Following more than 30 years of seismic and volcanic quiescence, the Canary Islands region located off the northwestern coast of Africa started to show signs of seismovolcanic activity at the end of 2003 (Figure 1). In spring 2004, there was a significant increase in the number of seismic events (a mixture of volcano-tectonic events and regional earthquakes with pure volcanic events such as tremors and long-period signals) located inland on Tenerife Island.

The increase of activity in 2004 coincided with an increase of fumarolic activity at the Teide volcano on Tenerife Island, an increase in the emission of carbon dioxide in the northwestern part of the island, and changes in the gravimetric field on the northern flank of the volcano. After several seismic events had been felt by the population, the first alert level was declared by the civil protection division of the local government. This apparent reawakening of Teide, which last erupted in 1909, provides an opportunity to study from the initial stages the reactivation of this volcanic area and its related phenomena.

This article presents an automatic seismic monitoring system, the Teide Information Seismic Server (TISS), that is monitoring the internal status of the volcano by means of real-time seismic background noise analysis. The system’s main goal is to detect precursors to a potentially dangerous eruptive episode at an early stage. The system, in operation at Teide volcano since November 2004, has proven useful in monitoring changes in the behavior of the volcano’s processes, such as fumarole venting and seismic activity. These external manifestations of the volcano’s processes have been preceded by changes in the monitored parameters (see Figure 2).

A Brief History

Several eruptions have taken place in the Canary Islands in the last 500 years, all of them of the effusive type, where lava flows freely without explosive power. Teide (28.27°N, 16.6°W) is a complex stratovolcano, the third-tallest volcano on Earth from base to tip, reaching an altitude of 3717 meters above sea level and approximately 7000 meters above the adjacent seabed. Teide’s last explosive-type eruptions have been dated as having occurred around 1500 years ago. Future eruptions are considered likely and will include the risk of highly dangerous pyroclastic flows similar to those on Mount Pelée (Martinique) and Mount Vesuvius (Italy). The Teide volcano’s explosive eruptions are the result of magma mixing processes in which basaltic eruptions act as a triggering mechanism.

In 1990, the International Association of Volcanology and Chemistry of the Earth’s Interior (IAVCEI) identified Teide as being worthy of particular study in light of its history of large, destructive eruptions and its proximity to populated areas. For the present high-risk level, since 1992 Teide has been considered by the IAVCEI as one of the European Laboratory Volcanoes, thus receiving special consideration from the European Union concerning research proposals.
TEGETEIDE Project

The special topographic characteristics of the Canary Islands, combined with the distribution of the islands’ more than two million inhabitants, increase the level of volcanic risk in this area. A Teide eruption similar to the last dated explosive type eruption (with a volcanic explosivity index (VEI) of 3) and comparable with the last eruptions of Unzen Volcano in Japan could affect up to 30,000 people; a VEI of 4 could affect more than 400,000 people.

The reported increase in seismic activity that has been observed since spring 2004 could represent the beginning of a reactivation of Teide Volcano. An urgent call by the Spanish government to the Spanish National Commission on Seismic and Volcanic Risk Evaluation to organize and manage the available scientific resources to evaluate the possibility of an imminent eruption has been considered. As a result of this call, financial support for research projects on this area was provided, and in the spring of 2005, the Spanish National Research Council (CSIC) initiated the TEGETEIDE project (Geophysical and Geodetic Techniques for the Study of the Teide-Pico Active Volcanic Area).

This project will develop and implement TISS, which is capable of characterizing the predominant frequencies and the seismic energy released that is observed in the background seismic noise at diverse frequency bands. TISS is capable of monitoring in real time changes of the status of the volcano by collecting information in the time and the spectral domains, using parameters in which changes due to variations in the recorded signals are easy to observe. The goal is to detect changes before the expected episodes of activity.

TISS is based on a real-time quality-control (RT/QC) analysis of continuously-collected waveform data from seismic stations, and it monitors changes in the behavior of the seismic signals. These changes reveal variations in local site effects caused by changes in the volcanic activity. The present TISS process involves two different stages. The first stage, termed ‘data preparation,’ and the second stage, called ‘data analysis.’ The main tasks in data preparation are to build the basic data format and to provide visual Live Internet Seismic Server-like outputs (http://www.eis.org). The data analysis stage, which is devoted to waveform analysis, selects fixed-length segments from the already established database, assigns time stamps, and applies subroutines of spectral analysis.

The current RT/QC analysis was developed in 2002 to test permanent stations at the Observatori Fabra in Barcelona, Spain [Llobet et al., 2003]. Its expansion to large networks was accomplished in 2004 when an adaptation of the QC procedure was developed [Sleeman and Vila, 2006] to monitor all stations of the Virtual European Seismic Network [Van Eck et al., 2004]. Its offline application for monitoring changes in background noise near active volcanoes is presented by Vila et al. (2005), who showed that continuous monitoring of the background seismic noise levels may provide signs of activity more than 40 days sooner than classical seismological methods based on earthquake analysis.

The adaptation of TISS for the Canary Islands uses a power spectral density (PSD) estimation to perform spectral analysis of the continuously incoming data [Welsh, 1978]. TISS computes the PSD of 60-minute segments, extracted from the pool of continuous data, and stores selected parameters as time series. These time series are selected frequencies of the PSD, integrated PSD in various frequency bands (energy related parameters), and absolute maximum PSD amplitude and its corresponding frequency, also in various frequency bands. Moreover, the lower envelope of all the PSD curves (minimum value for each frequency) obtained after processing time intervals of 24 hours is tracked, thus giving an estimation of all nontransient signals during one full day of operation. This envelope contains the noise that is always present at every frequency component [Vila et al., 2005] and is continuously compared with previous days. TISS provides details of the evolution of this information by means of report plots.

The post-analysis derived time series have a sampling rate of the order of one sample per hour, determined by the length of the segments analyzed. These time series are then suitable to be compared directly with many other signals, such as deformation, temperature, and gas emission, that are sampled at similar sampling rates, thus resulting in a multidisciplinary analysis. The sampling rates of the post-analysis derived time series also allow a fast and easy representation of the volcano’s seismic activity. The time series also can be used as new input for any supplementary near-real-time analysis. This corresponds to the third level of observatory automatic procedures [ESF-EVOP Working Group, 1994].

