Remote sensing of volcanoes and volcanic processes: integrating observation and modelling – introduction

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Volcanoes are often remote, and have footprints that may extend across many hundreds or thousands of square kilometres. They are generally inaccessible during eruption, and may continue to be inaccessible for extended periods of time after eruption, while their products can be scattered or dispersed over regional or global scales. Consequently, since direct measurement can only provide us with part of the picture of many volcanic processes, remote sensing is now playing an increasingly important role in advancing understanding of the science underlying volcanic behaviour, on this planet and beyond (e.g. Mouginis-Mark *et al.* 2000; Sparks *et al.* 2012). Satellite, airborne and ground-based remote sensing are increasingly vital tools for monitoring active or potentially active volcanoes, and assessing their likely, real-time or time-averaged impact (Fig. 1). At the same time, the synoptic-scale surveys that are often well suited to remote-sensing techniques allow us to address questions about the fundamental processes that control volcano behaviour in a way that is not necessarily possible from individual case studies. New research is often driven by technological advancements in the development of novel sensors or launching of new platforms, meaning that the space agencies are increasingly involved in identifying scientific questions and priorities (e.g. Ferruci *et al.* 2012).

Multiple and complementary data streams are increasingly being used both to monitor active volcanoes and advance volcanological science. The key geophysical parameters that comprise monitoring data streams typically include the categories of (i) seismicity, (ii) surface deformation, (iii) thermal measurements and (iv) gas flux and composition data as major components. While measurements of seismicity remain the domain of ground-based seismometers, remote-sensing techniques have made major contributions in each of the others. This Special Publication volume is concerned with the use of remote sensing at volcanoes. It is split into three parts, roughly arranged from the subsurface, to the surface, and then further afield as volcanic products are injected and dispersed into the atmosphere. The papers span a range of applications of remote-sensing techniques to monitor and understand (a) surface deformation, (b) surface thermal anomalies and (c) gas fluxes, as well as tracking ash and gas plumes from eruptions to gain insights into the extent of a volcano's impacts. Volcanology is driven, in part, by the operational concerns surrounding volcano monitoring and hazard and crisis management but the goal of volcanological science is, at its heart, to understand the processes that underlie volcanic activity. This Special Publication is also concerned with how we go from observations to this deeper understanding, including the progress that can be made by integrating observations and modelling. While this volume focuses mainly on satellite-based remote sensing, integrating datasets from different platforms is also of vital importance, and so papers on airborne remote sensing and measurement from both manned and unmanned aircraft are also included.

Historical perspective

Systematic volcano monitoring began in 1841 with the completion of the Osservatorio Vesuviano, on the flanks of Mt Vesuvius in Italy. Subsequently, observatories and monitoring networks were established at a number of volcanoes around the world (Shimozuru 1983; Tilling 1995), including Mt Etna, Sicily (1881), Mt Peleé, Martinique (1902; finally established in 1937), Asama, Japan (1911), and Hawaii (1912). Today, the World Organization of Volcano Observatories (wovo.org) includes over 70 partner observatories and national monitoring agencies around the world, including the nine Volcanic Ash Advisory Centres (VAACs) that are charged with the global coordination and dissemination of information relating to volcanic activity leading to atmospheric plumes (e.g. McNutt 2000; Webley & Mastin 2009).

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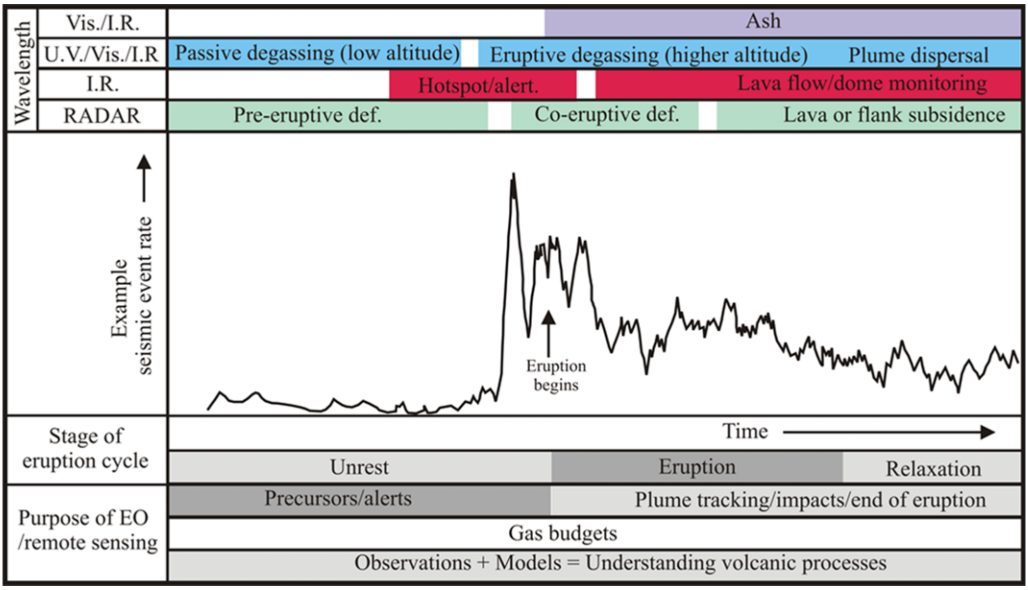

