, either directly or by incorporation of trace elements or other constituents into the coral;
• use the coral record to separate out the effects of El Niño-Southern Oscillation (ENSO) from the volcano-climate forcing signal on long time scales.

For the biologic archives, this working group encourages the use of existing global paleo-data repositories for the compilation of all high resolution climatic response information. The availability of high quality datasets with suitable chronological control and temporal resolution will allow global mapping of the climatic impact of explosive eruptions. This effort might begin with the selection of a group of key eruptions for global study. The study of very young eruptions which occurred during PAGES Stream I (the last 2000 years) would focus on tree ring data, and possibly coral records. It would also be useful to study the effects of larger and older eruptions. For example, a number of large explosive events around the world apparently occurred during late glacial time. Such studies of the effects of older volcanic events would likely rely on pollen studies.

4. VOLCANOLOGY AND CLIMATIC COMPONENTS

Working group members:

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Shinji Nagaoka
Haruldur Sigurdsson (Chairperson)

4.1 Introduction

Volcanism is a planetary-scale process that originally generated the Earth's atmosphere and plays an important role in continuing to maintain and modify it. To reliably assess the impact of volcanism on the atmosphere and specifically on the Earth's climate, an understanding of the temporal and spatial distribution of volcanic aerosols, their optical depth, and evidence of their climatic impact are required. It has been demonstrated that volcanic volatiles are a significant constituent of the Earth's stratosphere which interact with solar radiation to alter the Earth's radiative balance and temperature. A clear correlation exists between certain types of major eruptions and short-term climate character. As demonstrated for recent eruptions, global-average surface temperature declined by 0.2°C - 0.3°C for one to three years following a major eruption. These effects could be more intense on a local or regional scale and may have severe consequences for regional agriculture or other human activities.

4.2 Status of current research

Research on the degassing of sulfur and other volatiles during explosive eruptions is in its infancy and needs major strengthening. Emphasis should be placed on constructing a data base on sulfur and other gas emissions from important eruptions. A global volcanic sulfuric acid data base would contribute greatly to the interpretation of high-resolution paleoclimatic records and provide the basis for the evaluation of the possible effects of volcanism on climate.

Determination of physical parameters related to the dynamics of explosive eruptions, such as eruption column height and eruption rate, is essential for an understanding of the level of volcanic aerosol and ash injection into the atmosphere. Except for studies of co-ignimbrite eruption column height, much work has already been accomplished on eruption dynamics. Development of models of co-ignimbrite columns should be encouraged because they represent the most important type of ash fallout during major explosive eruptions.

4.3 Obstacles and Resources

Increased international collaboration is necessary to facilitate exchange of samples and to construct a global data base. In order to encourage collaborative studies, there is a need to agree on standardized methods of measurement for volcanological parameters (e.g. tephra volume) and to adopt standardized methods of reporting volcanological data.

The PAGES/INQUA program on the impact of volcanism on climate should be strongly coordinated with the IAVCEI (International Commission on Volcanism and Chemistry Interior) on volcanism and the earth's atmosphere. Together, these programs will be able to significantly enhance our ability to entrain the resources required to advance this effort.

4.4 Strategy and high priority topics requiring immediate attention

A wider recognition of the possible effects of volcanism on climate is needed in the global change research community. There is a need to create a greater awareness among geochemists and petrologists of the importance of volcanic processes within the environment. Workshops focused on the relationship of volcanic and climatic effects are an effective way of engaging the community and encouraging collaborative research efforts.

We recommend that during the next five years the volcanological community target for study the volatile output (S, Cl, etc.) from all of the major eruptions of the Holocene. The wide availability of sophisticated analytical facilities, such as electron and ion microprobe, is prerequisite for the advancement of this research.

Our highest priority item is the creation of a data base of major Holocene volcanic events that may have affected climate. Such a data base would allow critical comparison of volcanic output parameters and climate response, as well as the relation between sulfur volcanic output and sulfuric acid aerosol fallout. It should include the following components:

• global acid fallout, (e.g. ice core and satellite data),
• petrologic estimates of sulfur, chlorine and other volatile degassing to the atmosphere,
• tephra volume and tephra geochemistry,
• eruption column height, etc.

