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**MULTIVARIATE APPROACHES TO INFER VOLCANIC
SYSTEM PARAMETERS, TIMING, AND SIZE OF
EXPLOSIVE ERUPTIONS**

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ASIAN SCHOOL OF THE ENVIRONMENT

2019

MULTIVARIATE APPROACHES TO INFER VOLCANIC SYSTEM PARAMETERS, TIMING, AND SIZE OF EXPLOSIVE ERUPTIONS

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*A thesis submitted to the Nanyang Technological University in partial fulfilment of
the requirement for the degree of Doctor of Philosophy*

2019

Candidate Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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I have reviewed the content and presentation style of this thesis and declare it is of sufficient quality and grammatical clarity to be examined. To the best of my knowledge, it is free of plagiarism and the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. To the best of my knowledge, the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Authorship Attribution Statement

This thesis contains material from 3 papers published and under review in the following peer-reviewed journals:

Chapter 2 is published as Manta, F., & Taisne, B. (2019). A Bayesian approach to infer volcanic system parameters, timing, and size of Strombolian events from a single tilt station. *Journal of Geophysical Research: Solid Earth*.
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The contributions of the co-authors are as follows:

- A/Prof Taisne provided the initial project direction and edited the manuscript drafts.
- I prepared the manuscript drafts. A/Prof Taisne revised the manuscript.
- I co-designed the study with A/Prof Taisne and performed all the laboratory work at the Asian School of the Environment in Singapore. I also analyzed the data and developed the necessary coding.

Chapter 3 is published as Manta F., Emadzadeh A., Taisne B., New insight into a volcanic system: Analogue investigation of bubble-driven deformation in an elastic conduit. (Under review) *Journal of Geophysical Research: Solid Earth*.

The contributions of the co-authors are as follows:

- A/Prof Taisne suggested the materials area and edited the manuscript drafts.
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- I co-designed the experimental setup with A/Prof Taisne and performed all the laboratory work at the Asian School of the Environment in Singapore together with Dr. Emadzadeh.
- I also analyzed the data and developed the necessary coding.

Part of Chapter 5 has been submitted for publication as Manta F., Occhipinti G., Feng L., Hill E.M., Rapid identification of tsunami earthquakes using GPS ionospheric sounding. (Under review) *Scientific Report*.

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- A/Prof Hill, A/Prof Occhipinti designed the research.
- I wrote the drafts of the manuscript.
- The manuscript was revised together with A/Prof Hill, A/Prof Occhipinti and Dr. Feng.
- I analyzed and interpreted the data and developed the coding.
- Dr. L. Feng helped analyzing the GNSS data.

This thesis also contains material from 2 papers in preparation for submission:

Chapter 4 is under preparation as Manta F., Taisne B., Volcano in the lab: an analogue investigation of bubble driven surface displacement.

The contributions of the co-authors are as follows:

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- I wrote the drafts of the manuscript.
- The manuscript was revised together with A/Prof Taisne.
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- I also analyzed the data and developed the necessary coding.

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The contributions of the co-authors are as follows:

- A/Prof Hill, A/Prof Taisne designed the research.
- I wrote the drafts of the manuscript.
- The manuscript was revised together with all the authors of this paper.
- I analyzed and interpreted the data and developed the necessary coding

We the undersigned agree with the above stated “proportion of work undertaken” for each of the above published (or submitted) peer-reviewed manuscripts contributing to the thesis:

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Figure 5.12. Time evolution of (a) elevation angles of the satellite-receiver line of sight and (b) epicentral distances of the IPPs relative to the Sinabung eruptions: SI01 (black), SI02 (orange) and SI03 (green). Vertical dashed lines represent the time of the events. Zenith angles and distances between IPPs and vent are similar across events, indicating that the differences between TECII cannot be attributed to the observation geometry of the satellites. 113

Abstract

Volcanoes can exhibit a wide range of activities: from effusive eruptions, low-energy bursts, and mild explosive Strombolian eruptions that can cause minor localized effects on human populations, to more severe Plinian eruptions, which are characterized by large emission of ash in the atmosphere with consequent regional to global impacts on human life. To monitor the associated risk, volcanologists apply several ground-based and satellite techniques to analyse geophysical signals associated with the mechanisms happening deep inside the earth that can lead to an eruption. These techniques allow, with the appropriate instruments in place, to estimate the time and intensity of coming events and, in case a large eruption is ongoing, can provide information on ash ejection rates and column heights. Despite technological advancements, many active volcanoes still lack an adequate permanent monitoring network; moreover, harsh climatic conditions can complicate the application of the existing remote sensing techniques. Therefore, there is the need for complementing volcano monitoring with new supportive tools to enhance the current systems. Accordingly, in this thesis we propose two different methods based on volcano tilt observations and ionospheric sounding, respectively for close field and remote sensing applications, to detect and characterize eruptions prior, and during the event. We propose a method to exploit the time series of tilt signals recorded by a single station during Strombolian explosions to forecast the time and magnitude of a coming event. This is achieved by estimating, by mean of the Bayesian statistics and a physics-based model, the range of controlling parameters. To validate the proposed model and test its uncertainties we performed analogue experiments in a controlled environment. To date, analogue experiments in controlled environments have been focused on the uncertainties related to the dynamics of slugs inside rigid conduits, but little is known about how the slug dynamics changes in the elastic conduit, and how the slug ascent affects surface deformation. We finally focused on the development of a new tool that can support remote sensing techniques to detect and assess the intensity of eruptions. We tested whether the analysis of ionospheric Total Electron Content (TEC) can provide additional information to complement the existing monitoring system. To this end, we mined GNSS data recorded during 22 volcanic eruptions to measure the ionospheric TEC perturbation associated with the acoustic-gravity waves generated by volcanic explosions. We evaluated the relationship between a metric related to the energy of atmospheric disturbances, called TEC Intensity Index (TECII), and several well-known metrics obtained by seismology, and satellite remote sensing. The results presented in this thesis support the use of techniques based on the analysis of tilt observations and ionospheric sounding as complementary methods for volcano monitoring. The synergy of these new techniques and the classic ones will augment the possibility of preventing losses of life and mitigating damages by providing useful information for volcano observatories and alert systems.

Introduction

1.1 Importance of volcano monitoring

Explosive eruptions are normally attributed to the uprise of gas-rich magma within the volcanic conduit. According to the degassing rate and the volume of gas present in the magma, explosive eruptions can exhibit a wide range of eruptive styles (Ripepe & Harris, 2008). The style of the explosive activity can range from low-energy bursts, and mild explosive Strombolian eruptions, which cause minor local impact on the environment and population, to more severe Plinian eruptions, which are characterized by large emission of columns of ash in the atmosphere (plumes), with consequent regional to global scale effects (Houghton & Gonnermann, 2008; Parfitt & Wilson, 1995).

Throughout human history, large explosive eruptions have affected the year-to-year variability of the Earth's climate and even triggered crop failures and famines (e.g. Luterbacher & Pfister, 2015; Oppenheimer, 2015; Pyle & Hernandez, 2017). The explosion of Thera, Santorini, around 1500 B.C., is believed to have disrupted the Minoan civilization due to the consequent tsunamis and climate changes. The explosion of Vesuvius, Italy, in 79 D.C. is well known for the destruction of the Roman towns of Pompeii and Herculaneum. According to the Smithsonian Institution's Global Volcanism Program, the eruption of Laki volcano, Iceland, in 1783 resulted in a famine that killed one-fifth of the population. A recent work published in *Geology* by Genge (2018) claims that the defeat of Emperor Napoleon Bonaparte in the battle of Waterloo (18 June 1815) can be partly attributed to the cataclysmic eruption of Mount Tambora, Indonesia, (10 and 11 April 1815) that affected the global climate leading to the 'Year Without a Summer' of 1816 in Europe and North America. These examples show the impact that volcanic eruptions had over the course of human history. As the population is now exponentially increasing and the world economy is on the rise, volcanic eruptions pose an even more significant threat to the wealth of the world population and the development of modern society (Fekete, 2011). The eruption of Mount Pinatubo, Philippines, on June 1991, produced an estimated 20 million tons of sulfur dioxide, injecting a 20 km high plume into the atmosphere (Bluth et al., 1992) which caused the temporarily drop of global

temperatures by about 0.5°C from 1991 to 1993. The consequent ash fallout and lahars killed 847 people and caused damages to crops, infrastructures, and personal properties for more than 374 million dollars. A recent example of the economic impact of large explosive eruption can be observed after the eruption of the Icelandic volcano Eyjafjallajökull, that in 2010 caused the largest break-down of European airspace since World War II, despite a moderate Volcanic Explosivity Index (VEI) of 4 (Jenkins, 2010; Jenkins et al., 2015). Over 94.866 flights were cancelled with more than 10 million passengers forced to remain grounded. The economic effects of the volcanic crisis were disastrous with more than 1.7 billion dollars in losses, over 200 million daily loss caused by the necessity of staying grounded, electricity costs, rerouting of aircraft and the accommodation of passengers left on the ground (Ajtai et al., 2010).

Besides the global threat posed by large explosive eruptions, that have a long recurrence time of around 1 eruption every 10 years for VEI 5 (Simkin et al., 1994) and a considerably lower likelihood to occur, smaller Strombolian-like explosive eruptions are more frequent and pose a high local risk. Strombolian eruptions are usually displayed by persistently active volcanoes, and their power is controlled by the volatiles dissolved in the magma. Their recurrence time can vary from the order of several hours to minutes and can be divided into several subtypes according to the characteristics of the ejected material and the magnitude of the explosions (Del Bello et al., 2012; Gaudin et al., 2017; James et al., 2008; 2009; Seyfried & Freundt, 2000). These sub-types include gas dominated or “puffing” characterized by the frequent release of small over-pressurized pockets of magmatic gas, and “normal Strombolian explosions”, which are linked to the rise and burst of large over-pressurized gas pockets, referred as slugs, with associated ejection of ash and bombs (Gaudin et al., 2017; Leduc et al., 2015). Volcanoes that exhibit Strombolian activity have an unpredictable nature that may constitute a hazard for the numerous tourists and scientists that visit them in high number. About 40% of fatal incidents in 5 km radius of the vent are caused by ballistics (Brown et al., 2017).

A more accurate system for the estimation of the timing and magnitude of volcanic events could allow the issuance of warning that can prevent these tragic events. Accordingly, in this thesis, we present new tools to infer the magnitude of explosive events based on tilt data and Global Navigation Satellite System (GNSS) observations. In particular, tilt data are used to support the current monitoring approaches in persistently active volcanoes at the local scale, while the analysis

of GNSS data can be beneficial at a regional scale. With this work, we hope to open a new paradigm in volcano monitoring and alert system, based on the redundancy of information from the synergy of new and classic techniques. Our final goal is preventing losses of life and mitigating damages by providing useful information to volcano observatories and the Volcanic Ash Advisory Centers (VAACs) responsible for coordinating the response.

1.2 Volcano monitoring

1.2.1 Close field volcano surveillance based on seismic and geodetic data

Nowadays, volcanic surveillance relies mainly on seismic and geodetic networks, which allow real-time monitoring of even minor magmatic movements during a period of unrest (Dzurisin, 2006; McNutt, 2002). Volcano monitoring primary focus on the recognition of patterns of seismic activity and ground deformations that can be linked through modelling, to the dynamic of the volcanic system (Sparks et al., 2012).

As magma moves toward the Earth's surface, stress changes in the volcanic edifice, as well as magma rupture and stick-slip motion of the magma body, lead to highly regular seismic patterns, often referred to as volcanic tremor (Iverson et al., 2006; Rubin & Gillard, 1998). An established technique for measuring the volcanic tremor is the Real-time Seismic-Amplitude Measurement (RSAM), which was developed by the United States Geological Survey (USGS) to characterize the variation of seismicity in real-time (Endo & Murray, 1991). Techniques based on the detection of the seismicity migration associated with magma motion are commonly applied to infer the time and location of an eruptive feature (Aoki et al., 1999; Battaglia, Aki, & Ferrazzini, 2005; Battaglia, Aki, & Staudacher, 2005; Hayashi & Morita, 2003). More recently, Taisne et al. (2011a) introduced a method called Seismic Amplitude Ratio Analysis (SARA), which allows the tracking in near-real-time of the magma propagation by using the ratio of the seismic intensities at different seismic stations. A recent improved version, Red-flag SARA, showed the capability to discriminate between seismic episodes ending as an intrusion or a tremor-generating eruption in near-real-time (Tan et al., 2019).

Seismic and acoustic signals have also been related to the ascent of a large slug in the conduit (defined as a “large bubble” or “gas pocket” that fills the conduit diameter), and to the forces generated during its interaction with the surrounding medium (James et al., 2006; Lane et al., 2004;

O'Brien & Bean, 2008; Ripepe et al., 2001; Vergnolle & Brandeis, 1996). At Hachijo Island, Japan, Very Long Period (VLP) signals had been observed with a period of 10 s (Kumagai et al., 2003), while at Mount Erebus, Antarctica, they displayed a period between 8 and 20 s (Aster et al., 2003). At Stromboli, VLP signals ranging from 3 to 6 s (Neuberg et al., 1994) and seismic waveforms of 2 to 30 s (Chouet et al., 2003) have been observed. These recordings are believed to be linked to the gas slug ascent that anticipates the volcanic eruption.

Other than volcanic tremor, most volcanic eruptions are preceded and accompanied by ground deformation. The ascending magma displaces and interacts with surrounding rock and fluids as it creates new pathways, flows through cracks or conduits, and accumulates in underground reservoirs. The formation of new pathways and pressure changes within existing conduits and reservoirs causes stress and deformation of the surrounding rocks. Methods to measure surface deformation include high-precision levelling, electronic distance measurement with lasers, Global Positioning System (GPS), and ground tiltmeters (Dzurisin, 2006). Tiltmeters have been used for decades to monitor many volcanic areas: Mt St. Helens (Dvorak et al., 1981; Dzurisin, 1992; Dzurisin et al., 1983); Long Valley Caldera (Mortensen & Hopkins, 1987), Kilauea (Okamura et al., 1988); Piton de la Fournaise (Toutain et al., 1992); Montserrat (Voight et al., 1998); Merapi (Rebscher et al., 2000); Etna (Bonaccorso & Davis, 1999, 2004; Gambino et al., 2014). Generally, slow tilt variations (from weeks to months) indicate the inflation caused by rising magma prior to the eruption or the deflation linked to the energy release following eruptions. Fast tilt variations (from hours to days) are often related to the rapid rise of magma and slugs (e.g., Dzurisin et al., 1983; Mellors et al., 1991; Okamura et al., 1988; Toutain et al., 1992).

Tilt recorded at a short distance from the vent is well known to provide key information about the dynamic of the shallow portion of the conduit. The ground deformation appearing just before Strombolian activity has been reported at many volcanoes using precise tilt observations with an angular accuracy down to the nanoradian (Genco & Ripepe, 2010; Iguchi et al., 2008; Kamo & Ishihara, 1989; Lyons et al., 2012; Nishi et al., 2007; Nishimura et al., 2012; Wiens et al., 2005). A common feature of these signals is their duration, that appears to be short (order of minutes), and their amplitude (1-10 nrad). For instance, in Stromboli volcano, the explosive process is accompanied by a consistent deformation of the ground (~100 nrad) starting about 200 s before eruptions, associated with processes of gas recharge and discharge in the conduit. Tilt data

recorded during gas burst activity observed at Semeru volcano, Indonesia, exhibit a short duration (~ 30 s) and a small displacement ($\sim$ tens of nrad), proportional to the associated seismic energy (Nishimura et al., 2012). According to these features, in this thesis, we explore the possibility to maximize the use of the information carried by tilt data for the volcano monitoring in the close field.

1.2.2 Volcano remote sensing for regional risk assessment

Besides the in-situ and short-range techniques described in the previous section, volcano monitoring has been complemented with techniques exploiting satellite remote sensing. The satellite view provides a global perspective, which allows the exploration of volcanoes in remote, underfunded, or inaccessible environments.

Since the 1990s, InSAR (Interferometric Synthetic Aperture Radar), a satellite-based measurement that uses the phase difference between radar images taken at different time, allows to remotely measure centimetre-scale surface displacements. From the first application at Mount Etna by Massonnet et al. (1995), InSAR has successfully detected deformation at several volcanoes, including Okmok volcano, Alaska (Lu & Dzurisin, 2010; Lu et al., 2010) and Eyjafjallajökull, Iceland (Sigmundsson et al., 2010). The technique also allows the measurements at many volcanoes in tropical regions since, according to the wavelength, the radar beam can pass through clouds and thick vegetation (Ebmeier et al., 2010; Fournier et al., 2010; Philipposian & Simons, 2011).