Fig. 1. An illustration of some of the applications of remote-sensing techniques to a volcano during a hypothetical eruption cycle. The example seismic trace is intended to be schematic and is based on the number of seismic events per hour with magnitudes >3.2, 20 March–28 May 1980 at Mt St. Helens. (Robert Tilling) from GVN monthly reports Mount St Helens 05/1980 (SEAN 05:05) http://www.volcano.si.edu/world/volcano.cfm?vnum=1201-05-&volpage=var

The number, scope and sophistication of monitoring systems have increased dramatically in recent decades, providing a wealth of data on which to base models that represent the science of the underlying processes. In the past decades, technological developments have also enabled the development of a range of new tools that allow volcanoes to be monitored remotely (e.g. Francis *et al.* 1996). The results have revolutionized the ways in which volcano observatories may gather information, and at last provide a global perspective allowing observations of the vast majority of volcanoes for which no monitoring otherwise exists (Sparks *et al.* 2012).

As we illustrate in Figure 1, remote-sensing approaches using instruments operating at wavelengths from the ultra-violet to microwave (*c.* 300 nm–30 cm wavelengths) regions of the electromagnetic spectrum can now routinely be used to monitor volcanoes, volcanic processes and volcanic products throughout an eruption cycle – from pre-eruptive repose to post-eruptive relaxation. Instruments currently in orbit can, for example, measure ground deformation (radar), gas emissions and aerosols (IR/visible/UV), and heat (IR). Particular advantages of these remote-sensing techniques include the capacity to provide near real-time information that simply might not be available from any other source. In recent years, for example, several significant eruptions in the Afar (NE Ethiopia and Eritrea) and Red Sea region were either first detected or first reported following satellite observations of gas or ash plumes (e.g. eruptions of Jebel at Tair 2007; Alu-Dalaffilla 2008, the Manda Hararo Rift 2007 and 2009; and Nabro 2011: Ferguson *et al.* 2010; Pagli *et al.* 2012), while the scale of crustal rifting associated with a seismic crisis that heralded a major dyking event in the same region in 2005 only became clear from InSAR (Interferometric Synthetic Aperture Radar) observations (Wright *et al.* 2006).

Ground deformation, as measured by levelling, triangulation, electronic distance measurement (EDM) and global positioning system (GPS), has long been a key tool in volcano monitoring despite the time-consuming and hazardous requirements of ground-based instrumentation (e.g. Lipman & Mullineaux 1981; Dvorak & Dzurisin 1997). Since the 1990s, InSAR, a satellite-based measurement that uses the phase difference of repeat radar images, has enabled centimetre-scale surface displacements to be measured remotely. From the first application to Etna (Massonnet *et al.* 1995), InSAR has now detected deformation at over 140 volcanoes (Fournier *et al.* 2010), and has been used to monitor both individual eruptions (e.g.

Okmok Volcano, Alaska: Lu *et al.* 2010; Lu & Dzurisin 2010; Eyjafjallajökull, Iceland: Sigmundsson *et al.* 2010) and to identify and monitor volcanic unrest at volcano-, regional- and arc-scales (e.g. Amelung *et al.* 2000; Pritchard & Simons 2004*a*, *b*; Biggs *et al.* 2009, 2011; Philibosian & Simons 2011; Parks *et al.* 2012; Chaussard & Amelung 2012; Ebmeier *et al.* 2013*a*).

The first published applications of infrared (IR) imaging in volcanology were the aerial surveys of Hawaiian volcanoes with an IR imaging radiometer that depicted volcanic thermal patterns and structural features described by Fischer *et al.* (1964). The first use of satellite data to make thermal observations was in 1965, when data from the Nimbus I High Resolution Infrared Radiometer (HRIR) were used to compare the thermal radiance from Kilauea Volcano, Hawaii, with its inactive neighbour, Mauna Loa (Gawarecki *et al.* 1965). Although there were some other earlier applications (Surtsey, Iceland, in 1966: Williams & Friedman 1970), it was not until further pioneering work in the 1980s (Francis & Rothery 1987; Rothery *et al.* 1988) that thermal remote sensing, and in particular the Landsat Thematic Mapper (TM), became established as a tool for studying active volcanoes. Since then, research has applied and extended these techniques to a broad range of volcanic scenarios including the thermal analysis of active lava flows (e.g. Wright *et al.* 2001), lava domes (e.g. Kaneko *et al.* 2002), lava-lakes (e.g. Oppenheimer & Francis 1997), fumarole fields (e.g. Harris & Stevenson 1997) and, more recently, near-source volcanic clouds from explosive eruptions (early work reviewed in Oppenheimer & Rothery 1991). Efforts have also been made to automate volcano thermal alerts (e.g. MODVOLC: Wright *et al.* 2004). Over the last decade, portable handheld thermal cameras have become commercially available. These offer volcanologists a tool for collecting high-spatial resolution imagery at a safe distance from an erupting volcano. Spampinato *et al.* (2011) presented an overview of recent advances in volcano monitoring with portable IR cameras.