The working group recommends additional research emphasis on the following problem areas:

• degassing mechanisms of sulfur from magmas during ascent and eruption, by detailed glass inclusion studies.
• resolution of the "excess sulfur problem". Why is the sulfur mass release from some explosive eruptions an order of magnitude larger than can be accounted for by petrologically based estimates of degassing of erupted magma?
• refinement of volume estimates of tephra, such as by study of deep-sea sediment cores.
• the geochemistry of sulfur in magmas, including sulfur isotope studies.

5. TEPHRO-CHRONOLOGY

Working group members:

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Valerie Hall
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Tom Simkin
Shigeo Sugihara
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5.1 Introduction

Tephra studies are fundamental to both the dating of prehistoric eruptions, some of which were larger than any known in historic times, and to the reconstruction of the volcanologic characteristics of those eruptions that may modify climate. Tephrochronology also constitutes one of the essential dating tools for long proxy climate records. In some cases tephra horizons can be used to correlate specific volcanic eruptions or climate events as recorded in ice cores, tree-rings, varved sediments, and other high resolution proxy climate records. Tephra is found in a wide range of environments and in both organic and inorganic deposits. Studies of tephra will likely play an important role in the determination of the causes of short-term climatic fluctuation identified in Holocene and in older high resolution paleoclimate records.

5.2 Status of current research

Some areas are well studied and the characteristics of major tephra layers are well known, e.g., Japan, Western Europe, USA, New Zealand, Iceland. Many important areas, however, are much in need of additional work, especially in the low latitudes and throughout the circum-Arctic region.

5.3 Obstacles and Resources

There is an unfortunate lack of workers in some of the developing regions which are loci of explosive volcanic activity. An increased degree of recognition of the importance of regional and geochemical tephrochronology and tephra studies is needed on the part of national agencies to provide the resources needed to advance this effort. The community will require the financial resources to support state-of-the-art analytical studies of tephras and additional field studies to fill the wide spatial gaps in our knowledge of tephra distribution. The community must be able to readily access the newly developed high-precision, grain-specific techniques for major, minor, trace, and rare earth element analysis (WD microprobe, laser ICPMS, ion microprobe). These techniques are nec-

essary for successful correlation of proximal and distal tephra and the isolated shards recovered from ice cores.

The current PAGES/INQUA cooperative effort in this area needs to be further developed and strongly coordinated as an international program on the study of the impact of volcanism on global climate and this also should be coordinated with the IAVCEI commission on volcanism and the earth's atmosphere. The program should involve those individuals who have compiled tephrochronologic information for major volcanic centers or volcanic provinces.

5.4 Strategy and high priority topics requiring immediate attention

The working group recommends on the following areas of research an immediate focus:

- basic data on major tephra eruptions, including volume, chronology, geochemistry (sulfur and other volatiles) should be compiled and catalogued. This requires integration of field stratigraphic studies (including data from marine cores) and geochronology, augmented with tephra characterization by a combination of precise geochemical techniques.
- this working group encourages collaborative efforts between scientists working in all parts of the world. It would be desirable to hold workshops in volcanic regions with PAGES/INQUA sponsorship to encourage the development of regional communities of scientists focused on these studies.
- standardization of geochemical and geochronologic procedures for quality control for tephra studies and chronometric studies.
- precision geochemical characterization of tephras in ice cores and other high resolution records and correlation of these with tephras and specific eruptions recorded in local volcanic sequences.
- determination of the contribution of volatiles to the atmosphere during eruptions. Focused tephra studies should be carried out for major eruptions occurring within PAGES Stream I and II (the last 2000 years and the last two glacial-interglacial cycles) .

6.