Other satellite remote sensing techniques are more specifically applied to detect ongoing eruptions by tracking volcanic ash and gas in the atmosphere injected in the immediate after of a volcanic eruption (Hanstrum & Watson, 1983; Prata, 1989; Sawada et al., 1987). These techniques are used to support the VAACs in coordinating the response by the relevant organizations for the mitigation of volcanic ash hazards. A common technique for ash detection using satellite monitoring is the thermal infrared imagers (e.g., MODIS, AVHRR, GOES, SEVIRI), which is based on the measurement of the abundance of fine-grained volcanic ash, the temperature contrast between the volcanic cloud and the underlying surface, and the relative abundance of water within the volcanic cloud. Another method to approximate the position of volcanic ash plumes is based on the measurement of gases emitted by volcanoes, especially sulfur dioxide (SO_2), which is assumed to

follow similar atmospheric dispersion pattern than the ash. SO_2 can be easily tracked due to its low background concentrations in the atmosphere and its absorption bands in different distinct spectral regions (Carn et al., 2016).

In recent years, infrasound sensors have also been used to detect volcanic explosions from signals recorded in the thermospheric altitudes (>80 km) where their propagation over large distances is controlled by atmospheric winds and temperature (e.g., Dabrowa et al., 2011; Fee et al., 2011; Matoza, Le Pichon, et al., 2011; Matoza, Vergoz, et al., 2011). Large explosive events, such as the eruptions of Kasatochi (2008) and Okmok (2008) volcanoes in Alaska, USA have been detected by infrasound sensors located as far away as 4400 and 5200 km from the source, respectively (Arnoult et al., 2010), while the 2005 eruption of Manam volcano, Papua New Guinea, was recorded in Madagascar, about 11000 km from the vent (Dabrowa et al., 2011). However, all the techniques here discussed present some limitations, which are discussed in Section 1.4, which leads us to the design of a new technique to complement the volcano monitoring at the regional scale.

1.3 Modelling of volcanic process

1.3.1 Numerical models of ground deformation

The forecasting of pending volcanic eruptions is mostly based on modelling the processes happening within the volcanic systems directly linked to the observations made at the surface. Simple models of volcanic deformation have been widely adopted in volcano monitoring (Davis et al., 1974; Davis, 1986; Fialko et al., 2001; Mogi, 1958; Yang et al., 1988). These models use simplified geometry such as sphere and ellipsoid to represent a pressurized magma reservoir where, the accumulation of gas and magma causes the pressure to build up, resulting in the deformation of the surrounding medium. A recent example of the application of the Mogi source model has been presented by Hreinsdóttir et al. (2014), who showed that during the eruption of Grímsvötn Volcano, Iceland, on May 2011, the rate of pressure change in an underlying magma chamber correlates with the height of the volcanic plume over the course of the eruption. Bonaccorso and Davis (1999) formulated a model for a closed vertical conduit using a hydrostatically pressurized cylinder embedded in an elastic half-space. Their solution included a term corresponding to the integral of a line of dilatations (point pressure sources) and another term

for a line of vertical double forces, which represents the shear forces acting at the conduit wall. Based on this model, Nishimura (2006) introduced as a driven mechanism of the conduit deformation, the growth of bubbles in the stagnant magma filling the conduit. They finally observed that the growth of bubbles leads to an acceleration of the ground deformation comparable to the one observed in several natural systems, such as Merapi, Indonesia (Voight et al., 2000). Similar models explored conduit deformation related to the rise of the magma level within the conduit in relation to three different processes: Poiseuille flow, bubble growth for gas diffusion, and the rise of bubbles (Kawaguchi et al., 2013; Nishimura, 2009).

As described in section 1.2.1, also the rise of slugs within the conduit, normally associated with explosive Strombolian events, can induce perturbation in the existing pressure field. The perturbations produce different types of geophysical signals, such as VLP and tilt. Several authors (Del Bello et al., 2015; Del Bello et al., 2012; James et al., 2009) have numerically explored the dynamics of gas slugs in a cylindrical rigid conduit. James et al. (2008) investigated the slug expansion and numerically modelled the pressure and forces acting on the wall of a rigid conduit. The authors highlighted that the forces acting on the conduit wall due to the slug rising, cause the conduit to experience dilation at the slug nose, and compression at the slug base. Following this idea, Kawaguchi and Nishimura, (2015) proposed a model that links the time-dependent surface displacement with the rise of a slug in the volcanic conduit. In this thesis, we use this as a starting point to develop a model as described in Chapter 2.

The combination between the appropriate model, with the measurements coming from the techniques described in section 1.2 can be used to anticipate change in the explosive behaviour of volcanoes, and potentially anticipate exceptionally large events (Anderson & Segall, 2013; Anderson & Poland, 2016; Chaussard et al., 2017; Henderson & Pritchard, 2013; Passarelli et al., 2010; Segall, 2013). Inversion techniques are commonly used to infer parameters of volcanic systems and to forecast the time and intensity of eruptions (Bonaccorso, 2006; Carlà et al., 2016; Chouet et al., 2003). Probabilistic inverse procedures such as Bayesian inversion have been applied to infer properties of the volcanic conduit and the controlling parameters of the eruption from several datasets such as GPS, InSAR, seismic, tilt or their combination. In this thesis, we use tilt signals as input for the Bayesian inversion, a technique based on the probability that a certain set

of parameters will minimize the error between the available observations and a theoretical model, which includes some physical property of the system.

1.3.2 Analogue approaches

Analogue modelling can unveil the physical processes happening within the volcanic system leading to crustal deformation and seismicity (Kavanagh et al., 2018). Analogue models have also the distinct advantage over their numerical counterparts in that there is no need to program the physics of volcanic processes, allowing the modelling of a wide range of dynamics that are scaled to the natural system and need no assumptions on the transition between them.

Even though the dynamics of gas slugs control volcanic eruption, limited studies have evaluated the numerical models described in the previous section. However, gas slugs have been widely studied for application in several fields and experimental studies which considered rigid conduits have been proposed. These span from engineering, where slug flow has numerous industrial applications, encompassing hydrocarbon production and transportation (Morgado et al., 2016), to physiology (Martynov et al., 2009) where the formation and mobilization of microbubbles in blood vessels can be potentially harmful. Several experimental studies analysing the slug ascent in circular conduits can be found in the literature. Zukoski (1966) assessed how the velocity of the so-called “long bubbles” moving in a closed tube is affected by the viscosity and surface tension. The impact of cylindrical boundaries on the ascent of large bubbles was analysed by Collins (1967), while White & Beardmore, (1962) studied the behaviour of inviscid bubbles in tubes and their terminal velocity. More recently, Nogueira et al., (2006a) applied a combination of particle image velocimetry (PIV) and pulsed shadowgraphy for characterizing the flow around gas slugs, to determine the velocity profiles in the liquid around and ahead of the bubble, its shape, and the shear stress profiles in the liquid surrounding the slug. In a subsequent study, the same authors presented the modelling of the flow at the wake of the gas slug (Nogueira et al., 2006b), while its pattern was quantified by (Campos & De Carvalho, 1988).

The analogue approach has been used in several studies applied to basaltic volcanoes (James et al., 2004; 2006; 2008; 2009; Jaupart & Vergnolle, 1988; Seyfried & Freundt, 2000) providing useful insights into first-order conduit dynamics that are not accessible with other methods of investigation. For instance, James et al. (2004; 2006), modelled VLP-like signals related to gas

slug ascent in conduits with variable diameter showing that pressure transients and flow dynamics could be responsible for the VLP signals observed in natural systems. Among other experimental work, the study of Del Bello et al. (2012), presented the validation of theoretical models relating the thickness of the magma film descending around the slug to the overpressure during the slug's ascent and the subsequent eruption explosivity. More recently, analogue models have also explored the effect of a viscous plug on modulating the intensity of the explosions associated with Strombolian events (Del Bello et al., 2015).

Crustal deformation linked to magma intrusion and pressurized Mogi-like reservoirs have been modelled using different material to simulate the Earth crust properties such as mixtures of silica sand, and crushed silica powder (Acocella et al., 2013; Mathieu et al., 2008; Norini & Acocella, 2011). Gelatin is often used as rock analogue to study shallow crustal processes, especially propagation of dikes (Heimpel & Olson, 1994; Muller et al., 2001; Pansino & Taisne, 2019; Taisne & Tait, 2011; Taisne et al., 2011b; Takada, 1989; Watanabe et al., 2002) as it can scale to the Earth's crust. According to previous studies that used this material to simulate the volcanic edifice (Acocella & Tibaldi, 2005; Walter & Troll, 2003), in this thesis, we describe an analogue model which uses gelatin to analyse the dynamics of a gas slug in an elastic conduit.

1.4 Current limitations and proposed approach

During a volcanic eruption, a rapid response is essential to quickly assess and communicate the potential volcanic hazard and risk (Banks et al., 1989). Limitations affect the techniques discussed in section 1.2. In the close field, the RSAM technique relies on the average amplitude of the signal from individual seismometers rather than on the locations and magnitudes of the earthquakes, and it can be strongly affected by the weather conditions. The techniques that measure ground deformation, including measurement of ground tilt and GPS, require well-developed networks of stations and are labour-intensive. In the far field, we have shown that satellite-based remote sensing has provided a means of detecting and monitoring volcanic eruptions for decades (Gawarecki et al., 1965; see Appendix A of Harris, 2013 for a list of publications).

However, techniques such as thermal infrared are far from being straightforward (Brenot et al., 2014), and are limited by ice clouds in cold regions and high water vapor quantity in the tropics (Pavolonis et al., 2006) as well as ice coating phenomenon affecting the ash particles (Taisne et

al., 2019). In addition, not all the eruptions are accompanied by a detectable amount of SO₂, limiting also the application of SO₂ monitoring for plume detection. Infrasound sensors have also been successfully applied to detect volcanic explosions, showing the capability of detecting events with sensors located at considerable distances from the source (Dabrowa et al., 2011; Fee et al., 2010). Nevertheless, the density of the infrasound networks is currently limited, and an additional deployment in volcanically active regions is necessary to fully exploit this technique. Based on these considerations, new methodologies could complement the current set of tools available to quantify the power of volcanic events and potentially further mitigate the losses, especially in remote environments and when meteorological conditions hinder the application of the current techniques.

At the local scale, where the focus is more on forecasting time and intensity of future eruptions rather than monitoring their evolution in the immediate aftermath, the limitations are more convoluted. **On one hand, there is a need for improving and validating the models.** Classic models such as Mogi (1958) or Okada (Okada, 1985) are widely used. They can provide a good first-order parameter estimation (Hreinsdóttir et al., 2014; Sturkell et al., 2003) but show limitations when estimating the time evolution of volume and depth of the source as they do not consider the physical and chemical processes leading to pressure changes and consequent deformation of the elastic medium (Anderson & Segall, 2011). Physics-based models aiming at coupling the slugs with the edifice deformation have been proposed in the literature (Kawaguchi & Nishimura, 2015). However, these models do not take into account the counter-effect of the wall deformation on the dynamics of the slug. **On the other hand, there is a need for a more efficient inversion technique.** Despite inversion techniques are normally applied to infer properties of the volcanic system, to achieve a good estimation of the model parameters, these probabilistic inversions require prior information about the system, and observations from a developed network of monitoring stations, that are often limited or unavailable. When no prior information is available and observations are limited, the inversion results may be inadequate or even misleading (Anderson & Segall, 2013).

To quantify the uncertainties and to test the validity of the modelling assumptions, analogue laboratory simulations are commonly applied. In spite of the analogical studies aiming to a broader understanding of the slug flow in rigid conduits, and the development of advanced experimental

techniques (e.g., PIV), little has been done to investigate the coupling between the dynamics of the slugs and the elastic deformation of the surrounding medium. Additionally, in order to enhance the current techniques for estimating volcanic system properties and time of eruptions in persistently active volcanoes, there is the need of a method that can provide a reliable estimate while operating with a minimal number of stations.

1.4.1 Inferring volcano explosivity from single tilt station

To address the limitations encountered by the existing techniques on forecasting exceptionally explosive Strombolian events, we propose a new method that, by using tilt data recorded by a single station, allows to estimate of the time and amplitude of an incoming explosion. The method is based on the development of a new model coupled with a joint inversion technique as, described in Chapter 2. It exploits the large number of events recorded by a single station as a mean to gain a better knowledge on the parameters that do not change between events (i.e. density and viscosity of the magma, radius of the conduit, elasticity of the rocks constituting the volcanic edifice) by applying a Bayesian approach. As the number of events recorded increase, this method can reduce the variability of the estimate of invariant parameters, allowing a better assessment of mass and volume of gas involved, which instead are varying between explosions and are directly linked to the power of the events.

To address the limitations related to simplified numerical models, such as the one described in Chapter 2, we have designed an analogue experimental setup to replicate the Strombolian activity associated to the rise of gas slugs in an elastic conduit. Firstly, we analysed the dynamic of the slugs and the resulting deformation of the conduit by using a technique called particle image velocimetry (PIV) to track the displacement of the liquid and the solid phase. This approach, described in Chapter 3, allows us to have an open window on the complex three-phase interaction happening in the system (gas/liquid/solid) and provides new insights into the conduit dynamic. Secondly, in Chapter 4, we extend this knowledge to analyse the coupling between the deformation observed in the conduit and the displacement measured at the surface by mean of photogrammetry techniques. The innovation of this study is that the deformation of the solid medium related to slug rising with a conduit will be measured for the first time in a gelatin-based analogue model. The

results obtained by this simulation will be finally used to evaluate the uncertainties of the numerical model described in Chapter 2 and eventually provide useful information to improve the model.

1.4.2 Detection and assessment of volcano explosivity from GNSS-TEC

To support the remote sensing techniques currently applied to detect explosive eruptions, and to overcome the limitations related to complex environmental and meteorological conditions, we propose the application of the methodology known as GNSS ionosphere sounding (Jin et al., 2014). This method is based on the observation that powerful blasts, including volcanic eruptions, strong earthquakes, or even nuclear explosions, generate acoustic-gravity waves, which propagate upward in the atmosphere and perturb the ionospheric plasma density (Occhipinti, 2016).

As described in Chapter 5, ionospheric perturbations consist on the alteration of the ionospheric Total Electron Content (TEC) density, and they can be detected by using the available Global Navigation Satellite Systems (GNSS) as far as 1000 km from the source. Indeed, perturbations create noise in the communication signal travelling between the ground-based GNSS stations and the overlooking satellites which can be easily identified. Perturbations in the ionospheric TEC have been observed for a number of large earthquakes (e.g., Calais & Minster, 1995) and more recently for tsunamis (Artru et al., 2005; Occhipinti et al., 2006); the ionospheric signatures of those events have been detected (Occhipinti et al., 2013) and explored to estimate the tsunami risk and the seismic magnitude (Occhipinti et al., 2018). The analysis of TEC has also revealed perturbations after volcanic eruptions at Pinatubo Volcano (Cheng & Huang, 1992; Igarashi et al., 1994), Asama Volcano (Heki et al., 2006), Soufriere Hills Volcano (Dautermann et al., 2009) Calbuco Volcano (Shults et al., 2016) and Kelud Volcano (Nakashima et al., 2016). In this thesis, we evaluate whether the ionosphere monitoring can provide additional information to complement the existing monitoring system. To this end, in Chapter 5, we analysed the relationship between a metric related to the energy of atmospheric disturbances, called TEC Intensity Index (TECII), and several well-known metrics obtained by seismology, satellite remote sensing.

Chapter 2

Bayesian approach to infer time and amplitude of Strombolian explosion using a single tilt station

As introduced in Chapter 1, inverting techniques on geodetic datasets have been used to retrieve information about key parameters controlling the style of volcanic eruptions. However, up to date, the combination of multiple datasets is often required to obtain reliable estimates of the physical parameters, hindering the possibility to provide forecasting tools for time and magnitude of eruptions at volcanoes with limited monitoring network. In this chapter, we present a new approach for extracting valuable information out of limited number of sensors, exploiting the high frequency of events. Time series of tilt signals recorded by a single station are used to estimate, by mean of the Bayesian statistics and a physics-based model, the range of the controlling parameters. The information obtained could enhance the monitoring systems of those volcanoes characterized by frequent and potentially dangerous events.

2.1 Motivations

In order to enhance the current techniques for estimating volcanic system properties and time of eruptions in persistently active volcanoes, there is the need of new methods to provide a reliable estimate while operating with a minimal number of stations. We provide initial evidence on the feasibility of using the estimate of the controlling parameters, obtained by means of the Bayesian statistics and a physics-based model, to infer the explosion magnitude and timing.