**Evaluation of TISS During 2004**

Since first becoming operational in November 2004, TISS has shown itself to be very useful for monitoring changes in the behavior of the Teide volcano’s processes, such as fumaroles and seismic activity. For example, on 5 December 2004 a new fissure with fumarole emission appeared in La Orotava valley on the northeastern flank of Teide volcano (see Figure 2). This was preceded by a significant increase in low-frequency seismic energy nine days earlier, with a return to the normal level a few hours after the fissure aperture. During those nine days, the scientific team remained on alert.

TISS archives the original time series data in standard formats such as SEED (Standard for the Exchange of the Earthquake Data) or GSE (Group of Scientific Experts) and is thus a complete and open system that allows the data to be processed by means of standard seismological software packages. The software package runs under Linux, and all software used can be obtained through GNU and other free software sites. There are no intrinsic limitations for the number of chan-

**Fig. 2. Variations in parameters provided by TISS before and after the appearance on 5 December 2004 of the fumarole emission in La Orotava Valley:** (a) Daily lower envelope of all 60-minute PSD curves; (b) Evolution of the amplitude; (c) Predominant frequency; (d) Integrated PSD amplitude. Plots (b), (c), and (d) relates data in four frequency bands. [Eos, Vol. 87, No. 6, 7 February 2006]
The purpose of this article is to draw attention to the upper regions of the Earth's atmosphere. The source of the cathode rays is located in the upper regions of the Earth's atmosphere. The upper regions of the Earth's atmosphere are the source of the cathode rays.


The 20 to 30 years following the first International Polar Year in 1882–1883 was a period of quickly advancing knowledge and understanding of auroral phenomena. This was the time when hypotheses of aurora being due to, for example, reflections of fires from the interior of the Earth or sunlight from ice particles were abandoned and replaced by the mechanism of precipitating electrons. One of the auroral researchers at that time was the Dane Adam Frederik Wivet Paulsen (1833–1907). However, when reading literature about auroral history, his ideas and work do not seem to have attracted much interest outside his own and neighboring countries. For example, in his sweeping historical account Majestic Lights: The Aurora in Science, History, and the Arts [1980], author Robert Earther only referred to Paulsen in a couple of lines.

Eather did not mention any of Paulsen's original and still valid ideas, namely that electrical currents flowing parallel to the Earth's magnetic field exist and move upward within the auroral bands, that the aurora is produced by cathode rays (electrons), and that the source of the cathode rays is located in the upper regions of the Earth's atmosphere. The purpose of this article is to draw attention to Adam Paulsen and his contributions to the understanding of the aurora.

Paulsen and the 1882–83 Expedition to Greenland

Paulsen was born on 2 January 1833 in Nyborg, Denmark. He had planned to be an officer in the Danish army, and from 1849 to 1851 he participated in a war against Germany. However, an interest in physics changed his career path. Adam Paulsen earned a master's degree in physics in 1866 from the University of Copenhagen. He remained in Copenhagen, Denmark, and for two years later he was awarded a gold medal by the same for a prize essay on the different theories of galvanism (electricity produced by chemical processes).

After completing his university studies, Paulsen became a high school teacher in Copenhagen. In 1880, at the age of 47, he quit teaching after he was asked by the director of the Danish Meteorological Institute to head a Danish expedition to Greenland during the upcoming Polar Year. Denmark, as part of an international consortium that had pooled their resources to study the Arctic, was to conduct meteorological, geomagnetic, and auroral observations (including the shape, color, strength, movement, and position of aurorae). Paulsen, along with five other men, sailed from Copenhagen aboard the Royal Greenland Trade Department’s small three-masted sailing ship Ceres on 17 May 1882, bound for Godthaab (64°10’N, 51°40’W), a small town on the west coast of Greenland. After a four-week voyage they arrived at their destination.

The location was found favorable for auroral observations. Godthaab is located just on the poleward side of the belt of maximum auroral activity, an area advantageous for the study of the periodic variations of aurorae. The team also planned to investigate relationships between the aurora and magnetic disturbances, and to attempt to measure the height above the ground of the aurora, because such knowledge might help to disclose its causal mechanisms.

The height measurements were not successful, because the distance of about five kilometers between two observation sites on the ground was much too short for a good quality triangulation to be made. However, the study of the relation between aurora and magnetic disturbances inspired Paulsen to suggest that field-aligned currents exist. This was a milestone in auroral research.

The expedition team returned to Denmark in the autumn of 1883, and the following year Paulsen became the director of the Danish Meteorological Institute, a position he held until his death in 1907.

Paulsen’s Discoveries

In a comprehensive report about observations during the International Polar Year and the following years in Greenland, Paulsen [1893] presented, among other discoveries, observations indicating the existence and
Recent Unrest at Canary Islands’ Teide Volcano?

When a volcano that has been dormant for many centuries begins to show possible signs of reawakening, scientists and civil authorities rightly should be concerned about the possibility that the volcanic unrest might culminate in renewed eruptive activity. Such was the situation for Teide volcano, located on Tenerife in the Canary Islands, when a mild seismic swarm during April–July 2004 garnered much attention and caused public concern. However, that attention completely ignored the fact that the seismic recordings of the swarm were due to a much improved monitoring system rather than due to an actual event of alarming magnitude or extent.

It is important in any effective program of volcano-risk mitigation that the response to an apparent change in the status of a volcano should include the immediate implementation or augmentation of monitoring studies to better anticipate possible outcomes of the volcanic unrest. Equally important, emergency-management officials, using available scientific information and judgment, must take appropriate precautionary measures—including information of the populations at potential risk—while not creating unjust anxiety or alarm.

This article briefly reviews the circumstances and unfortunate societal consequences of the scientific, governmental, and media response to the seemingly heightened seismic activity on Tenerife in 2004. This article describes a series of misinterpretations of geophysical and geological data that led to raised levels of alarm on the island, although being of little actual volcanological significance.

Volcanological and Structural Evolution of Mount Teide

At 3718 meters, Mount Teide volcano is the third-highest volcanic structure on the planet and the highest peak in the Atlantic Ocean. Conversely to the intensely studied and geologically well-understood Hawaiian volcanoes, many crucial geological aspects of Teide volcano were insufficiently addressed until quite recently. As an example, only 2001, only a single radiometric age was available for the most recent activity of the Teide volcanic complex.