TEPHRA - DATABASES

Contributed by::

Valerie A. Hall

6.1 Introduction

Tephra studies are now one of the most dynamic sciences in Quaternary Studies. Research studies of tephra distribution have shown that, until recently, the geographical extent of volcanic ash has been consistently and seriously underestimated. Advances in analytical techniques now allow geochemically-confirmed site linkage over extensive areas, in some cases on a hemispheric and global scale. In addition to investigations of past environmental change, tephra studies also contribute to our understanding of volcanism and volcanic processes.

The development of databases for tephra are now underway. These databases seek to include information on present and past volcanism and will eventually include quantitative and qualitative information. No doubt there will be a major expansion in the scope and number of databases for this growing research area in the next few years.

6.2 Current Databases

Two databases contain a wide range of information on volcanism, explosivity indices, location of specific volcanoes and tephra geochemistry. A third is under development.

CATALOG - The "Catalogue of widespread tephra layers in the world" (managed by Koji Okumura and Hiroshi Machida) is a Working Group of the Commission on Tephra Studies of INQUA. It is currently the largest of the tephra databases and aims to compile a global database of widespread Quaternary tephra layers. Such a catalogue will include information on the volcanology, chronology and geochemistry of marker-tephra layers, such as source vent, type of explosive volcanism, age, distribution, and petrographic nature of constituent material. This will be essential for the global and regional correlation of Quaternary sequences. Okumura and Machida are working on data input but have difficulty in that the amount and quality of data are uneven on a global scale. More information from tropical regions and developing countries is required. A publication of

the world tephra catalogue is planned for late 1996. Guidelines and data input forms may be obtained from:

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The work of Tom Simkin and Lee Siebert (Global Volcanism Program, Smithsonian Institute, Washington, DC.) is complementary to CATALOG. Late in 1993, prior to publication of the second edition of Volcanoes of the World, they distributed a database of all Holocene eruptions with known VEI greater than 4 (and lava volumes greater than 1km3). An interesting interpretation of some of the data was published as “Terrestrial volcanism in space and time” in Annual Reviews Earth and Planetary Science 21, 427-452 (1993).

TEPHRABASE is currently being developed in the Department of Geography at the University of Edinburgh. The pages accessed will enable complex searches of the database to be carried out. Both published and unpublished data on tephra deposits and their source volcanoes will be available when the database is completed. At present only data on tephra layers sourced from Icelandic volcanoes will be stored. Further information can be obtained from:

Dr. Anthony J. Newton
Department of Geography
Drummond Street; Edinburgh
UNITED KINGDOM
E mail: AJN@geovax.ed.ac.uk
Tephrabase: Netscape Home Page:
http://www.geo.ed.ac.uk/tephra/tbasehom.html

6.3 Databases Under Construction

The International Commission on Volcanism and Chemistry of the Earth's Interior is expanding its database on major eruptions of the last two hundred years. Further information on this database may be obtained from:

Dr. Steven Self
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University of Hawaii at Manoa Honolulu, HI 96822
USA
Tel: +1-808-956-5996
Fax: +1-808-956-2538
E mail: self@lani.soest.hawaii.edu

The INQUA Commission on Tephra Studies (formerly Commission on Tephrachronology) has a number of working groups including databases. Further particulars may be obtained from:

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(NOTE: This section is reprinted with minor revisions from: Global Paleoenvironmental Data (1995), PAGES Workshop Report Series #95-2).

7. RECOMMENDATIONS OF FINAL PLENARY SESSION

At the workshop's final plenary session, recommendations of the individual working groups were presented by the working group chairpersons. In this final meeting, broad agreement was reached on the critical need for new and additional research in several areas.
These efforts are critical to an improvement of our understanding of the relationship between volcanic eruptions and climate change and are summarized here:

• It is essential that detailed records of the atmospheric loading and climatic effects associated with past volcanic eruptions be developed. These can best be produced from interdisciplinary studies of historic documents and multiproxy geologic records with annual resolution, including ice cores, varved sediments, corals and tree rings. Decadal-scale proxy climate records from pollen, loess and other sources are also required to establish the longer-term temporal context. Cross-correlation of acidity and particulate records in different ice cores, together with near-field studies of tephra at source volcanoes and regional paleoclimatic reconstructions, can help to identify the location and amplitude of major prehistoric eruptions and the magnitude and duration of concomitant climatic forcing.