Tilt observations recorded during the Strombolian activity of Semeru volcano, Indonesia, are chosen as test data. They present a very short time displacement of the volcanic edifice regardless of the amplitude of the event, as described by Nishimura et al. (2012). The authors report that, during a period of three weeks in 2010, thousands of gas burst events have been observed and recorded by a single tilt station located 500 m from the active vent. While the amplitude of the tilt signal was found to be proportional to the associated seismic energy, the duration of the inflation, starting ~ 30 s before the eruptions, remains fairly constant regardless of the amplitude, suggesting the gas content as a major controlling parameter for the intensity of an explosion without affecting

the duration of the process. This kind of activity observed at many volcanoes (e.g., Stromboli, Sakurajima, Suwanosejima and Fuego) is considered to be associated with a gas motion and accumulation into the volcanic conduit, which induces pressure perturbations in the magma column that results in the deformation of the surrounding rocks and the surface (Genco & Ripepe, 2010; Nishi et al., 2007; Nishimura et al., 2012).

Table 2.1. Parameters in the system of equations. The parameters marked by a star are the one we want to estimate in this work.

Parameter Description	Symbol	Value or Range	Unit
<i>Magma Density*</i>	ρ	<i>2000 to 3000</i>	<i>kg/m³</i>
<i>Magma Viscosity*</i>	μ	<i>10² to 10⁵</i>	<i>Pa.s</i>
<i>Shear Modulus*</i>	G	<i>10⁹ to 10¹²</i>	<i>Pa</i>
<i>Poisson's Ratio</i>	ν	<i>0.25</i>	<i>-</i>
<i>Gravity</i>	g	<i>9.81</i>	<i>m/s²</i>
<i>Atmospheric Pressure</i>	P_{atm}	<i>10⁵</i>	<i>Pa</i>
<i>Radial distance tilt station</i>	R	<i>500</i>	<i>m</i>
<i>Conduit Radius*</i>	r_c	<i>5 to 50</i>	<i>m</i>
<i>Gas Mass*</i>	M	<i>10³ to 10⁷</i>	<i>kg</i>
<i>Magma Level*</i>	c	<i>50 to 500</i>	<i>m</i>
<i>* The parameters we want to estimate in this chapter.</i>			

Volcanoes that exhibit this type of activity have an unpredictable nature that may constitute a hazard for the numerous tourists and scientists that visit them in high number. The development of a system able to infer exceptional explosive events could provide enough time to issue an alert. A recent study (Kato et al., 2015) showed that tilt and seismic observations would have been capable to capture precursors as early as 10 min prior to the Ontake 2014 phreatic eruption, providing enough time to raise the alarm. An early warning system for short-term explosion forecast, based on real-time tilt detection has been proposed (D'Auria et al., 2006), showing that alert level can be triggered 45 s before the blast using eight stations. However, many volcanoes have a limited monitoring network, and new approaches are necessary to extract valuable information out of limited datasets.

The work is structured as follow: 1) Model development to link several parameters of the volcanic system to the surface displacement; 2) Parameter estimation constraining the variability of those

parameters that are not evolving in a short time; 3) Parameter exploitation in a routine to forecast the time and magnitude of future events.

The forward model is used to link the deformation associated to the rise of a slug, (defined as a “large bubble” or “gas pocket” which has reached the size of the conduit), to its controlling physical parameters. The parameters include the varying mass of gas involved (M), and the physical parameters defining the volcanic system: density (ρ) and viscosity (μ) of the magma; Shear modulus (G) of the host rock; radius of the conduit (r_c) and the depth of the magma free surface (c) (Table 2.1). The range of variability of the different parameters used in this chapter is based on values reported in the literature. For the magma density, we have adopted a range that allows encompassing magma with different compositions (Murase & McBirney 1973), for the magma viscosity, we have selected range, which accounts for pre-eruptive basaltic to rhyolitic melts (Takeuchi 2011). For the shear modulus, we have chosen a range that incorporates values for competent rocks (e.g., Dzurisin, 2006, p. 281 Heap et al., 2009; Rocchi et al., 2004; Villeneuve et al., 2018). For the conduit radius, we selected a range of values that align with the values reported in the literature (Kolzenburg et al., 2019). The model used, incorporates both the conduit model, developed by Bonaccorso & Davis (1999) and further improved by Kawaguchi & Nishimura (2015), and the model of slug ascent process in an open conduit based on the one proposed by James et al. (2008; 2009) which consider the slug dynamic described by Llewellyn et al. (2011).

This model is used in conjunction with Bayesian Inversion technique to estimate the controlling parameters of the deformation recorded by a single tilt station. To evaluate the improvement of the estimate of the parameters, after multiple events recorded, we applied a Joint Bayesian Inversion (JBI) to six synthetic tilt signals of three different amplitude and with two different levels of noise with features similar to the ones of the tilt data recorded during Strombolian events at Semeru volcano (Nishimura et al., 2012). The synthetic data were generated by our model assuming reasonable values for the parameters. These parameters comprise both fixed parameters, associated to the volcanic system which do not change between events (ρ , μ , G , r_c , c), and the mass of gas free to change between events (M).

The outcome of the JBI consist in the fixed parameters and three separate gas masses which best fit the three synthetic signals with the same noise level at once. We demonstrated that, by analysing

events of different amplitude, the inversion technique can improve the estimation of the model parameters even in presence of a high noise level. Further, we applied the methodology to three events of different scale at Semeru (reported by Nishimura et al., 2012), for which we obtain reasonable values for all parameters.

Finally, we used the fixed parameters estimated by the JBI as prior information for the inversion technique of new signals to test the possibility to perform eruption forecasting using tilt data recorded by a single station. We replicated a real-time scenario where a tilt station is acquiring data from which the last five minutes are continuously compared to the signal generated by the model using known prior information and a variable gas mass. The best fitting signal was then used to forecast the time and magnitude of the explosion. A preliminary analysis of the accuracy and precision of the estimates in presence of noise was performed considering 8 signal in each of three levels of noise. Results support our hypothesis that the proposed methodology, which has the advantage of working on observation recorded by a single station, can be a useful tool for parameter estimation and eruption forecasting of Strombolian eruptions complementing volcano monitoring and alert system.

2.2 Materials and methods

2.2.1 Tilt observations

In open vent systems, geophysical signals such as tilt, recorded at a short distance from the vent, are well known to provide key information about the dynamic of the shallow portion of the conduit. Due to the high frequency of explosive events, this information can be used to forecast timing and intensity of future events. The ground deformation that appears just before Strombolian activity has been reported at many volcanoes using precise tilt observations with an angular accuracy down to the nanoradian (Genco & Ripepe, 2010; Iguchi et al., 2008; Kamo & Ishihara, 1989; Lyons et al., 2012; Nishi et al., 2007; Nishimura et al., 2012; Wiens et al., 2005). A common feature of these signals is the duration, that appears to be short (order of minutes), and the amplitude of the signal (1-10 nrad). For instance, in Stromboli volcano, the explosive process is accompanied by a consistent deformation of the ground (~100 nrad) starting about 200 s before eruptions, associated with processes of gas recharge and discharge in the conduit.

Figure 2.1. Stacked tilt records for gas burst eruptions recorded at Semeru volcano (modified from Nishimura et al., 2012). Each grey line represents stacked tilt records for events with different magnitudes of explosion: High amplitude (H), Medium amplitude (M) and Low amplitude (L). Black lines represent the tilt records averaged over 6 s.

In Semeru volcano, Indonesia, from March 15 to April 2, 2010, tilt signal related to 1000 small gas bursts were recorded by a single tilt station located at 500 m from the summit crater (Nishimura et al., 2012). The signal shows that the inflation started about 30 s before each explosion with tilt amplitude of tens of nanoradian (nrad). Nishimura et al. (2012) shows that the signal recorded can be categorized into groups based on the amplitude. By stacking the tilt signal related with different eruptions, they first reduced the effect of unknown long-period noise and long-term drift in the tilt signals, then they set the onset time of each eruption as the time at which the initial phase of the explosion earthquake is recorded at the summit seismic station. Figure 2.1 shows the groups, extracted from Nishimura et al. (2012), which were considered in this work: H, M and L.

2.2.2 Forward model

The model presented here relates pressure perturbations, due to a slug rising within the conduit, to stresses and strains in the host-rock (Bonaccorso & Davis, 1999; Kawaguchi & Nishimura, 2015). We assume that the rise of a gas slug in the stagnant magma causes a perturbation in the initial stress field and consequently displacement of the ground surface. In order to compute the elastic Green's function, we need to use a numerical method, which includes dynamics and physical properties of the system in order to predict the surface deformation.

Figure 2.2. Model of ascending gas slug within stagnant magma in an open conduit. (a) Schematic of a slug ascending in an open conduit at two different subsequent times (modified from James et al., 2008). Grey areas are occupied by the magma, and white by the gas phase (b) The ascent of a gas slug calculated by using the dynamic pressure model (solutions to equation 11 proposed by James et al., 2008) and the depth at which the slug becomes unstable (h_{slim}).

In this section, we firstly present the temporal evolution of the slug in relation with changes of pressure within the conduit as it rises toward the surface (Del Bello et al., 2012; James et al., 2008; James et al., 2009; Llewellyn et al., 2011; Nogueira et al., 2006a). Secondly, we explore in details how the pressure perturbation relates to the surface deformation.

2.2.2.1 Slug ascent model

In the initial condition (time = t_0) a cylindrical open conduit of radius r_c and infinite length along z axis is filled with stagnant magma. The conduit is further divided into different portions: c_0 , empty conduit; h_0 , initially occupied by the magma; and L_0 (which also corresponds to the initial length of the slug), occupied by the slug (Figure 2.2a). We assume that, at t_0 , the slug has a length equal to the maximum diameter it can take, $2r_s$, where r_s refers to the steady-state slug radius.

From previous studies, r_s has been defined as a function of the magma film thickness λ developing around the slug. Llewellyn et al., (2011), shows that λ is a function of the inverse viscosity $Nr = \frac{\rho}{\mu} \sqrt{gD^3}$, where D is the diameter of the conduit.

The initial depth of the slug head is $z_2 = h_0 + c_0$, which is function of the mass of gas within the slug (M) and its initial volume $V_0 = \pi r_s^2 L_0$ (Figure 2.2a). Considering a slug of water vapor under isothermal conditions ($P_0 V_0 = M R_w T$, where, P_0 is the initial pressure of the slug, V_0 is the initial gas volume, M is the mass of gas, T the temperature and R_w the specific gas constant for water

vapor), by fixing an initial value of gas mass, and conduit radius, we can find the value of h_0 and consequently the initial depth z_2 as follow:

$$h_0 = \frac{MR_w T}{\rho g V_0}. \quad (2.1)$$

The initial gas pressure of the slug P_0 , can be also expressed as the sum of the magma-static pressure related with the above column of magma with initial thickness h_0 , and the atmospheric pressure P_{atm} :

$$P_0 = \rho g h_0 + P_{atm}, \quad (2.2)$$

where, ρ is the density of the magma. Assuming that at t_0 the system is in equilibrium and there is no magma flux from the bottom of the conduit, no shear stress is applied to the conduit wall.

At time $= t_n$ the slug is rising and expanding within the stagnant magma perturbing the initial pressure equilibrium condition P_0 . Hence, following Kawaguchi & Nishimura (2015), we express the pressure with time, at the top of the slug P_s as:

$$P_s = P_0 \frac{L_0}{L}, \quad (2.3)$$

where, L is the new slug length (Figure 2.2a). The ascent velocity of the slug, U_s , has been derived from Goldsmith and Mason (1962) to solve the Navier-Stokes equation for laminar flow in a film around a Taylor bubble. The relationship between the ascent velocity and the thickness of the falling film was then extended by Brown (1965) to obtain:

$$U_s = \frac{2\rho g \lambda^3}{3\mu(r_c - \lambda)}. \quad (2.4)$$

As the slug ascends in the conduit with velocity U_s , the pressure at the top of the slug decreases and as consequence its volume increases. With initial distance between magma surface and top of the slug h_0 , conservation of liquid volume at any given time yields, according to James et. al. (2008), to:

$$h_0 \pi r_c^2 + L_0 \pi (r_c^2 - r_s^2) = (h + s) \pi r_c^2 + L \pi (r_c^2 - r_s^2), \quad (2.5)$$

where, s is the distance between the slug base and its initial position, and h is the time-dependent height of the fluid above the slug. Simplification of the above equation by James et al. (2008) allows h to be expressed as:

$$h = h_0 - s - (L - L_0)A, \quad (2.6)$$

where, $A = 1 - \left(\frac{r_s}{r_c}\right)^2$. Considering a slug with a constant base velocity s can be defined at any time t , as the product $U_s t$. The time dependent slug length and position are derived from the relation between slug expansion and forces acting in the conduit. Following James et al., (2008; 2009), the acceleration of the liquid above the slug can be defined in terms of the pressure, gravitational and viscous forces acting on the liquid cylinder, given by:

$$F_p = -\pi r_s^2 (P_s - P_{atm}); \quad (2.7)$$

$$F_g = \pi r_s^2 \rho g h; \quad (2.8)$$

$$F_v = 8\pi\mu h \bar{v}, \quad (2.9)$$

where, $\bar{v}$ represents the mean velocity in the region of the conduit above the slug assuming a Poiseuille flow. Following James et al. (2008), and assuming that the volume flux of the liquid above the slug is equal to the gas expansion, equation 2.9 can be rewritten as:

$$F_v = 8\pi\mu h \frac{dL}{dt} \frac{r_s^2}{r_c^2}. \quad (2.10)$$

Equating the product of mass and acceleration of the centre of mass of liquid column directly over the gas slug, to the sum of forces gives:

$$\pi r_s^2 \rho h \frac{d^2 (l_c - U_s t - L - \frac{1}{2} h)}{dt^2} = F_p + F_g + F_v, \quad (2.11)$$

where, l_c represents the length of the conduit from the surface to the base of the slug (Figure 2.2a). Substituting for the forces and using equation 2.6 to define h in terms of L , by expanding the differential we can define L as follows:

$$\frac{d^2L}{dt^2} = \frac{2}{\rho(2-A)} \left[\frac{P_0 L_0}{Lh} - \rho g - \frac{P_{atm}}{h} - \frac{8\mu}{r_c^2} \frac{dL}{dt} \right]. \quad (2.12)$$

By solving the second-degree differential equation numerically in *Matlab*[®], using an explicit *Runge-Kutta* formula, the positions of the slug and liquid surfaces is obtained (Figure 2.2b). The above parameters allow the modelling of the slug dynamics from the initial conditions to the time there is an insufficient volume of liquid between the surface and the slug to maintain a static pressure balance between the gas in the slug and to fill the liquid annulus surrounding it.

Figure 2.3. Time-dependent pressure gradient within the conduit (modified from Kawaguchi & Nishimura, 2015). (a) Comparison between pressure gradient at time = t_0 when the slug is deep, and time = t_n when the slug is approaching the surface. (b) Differential pressure highlighting the presence of two different pressure domains within the conduit: In red an overpressured domain in the region from the magma surface to the centre of mass of the slug; In blue the underpressured domain in the region from the base of the conduit to the centre of mass of the slug.

Accordingly, James et al. (2009) derived a parameter, P_{slim} , from a static-pressure model that allows to determine the stability of a slug, at any position, against a small perturbation ΔL , in its length. P_{slim} corresponds to the gas slug pressure immediately prior the failure of the static pressure model, after which the slug cannot be described under the assumption of purely static condition, and hence dynamic pressurization, cannot be disregarded. P_{slim} is obtained as:

$$P_{slim} = \sqrt{\rho g A P_0 L_0}. \quad (2.13)$$

This static pressure limit can also be described in terms of the liquid height above the slug's head (Figure 2.2b) at which the slug becomes unstable (James et. al., 2009):

$$h_{slim} = \sqrt{\frac{AP_0L_0}{\rho g}} - \frac{P_{atm}}{\rho g}. \quad (2.14)$$

As the slug rises in the conduit, it expands and lifts up the melt located above it. Consequently, the differential pressure from the initial condition increases in the conduit region above the slug. While in the region beneath the gas slug, the magma pressure becomes smaller than the initial pressure due to the low-density region generated by the rising. The region occupied by the slug is therefore a transition zone between those two regions. The magma pressure, shown in Figure 2.3, increases in the conduit with depth according to the bulk density of the magma (Kawaguchi & Nishimura, 2015), consisting of melt and slug as follows:

The regions above and below the slug ($z_1 < z < z_2$; $z_3 < z < z_4$) are characterized by large pressure gradient that is determined from melt density:

$$\frac{dP}{dz} = g\rho; \quad (2.15)$$

The region comprising the slug ($z_2 < z < z_3$) is characterized as a low-density region so that the pressure gradient is smaller:

$$\frac{dP}{dz} = g\rho A. \quad (2.16)$$

This pressure difference affects the normal stress field acting in the conduit wall, resulting in the deformation of the wall surface and the consequent displacement of the ground surface.