A joint Spanish-French project in 2001–2005 produced a detailed geological map of Teide and its northwest and northeast rifts, and provided 28 new radiocarbon ages and 26 K/Ar (potassium/argon) ages. This project completely changed the understanding of the geological and structural evolution of the Teide volcanic complex, allowing the majority of the eruptions to be separated into a stratigraphic sequence, particularly those eruptions that have occurred in the past 10,000 years (the Holocene).

The results of this study indicated that the central differentiated (phonolitic) Teide volcanic complex was the direct consequence of the activity of the rifts. The rifts developed a progressively steepening and unstable volcano at the center of Tenerife, and about 180,000–200,000 years ago rift activity triggered a massive landslide that generated an impressive horseshoe-shaped collapse embayment. The embayment’s headwall is the 17 by 10 kilometer Las Cañadas caldera. Subsequent rift and central activity progressively filled the embayment, finally building up the 3718-meter high Teide stratovolcano, which is nested in the collapse embayment. The main phase of construction of Teide concluded 30,000 years ago. Since then, the stratovolcano has erupted just once: the eighth-century summit eruption, during which the vent system and lavas increased the elevation of the volcano from about 3600 to 3718 meters.

This recent eruptive history is in stark contrast to the much higher explosivity, with frequent plinian eruptions, of the precollapse activity of the Cañadas volcano (>200,000 years ago). In the past 30,000 years, eruptions have occurred at a rate of only four to six per millennium, with a predominance (70%) of very low hazard, basaltic eruptions from fissures and cones on the rift zones, and the remaining eruptions from phonolitic lava domes with only localized explosive activity (e.g., Mña Blanca, ~2000 years ago) at the basal perimeter of the main stratovolcano.
Unrest at Teide Volcano?

The prediction of an explosive eruption in 2004 was based on reports of significantly increased earthquake activity and volcanic gas emissions. However, no major eruption followed and questions remain whether the available evidence was used in a correct and sensible way.

From 22 April to 28 July 2004, about 50 low-magnitude (M = 1–3) earthquakes were recorded in Tenerife, with most of the epicenters localized at the northwest rift zone, in the area of the Icod Valley. Only three were felt by residents. Earthquakes of this type are normal in volcanic oceanic islands (e.g., Hawaiian Islands, Reunión). In addition, moderate earthquakes (generally M < 3) have been reported in all of the Canary Islands (Figure 1). In May 1998, a bigger earthquake (M = 5.3) hit Tenerife, but television and newspaper sources notified the public that the seismic activity was not hazardous, and the event was promptly forgotten. Prior to 1998, smaller earthquakes were frequently recorded throughout the archipelago, but no volcanic activity took place since the 1971 Teneguía eruption on La Palma island.

In 2004, however, the local and international mass media were bombarded with persistent reports of unrest at Teide volcano with little to no mention of more conservative views, and predictions were made of an imminent, large-scale explosive eruption that was dubbed ‘El Volcán de Octubre’ (the ‘October Volcano’). The tourist island of Tenerife was renamed ‘Tenerife’ in the international press [Christie, 2004], and residents along the northern coast towns began sleeping fully dressed and panic-buying food and other household supplies.

Instead of providing clarifying and reassuring press communiqués, the authorities decided to raise the level of alert on the basis of a reported increase in seismicity and the emission of volcanic gases. At no time was there universally accepted scientific evidence of volcanic activity on the island, but the ‘volcanic crisis’ alert was officially maintained until February 2005, with frequent reports in the media of enormous emissions of volcanic gases, boiling of the island aquifer, movements of magma underneath the volcano, and impending explosive eruptions of Teide forecast for October 2004.

Was there any convincing evidence for this at all? The official institution responsible for monitoring seismic and volcanic activity in Spain—the Instituto Geográfico Nacional (IGN)—improved the seismic network of Tenerife in 2000. According to the IGN, the addition of new seismic stations immediately led to low-magnitude events within the island being recorded for the first time since surveillance work began in 1985 (Figure 1).

The focal depths of the majority of these events were not determined as part of the routine seismic monitoring, and therefore one of the most powerful constraints in locating the source of the seismicity was lacking. An initial interpretation of the seismicity suggested dyke emplacement at a depth of three to four kilometers. However, the majority of the epicenters were located far from the rift zone, in an area in the Icod Valley that satellite interferometry has shown to have subsided by up to 10 centimeters [Martín et al., 2006]. Groundwater has been continuously and intensively extracted in this area since the 1960s, depleting the aquifer and causing the ground to sink. Micro-sinking associated with the subsidence may well have caused seismicity. It is noteworthy that according to the interferometry study, this is the only area of recent ground deformation in Tenerife. The putative eruptive regions of Teide and Las Cañadas are completely stable.

But if the source of the seismicity is non-volcanic, what about the reported enormous increase in gas emission? Continuous, real-time monitoring of gas emissions at Teide and the rifts [Martín, 1999] provided evidence that the nearly constant total gas emission of the volcanic system (Figure 2a). Significant diurnal and seasonal variations in gas emission rates are observed [Soler et al., 2004] and linked to systematic changes in barometric pressure (Figure 2b). Therefore, if discrete measurements are taken and reported, apparent ‘significant’ increases in gas emissions can be obtained, which simply correspond to barometric pressure changes.

Nevertheless, a recent article [García et al., 2006] insists on the reawakening of Teide based on the aforementioned seismicity and volcanic gas emissions. In support of the prediction of increasing volcanic activity, these authors have cited two apparently new features: fumaroles at the summit crater of Teide and a new fumarole inside the Orotava Valley. Spectacular ‘plumes’ in the summit area of Teide (known locally as ‘la Toca del Teide’, or ‘Teide’s headdress’) are caused by strong winds and other atmospheric conditions as well as by increased fumarolic activity related to barometric pressure changes, and have frequently been cited over the centuries in ships’ logs (Figures 2c and 2d). The new ‘fumarole’ of the Orotava Valley, in turn, which gave a clear meteoric water isotopic signature, is located 50 meters from an unlined 40-meter-deep well used for the disposal of high-temperature wastes from a nearby cheese factory; suggesting a rather more simple explanation for the origin of this particular vapor exhalation site [Carracedo et al., 2006].

