GEOHAZARDS theme REPORT

IGOS

Integrated Global Observing Strategy

For the Monitoring of our Environment from Space and from Earth

April 2004

An international partnership for cooperation in Earth observations

The Integrated Global Observing Strategy (IGOS) is a partnership of international organizations that are concerned with global environmental change issues. It links research, long-term monitoring and operational programmes, bringing together the producers of global observations and the users that require them, to identify products needed, gaps in observations and mechanisms to respond to needs in the science and policy communities. Its principal objectives are to integrate satellite, airborne and in-situ observation systems.

The IGOS partners are comprised of the Global Observing Systems, the International Organizations which sponsor the Global Observing Systems, the Committee on Earth Observation Satellites (CEOS), and International Global Change Science and Research programmes.

The IGOS Partners recognise that a comprehensive global earth observing system is best achieved through a step-wise process focused on practical results. The IGOS Themes allow for the definition and development of a global strategy for the observation of selected environmental issues that are of common interest to the IGOS Partners and to user groups. The current IGOS Themes include the Oceans, the Carbon cycle, Geohazards, the Water cycle, and a Coral reef sub-theme.

The IGOS Geohazards theme was initiated in 2001 by the National Oceanic and Atmospheric Administration (NOAA), the United Nations Educational, Scientific and Cultural Organisation (UNESCO), CEOS and the International Council for Science Union (ICSU) in Paris. An ad-hoc Working Group was formed, chaired initially by the International Institute for Geo-Information Science and Earth-Observation (ITC) and then by the British Geological Survey (BGS), and co-chaired by the European Space Agency (ESA) and UNESCO.

The proposal to develop the theme was approved by the IGOS Partners at their 9th Plenary in June 2002 and a Theme Team was set up. With the support of a community of more than 200 people worldwide who expressed interest in this initiative, a draft report was submitted to the 10th IGOS Plenary in June 2003. Following an international peer review during summer 2003, the present Theme report was approved for implementation by the IGOS Partnership in November 2003.

The IGOS Geohazards Theme was developed under the IGOS Chairmainships of Jose Achache, of ESA, Greg Withee, of NOAA and Walter Erdelen, of UNESCO.

- Further information on IGOS can be obtained from: **http://www.igospartners.org**
- The GeoHazards theme report is available from: **http://dup.esrin.esa.it/igos-geohazards/**
- Inquiries about the IGOS Geohazards theme can be sent to: **igos@esa.int**

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The impact of geological and related geophysical hazards on society is enormous. Every year volcanoes, earthquakes, landslides and subsidence claim thousands of lives, injure thousands more, devastate homes and destroy livelihoods. Damaged infrastructure and insurance premiums increase these costs. Developed countries are affected, but the impact is highest in the developing world. As population increases, more people live in hazardous areas and so the impact grows. The World Summit on Sustainable Development recognised that systematic, joint international observations under initiatives like the Integrated Global Observing Strategy form the basis for all nations to improve their preparations for, and mitigation against, these hazards. In the same context, the IGOS Partners have developed this geohazards theme. Its goal over the next decade is to integrate disparate, multidisciplinary, and applied geohazards research into global, operational observation systems by filling gaps in organisation, observation and knowledge. It has four strategic objectives; building global capacity to mitigate geohazards; improving mapping, monitoring and forecasting, based on satellite and ground-based observations; increasing preparedness, using integrated geohazards information products and improved geohazards models; and promoting global take-up of local best practice in geohazards management.

Citizens need to know a hazard's location, timing, extent, likely behaviour, and duration. It is not yet possible to give firm answers to most of these questions. This makes crisis response initiatives like the International Charter on Space and Major Disasters and the United Nations Action Team on Disaster Management harder. Gaps remain between what is known and the knowledge required to answer these questions, what is observed and what must be observed to provide the necessary information and current data integration and the integration needed to make truly useful information products. The IGOS Geohazards will reduce these gaps and so make the responsible agencies better prepared for managing geohazards. It targets monitoring and advisory agencies, by aiming to improve the hazard inventories, maps and monitoring tools with which they supply the responsible agencies with information. It also targets the research scientists, aiming to help them refine the models that are used to understand geohazard behaviour. By building on previous work undertaken by individual IGOS Partners, this approach will ultimately deliver better answers to citizens.

Geohazards driven directly by geological processes all involve ground deformation. Their common observational requirements are for global, baseline topographic and geoscience mapping, against which surface deformation and seismic activity can be monitored. Systems that can meet these requirements include stereo optical and radar interferometry satellites, plus ground-based GPS and seismic networks. Beyond this, specific hazards like volcanoes require additional observations like temperature. All these observations must be stored in well-managed and accessible databases. Tools to produce information products through integration, modelling and assimilation must be developed and documented. Networking, education, training and skills transfer must be undertaken, in order to build the capacity to use these tools. Critical gaps exist in: the provision of detailed, global topographic data, hazard inventories and geoscience maps; continuity of the C- and especially L-Band radar interferometry that are needed to observe surface deformation under varying vegetation cover; density and coverage of local GPS and seismic networks; accessibility of relevant databases; adequacy of models and data integration; and the integration of the geohazards community.

An action plan is proposed that is designed to close these gaps over the next decade. The first step is to create an implementation mechanism based on UNESCO-International Union of Geological Sciences Geological Applications of Remote Sensing (GARS) Programme. The existing geological representation will be blended with space agency participation and more scientific disciplines from all regions. A bureau funded by the European Space Agency will support implementation through working groups on capacity building, observations and key systems, integration and modelling, databases and infrastructure and the underpinning science. Links will be developed with relevant sub-groups under the new Group for Earth Observation, linked to the Earth Observation Summit process. Priority actions are to: begin networking within the geohazards community; improve topographic data provision using existing observations; secure continuity of C- and L-Band radar interferometry with the space agencies; assess the potential for existing data to be integrated into geohazard products and services; evaluate ways to improve databases with the agencies that manage them; and promote research that increases geohazards knowledge. The progress against this plan will be assessed by a Steering Committee and reported to the IGOS Partners and the sponsoring agencies annually. The strategy will be reviewed and updated every three years.

Chapter 1 examines the impact of geohazards on society, describes the main operational and political responses, sets out the scope of the IGOS Geohazards and defines its strategic objectives

Chapter 2 explains who will benefit from the strategy, introduces three groups of targeted users, states their needs for geohazards information and acknowledges the roles of other stakeholders

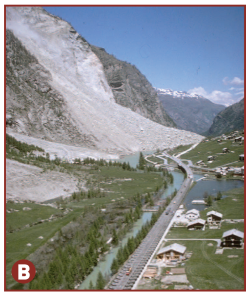
Chapter 3 lists the main observations required in order to meet users' information needs and identifies the main existing and planned in-situ, airborne and satellite observing systems needed to make them

Chapter 4 addresses data management, integration, modeling and assimilation issues and considers how to build capacity in the geohazards community by education, training and skills transfer

Chapter 5 analyses the critical gaps in capacity building, observations and key systems, integration and modeling, databases and infrastructure and underpinning science that must be filled

Chapter 6 defines an implementation mechanism, presents an action plan to fill the gaps over the coming decade, demonstrates commitments to act and proposes an assessment and review cycle

Every year thousands of people are killed by volcanic eruptions, earthquakes, landslides and subsidence. They are one of the main natural causes of damage to human settlements and infrastructures. They severely disrupt the economic life of many societies. As human population increases, habitation on hazardous land becomes more common and the risks posed by these hazards increase. The need to observe their behaviour, understand them better and mitigate their effects becomes ever more urgent. This is clear in the response of the international community and it is the driver behind the proposed strategy. The strategic objectives are to build a global capacity to better deal with geohazards, deliver the necessary observations, improve the integration of data and systems, and promote the take-up of best practice worldwide



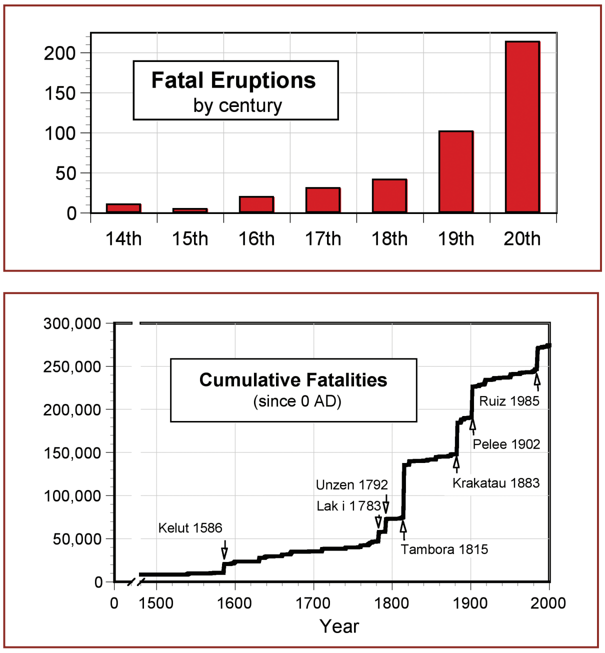
A - Piton de la Fournaise – La Réunion – Eruption November 2000 (courtesy of T. Staudacher OVPF/IPGP)
B - Rock Slide in Switzerland (courtesy of FOWG).
C - Collapsed houses in the town of Ratnal, in the epicentral region of the Gujarat earthquake (courtesy of USGS).

GEOHAZARDS' IMPACTS

Geohazards such as earthquakes, volcanic eruptions, landslides and subsidence inflict an enormous cost on society. Every year thousands of people are killed by volcanoes, earthquakes and landslides; the United Nations Environment Program (UNEP) on its GeoData portal reports that more than 26,000 have died in volcanic disasters between 1975-2000. The death toll of the 1976 earthquake in Tangshan, China alone was 242,000. Yet this is only part of the toll; for every life lost, many more are injured, or lose their homes or livelihoods; landslides in Bolivia in 1994 affected 165,000 people. A major disaster disrupts the economic life of a society for years or even decades. Even where loss of life is avoided, geohazards damage infrastructure, destroying roads, railways, buildings, airports, pipelines, dams, power grids and many other structures. The cost of these events is billions in any currency. Whilst the cost in absolute value is higher in developed countries, the cost in terms of Gross National Product is far higher in the poorest, developing countries.

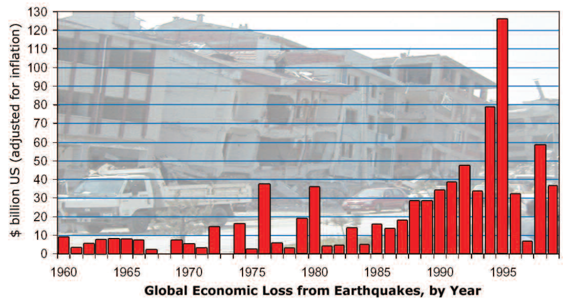
The damage from the Mount St. Helens eruption in 1980 was US$1 Billion (Blong, 1984). Consequently, private organisations most exposed to these risks seek to insure against them at an additional cost that is itself in the billions. The United Nations (UN) has established that the total costs of natural disasters as a whole have risen 10 fold in the past 40 years. The principal driver is the increase in human population and a consequent increase in the intensity of development in hazardous areas, such as on steeper slopes and along coastal zones. Geohazards therefore pose an increasing risk to society that can only be reduced by developing a better understanding of the occurrence and behavior of the hazards.

Volcanoes and volcanic eruptions have captured the imagination of the human race for many centuries. In earlier times, eruptions caught the local population by surprise and often caused great loss of life, in addition to inflicting material damage on nearby areas that lasted for decades. Even today, with the flood of other news served up daily, there is a ready audience for reports of any volcanic activity. This shift from regarding volcanic eruptions as completely unpredictable and terrible events, to viewing them as one of nature's foremost made-for-television spectaculars, reflects in part the increasing success of volcano scientists in interpreting signs of volcanic unrest and communicating the risk to local authorities and the general public. Complacency is dangerous, however. Important aspects of volcanic activity remain poorly understood. Many active volcanoes in inhabited areas are inadequately monitored. Furthermore, the increase in population worldwide means that both the number of people and the value of infrastructure sited close to active volcanoes are increasing. Recent examples include: El Chichon (Mexico) which was completely unmonitored prior to 1982 when it erupted, killing 1800 people and devastating the surrounding area for a decade; and Nyiragongo (Congo) where over 70 people were killed by fast-moving lava flows in 1977 (Simkin and Siebert, 1994). Nyiragongo was known to be poorly monitored, and was identified as a Decade Volcano under the UN-sponsored International Decade for Natural Disaster Reduction (IDNDR). Nevertheless, 25 years later the January 2002 eruption of Nyiragongo killed 147 people and wiped out the center of Goma, a town of over half a million people. Evidence for increased exposure to volcanic hazards includes a steady increase in the number of eruptions causing fatalities over the last 500 years.



Fatal eruptions (14th century to present) and cumulative eruption fatalities (1500 to present). The overall exposure of human population to volcanic activity can be seen in the first graph, where the number of eruptions causing at least one death has steadily increased, over the last 5-6 centuries. The second graph shows that most of the lives lost during this period were lost in a few, very large eruptions. (from Simkin, Siebert and Blong, 2001)

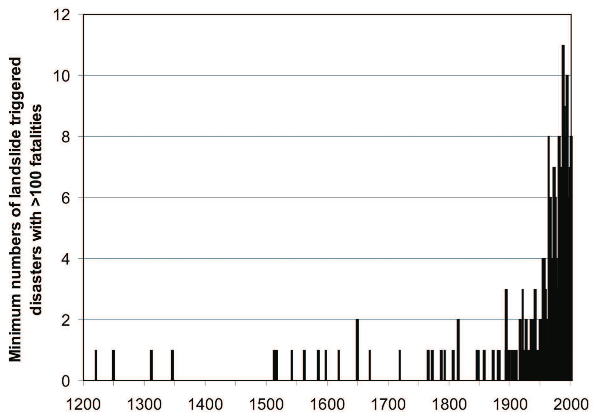
Earthquakes are probably the most devastating of all the geological hazards. They killed more than 460,000 people worldwide between 1975 and 2000 (UNEP) and rendered more than 8 million people homeless during that same period. The United States Geological Survey (USGS) National Earthquake Information Center (NEIC) reports that, every year, seismic networks around the world record some 12,000 to 14,000 earthquakes. This is equivalent to approximately 35 every day. At least one of these will be of Magnitude 8 or higher and in a typical year there are 20 of Magnitude 7-7.9. Large earthquakes are thus more frequent than large volcanic eruptions. The extensive distribution of plate boundaries and associated fault zones, in comparison to the more localised occurrence of volcanoes, means that the number of countries at risk is higher. Consideration of devastating earthquakes over the past decade shows that there is also a marked difference in the effects that earthquakes have in developed and developing countries. Fatalities caused by the Northridge (M 6.7) and Kobe (M 6.5) earthquakes were relatively low (57 and 5,500 respectively), but the economic costs to the USA and Japan were huge, estimated at $40 billion and $100 billion respectively. In contrast, the larger earthquakes that struck Izmit (M 7.4) and Gujarat (M 7.8) produced death tolls of roughly 17,000 and 20,000 respectively. This enormous loss of life was largely a consequence of poor building construction practices. Whilst the dollar estimates of damage for these two earthquakes may be lower than Northridge and Kobe, their impact on the economies of Turkey and India was no less devastating. Data on these and other significant earthquakes are compiled on the NEIC web site. These data demonstrate that earthquake hazards are not only more frequent and widespread than volcanic hazards, but also that the impact of earthquakes on human life is significantly higher than that of the even more widespread landslides and subsidence hazards.



Global direct economic loss from earthquakes is increasing with time, as depicted by this graph based on Munich Re data. In the last 20 years or so, world's vulnerability to earthquakes has increased hugely. It is only by lucky circumstances that the death toll has not been peaking: there are a number of potential mega-death earthquakes which are far more to be feared than exact re-runs of any of the earthquakes of recent years. Background picture courtesy of Russ Evans, BGS

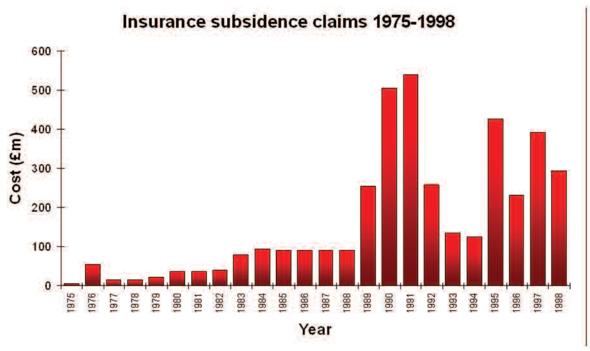
Ground Instability caused by landslides and subsidence is one of the most widespread geological hazards. It ranges from devastating landslides, involving the chaotic movement of large quantities of rock and soil down steep, unstable slopes, to progressive downward or upward surface movements, commonly referred to as subsidence, that are produced by ground water withdrawal, mineral extraction, underground storage and engineering works, the collapse of buried natural or man-made cavities and settlement of loose sediments. All such ground failure is observable through surface deformations and displacements. Its destructive effect on the population is greatest in developing countries, where there are an average of a thousand deaths per year caused by landslides, but even in developed countries deaths are in the hundreds. Economic losses are largest in developed countries.

A study commissioned by the British National Space Centre (BNSC) and conducted by BGS and Nigel Press Associates (NPA) estimated that the cost of subsidence in the United Kingdom alone amounts to several hundred million of Euros every year.



Minimum frequency of worldwide natural disasters caused by landslides of more than 100 casualties. This figure is based on a review of available archives and thus, heavily dependent on reporting procedures. However, it offers some information on increased casualties due to landsliding. The implication is twofold: landslide occurrence might have increased, or, as a result of population growth, more people have moved into more disaster-prone areas. It can be suspected that both factors are responsible for the shown trend (from Glade & Dikau, 2001).

World population growth, consequent intensive land use on steep slopes and in coastal zones, increased needs for water, oil, gas and minerals extraction and the potential increase in triggering events like major storms due to global climate change will all serve to increase the occurrence of these hazards.



Insurance subsidence claims in UK between 1975 and 1998 (courtesy of NPA, BNSC and BGS).

Although individual landslides occur at single locations, the phenomenon can affect large areas. For example, the Bola cyclone in March 1988 triggered more than nineteen thousand landslides covering an area of fifty square kilometres in New Zealand (Glade, 1997). Basic landslide inventory maps are lacking in many regions and several aspects of ground instabilities need to be better understood, including the causative factors, the triggering mechanisms and the different temporal and spatial scales involved.

RESPONSES

Events such as the 1999 Izmit earthquake in Turkey, the 2002 eruption of Nyiragongo Volcano, which cut the Congolese city of Goma in two, and the recent series of devastating landslides in South America and Italy have caught the attention of the world. The costs of geohazards are clear and therefore these issues are increasingly prominent on the political and social agendas of many governments and international agencies.

At a global scale, the benefits of mitigation have been explored at length during the 2002 World Summit on Sustainable Development (WSSD). Benefits demonstrated by several case studies are described in Chapters 2 and 3 and include a reduction not only in the lives lost but also in the damage to infrastructure. In the longer-term, the money no longer spent on disaster response could be transferred to more proactive development initiatives. The summit therefore decided to strengthen capacities and to promote systematic, joint international observation and research, recognising the role that an integrated global observing strategy can play in this process. It recommended an integrated, multi-hazard approach to prevention, mitigation and preparedness.

In May 1998, the European Commission (EC) and ESA jointly launched the Global Monitoring for Environment and Security (GMES) initiative to establish a European capacity that would provide a permanent access to reliable and timely information regarding the status and evolution of the Earth Environment at all scales. The GMES capacity, that should be in place and operating from 2008, will provide information that would meet the European environmental obligations (from European policies to national regulations and international conventions), support the sustainable development both within European Union territory and globally, and contribute to the citizen's security by providing adequate information in support to civil protection and humanitarian aid. One of the key GMES services to be offered is the provision of information to improve the preparedness and response capacities of civil protection and other security-related authorities. This covers geophysical hazards and crisis management. Both EC and ESA are also funding, within their regular programs, like the EC's Sixth Framework and ESA's Data Users Element, the necessary preparatory work and research on applications that are not yet sufficiently mature for an operational GMES service.

In North America, the National Aeronautics and Space Agency (NASA) has published "Living on a Restless Planet" to encourage work in this area. The Earthscope initiative is receiving significant funding from the US National Science Foundation and other agencies to study geohazards on a continental scale.

In July 2003, the US Government convened a ministerial-level Earth Observation Summit in the hope of obtaining broad international consensus on the need for timely, high-quality, long-term global environmental information as a basis for sound decision making. The Summit was followed by a meeting of the newly constituted Group on Earth Observations (GEO), which has laid out an ambitious schedule for developing a set of in-situ, airborne, and satellite-based global observational requirements for a wide range of environmental and hazards monitoring. Participating international organizations included CEOS, IGOS, ICSU and UNESCO. The time frame set for this exercise is 10 years. The IGOS Geohazards and the other IGOS themes will all provide important technical input into this broader, international political initiative.

There are similar initiatives in other regions and international funding agencies increasingly fund work on the geohazards, as do national funding agencies such as the UK's Department for International Development. But there are several things missing that make all this work harder to undertake and less productive.

THE NEED FOR A STRATEGY

Several factors determine the need for a strategic approach to this issue.

Firstly, an integrated approach is needed. The scale of the problem demands cooperation from all affected societies and within all relevant technical fields. Existing initiatives on specific topics need to be brought together under one umbrella. The user and scientific communities need to come together so that those who deal with the problems in the real world interact with those who have potential solutions. Technologies and methodologies that could each address part of the problem will have more effect if used in concert, as part of a multidisciplinary approach. For example, ground-based measurements can be continuous in time but are often limited in extent, whereas satellite observations are periodic but cover wide areas in a uniform fashion. A model developed to understand a well-monitored volcano might help explain the behavior of another, despite a lack of adequate measurements. The geohazards lend themselves to such an approach. Such integration will have the benefit of releasing the synergy that is found in using complementary methods and the accelerated learning that comes from a multidisciplinary approach.

Secondly, geohazards arise from global geological processes inside the Earth, driving deformation and displacement of its crust. Ground deformation is the linking phenomenon and so similar modeling and observational techniques can be used to address all these hazards. They are also global in extent, occurring on all the continents, affecting the citizens of every country, and causing problems for every government. They do not respect national boundaries and so cannot be dealt with at the national or regional level. An earthquake may span several countries or send refugees from one into another. Responses need coordination on a scale that matches the global scale of the problem itself.

Thirdly, current observations are inadequate and the lack of historic databases constrains our approach. For example, few countries in even the developed world have inventories of historic landslides, yet these are the first step in understanding where landslides will occur in the future. By no means are all faults mapped and the interseismic processes along those that are mapped are poorly understood. A few volcanoes are well monitored but many are not yet observed in any detail. A range of observations is commonly needed: topography and landform, surface deformation and displacement, strain, geology, soil, land-use, temperature, rainfall, moisture and gases, to name a few of the more important. Some can be observed from space, taking advantage of Earth Observation (EO) systems already in orbit. These can offer significant cost-savings compared to other means of gathering the data and enable the rapid measurement of key parameters over wide areas without disturbing the object under observation. The nature or scales of occurrence of other necessary observations require that in-situ measurements be made. In both cases technology exists or is being developed, but its application needs to be integrated and extended from local, specific case studies, often using experimental systems, to global operational scenarios based on long-lived sensor deployments.