Figure 2.4. Shear stress on the conduit wall relates to the slug rising in the conduit at time = t_n . (a) Conduit regions where the shear stress is acting, where T_s represents the shear stress related to the slug rising in the stagnant magma and T_m is the shear stress related to the uplift of the magma surface due to the slug expansion. (b) Velocity profile in the conduit where V_m represents magma velocity above the slug, and V_{film} the magma velocity flowing between the slug and the conduit wall.

We can identify two regions within the conduit where the shear stress can be originated during the slug ascent, as depicted in Figure 2.4: first, the downward flow of viscous magma film around the slug rising generates shear stress on the conduit wall, as reported in experimental studies by Nogueira et al. (2006a); second, as a consequence of the slug length expansion, which follows the conservation of liquid volume law, the magma located at the surface migrates upward, resulting in a shear stress on the wall with an opposite direction. From Newton's law of viscosity, the shear stress can be expressed by the differential equation:

$$T = -\mu \frac{dV}{dr}, \quad (2.17)$$

where, μ is the magma viscosity and dV/dr is the magma velocity profile. Following Nogueira et al. (2006a) and Brown (1965), we can describe the velocity profile of the magma film surrounding the slug as (Figure 2.4a):

$$V_{film} = \frac{\rho g}{\mu} \left[\frac{r_c^2 - r^2}{4} - \frac{r_s^2}{2} \ln \left(\frac{r_c}{r} \right) \right]. \quad (2.18)$$

By substituting and differentiating this equation, we obtain the shear stress gradient in the region around the slug:

$$T_s = -\rho g \left(\frac{r_s^2}{2r_c} - \frac{r_c}{2} \right). \quad (2.19)$$

Considering a laminar flow under Poiseuille Law, the velocity profile in the region above the slug can be expressed as (Figure 2.4b):

$$V_m = 2\bar{v} \left(1 - \frac{r^2}{r_c^2} \right). \quad (2.20)$$

Figure 2.5. Model setting for surface displacement induced by an ascending gas slug in an open conduit filled with magma. (a) The shear stress component of the ground deformation U_τ calculated using the Boussinesq solution. (b) The normal stress component of the ground deformation U_σ observed at the surface is attributed to the conduit wall deformation b induced by the pressure gradient ΔP .

Considering the volume flux of the liquid above the slug is equal to the gas expansion, equation 2.20 can be rewritten:

$$V_m = 2 \frac{dL}{dt} \left(\frac{r_s^2}{r_c^2} \right) \left(1 - \frac{r^2}{r_c^2} \right). \quad (2.21)$$

By substituting and differentiating this equation, the shear stress gradient in the region above the slug is:

$$T_m = \mu 2 \frac{dL}{dt} \left(\frac{2r}{r_c^2} \right). \quad (2.22)$$

The sum of the shear stress components T_m and T_s causes a vertical deformation of the conduit wall that results in a minor contribution of the surface displacement, as demonstrated by Kawaguchi and Nishimura (2015): the shear stress displacement component was found to be several orders of magnitude smaller than the normal stress component. In this work, however, we consider the shear stress effects because this component appears to be not negligible as the station is closer to the vent.

Ground displacement model

The vertical displacement at the horizontal ground surface is obtained applying an approach similar to the analytical solution developed by Bonaccorso and Davis (1999) for the displacement field caused by magma rising in an open conduit (Figure 2.5b):

$$U_\sigma(t) = r_c \int_{z_1}^{z_4} b(z, t) \left[\frac{z}{R^3} - \frac{z}{2} \left(\frac{3z^2}{R^5} - \frac{2\nu}{R^3} \right) \right] dz, \quad (2.23)$$

where, b represents the deformation of the conduit wall across the conduit of radius r_c ,

$$b(z, t) = \frac{\Delta P(z)}{G} r_c, \quad (2.24)$$

where, $R = \sqrt{r^2 + z^2}$ and r is the horizontal radial distance between the vent and the hypothetical geodetic station measuring the deformation. ν is the Poisson's ratio and G is the shear modulus of the elastic medium. ΔP is the differential pressure with respect to the initial condition, see paragraph 3.1.3 and Figure 2.3a.

The tilt is calculated by differentiating the vertical component U_σ with respect to the radial distance r :

$$Tilt_{\sigma} = -\frac{dU_{\sigma}}{dr}. \quad (2.25)$$

As the gas slug is rising within the stagnant magma, the pressure acting on the wall and the resulting deformation of the conduit wall b is not constant. We can divide the conduit in 3 different domains depending on the deformation trend (Figure 2.5b): a region located above the slug where the overpressure linked to the slug pushing the magma upward induces a general positive deformation, a region located below the slug where the underpressure causes a contraction of the conduit induces in a negative inward deformation, and a third region corresponding with the portion of the conduit occupied by the slug considered as transition region between the two.

To calculate the ground deformation attributable to the shear stress acting on the conduit wall, we apply the Boussinesq's solution (Figure 2.5a). As suggested by Nishimura (2009), by assuming that the conduit radius is small compared to the distance from the vent to the measuring station, we can approximate the shear stress as a vertical point force. From Boussinesq (1885) we can then estimate the vertical stress contribution σ_z , acting at a hypothetical point A located at depth (Figure 2.5a) due to the point force (F) applied at the point load o located at the surface:

$$\sigma_z = \frac{3F}{2\pi} \frac{z^3}{R^5}, \quad (2.26)$$

where, z represents the vertical distance between p and x , R represents the direct distance (see panel in Figure 2.5a). From the generalized Hooke's law, which described the relation between stress and strain as function of the elastic properties of the medium, we can express the vertical deformation U_{τ} at the point x as:

$$U_{\tau} = \sigma_z \frac{1}{2G} \left(\frac{1-2\nu}{1-\nu} \right). \quad (2.27)$$

In our case, the problem is reversed, the force load is acting at depth, and the vertical stress is calculated at a point located at the surface (Figure 2.5a). By substituting F with the shear stress T in equation 2.26, and combining it with equation 2.27, we obtain:

$$U_{\tau} = \frac{3T}{4\pi G} \frac{z^3}{R^5} \left(\frac{1-2\nu}{1-\nu} \right). \quad (2.28)$$

Simplifying the previous equation and integrating, for both slug and magma, over the vertical distance we find:

$$U_{\tau}(t) = \int_{z_2}^{z_3} s_s(z, t) \left[\frac{z^3}{R^5} \left(\frac{1-2\nu}{1-\nu} \right) \right] dz + \int_{z_1}^{z_2} s_m(z, t) \left[\frac{z^3}{R^5} \left(\frac{1-2\nu}{1-\nu} \right) \right] dz, \quad (2.29)$$

where:

$$s_s(z, t) = \frac{3T_s(z, t)}{4\pi G} \quad \text{and} \quad s_m(z, t) = \frac{3T_m(z, t)}{4\pi G}. \quad (2.30)$$

The tilt is then calculated by differentiating the vertical component U_{τ} with respect to the radial distance r :

$$Tilt_{\tau} = -\frac{dU_{\tau}}{dr}. \quad (2.31)$$

The total tilt is given by the sum of the two tilt components:

$$Tilt = Tilt_{\sigma} + Tilt_{\tau}. \quad (2.32)$$

2.2.3 Statistical inference

Inversion of monitoring data has been extensively used in geoscience as a method to estimate parameters controlling the behaviour of the observed natural system. Within the different techniques available, the Bayesian inversion is frequently used to estimate model parameters (Anderson & Segall, 2013; Segall, 2013). In Bayesian statistics, the main principle is that the probability associated with a given set of model parameters ($\mathbf{m}$) is a function of how well these parameters are able to explain the observed data ($\mathbf{d}$). This probability is weighted depending on uncertainties of both the model and the observations. Any additional a priori information that may be available is used to constrain the range of values for each parameter. This conditional probability is known as posterior distribution and is calculated using Bayes' Theorem:

$$P(\mathbf{m}|\mathbf{d}) \propto P(\mathbf{d}|\mathbf{m}) \cdot P(\mathbf{m}), \quad (2.33)$$

Where, the likelihood function $P(\mathbf{d}|\mathbf{m})$ measures the fit between the model predictions and the observed data and $P(\mathbf{m})$ encodes prior information on the model parameters. If no prior information is available the Bayes' Theorem can be simplified as $P(\mathbf{m}|\mathbf{d}) \propto P(\mathbf{d}|\mathbf{m})$. Here we define as $\mathbf{d}$ the data vector that includes the observations such as the tilt time series. The vector $\mathbf{d}$ is a function of the model parameters $\mathbf{m} = [\mathbf{m}_1, \mathbf{m}_2, \dots, \mathbf{m}_n]$, plus a Gaussian error such that $\mathbf{d} = \mathbf{\Gamma}(\mathbf{m}) + \mathbf{error}$, where the function $\mathbf{\Gamma}$ is the forward model described in section 2.3. This simple equation states that the

observed data can be predicted by Γ and may include diverse time-varying datasets (the datasets used in this work are described in section 2.2).

In this study, the set of key parameters include density (ρ) and viscosity (μ) of the magma, the conduit radius (r_c), the mass of gas (M) and initial level of magma (c) in the conduit, since they control the spatial and temporal variation of the stress component within the conduit. Another important parameter controlling the deformation is the shear modulus of the host rock (G). Therefore our set of model parameters is express as:

$$\mathbf{m} = [G, \rho, \mu, r_c, c, M]. \quad (2.34)$$

The best fitting model will correspond to the maximum of the Probability Density Function (PDF). Each point of the PDF is associated with a different set of model parameters $\mathbf{m}$. To find the combination that gives the best fit we use a sampling technique known as Markov Chain Monte Carlo (MCMC). MCMC sampling allows for an efficient characterization of posterior probability distributions by sampling the model space according to a probability distribution that is the closest to the posterior distribution, such that sets of parameters consistent with both prior information and the fit-to-data are picked more often than incompatible, or low-probability, models (Mosegaard & Tarantola, 1995). The Metropolis-Hastings rule (Hastings, 1970; Metropolis et al., 1953) is perhaps the most important technique for controlling the random walk such that, after a large number of iterations, the density of samples begins to approximate the posterior probability distribution itself.

Following this approach, a set of candidate model parameters $\mathbf{m}^*$ is generated from the current set of model parameters $\mathbf{m}_j$ (j indicates the step number) by perturbing each parameter of $\mathbf{m}_j$ by an amount $s_n \Delta m_n$, where s_n is a random number generated from a uniform distribution on the interval $[-1, 1]$ and Δm_n is the random walk step size for the n -th parameter. The next set of model parameters $\mathbf{m}_{j+1}$ is then chosen according to the acceptance test as follow:

$$\frac{P(\mathbf{m}^*|d)}{P(\mathbf{m}_j|d)} \geq w^*, \quad (2.35)$$

where, w^* is a random number generated from a uniform distribution on the interval $[0, 1]$. Candidate models that improve upon the probability of the current model are always accepted,

while candidate models with lower probability may or may not be accepted (allowing the inversion to escape from local minima). The step size Δm plays an important role in the convergence toward final values of m and can be optimized by calculating the percentage of models accepted. While there is no ideal theoretical value, several studies suggest that less than 50% acceptance rate is appropriate (Gamerman & Lopes, 2006), but very small acceptance rates are not efficient so trial-and-error may be required. To further reduce the risk to be stuck in a local maximum of probability we apply a technique known as “*simulated annealing*” (Mosegaard & Tarantola, 1995). This technique consists on including a temperature parameter during the MCMC, that affect the acceptance test described in the previous equation by initially maximizing the acceptance rate to 100%. Following a sigmoid trend, the acceptance rate then decreases to 0% as the solution converges. After the best fitting model has been found, we apply a refining MCMC cycle to explore the model space in the area surrounding the best solution. As a result, we obtain the Probability Density Function PDF for each of the model parameters.

Figure 2.6. Synthetic tilt signal, for a station located 500 m from the vent, related to the rise within the conduit of three slugs with different gas mass. (a) Table of parameters used to generate the three signals without noise. (b) Plot of the synthetic signals. The reference time, $t = 0$ s, corresponds to the slug reaching the depth at which it becomes unstable (h_{slim}). The vertical dash line corresponds to the time at which the three slugs cross the same reference depth. (c) Graphic

representation of the conduit geometry and slug size related to the three signals, dashed line represents a given reference depth z_n .

2.3 Parameters estimation

We have applied a Bayesian approach to predict the value of the controlling parameters related to a volcanic system from a model linking conduit processes with tilt signals recorded at the surface. Assuming that no prior information of the parameters is available, we consider $P(m) = I$ meaning that initially all values, within a given range, for each model parameters are equally possible and they follow a uniform distribution.

2.3.1 Synthetic tilt signal

We initially generated three synthetic tilt signals with different initial masses of gas, so that the final amplitude mimics the different scale of the data recorded at Semeru volcano during Strombolian eruptions (see section 2.2). To simulate similar observational conditions of Semeru volcano, all the synthetics were calculated mimicking a station located 500 m from the vent, and a noise equal to 10% and 100% of the mean level is added to the signal to reproduce the non-negligible noises observed in real tilt records. This initial step is necessary to optimize the inverse method proposed and quantify the uncertainties. Considering the short time interval between explosions observed in Semeru (few minutes), we assume that parameters related to the conduit properties (i.e. radius r_c , magma level c , and shear modulus G) and parameters related to the magma properties (i.e. viscosity μ , density ρ) do not significantly change between events. The gas mass M_i is therefore considered to be the main controlling parameter for the differences observed in the tilt signals (d_i):

$$d_i = \Gamma(G, p, \mu, r_c, c, M_i) + \text{random noise}, \quad i = (1, 2, 3). \quad (2.36)$$

The sets of parameters used to generate the three synthetic signals in each noise level are shown in Figure 2.6a. The different initial masses of gas released at t_0 result in different initial slug depths. Initial slug depth is assumed when the length of the slug is equal to the diameter of the conduit, as discussed in paragraph 2.2.1.1 (Figure 2.6b, c). The length of the slugs increases with decreasing depth, and at a given reference depth z_n the three slugs will have different sizes that are proportional to the initial gas masses. Similarly, the tilt amplitude of the signal at the time of the burst, $t = 0$ s, shown in Figure 2.6b, is proportional to the initial mass of gas.

2.3.1.1 Bayesian Inversion on single events

We apply the inversion technique independently to the three different synthetic signals to retrieve the best set of independent parameters fitting each time series. In order to evaluate the stability of the parameter estimation in presence of noise, the inversion was performed on two synthetics with noise equal to 10% and 100% of the mean value of the tilt signal. Figure 2.7 (white panel) shows the distribution, in the form of box plots, for individual parameters obtained after the application of the Bayesian inversion for the different synthetic signals. We define the error as:

$$Error = \frac{(measured\ value - true\ value)}{true\ value} \cdot 100 . \quad (2.37)$$

By comparing the results obtained by the inversion on the three synthetic signals independently, we can notice that despite errors in the estimation of the fixed parameters, the technique correctly reports decreasing values of gas mass as the amplitude of the signals decreases as shown in the lower panel of Figure 2.7). The left panel of Figure 2.7 shows the distribution of the estimates, where the different colours refer to the two signals with different noise levels. For a noise level equal to 10% of the mean value (yellow box plots), we obtained an overall mean error in the estimation of all the model parameters of $\pm 24\%$ compared to the true values for the high amplitude signal (H). The spread in the error is remarkably large, nonetheless, the true values lie within the interquartile box for most of the variables. No important skewness distribution has been observed and the variability for some parameters increases as the amplitude of the signal decreases. This increase is particularly visible for the mass of gas and magma level. Despite capturing relative variations of mass, errors are still remarkable: the estimated best values for the masses are 20%, 70%, 60% smaller compared to the true value for H, M and L respectively. Moreover, estimated errors for the fixed parameters show inconsistencies: for instance, the best value found for the magma viscosity has one order of magnitude of variability between H and M with estimated values of about 6000 Pas and 600 Pas respectively. Worse estimations are observed for the synthetics in the 100% noise levels, represented by the red box plots in Figure 2.7. An important variability in the best estimates can be observed especially for the low amplitude signal (L), for which it is clearly visible that the error increases as the noise level increase. These observations highlight the instability of the model when operating independently on the different signals. To reduce the variability in the parameter estimation and inconsistencies, we applied the Joint Bayesian Inversion (JBI) as described in the next section.