It would thus seem that the prediction of an imminent volcanic eruption at Teide was and is lacking hard scientific evidence, and its dramatic presentation by the media was not only
unnecessarily damaging to the tourism-based economy of the island industry, but also caused undue anxiety and hardships for citizens coping with the alarmist forecasts (Note, none of the authors is in any form associated with the tourism industry anywhere).

Effective and reliable communications must be established among scientists, government officials, the news media, and the populace affected, and must be tried and tested before an actual crisis. This is an essential step in restoring the credibility of the scientists and civil authorities, so that they working together, will be much better positioned to respond adequately to a potential genuine volcanic crisis at Teide.

Acknowledgments

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Refocusing NASA Planetary Science Funding

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NASA should invest more money in data analysis for its planetary science missions, even if it means delaying or canceling a future mission, members of the science committee of the NASA Advisory Council (NAC) suggested at a 12 October meeting.

Science committee member Mark Robinson, director of the Center for Planetary Sciences at Northwestern University in Chicago, Ill., said that large amounts of data from NASA planetary science missions are accumulating, and the funds for data analysis often are inadequate to properly analyze all of it. For example, there is a large amount of currently unanalyzed Mars data that could be used in planning for the Mars Science Laboratory (expected to launch in 2009), and particularly for site selection. This includes data from the recently arrived Mars Reconnaissance Orbiter, which is likely to send more data to Earth in its first year than has been collected by all previous Mars missions combined.

Science committee member Alan Stern, executive director of the Space Science and Engineering Division of the Southwest Research Institute in San Antonio, Tex., explained that missions need to have more research and analysis (R&A) funds attached to them from the beginning. As a comparison, in the field of astrophysics, researchers who are awarded observing time with the Hubble Space Telescope also are provided funds for analyzing the data and publishing results. In planetary missions, the data usually are certified and archived, but very little of it is properly analyzed and transformed into scientific results, he said.

"This is really an issue of getting our value for the dollar. We spend hundreds of millions, sometimes billions, [of dollars] on these planetary missions, and very little of the data is ever looked at," Stern said. "I think that it is the sense of the planetary [science] community that skipping a future mission to solve this problem would be worth it," he said.

Mary Cleave, associate administrator for NASA's Science Mission Directorate, said that the agency has been trying to maintain an opportunity for launching a mission to Mars every 26 months. The agency could skip one of these launch opportunities and put more money into R&A, but it needs guidance from the NAC, she said.

NAC Chair Harrison Schmidt asked Robinson to draw up a formal recommendation emphasizing the need for NASA to provide funds for data analysis for these missions. The council could consider the recommendation at its next meeting in February 2007.

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Author Information

Juan Carlos Carracedo, Estación Volcanológica de Canarias, Consejo Superior de Investigaciones Científicas (CSIC), La Laguna, Tenerife, Spain; Email: jccarracedo@ipna.csic.es; Valentín R. Troll, Department of Geology, Trinity College, Dublin, Ireland; Francisco J. Pérez-Torrado, Departamento Física-Geología, Universidad de Las Palmas de Gran Canaria, Spain; Eduardo Rodríguez-Badiola, Departamento de Geología, Museo Nacional de Ciencias Naturales, CSIC, Madrid, Spain; Alex Hansen Machín, Departamento de Geografía, Universidad de Las Palmas de Gran Canaria; Raphael Paris, Maison de la Recherche, Centre National de Recherche Scientifique (CNRS), Clermont-Ferrand, France; and Hervé Guillou and Stéphane Scaillet, Laboratoire des Sciences du Climat et de l’Environnement, Comision Energetique Atomique, CNRS, Paris, France.

Another issue that could be addressed by the NAC in February, following initial discussion at the October meeting, is the future availability of rockets for small- and medium-sized science missions.

Science committee member Neil DeGrasse Tyson, director of the Hayden Planetarium at the American Museum of Natural History in New York, N.Y., noted that the marketplace for these rockets has diminished, and that this could threaten the ability of NASA to obtain them on time and in needed quantities. He suggested that the NASA administrator should discuss with other federal agencies the potential for using other types of rockets as launch vehicles for NASA science missions.

Science Committee Chair Edward David, Jr., president of EED, Inc., and a former presidential science advisor, said that “it is important that the whole NAC continues to monitor the situation and make suggestions how to address the shortage of access.” Schmidt noted that there are many other potential launch systems available and in use by other federal agencies, particularly the U.S. Department of Defense.

David also told the NAC that the science committee needed a member with expertise in Earth science, citing the departure of former committee chair Charles Kennel. Schmidt said that he hoped such an appointment would be made by the NASA administrator within the next few weeks. Kennel was one of three science committee members who resigned in August and were replaced the next month (see Eos 87(40), 2006).

—SARAH ZIELINSKI, Staff Writer
Successful communication between scientists, officials, media, and the public is imperative during a volcanic crisis. Misunderstanding can lead to confusion and distrust, and it ultimately can transform an emergency into a disaster.


- Ensuring effective communication and appropriate understanding of information within and between groups managing the crisis.
- Disseminating only one clear and consistent message—the one established by the officials in charge.
- Building trust among participants and the public through unanimous support of official decisions, maintaining the credibility of all groups and individuals involved in the crisis, and being responsible and honest with media by keeping them informed of all facts and any changes in the situation.

However, during the 2004–2005 seismic crisis on the Canary Island of Tenerife (see “Monitoring the reawakening of Canary Islands’ Teide volcano,” by A. García et al., Eos Trans. AGU, 87(6), 61, 2006), scientists did not always follow this protocol, and confusion and occasional panic within the population ensued (see “Recent unrest at Canary Islands’ Teide volcano?”, by J.C. Carracedo et al., Eos Trans. AGU, 87(43), 2006). The island is volcanically active, and the most recent eruption took place in 1909. In 2004, scientists working on the island interpreted observed changes in geochemistry and seismicity as being of volcanic origin, which led to the creation of an official scientific committee to forecast the likely evolution of the crisis and to assess different possible scenarios.