Owing to its low concentrations in the background atmosphere and characteristic molecular absorption bands in the ultraviolet (UV) region (similar to those of ozone), the first, and still the majority of, satellite remote-sensing measurements of volcanic gases were of sulphur dioxide. This started with the detection of the large SO_2 cloud released in the 1982 eruption of El Chichón by the Total Ozone Mapping Spectrometer (TOMS), the first successful observation of volcanic SO_2 emission from space (Krueger 1983; Krueger *et al.* 2008). The TOMS instrument family provided a robust and near-continuous record of volcanic SO_2 releases by large eruptions for over two decades (Carn *et al.* 2003). Since TOMS, various other satellite instruments utilizing both the UV (e.g. OMI, GOME, SCIAMACHY[1]) and IR (IASI, SEVIRI, MODIS, AIRS[2]) regions of the spectrum have been used to monitor volcanic gas emissions from space. From the late 1980s, satellite instruments such as AVHRR and GOES have also been used to make measurements of volcanic ash clouds also (e.g. Prata 1989; Rose *et al.* 2000).

The use and importance of modelling

As in other branches of science, the use of models is important and widespread in volcanology. The realm of volcanological remote sensing includes a diverse range of modelling approaches and applications. The uses to which models in this area are put includes: (a) to aid the extraction of useful information from many remote-sensing datastreams; (b) to explore the underlying processes leading to the observed signals; and (c) to make operational forecasts and to manage volcanic hazards. In this subsection we give a brief illustrative (and, by no means, complete) examples of the ways in which models are used in each of these ways.

Extracting useful information from remote-sensing datastreams

Modelling plays a central role in extracting useful information from many remote-sensing datastreams. Almost by definition, remotely-sensed data must pass through the atmosphere on its path from the volcano to the sensor. Different types of measurements are affected in different ways and by different components of the atmosphere. For example, InSAR measurements are affected by tropospheric water vapour (e.g. Li *et al.* 2005), while algorithms using different band combinations of

[1]Ozone Monitoring Instrument (OMI) on the NASA AURA mission; Global Ozone Monitoring Experiment (GOME) on the ESA ERS mission; SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) on the ESA Envisat mission.

[2]Infrared Atmospheric Sounding Interferometer (IASI) on EUMETSAT MetOp; Spinning Enhanced Visible and Infrared Imager (SEVIRI) on EUMETSAT Meteosat 8; Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra and Aqua satellites; Atmospheric Infrared Sounder (AIRS) on NASA's Aqua satellite.

thermal infrared (TIR) data can be used to separate the influence of ash and SO_2 within a plume (e.g. Watson *et al.* 2004). Before accurate values of the required parameters can be obtained, these nuisance parameters must be accounted for using assumptions, external data or more commonly modelled values (Vaughan *et al.* 2010; Kinoshita *et al.* 2013).

Other model uses are specific to different retrievals. For example, models can be used to simplify the mathematics involved in data extraction (e.g. application of two- versus three-component models for characterizing active lava-lake surfaces: Flynn *et al.* 1993) or to provide retrieval input parameters that would otherwise have to be assumed (e.g. modelled plume heights for SO_2 gas retrievals: Krotkov *et al.* 2010).