2.3.1.2 Joint Bayesian Inversion

The Joint Bayesian Inversion (JBI) approach consists in the application of the inversion technique simultaneously on the three different signals (d_1, d_2, d_3) with three curves generated with the same set of fixed parameters and three independent gas masses (m_1, m_2, m_3). The quality of the inversion is based on the assumption that the total likelihood $P(d|m)$, which measures the fit between the data and the model prediction, is equivalent to the sum of the single likelihood obtained from the fitting of the three different signals and the three curves generated with the model:

$$P(d|m) = P(d_1|m_1) + P(d_2|m_2) + P(d_3|m_3). \quad (2.38)$$

Error plots for the estimated parameters by the JBI are depicted in the grey panel of Figure 2.7. The error distributions obtained by the JBI result generally closer to the zero-error line, in green, suggesting better accuracy compared to the independent inversion, and its distribution is drastically reduced. We can also observe that the noise level does not affect the estimation of the parameters. For a 10% noise level, the mean overall error, between best value and true value, results to be $\pm 23\%$ for the fixed parameters and is reduced to $\pm 4\%$ when excluding the magma viscosity, that exhibits a large spread in its estimation. The larger variability observed on the density estimation suggests a lower sensitivity of the model to variation of this parameter. The overall spread in the distribution is improved regardless of the amount of noise, suggesting higher confidence in the parameters estimation due to the increased number of observations and a better stability of the model when operating in JBI mode. This principle will be used as base for designing the forecasting tool described in section 2.4.

2.3.2 Comparison between synthetics and natural system (Semeru)

We applied the JBI technique on stacked tilt records from events with different explosive magnitudes at Semeru volcano recorded between March 15 and April 2, 2010 (Figure 2.1).

Figure 2.7. Box plots of the normalized errors for each parameter for inversion on synthetics with respectively 10% (yellow), and 100% (red) of noise level. Within the white background are represented errors related to the independent inversion on the synthetics H, M and L signals. Within the grey background are represented errors obtained applying the JBI. Green horizontal lines represent the true value which correspond to zero error. Diamonds represent the value obtained for the best inversion, where the colour refers to the noise level of 10% (yellow), and 100% (red).

Results of the JBI are shown in Figure 2.8, where a good fitting of the three different time series can be observed. The results confirm that the mass/volume of gas is a major controlling parameter to explain different magnitude of eruptions while other parameters remain constant across events. The estimated elastic modulus of 31 GPa is in agreement with previous estimations found in literature which attest that the shear modulus may vary greatly due to presence of fractured rocks from values <1 GPa to values > 40 GPa for more competent rocks (e.g., Dzurisin, 2006, p. 281 Heap et al., 2009; Rocchi et al., 2004; Villeneuve et al., 2018). We estimated a magma viscosity of $10^{4.9}$ Pa·s and density of 3000 kg/m^3 within the range of values commonly reported in the literature. Nishi et al. (2007) reported that, at Semeru, the magma has basaltic andesite composition ranging from 56 wt% to 57 wt% SiO_2 , and could have a viscosity of the order of 10^5 Pa·s, which is similar to the result of the JBI. Despite the estimation agrees with values in the literature, the JBI estimates have a large variability for this parameter. Figure 2.8 also shows that the JBI estimated an initial depth of the slug around 4600, 1500 and 900 m for H, M and L respectively, and an initial magma level (c) depth of ~ 400 m. The best-estimated conduit radius was ~ 25 m, corresponding to a slug with an initial volume of $3.2 \cdot 10^4 \text{ m}^3$ and a gas mass of $10^{6.2}$ kg for the medium amplitude event M. To the best of our knowledge, the only gas mass estimate at Semeru is from Smekens et al. (2014) with measurement done in 2013, three years after the recording of the tilts from Nishimura et al. (2012) used in the current study. Smekens et al. (2014) measured the SO_2 emissions at Semeru during single events finding values between 200 and 1460 kg. Accordingly, for an average magmatic arc gas composition ($\text{H}_2\text{O} = 95.6 \text{ mol\%}$, $\text{CO}_2 = 3 \text{ mol\%}$; $\text{SO}_2 = 1.4 \text{ mol\%}$, following values from Aiuppa et al., 2017; Burton et al., 2000; Fischer, 2008) we estimated that at Semeru for single events the expected total mass of gas should be between 10^3 - 10^4 kg. Those estimates are smaller than the one we obtained, which could be due to differences in the eruption phases, highlighting uncertainties in the SO_2 measurement. Subsequently, the slug starts ascending the conduit and only when it reaches ~ 900 m of depth the related pressure perturbation becomes significant enough to cause the increasing of the tilt signal (see z_n in Figure 2.6 and 2.8). As a consequence of the slug expansion, the magma level starts to rise until the slug reaches the critical depth h_{slim} at ~ 480 m (eq. 2.13) at which it bursts.

Figure 2.8. Best fitting model obtained by applying the JBI to tilt data recorded at Semeru volcano. Cross section of Semeru volcano with plots of the best estimation for conduit dimension, slug initial depth and dimension, and initial magma level. The red triangle represents the location of the tilt station. Right panels show three tilt signals extracted from Nishimura (2012) in black, where grey lines represent the noise, and the best fitting model, in green, obtained applying the JBI. Top panels show the box plots of the distribution for each of the estimated parameters.

2.4 Results and discussions

We designed a tool to forecast the time and amplitude of explosions based on the mass of gas involved. First, we considered that a series of events is acquired; we then employed the JBI to estimate the fixed parameters (Figure 2.9a). At this stage, we assumed that the system is well-

known and values for the shear modulus (G), viscosity (μ), density (ρ), conduit radius (r_c) and magma level (c) are fixed. Based on these fixed parameters, we generated an array of different tilt signals (called “*Model Tilts*”, see Figure 2.9b) exploring the whole range of gas masses (M). The proposed forecasting procedure is based on the last 300 s of data available (called “*Test Tilt*”, see Figure 2.9c) that are compared to the various *Model Tilts*. For each *Model Tilt* generated, we consider all the possible time windows including 300 s of continuous signal, here called “*Candidate Tilt*” (Figure 2.9d). All the *Candidate Tilts* are compared to the single *Test Tilt* in a search grid approach. Once all the segments (*Candidate Tilts*) of all *Model Tilts* are compared to the *Test Tilt*, the best fitting candidate is chosen and the corresponding *Model Tilt* is selected to determine the time of the eruption and the gas mass involved. At each time iteration, the values of time and amplitude within 50% from the max probability are plotted to represent the confidence interval (Figure 2.9e). The predicted time of the event is equal to the difference between the time of the last data point of the best *Model Tilt* and the time of the last data point available of the *Test Tilt*. This procedure is repeated continuously as new data are acquired by the system.

Figure 2.9. Schematic showing the procedure to forecast future events described in the text.

To test this method, we run a simulation using synthetic data. A hypothetical volcanic system, modelled with the properties shown in red in Figure 2.6a, is considered for this section. The workflow of the method is described as follow: tilt data are recorded by a single station in real-time, which initially consisted of a 300 s Gaussian noise signal set at 10% of the mean value, simulating a quiet state. The total length of the medium amplitude synthetic signal is 490 s. The last 300 s of the recorded data (*Test Tilt*), are fed every 19 s (time step size) to a search grid technique to estimate the time of explosion and gas mass. The time step size was chosen to be one-tenth of the total length of the synthetic signal initially modelled, which is 190 s. At the beginning of the simulation (Iteration #1), the test tilt window is capturing only the noise as shown in Figure 2.10. The technique employs the model to create an array of 500 *Model Tilts*, with the prior

knowledge of the fixed parameters provided in the earlier stage by the JBI and one of the 500 possible masses between 10^4 and 10^6 kg. Each of these curves, if shorter than the 300 s time window considered, is padded with zeros to ensure that the *Model Tilt* can be compared with the *Test Tilt*. *Candidate Tilt* of 300 s is obtained from a sliding 300 s window of the *Model Tilt*. The number of *Candidate Tilts* tested depends therefore on the length of the *Model Tilt*.

Figure 2.10 shows an example of forecast which is running on synthetic data: at iteration 1, the inversion on the tilt (zero signal with 10% noise) cannot detect a best fitting model, and results in a large distribution of possible gas masses with similar low values of likelihood. The best predicted values for the time and amplitude of the event (blue area in Figure 10), are divided into two main groups: one favouring large masses of gas and amplitude, and a second group of values converging to zero for both time and amplitude. On one hand, large masses of gas produce long deformation signals with an initial phase of low amplitude deformation that could fit the noise level of the signal tested, and on the other hand, negligible masses of gas produce short-lived signals that are padded with zeros (to ensure consistency in the duration of signal compared) and therefore produce a good fit to the noise level of the tested signal. As soon as data simulating a volcanic activity enter the 300 s window considered (e.g., Iteration 5 in Figure 2.10), the number of models that can fit the data decreases resulting in a more focus region of solutions localized at high values of amplitude and forecasted time. At iteration 8, the distribution of the best fitting models drastically decreases: the iteration stops and the best fitting curve (represented by the black lines in Figure 2.10), for which the PDF has a Gaussian distribution with a standard deviation lower than a threshold set to be 1% of the total range of variability in this example, is used to forecast the time and magnitude of the eruption. The time of the eruption at iteration 8 is expected to be 58 s after the last sample of the *Test Tilt*, which is equal to the time estimated by the best *Model Tilt*, resulting in an error between estimated and real eruption time equal to 0 s. To test the stability of the solution we run the method on 8 signals with the same noise level, which resulted in very similar solutions, i.e. the best *Model Tilt* was always detected 58 s before the eruption, and the estimated time had an error in the range of -2 to 1 s (mean $\pm$ SD = -0.3 ± 1.0 s), where negative errors indicate that the model estimate the eruption time before the real one.

Figure 2.10. Forecasting of time and amplitude of a hypothetical event with corresponding mass of gas involved. From top to bottom, the panels show three different time steps of our forecasting procedure. The dotted red lines represent a hypothetical tilt signal that is acquired in real-time and

the grey box highlights the last known 300 s of the signal. At each time iteration, the window defined as “Test Tilt” shifts as more data are coming in. Blue clouds represent the prediction of time and amplitude for each time iteration with 50% from the max probability value. Red diamonds indicate the real-time and amplitude of the synthetic event used as a case study, black diamonds indicate the best prediction. The right panels show the marginal distributions of the time and mass of gas involved and joint distribution of the two variables. In this case, the solution converges at the 8-th iteration.

While the estimate was very precise and accurate when using the synthetic data, the signal to noise level in real tilt signals can be higher and act as a limiting factor for the method. Indeed, it has been observed that several volcanic systems, such as Stromboli in Italy and Suwanosejima in Japan, display a non-negligible noise level in the tilt record (Genco & Ripepe, 2010; Nishimura et. al., 2013). In order to test the effect of noise on the model estimates, we run the method on new signals with a noise level equal to 50% and 100% of the mean value (Figure 2.11). Again, the stability of the estimates was evaluated by testing the method on 8 signals in each noise level. Similarly to the 10% noise level, the best Model Tilt was detected during iteration 8 (58 s before the eruption) in 6 out of the 8 tests run for the 50% noise level signals. In two instances, the method required 10 iterations to detect the best Model Tilt, meaning that the alert could be issued only 20 s before the real eruption. However, such Model Tilt resulted in the most accurate prediction, with an error of 0 s, while the Model Tilts obtained in the other runs had an error in the range of -7 s to 2 s (mean $\pm$ SD = -2.7 ± 3.3 s). The performance of the method worsens for synthetic signals with a noise level of 100%. Indeed, the number of iterations required to find the best Model Tilt was between 9 and 10, meaning that the alert could be issued between 20 and 39 s before the real event. The models estimated times for the eruption with an error between -5 s and 8 s (mean $\pm$ SD = 1 ± 4.6 s). However, the limited alert time is also associated to the size of the time step used for the tests, as a new Test Tilt was generated every 19 s. We run an additional test on the signal containing the 100% noise level to replicate a possible real-time scenario where the Test Tilt is updated every second. Results show that the best Model Tilt could be detected 53 s before the event, which estimates the eruption time with an error of -2 s.

Figure 2.11. Effects of noise equal to 50% (top) and 100% (bottom) of the signal mean value on the time and amplitude estimation of a hypothetical event. Color areas represent the prediction of time and amplitude for the corresponding iteration with 50% from the max probability value. The right panels show the marginal distributions of the time and mass of gas involved and joint distribution of the two variables.

The limitations of the proposed forecasting tool are linked to both the availability of a robust numerical model that can well describe the volcanic system, and the feasibility for a real-time application of this technique. Considering the complexities and variability linked to the triggering mechanisms existing at different volcanoes, the development of realistic numerical models can be time consuming. Here we have proposed a numerical model, which has the potential to be applied to estimate several parameters linked to tilt signal recorded during strombolian-like explosions.

Nevertheless, this model may not be the most appropriate in other volcanic scenarios and for these reason preliminary studies may be required. The limitations related to the real-time application are twofold: On one hand, real-time data acquisition is still new and may not be always available. On the other hand, the computation time required to find the best fitting model can be longer than the time scale of the vent. Further work will be necessary to develop the software and testing its real-time applicability.

2.5 Summary

In this chapter, we proposed a new approach to exploit tilt data recorded at a single station to provide an estimate of volcanic systems parameters and to apply such knowledge to a forecasting tool designed to predict time and magnitude of eruptions. The method first constraints the range of values for parameters that are believed to remain constant across events, such as density and viscosity of the magma, the elastic modulus of the host-rock, and radius of the conduit. These estimates are refined with time as new events are recorded. We tested the estimation of the fixed parameters done in the case of three different scales of explosions at Semeru, Indonesia, and the results provided parameters comparable to those found in the literature. Discrepancies in the estimation of some parameters can be related to simplifications in the model, such as the implication of a perfect cylindrical conduit and the absence of a plug. The estimated fixed parameters can be used by the forecasting tool to predict timing and amplitude of an upcoming event up to 58 s before it occurs and with 1% error on amplitude estimation. The results show the potential of the automated tool for real-time application for complementing current monitoring techniques.

Data from new explosion enhance knowledge of the volcanic system, therefore improving the capability of the tool to forecast time and amplitude of upcoming events. If the forecasted amplitude is larger than a defined threshold, an automated alert system could be triggered to inform nearby populations. The example given in this chapter led to a short time frame that could be of the same order of magnitude as the computation time needed to produce the forecast. Future work will aim at validating and determining the limitations of the forecasting method on raw tilt data and at improving the computation time of the model so that it can be efficient enough to be used in real-time and on real case scenarios. Further, improvements of the model to account for variable geometry of the conduit, and other potential short-scale variation will be subject of future study.

Chapter 3

Analogue modelling of slug-driven conduit deformation

Numerical models and simulations have been widely used to describe the mechanisms of bubbles and slugs ascent during volcanic eruptions, and in Chapter 2, we presented a new model that links the surface deformation to the tilt data. Nevertheless, little is known about the mechanical interaction between the slug, its surrounding fluid and the conduit. In this chapter, we report the results from analogue experiments designed to replicate the bubble-driven deformation of the surrounding medium observed during Strombolian activity. For the first time, we investigate the dynamics of bubbles in an elastic conduit, which can unveil the relationship between slugs and crustal deformation. Moreover, we discuss the retroactive effects of the deformed conduit wall on the rising dynamic of a slug, in particular, on how the flow is affected, and the eventual implications on the intensity of the eruption.

3.1 Motivations

Several studies highlight that Strombolian explosions have a greater complexity compared to simple bursting of an over pressurized slug (Gaudin et al., 2014; 2017; Johnson & Lees, 2000; Lyons et al., 2012; Taddeucci et al., 2012). A recent study on Santiaguito volcano (Guatemala) has shown two distinct behaviours characterized by passive degassing linked to slow inflation, and explosive events linked to fast inflation associated with VLP (Johnson et al., 2014). The study suggests that the gas behaviour is strongly affecting the deformation resulting in variation of the intensity of the activity happening in a short time interval. The alternation between passive degassing and explosive behaviour has been observed also at Stromboli volcano and it has been linked to the different level of overpressure of the slug preceding the burst (Del Bello et al., 2012). The overpressure of the slug during its ascent is related to the equilibrium of several forces: magma-static, viscous, and inertial according to the Rayleigh-Plesset equation (Plesset & Prosperetti, 1977). James et al. (2009) provided a qualitative correlation between overpressure expressed by geophysical proprieties such as pressure transients and acoustic signals, to the magnitude and the style of an eruption.

Despite, the large extent of geophysical records, currently almost no direct observations of the phenomena related to gas slug ascent can be made. Seismicity and/or ground tilt can provide an indirect measurement of the source dynamics, which have been complemented by more recent methodologies such as microgravity to provide useful information for imaging underground processes (Carbone et al., 2017; 2015). Nevertheless, the application of these techniques is still limited because of the high instrumental cost and the lack of adequate equipment robust enough to be deployed in noisy and harsh volcanic environments. As a result, the study of slug dynamic in volcanic systems is strictly based on: 1) numerical models and 2) analogue modelling and simulations which often rely on strong assumptions and simplifications.