At the beginning of the crisis, the flow of information was constrained to the monitoring scientists and civil authorities. When the general population felt three earthquakes, the scientific committee deemed it necessary to communicate the nature of the crisis to the public. As the media pressed for news, scientists involved in the official committee, and some who were not involved, volunteered their views on potential scenarios, including improbable catastrophic ones that made headlines. This information contradicted the official ‘call to calm’ and caused confusion among the public. Although the head of the official committee tried to clarify the situation, the official scientific team was continually criticized by scientists not involved in the management of the crisis, some of whom had rejected the offer to become a part of the official team.

While the crisis in Tenerife did not result in an eruption, it is vital to learn from it lessons about scientific communications and relations, specifically during volcanic crises. While volcanic areas host many competent experts, during times of crisis responsible scientists should never volunteer their personal forecasts and opinions to the media and should support the decisions taken by the civil authorities and the official scientific group. Differences of opinion among scientists are expected, and dialogue and discussion should be encouraged. However, this should be conducted out of the public eye. Before a crisis, encouraging open dialogue between the parties involved to agree to a protocol of communication can prevent a future recurrence of the situation encountered on Tenerife.

—CARMEN SOLANA and CLAIRE SPILLER, School of Earth and Environmental Sciences, University of Portsmouth, Portsmouth, UK; Email: Carmen.solana@port.ac.uk
Feature

Seismicity and gas emissions on Tenerife: a real cause for alarm?

In recent months the media has been drawing attention to the possibility of a dangerous eruption of the Teide Volcano on Tenerife in the Canary Islands. Before accepting this prediction, which may well be detrimental to the tourist-based economy of the island, it would be wise to examine the evidence on which it is based.

Teide has long been recognized as a significant volcano. At 3718 m above sea level, it is the third highest volcanic structure on the planet (Fig. 1), after Mauna Loa and Mauna Kea in the Hawaiian Islands, and early drew the attention of renowned scientists such as Leopold von Buch and Alexander von Humboldt. Regrettably this interest was not sustained into the twentieth century; whilst Hawaii attracted intense study, geological investigations of Teide’s history languished. For example, hundreds of radiocarbon age determinations have allowed for a precise reconstruction of the Hawaiian volcanic history, but until 2001 only one single radiometric age was available for Teide volcano. With no regular recordings, evidence of historic seismic and volcanic activity has only been by word of mouth.

The situation changed in 2001 when a five-year, joint Spanish–French research project began; a project which produced a detailed geological map of Teide and the NW and NE rifts (Fig. 2), petrographic analysis of numerous samples, and radiometric studies, which produced 28 new radiocarbon ages and 26 new K/Ar ages.

This project completely changed our understanding of the geological and structural evolution of the Teide volcanic complex, and identified the sequence of eruptions that had occurred in the last 10 000 years. For example, one eruption of historic significance was that of 24 August 1492, which Christopher Columbus reported as ‘a big fire in the sierra of Tenerife... similar to those of Mount Etna in Sicily’. It seems it was not a summit eruption of Teide; a radiocarbon age from an eruption of the Boca Cangrejo cinder cone (Crab’s Mouth cone), located in the NW Rift, is in close agreement with this historic date. It had been believed that the ‘Columbus eruption’ was the final summit eruption of Teide, but the new radiometric data now shows that eruption to have been much older, 1140 ± 60 years before present, i.e. in the eighth century AD.

One of the interesting features this study has revealed is that the Teide central volcanic complex was a direct consequence of the activity of the rifts. The rifts developed a progressively steepening, unstable volcano at the centre of the island, and about 180–200 000 years ago triggered a massive landslide that generated the impressive horseshoe-shaped collapse embayment, whose headwall is the

Fig. 1. View of Teide volcano from the north east.
famous 17 × 10 km Las Cañadas caldera (Fig. 3). Following this, further rift and central activity progressively filled the embayment and built up the 3718 m-high Teide stratovolcano, nested in the collapse embayment (Fig. 4). The main phase of construction ended 30 000 years ago, since when the stratovolcano has erupted only once. That eruption was the eighth century AD summit eruption, which raised the volcano from a height of 3600 m to its present 3718 m.

This recent eruptive history is in stark contrast to the pre-collapse activity of the Cañadas volcano, which was much more explosive, with frequent plinian eruptions that generated extensive ash flows and ash falls. In the last 30 000 years, eruptions have occurred at a rate of only 4–6 per millennium, the majority (70 per cent) being low-hazard basaltic eruptions from fissure and cones on the rift zones, and the others producing phonolitic lava-domes with only very localized explosive activity (Fig. 5), as for example Mña Blanca, around 2000 years old, which is situated at the foot of the main stratovolcano.

It can be seen from the results of the study that in the present phase of the island’s volcanic activity there appears to be little risk of major volcanic hazards, with any eruptions likely to pose only very localized threats to the inhabitants of Tenerife or to visitors to the Teide National Park (about 4.5 million annually). Why then are there dire predictions of volcanic catastrophe (Fig. 6)?
Unrest at Teide volcano?

The prediction of an explosive eruption seems to be based on reports of significantly increased earthquake activity and volcanic gas emissions. But is this evidence correct, and does it imply an imminent violent eruption?

From 22 April to 28 July 2004, about 50 low-magnitude (1 to 3) earthquakes were recorded in Tenerife, with most of the epicentres localized on the NW rift zone in the area of the Icod Valley. Only three were actually felt by residents. This frequency is nothing special, such earthquakes are normal in volcanic oceanic islands; about 10,000 are recorded annually in Hawaii, of which only 1,200 are greater than magnitude 3. Low magnitude earthquakes (generally less than magnitude 3) have been recorded in all the Canary Islands. In May 1998 a bigger quake (magnitude 5.3) hit Tenerife, but a hazard-disclaiming statement was published in the media and the event promptly forgotten.

So why, in 2004, were the local and international mass media bombarded with persistent reports of unrest at Teide volcano, and predictions made of an imminent, large-scale explosive eruption that became dubbed ‘El Volcán de Octubre’ (October Volcano)? The publicity had such a bad effect that Tenerife was nick-named ‘Terrorife’ and residents along the northern coast in the towns of Icod, Garachico, etc., began sleeping fully dressed and panic-buying food and other household supplies. Some even sold their houses! Evacuation instructions were given in schools and hospitals, and gas masks, power generators and other supplies were stockpiled in public buildings.