Fourthly, the challenges are not only technical but also strategic. These hazards demand concerted action from integrated, cohesive networks of users, scientists and policy makers. How can they engage with each other and build the geohazards community? What are the barriers to global application of local best practice? Will solutions that work in the developed world also work in developing countries? This document describes the main components of a strategy designed to answer these questions, as well as to make sure that the necessary observations are made. It is therefore aimed at both the international geohazards user community, who manage the problem, and the IGOS partners, who make the observations. The strategy's objective is to integrate dispersed, multidisciplinary and applied research into future cohesive, operational systems by filling observational, organizational and knowledge gaps over the next decade. The benefits will include: maximising returns on investments made by international agencies, through optimised use of the resulting observations; linkage of established in-situ monitoring systems with new satellite-based techniques; coordination of activities and observations; and the development of a coherent, well informed global geohazards community to address the underlying issues.

These missing pieces of the jigsaw can best be provided not through an isolated approach for the geohazards, but rather through developing a place for geohazards in the Integrated Global Observing Strategy. The IGOS Partnership brings together the key international agencies that make and use global observations, either from space or on the ground. It provides a coordination mechanism to support the integration of these observations, as well as the communities that work with them. Its long-term aim is to put in place all the pieces necessary for the IGOS to become a reality. It is the ideal framework within which to address the deficiencies in current approaches to the geohazards issue, avoiding overlap but ensuring that the key gaps are filled.

CONTEXT AND SCOPE

For the strategy to be capable of implementation, it is necessary to set out clearly the scope of this IGOS theme, defining its place alongside other initiatives. The UN's now completed IDNDR, culminated in the current International Strategy for Disaster Reduction (ISDR). The ISDR forms a framework for action, to which this proposal is intended to respond. The starting point for the necessary technical development is the work of the CEOS Disaster Management Support Group (DMSG), on whose foundations this strategy builds and whose members helped write it. That group has considered a range of natural disasters and documented appropriate responses to them, especially in terms of EO data. This strategy takes forward a coherent subset of CEOS DMSG recommendations covering the geohazards specifically – volcanoes, earthquakes, landslides and subsidence - leaving floods, fire, ice and oil spills to other initiatives. This strategy's scope has been tightly defined in this way in order to provide a unique, coherent IGOS theme on geological and geophysical hazards. Defining the scope so tightly leaves aside some important hazards that are, in part, related to geology. These will be addressed through cooperation with other IGOS themes. The complex interaction of earthquakes, submarine landslides and the ocean that produces tsunamis is an area of potential cooperation with the Ocean theme. Flooding is influenced by geology and is an area for future collaboration with the Water Cycle theme. Volcanic ash clouds can form the basis for discussions with the Atmospheric Chemistry theme.

What provides the theme's cohesion? Each geohazard is a response to a specific set of geological and environmental conditions, but there is a common Earth system process linking all such geological and geophysical hazards: deformation and displacement of the Earth's crust. This means that similar observational and modeling techniques can be used to address all three geohazards. The strategy aims to strike a balance between the many common aspects of the geohazards that make this a coherent theme and individual characteristics that are also important. This is achieved by considering the user needs for each geohazards separately in Chapter 2 before drawing out the common observational requirements in Chapter 3. The strategy then places most emphasis on the common needs, whilst allowing the specific needs of a particular hazard to be addressed wherever necessary.

The scope must also be limited in terms of the type of response to these hazards. Disaster management and damage assessment are already being addressed by initiatives such as the UN Action Team on Disaster Management and the International Charter on Space and Major Disasters. The UN Action Team is tasked with implementing, through international cooperation, an integrated global system to manage natural disaster mitigation, relief and prevention efforts through EO and other space-related services, making maximum use of existing capabilities and filling gaps to provide worldwide coverage. The International Charter aims to provide a unified system of space data acquisition and delivery for users affected by disasters, to promote cooperation between space agencies and space system operators and to allow their participation in the organization of emergency assistance. When a disaster occurs, a participating end-user activates the Charter. Earth observation data are then provided by a participating space agency, and often enhanced by a value adding company, to produce a useful information product ready for disaster management activities. Both the Charter and the Action Team cover a wide range of disasters and, in practice, they emphasise the disaster response element. In contrast, the IGOS Geohazards is restricted to geological hazards and emphasises the preparedness element.

The strategy proposed here is to develop close links with all these complementary initiatives through cross-membership and only cover in detail those activities where there is a unique gap that needs addressing. This means that the focus of the geohazards theme is on disaster preparedness, rather than post-event response. It includes work such as assessing the spatial and temporal distribution of these hazards, expanding the means of monitoring them, improving data management and developing better models, so as to produce more comprehensive management plans, information and reports in support of improved mitigation. The aim of these processes is to improve our capability to forecast the hazard's behavior and ultimately to predict their occurrence reliably. Within this scope, these developments will make an underpinning contribution to crisis response through the related initiatives, for example resulting in products that form a starting point for damage mapping. Similarly, the strategy does not address risk directly. Risk is a measure not just of the location, magnitude and frequency of a hazard but also of the value and vulnerability of elements, such as population or infrastructure, that are exposed to it. Its assessment therefore requires a consideration not just of the hazard itself but also of the value of economic activity and infrastructure, as well as their vulnerability and society's perception of its ability to cope with exposure to the hazard. To illustrate the point, a volcano on Mars may be hazardous and yet pose no risk to someone on the Earth. Because of these needs for different types of information, an entirely different community carries out this type of assessment. Nevertheless, the information products arising from the IGOS Geohazards will form an input to such risk assessment procedures, by characterising the hazard that contributes to the creation of the risk.

GOAL AND STRATEGIC OBJECTIVES

Despite much valuable work being done through existing initiatives, there is still a lack of integration, key observations are not widely available, approaches are often local rather than global in scale and there is no overarching framework to pull all these initiatives in the same direction. This means that the geohazards community, the observations made to manage geohazards and the science needed to understand them are still in a transitional state between research and operations. The goal of the IGOS Geohazards is therefore to integrate disparate, multidisciplinary, applied research into global, operational systems by filling gaps in organization, observation and knowledge over the next decade. In order to achieve this, the IGOS Geohazards Theme has the following four strategic objectives:

- **Building capacity**: engage and build the global geohazards community, so as to achieve the best from the human as well as the technological resources available to address the geohazards, ensuring that users needs are fully explored, understood, documented and acted on;
- **Observations**: put in place systems to deliver reliable, cost-effective and sustainable satellite and ground-based observations that make best use of existing tools, help define and take advantage of emerging technologies and meet the observational needs of the geohazards user community globally;
- **Integration**: ensure that end users and scientists work together to define information needs, extract the maximum value from existing, planned and future observations by using EO and ground-based systems in concert, and develop Geographic Information Systems (GIS) and modeling technologies that integrate these data into geohazards information products that meet the stated needs; and
- **Promotion**: develop education, sharing of data and information, knowledge and know-how, global databases and networks, and knowledge and skills transfer to the developing world, thereby increasing the capacity of all countries to manage risk related to geohazards.

The strategy's impact will be judged not only by how many new satellites result but also by the degree of technical integration achieved and by the extent to which the more intangible human elements are put in place. The benefits may be hard to predict but the costs of not acting are clear. It is salutary to examine the benefits derived from over three decades of global ocean observations. In addition to all the obvious benefits related to navigation and other marine operations, this investment has delivered major scientific advances such as the measurement and understanding of El-Niño. These advances in knowledge have transformed our understanding of how the oceans work in such a way, and with such benefits, that could not have been foreseen during the initial phase of investment. The IGOS Geohazards has hopes that the provision of long-term continuity in geohazard observations will have a similar impact, perhaps ultimately even in terms of prediction. The impact must therefore be sought in the statistics associated with the phenomenon. If the hazard has been mitigated and, better still, one day predicted reliably, the risk will have been reduced, fewer lives will be lost and the money saved will be flowing to aspects of global development ■

The starting point for this IGOS Geohazards is to identify those who will benefit from the strategy, its main users, and other stakeholders with significant roles to play. The ultimate beneficiaries are the citizens affected by the hazards, who want to know what will happen, where, when, how and for how long. Responsible authorities need information about geohazards in order to attempt to answer these questions. Monitoring services and information providers need basic observations to integrate into useful information products that address these issues. This process is based on current understanding, but researchers need the same data in order to increase our knowledge about how these hazards behave. All these users therefore depend on the agencies making the critical observations and each have needs that the strategy must address. The IGOS Geohazards aims to do this by meeting the common needs of the three specified users in particular; for geohazard inventories, monitoring and rapid information supply, all based on improved geohazard knowledge.

THE USER COMMUNITY

The populations affected by geohazards globally will be the ultimate beneficiaries of this strategy. More accessible, improved and where possible standardized geohazards information will improve both the citizen's preparedness for such hazards and the effectiveness of society as a whole in responding to major disasters. However, these ultimate beneficiaries will not be instrumental in developing and delivering that information or in deciding how to act upon it. The critical users specifically targeted by this strategy are those who will do that as part of their professional duties, on behalf of the public at large. These users of geohazards information and observations fall into three distinct classes, according to their different roles and consequent needs, as described below. They would all benefit from a successful IGOS Geohazards. Other stakeholders include those who provide observations required by these users, as well as those concerned with information dissemination.

The first group of end-users is the **Responsible Authorities**. They are responding to the social needs set out in Chapter 1 and are the primary consumers of geohazard information. The responsible authorities use information to manage the geohazards on a day-to-day basis, to issue public alerts and to make ongoing assessments of evolving hazards. The group includes a wide range of government officials at the national, regional or local level. It includes elected officials and representatives, emergency managers, police and fire officials, civil defense or military personnel, staff of Non Governmental Organizations and land use planners. The role of this group is crucial to the successful mitigation of loss of life and property. They decide when, and where, to evacuate threatened areas and provide shelter, food, and water for the displaced population. In addition, these bodies interact with a range of other end-users that include insurance companies, engineering and construction companies, mining and exploration companies, and infrastructure operators in the public and private sectors as appropriate. All these users generally need derived information products rather than the raw data on which they are based. They are interested in the long-term identification of geohazards, to support their role in long-term hazard mitigation through their control of, influence on or implementation of land-use planning decisions. But in the short term they need information from high frequency observations, delivered in "near real time" whenever a hazard threatens to become a disaster. Their needs have led to the development of those monitoring systems that exist today.

The second group of critical users consists of **Scientists in Monitoring and Advisory Agencies**. These vital, intermediary users provide the primary information products that support the decisions made by the responsible authorities. The group includes scientists who are directly responsible for monitoring specific geohazards in the long term, for synthesising the available data into information and for providing continuously updated assessments of the phenomenon monitored and the hazards it poses, so long as the activity continues. These scientists are found in governmental agencies such as geological surveys, running seismic networks and staffing volcano observatories. They have a mandate to monitor a specific type of geohazard, often within a defined geographic area, and are responsible for the maintenance of monitoring devices making in-situ observations. This group uses and integrates data daily and is the contact point with the local civil authorities during a geohazards-related emergency. During emergencies they provide interpretations and recommendations directly to those authorities. They may also work with key specialists in the private sector who have an expertise in the production of certain types of value added products. At the same time, they may carry out research, especially when the hazard they monitor is less active, and pursue long-term mitigation as well as short-term crisis response.

The third group of critical users comprises **Research Scientists** doing research that may improve our understanding of the geohazard, ability to mitigate its effects and capacity to forecast events. Research into geohazards is usually performed in universities and large public laboratories, but some is conducted by private sector organizations. There is often overlap with the second group, who typically apply research findings as they emerge and provide feedback on their effectiveness on the ground. The key difference is that researchers do not normally have a specific mandate for studying, analysing or monitoring the geohazards. Their host institutions rarely run operational monitoring networks providing information on a daily basis. Consequently, there is a real difference between the basic research done by this group, and the continuous monitoring and synthesis performed by their colleagues in the monitoring and advisory agencies. This leads to somewhat different needs and perspectives, but the two groups are close enough that scientists may move between them several times over the course of their careers.

Beyond the immediate user community there are other important stakeholders to consider. The supply of basic Earth Science data is critical to all users. Agencies and commercial operators that collect and distribute EO imagery of the earth's surface, or that enable data collection from airborne and in-situ platforms, or that provide communications facilities all have a role to play. Organizations that provide and support facilities for operational monitoring and research campaigns on geohazards are a vital partner. International groups, especially the IGOS Partners who will support and oversee the implementation of this strategy, play an important integrating role. A priority for the IGOS Geohazards will be to suggest ways for the satellite agencies to facilitate more effective transfer and continuity of in-situ and spaceborne data to the scientists monitoring and researching individual geohazards.

Finally, the media are an important player, having a strong influence on successful responses to events. They convey the messages, alerts and reports, but are not truly users of the information. Their most critical role is to relay the decisions of the emergency managers and decision makers in responsible agencies to the population at risk. The media also transmit information from monitoring and advisory agencies to the public. The first two user groups must communicate directly with each other, and coordinate their messages, so that information released to the public through the media is clear and consistent. The article on "Professional conduct of scientists during volcanic crises" (IAVCEI, 1999) provides an excellent overview of this process and other communication issues that arise during volcanic crises. There are educational aspects to geological hazards that also require the authorities, scientists in the monitoring agencies, and researchers to speak to the public with one voice.

NEEDS FOR INFORMATION

There is a common set of questions to which all beneficiaries, users and stakeholders need answers: the most important are what will happen, where, when, how and what will be the duration and the extent of the affected area. The answers vary depending on the user's category and on the type of geohazard and may imply very different time-scales. Unfortunately, it is not possible to give firm answers to most of these questions. The gaps, between what is known and the knowledge required to answer these questions, from what is observed to what must be observed to provide the information, in how well data are integrated compared to the degree of integration needed to make appropriate information products, remain large. The purpose of the IGOS Geohazards is to close that gap by making the best possible use of all available information and by defining clearly the extra information that is required. Users' needs within each of the three main categories of geohazard are analysed in the following sections, but common needs fall into three main categories: an inventory of the hazard to provide a baseline; ongoing monitoring of change against that baseline; and rapid supply of information during a crisis.

VOLCANIC HAZARDS

What the various users need in detail is dictated by the nature of volcanoes and volcanic eruptions. Key features peculiar to volcanic unrest and activity are that:

1 Scientists know where the problematic volcanoes are. Volcanoes usually give some warning of impending eruptions, the signals of which are detectable if appropriate monitoring is occurring. This contrasts with earthquakes and landslides, where detailed location and times of events can not be predicted.

2 The basic technique for minimising loss of life and property is to move out of the way, or to build out of reach of the volcano. There are no foreseeable advances in technology that will change this: it is not possible to prevent a volcanic eruption from happening and large eruptions are sufficiently rare that it is difficult to anticipate their consequences.

3 Volcanic hazards vary from one volcano to another and from one eruption to the next. The big killers are pyroclastic flows, lahars, and tsunamis triggered by volcanic eruptions (Blong, 1984). The most frequent lethal events are tephra explosions (Simkin and other, 2001). The longest-lasting damage is usually inflicted by thick lava flows or major collapses of volcanic edifices, as at Mt. St. Helens in 1980.

4 Eruptions leave traces in the geologic record, allowing reconstruction of the eruptive history (frequency, type of eruption, size of eruptions, ages of eruptions) of a volcano. This gives some indication of what the next eruption at a given volcano will be like.

The needs of the three groups of critical volcanic hazards users are summarised in Table 1. The end-users in the responsible authorities need information, not data, whether for crisis response or long-term mitigation via land-use planning. The other two groups of users need data to create information products and undertake research. The research scientists will produce more detailed models and work over longer time periods than the scientists in the monitoring and advisory agencies. Between them they are responsible for producing the interpretations and models needed by the end-users. The needs are also somewhat different for crisis response, compared to monitoring and mitigation.

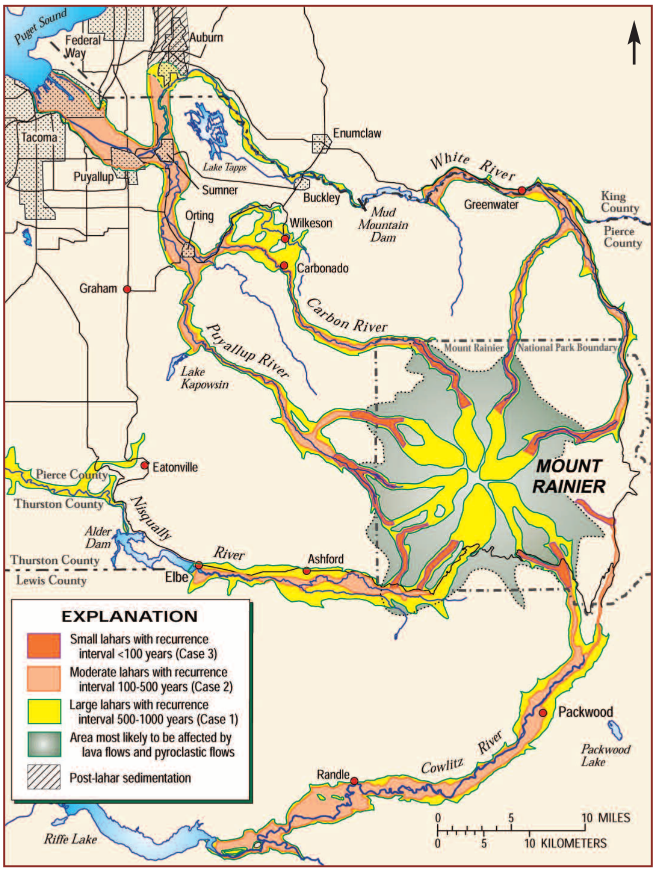
USER NEEDS FOR VOLCANIC HAZARD INFORMATION

TYPE OF USER	NEEDS FOR VOLCANIC CRISIS RESPONSE	NEEDS FOR VOLCANIC HAZARD ASSESSMENTS
Responsible Authorities ("end users")	Clear, authoritative information on most likely course of the unrest/eruption. Timely updates are critical. Best guesses on when and what type of eruption, possible size, which areas will be affected and where will be safe.	Hazard zonation maps: paper maps or GIS databases showing areas of lower vs. higher risk, for future eruptions. The maps for the various major hazards (lava flows, lahars, ash fall, etc.) will be different.
Scientists in monitoring and advisory agencies	All monitoring data relevant to the hazard (seismic, deformation, thermal and gas in particular), collected in real time but accessed when needed. Digital Elevation Models (DEM) and mathematical models to help predict distribution of pyroclastic or lava flows, or lahars, so as to identify both areas of high risk and safe areas.	Base maps and DEMs. Maps showing the distribution of all young volcanic deposits, with dates, to determine type, size and recurrence intervals of eruptions over significant time (10,000 years or more). 3-D models of volcano structure. Monitoring of deformation, seismicity and other geophysical and geochemical parameters. Continuity of observation of all related geophysical and geochemical data.
Research scientists	All data relevant to their research, collected in real time but accessed when needed. Feedback on the performance of models and scenarios.	Same as above, if research involves detailed geologic mapping of young volcanoes. Feedback on the performance of conceptual models

Table 1: Needs of the three groups of critical volcanic hazard users

When volcanic unrest or an eruption occurs, the civil authorities need clear information and interpretations of all aspects of the activity that are relevant to the hazard and risk assessments being presented and can be detected by the local populace. This includes reports of felt earthquakes, visible ground cracking, detectable changes in emissions of SO2, and so on. Even where there is no immediate risk of an eruption, if people can see signs of unrest for themselves, the local authorities need to understand the situation well enough to reassure the public. The stream of information needs to be continuously updated, as events unfold. The scientists responsible for assessing the incoming data may provide scenarios on the likely course of an eruption and how soon it might occur. Based on the prior history of the volcano, they will identify areas that are relatively safe, in the event that evacuations might be needed. Both activities require up-to-date, relatively high-resolution topography for the volcano, in addition to the data streams mentioned above. Once an eruption begins, the flow of information must speed up, as the responsible authorities need to know what will happen next, which areas will be affected, and how thick any volcanic deposits may be. Many additional activities and methods come into play only after an eruption has started. In addition to mapping the activity in real time, observers must note changes in seismic behavior or deformation patterns, especially any that suggest that the site of the eruption may change from the summit to the flank of the volcano. Such changes need to be recognised and conveyed to the authorities and the public as quickly as possible.

Volcanoes that have been dormant awaken gradually, with the onset of unrest typically occurring weeks or months before an eruption (as happened at Mt. St. Helens (1980), El Chichon (1982), Nevado del Ruiz (1985), and Pinatubo (1991)). Volcanologists know to use this period to raise the awareness of civil authorities and the general public about possible impending events, based on the observed unrest or activity. Their task is easiest where the volcano in question erupts frequently, so that many are familiar with the symptoms and the hazards involved. However, there have been some notable successes even for eruptions at long-dormant volcanoes (Mt. St. Helens, 1980; Pinatubo, 1991; see Newhall and Punongbayan, 1996). In these two cases, success depended on persuading the responsible authorities that the probability of a large eruption was high enough to justify ordering the evacuation of large areas near the volcanoes. Evacuations of people and moveable property resulted in saving thousands to tens of thousands of lives and millions of dollars in property damage. Whilst immediate crises dominate



Hazard zonation map for lahars, lava flows, and pyroclastic flows from Mount Rainier (from Hoblitt and others, 1998).

the public's attention, the responsible authorities must also address issues of longer-term planning and mitigation of volcanic hazards. The principal tool for this is the volcano hazard zonation map. Volcanologists prepare these specialised maps for the end-users and the general public. They show, with a different map for each hazard, the areas at risk and their susceptibility to the hazard in question. The probability of occurrence may be classified as simply high-moderate-low, or it may be more quantitative. Before a hazard zonation map can be prepared, scientists must have a geologic map of the volcano and all of its youngest products. To produce such a map involves determining the areas covered by each eruption, the type of materials produced, and the ages of all young eruptions, going back at least 10,000 years. This information defines the eruptive style and history of the volcano, the frequency of its eruptions, and its characteristic repose period. Beyond the geologic and hazard zonation maps, most longer-term mitigation efforts require other kinds of information, such as process research, the development of 3-D and mathematical models of volcano structure and behavior or new instrumentation. Mitigation of volcanic hazards over the longer term, in the absence of volcanic unrest and an impending eruption, is a complex scientific and social undertaking.

EARTHQUAKE HAZARDS

Characteristic features of earthquakes that are relevant to user needs include:

1 The epicenters of large earthquakes are usually located along known seismically active zones, although the disruptive effects of an earthquake may extend over areas 100s of kilometres away.
2 Ground shaking hazard decreases with distance from the epicenter, but it may be strongly amplified in areas underlain by weak materials such as unconsolidated sediments.
3 An earthquake usually produces a conspicuous lateral or vertical displacement where the active fault intersects the surface, which is recorded in the geology and geomorphology of an area.
4 Earthquakes may cause liquefaction, landslides, marine landslides and tsunamis.
5 All these landscape features can be mapped in detail and used to reconstruct the paleo-seismicity of an area, allowing the identification of probable active seismic zones even where there is little historic record of large earthquakes.