Apart from the numerical model discussed in Chapter 2, other models aiming at coupling the slugs with the edifice deformation have been proposed in the literature (Kawaguchi & Nishimura, 2015), which however do not take into account the counter-effect of the wall deformation on the dynamic of the slug. O'Brien and Bean (2008) numerically investigated the relationship between seismicity and slugs ascending the conduit, confirming that gas slug ascent can produce VLP-like signals. They highlighted that the slug ascent yields a source mechanism consistent with a vertical pipe. In addition, Araújo et al. (2012) numerically investigated the dynamic of slugs rising through stagnant liquids in conduits with different diameters and in liquid with different viscosities.

Among the analogue models proposed, the major simplification is the use of a rigid conduit to simulate the volcanic conduit. However, the combination of the effect of the temperature with the presence of cracks and porous medium observed in several studies suggest that a soft, deformable elastic conduit would better represent the shallower portion of the volcanic edifice. Indeed a recent study of Villeneuve et al. (2018) show that fractures and high temperature can reduce rock-mass strength. Variations in rock-mass elastic modulus can vary greatly from values <1 GPa to values > 40 GPa for more competent rocks (Dzurisin, 2006; Heap et al., 2009; Rocchi et al., 2004; Villeneuve et al., 2018). Experimental results on samples from Etna and Vesuvius (Rocchi et al., 2004), show that rocks strength drop to 10% of the initial values at 800 °C to 900 °C.

In spite of the extensive studies aiming to a broader understanding of slug flow in conduits and the development of advanced experimental techniques (e.g., PIV), little has been done to investigate the coupling between the dynamic of the slugs and the elastic deformation of the surrounding medium.

Here we propose the analogue modelling of slug rising within an elastic conduit, analysing the interaction between the flow in the conduit and the displacement of the surrounding medium using PIV and image processing techniques.

3.2 Materials and methods

3.2.1 Scaling of the analogue models

We conducted a series of experiments to simulate a two-phase flow regime known as “gas slug” typically associated with Strombolian eruptions. The gas slug condition represents a two-phase flow where large bubbles, with diameters approaching that of the conduit and lengths at least 2 times larger than the conduit diameter, rise within a continuous liquid phase. As a convention, we adopted the terminology commonly used in volcanology in which the gas phase is referred to as the slug (e.g., Clift et al., 2005; James et al., 2004; Jaupart & Vergnolle, 1989; Ripepe et al., 2001; Seyfried & Freundt, 2000). The analogue approach has been used in several studies applied to basaltic volcanoes (Capponi et al., 2016; 2017; Del Bello et al., 2015; 2012; James et al., 2004; 2006; 2008; 2009; Jaupart & Vergnolle, 1988, 1989; Pering et al., 2017; Seyfried & Freundt, 2000) providing useful insights into first-order conduit dynamics that are not accessible with other methods of investigation. The experiments that we conducted are designed to simulate a range of different scenarios that can be compared to medium/low-viscosity magmatic systems.

The bubble dynamic depends on physical and geometrical properties of the conduit system such as the viscosity μ , the density ρ , and surface tension γ of the liquid filling the conduit, the gravitational acceleration g and diameter of the conduit D . These quantities are combined into various dimensionless numbers to scale slugs simulated in the laboratory to the natural conditions (Seyfried & Freundt, 2000; Wallis, 1969; White & Beardmore, 1962).

The Froude number is related to the balance between inertia and gravity and is defined as:

$$Fr = \frac{V_b}{\sqrt{gD}}, \quad (3.1)$$

where, V_b , represents the theoretical ascent velocity of the slug, derived by Goldsmith & Mason (1962) and extended by Brown (1965), to account for the relationship between the ascent velocity and the thickness of the falling film λ :

$$V_b = \frac{2\rho g \lambda^3}{3\mu(r_c - \lambda)}. \quad (3.2)$$

The Morton number reflects the balance between viscosity and surface tension, expressed as:

$$Mo = \frac{g\mu^4}{\rho\gamma^3}, \quad (3.3)$$

and the Eötvös number is a measure of the balance between gravity and surface tension:

$$Eo = \frac{\rho g D^2}{\gamma}. \quad (3.4)$$

The dimensionless inverse viscosity is:

$$N_f = \left[\frac{Eo^3}{Mo} \right]^{1/4}. \quad (3.5)$$

For low viscosity magmatic systems, the typical range of these parameters are: $0.1 < Fr < 0.35$, $10^5 < Eo < 10^7$, $10^2 < Mo < 10^{15}$ and $2.1 < N_f < 1.2 \cdot 10^4$, assuming $10 < \mu < 10^5$ Pa·s, $\rho = 2600$ kg m⁻³ and $\gamma = 0.4$ N m⁻¹ for basalt, and $1 < D < 10$ m for the conduit (Seyfried & Freundt, 2000). These ranges consider an ascent within inertial and transitional regimes, for which the velocity depends on slug buoyancy and liquid viscosity (White & Beardmore, 1962). For our study, we considered $0.015 < D < 0.025$ m, $0.001 < \mu < 1$ Pa s, $970 < \rho < 998$ kg m⁻³ and $0.025 < \gamma < 0.073$ N m⁻¹, $0.034 < Fr < 0.34$, $30 < Eo < 237$, $10^{-11} < Mo < 10^2$, and $3 < N_f < 12355$ (Table 1). The range of slug velocity observed in our experiments are $0.006 < V_{obs} < 1$ m s⁻¹. We refer to V_{obs} as the observed ascending slug velocity, to differentiate it from the theoretical velocity V_b that is based on a rigid conduit model (eq. 3.2).

According to Equation 3.4, the diameter of the conduit strongly controls the Eötvös number and at our laboratory scale, the conduit produces a much smaller Eötvös number compared to low viscosity magmatic systems, potentially enhancing the effects of the surface tension. However, it has been shown that for $Mo > 10^{-6}$ and $Eo > 40$, surface tension does not significantly affect the slug ascent and therefore the difference is not considered as a controlling factor (Llewellyn et al., 2011; Seyfried & Freundt, 2000; Viana et al., 2003). Further, the inverse viscosity spans regimes for both

viscous control ($N_f < 2$) and for an inviscid approximation ($N_f > 300$) (Fabre & Liné, 1992). The dimensionless quantities suggest that our experiments can capture steady slug ascent regimes that are similar to those expected in low-viscosity magmatic systems. Therefore, processes observed within the laboratory should provide insights into the dynamic of volcanic systems.

Table 3.1. Dimensionless parameters for experimental conditions representing a basaltic conduit and volcanic slugs calculated assuming typical Strombolian's parameters (Del Bello et al., 2012).

Symbol (unit)	Laboratory-scale		Volcano-scale
	Water	Silicon oil	
μ (Pa·s)	0.0012	1.00	$10 - 10^5$
ρ (kg·m ⁻³)	999.7	970	1300-2600
γ (N·m ⁻¹)	0.073	0.025	0.4
Mo	$2.5 \cdot 10^{-11}$	647.3	$10^2 - 10^{15}$
Eo	30 - 83	38 - 237	$10^5 - 10^6$
N_f	5742 - 12355	3 - 12	$2.1 - 1.2 \cdot 10^4$
Fr	0.34	0.03 - 0.109	0.02 - 0.34

Gelatin has been shown to be a good analogue for the shallow Earth's crust (Di Giuseppe et al., 2009). Indeed, gelatin shows a variable behaviour depending on its state (elastic to viscoelastic rheology in the solid one, and viscous rheology in the non-solid one), its composition, concentration, temperature, ageing, and the applied strain rate (Barrangou et al., 2006; Bot et al., 1996a; 1996b; Kavanagh & Ross-Murphy, 1998; Kavanagh et al., 2013; Norziah et al., 2006). Gelatin is often used as rock analogue to study shallow crustal processes, especially propagation of dykes (Heimpel & Olson, 1994; Muller et al., 2001; Pansino & Taisne, 2019; Takada, 1989) as it can scale to the Earth's crust. It has also been used to simulate the volcanic edifice (Acocella & Tibaldi, 2005; Walter & Troll, 2003). At the time scale of our experiments, we consider the gelatin to be an ideal-elastic medium in the solid state, and therefore:

$$\sigma = E \cdot \varepsilon , \quad (3.6)$$

where, σ is stress, E is the solid Young's modulus, and ϵ is the strain (Hooke's law). The characteristics of this state of the gelatin are assumed to be representative of the elastic way the Earth's upper crust behaves in the presence of instantaneously applied stress (Ranalli, 1995). Following Pansino & Taisne (2019), we measured the shear modulus before each experiment, which was consistent across experiments. An average value of 5000Pa is used in this study. To represent the observed conduit deformation, we define the dimensionless parameter, b^* , which represents the conduit deformation as the ratio between the conduit wall displacement b , and the undeformed conduit radius r_c . We assume that the elasticity of the gelatin and the scale of deformation observed in our experiments are comparable with those of a shallow sustained conduit in a natural volcanic system, where the high temperature and the low competence of the materials can justify a low shear modulus of the surrounding rocks.

Finally, the gelatin had a concentration of 3.75 wt% and a measured density of $\sim 1010 \text{ kg/m}^3$, which leads to a density ratio of 1.01 between gelatin and water and 1.04 between gelatin and silicon oil. These values are similar to the one of host rock/magma so that the experiment allows the scaling of the natural phenomena (Acocella et. al., 2005).

3.2.2 Experimental setup

To represent the interaction between bubbles rising within the conduit and the volcanic edifice that surrounds it, we had to develop an apparatus that allowed the full coupling between fluid and solid phase. To this end, we conducted experiments using gelatin to simulate the volcanic rock pile, and an experimental trick to form a conduit within it. This allows for a full coupling between the magma and wall analogues as no barrier between the solid gelatin and the fluid within the conduit was used.

The tank is composed of two sections as shown in Figure 3.1a: a narrow lower portion (base: 25 cm x 25 cm, height: 70 cm), and a wide upper portion (base: 80 cm x 80 cm, height: 30 cm). This geometry is chosen to reduce the wall effect in the uppermost portion of the gelatin and consequently reduce biases (side effects) in the recorded deformation data. The bottom part of the tank is connected to a removable reservoir, which stored the air used to generate the slugs. The gelatin (250 bloom, industrial grade gelatin) was prepared by mixing gelatin powder with hot water (60 °C), to dissolve the solid gelatin. Subsequently, a thin layer of oil was added on top of the

gelatin to prevent evaporation during the cooling phase in a cold room at 15 °C for 48 h that allowed its solidification.

Figure 3.1. Experiment set-up. (a) Front view of the experimental set-up showing the conduit preparation, and the geometry of the tank. (b) Detailed schematic of the bottom chamber showing the gas trap used to generate the slugs. (c) Schematic of the data acquisition set-up consisting in a front camera and a single laser, both placed in two different configurations: 1) depicts the configuration laser/cameras used for experiments focused on the upper section of the conduit; 2) depicts the configuration laser/cameras used for experiments focused on the lower and upper section of the conduit.

In order to obtain a smooth and continuous conduit from the base of the tank, to the top free surface, we designed a simple mechanical apparatus to cast the conduit in the gelatin without damaging it facilitating its removal. During the preparation phase of the experiment (Figure 3.1a), a rigid vertical rod was introduced into the cooling gelatin. The constant motion of the rod prevented the gelatin from solidifying at the rod/gelatin interface and decreased the chances of developing discontinuities at the conduit wall. To maintain the rod in motion until the complete solidification of the gelatin, we designed and developed a motorized device. It consisted of a linear actuator, which motor-control board was connected to an Arduino board, a programmable microcontroller extensively used in robotics engineering to control different technologies via a centralized system. This configuration was used to control the frequency and amplitude of the rod displacements (see the upper panel in Figure 3.1a). Once the gelatin solidified, the rod was extracted. During this

phase, the rod was heated up circulating water in the inside to further reduce the cohesion at the interface and slowly pulled out of the gelatin. At the same time, the hollow cylindrical space left by the rod was filled with a fluid representing the magma analogues, water, and Silicon oil, chosen to explore a range of viscosity between 10^{-3} to $1 \text{ Pa}\cdot\text{s}$.

At the bottom of the tank, we designed a small chamber with an air trap which can be controlled from outside to generate the slugs. To fulfil the principle of mass and volume conservation, the air trap was charged before the experiments in order not to affect the initial volume (Figure 3.1b) and to prevent fluid motion into the conduit before slugs are released.

The images were recorded with a Canon EOS 1200D at 24 and 50 frames per second (fps) and Phantom Miro M120 at 100 and 200 fps. The camera and laser were setup in two different configurations according to the area of focus of the experiments (Figure 3.1). The field of view was illuminated by a laser light sheet, which was produced with a combination of laser pointers and cylindrical solid glass rods. The glass rods transformed the beam into a sheet with less than 1mm thickness illuminating the region of interest. To visualize and acquire deformation data, we applied Particle Image Velocimetry (PIV) and image processing techniques to detect the strain in the region around the conduit. These methods are both non-intrusive and can provide quantitative data on the velocity field within the conduit and displacement in the surrounding gelatin when bubbles are ascending (Figure 3.1c).

Polyamide particles with diameter of $100 \mu\text{m}$ and specific density of 1.2 g/cm^3 were used as seeding particles to visualize the flow dynamics in the conduit and track the deformations in the gelatin. The seeding particles were added to the liquid gelatin before solidification and were only distributed in the sheet in the central x-y plane of the tank crossing the conduit. This would enhance the visibility of the deformations and the quality of measurements. Particles of the same size but at higher concentration were added to the fluid in the conduit in order to visualize and measure the flow dynamics during the bubble rise. Figure 3.2 illustrates raw images of the analogue crust and magma with the seeding particles.

Figure 3.2. (a) raw image of the upper portion of the conduit related to laser/camera configuration 1 showing particles in the liquid, (b) raw image of the gelatin around the lower portion of the conduit, related to laser/camera configuration 2.

The raw images were pre-processed and PIV analyses were carried out by the commercial software DaVis 10 (product of Lavisision www.lavisision.de). PIV analysis can provide the instantaneous velocity field and displacements in the conduit and the surrounding solid gelatin respectively. The software analyses the position of the seeding particles at discrete time instants by cross-correlation and provides two-dimensional velocity data on a planar domain. The observation area was divided by 64×64 pixels and subsequently by 32×32 interrogation areas and the average motion of particles was studied. The determination of the average particle displacement was also accomplished by computing the spatial cross-correlation of the particle images.

Table 3.2 presents a summary of experimental conditions including the size of the observation area, sampling rate, size of the conduit and the physical properties of the fluid and the solid medium analogues of the magma and the elastic crust.

Table 3.2. Summary of tests, observation areas, and physical properties of gelatin.

Test No	Camera/Laser configuration	Sampling rate	Size of the observation field	Conduit diameter	Fluid medium	Physical properties liquid			Physical properties solid	
						$\mu(\text{Pa}\cdot\text{s})$	$\rho(\text{kgm}^{-3})$	$\gamma(\text{N}\cdot\text{m}^{-1})$	G(Pa)	$\rho(\text{kgm}^{-3})$
1	2	24	31 x 20	2.5	oil	1	970	0.025	5000	1010
2a	2	24	14 x 11	2.5	water	0.001	998	0.073	5000	1010
2b	2	50	25 x 20	2.5	Liquid gelatin	0.001	1000	0.073	5000	1010
3	2	100-200	25 x 20	1.5	oil	1	970	0.025	5000	1010
4	1	100	25 x 20	1.5	oil	1	970	0.025	5000	1010
5	1	100	25 x 20	1.5	oil	1	970	0.025	5000	1010
6	1	100-200	25 x 20	2.5	oil1	1	970	0.025	5000	1010
7	1	200	25 x 20	2.5	oil2	0.5	970	0.025	5000	1010
8	1	200	25 x 20	2.5	water	0.001	998	0.073	5000	1010

3.2.3 Slug flow simulation

Slugs of air are released from a reservoir located at the base of the tank, which is also linked to the conduit to simulate a typical Strombolian activity. To meet the principle of mass conservation, the air is stored within the conduit system before running the simulations. Injection of gas from an external source may produce misleading deformation signals due to the increase of pressure in the conduit. To avoid this issue, we designed a special reservoir equipped with a “gas trap” previously charged with air that it is in contact with the liquid phase constituting the magma analogue (Figure 3.1b). The trap was dome-shaped and had a volume of 70 cm³. By rotating the handle, a part of the air pocket is gradually released forming a bubble, which volume depends on the amount of time the trap is open. The bubble is driven by the buoyancy to the conduit where it begins to rise towards the surface. The limited volume of the gas trap determines the number of slugs that can be released during the experiment. The trap is then recharged in between experiments to restore the initial volume condition. While this setup does not allow a precise control over the volume of gas released for each slug, this parameter could be measured from the video recorded during the experiment. We identified frames containing clear images of the slugs and we analysed them with the image processing toolbox available in Matlab. We extracted the boundary coordinates which were fitted by a polynomial function used to compute the volume by disk integration. Slug volumes ranged from 3 to 21 cm³.