The situation was made even worse by the authorities who, instead of clarifying the situation, raised the level of alert apparently only on the basis of what was reported as an increase in seismicity and the emission of volcanic gases. However, at no time was there any universally accepted scientific evidence of actual volcanic activity on the island. The ‘volcanic crisis’ alert was officially maintained until February 2005, with frequent reports in the media of enormous emissions of volcanic gases, boiling of the island aquifer, presumably from raised volcanic temperatures, movements of magma underneath the volcano and an explosive eruption forecast for October 2004.

Fig. 4. Teide volcano nested in the Las Cañadas caldera. Image by NASA.

Was there really any convincing evidence for any of this?

Firstly, consider the seismicity. Prior to 2000 there were only two seismic stations on Tenerife, both at the far north-eastern end of the island. In that year a third station was deployed inside the Caldera de Las Cañadas, and immediately low-magnitude events within the island began to be recorded for the first time since surveillance began in 1985. Unfortunately the focal depths of these events were not determined, thus depriving observers of one of the most powerful constraints on locating the source of the seismicity. In the initial reports, the activity was interpreted as being due to dyke emplacement at a depth of 3–4 km. However, it is possible that a number of the events may have had a non-volcanic origin, such as traffic or explosions made during the excavation of water tunnels for groundwater mining.

The majority of the epicentres were located far from the rift zone, in an area in the Icod Valley which satellite interferometry has shown to have subsided by up to 10 cm. Groundwater has been continuously and intensively extracted in this area since the 1960s, depleting the aquifer and causing the ground to sink. Microfaulting associated with the subsidence may well have caused seismicity. It is noteworthy that according to the interferometry study this is the only area of recent ground deformation in Tenerife. The putative eruptive region of Teide and Las Cañadas is completely stable.

Fig. 5. Geological map of Teide’s peripheral phonolitic domes.
Continuous real-time monitoring of gas emissions at Teide and in the rifts, reported in 1999, gave evidence of a nearly constant total gas emission from the volcanic system. On a day-to-day basis, local emissions may vary and significant diurnal and seasonal variations in gas emission rates do apparently relate directly to systematic changes in barometric pressure. If spot measurements are taken in periods of low barometric pressure, they can show an apparent ‘significant’ increase in emissions. In 2004, shortly before the predicted October eruption, a visit to the summit crater of Teide, (in which both of us took part), did not reveal any fumarolic activity at all.

In support of the prediction of increasing volcanic activity, observers have cited two apparently new features: fumaroles at the summit crater of Teide and a new fumarole inside the Orotrava Valley. In fact spectacular ‘plumes’ are commonly seen in the summit area of Teide and are known locally as ‘la Toca del Teide’ or ‘Teide’s head-dress’ (Fig. 7). These are caused by atmospheric conditions as well as by increases in fumarolic activity related to barometric pressure changes and have frequently been cited over the centuries in ship’s logs. They are in no way unusual for the volcano. The new ‘fumarole’ in the Orotrava Valley probably has a quite different explanation. Its water isotope signature is clearly phreatic, not volcanic, and it is located 50 m from an unlined 40 m-deep well used for the disposal of high-temperature wastes from a nearby cheese factory.

It would thus seem that the prediction of an imminent volcanic eruption at Teide is based on distinctly flimsy and dubious evidence, and its dramatic presentation by the media is not only unnecessarily damaging to the tourism-based economy of the island, but also to the credibility of responsible scientists, the true value of which will be crucial for the correct management of any future genuine volcanic crisis.

Suggestions for further reading


New evidence for the reawakening of Teide volcano

J. Gottsmann,1,2 L. Wooller,3 J. Martí,1 J. Fernández,4 A. G. Camacho,4 P. J. Gonzalez,4,5 A. García,6 and H. Rymer3

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[1] Geophysical signals accompanying the reactivation of a volcano after a period of quiescence must be evaluated as potential precursors to impending eruption. Here we report on the reactivation of the central volcanic complex of Tenerife, Spain, in spring 2004 and present gravity change maps constructed by time-lapse microgravity measurements taken between May 2004 and July 2005. The gravity changes indicate that the recent reactivation after almost a century of inactivity was accompanied by a sub-surface mass addition, yet we did not detect widespread surface deformation. We find that the causative source was evolving in space and time and infer fluid migration at depth as the most likely cause for mass increase. Our results demonstrate that, even in the presence of previous baseline data and ground deformation, microgravity measurements early in developing crises provide crucial insight into the dynamic changes beneath a volcano. Citation: Gottsmann, J., L. Wooller, J. Martí, J. Fernández, A. G. Camacho, P. J. Gonzalez, A. García, and H. Rymer (2006), New evidence for the reawakening of Teide volcano, Geophys. Res. Lett., 33, L20311, doi:10.1029/2006GL027523.

1. Introduction

[2] Anomalous geophysical signals at dormant volcanoes, or those undergoing a period of quiescence, need to be evaluated as potential precursors to reawakening and possible eruption [White, 1996]. There are several recent examples of volcanic re-activation after long repose intervals culminating in explosive eruption [Nakada and Fujii, 1993; Robertson et al., 2000], but non-eruptive behaviour is equally documented [De Natale et al., 1991; Newhall and Dzurisin, 1988]. The dilemma scientists are confronted with is how to assess future behaviour and to forecast the likelihood of an eruption at a reawakening volcano, when critical geophysical data from previous activity is missing due to long repose periods. In Spring 2004, almost a century after the last eruption on the island, a significant increase in the number of seismic events located inland on the volcanic island of Tenerife (Figure 1) marked the reawakening of the central volcanic complex (CVC), the third-highest volcanic complex on Earth rising almost 7000 m from the surrounding seafloor [García et al., 2006]. The increase in onshore seismicity, including five felt earthquakes, coincided with both an increase in diffuse emission of carbon dioxide along a zone known as the Santiago Rift [Pérez et al., 2005] and increased fumarolic activity at the summit of the 3718 m high Teide volcano [García et al., 2006].