As in the case of volcanoes and ground instability, the needs of the three critical categories of users can be analysed from the point of view of inputs needed for hazard mapping and mitigation, as well as rapid responses to specific earthquake events (Table 2).

When a large earthquake occurs, the most pressing need is for information on the location and magnitude of the event and the likely timeframe of the aftershock sequence. Because there is a time lag between arrival of the first seismic wave (the P-wave) and the more destructive shear and surface waves, in favorable circumstances it is possible to issue up to tens of seconds of warning of the arrival of the later waves. Given rapid (or fully automatic) communication systems, such information could be used to trigger emergency mitigation activities, such as stopping trains, shutting down nuclear facilities or parts of an electric power grid, and so on. Few such systems exist at present but some have been tried out in Japan and Mexico. A product that is more widely needed, and can be produced with present systems, is a shake map: this is a map, generated within 5 minutes of a damaging earthquake, that shows the

USER NEEDS FOR EARTHQUAKE HAZARD INFORMATION

TYPE OF USER	NEEDS FOR SEISMIC CRISIS RESPONSE	NEEDS FOR EARTHQUAKE HAZARD MITIGATION
Responsible Authorities ("end users")	Clear, authoritative information on the location and magnitude of the shock and the timeframe (in days) of aftershocks. Timely updates are critical for activating shutdown of critical facilities (power plants, trains, etc.). Post-event maps (shake maps, damaged/ affected areas, identification of safe areas).	Hazard zonation maps: paper maps or GIS databases showing areas of lower vs. higher intensity of ground motions. The maps for various secondary effects of seismic hazards (landslides, liquefaction etc.) are also needed. Ultimate need: reliable prediction of events.
Scientists in monitoring and advisory agencies	All data available, in as near to real-time as possible, on the following in particular: seismicity, intensity, strain, DEMs, soil type, moisture conditions, infrastructure and population.	Compilation of seismic archives. Base maps (geological, soil, active faults, hydrological, DEMs) and conceptual models. Monitor post-seismic events to identify fault geometry. Continuous monitoring of deformation, seismicity and other geophysical and geochemical parameters.
Research scientists	All data relevant to their research, collected in real time but accessed when needed. Feedback on performance of models and scenarios.	Same as above. Feedback on the performance of conceptual models.

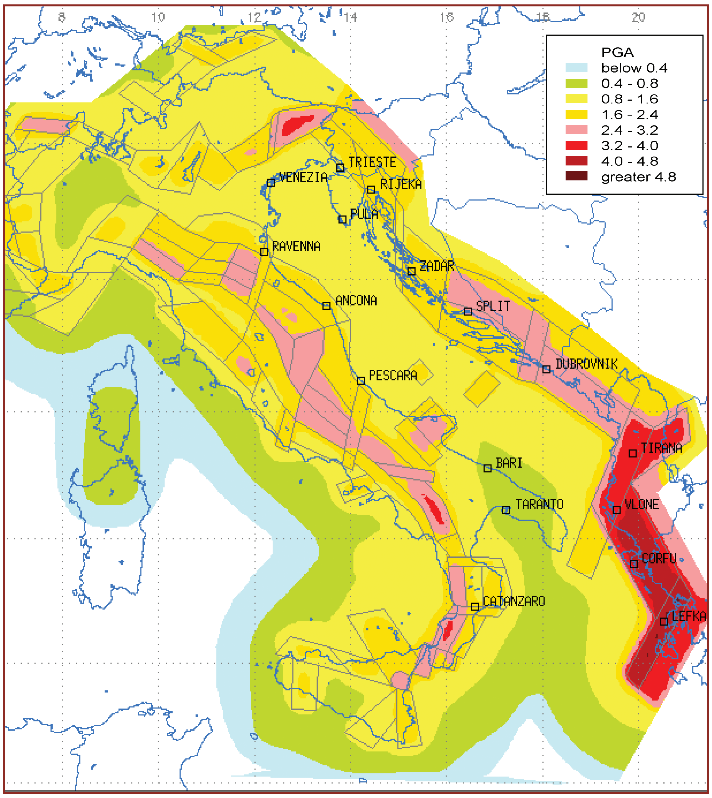
Table 2: Needs of the three groups of critical earthquake hazard users

intensity of ground shaking for the area affected by the particular earthquake. This product allows more efficient recognition of which areas are likely to have sustained the most damage, and which areas are zones of relative safety, where facilities should be relatively intact. The possibility that the combination of Global Positioning System (GPS) and seismic observations may help determine location and extent of co-seismic deformation has led to the deployment of the Southern California Integrated GPS Network (SCIGN) in Los Angeles. In urban areas in major seismic zones, in addition to a need for GPS monitoring, there is a need for specialised instrumentation such as strong-motion detectors and for strain detectors in critical locations.

Over longer periods, plate tectonics provides a general framework that allows us to delineate major seismic zones, along which most earthquakes occur. However, we lack detailed characterization of structures and deformation patterns in most known regional seismic zones. This can be achieved by more extensive deformation monitoring, plus systematic analysis of background seismicity, in addition to a range of mapping activities. Spatial and temporal patterns of deformation are derived from historic data, paleo-seismic studies, and soils and structural mapping. More detailed studies, including quantification of the intensity of groundshaking and damage produced by past earthquakes, and location of areas of weak materials, are essential to mitigation efforts. The resulting products include earthquake frequency maps and probabilistic ground shaking maps. These in turn provide support for strengthened building codes and better engineering practices. They may also be used directly by responsible authorities to modify land use and building policies and practices.

The transfer of seismic information to the design engineer has always been less than ideal for a variety of reasons. The seismologist frequently does not know which parameters of seismic data have influence in the design, or the relevant parameters are not available for many locations, and the engineer had limited capability to include seismic data into design calculations. Consequently, building codes and specific building designs have large safety factors built into them, which increases the cost of construction. Improved understanding of which specific components of the suite of seismic data that describes the earthquake have a direct effect on specific engineering designs, along with an increased understanding of the interaction of these data with the design parameters, would result in better building codes, the ability to enforce them and more cost effective building designs in seismic zones.

Unlike the situation for volcanoes, where we have widely recognised signals of unrest and potential eruption, we lack comparably reliable pre-event signals for earthquakes. Forecasting a hazard depends on the recognition and detection of anomalous precursory phenomena. But, to date, earthquake locations are only known after the fact, so it has been difficult to define monitoring strategies for any seismically active zone that might confirm the existence of such precursors. Whilst there are candidate phenomena, such as regional strain fields, foreshocks, seismic quiescence before strong aftershocks, variation in radon concentration and the temperature or level of groundwater, not all earthquakes are preceded by such phenomena. The recognition and vetting of viable pre-earthquake phenomena should be a major target on the agenda for earthquake-related research.



Results of the seismic hazard evaluation in the Adria region. Values of PGA in m/sec2 have been computed for a return period T=475 years (corresponding to the 90% non-exceedance probability in 50 years), and taking into account the uncertainty in attenuation. Scale and orientation is given by coordinates. This map was produced by the Global Seismic Hazard Assessment Programme launched in 1992 by the International Litosphere Program (ILP) with the support of ICSU, and endorsed as a demonstration program in the framework of (UN/IDNDR).

GROUND INSTABILITY HAZARDS

Ground instability, the two main sub-categories of which are landslides and subsidence, is characterised by movements of solid rock, debris or soil that are driven by gravitational forces acting at the surface and in the shallow sub-surface. It encompasses a wide variety of surface deformations and displacements. The triggers are either natural factors, such as extreme rainstorms, prolonged wet periods, and earthquakes, or factors related to human activity like mining, excavations and blasting. There are preparatory factors, which predispose a given area to failures, including natural and induced changes in land cover and land use, presence of soil and physical characteristics, hydrology, and geological conditions, including weathering status. The key points of interest when analysing ground instability include the following:

1 Landslides are one of the main processes by which landscapes evolve and so the related hazards result in a complex, changing landscape that must be mapped and understood in detail in order to assess its future behavior.
2 Landslides and subsidence both vary enormously in their distribution in space and time, the amounts of energy produced during the activity and especially in size. This means that the resulting surface deformation or displacement varies considerably from one type of instability to another.
3 Individual landslides and subsidence failures are local landscape phenomena. Data about site-specific conditions must be available in order to associate the identified deformation or displacement patterns with causative factors and hence model zones of different degrees of susceptibility to the specific type of ground instability.
4 Collectively, individual ground instabilities may have a common trigger, such as an extreme rainfall event or an earthquake, and therefore occur alongside many equivalent occurrences over a large area. This means that they can have a significant regional impact.
5 Ground instability analysis is interdisciplinary, involving geotechnics, geomorphology, geophysics, hydrology, hydrogeology, solid and fluid mechanics and various information sciences.
6 Ground instabilities, even when catastrophic, tend to evolve to become progressive failures: once they start, there is a high probability that they will develop further in space and time.

The three main categories of users and their corresponding needs are shown in Table 3. Determining where, when and to which extent ground instabilities will take place is a short-term requirement as far as the safety of exposed people is concerned. These questions are easier to answer for subsidence than they are for landslides. The mechanics of subsidence are better understood and, once the phenomenon has been triggered, its evolution can be

USER NEEDS FOR GROUND INSTABILITY HAZARD INFORMATION

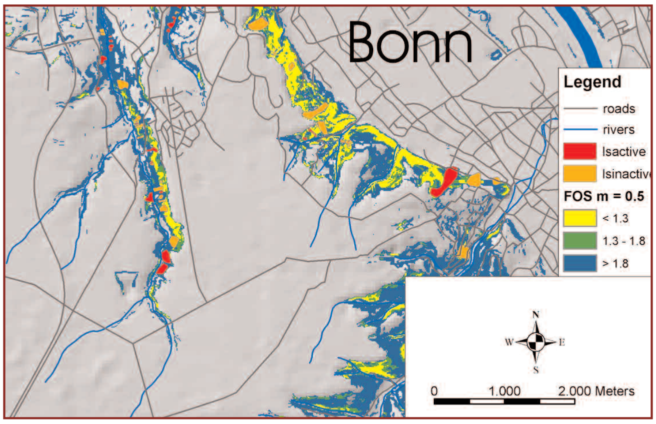
TYPE OF USER	NEEDS FOR CRISIS RESPONSE	NEEDS FOR HAZARD MITIGATION
Responsible Authorities ("end users")	Updated maps of affected areas and scenarios for ongoing instability. Early warning information.	Regularly updated inventory, susceptibility and hazard zonation maps: landslides, debris flows, rockfalls, subsidence (at scales as appropriate). Ground instability scenarios. Land use planning and enforcement information.
Scientists in monitoring and advisory agencies	Local rapid mapping of affected areas, magnitude of instability, updated scenarios during ongoing instability, impact analysis. Near real-time observational tools. As for mitigation, plus seismic data, weather forecasts.	Data on landslide inventory, DEM, deformation (to the ground and critical infrastructure), hydrology, geology, soils, geophysical, geotechnical, climatic, seismic zonation maps, land cover, land use, historical archives, relevant human activities (at scales as appropriate). Regular and consistent observations. Methods and models for susceptibility and hazard evaluation. Data from well-observed past events.
Research scientists	As for mitigation. Feedback on performance of scenarios and models.	Continuity of observations, appropriate data as above for understanding processes and for development of models and observational tools. Access to other scientific information. Data from well-observed past events.

Table 3: Needs of the three groups of critical ground instability hazard users

modeled and hence predicted with some accuracy. Triggers are also better understood; removing a certain amount of subsurface material results in a predictable amount of subsidence and size of area affected. Landslides are more complex in their motion and have highly variable triggers. Predicting when this type of failure will happen is conceivably the most difficult challenge for the relevant scientists. Major landslide disasters, such as the Vajont in 1963 (1,900 fatalities -AVI database) and Caracas in 1999 (19,000 fatalities, cited in Larsen and others, 2001), can be as devastating to society as volcanoes or earthquakes. Large landslide and debris flow disasters triggered by extreme weather are more frequent than volcanic eruptions and about as common as earthquakes. They may be preceded by precursory evidence of landslide movement such as appearance of cracks, accelerating movement, or increased rock-fall activity.

Appropriate real time monitoring of known landslide hazards, transmitting a continuous stream of information to remote control stations and alert systems, can play a crucial role. Movement detectors can be used to issue alerts any time the movement rate increases. The threshold for the alert to be issued is generally computed as the measured acceleration, deformation or displacement, versus a theoretical model that has been developed for the specific hazard. Other techniques for early warning systems focus on the triggers rather than the deformation: in this case a sound model generally based on hydrologic forecasting is also needed and, for a defined rainfall threshold, alerts can be issued. But due to the amount of information to be collected, processed and analysed, early warning based on site-specific analyses is not practical for large areas. Thus, a two-fold strategy of spatial susceptibility and hazard mapping coupled with monitoring of the most hazardous zones offers the best hope of providing useful information, on which responsible authorities can base both informed land-use decisions and then evacuation plans and responses during a crisis.

The end-users also need simple, qualitative information concerning the longer-term threats posed by the geohazard so that they can mitigate them. Depending on the extent of the area and data availability, such information may be provided in susceptibility or hazard maps. Areas with present or past ground instability must be identified and classified. Within active landslide and subsidence zones, the extent and pattern of surface deformation or displacement must be determined. A clear knowledge of the location, areal extent, volume of displaced material and evolution of the phenomenon in space and time is a fundamental step toward correlation of the hazard with its causative or triggering factors. These must be identified and can be natural or anthropogenic. Factors of natural origin embrace a wide range of phenomena such as geodynamics (e.g. earthquakes, volcanic eruptions) and climate (e.g. rain, snowmelt, erosion, floods). The human actions that may result in ground instabilities include: mining, engineering works, deforestation, irrigation, and the extraction of minerals, fluids and gases from the ground. Identification of the processes and mechanisms responsible for loss of strength and increase in shear stress leading to instability is the main step for comprehension and therefore mitigation of ground failure. Mitigation actions to reduce the negative effects of the phenomenon include the strengthening of buildings, specific land-use regulations and controls, and targeted agricultural programs or protection works. The better the phenomenon is delimited and understood, the easier the decision concerning the actions to be taken. Understanding the processes and mechanisms associated with each individual instability phenomenon makes it possible to establish physical and mathematical models. There is a dearth of sensitivity analysis for the existing, predictive models and the relative influence of key physical quantities remain to be identified. The development of such models is critical in supporting production of landslide or subsidence susceptibility and/or hazard maps. Associations between the deformation or displacement observed and the causative and triggering factors can be made empirically, through statistical analysis or within 3-D geotechnical models. The type of analytic tool used depends on the working scale, on the application goal and on the variety, quality and resolution of available data ■



Landslide susceptibility map using a regional physical-based modeling approach for the Bonn area. Inactive and active landslides refer to the activity of respective locations. FOS m=0.5 refers to the Factor of Safety using the Infinite Slope Model and applying a 0.5 ratio of water table depth to regolith thickness. For additional security in engineering applications, FOS are classed below 1.3 as 'unstable', FOS between 1.3 and 1.8 as 'marginally stable', and FOS >1.8 as 'stable' (from Mouline-Richard & Glade 2003).

This chapter describes the observations required by the scientists in monitoring and advisory agencies and the researchers undertaking related scientific research, in order to meet users' needs for information. Commonalities in requirement between the three main hazards are emphasised. These include the observation of topography, deformation, seismic activity and various geoscience parameters commonly recorded on geology and soils maps. These common requirements form the basis for a common approach in the rest of the report.

Information products and advice required to support decision-making by end users in responsible authorities are based on a wide range of observations that are made using many different optical, radar and other systems. Some are satellite-based, some made by aircraft and many are measured by critical, ground based systems. There is no way that events like earthquakes or volcanic eruptions can be prevented, so the emphasis is put on observations made between events that permit better forecasting and mitigation planning. Scientists in monitoring and advisory agencies take these observations, integrate and assimilate them

MOST REQUIRED VOLCANIC HAZARD OBSERVATIONS AND BEST AVAILABLE OBSERVATION SYSTEMS

REQUIRED OBSERVATIONS	BACKGROUND MONITORING/ASSESSMENT	CRISIS RESPONSE
Characterise seismicity of volcano or group of volcanoes [magnitude, 3-D location, and type of earthquake(s)].	Individual volcanoes require at least 3-6 seismometers, ideally with 3-directional sensors, to detect and locate earthquakes of Magnitude 0.5, with digital data relayed/processed in real time.	Repairs as needed and feasible.
	Regional network good enough to detect and locate earthquakes of Magnitude 2.5, data relayed and processed in real time.	Additional stations, deployed near or on the volcano, to detect and locate earthquakes of Magnitude 0.5
Characterise deformation of volcanic edifice (horizontal and vertical); monitor changes in gravity; characterise topography; determine location of faults, landslides and ground fractures.	EDM and/or permanent GPS network of stations, either continuously transmitting or reoccupied as necessary.	Additional GPS stations as needed to capture deformation; more frequent occupation (if data not continuously transmitted).
	Leveling and tilt networks surveyed as needed. Borehole strainmeters (continuous recording). Gravity surveys (1-5 years).	More frequent occupation (if not continuously recorded and transmitted).
	SAR interferometry (frequency depending on the volcano's historic activity).	Request more frequent tasking plus search data archives for additional possible image pairs.
	Map existing geologic structures on volcanoes using high spatial resolution satellite, aerial photography, aerial surveys and geological and geophysical ground surveys as needed.	Request repeat overflights to check for new cracks; possibly install strainmeters across selected cracks.
Characterise gas and ash emissions of volcanoes by species (SO_2, CO_2) and flux (tons per day)	COSPEC, LICOR surveys at regular intervals (weekly, monthly or annually).	More frequent surveys, perhaps using small aircraft if plume not accessible by road.
	Routine checks of appropriate satellite imagery.	Additional requests tasking for higher-resolution data, check archives for useable Imagery.
Characterise and monitor thermal features of volcanoes (their nature, location, temperature, possibly heat flux).	Map and monitor hot springs, fumaroles, summit craters, crater lakes, and fissure systems for temperature variations using ground-based instruments and high spatial resolution satellite data.	More frequent observations, including visible and IR photography and pyrometry as appropriate.
	Systematic acquisition and analysis of imagery from airborne digital IR cameras, moderate resolution to higher-resolution resolution satellite imagery for thermal background and thermal flux.	More frequent overflights with digital IR camera; additional requests tasking for higher resolution satellite data, check archives for time series of thermal data.
Characterise eruptive style and eruptive history of volcanoes.	Characterise, map and date all young eruptive deposits of the volcano.	Observe eruption columns, plumes and surface deposits (using overflights with visible and IR photography, video). Monitor their motions (speed, direction, areas covered and threatened), character, and thickness. Update maps.

Table 4: Volcanic hazard observations most required and the best available observational systems

and use them in models of critical Earth system processes to produce hazard maps, scenarios and forecasts that answer questions such as: how do the relevant Earth system processes operate; what are the main hazards in each case; which areas are exposed to those hazards; which are safe; and what is the best estimate of the timing, duration and extent of the hazardous activity?

The IGOS Geohazards has identified a wide range of observations that are required to answer these questions and mitigate each geohazard effectively. This inventory builds on previous works, in particular the reports on EO requirements for earthquakes, volcanoes and landslides presented in the CEOS DMSG final report. The observations, documented on the Geohazards website will be added to the IGOS observational requirements database, maintained by the World Meteorological Organization (WMO) on behalf of the IGOS Partners. This document summarises the most important parameters to observe in three tables below covering volcanoes, earthquakes and ground instability. A set of observational requirements emerges, many of which are common to all three hazards, and a suite of key observational systems is described that support both monitoring and ultimately crisis response.

> Volcanic Hazards

Volcanic hazard mitigation requires a wide variety of information. Essential volcano monitoring includes analysis of data on the volcano's seismicity, surface deformation, gas emissions and thermal features. In addition, detailed topography and geologic mapping are required for complete volcano hazards assessments.

> Earthquake Hazards

Earthquake hazard mitigation also requires monitoring of seismicity and deformation, albeit with a slightly different focus and scale than for volcanoes. Geological mapping for earthquake mitigation emphasises the mapping of structures like faults. The possibility of using surface temperature or soil gas anomalies should also be evaluated.

> Ground Instability Hazards

Ground instability hazard mitigation requires a slightly wider range of observations, including geological and soils mapping, topography analysed as elevation, slope and aspect, deformation, climatic and meteorological parameters, in-situ geotechnical observations and seismicity. In many cases the focus is on surface geology and soils.

MOST REQUIRED EARTHQUAKE HAZARD OBSERVATIONS AND BEST AVAILABLE OBSERVATION SYSTEMS

REQUIRED OBSERVATIONS	BACKGROUND MONITORING/ASSESSMENT	CRISIS RESPONSE
Characterise seismicity of seismically active region [magnitude, 3-D location, and type of earthquake(s)].	Global monitoring network able to characterise earthquakes of Magnitude 3.5 with data relayed and processed in real time.	Network is being putting in place, developed to verify the Comprehensive Test Ban Treaty.
	Regional network of strong-motion detectors, capable of surviving ground motions.	If none deployed, add stations afterwards to capture aftershock sequence.
Characterise baseline topography and ongoing deformation of region (horizontal and vertical).	EDM and/or permanent GPS network of stations, either continuously transmitting or reoccupied as necessary.	Additional GPS stations as needed to capture post-earthquake deformation; more frequent occupation (if data not continuously transmitted).
	Borehole strainmeters (continuous recording). Strainmeters on critical structures such as dams, bridges, etc .	More frequent occupation (if not continuously recorded and transmitted); additional strainmeters on critical structures to monitor their structural integrity during aftershock sequence.
	SAR interferometry (frequency depending on the region's historic seismicity).	Request more frequent satellite tasking plus search archives for additional possible image pairs.
Characterise thermal signature of region.	Obtain and process time series of low/medium resolution IR imagery from polar and geostationary satellites for thermal background characterisation.	Evaluate time series for possible thermal anomalies before and after the earthquake.
Determine location of faults, landslides and ground fractures. Characterise historic seismicity and paleo-seismicity of region	Map existing structures in the region using high spatial resolution satellite and airborne imagery, aerial photography and geological and geophysical ground surveys. Study and date features that provide evidence for major prehistoric earthquakes.	Request over-flights to check extent of ground breaking and offset, for new cracks, landslides, patterns of liquefaction and building collapse, etc.

Table 5: Earthquake hazard observations most required and the best available observational systems

It is clear from the tables 4-6 that observational requirements form a strong link between the three main geohazards and can be considered together, emphasising the coherence of the geohazard theme. They are categorised into baseline observations, needed above all for the production of maps, and into time-series observations, which form the basis for hazard monitoring. For each group of parameters, both current and planned observational techniques and systems are described, covering ground-based, airborne and satellite-based technologies. In general, ground-based methods provide the highest data accuracy and resolution and the greatest continuity in time, but have limitations on areal coverage. Satellite-based systems have variable and generally lower spatial and temporal resolution, but they have the advantage of providing synoptic regional coverage and offer spatial continuity. The intermediate scale of airborne systems is used to combine the advantage of spatial coverage offered by EO with either higher resolution, and better control on acquisition timing when sensing a specific event. To get the most appropriate spatial, spectral and temporal resolution, a global observing strategy for geohazards must integrate all these data streams.