3.3 Results and discussions

During the experiments, we observed different shapes of slugs. It is well known that slugs rising in rigid conduits have a shape that is controlled by variations of the fluid viscosity, the surface tension, and the buoyancy forces. The slug exhibited a bullet-like shape (Figure 3.3a) characterized by a flattened tail when rising within low viscosity fluids, changing to hemispheric concave shape (Figure 3.3b) for high values of viscosity (Campos & De Carvalho, 1988). Besides the bullet-like geometry which is widely described in literature (i.e. Morgado et al. 2016, review paper), in the experiment here presented, we observed a second type of slug regime here called “super slug”, which presents a tapered shape body characterized by a larger radius at the head of the slug, and a smaller radius at the tail of the slug (Figure 3.3c). In silicon oil, the shape of this second type of slugs is more emphasized, presenting a streamlined body (Figure 3.3d). Cusped tail bubbles have been observed before in non-Newtonian fluids (Chhabra, 2006; Divoux et al., 2009; 2008;

Hassager, 1979; Liu et al., 1995; Sousa et al., 2004) showing a relation between the shape of the bubble, its volume, and the concentration of the gel-based fluid. Considering that in our experiments we used Newtonian fluids, we can attribute the presence of slugs with a narrow and cusped tail to changes of the slug dynamic induced by the deformation of the elastic conduit rather than to rheological properties of the fluid.

Figure 3.3. Comparison between shapes of slugs rising into different mediums, water and oil in relation to rigid conduits (a) (b), and elastic conduits (c) (d). Red lines represented the contour of the deformed conduits. We can see that in a rigid conduit the slug maintain its classic bullet shape independently of the viscosity. In a elastic conduit the slug assume a tapered shape for experiments in water, and a steemlined shape for for experiments in silicon oil.

Figure 3.4 shows the variation of the shape of slugs as the volume increase in both silicon oil and water for two different conduit diameters. We can see that in silicon oil as the volume of the slug increases its shape evolves into a streamline, so that we observe a super slug for both conduit diameters (Figure 3.4a, b). In the experiments conducted using water as magma analogue, the tapered shape was not as accentuated as in oil experiments, and was only prominent for large volumes of gas (Figure 3.4c, d). Another characteristic of super slugs is that they exhibit a higher rising velocity V_{obs} , compared to the theoretical slug velocity, V_b , inducing a great deformation at the conduit wall b, of up to 50% of the original diameter ($b^* = 0.5$). In experiment conducted using water as magma analogue, the ratio between V_{obs} , and V_b was smaller indicating that the slug

velocity was similar to the theoretical one. In this cases, the deformation on the conduit wall was smaller and independent from the size of the slug with a maximum deformation of the conduit of around 10% of its original size ($b^* = 0.1$).

Figure 3.4. Shape variation of slugs for different values of viscosity of the fluid in two different conduit diameters: (a) Slugs rising in silicon oil (viscosity = 1 Pa·s) in a small diameter conduit ($D = 0.015$ m); (b) Slugs rising in silicon oil (viscosity = 1 Pa·s) in a bigger diameter conduit ($D =$

0.025 m), (c) Slugs rising in water (viscosity = 0.001 Pa·s) in a small diameter conduit ($D = 0.015$ m), (d) Slugs rising in water (viscosity = 0.001 Pa·s) in a bigger diameter conduit ($D = 0.025$ m).

Differences in the stress and strain pattern between slugs rising in water and silicon oil are also visible using polarized film (Figure 3.5). The gelatin is photoelastic, allowing visualization of stress patterns as fringes of colour. This technique allows a first qualitative estimate of the stress field surrounding the slug but does not allow us to quantitatively estimate the stress. Figure 3.5 shows differences in the stress pattern between “super slugs” and “regular slugs”. For slugs in silicon oil (Figure 3.5a and Figure 3.5b) an important stress region is visible above the head of the slug which appears to be related to the conduit geometry, smaller for a narrower conduit, as highlighted by a dimmer intensity of the colours. For slugs rising in water, the stress region is almost absent (Figure 3.5c) suggesting a smaller deformation of the conduit wall. As a first assumption, super slugs form when the conduit walls stretch as consequences of the higher pressure, a situation that allows a more efficient return flow. According to Brown (1965), the velocity of a slug is mainly affected by the viscosity of the fluid, which also control the thickness of the liquid film around the slug, and the radius of the conduit (see eq. 3.2).

Figure 3.5. Stress fields visualization around slugs rising within different conduits and mediums: (a) Silicon oil (experiment 13) in a conduit of 0.025m diameter. (b) Silicon oil (experiment 12) in a conduit of 0.015 m (c) Water (experiment 27) in a conduit of 0.015 m diameter. The intensity of the colour in the region under stress is lower for small diameter conduit and for less viscous fluids.

We speculate that the super slug condition is related to the deformation of the conduit, which causes the acceleration of liquid film flowing around the slug due to the Bernoulli Effect. According to Bernoulli's equation, the reduction of the conduit diameter causes the fluid to move faster causing a pressure drop compared to the regions where the diameter is larger and the water is moving slower causing a pressure increase. For experiments conducted on viscous silicon oil, this condition becomes more evident due to the higher viscous forces that contrast the strong buoyancy of the bubble: when the slugs are compressed along their longitudinal axes, an increasing downward flow around the slug applies larger shear and pressure on the conduit wall resulting on its greater deformation. If the volume and mass of the slug are bigger than a certain threshold, the

slug causes a deformation in the conduit that allows the slug to become a “super slug” and accelerate. Figure 3.6 depicts the relationship between the normalized slug ascending velocity V_{obs} with respect to the theoretical velocity V_b , and the length of the slug L_b , normalized by the diameter of the conduit D_c for all the experiments. For experiments in which water was used as magma analogue, the velocity of the slugs is mildly affected by their size. Differently, experiments conducted using silicon oil suggests that the velocity of the slugs is proportional to their length. This is also visible in Figure 3.6, where we can see that the observed slug velocity V_{obs} , diverge from the theoretical velocity V_b for b^* greater than 0.1. On the contrary, smaller slugs show a reduced or absent streamlined shape that is substituted by the bullet shape usually observed in the literature (Araujo et al., 2012). As showed by equation 2, the velocity of bullet shape slugs is strongly dependent on the radius of the conduit (r_c), and the thickness of the liquid film around the slug which are considered constant. Accordingly, this formulation is not suitable for describing the dynamic of super slugs, which instead show variability in the thickness of the liquid film, and conduit diameter along the length of the slug.

Figure 3.6. Normalized observed slug velocity V_{obs} with respect to the theoretical velocity V_b as a function of its normalized length L_b with respect to the conduit diameter D_c . The vertical dashed line marks the threshold between normal slugs, and super slugs. Circles represent values from experiments conducted using water as magma analogue (viscosity = 0.001 Pa.s), and triangles

represent values for silicon oil (viscosity = 1 Pa·s). The colour scale represents the dimensionless conduit deformation, b^* normalized for the undeformed conduit radius r_c .

We believe that the different behaviour associated with the two types of slugs here described (i.e. “regular slugs” and “super slugs”), can be linked to important variation of the stress field in the slug region. Regular slugs linked to small volumes of gas, rise the conduit in equilibrium inducing small deformations of the conduit, on the contrary super slugs which are related to large volume of gas, perturb the stress field generating a large deformation of the conduit wall. These observations can be compared with natural systems, where a relationship between the amplitude of the deformation signals and the seismic energy with the gas volume emitted during explosions is observed (Nishimura et al., 2012).. Observations support that a change in explosive behaviour can be linked to an increase in volume and energy at burst of the slugs. More details related to the dynamic of the slug in an elastic conduit will be presented in Chapter 4.

The analysis of the displacement within the surrounding medium performed with the PIV technique allowed us to observe, for the first time, the displacement pattern previously hypothesized by considering the pressure observation made in rigid conduits, and numerical approaches (Figure 3.7). We distinguished two main stress regions: one located above the slug where the overpressure related to the rise of the slug is causing the opening of the conduit and motion of the particles outwards; and a second one below the slug where the conduit experiences contraction due to the reduction of fluid filling the conduit, that has been pushed upward by the slug and struggles to flow in film surrounding the slug. The region of the conduit occupied by the slug can be therefore considered as a transition zone between where the conduit experiences over pressurization, above the slug, and under-pressurization, below the slug. In this transition region, as we can see from Figure 3.7, the displacement is oriented downward affecting a very narrow section of the conduit. This zone linked the passage from an upper region where the orientation of the displacement is clearly outward with respect to the centre of the conduit, to a lower region where the displacement is oriented inward. The observed downward displacement of gelatin implies that a shear stress component indeed exists, and it is strongly contributing to the total deformation of the surrounding medium. This observation is in agreement with conduit forces modelled by James et al. (2008), who showed forces acting on the conduit during the slug ascent lead to dilation, at the slug nose, followed by a region of compression at the slug base as observed in our experiments.

Figure 3.7. Deformation pattern of the gelatin surrounding the elastic conduit linked to the rise of slugs of different size. The shear modulus (G) of the gelatin is ~ 5000 Pa, the viscosity of the oil used to represent the magma is 1 Pa·s. The arrows show the magnitude and direction of the displacement. The colour surfaced shows the magnitude of the horizontal displacement.

Figure 3.7 also shows the link between the size of the slug and wall displacement. We measured displacement of the wall in a range from almost 7 mm for a slug with a length of 14 cm, to 0.1 mm for a slug with a length of 3 cm. Differences in the wall displacement and consequently in the conduit diameter have a strong effect on the slug terminal velocity.

The PIV technique also allowed us to analyse the liquid flow within the conduit and around the slugs (Figure 3.8). Interestingly, we found that for super slugs there is a region of very high upward velocity immediately above the slug head, while for regular slugs all the liquid column above the slug is moving upward at a lower velocity causing a gradual upward motion of the free liquid

surface when still at depth. Our results showed also that the viscosity controls the extent of the liquid flow-field ahead of the rising slug, with a greater fluid region affected at low viscosity. (Nogueira et al., 2006a) observed that the presence of the slug is ‘felt’ for some distance ahead of the nose. This distance resulted slightly larger for decreasing liquid viscosities, suggesting that the presence of the bubble affects an area further away, as the inertial forces are higher relative to the viscous ones. In our experiments, we observed that the extent of this region is also controlled by the size of the slug. This region appears smaller in the presence of super slugs compared to the one produced by normal slugs.

Figure 3.8. Velocity distribution within the conduit due to slug ascent in three different fluids with particular focus on the difference between small and big bubbles. Viscosity is increasing from the left to the right for water and two silicon oils with viscosity of 0.001, 0.5, and 1 Pa·s respectively. The vector field shows the magnitude and direction of the velocity v . The colour scale highlights

when the fluid is flowing upward (red) or downward (blue). Big bubbles cause a high-velocity region, especially at high viscosity.

As a consequence of these two distinct behaviours, we observed a gradual upward movement of the liquid free surface during the ascent of regular slugs, while the liquid free surface does not rise in the initial phase of the ascent of super slugs but dramatically accelerated upward when the slug is approaching the surface. These observations are very similar to that observed in a natural system where different uplift patterns have been observed in relation to passive and explosive degassing. For instance, at Santiaguito volcano (Guatemala), rapid inflation rates of the dome surface are linked to explosive events that generate very long period (VLP) earthquakes. On the other hand, less rapid inflation episodes are linked to passive degassing events that do not generate VLPs (Johnson et al., 2014). Figure 3.8 shows the comparison between the flow profile generated by a “regular slug” and a “super slug”. The high-velocity region observed in the head region of super slugs can be directly related to the overpressure of the slug, while we believe that on the contrary the regular slugs that do not show a high-velocity region rise at pressure equilibrium. This observation can be compared to the modelling of Del Bello et al. (2012) that links the overpressure to the amount of gas in the slug and the thickness of the film of magma descending around the slug.

To relate the velocity measured within the liquid column with the overpressure observed in natural systems, we used the drag force equation:

$$F_D = \left(\frac{1}{2} \rho V_b^2 \right) C_D \pi r_b^2, \quad (3.7)$$

Where C_D is the drag coefficient, which depends on the shape of the slug and on the Reynolds number, and the term in brackets corresponds to the dynamic pressure. Based on this equation we can assume that if the radius of a slug increases, following the conduit deformation, its rising velocity also increases. Therefore, the drag force acting on the slug also increases, causing an increment of the dynamic pressure at the head of the slug. Super slugs are therefore over-pressured, while regular slugs, which rise the conduit with an observed velocity closer to the theoretical one, are more likely to have an internal pressure in equilibrium with the surrounding liquid. These results can be compared to observation at open vent systems (e.g., Stromboli and Santiaguito) where the degree of overpressure in the slug has been correlated to the intensity of the explosions, linking the magnitude of the geophysical effects of overpressure to the style of an eruption at the

surface. Previous analogue models and numerical studies have suggested that the origin of the signals recorded at the surface and the slug overpressure are mostly linked to the dynamic of bubble expansion and the volume of gas involved. Our results support the hypothesis that conduit deformation plays a fundamental role in controlling the dynamic of a slug and its overpressure.

3.4 Summary

This chapter presented a series of analogue experiments to simulate the dynamics of slugs rising in an elastic deformable volcanic conduit. For the first time, the effect of slugs on an elastic conduit in gelatin was analyzed by applying PIV techniques to measure both displacements in the fluid and the surrounding elastic medium. We observed a different type of slug, here called “super slug”, characterized by a tapered shape body which culminates in a streamlined shape for high viscous fluids. Super slugs present higher rising velocity compared to “regular slugs”. Interestingly, we have found that the dynamic of the two types of slug affects the magnitude of the event observed at the surface. While “regular slugs” have low velocity and rise at pressure equilibrium causing very little or none conduit wall deformation, “super slugs” rise at high velocity and cause significant deformation of the conduit. This might explain the generation of more energetic explosions at the surface due to high internal pressure. We were able to visualize and quantify the presence of three different stress regions: in the conduit characterized by an over-pressure above the slug; a transitional region along the slug body, where the shear stress is more dominant; and an under-pressure below the slug. This structure of the conduit stress has been hypothesized and numerically modelled, and is now being visualized in this experimental study.

Moreover, we have found similarities between the acceleration patterns of the liquid free surface in the experiments, and dome uplift observed in natural systems, which we are going to explore with more details in the next chapter. Rapid inflation rates of the dome surface are linked to explosive events, while, less rapid inflation episodes are linked to passive degassing events. These observations could be key to discriminate passive degassing from explosive events, hinting towards the potential to use such observations as a monitoring tool to forecast the explosive style. Further work will be necessary to assess the impact of the conduit elasticity variations on the genesis of super slugs. The implications for volcano monitoring are that this study will provide information on which volcanoes are more prone to exhibit super slugs, allowing to quantify the minimum volume of gas above which this phenomenon occurs.

Chapter 4

Volcano in the lab: an analogue investigation of bubble-driven surface displacement

Very short time displacements of the volcanic edifice associated with Strombolian activity have been observed in many volcanoes and, as discussed in the previous chapters, have been related to the rise of bubbles in the volcanic conduit. The resulting inflation of the ground surface was modelled in Chapter 2 and the related conduit deformation was observed in Chapter 3. Here, we present analogue experiments in a controlled environment used to measure the surface displacement linked to a slug rising within the conduit. Furthermore, the experimental results are used to test the uncertainties of the model proposed by applying the Bayesian inversion on the surface deformation recorded.

4.1 Motivations

The method designed for forecasting coming volcanic eruptions, presented in Chapter 2, is based on the estimate of the parameters of the volcanic system under the constraint that density and viscosity of the magma, the elastic modulus of the host-rock, and radius of the conduit remain constant across events, and their estimation is refined with time as new events are recorded. Tilt signals recorded during three different scales of explosions at Semeru, Indonesia, were analysed and the inversion technique provided values for the parameters of interest that are comparable to those available in the literature, with some discrepancies in the estimation of some parameters.

To address the limitations of the model proposed, we have designed the analogue model, presented in Chapter 3, to replicate the Strombolian activity associated with the rising of gas slugs in an elastic conduit, where the displacement of the surrounding medium was measured by advanced experimental techniques (i.e. particle image velocimetry). We observed a transition between two different slug regimes: above a certain volume threshold, the slug regime is linked to overpressure and more energetic explosive events, while modest volumes of gas are linked to small to passive explosions.

In this chapter, we want to extend the knowledge gained so far to quantify how the resulting surface deformation, from which the inversion technique can be used to estimate the controlling parameters, is affected by the processes within the small-scale gelatin-based models of volcanic systems previously observed. Further, we would like to analyse the limitations of the current numerical model and sources of errors in the estimation and how they are related to the presence of different bubble dynamics observed in the analogue setup which were not taken into account in the model design.