Exploring the underlying processes leading to the observed signals

In recent years, there have been tremendous advances in the modelling and simulation of volcanic processes, both subterranean and eruptive (e.g. Sparks *et al.* 1997; Segall 2010; Fagents *et al.* 2013). In fact, perhaps the most widespread and routine application of modelling in this context to remote-sensing data over recent years has been within the InSAR community. Deformation measurements are traditionally point-based, and InSAR has dramatically improved the spatial resolution of deformation patterns. Analytical models based on elastic half-space assumptions, such as the Mogi source (Mogi 1958) or the Okada solution for a rectangular dislocation (Okada 1985) can be used to represent simple geometries such as spherical chambers, dykes and sills. Despite the high spatial resolution of InSAR data, these simple models provide satisfactory fits in the majority of cases suggesting that, to the first order, magmatic plumbing systems tend to favour simple geometries (e.g. Biggs *et al.* 2009). However, subsurface structures and the thermal influence of the magma system itself may introduce complexities that may bias the model results (Hickey *et al.* 2013). Such influences are best investigated using Finite Element Analysis but the high computational requirements and huge number of parameters means that full testing of the parameter space, error estimates and non-unique solutions are challenging. It is increasingly clear, though, that the breakthroughs in understanding the processes associated with magma migration, storage and pre-eruptive evolution will require the integration of these different modelling approaches with the principle monitoring streams: seismicity, deformation, thermal and gas (including from remote-sensing datasets), and with constraints extracted from petrological and geochemical data. Up until now, much of the focus on modelling has been to understand intrusive and eruptive processes but not necessarily on the length- and timescales that can now be measured by remote sensing. The ultimate goal of such modelling is to move beyond simple kinematic descriptions of a single observable to a full understanding of the driving forces, transferable between at least volcanic systems that show some commonalties and be capable of forecasting future consequences.

Making operational forecasts and managing volcanic hazards

Models are used in operational settings both to prepare for future volcanic threats via the production of products, such as scenarios and hazard maps, and increasingly also in real-time or near real-time to inform hazard assessments as a volcanic crisis evolves. Data from remote sensing have a role to play in both types of application (e.g. Pareschi *et al.* 2000; Folch *et al.* 2008). For example, lahars are among the most serious and far-reaching volcanic hazards, and, in populated lahar-prone regions, assessment of the related hazards is crucial to reduce the associated risks. While remote sensing has been used to track the paths of lahars (Joyce *et al.* 2009) and so has the potential to contribute to databases of previous activity, modelling of lahars has become an important tool in such assessments, in particular where the geological record of past events is insufficient. Such efforts rely strongly on digital terrain data, with availability of digital elevation models (DEMs) often limited. Remote-sensing technology has opened new perspectives in generating DEMs; for example, those derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Shuttle Radar Topography Mission (SRTM) (Huggel *et al.* 2008), and, in the next few years, TanDEM-X. Remote sensing can also contribute to the assessment of hazard from lava flows (Ganci *et al.* 2012), pyroclastic flows (Terunuma *et al.* 2005) and lava domes (Wadge *et al.* 2011).

Models describing the dispersal and sedimentation of volcanic particles have also been used to make future hazard assessments related to ashfall (e.g. roof collapse: Biass *et al.* 2013). However, it is, perhaps, in terms of ash dispersal that numerical models have been put to most use in real-time to forecast plume evolution and sedimentation (Brown *et al.* 2012 and references therein), particularly driven by disruption to the aviation industry by eruptions such as that of Eyjafjallajökull in 2010. This has led to much work to test model sensitivity to volcanic input parameters (Bursik *et al.* 2012); to compare model outputs with direct measurements (Dacre *et al.* 2013) and remote-sensing data (Webley *et al.* 2012). Model validation using remote-sensing data, the combining of data with models via data assimilation (Folch 2012), and the use of remote-sensing data to understand and parameterize processes such as particle aggregation (Brown *et al.* 2012) are now firmly on the research agenda.

Remote sensing of surface deformation

Many subsurface magmatic and volcanic processes cause deformation of the Earth's surface. Uplift is often interpreted as the input of new magma, either immediately preceding an eruption (e.g. Sigmundsson *et al.* 2010) or as a dyke or sill is intruded (e.g. Biggs *et al.* 2009), with post-eruptive subsidence following the evacuation of magma stored in the crust (e.g. Bathke *et al.* 2011; Parks *et al.* 2011). However, many other processes may also cause deformation, including hydrothermal circulation (e.g. Gottsmann *et al.* 2006; Chiodini *et al.* 2012), lava flow compaction (e.g. Ebmeier *et al.* 2012 and references therein), edifice instability (Ebmeier *et al.* 2010; Ruch *et al.* 2012), dome extrusion (e.g. Wadge *et al.* 2011) and gravitational loading (Dzurisin *et al.* 2002) (Fig. 2). This volume includes papers that cover the full range of volcano geodetic research, from assessing the global applicability of particular InSAR satellites, through to providing observations and kinematic models of subsurface geometry at case-study volcanoes to a new physics-based approach to integrating monitoring data.