MOST REQUIRED GROUND INSTABILITY HAZARD OBSERVATIONS AND BEST AVAILABLE OBSERVATION SYSTEMS

REQUIRED OBSERVATIONS	BACKGROUND MONITORING/ASSESSMENT	CRISIS RESPONSE
Characterise deformation with high accuracy and frequency (horizontal and vertical).	GPS network of stations continuously transmitting or reoccupied as necessary.	Additional GPS stations as needed to capture deformation. More frequent occupation (if data not continuously transmitted).
	Satellite, airborne and ground-based SAR interferometry at various wavelengths. Frequency depending on the type of ground instability (1 month to 1 year).	Request more frequent satellite tasking plus search archives for additional possible image pairs.
	Other surveys e.g. leveling, laser scanning (terrestrial and airborne), aerial photography and high-resolution stereo satellite data, borehole inclinometers. Frequency depending on the type of ground instability (1 month to 1 year).	More frequent occupation of all ground-based instrumentation (if data not continuously recorded and transmitted).
Map landslides, geomorphology, land-use, land cover, geology, structures, drainage network.	Map existing landslides, depositional/erosional processes, geologic structures, land-use and land cover using high spatial resolution satellite and airborne imagery, aerial photography and geological and geophysical ground surveys.	Request over-flights to check extent and distribution of landslides.
Topography/Elevation (incl. slope angle, slope length, slope position).	High quality DEM from LiDAR, photogrammetry or high-resolution satellites.	Rapid local update needed of how the landscape has changed.
Soil strength parameters and physical properties (incl. pore water pressures).	Regular updated when necessary. Geotechnical field logging and sampling, in-situ and laboratory test to determine specific site conditions and engineering parameters . Variation of pore water pressure is monitored by piezometers over time	Request more frequent observations and if possible continuous recording of soil moisture.
Climate Trigger precipitation (rainfall, snow, magnitude, intensity, duration), temperature.	Meteorological data field measurements. Meteorological satellites data.	Continuous recording.
Seismic trigger Magnitude, intensity, duration, peak acceleration. Decay of shaking level with source distance (source, propagation shaking and site effects).	Accelerometer network monitoring. (Frequency: continuous or reoccupied as necessary) Models (Pseudo-static stability, Dynamic instability...).	Continuous recording.

Table 6: Ground instability hazard observations most required and the best available observational systems

BASELINE OBSERVATIONS

> Topography

Topographic data are required to analyse all three hazards. Such data are critical to the modeling of any gravity-driven process, such as the emplacement of a lava flow or the progress of a landslide. They also form a key requirement in the subsequent analysis of deformation, providing the baseline against which to measure topographic change and so calculate the volume of displaced material. The basic requirement is for a digital terrain model, from which elevation, slope and aspect can be calculated. Earthquakes need only low, regional resolution. Volcanic hazards usually require slightly higher resolution. Highest resolution is used for ground instability, especially small landslides, whose recognition relies largely on landform analysis often done at around 1:10,000 scale, with a vertical resolution of better than 1m.

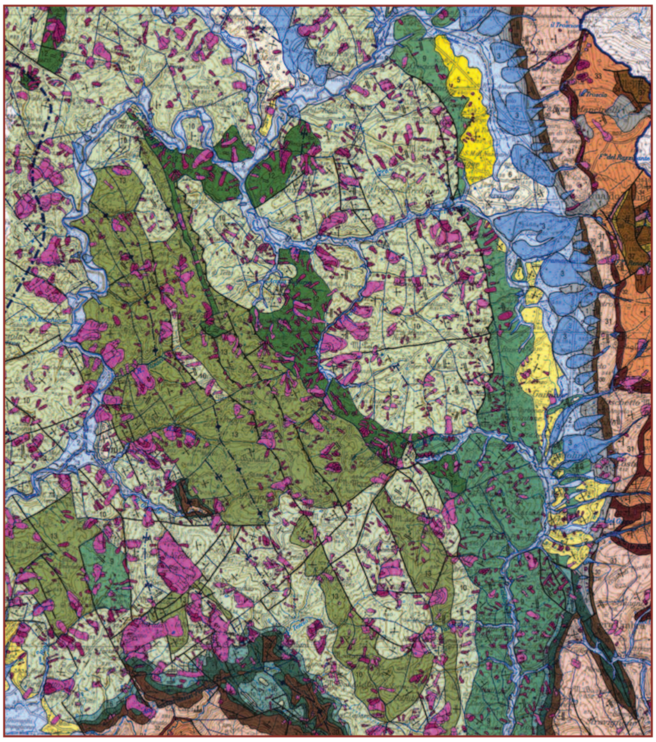
Whilst ground-based methods like traditional surveying and GPS measurements are still used, topographic surveying now has a long history of using EO and especially airborne solutions. The most common approach is photogrammetry, based on scanned analogue and increasingly on digital aerial photography. This will remain important, especially at the site-specific scale. Radar altimeters, single-pass airborne radar interferometers and airborne Light Detection and Ranging (LiDAR) are all used to improve available topographic maps and Digital Elevation Models (DEMs). Satellite data sources include high-resolution stereo optical satellite imagery, radargrammetry, interferometry and altimetry. The closest that such data come to providing a global, high-resolution dataset is the Shuttle Radar Topography Mission (SRTM). This was designed to provide coverage between 60N and 56S at 90 m resolution. Current and planned EO systems that might be used for topographic observations are listed at the end of the Chapter.

> Mapping

Mapping, whether of bedrock geology, structure or surficial deposits and soils, is essential in trying to understand geohazards. All three hazards require various types of mapping based on satellite and airborne EO imagery, aerial photography and fieldwork. Terrain analysis in three dimensions, both on the ground and using remote sensing data, is used to map landform, geology, structure and soils, based on either a terrain model or stereography. For volcanoes, mapping focusses on eruptive deposits less than 10,000 years old and related structures. For earthquakes, the most important features to map are faults, existing fractures and other lineaments related to structure. For landslides, soils and superficial deposits are critical and mapping must also result in an inventory of current and historic landslides in the region. Scales may vary from regional mapping at 1:50,000-250,000 to local mapping at 1:5,000-10,000.

Image of Nyiragongo Volcano, in Congo, shortly after the January 2002 eruption. The image shows ASTER and Landsat 7 thermal imagery, draped over a DEM derived from SRTM data (courtesey of JPL).

Field-based geological mapping not only provides observations that are impossible to achieve any other way, such as deformation fabrics that reveal the strain history in rocks, but it is also central to the development of knowledgeable and skilled geohazard scientists. It results in scientists that understand the phenomena in detail and who can successfully apply the other observations to their mitigation. Fieldwork is supported by airborne and satellite data. Aerial photography analysed in stereo allows virtual fieldworks in the laboratory, favouring targeted field visits on key exposures. Ground instability phenomena are best recognised this way. Airborne hyperspectral imagery from sensors like the



Detail of the photo-geological and landslide inventory map of the upper Tiber river basin, Italy (from Cardinali and others, 2001) Original image scale: 1:100.000, the map is North oriented.

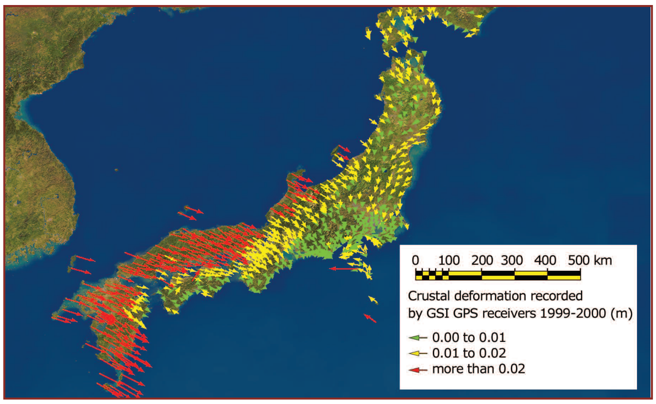
Multispectral Infrared and Visible Imaging Spectrometer (MIVIS), Airborne Visible and Infrared Imaging Spectrometer (AVIRIS), Hyperspectral Mapper (HyMap) and Airborne Hyperspectral Imager (AHI), multi-spectral optical EO data and satellite radar imagery are all used alongside field work to identify surface mineralogy, soils, lithologies, topography, drainage networks, structures, land cover and land use. Local mapping of individual small landslides requires either stereo aerial photography or very high-resolution, stereo satellite data. Such data might increasingly substitute and integrate aerial photography in identifying the characteristic geomorphologic features of geohazards and in supporting both geological and soils mapping. The earthquake section of the CEOS DMSG report includes an extensive bibliography illustrating the use of aerial photography and EO data in mapping related to earthquake hazards. Mapping may be used both to establish a baseline and as a rapid reconnaissance after an event. Current and planned EO systems that might be used for mapping are listed at the end of the Chapter.

TIME-SERIES OBSERVATIONS

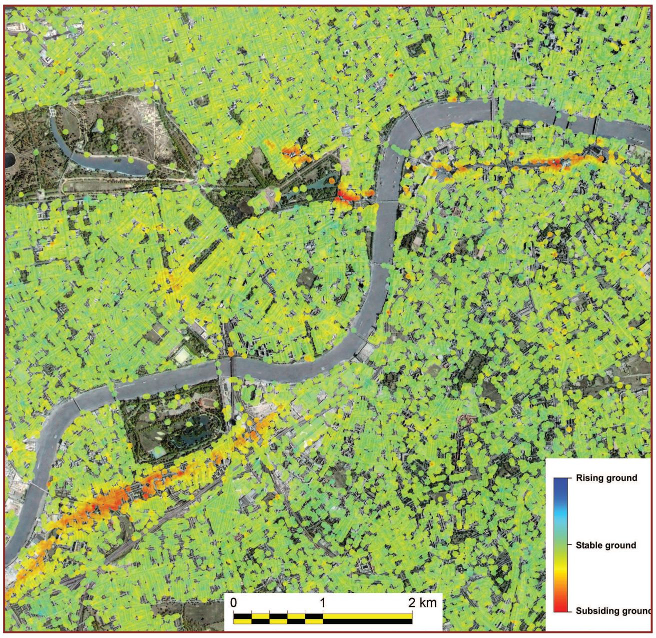
> Deformation and Displacement

All three hazards deform the Earth's crust. Observing this displacement is central to the IGOS Geohazards theme. Deformation can be sudden, for catastrophic events like landslides, more gradual, due to processes such as the inflation of a volcano during recharge of its magma chamber, or ongoing, as in the ceaseless motion of Earth's crustal plates that leads to the buildup and release of strain during earthquakes. Motion can be on the scale of kilometres, in the case of major landslides or lava flows, metres, which is typical of many earthquakes, and millimetres, as found for the gradual down-warping of the crust over a sinking water table or the steady growth of a lava dome on a volcano. All these motions can be in either horizontal or vertical planes and occur over a period of days, months or even years. There is good evidence that small motions are the precursor to more significant events and so they must be monitored, for all the geohazards, as a first step towards forecasting hazard events.

Both ground-based and satellite based techniques are used to measure ground displacements and monitor deformation. Increasingly, GPS networks, whether regional or local, are the mainstay of deformation monitoring, especially over large areas. The global geodetic infrastructure is provided by a combination of GPS, Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR), which together form the basis for the precise International Terrestrial Reference System (ITRS). Dense regional networks, such as SCIGN and the similar GPS Earth Observation NETwork (GeoNet) in Japan, already exist and demonstrate the value of such systems. They offer high accuracy and continuous observation, but they require the installation and maintenance of permanent stations and provide monitoring only at installation points. Although GPS networks are in place at a number of volcanoes, older techniques, including tilt, leveling, Electronic Distance Measurement (EDM) and strain measurements are still performed in many active volcanic areas, together with the measurement of other



Crustal Deformation of Japan 1999-2000 detected by the Japanese Geographical Survey Institutes' GPS Earth Observation Network (GEONET). The GEONET network comprises nearly 1,000 recording stations distributed throughout Japan. Image Copyright: NPA Group, 2003. Publicly available GSI GEONET data obtained from GSI web-site: http://mekira.gsi.go.jp/ENGLISH/.



Average annual displacement map over London calculated between 1992-2000: the deformation bar on the right enables identification of subsiding areas. (Image courtesy of NPA/TRE).

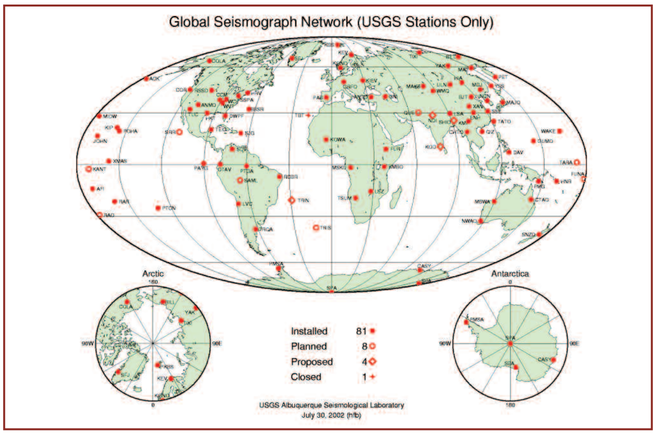
related parameters such as water levels in bore holes, as summarised in Van der Laat (1996).

Airborne systems can sometimes detect surface displacement, but a need for platform stability and regular observations mean that satellite solutions are increasingly important. The principal technique in use is synthetic aperture radar differential interferometry (DInSAR), which enables detection of centimetric ground displacements over wide areas. Existing satellite InSAR instruments are C-band (wavelength in the order of 5.6 cm), offering high resolution, and typically collect data every month, but they only provide information on non-vegetated surfaces. Data from the earlier JERS-1 satellite demonstrated that L-band satellites (wavelength in the order of 23.5 cm) can provide lower resolution interferograms over a far greater range of surface cover types. The next L-band SAR will be the Japanese PALSAR sensor on the ALOS satellite, scheduled for launch in 2004. This instrument is designed to test several applications, including interferometry, so it will provide some support for deformation analysis. Monitoring crustal displacement is one of the main design aims of the proposed L band TerraSar mission. Other limitations of current InSAR systems are the fact that measurement of displacement in the satellite's line-of-sight is difficult to resolve into three dimensions and the time gap between repeat observations. Approaches to overcome limited information over natural surfaces have been documented in the CEOS DMSG report and include: placing artificial corner reflectors or active transponders in strategic locations; availability of new InSAR techniques that can identify coherent targets in time-series of radar images. Such approaches allow the removal of atmospheric effects and the construction of displacement histories for each identified point target. Current and planned EO satellite systems that might be used for displacement quantification are listed at the end of the Chapter.

> Seismicity

Seismic activity is a feature of all three hazards. For earthquakes, seismic monitoring is the most critical observation required, and for volcanoes it is the best-established tool to evaluate the status of a volcano, both between and during eruptions. Seismic monitoring is needed to describe a earthquake's magnitude and its location in three dimensions. It is also the best tool to determine what is happening at depth, allowing the plumbing inside a volcano and the position of subsurface faults to be defined. It is important in ground instability assessment, too, because seismicity is one of the main triggers for landslides in some geological settings, especially mountainous terrain near active plate boundaries. It is also associated with some subsidence phenomena. The size of significant events varies with the hazard: whilst most earthquakes smaller than M 5.5 do little harm, earthquakes of M 0.5 or less may be important for volcano monitoring purposes.

Seismic monitoring requires networks of ground-based instruments. The Global Seismic Network (GSN), supported by the USGS, the US National Science Foundation and the organization Incorporated Research Institutions for Seismology (IRIS), is a global network capable of locating and characterising seismic events >M3.5, in the northern hemisphere (Sykes, 2002). It has been installed, in part, to monitor underground nuclear explosions as part of the Comprehensive Test Ban Treaty (CTBT). The existence of this and other networks means



Stations of the Global Seismic Network operated and maintained by the US Geological Survey. (From the NEIC web site).

that locations and magnitudes for large earthquakes (>M5.5) occurring anywhere in the world are posted on the web within minutes of their occurrence. One such website is the National Earthquake Information Center of the USGS. Strong-motion detectors are used to measure the local effects of major earthquakes, while the smaller tremors associated with volcanoes are monitored using more sensitive instruments, including broadband seismometers that detect the longer-period events characteristic of the movement of fluids within the Earth's crust. Critical requirements for all networks are sufficient coverage and station density and real time data transmission capabilities.

OBSERVATIONS FOR SPECIFIC GEOHAZARDS

The climatic and meteorological observations required for monitoring ground instability can be met using normal weather observations. There are also a number of promising new observations and observing technologies that are not yet operational. These are described in Chapter 5 under the research agenda. This leaves three other types of observations that are important for one or more specific hazards:

> Gas Emissions

For volcanic hazards, SO2 and CO2 emissions are critical indicators of volcanic activity and hence the monitoring of these gases plays an important role in forecasts. In addition, these gases are hazards in their own right, so they must be considered in any observation system designed to address volcanic hazards. For earthquakes, there is widespread interest in the possibility that certain gas species may be precursors to earthquakes. Soil gas monitoring along active faults has been attempted, but a key difficulty for this work is to know where to put the sensor. These investigations remain part of the research agenda for earthquakes.

Volcanic gas emission rates and plume composition are commonly measured using correlation spectrometers and infrared analysers (e.g. the Correlation Spectrometer (COSPEC), LICOR) and, more rarely, the new Open-Path Fourier Transform Infrared spectrometers (OP-FTIR). These can be stationary or can be mounted on trucks or small aircraft. The necessary measurements require repeated passes beneath the plume under sunny conditions, preferably at different elevations. Such surveys are normally carried out on a monthly or annual basis, unless the volcano is in a state of heightened activity. Direct sampling using specific geo-chemical sensors at critical sites is also used to monitor gases, in particular CO2 concentrations in soils at volcanoes that are known CO2 emitters.

Airborne hyperspectral sensors can be used to measure relative gas concentrations. SO2, the most characteristic volcanic gas, can be detected using multispectral ultraviolet and infrared satellite sensors. The use of infrared sensors on meteorological satellites for monitoring SO2 plumes is reviewed in the CEOS DMSG report. Coarse spatial resolution and low sensitivity have limited satellite detection of SO2 to volcanic plumes that reach the stratosphere. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor's infrared bands and its higher spatial resolution allow better monitoring of tropospheric and more dilute SO2 plumes. ASTER data (every 16 days) integrated with more frequent observations from lower spatial resolution sensors such as the Moderate-Resolution Imaging Spectroradiometer (MODIS) (every few hours) and the Scanning Enhanced Visible and Infrared Imager (SEVIRI) (every 15 minutes), offers the best opportunity to map such plumes from space. Current and planned EO systems that might be used to make gas (mainly SO2) observations are listed at the end of the Chapter.

> Temperature

Volcanic activity is intrinsically a high-temperature phenomenon, so in theory thermal monitoring ought to be useful in forecasting eruptions. The range of temperatures of interest is large, from 30-40 degrees centigrade in hot springs to over 1200 degrees centigrade for lava. Most of the heat sources are only metres to tens of metres in dimension, so there is at present little consistency in how temperature is monitored. Thermal flux, though almost certainly a precursor for eruptions, is rarely monitored. For earthquakes, some studies suggest that local thermal anomalies may precede an earthquake. Specific cases are few, but the possibility deserves rigorous evaluation. Temperature has only a marginal place in landslide studies, although it can be used as an indirect indicator for the soil moisture variations that can affect the strength of certain slopes and therefore their susceptibility to landslide initiation. It has no obvious role to play in subsidence observations.

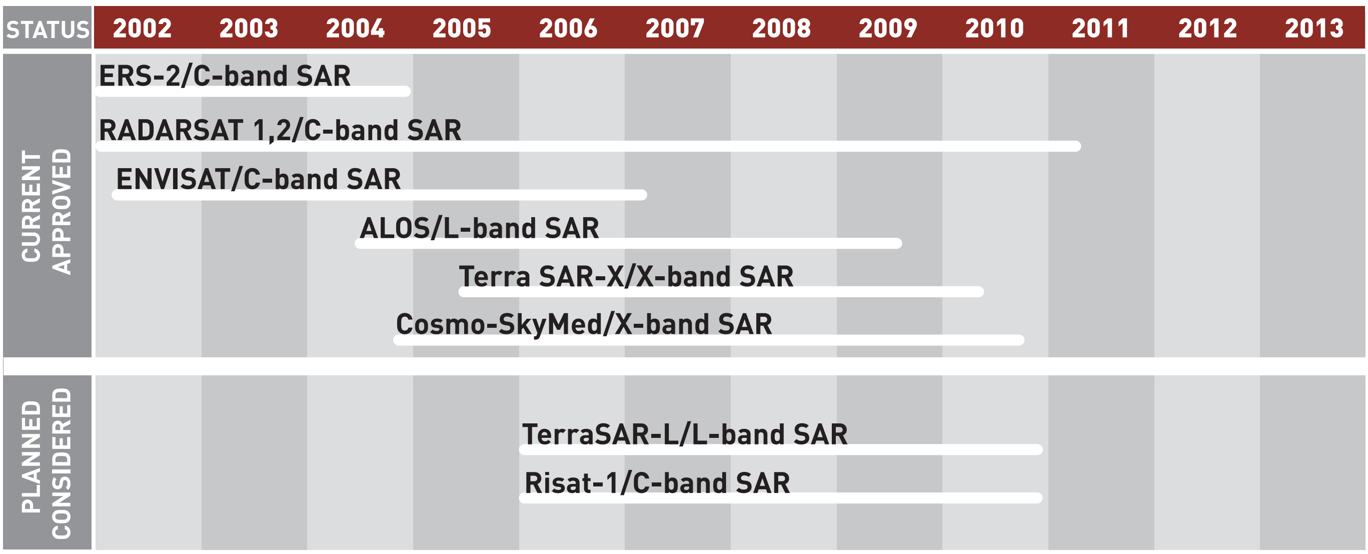
Ground-based methods include thermocouples, pyrometers, and other kind of standard temperature sensors. These approaches provide measurements only at point localities, but are the principal means of evaluating thermal trends of lower-temperature sites such as hot springs, whether associated with volcanoes or with active faults. Fixed-position or airborne infrared cameras that measure emissivity and temperature provide detailed information on the structure of active lava domes, flow fields, and tube systems.

Lava flow mapping and thermal surveys from hyperspectral sensors are also possible. Satellite remote sensing at various infrared wavelengths has been widely used for thermal monitoring of active volcanic areas. Its effective application depends on a good match between the resolution of the sensor and the size of the target. Available sensors with higher resolution include Landsat and ASTER, though they offer only low observational frequency. For near real-time monitoring, high temporal resolution satellites in both polar and geostationary orbits are widely used. Data from NOAA's Geostationary Operational Environment Satellites (GOES) is routinely used for volcanic hotspot analysis, and the results posted on the web (Harris and others, 2000). NOAA's operational system of polar orbiting satellites provides observations of the entire globe at least every 6 hours at spatial resolutions of 1-5 kilometres, but the sensors saturate far below magmatic temperatures. Efforts to document thermal anomalies as possible precursors to earthquakes have drawn on the stream of Advanced Very High Resolution Radiometer (AVHRR) and Along-Track Scanning Radiometer (ATSR) data. New sensors like MODIS and SEVIRI, which have a wider range of infrared bands, should allow monitoring of a wider range of temperatures. In fact, the MODIS sensors are already used to detect volcanic hotspots, with the results posted on the web. Unlike the GOES site, the MODIS hotspot site has global coverage. Current and planned EO systems that might be used for thermal observations are listed at the end of the section.