• Data are needed on the fundamental characteristics of large volcanic eruptions, including the processes involved in the release of aerosols from magma. The establishment of an international data base or catalogue that contains key information on the physical properties of all major tephras (i.e., geochemistry, volume, volatile content, etc.) is of the highest priority. This will improve our knowledge of eruption dates, eruption character and explosivity, and volumes of particulate and aerosol release. These efforts should be coordinated between the existing groups: U.S. Smithsonian Institution Volcanoes of the World project, the IAVCEI Commission on Volcanism and the Earth's Atmosphere, and the Global Catalogue of Tephra Eruptions sponsored by the INQUA Commission on Tephra Studies.

• A group of eruptions should be targeted for detailed interdisciplinary studies on volcanism and global climate forcing. This group should include some well-known historic eruptions as calibration for the paleorecords, and also representative examples of some of the much larger prehistoric eruptions. Among historic events, the causes of the "year without a summer" in 1816 and its relation to the large 1809-1810 eruption recorded in both Greenland and Icelandic ice cores, and the 1815 Tambora eruption, should be investigated. The following large prehistoric eruptions should be studied to determine if they produced significant climatic forcing: Taupo (ca. 1850 yr BP), Santorini-Aniakchak (ca. 3700 yr BP), Kawakawa (ca. 22,000 yr BP) and Toba (ca. 73,000 yr BP).

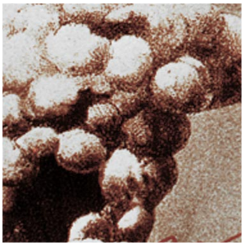
• The possible effects of large eruptions or extended periods of volcanism should be studied in relation to longer-term climate change. In particular, during PAGES Stream I, possible relationships between volcanic eruptions and the initiation and pattern of the "Little Ice Age" during the 15th-19th centuries should clarified. Other intervals of interest include earlier Holocene climatic perturbations, the Pleistocene-Holocene transition, and the Younger Dryas climate event.

• The development and use of Earth system models which are capable of explicitly accounting for the effects of stratospheric aerosols and their chemical and microphysical evolution and transport, should be encouraged. Model studies of the simultaneous occurrence of eruptions and El Niño occurrences, such as 1982 and 1991, should be conducted to examine the complex climatic response to these different forcings. Also recommended are model studies of the possible effects of volcanic eruptions on global climate following greenhouse warming, during the "Little Ice Age", and at glacial/interglacial transitions.

8. CONCLUDING STATEMENT

The results of research presented at this workshop demonstrate that the global effects of Quaternary volcanism on the environment and the widespread distribution of volcanic products has been constantly and seriously underestimated. The products of past volcanism are unique because they are found in such wide-ranging deposits as polar ice, peats, ocean and lake deposits. Volcanically-induced climatic deterioration affects living organisms like trees and corals, whose annularity provides proxy records of climate change spanning millennia. As time-scales are refined, the magnitude of past eruptions is estimated and the geochemical signature of the most minute volcanic particles is established, palaeoenvironmental scientists will gain improving insight into the sources and effects of past volcanism.

It is clear that research is concentrated in places often far from volcanoes. We encourage the paleo-environmental scientific community to recognize the widespread effects of past volcanism and to co-ordinate research, especially in conjunction with workers in volcanically-active developing countries. Refining the timeframes which constrain the study of past volcanism and volcanic products will further the aim of PAGES, to catalogue past global environmental change at the most precise timescales possible.



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2 Eruption ov Vesuvius, Italy, in 1822 (courtesy V. Maurin)
3 Tephra enlarged (V. Hall)
4 Eruption of Mt. Ruapehu, New Zealand, in 1996 (D.J. Lowe)

Back: 1 Tephra layer enlarged (V. Hall)
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