2. Integrated Geodetic Network on Tenerife

[1] As a reaction to the developing crises, we installed the first joint ground deformation/microgravity network on the island in early May 2004, two weeks after the start of increased seismicity. The network consists of 14 benchmarks, which were positioned to provide coverage of a rather large area (~500 km$^2$) of the CVC, including the Pico Viejo-Pico Teide complex (PV-PT), the Las Cañadas caldera (LCC) as well as the Santiago Rift (SR) (Figures 1 and 2). The network was designed to meet rapid response requirements, i.e., the network can be fully occupied to a precision of less than 0.01 mGals of individual gravity readings and less than 0.04 m in positioning errors within six working days despite the frequently rugged terrain. The first reoccupation of the network was performed in July 2004, followed by campaigns in April 2005 and July 2005. Benchmark locations and cumulative ground deformation and gravity changes between May 2004 and July 2005 are given in Table 1 in the auxiliary material.1 All results are given with respect to a reference located south of the LCC (benchmark LAJA). Within the average precision of benchmark elevation measurements (±0.03 m), using two dual-frequency GPS receivers during each campaign, we did not observe widespread ground deformation. However, between May 2004 and July 2005, four benchmarks, two located in the eastern sector of the LCC (MAJU and RAJA), one marking the northern-most end of the network and also the lowest elevation (766 m; CLV1) and finally a benchmark located on an isolated rock spur on the western LCC rim (UCAN, supporting online material) did show ground uplift above measurement precision. Residual gravity changes (corrected for the theoretical Free-Air effect), observed during the May–July 2004, May 2004–April 2005, and May 2004–July 2005 periods are listed in the supporting online material and shown in Figure 2.

3. Results

[4] The observed gravity changes do not fit a simple symmetrical pattern as observed, for example, during cal-

Following the same rationale, perspective view of Tenerife island located in (GOTTSMANN ET AL.: NEW EVIDENCE FOR REAWAKENING TEIDE VOLCANO/C176 Las Canadas caldera. Black rectangle identifies the area covered by the joint GPS/gravity network. LCC indicates the location of the open squares indicate epicentres of seismic events recorded only slightly higher than the precision level (±0.015 mGal where cumulative changes over the 14-month period where observed in the central and eastern depression of the LCC, distribution of gravity changes across the area under investigation is asymmetrical. The smallest gravity changes were observed in the central and eastern depression of the LCC, where cumulative changes over the 14-month period where only slightly higher than the precision level (±0.015 mGal on average; 1 mGal = 10 μm/s²). A marked positive gravity anomaly, with a maximum amplitude of around 0.04 mGal, developed in the Northwest of the covered area between May 2004 and July 2004, while a negative anomaly was found to the east, centered on station MIRA. The gravity increase noted between the first two campaigns (benchmarks C774 and CLV1) was followed by a decrease sometime between July 2004 and April 2005. During the same period, a N-S trending positive anomaly appears northwest of the PV-PT summit area between, reaching the western part of the LCC (Figures 2a–2b). In addition, gravity increased significantly along the northern slopes of Pico Teide, including benchmarks TORR and FUEN located close to the La Orotava valley between July 2004 and April 2005, adding to the impression of a spatio-temporal evolution of the causative source. It is interesting to note that on 5 December 2004 a new fissure with fumarole emission appeared in the Orotava valley (further information available at http://www.iter.es). A gas plume emanating from the summit fumaroles of Pico Teide was particularly noticeable during October 2004 [Garcia et al., 2006], between surveys 2 and 3. In summary, significant gravity changes occurred mainly across the northern flanks of the PV-PT and along a ca. 6 km wide zone along the western side of the volcanic complex into the westernmost parts of the LCC between May 2004 and July 2005 (Figure 2c). During the same time, a marked gravity decrease was recorded at the intersection of the Orotava Valley (OV) and the LCC (Figure 2c).

4. Effect of Water Table Fluctuations

Data from two drill holes, located in the eastern half of the LCC (Figure 2d), provide information on water table fluctuations during the period of interest. A drop of ca. 5 cm/month between surveys 1 and 4 was recorded in one drill hole located close to benchmarks 3RDB and MAJU, which is similar to the average monthly drop in water level due anthropogenic extraction over the past 3 years [Farruigia et al., 2004]. Water levels decreased by 22 cm/month on average between February 2000 and January 2004 in a drill hole located close to benchmark MIRA. The gravity decrease of 0.025 mGal recorded between May 2004 and July 2005 at benchmark MIRA, located at the intersection of the Las Cañadas caldera and the Orotava valley, can be explained by a net water table decrease (δh) of 3 m, consistent with this earlier trend, assuming a permeable rock void space (ρ) of 20% and a water density (ρ) of 1000 kg/m³ (Δgw = 2πρgρδh) [Battaglia et al., 2003]. Following the same rationale, gravity changes at 3RDB and MAJU are corrected by −0.008 mGal to account for the recorded water table fall in the nearby borehole. Hence, any gravity change observed within the central and eastern parts of the LCC (3RDB, MAJU, RAJA, MIRA) can be fully attributed to changes in (shallow) groundwater levels and we treat the net mass change as zero for this area in the computation of overall mass changes in the following sections (Figure 2d).

5. Interpretation

The coincidence of earthquake epicenter concentration (a mixture of volcano-tectonic events and regional earthquakes with pure volcanic events such as tremors and long-period signals) in the area of gravity change over the same time period (Figure 2d), suggests that both signals are related to the same or linked phenomena. Unfortunately, precise data on earthquake hypocentres are not available, but a semi-qualitative analysis suggests a depth of several kilometres (R. Ortiz, personal communication, 2005). The...
spatial coverage of the benchmarks does not allow the wavelength of the May 2004–July 2005 gravity anomaly to be assessed precisely. In particular, the lower limit of the wavelength along the northern slopes of the PV-PT complex cannot be unambiguously retrieved on the basis of the available data. The maximum wavelength of the gravity anomaly is on the order of 17 km if defined by both observed and interpolated (kriging) data (Figure 2d) on the northern slopes of the PV-PT complex, which implies a maximum source depth of between 2.5 to 5.2 km below the surface, assuming simple axisymmetrical source geometries [Telford et al., 1990]. This would place the source to within the depth of the shallow magma reservoirs beneath the PV-PT complex believed to host chemically evolved magma [Ablay et al., 1998]. However, since the positive anomaly is only defined by four benchmarks (CLV1, C774, CRUC, and TORR) its actual wavelength could be smaller than 17 km and the source depth could be shallower than inferred above. Furthermore, ambiguities remain on the actual amplitude of the anomaly, which is defined only by data observed at CRUC. The continuation of the positive anomaly in the western part of the LCC (Figure 2c) shows a shorter wavelength indicating a shallow (few km deep) source.