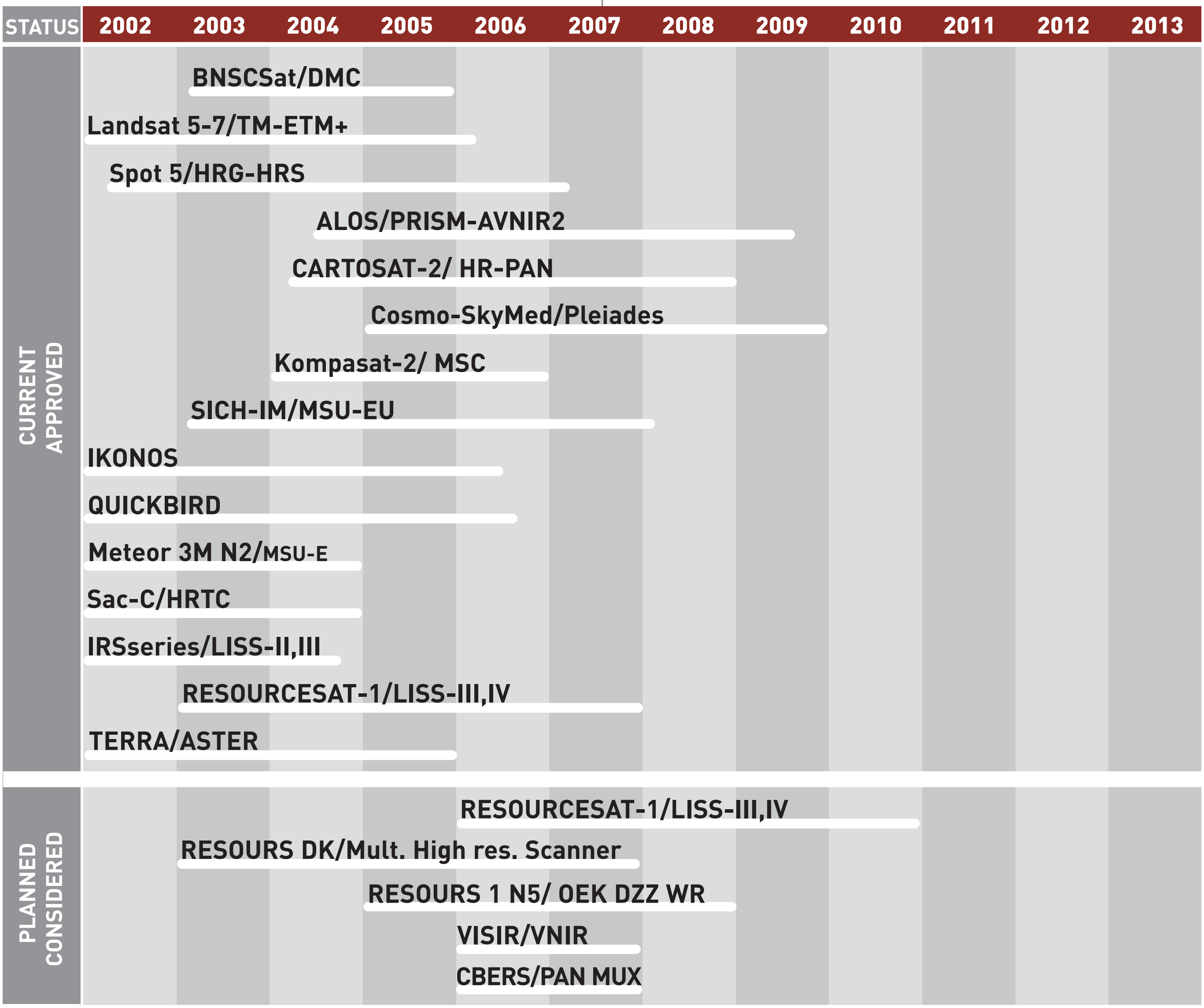
> Physical Properties

For ground instability, understanding the behavior of the hazard requires the collection of detailed geotechnical information on the physical properties of soils and superficial geological deposits. Measurements that are necessary include moisture content, strain, strength, porosity and pore-water pressure. These data are predominantly gathered on the ground, using a variety of instrumentation deployed at specific hazard sites.

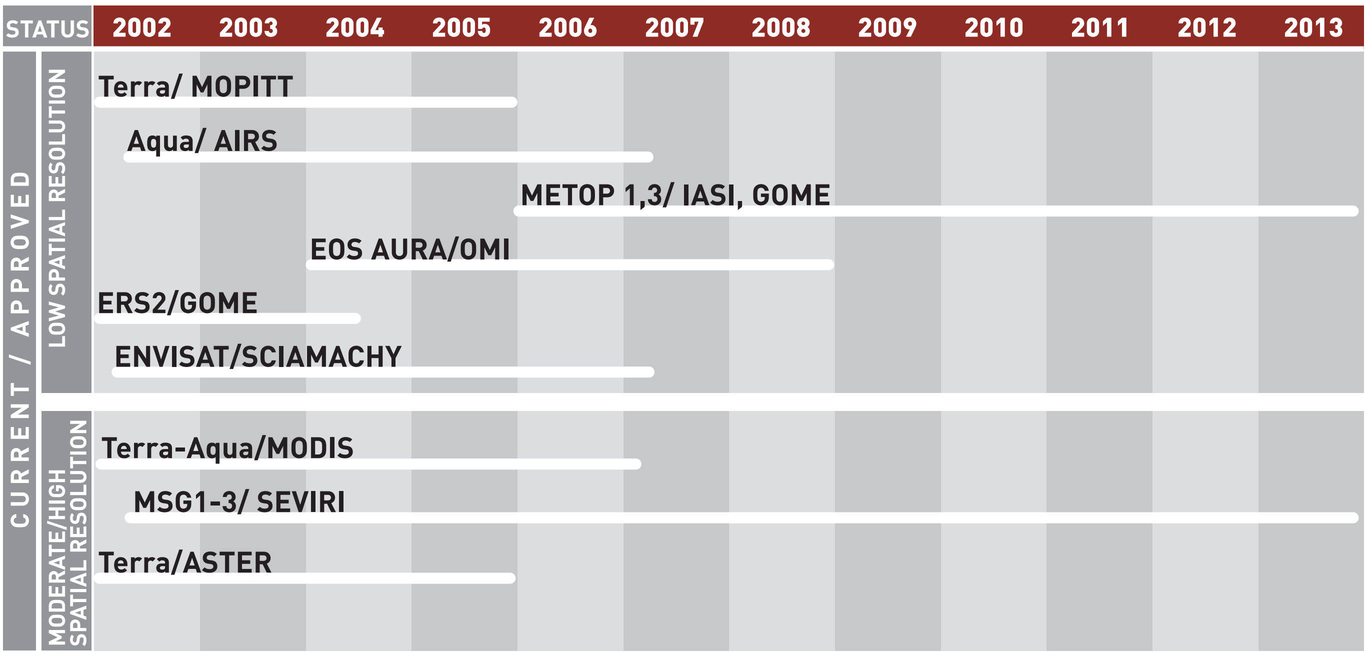
Field and laboratory measurements, including geotechnical and geophysical techniques, furnish information on strain-state, hydromechanical and hydrogeological properties and geological structure, especially within active landslides. In some cases, they help detect early-activated zones and so are usually included in early warning systems. Geotechnical instruments used include extensometers, inclinometers, crack metres, rupture and contact detectors, water-level metres and pore-water pressure sensors. Ground based geophysical techniques such as electric, electromagnetic, ground penetrating radar, protonic resonance magnetics and active seismic reflection and refraction are all used to detect and characterise parameters relevant to ground stability assessment. They permit noninvasive investigation of subsurface conditions. These measurements are used to deduce permeability, water content, porosity, chemical constituents, stratigraphy, geologic structure, and other properties. The detail needed from such measurements is dictated by the size of the phenomenon and the purpose of the analysis. Soil moisture is measured from airborne thermal data and in favorable conditions by satellite radar, but EO-based soil moisture monitoring is not yet operational ■



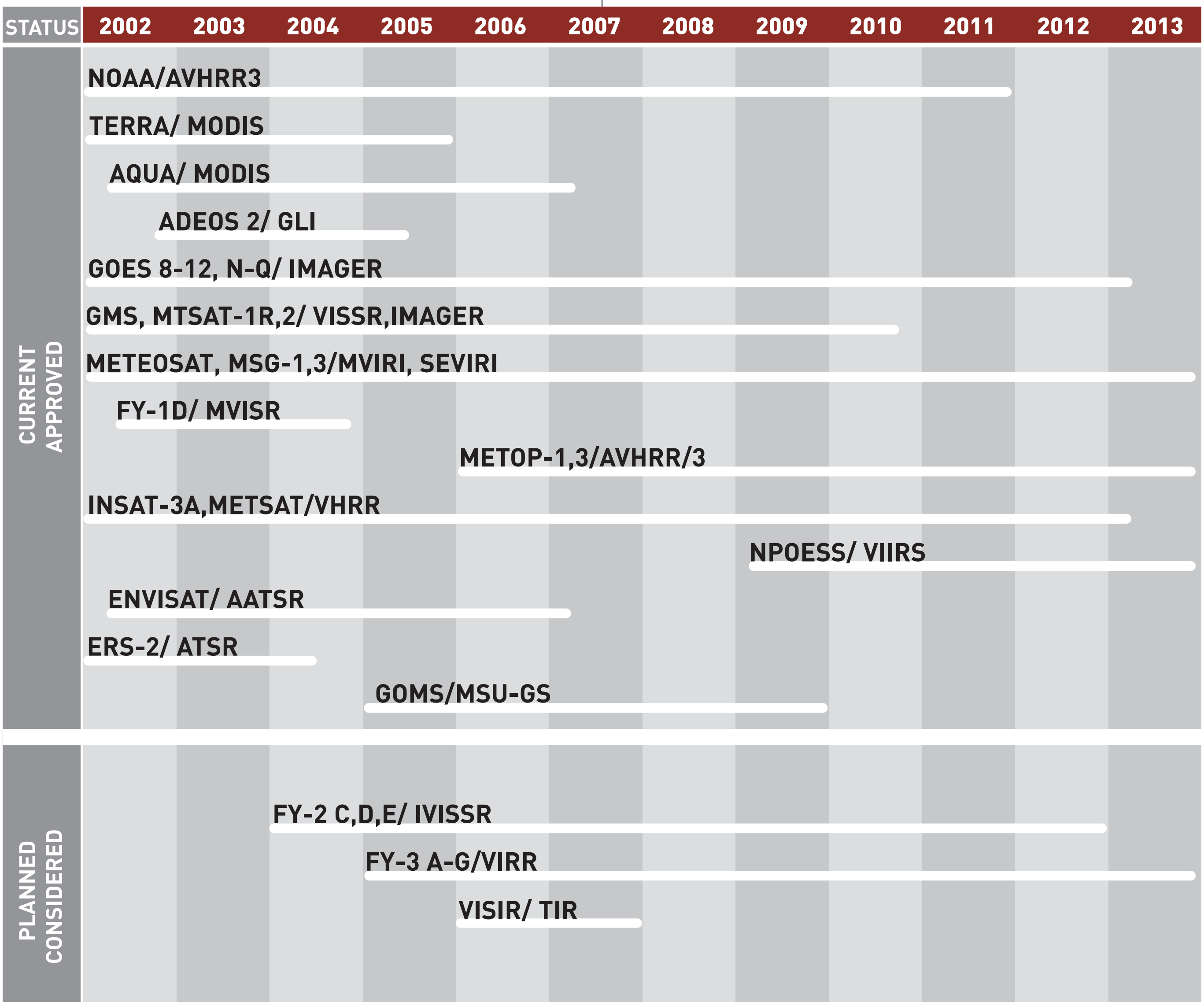
The key current and future satellite missions and sensors for ground displacements observations and topographic mapping by InSAR techniques.



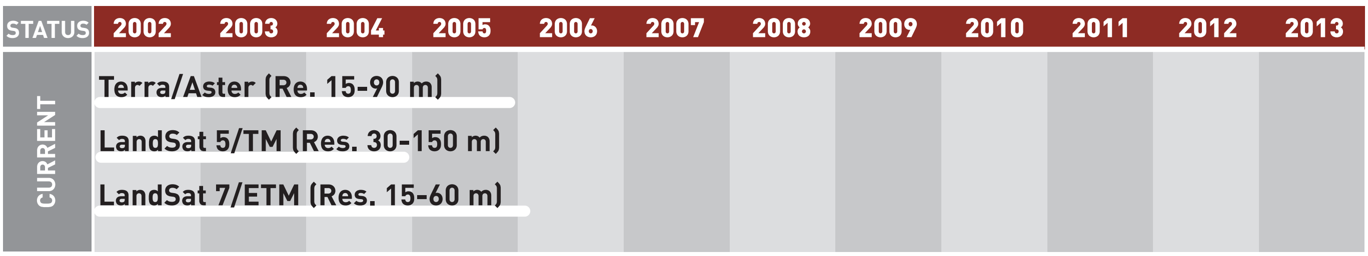
The key current and future satellite missions and sensors for baseline mapping



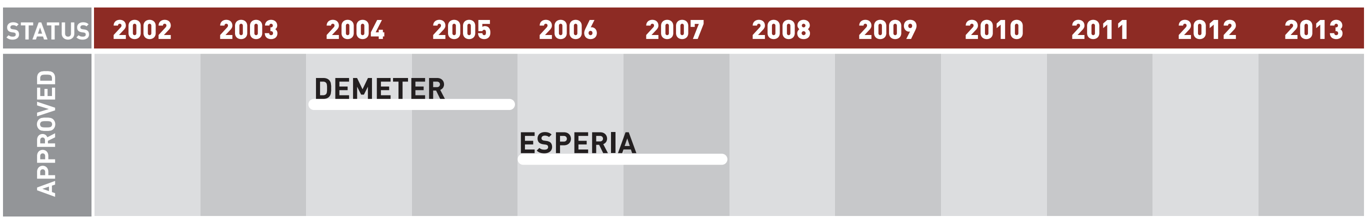
The key current and future satellite missions and sensors for volcanic gasses (mainly SO2) observation.



The key current and future satellite missions and sensors for thermal monitoring at moderate spatial resolution (from hundreds to thousands of metres) and high observational frequency (from tens of minutes to few days).



The key current satellite missions and sensors for thermal monitoring at high spatial resolution (from tens to hundreds of metres).



Future missions for ionosphere observations

Geohazard mitigation requires far more than simply making the correct observations. Satellite, airborne and ground-based observations need to be integrated, assimilated and used in models in order to generate useful information products. The resulting data must be properly managed and made accessible to the geohazards community in a timely fashion. An infrastructure capable of supporting this has to be put in place. Integration must also be extended to the user community, to ensure that the right products are created and put in the hands of those who need them. The biggest long-term challenge is to build on existing capacity within the geohazards community and promote the global application of local best practice, through programs of education, training and technology transfer.

Integration is needed on many levels, from the observations systems, through the observations that they make, to the communities making them. Systems integration is needed in order to ensure that observations made by different observing technologies are compatible. The integration of these separate observations aims to release the synergy between them and so produce a richer information product by, for example, adding temporal continuity from ground-based observations to spatial coverage from satellite observations. Integrating the geohazards community is perhaps the most difficult challenge, because it involves building on the capacity of disparate people and organizations to help them perform their functions effectively, efficiently and sustainably. The International Strategy for Disaster Reduction affirms the need to increase international collaboration, in order to reduce the impact of natural disasters. The World Summit on Sustainable Development placed this issue at the heart of the sustainable development agenda. But it is the sheer complexity of developing an integrated approach to geohazard mitigation that demands better international networks and partnerships. These will support the development of new tools, provide wider access to knowledge, and enable sharing of experience and expertise.

DATA MANAGEMENT

The first set of integration issues concern the establishment and maintenance of properly collected and evaluated observational data for the geohazards. The observations from the various observation systems and the information products that are created from them need to be added to databases that ensure long-term preservation and curation. These archives or databases need to be complete in terms of global geographic coverage and the range of appropriate data types, contain validated, consistent, geographically registered data and be archived securely. Their very existence encourages long-term continuity of observations, supporting ongoing monitoring and research whilst at the same time ensuring that historic data exist when they are required during a specific event. Both update and access must be rapid and efficient, even when operating in remote locations, and should be supported by appropriate metadata. Pricing, intellectual property rights and copyright apply to any data but policies should not hinder access by those who need multiple repeat acquisitions of EO data in order to solve geohazard problems. Data formats and database designs should foster data sharing and interoperability.

Many essential databases and archives already exist for selected geohazards data. The Smithsonian Global Volcanism Project and its monthly bulletin are the archive of record for volcanic activity, worldwide. The USGS NEIC maintains on-line files of major earthquakes, with some supporting descriptive material, but it does not include full descriptions of all related data and events, and there is nothing comparable for ground instability hazards. Similar international initiatives for developing a global landslide database for the collection, storage and dissemination of landslide information have not yet been organised, although the International Consortium on Landslides formed after the Kyoto summit in 2002 may support this in the longer term. Examples of other relevant databases include IRIS, the global archive for seismic records supported by the US National Science Foundation, which makes data freely available to participating institutions and investigators, and the International GPS Service (IGS), which has provided valuable scientific data and products to users since 1994. The University NAVSTAR Consortium (UNAVCO) also serves the GPS data user community. The EROS Data Center of the USGS archives all Landsat and ASTER data, as well as other airborne and EO data streams, and similar archives exist at the various space agencies for other relevant EO data such as ERS and RadarSat.

DATA INTEGRATION AND MODELING

The existence of such databases facilitates the development of software for integration of the different streams of geohazard data. Integration aims to create a richer data product that contains the strengths, but overcomes the weaknesses, of each contributing dataset. Examples include the integration of 3-D point observations of topographic change from GPS, which are continuous in time but limited in spatial extent, with DInSAR measurements which cover wide areas but are not continuous in time and only available in the radar's line of sight. Another common approach to help users visualise satellite or airborne data and understand its information content in a more familiar context is to combine it with a terrain model and topographic base map. Most common image analysis and GIS software can perform these basic types of integration. More complex, problem specific integration is supported by specialised software such as the Volcano Analysis and Visualization Element (VALVE) (Cervelli and others, 2002) for volcanic hazards and the Geographic Information Systems for Slope Instability Zonation (GISSIZ) developed at ITC in Holland for landslide hazards (Van Westen, 1993). A variety of integrated data management systems have been proposed for volcano-related data, including the Geospatial warning system (Geowarn) and the European Mobile Early Warning System (EMEWS). An example of a second-generation, integrated database for historic examples of volcanic unrest is the proposed WOVOdat project. Here the input is to be the integrated, evaluated results of well-characterised volcanic eruptions or episodes of volcanic unrest that did not lead to eruptions. The goal of this project is to facilitate the sharing of experience among the volcano observatories of the world, to help compensate for the relative infrequency of eruptions at any one volcano. This type of global sharing of data and information products will be that much easier in future as the scientific Information Technology infrastructure known as the GRID is developed.

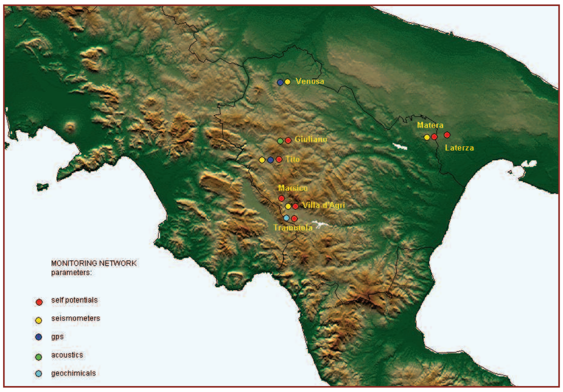
Scientists in monitoring and observation services and research institutes also access these databases in order to feed data into models that describe the behavior of the various geohazards. A research agenda must exist that results in increased knowledge of geohazards and continuing improvements to these models. As the science develops, more complex models will require the integration of a large number of in-situ, airborne, satellite and other geoscience data sources to fully describe a given aspect of the Earth system, characterise the processes affecting it and provide reasonable advice on what can be expected to happen under various scenarios. Such models support scenario planning and informed decision-making. Process modeling software is also therefore required and examples include LAHARZ, which models lahar development and run-out (Schilling, 1998). Data assimilation can also be used to bridge the gap between detailed observations that are limited to specific sites and global observations at reduced resolution. Such applications tend to be computing intensive and involve access to disparate data sources. Hence, they are also a candidate for the development of new approaches based on the GRID.

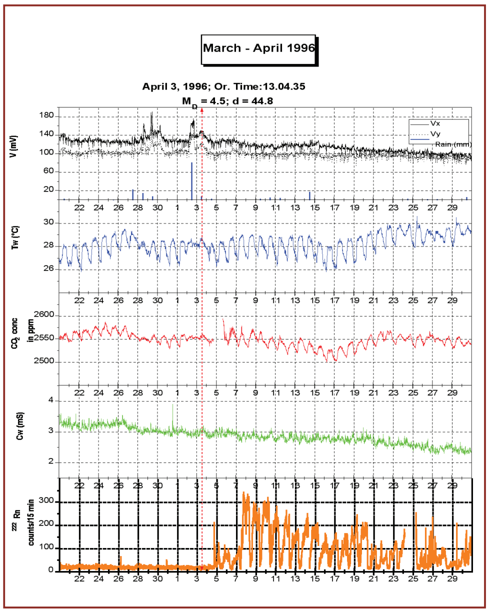
CAPACITY BUILDING

Another critical step in improving global mitigation of the geohazards is capacity building to strengthen the global scientific and monitoring infrastructure. This section describes organizations that could form the building blocks of a global geohazards community.

The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) has supported research and mitigation of volcanic hazards for 75 years. It is organised into a number of relevant Commissions. The Commission for Mitigation of Volcanic Disasters, which serves as a vehicle for communication between professional volcanologists and the responsible authorities, focuses on hazard maps as a mitigation tool.

WOVO, the World Organisation of Volcano Observatories develops materials to support monitoring activities, including a directory of member observatories. There is a Remote Sensing Commission looking at the application of such technologies to the mitigation of volcanic hazards.





Multiparameric monitoring network installed in a seismic active area of Southern Apennine chain. The stations can detect seismometric, geodetic, geochemical and electromagnetic parameters. Contemporary plots of Self-potential, Water spring temperature, CO2 concentration, Water electrical conductivity, and Radon emission, during two months before and after an earthquake occurred in the area on April 3rd 1996 (courtesy of IMAA-CNR).

Finally, the Cities and Volcanoes Commission has set up the System for Technology Exchange for Natural Disasters (STEND) as a conduit for exchange of information and ideas between cities affected by volcanoes and volcanologists and emergency planners who work in them. Good examples of other existing programs with capacity building as their purpose include the Volcano Disaster Assistance Program (VDAP) of the US Geological Survey, formed in 1985 in response to the disaster at Nevado del Ruiz. At the invitation of the host country, VDAP personnel bring and install seismic, deformation and gas monitoring equipment, train local personnel in its use and maintenance, and offer their experience in interpreting volcanic unrest to local scientists. A related program is the Center for the Study of Active Volcanoes (CSAV), a cooperative project between the University of Hawaii and the Volcano Hazards Program of the USGS. Based in Hilo, this program provides small groups of carefully selected scientists from developing countries a 6-week course of intense training in volcano monitoring techniques, with Kilauea volcano as the laboratory. Over 70 scientists and technicians from developing countries have been trained at CSAV since 1989.