In terms of remote sensing of deformation, volcanoes in the tropics have been understudied in

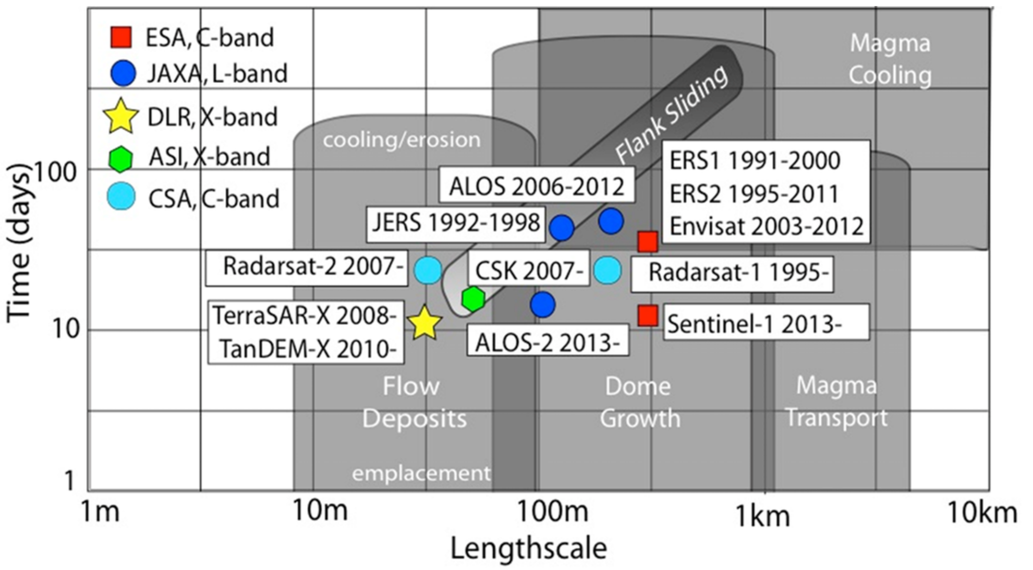

Fig. 2. A schematic illustrating the typical length- and timescales of processes that cause deformation at volcanoes, and the detection limits of past, current and planned satellites. The majority of InSAR studies concern magma transport but flow emplacement, dome growth, flank sliding and magma cooling are also expected to cause deformation. Individual flow deposits are typically on the order of 10–100 m wide, whereas domes can be up to 1 km in diameter. Owing to the smoothing effect of the overlying crust, the lengthscale of magma-related deformation can range from <1 km for conduit-related processes to 10s of kilometres for mid-crustal sources. Deformation associated with magma cooling is only expected to be significant for large intrusions and, therefore, has a medium–large associated lengthscale. The processes of magma transport, volcanic flows and domes typically produce a measureable deformation signal (i.e. in 'good' conditions *c.* 1 cm for a single interferogram or 2–3 mm a^{-1} using a timeseries) in less than 1 year even for low-volume fluxes, whereas flank instability and magma cooling are long-lived processes that occur much more slowly and so may take longer periods to be measureable. This figure assumes permanent rather than reversible deformation for simplicity. Satellite detectability limits are plotted with the repeat interval on the 'timescale axis' and the size of 10 pixels (considered the minimum for detectability) on the 'lengthscale' axis. This refers to the minimum time- and lengthscales detectable, and any processes that plot to the right and above these points would also be observable. Abbreviations in the figure: ESA, European Space Agency; JAXA, Japanese Space Agency; DLR, German Space Agency; ASI, Italian Space Agency; CSA, Canadian Space Agency.

comparison to those at higher latitudes owing to the dense vegetation cover and high atmospheric water vapour. **Ebmeier *et al.* (2013*b*)** perform a systematic survey of the Central American Volcanic Arc using the L-band ALOS satellite to investigate the applicability of InSAR to volcanoes in the tropics and to develop a systematic approach to classifying signals.

The Virunga volcanoes, Nyamulagira (or Nyamuragira) and Nyiragongo, in the Democratic Republic of Congo, are difficult to access, yet present a high risk to the nearby city of Goma. **Wauthier *et al.* (2013)** present detailed InSAR observations of each of the eruptions of the volcano Nyamulagira from 1996 to 2010. They apply Mixed Boundary Element Methods to develop a model of the plumbing system and eruptive dynamics.

Volcano deformation data give us great insights into the subsurface processes at volcanoes. However, these data become an ever-more powerful way to interrogate these processes when combined with other geophysical datastreams. **Aoki *et al.* (2013)** combine deformation data (GPS) with active source and ambient noise seismic tomography for recent eruptions at Asama volcano, Japan in order to understand the subsurface movement of magma, and to show that the intrusions are under structural control.

Finally, in this section, **Segall (2013)** reviews conduit models that can be combined with monitoring data to move beyond empirical pattern recognition to forecasting based on deterministic, physical–chemical models of the underlying dynamics.