Due to the spatial separation of benchmarks an assessment of sub-surface mass addition is greatly biased
on the selection of the area affected by gravity increases. We define a maximum area by a kriging-based interpolation of the gravity changes between May 2004 and July 2005 in the northern and western parts of the CVC. A Gaussian Quad-rature integration over this area gives a mass addition of $1.1 \times 10^{11}$ kg, with lower and upper 95% confidence bounds of $8.4 \times 10^9$ kg and $2.0 \times 10^{11}$ kg, respectively. These values should be regarded as maximum values.

In theory, subsurface volume changes derived from ground deformation data can be correlated to sub-surface mass changes from gravity data to infer the density of the causative source. However, in the absence of significant surface deformation, the source density cannot be determined directly and the nature of the source remains ambiguous. However, three scenarios are worth considering when assessing causative processes for the observed gravity increase: (1) arrival of new magma at depth, (2) migration of hydrothermal fluids, and (3) a hybrid of both. Volcanic eruptions of the CVC over the past few centuries were dominantly fed by basic and intermediate magmas in the form of fissure eruptions along the Santiago Rift [Ablay and Marti, 2000], implying shallow dyke emplacement along this NW-SE trending extension zone. The observed gravity increase between May 2004 and April 2005 (Figure 2) appears to denote a zone at a 45° angle to the strike of the rift. The wavelength of the anomaly in the western and central parts of the LCC (Figure 2d) is not consistent with shallow dyke emplacement to perhaps within a few tens or hundred meters depth. There is also no other direct geophysical or geochemical evidence in support of magma emplacement in the form of a shallow dyke over the 14-month observation time. However, dyke emplacement at greater depth (a few km below the surface) into the Santiago Rift (with partial contribution to the gravity increases at benchmarks CLAV1, C774 and CRUC), perhaps recharging an existing reservoir, cannot be unambiguously excluded for the period May–July 2004, coinciding with the peak in the number of earthquakes recorded by the National Geographic Institute (available at http://www.ign.es). Dykes along the Santiago Rift are on average less than 1 m wide. Ground deformation caused by an individual dyke of this size a few km below the surface would be below the precision of our GPS measurements. Thus, a magma injection into a conjugated fault system, perhaps at some angle to the Santiago Rift, cannot be unambiguously ruled out as the trigger for the reawakening of the volcanic complex in May 2004. There is, however, little evidence to support the idea that the mass increase observed during campaigns 2 and 3 is caused solely by magma movement.

An alternative explanation for the observed gravity increase is fluid migration through the CVC. Volcanotectonic events detected in the seismic record [García et al., 2006; Tárraga et al., 2006] may have triggered the release and upward migration of hydrothermal fluids from a deep magma reservoir. Alternatively, fluid migration may have resulted from (1) the perturbation of an existing deep hydrothermal reservoir and resultant upward movement of fluids due to magma injection or (2) from pressurising seawater saturated rocks.

Migration of hydrothermal fluids through a permeable medium causes little surface deformation, but the filling of pore space increases the bulk density of the material resulting in a gravity increase at the ground surface. To explore this scenario, and as a first order approximation, we performed a inversion of the gravity change recorded between May 2004 and July 2005 along the northern and western slopes of the PV-PT complex for a source represented by a N-S striking infinite cylindrical horizontal body [Telford et al., 1990]. The approximation of an infinite body is valid as long as the radius of the cylinder is far smaller than its length. The model results depend linearly on density change but non-linearly on both the radius and depth of the body. Using a global optimization iterative method [Sen and Stoffa, 1995] with various initial values for depth and
radius, we find convergence of the inversion results at a depth of 1990 ± 120 m below the surface using residual gravity data from all benchmarks. While depth is insensitive to the assumed source density change, the radius scales to the inverse of density. Assuming a volume fraction of 30% which is fully permeable, filling this void space with (hydrothermal) fluids of density 1000 kg/m³ produces a bulk density increase of 0.3 kg/m³. The resultant source radius is around 80 ± 20 m. Although the fit to the data is within errors very good (Figure 3), we find that the positive anomaly in the eastern part of the LCC cannot be satisfyingly modelled. For this area, we conclude on either a local effect or, more likely, an error in the GPS measurements during the installation of benchmark RAJA, since the reported gravity increase results from the free-air effect of the 7 ± 4 cm inflation detected over the 14 months period. Ignoring the potentially erroneous GPS measurement, the gravity residual for RAJA matches those of neighbouring benchmarks MAJU and 3RDB. Combining all available geophysical information, we conclude that migration of hydrothermal fluids along a permeable N-S striking zone is the most likely cause of the observed perturbation of the gravity field. A conceptual model of mass migration covering the 14-month observation period is shown in Figure 4.

6. Conclusions

While magma recharge at depth into the northwestern rift zone of Tenerife is likely to have triggered the reawakening of the CVC, the cause of the 14-month perturbation of the gravity field is most probably not related to magma flow. A more likely scenario is the migration of fluids inside the complex triggering the observed gravity changes.

We demonstrate that time-lapse microgravity monitoring of active volcanoes can provide vital insights into their sub-surface dynamics, particularly where structural complexities and heterogeneous mechanical properties of the subsurface do not obey a simple linearly elastic relationship of stress generation and resultant ground deformation [Dvorak and Dzurisin, 1997]. Arrival of a small batch of magma at depth and the release and upward migration of hot fluids may be a common trigger of reactivation after long repose periods and may be quantifiable by perturbations in the gravity field but may not be accompanied by ground deformation. Quantification of sub-surface mass/ density changes must be regarded as essential for the detection of potential pre-eruptive signals at reawakening volcanoes before ground deformation or other geophysical signals become quantifiable [Rymer, 1994].

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J. Gottsmann, Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, UK. (j.gottsmann@bristol.ac.uk)

H. Rymer and L. Wooller, Department of Earth Sciences, Open University, Walton Hall, Milton Keynes MK7 6AA, UK.

J. Martí, Institute of Earth Sciences “Jaume Almera,” CSIC, Lluís Solé Sabaris s/n, Barcelona 08028, Spain.


A. García, Department of Volcanology, Museo Nacional de Ciencias Naturales, CSIC, C/José Gutiérrez Abascal, 2, 28006 Madrid, Spain.