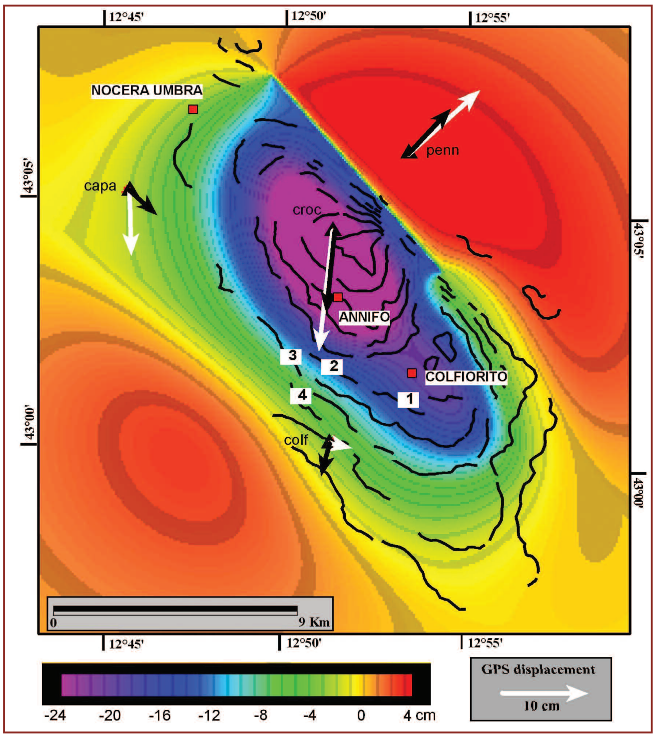
The International Association of Seismology and Physics of the Earth's Interior (IASPEI) promotes research on earthquakes and applied seismology that depends on co-operation between different countries. Its Earthquakes and Megacities initiative has similar objectives to STEND. IASPEI's European Seismological Commission (ESC) aims to extend and enhance European cooperation, minimising the divergence between countries and establishing European seismology so that it can fruitfully interact with the international community. ESC is now collaborating with countries in North Africa and the Near East. Also on the European level, UNESCO and the USGS run a Program on Reducing Earthquake Risk in the Eastern Mediterranean Region. In cooperation with the Euro Mediterranean Seismological Center and Observatories and Research Facilities for European Seismology, this has been working for the past decade to promote seismic data exchange, joint data processing, instrument calibration, training and the reduction of seismic hazards through the development of seismic hazard maps. As well as the US and Europe, almost 20 Mediterranean countries are now involved. UNESCO has also supported this type of initiative in other regions, such as the Centro Regional de Sismologia para America del Sur, which is based in Peru and has 12 member states in South America.

In the field of ground instability, such developments are less advanced, probably because of the distributed and localised expression of this global phenomenon. The main initiative is the International Consortium on Landslides, which was founded in 2002 after the Kyoto summit. It aims to combine and coordinate international expertise on landslide hazard mitigation and risk assessment. It plans capacity building, communication and information activities. These include: networking with other relevant initiatives; the publication of the journal Landslide News, books and guidelines; conference organization and sponsorship; raising public awareness through the press and meetings; training courses; and the supply of expert knowledge. The IGOS geohazards theme is not aware of any similar initiatives for subsidence.

The EO provider community concerned with geohazards has organised itself under the leadership of the Committee on Earth Observation Satellites, which sponsored the DMSG Project. Many CEOS members have strong programs in geohazards research and mitigation. The CEOS DMSG report includes chapters with extensive discussion and recommendations for each of the three geohazards and these recommendations form the starting point for much of this IGOS theme's work. There is strong cross-membership between the DMSG Working Groups and the IGOS Geohazards Theme Team to facilitate this. The CEOS Strategic Implementation Team has recommended that CEOS be closely involved in the implementation of the IGOS Geohazards in the field of space-based observations. CEOS is therefore a key component of any future capacity building activities.

One of the most effective steps that can be taken is to spread best practice: for example, ways should be found to apply new techniques developed at a few well monitored volcanoes to the majority of dangerous volcanoes around the world. For earthquakes, the USGS's Shakemap is an example of an information product produced locally that could be extended globally relatively easily. Similar steps can be taken for each hazard, using strong case histories to facilitate this knowledge transfer process. Such case histories can form part of dedicated geohazards curricula and courses to grow the community in the future.

Education and training, especially of scientists from the developing world, underpins capacity building by delivering skilled, knowledgeable staff to work in geohazards institutes worldwide. Many organizations deliver such training, but the ITC has been particularly active in geohazards, collaborating with UNESCO and supporting the development of this IGOS theme. Providing sup-



Ground displacement after the September 1997 Umbria – Marche earthquakes (Central Italy) detected and modeled from GPS and SAR data. Observed (white arrows) and predicted (black arrows) GPS displacements plotted over the contour of slant range displacements traced from the interferogram fringes (from Salvi et al., 2000).

port to both institutions and individuals from less developed countries, ITC aims to build their capacity to collect, store, process, analyse, use and disseminate EO data and geoscience information. The best capacity building is achieved using application-oriented approaches that combine training with finding solutions to local, national or global issues and strengthening civil society. A good example is provided by five pilot studies conducted in Central America as part of the UNESCO Capacity Building for Natural Disaster Reduction Program, in collaboration with ITC and the Centro de Coordinacion para la Prevencion de los Desastres Naturales en America Centrale. Specialists from the relevant institutions in Costa Rica, Dominican Republic, El Salvador, Guatemala, and Honduras were first trained at ITC in geo-information and geohazards management techniques, before returning to their countries to be responsible for implementing the pilot studies. The deliverables are hazard zonation maps, but also include the transfer of knowledge from the trained individuals to their colleagues in order to extend the capacity building effect. Case study meetings and a final workshop are being organised to share experiences, draw conclusions and make recommendations on the best methods to apply to integrated hazard and risk mapping. Finally, training packages will be created, based on the pilot studies, and disseminated more widely.

There are also regional initiatives pursued by particular nations. For example, Canadian economic support has been provided to the Multinational Andean Project: Geosciences for the Andean Communities. The aid programs of many developed countries support much similar hazard mitigation activity. The relevant scientific unions, International Union of Geodesy and Geophysics (IUGG) and International Union of Geological Sciences (IUGS), also fund relevant international programs. For example, IUGS and UNESCO fund the GARS Program. This has had initiatives on landslide hazards in Latin America and volcanic hazards in Southeast Asia over the past 20 years, in each case teaming up scientists from developing countries with their counterparts from the regions concerned. GARS is one of the main sponsors for the development of this IGOS Geohazards. The geohazards theme presents an opportunity for IUGG and IUGS to strengthen their cooperation over such initiatives with both the space agencies and the relevant end-user communities.

It is clear that there are many building blocks in place that could benefit from further coordination, with a view to integrating the global geohazards community. However it is conspicuous that there is at present no one community and no one organization that encompasses all the geohazards and is therefore well placed to take on this coordination role. Making best use, globally, of the existing infrastructure requires an integrated geohazards community, both between the three geohazards and between the various stakeholders and users. The strong commonality emphasised in this strategy between volcanic, earthquake and ground instability hazards needs to be exploited by sharing experience and solutions. Users and scientists in both the public and private sectors must communicate in order to understand both what is required and what is possible, so that appropriate information products can be developed.

The lack of an integrated community has a negative effect on the wider recognition of the impact of the geohazards and consequently on the effort that is put into meeting the needs of the geohazards community. It reduces the effectiveness of attempts to seek sponsorship and funding for large-scale projects critical to geohazard mitigation. Focused, coherent funding mechanisms are needed to underpin initiatives such as the International Strategy for Disaster Reduction, as well as this IGOS Geohazards, especially as it seeks to move beyond applied science in the developed countries into global observing to support operational monitoring in all countries, via education and training, knowledge and technology transfer and capacity building in appropriate institutions and industries ■

This chapter assesses the current provision of observations, key systems, data management, integration, modelling, and community building against the requirements in these areas set out in Chapters 3 and 4. Its purpose is to identify gaps that the IGOS geohazards must fill over the coming decade if the strategic objectives are to be achieved. It also identifies gaps in the scientific knowledge that underpins the delivery of this strategy and proposes a science research agenda to deal with them.

GAPS IN OBSERVATIONS AND KEY SYSTEMS

In general, observational gaps and challenges arise from the difficulty of ensuring the continuity of adequate observations at remote sites. And long-term hazards, such as volcanic eruptions that last for decades or more, or long-lived landslides, pose maintenance burdens on monitoring networks and data management systems. Dozens of parameters could be monitored, because they have been shown to be useful at a limited number of sites, but many are not yet well established. To minimise these overheads, the IGOS geohazards sets out to define a minimum observational plan for all the geohazards. This is based on a short list of parameters that are absolutely critical to monitor and that can be measured reliably, using repeatable observations suitable for operational use. Other promising parameters and measurement techniques form part of the science research agenda, which is set out at the end of this Chapter.

> Topography

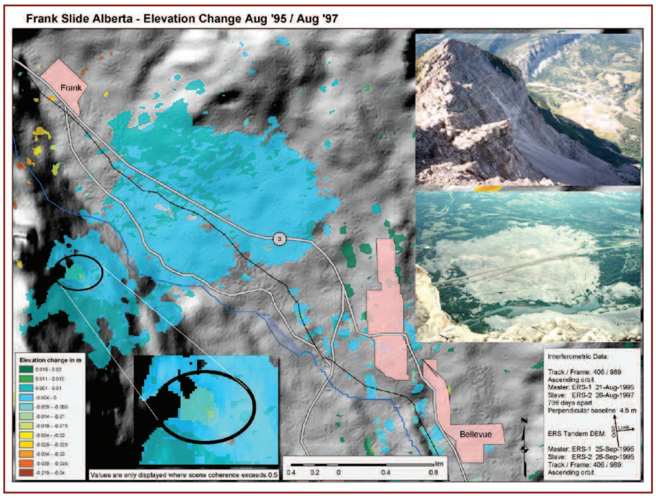
The global coverage of topographic data at sufficiently high spatial resolution is currently inadequate. DEMs are essential input for interferometric processing, and they provide a critical basis for all geohazard mapping and modeling. There are large parts of the globe for which the scale of DEM required by the science is not currently available. DEMs derived from satellite imagery can potentially cover large areas with a far lower cost than aerial surveys. The main limitations are the products' resolution, availability and cost. Interferometric DEMs derived from SRTM, ERS or Radarsat might, in the best case, have a spatial resolution of tens of metres. Techniques based on photogrammetry can be applied to imagery with higher ground resolution such as ASTER, Spot5, Ikonos or Quickbird to provide vertical resolutions of up to a few metres or better. SRTM has mapped the globe between 60N and 56S and much useful stereo EO imagery exists: the challenge is to find ways to support and streamline systematic acquisition and processing, so that the resulting topography can be used systematically by the geohazards community, rather than as it becomes available.

> Mapping

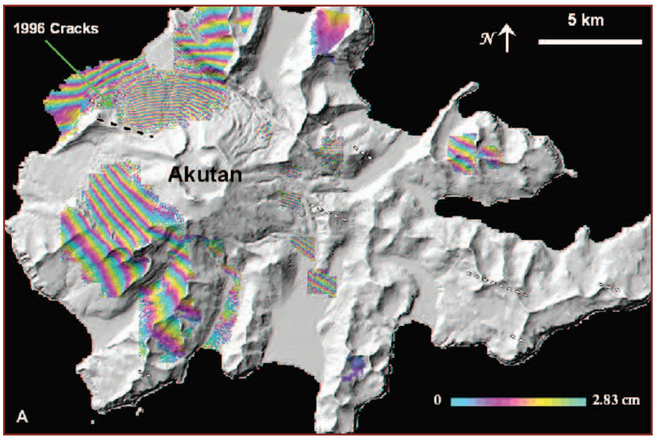
There are fundamental inadequacies in the baseline mapping of the geohazards with respect to hazard inventories and geoscience maps. In contrast to volcanoes and earthquakes, where regional-scale hazard maps generally exist, comparable maps for the various types of ground instability are lacking in many regions. Landslide inventories and subsidence histories must be constructed for all affected regions. Adequate geological and soils maps, at appropriate scales, do not exist for many volcanoes, seismic zones and unstable regions around the world. Filling these gaps will be labour-intensive, require the funding of appropriate mapping projects and occupy many experienced geoscientists. Projects designed to produce appropriate maps should also aim to provide accessible, GIS-ready, digital maps.

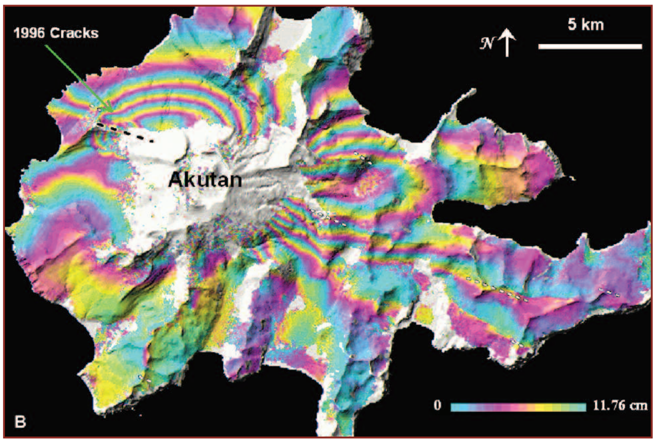
> Deformation

Deformation monitoring is required for all the geohazards and at many scales. Over the last decade, two new methods (GPS and SAR differential interferometry) have emerged that allow us to quantify even small displacements over wide areas. These are already the methods of choice for monitoring seismic zones. They are gradually integrating and replacing the traditional ground-based systems for determining horizontal and



Differential InSAR of Frank Slide, Alberta, shows 3 cm motion prior to 6000 tons rockfall, indicating that this rock slide is still active. InSAR will be used to supplement in-situ tools and to monitor regional motion of the active slide area. The right/left look direction, high resolution and variable viewing geometry of RADARSAT -2 will be used to monitor most the active slides. (image Courtesy of CCRS)





A: interferogram of Akutan Volcano in the Aleutians, made from C-band ERS imagery (Lu and others, 2000) is only locally coherent (rainbow areas).
B: interferogram made from L-band JERS data (Rykhus and others, 2002) has fewer fringes, but achieves coherence over almost the entire surface of the island, allowing us to see the entire deformation pattern. To date, the JERS SAR mission has not been followed up with a new L-band instrument and so such observations are not currently possible. (image Courtesy of USGS)

vertical displacements and tilt that were developed for monitoring deformation at volcanoes. DInSAR is being used in a pre-operational system to monitor subsidence in Europe. In the case of GPS, we can obtain precise, long-term measurements of topographic change, whether in regions of high interest (southern California, with the SCIGN network) or globally (the IGS network). The main limitation is that the high-density networks needed for hazards monitoring exist only locally. A major challenge for the integration of local GPS data globally, and the integration of GPS data with older, heritage deformation data sets, is a lack of standard formats and established archives, plus limited accessibility for the different kinds of deformation data.

Satellite radar differential interferometry provides the capability to map past and ongoing crustal displacements, day or night, in all weather and over wide areas. The CEOS DMSG Report concluded that building up long time series of radar images over sensitive locations would enable more systematic exploitation of multi-interferometric techniques. Their wider application to displacement monitoring is limited by: inadequate temporal resolution; a lack of coherent data, due to the radar frequency at which observations are currently made; the difficulty of resolving line-of-sight measurements into three dimensions; and insufficient mission continuity. The most frequent observation was achieved during ERS's Tandem Mission, when it was shown to be possible to monitor even certain types of landslides using DInSAR. This was based on a 1-day revisit interval, whereas SAR satellites typically have revisit interval in the order of 1 month.

Development has also been limited by the relative inability of existing (C-band) systems to produce information over unconsolidated or vegetated natural surfaces. L-band DInSAR has been shown to be applicable over a wider variety of natural land surfaces than C-band during the now-completed JERS mission. This is illustrated here by two interferograms, one of ERS data and one of JERS data, showing the deformation field produced in the 1996 seismic crisis at Akutan Volcano in the Aleutians. The recent report from the Solid Earth Science Working Group (SESWG) "Living on a Restless Planet" also emphasises the relevance of L-band SAR for differential interferometry over natural surfaces. Filling this gap in observations, perhaps using the forthcoming PALSAR or the proposed TERRASAR-L systems, is critical to the success of the IGOS Geohazards.

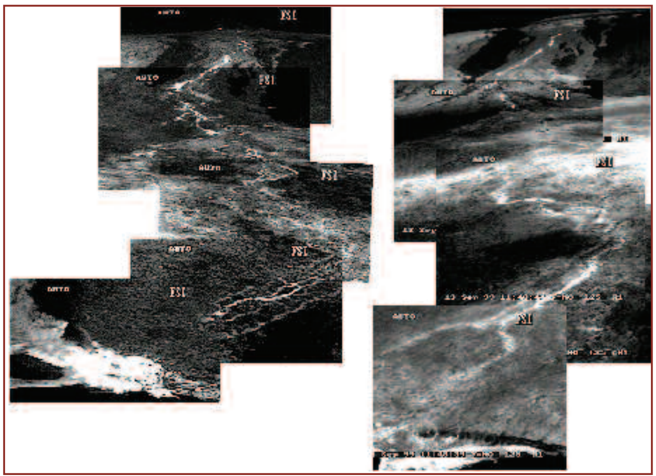
At either wavelength, there is an urgent need for long term continuity of observations. The phenomena to be observed are often slow but continuous, and their successful monitoring can only be achieved with decades of satellite data. Other requirements are that the orbit and satellite design be optimised for this application, be tasked specifically with interferometry in mind, in order to provide sufficient frequency of observation and have sufficient look directions to resolve motion in three dimensions. More generic missions have been used to great effect in research mode but they involve compromises in spatial, spectral and temporal resolution that limit the utility of these observations for operational geohazard mitigation in general and long-term monitoring in particular.

> Seismicity

As noted earlier, earthquakes large enough to cause damage (M > 5.5) can be detected worldwide and are generally reported within minutes, although the global availability of the supporting seismic data could be improved. But the principal gap here is that many urban areas in high-risk seismic zones have inadequate local monitoring, plus inadequate building and land-use planning practices. For volcanoes the key issue is the provision of adequate seismic networks at all hazardous volcanoes sited in populated areas. Experience at well-monitored sites has shown that six seismometers provide a minimally adequate network for one volcano, but many hazardous volcanoes are inadequately monitored or completely unmonitored.

> Thermal monitoring

Thermal data have obvious application to volcanic eruptions and less well-established links to earthquakes. Meteorological satellites have provided frequent but low-resolution thermal imagery for more than twenty years. Such data have proven useful as detectors of volcanic activity, and at dispelling erroneous reports of eruptions at remote volcanoes. But the spatial resolution is too low to be of much use to volcano observatories. This low-resolution data has been supplemented by less frequent but more detailed data from sensors such as Landsat TM/ETM and ASTER. There is a need for data continuity, whether of a Landsat TM/ETM or ASTER sensor, in order to let the potential of this intermediate-resolution imagery develop. However the most promising technique for detailed thermal monitoring of volcanic activity is the use of portable digital infrared cameras. This rapidly spreading technique can produce highly detailed thermal images of active lava flow fields and domes, at whatever time interval scientists require. The cost of supplying digital IR cameras to all of the volcano observatories in the world would be a small fraction of the cost of building even one satellite that could achieve the same resolution from space. A coordinated system would exploit the complementary attributes of all these existing systems, allowing improved time series thermal data of hazardous areas at all resolutions.



Infrared video images showing details of the flow field and lava tube system at Kilauea Volcano, Hawaii. The view is upslope (to the west). The tube systems are about 10 km long. (from Kauahikaua and others, 2003).

GAPS IN DATA MANAGEMENT

The target here is to establish well-managed, visible and accessible databases of the relevant observations and to use these to create "strategic datasets" for particular geohazards, backed up by well-documented case studies. The existence of such datasets will facilitate the production of ancillary data for hazard mapping, guide ongoing systematic acquisitions over hazard-prone areas and drive new, targeted acquisitions during a crisis. At a basic level databases exist for most types of Earth Observations, often as part of a processing and archive facility, and for many ground-based measurements, as part of particular organisations' data management strategies. The gaps that exist relate to the visibility and fitness for purpose of these data stores. The requirement is for much more than storage within a single organisation. Databases are needed with a high visibility within the geohazards community, which facilitate the transfer of data, information and knowledge between different types of users in different countries. Interoperability of databases is crucial, as geohazards require multidisciplinary research. The heterogeneous nature of existing databases can be an obstacle to the progress of our understanding of failure mechanisms. This leads to the need for the creation and population of international geohazards databases.

A good example of what is required is provided by the evolving World Organisation of Volcano Observatories database. Similar initiatives are needed for all the geohazards. Such databases should contain both baseline data and the outputs of monitoring activities, including relevant ground-based data from geoscience organisations and also data from existing satellite archives. The data in them should be calibrated, validated, put into a standard format and quality assured prior to databasing. This IGOS Geohazards should develop operational, and perhaps even automated, arrangements that will make the translation of data into information contained in useable products happen more efficiently. Mechanisms are needed to facilitate the rapid and smooth transfer of data from the space agencies to the scientists monitoring geohazards and of information from the scientists to the users. As soon as an image is acquired over sensitive areas, the data provider should send an automatic notification to a list of subscribers interested in imagery over specific geographic locations.

Pricing strategies are not currently designed to support cost-effective data access by developing countries and they should be reconsidered. Some InSAR studies of displacement require the purchase of many images, over a ten-year period, as part of a strategic monitoring programme with long-term continuity. Such repeat data purchases for operational use should also be made easier and more cost-effective to facilitate long-term monitoring. In a more advanced phase, data could be automatically processed at the scientist's premises and, as soon as useful information on a hazard existed, the processed image products could be sent to the local users. Technological developments like extranet solutions and the emerging, advanced computing GRID network should be used to manage, access, exploit and distribute the large amounts of data and information products required by geohazard mitigation. Provided that adequate models, appropriate software tools and sufficient observations exist, the end users could even activate this process rather than the scientists, as happens in the International Charter on Space and Major Disasters.

GAPS IN INTEGRATION AND MODELING

Improved databases, complemented by shared experience and improved analysis and modeling tools like neural networks, fuzzy logic, statistical, stochastic and geostatistical methods, will open new possibilities for developing data integration in support of geohazards analysis. Integration of data acquired at different resolutions, with different accuracies and geometric characteristics and from different observation systems, still needs a major effort from the scientific community. For example, the techniques needed to monitor crustal deformation and surface displacement include both satellite-supported DInSAR and ground-based monitoring, with GPS monitoring combining elements of both. The methods are complementary: ground-based monitoring can provide a record of deformation at a specific point on the ground that is continuous in time, while DInSAR gives us periodic measurements of the areal distribution of displacement over wide areas. Both are needed in an operational monitoring scenario and they can also be used to cross-validate the observed deformation, increasing confidence in both individual results. Bawden and others (2001) provides an example of the value of combining the two approaches in a tectonically complex area. But, in the main, the integrated use of ground and satellite data is generally limited to intercomparisons and data calibration.