Remote sensing of thermal signals on the surface

Since volcanic eruptions are almost invariably associated with thermal disturbances, whether through changes in temperatures of crater lakes, extrusion of hot material onto the Earth's surface or injection of hot ash and gas into the atmosphere, the potential for using TIR measurements to track volcanic eruptions and to constrain volcanic processes has been recognized for many years (e.g. Oppenheimer & Rothery 1991), with an automated volcanic alert system in operation since 2002 (Wright *et al.* 2002). Space-based measurements have even been used to estimate the global volcanic heat flux to the atmosphere (Wright & Flynn 2004). This section of the volume focuses on remote sensing of thermal features on the surface of the Earth at or near volcanoes. Ash tracking is covered in the section on 'Remote sensing of volcanic plumes'.

Blackett (2013) presents a historical review of the use of IR remote sensing for the monitoring of volcanic activity, presenting a description of the various sensors that have been used and are currently available, and examining the theoretical basis of these observations and the techniques that have been developed to analyse the data. This review is illustrated via a case study of data derived from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) shortwave infrared (SWIR) observations of Lascar Volcano in Chile. The development of new techniques to make sense of thermal data is important. While remote radiant power (RP) measurements contain useful information about the activity status of a volcano, they also contain uncertainty and noise for reasons such as atmosphere effects and instruments characteristics. **Zakšek *et al.* (2013)** present a method to estimate the uncertainty of RP measurements and, in addition, reduce the temporal noise of the time series by applying a Kalman filter, critically evaluating their new scheme by applying it to an eruption of Etna in 2002 and the eruption of Nyamulagira in 2010.

The other three contributions in this section are examples of distinct but important applications of thermal remote sensing to volcanic scenarios. **Jay *et al.* (2013)** utilize the potential of satellite remote sensing to allow regional-scale surveys of volcanic activity, examining 150 volcanoes and geothermal areas in the central, southern, and austral Andes for thermal anomalies between 2000 and 2010. They found that most of the thermal anomalies were related to known activity but also observed other anomalies of unknown origin, or activity at volcanoes that were not thought to have surface activity. This suggests that low-amplitude volcanic hotspots detectable from space are more common than expected based on lower spatial resolution data, and that these features could be more widely used to monitor changes in the activity of remote volcanoes.

Specific studies of individual volcanoes are also of great utility in terms of understanding the underlying processes governing volcanic behaviour. Forecasting volcanic eruptions remains one of the key goals of volcanology. **van Manen *et al.* (2013)** use the observations that Bezymianny (Kamchatka) commonly shows an increase in lava extrusion rate, which can be detected by satellites as an increase in thermal radiance, prior to exploding, to present the first method of forecasting explosive eruptions based solely on satellite data. They develop a pattern recognition algorithm using Advanced Very High Resolution Radiometer (AVHRR) data based on known precursory trends of increasing radiance prior to 19 explosions at Bezymianny Volcano in 1993–2008, and test its efficacy in terms of retrospective forecasting during this period and on independent data during 2009–2011. Lava dome eruptions present significant volcanic hazards, and understanding their emplacement, architecture and evolution is of key importance. **Hutchison *et al.* (2013)** investigate high-resolution digital photographs and IR images of the lava dome eruption at Volcán de Colima, from 2007 to 2010. This study combines both qualitative and quantitative observations in order to provide important insights into active volcanic processes occurring during a period of dome growth. As the dome initiates and grows, a substantial cooled talus apron develops that stabilizes the structure until it reaches the crater rim, resulting in the development of a lava lobe, extruding hot lava from deeper within the dome. The highest temperature hotspots migrate from the dome sides, to the top and, finally, to the lava lobe as the structurally unstable areas expose fresh material. These observations lead to the proposal that the mechanical stability of the Volcán de Colima dome arises from the shear strength of flanking talus that stabilizes a hot viscous core; a model that may have broader applicability to other dome-forming systems.

Remote sensing of volcanic plumes

Once volcanic products such as ash and gas are ejected into the atmosphere, remote sensing is important in terms of tracking their short-term impacts (e.g. aviation hazard) and assessing their long-term impacts (e.g. time-averaged budgets of volcanic degassing, global cooling). Up until now only SO_2 and ash measurements of major eruptive plumes (i.e. punching higher into the upper troposphere and stratosphere) have been made as a matter of routine. More recently, though, efforts have been made to measure other gases; for example, the minor volcanic plume component BrO measured in the eruptive plumes from both Kasatochi (Theys *et al.* 2009) and Eyjafjallajökull (Heue *et al.* 2011; Rix *et al.* 2012). Measurement of volcanic CO_2 from satellites is in its infancy but has great potential. The first dedicated greenhouse gas sensor, GOSAT, was launched by the Japanese Space Agency in 2009 (Hamazaki *et al.* 2005; Yokota *et al.* 2009). GOSAT flies in a sun-synchronous orbit with a 3 day repeat cycle. CO_2 and CH_4 columns can be retrieved from SWIR spectra with high precision and high sensitivity to the lower atmosphere, where the volcanic enhancements will be located (e.g. Butz *et al.* 2011). GOSAT employs a target-pointing ('stare') mode providing great potential for observing volcanic enhancements. NASA expects to launch OCO-2, its CO_2-measuring mission, in 2014.