Prediction of future events requires models and numerical simulations based on well-understood Earth system processes. There is a proliferation of different models with widely differing assumptions, depending on the scales of investigations. This is of major importance for hazard mapping and monitoring of events ranging from local to regional distributions. Models vary from simplified to complex. The former are approximate, but they necessitate fewer input parameters and may be applied to large zones. The latter are sometimes indispensable for evaluation of the stability of a specific, dangerous ground instability hazard but are data hungry. In both cases, it is necessary to establish their capability, accuracy, and sensitivity with respect to the needed effort for gathering model inputs. Numerical simulations are still rare, especially for example in ground instability studies, due to the difficulty of obtaining the required input parameters and the heavy 3-D computations involved. The development of reliable physical models requires a better understanding of physical processes, thresholds in physical properties and triggering mechanisms. Field observations and laboratory experiments should be carried out to advance this.

This IGOS Geohazards can also contribute to the development and documentation of standard data processing software and protocols and standard information products. Some standard products exist but only in certain countries and for certain hazards. The IGOS Geohazards should extend this to all hazards and ensure that such standard products become established in the wider geohazards community. Similarly, standard visualisation tools are needed that can be used by scientists and users alike to rapidly analyse new information products as they a reproduced, whether working in the laboratory, at an observatory or in the field. Finally, work should continue on the improvement of Earth system process models via the research agenda proposed below.

BUILDING THE GEOHAZARDS COMMUNITY

Currently there is no global coordination mechanism to implement the IGOS Geohazards. One result of this is relatively poor integration within the geohazards community in comparison to, for example, the Oceanography or Meteorology communities. Communication needs to be increased between all the key players and across all the continents. This lack of integration hinders many other desirable actions. Users do not consistently define information products through dialogue with monitoring and advisory agencies. Scientists do not consistently define the required observations that the observing systems should make and do not work in an integrated fashion across their disciplines, technologies, or application areas often enough. Appropriate technologies and methods for developing global applications are lacking. The best students are not attracted to study and consider careers in geohazards, with most expertise developing during general geoscience careers and coming into the geohazards field by serendipity in mid-career. Funding is also dispersed and predominantly governed by the priorities of individual organisations, regions or nations. An example of this is that the International Strategy for Disaster Reduction, the most visible international initiative in the field of geohazards over the past decade, has no dedicated funding, unlike equivalent initiatives in other environmental application areas.

Geohazards sometimes have limited visibility in wider decision making processes. For example, the impact on hazard monitoring of the high price of bandwidth for satellite data links, caused by the telecommunications market, is not being addressed, because the geohazards community does not have a voice in that decision making process. The first step must be to create a coordinating mechanism. This should then be used to encourage improved communication throughout the geohazards community, foster the transfer of knowledge and information from the developed to the developing world, and develop curricula to stimulate study courses dedicated to geohazards. The development of a more integrated geohazards community will also have spin off benefits in crisis response, by enabling the rapid gathering of expertise during a crisis. And that geohazards community will be in a better position to present a coherent case to politicians and funding agencies when this is necessary.

SCIENCE RESEARCH AGENDA

The social and economic issues created by the geohazards require an improved understanding of these hazards. To do this, we need not only more extensive observations but also better models. Their purpose is to produce refined hazard scenarios, and so increase our ability to mitigate hazards, with the ultimate goal of being able to issue forecasts for individual geohazards. In order to offer forecasts, geoscientists must reach consensus on identifying and validating precursory signals. Useful precursory signals are those that allow us to specify with reasonable confidence where an event will occur, how big it will be, and something of its character. This must be done with enough lead-time for the responsible agencies, governments and citizens to respond to the warning. Progress toward adequate forecasting is uneven across the geohazards, with volcanic hazards being quite advanced in this respect and earthquake forecasting perhaps offering the most difficult challenge. The scientific agenda outlined below indicates both some promising areas of research, some of the remaining challenges, and additional observations and systems that should be investigated to see if they can one day be used operationally.

> Volcanoes

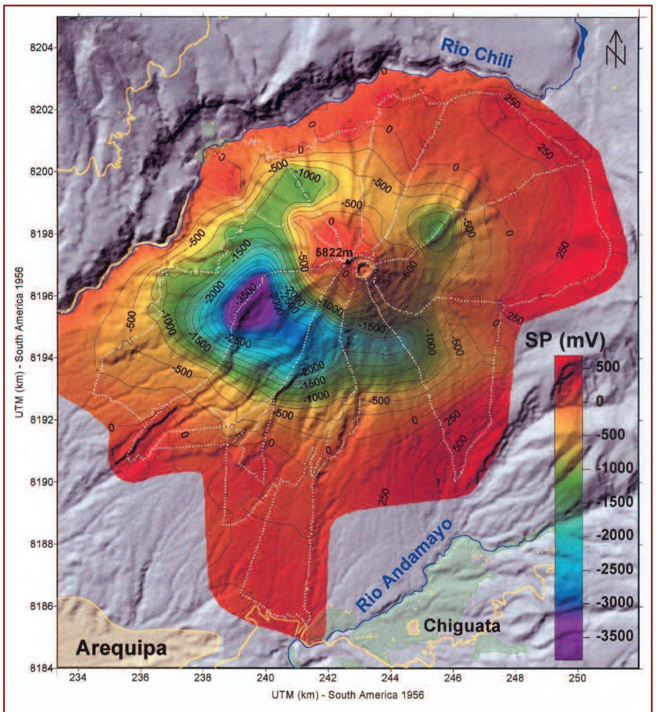
At well-monitored volcanoes we can anticipate the nature of the activity and give some early warning of events, but we still lack the ability to forecast the size and timing of eruptions. We need to refine our understanding of volcano seismicity, deformation patterns, and degassing behaviour, and the relationship between a volcano's geothermal and magmatic systems. Specific areas of interest include:

The recent development and deployment of broadband seismometers, capable of recording long-period earthquakes with individual events lasting 10-100 seconds. This has revealed a wide, previously undetected range of seismic signals, produced by the movement of magma, hydrothermal fluids and gas within volcanoes. Progress in their interpretation is limited, in part by the complexity of the phenomena, and in part by the enormous computer processing capacity required to take full advantage of the data. At present, evaluation of these data is in the sphere of research but it will improve our models of how volcanoes work significantly. If certain types of events are shown to be reliable indicators of magma movement, and hence of an impending eruption, the geohazards community will need to consider how best to support wider installation of these instruments, as well as how to support the large, shared computing facilities required to process the data.

Wider observations of gravity changes at volcanoes would increase our understanding of volcanic processes. Recent research using InSAR has shown that volcanoes can steadily inflate, presumably because new magma is rising within them, even though there is not yet any associated seismic activity during this steady inflation phase (Wicks and others, 2002). To distinguish between inflation caused by magmatic intrusion and inflation caused by pressurisation of a geothermal system, it is necessary to monitor changes in gravity at the same location. At present, relatively few volcanoes are monitored for gravity changes and so more extensive gravity monitoring is needed, especially at deforming volcanoes where there is inflation.

Other techniques that have been applied at volcanoes include the in-situ measurement of electric or electromagnetic properties, which are affected by the migration of fluids and gases in the subsurface. Such migrations occur for all three hazards but the related electro-magnetic effects are not yet well enough understood to demonstrate their value to operational monitoring. For example, the signature of the geothermal system that exists under an active volcano dominates its EM response and so the relationship to the magma system itself is uncertain. Further study of these parameters at active volcanoes may serve to reduce ambiguity in their interpretation.

Increased emission of steam, SO_2 and/or CO_2 frequently precedes volcanic eruptions, but quantitative linkages are mostly still lacking. For SO_2, the principal scientific challenge has been the difficulty of mapping low-altitude SO_2 and aerosol plumes over wider areas with high resolution data. This could be done with ASTER, if such imagery were available more frequently. Obstacles to the routine monitoring of volcanic CO_2 from space are the relatively high CO_2 content of the atmosphere and the fact that most CO_2 emissions are not associated with eruptions, but are non-explosive, diffuse, and occur at low temperature. Because CO_2 is



Electrical potential field (in volt) recorded at the Misti volcano (from Finizola et al., in press)

heavier than air, it flows along the ground, or seeps out through the soil, making it difficult to detect by satellite techniques. CO_2 plumes are deadly, however; the 1986 CO_2 emission at Lake Nyos, Cameroon, killed more than 1,700 people and much livestock. Mitigation of this hazard will require ground-based monitoring and warning systems and these have yet to be developed.

Volcanoes emit other gas species, such as HCl and HF among others. The newly available Open-Path Fourier Transform Infra-Red spectrometer permits the detection and characterization of all gas species present in active volcanic plumes, at temperature. Its use will advance understanding of volcanic degassing, and could lead to ground or even space-based monitoring of the particular gas species that best predict volcanic activity, once these have been firmly established.

> Earthquakes

We are further from being able to provide meaningful forecasts for earthquakes than we are for volcanic eruptions. There are still major research issues surrounding the initiation of earthquakes, and documentation and interpretation of the ground motions and deformation that constitute the earthquake itself. In addition, whilst a wide range of phenomena have been observed at the same time as some large earthquakes, it is not yet clear how closely and in which way these phenomena are linked to earthquakes. There is as yet no consensus on any consistent precursory signal of an impending earthquake. Promising research areas include:

The need for better understanding of pre-, co- and post-seismic ground motions. Relative displacements along faults are typically measured after the earthquake. Wider deployment of permanent, continuously recording GPS networks will provide a more complete picture of pre- and post - event displacement. Wider use of DInSAR across all the main active faults can help document continuous strain and identify locked segments of major faults. These data, coupled with other geodetic, hydrologic and geophysical data, will help scientists to understand how the crust deforms in inter-seismic periods. This will, in turn, form the basis for refined seismic probability forecasts. Other questions concern the focal mechanisms of the earthquakes and how ruptures evolve, both kinematically and dynamically.

New tomographic techniques for geophysical data inversion (resistivity imaging, reflection and refraction seismology, self potential) can be applied to the mapping of active faults, to define the geometry of complex tectonic structures and to characterise shallow geological environments that generate local seismic amplification.

Ancillary phenomena that may be associated with earthquakes include: surface thermal anomalies and surface and near-surface temperature changes (reported for a number of earthquake events), sometimes accompanied by changes in soil moisture, changes in chemistry of pore waters and pore gases, and changes in atmospheric composition (for components such as CH4, CO2, He, H2). Much of the work to date relies on historic data and isolated reports, so no consensus has yet emerged. A good summary of the very varied phenomena reported as occurring during earthquakes is given in Singh (2003) for the recent Gujarat earthquake. More consistent monitoring of such events is required to lead to an improved understanding of their relationship to earthquakes and enable a full assessment of their utility as precursors.

Possible links between earthquakes and electromagnetic phenomena is an emerging area of research. The next mission focused on electromagnetic signals and their possible correlation with earthquakes is DEMETER, to be launched in 2004, with an expected lifetime of two years. Ground-based EM measurements (including self-potential anomalies and Ultra Low Frequency (ULF) emissions) will be an essential component of validating the connection between anomalies detected by satellites that are suggested to be related to earthquakes and volcanoes and earth system processes.

Similarly, possible links between earthquakes and changes in the Earth's gravitational field are being researched actively at the present time. Satellite missions to monitor changes in the Earth's gravitational field, such as GRACE, CHAMP and the planned GOCE may elucidate the link between deeper tectonic processes and the geohazards. Once understood in detail, these phenomena might offer promise as a precursor.

> Ground instability

For the various types of ground stability, the need for forecasting capability is a function of how fast the particular type of ground failure or motion can occur. For landslides triggered by earthquakes, our ability to forecast is limited by our current inability to forecast earthquakes. For ground failures triggered by severe weather, we depend in part on weather forecasting. Areas of research that will lead to a better understanding of what controls ground instability include:

The processes that trigger the motion, which are of critical importance whether natural or anthropogenic and include rainfall events, earthquakes and human modification of land-cover and land-use. Soil moisture variations are a natural triggering mechanism that deserves particular attention, because there are emerging techniques that offer the potential to measure the parameter remotely and in-situ monitoring is also being improved. The Soil Moisture and Ocean Salinity (SMOS) satellite mission offers an opportunity for a strong research project on this topic. Mining triggers subsidence in a predictable fashion, but the links between mine closures, rising water tables, mine gas emission, seismicity and fault reactivation over a period of decades need urgent investigation.

Delimiting the true extent of the subsidence problem is difficult, because of the disparate causes and the lack of global observations until now. There is some evidence that it is more widespread than first thought, may be accelerating in some areas and could be spreading to new regions. Improved global observations will not only help to monitor the known problem areas but they will also provide a time-series dataset capable of answering these wider questions.

Similarly, there is evidence for a link between climate change and the frequency of landslide occurrence. The role of landslides as a landscape evolution process and their response under the future climate scenarios currently being evaluated presents an interesting area of interaction between geoscientists and climate researchers. It could eventually support high-level, long-term, regional landslide forecasts.

Better understanding is needed of the patterns of motion before, during and after events. The speed of motion ranges from millimetres per year, which can be effectively monitored rather than requiring a forecast, to metres per second, which represents a catastrophic event that does need forecasting. The speed of these motions changes with time and it is possible that such changes are precursors to the more significant events. DInSAR may allow slow, small-scale motion to be observed systematically for coherent targets. Field instrumentation to monitor ongoing deformation is essential, as well as the development of satellite based monitoring that can be applied to targets that may decorrelate over small time-intervals, like landslides.

Ground-based interferometers may be a solution for monitoring landslides, because of their high temporal frequency. The main advantages are continuous monitoring, optimal illumination geometry, flexibility and the possibility to remotely monitor landslides up to a distance of about a kilometre, the latter being especially important when landslide sites are not easily accessible with traditional instruments. These systems also offer two-dimensional images, and can provide cost-effective solutions for specific sites, where the system can be properly installed and long-term monitoring properly established.

TIME SCALE ISSUES

One of the most formidable obstacles to effective global monitoring of geohazards is that activity occurs at an enormous range of time scales. Explosive eruptions may be over in a few hours to a few days, while pyroclastic flows and lahars can move at metres or tens of metres per second. Even the largest earthquakes are over in minutes. Landslides may be rapid, catastrophic events on similar time scales to eruptions. For rapid events, scientists are dependent on monitoring networks already in place, or geostationary satellites (which can take an image every 5-15 minutes), or strategically placed time-lapse or video cameras, or observers in aircraft, to capture details of the events. One scientific challenge, then, is that effective EO monitoring will require either a range of higher-resolution sensors on geostationary satellites, or larger constellations of low-Earth-orbiting (LEO) satellites than currently exist.

Other events are far slower: eruptions can last for decades, like the current long-lived eruptions at Montserrat (1995-present), Popocatepetl (1995-present), Etna (1991-3 and 1995-present) and Kilauea (1983-present). Regional subsidence can be a slow, relentless process occurring over similar timescales. These long-lived events tax the patience of scientists, emergency managers, and the general public alike. The need for continual monitoring becomes very expensive, whether it is ground-based or uses satellite observations. Improved monitoring and archiving of long-lived events will help establish which parameters are most useful, in order to make long-term monitoring as efficient as possible.

Then there is also the issue of the long repose time between large events. Taking volcanoes as an example, about 60 of the world's 1500 potentially active volcanoes erupt in any given year. Most erupt only once a century or less frequently. Volcanoes with long repose times do not make good neighbours, however; they generally produce much larger and more dangerous eruptions when they finally awake. El Chichon (1982, repose time 600 years) and Pinatubo (1991, repose time 500 years) are recent examples of such behaviour. The population near those two volcanoes can take some comfort in the thought that it is unlikely that their volcano will erupt again in their lifetimes. However there are many such volcanoes around the world, and there is no easy way to anticipate which will be the next Pinatubo. There is a similar long repose time between extremely large earthquakes at any one location.

It is difficult, for scientists and for society, to watch for an event that may not occur for several centuries. For example, at Mt. Rainier, the USGS has installed acoustic flow detectors, to warn of life-threatening but rare large lahars, and extensive efforts have been made to ensure that the public understands the hazard and the warning system, and will respond appropriately to an alarm. But how often must the education process be repeated, to keep the population informed? How many times will the equipment need to be upgraded or completely replaced, if centuries pass before a lahar rumbles down from Mt. Rainier and justifies the whole enterprise? A similar issue exists for how best to mitigate for earthquakes that may occur once in a century or less. Perhaps the most difficult part of establishing an effective IGOS Geohazards will involve developing systems to monitor and prepare for these highly dangerous, but relatively rare, catastrophic events ■

This chapter sets out the implementation mechanism for the strategy, based on the UNESCO-IUGS Geological Applications of Remote Sensing Program. It proposes an action plan to achieve its four strategic objectives over the coming decade and the establishment of a working structure to follow the plan. The roles of key players who are committed to act are identified, including the BGS, UNESCO, ICSU, CEOS and ESA. Three, six and nine-year reviews will assess implementation of short, medium and long-term actions. Feedback will be provided to the IGOS Partners and the wider geoscience community.

IMPLEMENTATION MECHANISM

The IGOS Partnership prefers themes to be implemented using an existing mechanism and, wherever possible, one of the Global Observing Systems (Global Ocean Observing System-GOOS for the Oceans, Global Terrestrial Observing System-GTOS for Terrestrial or Global Climate Observing System-GCOS for Climate). This is designed to ensure integration, avoid duplication, reduce the need for new structures and maximise the chances of successful theme implementation. Some IGOS themes are well suited to this implementation model, like the Ocean Theme whose natural home is within GOOS. But the IGOS Geohazards does not have an obvious home of this kind. None of the existing global observing systems encompass the active, ground-based geohazards community in geological surveys, institutes, university departments, observatories and related monitoring networks adequately. Consequently, they have not been significant players in the Theme's development and they do not have the appropriate vehicles to lead its implementation. An alternative mechanism must be identified.

Two IGOS Partners, UNESCO and ICSU (through IUGS), represent the active ground-based element of the geohazards community within IGOS. They have funded a joint initiative called the Geological Applications of Remote Sensing Programme (GARS) since 1984. Its aim, on the scientific level, is to assess the value and utility of remotely sensed data for geoscience applications. At the same time, it has been building capacity by assisting institutes in developing countries to acquire and apply modern technology. GARS has been chaired by the geological surveys of France, Germany and, since September 2003, Britain, in the person of the IGOS Geohazard Theme Team Chairman. The ground-based geoscience community from other geological surveys, geoscience research institutes and academia is well represented. Over 20 years, it has run projects in Africa on geological mapping, in Latin America on landslide hazards and in Asia on volcanic hazards. It is a main sponsor of the IGOS Geohazard Theme's development.

Rather than invent a new mechanism to implement the geohazards theme, the IGOS Geohazards Theme Team proposes to transform GARS into a suitable vehicle for theme implementation. UNESCO and IUGS have given the GARS Chairman a mandate to modify the program to achieve this end. The main steps will be to secure formal involvement from the space segment and seek the representation of a wide range of scientific and applied disciplines worldwide. Space agencies with an interest in or with active programs on geohazards issues include BNSC, CNES, ESA, NASA and the Japanese Aerospace Exploration Agency (JAXA). The representative body within IGOS for these agencies, CEOS, is committed to assisting the space element of theme implementation through its Strategic Implementation Team. To support this, CEOS SIT has agreed to become associated with GARS, which will be expanded to include the interested space agencies. As a co-Chair of the IGOS Geohazards, ESA will be invited to participate in defining the shape of the new GARS Program. GARS will also strengthen its links with other relevant ICSU member communities to draw on the expertise of other scientific disciplines and will use its networks to seek worldwide representation.

ACTION PLAN 2004 - 2012

A series of short, medium and long-term actions are proposed over the coming three, six and nine years, tied into a review cycle proposed later in this chapter. Summarised in the accompanying text boxes, they are described here in the order in which they address the strategic objectives set out in Chapter 1: building capacity; improving observations, increasing integration and promoting take-up.

> Capacity building actions

None of the strategic objectives can be fully achieved without the participation of a coherent, integrated geohazards community. The development of a global coordinating mechanism to implement the strategy is the biggest challenge facing the IGOS Geohazards. The immediate priority will therefore be to establish GARS as a fit vehicle for theme implementation.

In the short term GARS will begin to foster improved international cooperation between the key players, including the representative bodies within ICSU for all affected scientific disciplines, the associations of all relevant professionals and organizations working on the geohazards in regions that have not yet played an active role in the theme. Collaboration with other themes will be explored to assess its potential for dealing with hazards, such as tsunamis, ash clouds and floods, which fall on the boundaries between the geohazards, oceans, atmospheric chemistry and water cycle themes. As the lead body for theme implementation, GARS will have several important roles. The most important will be to initiate actions, assess their outcomes and report the resulting progress on achieving its strategic objectives to the IGOS Partnership, through its lead partners UNESCO and ICSU. But it is hoped that GARS will also be in a position to help overcome the fragmentation of the geohazards community. For 20 years, GARS has worked via integrated regional initiatives on particular topics to achieve its capacity building objective. This successful model will be developed in order to support stronger participation in the IGOS Geohazards from Africa, Asia, South America and Australasia than has been possible to date. Contacts made during the IGOS Geohazards workshop, via the IGOS Geohazards website and user group and through the international peer review of this document will form the basis for this expansion. GARS will seek ongoing participation in the relevant international conference sessions that are run by IUGS, ISPRS, IGARSS, IAF, COSPAR and other international organisations on the geohazards theme.

In the medium term GARS will support curriculum development within international educational programmes run by UNESCO and organizations such as ITC in the Netherlands. It will establish regional training workshops, another successful feature of past GARS activities. These will be used to build north-south networks and so increase capacity in developing countries. In the longer term, technology transfer will follow through these networks.

> Observations and key systems actions

Significant improvements in geohazard mitigation must be supported by enhanced global observations. Initially, better use should be made of existing observations and the systems used to make them. Ultimately, operational observation will require some new satellite and ground-base observation technologies to be put in place.

The short-term priority will be to build on existing and planned systems. One way to do this is to seek the release of data already collected but not yet widely available. The most important examples where this should be achieved concern topographic data collected by the Shuttle Radar Topographic Mapping Mission and the ASTER data, which could be used to provide global topographic data at a more adequate resolution than is currently available with minimal delay. NASA and Japan's Ministry of Economy, Trade and Industry (METI) will be approached to explore how to achieve this. In order to get the maximum return out of all existing and planned observations, including C- and L-band SAR, sensors described in this report will be the subject of an early evaluation of their current or expected utility for geohazards observation. In this way, the theme's observational requirements will be subjected to an early review, documented with reference to published case studies and updated within the IGOS Partner's database. Discussions will be held with those space agencies planning missions that could provide whole or partial solutions to these requirements. At the same time, arguments will be made concerning the need for continuity of ASTER data to provide thermal infrared observations. Continuity and integration of GPS, GLONAS and GALILEO geodetic observations, and especially of C band interferometry data, will also be pursued. This is necessary in order to facilitate exploitation of the systematic data archives built up over the past 15 years.