As well as pushing satellite remote sensing to measure other volcanic gases, it is also of great importance to push sensor capability to be able detect and quantify the SO_2 emissions from non-eruptive or quiescent volcanic activity. These emissions are, by their very nature, to lower levels of the atmosphere but, in a time-averaged sense, they contribute at least as much gas to the Earth's atmosphere as sporadic emissions from larger eruptions (Pyle *et al.* 1996; Pyle & Mather 2003). The varying rates of these emissions contain important information in terms of the eruptive state of a volcano, much needed for volcanic hazard monitoring, especially where other ground-based measurements are lacking. Both **Carn *et al.* (2013)** and **McCormick *et al.* (2013)** review the OMI instrument's use for volcanic SO_2 measurement, with particular focus on its capabilities to measure quiescent volcanic plumes in the lower troposphere. Carn *et al.* (2013) focus on some of the technical aspects surrounding OMI's sensitivity to volcanic SO_2 in different scenarios, and illustrate this with references to case studies illustrating OMI's potential to monitor and understand degassing processes during an eruption or at individual volcanoes. McCormick *et al.* (2013) focus more on OMI's use for synoptic-scale studies of degassing with case studies focused on the country- (Mexico, Italy) to arc-scale (Kamchatka, Central America) in order to illuminate the opportunities and challenges of using satellite remote sensing to understand degassing patterns and budgets on these scales.

The recent travel disruption and economic losses resulting from airspace closures following volcanic eruptions (e.g. Eyjafjallajökull in Europe in 2010, and Puyehue-Cordón Caulle in South America, Australia and New Zealand in 2011) have clearly demonstrated the vulnerability of modern society to volcanic ash and the importance of developing effective methods to track the location of this ash. The quantitative use of satellite imagery and the full exploitation of high-resolution spectral measurements depend upon the optical properties of the observed ash. **Grainger *et al.* (2013)** use new laboratory measurements of ash refractive indices to retrieve plume height, optical depth and ash effective radius from measurements by AATSR and SEVIRI, and develop a new method to provide rapid identification of volcanic ash for the MIPAS instrument. They demonstrate the utility of these techniques by application to the Eyjafjallajökull, Puyehue-Cordón Caulle and Nabro eruptions.

Both gas and ash measurements from satellites require ground-truthing, and in the final paper in this Special Publication, **Pieri *et al.* (2013)** are concerned with the development of unmanned aerial vehicles (UAVs) to overcome some of the challenges in terms of such ground-truthing. UAVs potentially allow measurements of the parts of volcanic plumes otherwise inaccessible to manned vehicles due to safety concerns or ground-based remote sensing owing to plume height, measurement geometry constraints, plume opaqueness or other factors. Pieri *et al.* (2013) detail a programme to make *in situ* observations simultaneously with ASTER orbital multispectral TIR data acquisitions, in order to compare the two datastreams in terms of SO_2 mass loading and plume dispersion.

Future perspectives

This Special Publication comes at an exciting time for the application of remote sensing to volcanoes, with the last two decades seeing a steady increase in the number of published studies in this area, particularly in the application of InSAR to volcanoes (Fig. 3). New satellite missions will undoubtedly continue this development. In terms of InSAR research, the year 2012 saw the end of the 'workhorse' Envisat mission (2003–2012) that provided the backbone of InSAR observations for the last decade, and the end of the ALOS mission (2006–2012), which provided an all-too-brief observation window into the densely vegetated tropics. In their place, 2013 will see the launches of two successor missions; ALOS-2 and Sentinel-1A. With its stated goal of providing consistent, real-time coverage of all continental areas at least every 12 days for the next 25 years, the Sentinel system looks set to revolutionize the way in which InSAR is used. Sentinel should see InSAR through the transition from an opportunistic, research-led science tool, into a practical, operational system. In terms of studying gas and particle emissions, geostationary observations by the current SEVIRI on MSG, the forthcoming Advanced Baseline Imager onboard GOES-R (2016) and the Flexible Combined Imager onboard MTG (2017), represent a sustainable global capacity of dealing with multiple eruptions at least to 2030. Thanks to greatly improved spectral and spatial resolutions, these meteorological payloads are expected to improve global volcano monitoring (Ferruci *et al.* 2012).

However, there are numerous challenges to be addressed in terms of maximizing the scientific benefit and utility, in terms of monitoring, of Earth Observation (EO) applied to volcanoes. Recent initiatives such as the Geohazard Supersites and Natural Laboratories (GSNL) initiative (www.earthobservations.org/gsnl.php) seek to offer a framework to address some of these challenges. Their strategic aims include: promoting global systematic background observations; increasing systematic

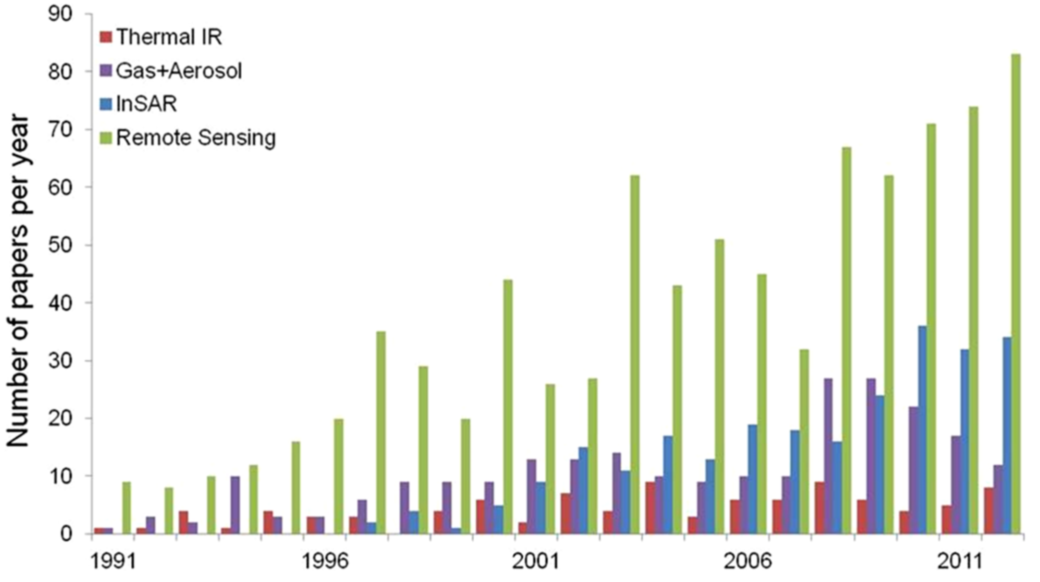

Fig. 3. Graphical analysis of published scientific papers on remote sensing of young terrestrial volcanoes from the ISI database from 1991 to 2012. Note the growth in applications of remote sensing in general over the whole period, and the particular growth in InSAR applications to volcanoes since 2000. Search strings: (volcan* + remote sensing); (InSAR + volcan*); 'gas + aerosol' from searches for volcan* with TOMS, OMI, COSPEC and DOAS; 'Thermal IR' (focused for illustrative purposes on 'thermal alert studies') from (volcan* + MODIS or MODVOLC). Searches were corrected to remove non-terrestrial and irrelevant examples.

observation capability for early warning and alerts; promoting the ability to target any eruption worldwide; improving and/or developing the capability to carry out novel measurements; securing continuity and sustainability of all the above for a 20 year horizon; and improving the uptake of EO through training for end users (Ferruci *et al.* 2012).

Improving uptake by end users is key to realizing the full potential for EO in terms of volcanic hazard management and mitigation, as well as maximizing future scientific gains. This will be achieved through improved training but also better processing algorithms and more automation. The EVOSS project (www.evoss.eu) is currently trialling the 'World Virtual Orbiting Volcano Observatory', including the incorporation of data from many satellite platforms to automatically monitor thermal and SO_2 parameters at target volcanoes within Europe and Africa in near-real time. More similar efforts are desirable in the future; for example, before volcano observatories can rely on ground deformation outputs from the new Sentinel system as a basis for hazard assessments and warning, further work on automation and error analysis is required, as well as research into the subsurface interpretation and implications of deformation patterns.

The understanding of underlying causes of deformation patterns is an example of some of the fundamental science that is also needed to feed in to such advances. Breakthroughs will be made in our understanding of volcanic behaviour through the systematic homogenization and harmonization of huge data archives as volcanology becomes ever more data-rich, and by integrating different datastreams from EO and ground-based remote sensing, as well as other direct measurements and petrology/geochemistry. The intelligent application of modelling will also undoubtedly play a role. The integration of satellite data and numerical modelling represents a step towards the next generation of EO-based hazard assessment in volcanic areas and affected regions. A long-term challenge for the science of volcanology is the development of generalizable numerical models of volcanic behaviour, in which inputs such as magma composition, gas content and conduit geometry give numerical predictions that can be compared with observations to investigate the role of relevant factors affecting volcano unrest, to provide a quantitative estimate of a volcano's internal state and to identify the critical conditions that may cause a volcano to erupt, or to shut down. While such models are still a way off in the future, especially given the chaotic nature of many types of volcanic activity, there is much of great use and interest to be learnt on the road towards this aim. There is no doubt that remote sensing will continue to play a critical role in future milestones of volcanological science.

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