In the medium term, the IGOS Geohazards will seek support for the development of new instruments to provide any critical, missing observations. The primary new instrument required is an L-band SAR interferometer designed for, and tasked with, the observation of deformation in three dimensions. Research that has been documented in order to demonstrate this requirement will be used in order to put forward a strong case for a dedicated L-band interferometry mission. This case will be disseminated widely and it will form the basis for discussions with CEOS, in order to assess whether a dedicated mission can be achieved. On the ground, the main effort should be directed at increasing the coverage and density of seismic networks and improving real time data transmission capabilities and accessibility. Emerging technologies such hyperspectral thermal sensors will be kept under review. In the long term, the required sensors should be launched and commissioned.

> Integration and modeling actions

Studies will be encouraged that develop an integrated approach to the geohazard issue, improve our models of these hazard's behaviour and so add to the store of knowledge underpinning geohazard mitigation.

In the short term, an evaluation will be made of the useful information products that could be created by integrating existing observations and how these can be used more widely. Liaison will be established with, and encouragement given to, projects that seek to do this. Discussions will be held with projects initiated under the Global Monitoring for Environment and Security initiative in Europe, such as TerraFirma, and as part of Earthscope in North America. A dialogue will be established with the Global Earth Observation groups concerned with data integration and information products that emerge from the EO summit series. To look at the full range of integration issues, an international project will be established on InSAR-GPS integration as a centerpiece of the IGOS Geohazards. This will demonstrate the synergy to be achieved by integration in: satellite and in-situ observations; periodic and continual measurement; areal coverage and point data; Earth Observation and geodesy; modeling and visualisation tools; and the scientific communities studying all three of the geohazards.

In the medium term, services identified by the initial evaluation that are not yet established should be developed by using existing international funding mechanisms to initiate bids from within the geohazards community. Long-term efforts will aim at coordination of all these services globally and their integration into a geohazard observation infrastructure for the monitoring and advisory agencies akin to those already developed for Oceanography and Meteorology.

> Databases and infrastructure actions

Promotion of these better ways of working requires improvements to the underlying infrastructure in order to facilitate the transfer of data, information and knowledge between different types of users in different countries. The IGOS Geohazards Theme will seek more efficient operational arrangements. Improvements in geohazards databases are a strategic goal that underpins the rest of this strategy.

Short-term action will focus on improving continuity of access to reliable remote sensing data. Actions will be taken to make the most of existing databases, addressing issues of visibility, completeness, interoperability and pricing with the agencies who maintain them. For example, an easy improvement that could be made to several EO databases would be the provision of email-based alerts to key observatories when cloud-free data are acquired over specified targets. Such improvements will be sought through discussion with those organizations that manage these databases. In a parallel action, support will be given to the design and population of the WOVO database, as an example of a dedicated geohazards database that could form the design blue print for others in the future. A dialogue will be opened with WOVO at an early stage in the IGOS Geohazards implementation process.

In the medium term, strategic datasets will be developed on which to base validated and documented case histories for each of the geohazards. These should be designed to accompany the database improvements and developments by illustrating their utility and so increasing take-up by the global geohazards community. They will be used to disseminate best practice to the international geohazards community. Improved databases will also facilitate the production of ancillary data for hazard mapping, guide systematic acquisitions over hazard-prone areas and drive new, targeted observations in times of crisis. In the longer term, the IGOS Geohazards will seek to establish equivalent databases for earthquakes, landslides and subsidence to that proposed by WOVO for volcanoes.

> Underpinning science actions

Underpinning all of this will be an integrated global geohazards science research agenda, developed and coordinated through the above mechanism and involving ICSU-IUGS, ISDR and other relevant international research organisations.

In the short term, the priority will be to establish the detail of this agenda via international consultation and to initiate flagship projects on the key elements. Emerging observations linked to poorly understood processes are one such area where significant progress can be expected. A consensus will be sought on the most appropriate observations to promote first. Candidates include gases and gravity responses to magma movements in volcanoes, electromagnetic effects of volcanoes and earthquakes and triggering mechanisms for landslides, especially those related to climate change like moisture content. A tool that requires further work to be operational, but which could be applied to the measurement of complex deformation and motion in challenging, vegetated terrains for all the geohazards, is the use of advanced forms of interferometry, including three dimensional measurements based on multiple look directions and measurements where coherence is low using active transponders. All these projects will have major significant involvement from the academic sector and are ideal candidates for associated doctorate research topics in participating universities and research institutes. But they should also include the participation of monitoring and advisory agencies to assess how such measurements could be integrated with the established routines that are used to monitor geohazards today. Ground truthing should be the focus for a significant effort here.

In the medium term, these flagship projects will be run and the results reported in peer-reviewed journals and at appropriate international conferences. In the longer term, issues requiring data continuity can be addressed. Time series measurements are required to assess the utility of several types of observation, supporting for example a thorough evaluation of the potential relationship of thermal anomalies to earthquakes.

ORGANISATION, ASSESSMENT AND FEEDBACK

The action plan described above will be organised under the modified GARS Program. Modification of the GARS program to support the implementation of the IGOS Geohazards can be achieved by changing its working group and steering committee structure so that the IGOS Geohazards is the focus of activity in the coming years and has strong representation on the committee. A series of IGOS Geohazards working groups will cover Capacity Building, Observations and Key Systems, Integration and Modeling, Databases and Infrastructure and Underpinning Science. They will be represented on, and report to, the GARS steering committee, alongside its other, existing working groups. In this way, the IGOS Geohazards can be managed as a standard, albeit dominant, activity within the GARS Program. At the same time, GARS will retain the flexibility to pursue other aspects of geological remote sensing if this is thought to be necessary by the steering committee. This committee already has representation from a mixture of geological surveys and academic institutes in both developed and developing countries. It has already run collaborative projects and workshops in the developing world including Latin America, Asia, and the Middle East. The addition of space agencies and improved balance in scientific and regional representation will be the two mains goals of the GARS re-organization.

The GARS program is required to report through IUGS to ICSU annually. The GARS Steering Committee will assess progress on the implementation of the IGOS Geohazards annually, on a schedule designed to support reporting to both ICSU, whose requirement will continue, and the IGOS Partnership. In addition, more extensive reviews will be held at approximately three, six and nine years in order to assess progress toward achieving the theme's four strategic goals. At these stages, the programme proposes to publish a formal assessment of progress and future prospects, in the form of an update to the theme report. It will also meet any further reporting requirements thought to be necessary by the IGOS partners and ICSU.

In order to support and guide the development of the Theme it is proposed to form a high level Advisory Committee. This will have representatives from all of the key users and stakeholders groups. It is expected to include the senior management of a Space Agency, a Geological Survey, a relevant Responsible Authority and a senior member of the academic community, but it will be broadened as necessary to ensure balanced representation. It will meet annually as part of the review process, providing an independent check on progress that can also be fed to the IGOS Partners during their annual plenary, accompanying the Theme's annual report.

COMMITMENTS TO ACT IN 2004

During preparation of this theme a strong Theme Team formed, whose activities covered all of the key users and stakeholders groups. Active involvement of end users in an international workshop held in March 2002, and attended by ninety people from sixteen countries, was central to the Theme's definition. The key role of scientists in monitoring and advisory agencies, as the link between the science and its application, is recognised by their membership of the Theme Team; a large group of such organizations is intimately involved in the preparation of this proposal. Several of the longest-established geological surveys are active, alongside related geoscience research institutes. The scientific user community is also well represented by active researchers in the full range of geohazards, providing links with ICSU. Key stakeholders from the remote sensing industry are also well represented by space agencies, institutes and industrial partners from the value-adding sector in several countries. The IGOS Partners are well represented, with ESA, UNESCO and ICSU primary sponsors of the Theme's development. Team members come from Asia, Europe and North America. The regions that were not so well represented in the formative stages of the theme were included during the international peer review of this document during 2003, including India, Africa, South America and Australasia.

The development of the IGOS Geohazards Theme has now been actively supported by the following organisations with staff effort and travel funds for two years:

> **Geological Surveys:** British, French, German and United States
> **Space Agencies:** European, British, Canadian and French
> **International Bodies:** UNESCO, ICSU, IUGS and GARS
> **Research Institutes:** CNR/IMAA (Italy), CNR/IRPI (Italy), CNRS/IPG-P (France), MRAC (Belgium), and RAS (Russia)
> **Private Sector:** DMT (Germany) and NPA (United Kingdom)
> **Universities:** ITC (Netherlands), Basilicata (Italy) and Bonn (Germany)

All these organizations are committed to support the implementation of the theme. The milestones set out in the original proposal have been met, demonstrating the track record of the Theme Team regarding delivery. In the longer term, they all have active programmes on geohazards research and applications projects so that they have a strong incentive to remain involved.

The co-chairs have already taken actions regarding the development of an adequate structure for the implementation of this theme beyond 2003, with the backing in place to re-shape the GARS program and to establish an ESA-funded bureau for the executive management of the IGOS Geohazards. There is an infrastructure yet in place that includes a website with the Theme documentation produced so far and an email contact mechanism, electronic file transfer facilities for the Theme Team members' work and an international contact list of interested parties ready for future dissemination and capacity building activities. Implementation will call on all these resources and commitments to ensure the maximum chance of success.

The following commitments are in place for theme implementation in 2004:

> Publication of the theme report and website update by ESA
> Establishment of an ESA-funded Bureau for the IGOS Geohazards
> Commitment of funding for its full-time staffing over the first 3 years
> International Workshop to launch the theme in the second quarter
> Modification of the GARS Program by UNESCO, IUGS and BGS
> Establishment of Working Groups, Steering and Advisory Committees

The workshop will be used to begin the integration of the geohazards community, through as wide an international participation as possible. It will guide the establishment of the various implementation structures and seek additional membership for them. In this way, the action plan set out above will be given a firm foundation and implementation will begin in earnest ■

2004

Secretariat publish Report, update website
Establish IGOS Geohazards Bureau
Hold Theme Launch Workshop
Complete the modification of GARS Program
Establish Steering Committee and Working Group

2004-2006

Capacity Building
> Cement establishment of implementation mechanism
> Regional outreach to interested parties and projects
> Participate in relevant International Conferences

Observations and Key Systems
> Seek release of SRTM/ASTER topography products
> Evaluate existing/planned sensors for geohazards
> InSAR, positioning systems, ASTER, continuity
> Update IGOS Observational Requirements database

Integration and Modeling
> Assess existing data's potential for products/services
> Establish IGOS InSAR -GPS integration project

Databases and Infrastructure
> Assess options to improve data and databases
> Liase with WOVO as a demonstrator project

Underpinning Science
> Select and initiate flagship science project(s)

2007-2012

REVIEW AND UPDATE THEME REPORT IN 2007 & 2010

Capacity Building
> Begin geohazards curriculum development
> Hold a series of Regional GARS workshops
> N-S networks and technology transfer projects

Observations and Key Systems
> Put forward case for dedicated L band InSAR
> Seek support for seismic network improvements
> Review emerging technologies (thermal, hyper)

Integration and Modeling
> Review existing services to identify gaps
> Assess requirements for service integration

Databases and Infrastructure
> Create strategic datasets and case histories on them
> Establish WOVO equivalents for other hazards

Underpinning Science
> Run science projects on key topics
> Develop a project on long time series data

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Aftershock A ground tremor caused by the repositioning of rocks after an earthquake. It may continue to occur for as long as a few years after the initial earthquake, their intensity decreases over time

Decade Volcano initiative A IAVCEI contribution to IDNDR aimed at better utilising science and emergency management to reduce the severity of natural disasters.

Earthquake A series of shock waves generated at a point (focus) within the Earth's crust or mantle.

Earthquake Magnitude A measure of the strength or energy of an earthquake as determined from seismographic information. It might be measured in the Richter scale.

Earthscope A US initiative to apply modern observational, analytical and telecommunications technologies to investigate the structure and evolution of the North American continent and the physical processes controlling earthquakes and volcanic eruptions.

GRID is a virtual supercomputer that can be harnessed to power computational research and analysis projects on a massive scale. This is achieved by combining millions of online CPUs worldwide

Ground instability Term encompassing all sizes and shapes of different failures. Mobilised material include earth or soil, debris, rock, and reef. Whereas different classifications are available in the scientific literature, with respect to the main physical mechanism, which determines ground instability, the following categories may be considered: a) Gravitational Force; b) Forces caused by Phase Changes; c) Tectonic Forces

Ground subsidence Term used for a wide variety of a sudden or gradual downward-upward with no or very little horizontal ground movements of earth. This motion might be caused by ground water withdrawal, underground storage, collapse of buried natural or man-made cavities and settlement of loose sediments. It could be considered as a gravitational motion if the phenomena related to the fluid (liquid and gas) extraction were excluded. They represent a major challenge more specifically in industrial countries due to either the exploitation of the underground resources (e.g. mines) or construction of underground facilities (e.g. subways, sewage system, tunnels) during the past two centuries.

Lahar debris flow or mudflow consisting largely of volcanic material. Lahars can be triggered during an eruption by interaction of erupting lava with snow, ice, lakes, streams or heavy rainfall, as occurred during the 1985 eruption of Nevado del Ruiz. Secondary lahars, which have occurred at Pinatubo for a decade following the 1991 eruption, can have as much impact on the surrounding area as the eruption itself. Lahars travel downstream for distances of 20-300 km, at average speeds of 10-30 km/hour. (Data from Blong, 1984).

Landslide A downward movement of masses of soil or rock material

Lava magma extruded by a volcano

Licor Infrared carbon-dioxide analyser

Plate tectonics study of the major architectural features of the Earth's crust

Pyroclastic flow Avalanches of hot ash and lava fragments, volcanic gas and air, formed during explosive eruptions or by collapse of growing lava domes. Their internal temperatures are 200-1100EC and they move at speeds of 10-100 m/sec. (Data from Blong, 1984).

Regolith Unconsolidated rock material resting on bedrock

Seismic Wave One of a series of progressive disturbances that reverberate through the Earth to transmit the energy released from an earthquake. According to their characteristics they are subdivided in: L, S and P waves

Shakemap A product of the USGS Earthquake Hazards Program in conjunction with regional seismic network operators. Shakemap Websites provide Near-Real-time maps of ground motion and shaking intensity following significant earthquakes occurred over the US.

Tephra explosion Ejection of fragmental volcanic products through the vent. Size of the products range from fine dust to massive blocks

Tsunami A gravity wave that follows a short-duration, large-scale disturbance of the free sea surface

Volcano A vent or fissure in the Earth's crust through which molten magma, hot gases and other fluids escape to the surface.

TECHNICAL ACRONYMS AND ABBREVIATIONS

AATSR Advanced Along-Track Scanning Radiometer

AHI Airborne Hyperspectral Imager

ALOS Advanced Land Observing Satellite

ASAR Advanced Synthetic Aperture Radar

ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer

ATSR Along-Track Scanning Radiometer

AVHRR Advanced Very High Resolution Radiometer

AVI Aree Vulnerate Italiane

AVIRIS Airborne Visible and Infrared Imaging Spectrometer

COSPEC Correlation Spectrometer

CTBT Comprehensive Nuclear-Test-Ban Treaty

DEM Digital Elevation Model

DEMETER Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions

DInSAR Differential SAR Interferometry

EDM Electronic Distance Measurement

EM Electro Magnetic

EMEWS European Mobile Early Warning System

ENVISAT ENVironmental SATellite

EO Earth Observation

ERS European Remote Sensing

FOS Factor Of Safety

GEOWARN Geo-spatial warning system

GIS Geographic Information System

GISSIZ Geographic Information Systems for Slope Instability Zonation

GOES Geostationary Operational Environmental Satellite

GPS Global Positioning System

HyMap Hyperspectral Mapping

IGARSS International Geoscence and Remote Sensing Symposium

InSAR SAR Interferometry

IR Infra Red

ITRS International Terrestrial Reference System

JERS Japanese Earth Resources Satellite

LEO Low-Earth-Orbiting

LiDAR Light Detection and Ranging

MERIS Medium Resolution Imaging Spectrometer

MIR Mid Infra Red

MISR Multi-Angle Imaging Spectro-Radiometer

MIVIS Multispectral Infrared and Visible Imaging Spectrometer

MODIS Moderate-Resolution Imaging Spectroradiometer

OP-FTIR Open-Path Fourier Transform Spectrometer

PALSAR Phase Array type L-band Synthetic Aperture Radar

PGA Peak Horizontal Ground Acceleration

RADARSAT RADAR SATellite

SAR Synthetic Aperture Radar

SEVIRI Scanning Enhanced Visible and Infrared Imager

SLR Satellite Laser Ranging

SMOS Soil Moisture and Ocean Salinity

SRTM Shuttle Radar Topography Mission

TIR Thermal Infra Red

TOMS Total Ozone Mapping Spectrometer

ULF Ultra Low Frequency

VALVE Volcano Analysis and Visualization Element

VLBI Very Long Baseline Interferometry

BGS British Geological Survey

BNSC British National Space Centre

CCRS Canadian Center for Remote Sensing

CEOS Committee on Earth Observation Satellites

CEREGE Centre Européen de Recherche et d'Enseignement des Géosciences

CNR Consiglio Nazionale delle Ricerche

COSPAR Commitee on Space Research

CSAV Center for the Study of Active Volcanoes

CSIRO Commonwealth Scientific & Industrial Research Organisation

DIFA Dipartimento di Ingegneria e Fisica dell'Ambiente

DINAGE Direccion Nacional de Geologia

DMSG Disaster Management Support Group

DMT Deutsche Montan Technologie

DPC Dipartimento della Protezione Civile

EC European Commission

ESA European Space Agency

ESC European Seismological Commission

FAO Food and Agriculture Organization of the United Nations

FOWG Federal Office for Water and Geology

GARS Geological Applications of Remote Sensing

GCOS Global Climate Observing System

GEO Group on Earth Observations

GEONET GPS Earth Observation NETwork

GMES Global Monitoring of Environment and Security

GOOS Global Ocean Observing System

GSI Geographic Survey Institute

GSN Global Seismic Network

GTOS Global Terrestrial Observing System

IAF International Astronautical Federation

IASPEI International Association of Seismology and Physics of the Earth's Interior

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

ICSU International Council of Scientific Unions

IDNDR International Decade For Natural Disaster Reduction

IGOS Integrated Global Observing Strategy

IGS International GPS Service

ILP International Lithosphere Program

IMAA Istituto di Metodologie per l'Analisi Ambientale

INGV Istituto Nazionale di Geofisica e Vulcanologia

IPG-P Institut de Physique du Globe de Paris

IRIS Incorporated Research Institutions for Seismology

IRPI Istituto di Ricerca per la Protezione Idrogeologica

ISDR International Strategy for Disaster Reduction

ISPRS International Society for Photogrametry and Remote Sensing

ITC International Institute for Geo-Information Science and Earth Observation

IUGG International Union of Geodesy and Geophysics

IUGS International Union of Geological Sciences

JAXA Japanese Aerospace Exploration Agency

JPL Jet Propulsion Laboratory

METI Ministry of Economy Trade and Industry

MEXT Ministry of Education, Culture, Sports, Science and Technology

MRCA Royal Museum for Central Africa

NASA National Aeronautics And Space Administration

NEIC National Earthquake Information Center

NERC Natural Environment Research Council

NOAA National Oceanic and Atmospheric Administration

NPA Nigel Press Associates

OVPF Observatoire Volcanologique du Piton de la Fournaise

RAS Russian Academy of Sciences

SCIGN Southern California Integrated GPS Network

SESWG Solid Earth Science Working Group

STEND System for Technology Exchange for Natural Disasters

TRE Tele-Rilevamento Europa

UN United Nations

UNAVCO The University NAVSTAR Consortium

UNEP United Nations Environment Program

UNESCO United Nations Educational, Scientific and Cultural Organization

USGS United States Geological Survey

VDAP Volcano Disaster Assistance Program

WMO World Meteorological Organization

WOVO World Organisation of Volcano Observatories

WSSD World Summit on Sustainable Development

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IGOS GEOHAZARDS
http://dup.esrin.esa.it/igos-geohazards

The IGOS Partners

CEOS
Committee on Earth Observation Satellites
http://www.ceos.org

FAO
Food and Agriculture Organization of the United Nations
http://www.fao.org

GCOS
Global Climate Observing System
http://www.wmo.ch/web/gcos/gcoshome.html

GOOS
Global Ocean Observing System
http://ioc.unesco.org/goos/

GOS/GAW
Global Observing System/
Global Atmosphere Watch of WMO
http://www.wmo.ch

GTOS
Global Terrestrial Observing System
http://www.fao.org/gtos/

ICSU
International Council for Science
http://www.icsu.org

IGBP
International Geosphere-Biosphere Programme
http://www.igbp.kva.se/

IGFA
International Group of Funding Agencies
for Global Change Research
http://www.igfagcr.org

IOC-UNESCO
Intergovernmental Oceanographic
Commission of UNESCO
http://ioc.unesco.org/iocweb/

UNEP
United Nations Environment Programme
http://www.unep.org

UNESCO
United Nations Educational,
Scientific and Cultural Organization
http://www.unesco.org

WCRP
World Climate Research Programme
http://www.wmo.ch/web/wcrp/wcrp-home.html

WMO
World Meteorological Organization
http://www.wmo.ch

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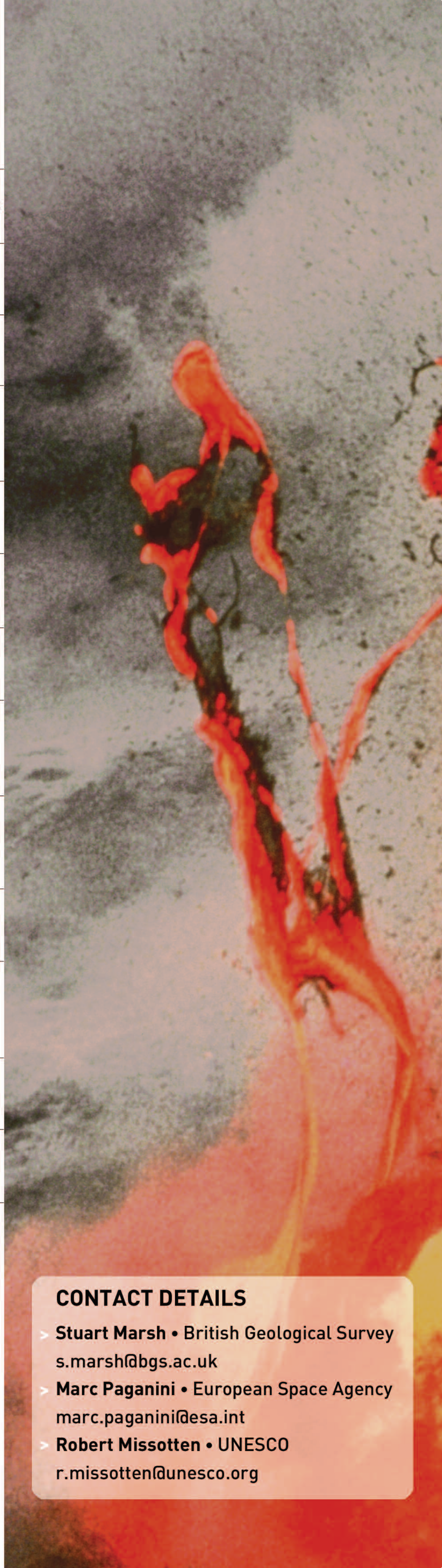

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