The innovation of this study is that surface deformation will be measured for the first time in a gelatin-based analogue model, with a setup that allows the measurement of the geometrical and physical parameters of the investigated model as well as the clear observation of the interaction between fluid dynamics and solid mechanics. In addition, the method will be used to build confidence in the theoretical model proposed, and strengthen the possibility of using the limited monitoring resources often available to estimate the size of imminent events.

4.2 Materials and methods

4.2.1 Experimental scaling

We conducted a series of experiments aiming to simulate the gas regime known as “gas slug” typically associated with Strombolian eruptions. The gas slug condition represents a two-phase flow where large bubbles, with diameters approaching that of the conduit, rise within a continuous liquid phase. As a convention, we adopted the terminology commonly used in volcanology in which the gas phase is referred to as slug (e.g., James et al., 2004; Jaupart & Vergnolle, 1989; Ripepe et al., 2001; Seyfried & Freundt, 2000; Clift et al., 1978).

Similar dynamic of the slugs in the laboratory and in the natural conditions can be observed when various dimensionless parameters (Seyfried & Freundt, 2000; Wallis, 1969; White & Beardmore, 1962) are comparable. We therefore translated the physical and geometrical properties of the conduit system into four parameters as follows:

$$Fr = \frac{V_b}{\sqrt{gD}}, \quad (4.1)$$

$$Mo = \frac{g\mu^4}{\rho\gamma^3}, \quad (4.2)$$

$$Eo = \frac{\rho g D^2}{\gamma}. \quad (4.3)$$

$$N_f = \frac{\rho}{\mu} \sqrt{g D^2}. \quad (4.4)$$

The Froude number Fr is related to the balance between inertia and gravity; the Morton number Mo reflects the balance between viscosity and surface tension; the Eötvös number Eo is a measure of the balance between gravity and surface tension; and N_f represents the dimensionless inverse viscosity. The properties of the conduit system and the dimensionless metrics for the experimental and a natural system conduit are listed in Table 4.1.

According to Equation 4.3, the diameter of the conduit strongly controls the Eötvös number and at our laboratory scale, the conduit produces a much smaller Eötvös number compared to low viscosity magmatic systems, potentially enhancing the effects of the surface tension. However, it has been shown that for $Mo > 10^{-6}$ and $Eo > 40$, surface tension does not significantly affect the slug ascent and therefore the difference is not considered as a controlling factor (Llewellyn et al., 2011; Seyfried & Freundt, 2000; Viana et al., 2003). Further, the inverse viscosity spans regimes for both viscous control ($N_f < 2$) and for an inviscid approximation ($N_f > 300$) (Fabre & Liné, 1992). According to the dimensionless quantities observed, we can claim that our analogue model can capture steady slug ascent regimes that are similar to those expected in low-viscosity magmatic systems. Therefore, processes observed within the laboratory should provide insights into the dynamics of volcanic systems.

Table 4.1. Dimensionless parameters for experimental conditions representing a basaltic conduit and volcanic slugs calculated assuming typical Strombolian parameters (Del Bello et al., 2012).

Parameter (unit)	Laboratory-scale		Volcano-scale
	Water	Silicon oil	
μ (Pa·s)	0.0012	1.00	$10 - 10^5$
ρ (kg·m ⁻³)	999.7	970	1300-2600
γ (N·m ⁻¹)	0.073	0.025	0.4
Mo	$2.5 \cdot 10^{-11}$	647.3	$10^2 - 10^{15}$
Eo	30 - 83	38 - 237	$10^5 - 10^6$

N_f	5742 - 12355	3 - 12	$2.1 - 1.2 \cdot 10^4$
Fr	0.34	0.03 - 0.109	0.02 - 0.35

Gelatin has been shown to be a good analogue for the shallow Earth's crust. Indeed, gelatin shows a variable behaviour depending on its state (elastic to viscoelastic when in the solid state and viscous when in the liquid state), its composition, concentration, temperature, ageing, and the applied strain rate (Barrangou et al., 2006; Bot et al., 1996a, 1996b; Kavanagh & Ross-Murphy, 1998; Kavanagh et. al., 2013; Norziah et. al., 2006). Di Giuseppe et al. (2009) demonstrate that 2.5 weight percent (wt%), industrial grade, bloom 250, gelatin cured at 10 °C possesses the required rheological properties to model crustal deformation. At the time scale of our experiments, we considered the gelatin to be an ideal-elastic medium in the solid state, and therefore:

$$\sigma = E \cdot \varepsilon, \quad (4.5)$$

where, σ is stress, E is the solid Young's modulus, and ε is the strain (Hooke's law). The characteristics of this state of the gelatin are assumed to be representative of the elastic way the Earth's upper crust behaves in presence of instantaneously applied stress (Ranalli, 1995). Following Pansino & Taisne (2019), shear modulus measurements are performed before each experiment and an average value of 5 kPa is used in this study. We assume that the elasticity of the gelatin and the scale of deformation observed in our experiments are comparable with those of a shallow sustained conduit in a natural volcanic system, where the high temperature and the low competence of the materials can justify a low shear modulus of the surrounding rocks.

4.2.2 Experimental setup

We adopted an experimental apparatus similar to the one described in Chapter 3, previously used to analyse how the gas slug deforms the elastic conduit and how this affects its own dynamic. The setup consisted of a tank filled with solid gelatin provided with a cylindrical cavity filled with oil or water, which allowed for a full-coupling between the magma analogues (oil or water) and the elastic conduit. The tank was composed of two sections as shown in Figure 4.1a: a narrow lower portion (base: 25 cm x 25 cm, height: 70 cm), and a wide upper portion (base: 80 cm x 80 cm, height: 30 cm). This geometry was chosen to reduce the wall effect in the uppermost portion of the gelatin and consequently reduce biases (side effects) in the recorded deformation data (Figure 4.1a). The bottom part of the tank was connected to a removable reservoir, which stored the air

used to generate the slugs. The gelatin (250 bloom, industrial grade gelatin) was prepared by mixing gelatin powder with hot water (60 °C), to dissolve the gelatin granules. Subsequently, a thin layer of oil was added on top of the gelatin to prevent evaporation during the cooling phase, which took place in a cold room at 15 °C for 48 h to allow its solidification.

Figure 4.1. (a) View of the experimental setup showing the lights and cameras configuration adopted during the experiments. (b) Top and side view schematics of the data acquisition set-up consisting of two front cameras and four top cameras. In red we highlighted the areas of interest where the cameras were focused. In the top view, we use the region with 100% of overlap between the field of view of the four cameras to reduce the distortion in the surface modelling.

A smooth and continuous conduit from the base of the tank, to the top free surface, was created by the constant motion of a rod, which prevented the gelatin from solidifying at the rod/gelatin interface, which was then extracted once the gelatin solidified (see section 3.3.2 for more detail about this procedure). The hollow cylindrical space left by the rod was filled with a fluid representing the magma analogues where the gas slugs could rise.

In order to capture the slugs ascents, that in our simulation is relatively fast (order of seconds), the observations were acquired in video mode using Canon EOS 1200D cameras at 24 frames per second (fps) for a size of 1920 x 1088 pixels, which were triggered simultaneously by using the software DSLR Remote Pro Multi-Camera. The configuration used during our experiment, shown in Figure 4.1, comprised an array of six Canon EOS 1200 cameras: four top cameras dedicated to the measurement of the vertical displacement and two front cameras dedicated to track the rise of the slugs in the conduit. Top cameras had a 55mm fix lens and were installed in a frame placed on top of the tank, with a distance from the gelatin surface of 0.5 m allowing us to obtain a resolution of 0.257 mm/px; front cameras mounted a 18-55mm lens and were placed at 0.7 m from the tank allowing to reach a resolution of 0.186 mm/px.

The surface's vertical deformation was analysed by means of the close-range photogrammetry technique, which enables the construction of the three-dimensional digital model of the gelatin surface from photographs (e.g., Koenderink & Van Doorn, 1991; Turner et al., 2012). The fundamental principle used by photogrammetry is triangulation: taking images of the same object from different angles, the intersection between the different "lines of sight" (lines between the camera and a targeted object) can produce the 3-dimensional coordinates of the points of interest (Figure 4.1). To successfully apply this technique to a transparent gelatin surface, a random pattern was applied on the top surface using coloured sand (Figure 4.2a). Moreover, we ensured a complete 3D reconstruction by placing the top cameras with an angle that allowed 100% of overlap over the region of interest, and by using a set of LED lights equipped with diffusive filters which provided a homogeneous illumination.

4.2.3 Experimental procedure

We conducted several experiments to model the relationship between slugs, and the short time deformation of the surface, and compare these observations with data of the natural system that are normally detected by using geodetic techniques such as tilt and GPS. In order to evaluate the effects of the different parameters on the recorded signals, we considered four different experimental conditions which tested two different conduit diameters (1.5 cm and 2.5 cm), and two different fluids as magma analogue with viscosity of 0.001 Pa·s (water), and 1 Pa·s (silicone oil). Experiment 1 and 2 refer to the tests run in water respectively in a big and small conduit diameter, while Experiment 3 and 4 refer to the condition where the silicon oil was chosen as

magma analogue placed in the big and small conduit diameter. In order to encompass the larger variety of slug dimensions linked to eruptive events, several slugs of air were released into the system from a reservoir located at the base of the tank (see section 3.2.2 for a full description of the reservoir). The reservoir was filled with air before running the simulations to meet the principle of mass/volume conservation and avoid deformation signals due to the increase of pressure in the conduit unrelated to the slug rise. The buoyancy drove the bubbles to the conduit where they began to rise towards the surface. The limited volume of the gas trapped in the reservoir determined the number of slugs that could be released during the experimental session, which therefore varied across test runs (5, 4, 7 and 7 slugs respectively for Experiment 1, 2, 3 and 4) (Table 2). In between experiments, the reservoir was then recharged to restore the initial volume condition. Videos were recorded during each experiment to extract the variables of interest thanks to the array of six cameras (4 to cameras, 2 front cameras), which allowed to follow each slug within the conduit and simultaneously record the surface deformation.

4.2.4 Data analysis

The process used to compute the vertical displacement comprised three steps: 1) the videos recorded from each of the four top cameras were processed to extract the frames of interest (Figure 4.2a); 2) these frames were processed by the photogrammetry software Agisoft Photoscan, that produced the Digital Elevation Models (DEM) representing the elevation matrix of the object surface at each time step (Figure 4.2b); 3) the DEMs were differenced with respect to the first one, recorded during the quiet state, to calculate the absolute time evolution of the vertical displacement (U_{xy}). Figure 4.2c, shows an example of vertical displacement related to the rise of a slug during one experiment. The red colour represents the upward displacement of the surface with respect to the first frame, the blue colour indicates downward displacement.

To compare this data with the tilt signal recorded in natural system, we reduced the large amount of information in the DEM into a time series vector form of the vertical displacement ($U(t)$). To this end, we extracted the vertical component z at the same planar coordinates x and y for all frames, where x and y were placed on the arcs centred at the conduit with radial distances of 10, 20 and 30 cm (see panels in Figure 4.2c). We chose these distances to simulate natural systems, such as Stromboli volcano. Considering a maximum diameter of about 10 m for Stromboli (Arnoult et al., 2010; Chouet et al., 1974; Giberti et al., 1992; Harris & Stevenson, 1997; Settle & McGerchin,

1980), by using a simple proportion, the three selected radial distances can be compared to distances from the volcanic vent between 67 and 200 m for the 1.5 cm lab conduit, and between 40 and 120 m for the 2.5 cm diameter. If we take Semeru volcano as a reference system, considering its estimated conduit diameter to be about 40 m (estimated from satellite images), the three selected points cover a distance between 266 and 800 m and between 160 and 480 m for the 1.5 and 2.5 cm conduit respectively. To obtain from each radial distance a single time series, we averaged the vertical displacements by applying a moving filter (Figure 4.2c). We compared the vertical displacement by defining the Peak Vertical Displacement (PVD) as the maximum vertical displacement with respect to the initial position measured at 20 cm from the centre of the conduit, to the length and volume of the slugs, obtained from videos recorded from the front cameras. The time at which we observed the maximum displacement correspond to the burst of the slug at the surface. Further, we measured the velocity of the displacement at 20 cm by detecting the beginning of the deformation and the time of the PVD and dividing it by the corresponding number of frames (sampling rate of 24 fps). Finally, we computed the tilt as the variation of the vertical displacement with respect to the radial distance $\partial U / \partial r$. This was necessary in order to be able to compare the displacement data measured in the laboratory with data recorded in the natural system, which are normally acquired using tiltmeters.

We used videos recorded from the front cameras to associate the deformation with the slug position and shape. These were analysed with the image processing toolbox available in Matlab to extract the slugs boundaries. The boundaries coordinates were subsequently fitted by a polynomial function which was then used to compute the slug volume by disk integration. We measured the slug velocity V_{obs} in the upper part of the system as the ratio between the distance travelled by the slug in three frames (time interval of 125 ms) for the experiments in the silicon oil and 10 frames (time interval of 416 ms) for water. We measured the theoretical ascent velocity of the slug V_b , as derived by Goldsmith & Mason (1962) and extended by Brown (1965) as:

$$V_b = \frac{2\rho g \lambda^3}{3\mu(r_c - \lambda)} \cdot \quad (4.6)$$

According to Nusselt (1916) the thickness of the falling film is function of the fluid dynamic viscosity and many other factors. The thickness of the falling film is $\lambda = r_c \cdot \lambda'$, and can be

represented as function of the Froude number (eq. 4.1) and inverse viscosity (eq. 4.4) $\lambda' = (6\text{-Fr}/N_r)^{1/3}$ (Llewellyn et al., 2011).

Finally, we computed the deviation of the observed velocity from the theoretical one as:

$$V^* = \frac{V_{obs}}{V_b}. \quad (4.7)$$

Figure 4.2. (a) Top surface of the gelatin covered by coloured sand in order to obtain a random texture. This procedure is essential in order to correctly apply the photogrammetry technique described in this work. (b) 3D surface measurement obtained with the photogrammetry software Agisoft. Recording from four different points of view the same object allows to determine the size

and the exact position of each point constituting the surface (c) Differential vertical displacement calculated at time = t_n . The red colour represents the upward displacement of the surface with respect to the first frame, the blue colour indicates downward displacement. Time series of the vertical displacement U , are extracted from three different radial distance from the conduit and averaged along the arc perimeter to reduce the noise level. Red boxes show the time series of vertical displacement measured at three radial distances. Black lines represent the filtered signal, while the grey lines represent the noise level. Blue tick marks the Peak Vertical Displacement (PVD). Note that the PVD correspond with the burst of the slug at the surface.

4.2.5 Forward modelling and Bayesian inversion

Assuming that the analogue experiments represent at their best the natural system, by comparing the known parameters of the laboratory system (i.e conduit radius, fluid viscosity, and density) with the best estimates obtained by applying the model inversion on the recorded tilt data, we are able to evaluate the precision of the numerical model. The numerical model considered here, based on the work of Bonaccorso & Davis, (1999) and Kawaguchi & Nishimura (2015) and fully described in Chapter 2, relates pressure perturbations, due to a slug rising within the conduit, to stresses and strains in the host-rock. It is based on the assumption that the rise of a gas slug in the stagnant magma causes a perturbation in the initial stress field resulting in the displacement of the ground surface. Consequently, the recorded deformation is a function of the parameter related to the geometry of the conduit system, and of the dynamic of the slug as described by Llewellyn et al. (2011) (Table 4.1). The parameters include the mass of gas involved (M), the slug length (L), and the physical parameters defining the volcanic system: density (ρ) and viscosity (μ) of the magma, shear modulus (G) of the host rock, radius of the conduit (r_c), and the depth of the magma free surface (c).

The resulting displacement observed at the surface can be divided into two components U_σ and U_τ related to the normal stress and the shear stress respectively:

$$U_\sigma(t) = \int_{z_1}^{z_4} \frac{\Delta P(z,t)}{G} r_c^2 \left[\frac{z}{R^3} - \frac{z}{2} \left(\frac{3z^2}{R^5} - \frac{2v}{R^3} \right) \right] dz; \quad (4.8)$$

$$U_\tau(t) = \int_{z_1}^{z_4} \frac{3T(z,t)}{4\pi G} \left[\frac{z^3}{R^5} \left(\frac{1-2v}{1-v} \right) \right] dz; \quad (4.9)$$

where, ν is the Poisson's ratio, z is the depth along the conduit, ΔP represents the differential pressure gradient along the conduit, T is the shear stress at the conduit wall, $R = \sqrt{r^2 + z^2}$, and r is the horizontal radial distance between the conduit and the point in the top surface where we are measuring the deformation. The first component is linked to pressure variations acting on the wall and the resulting deformation of the conduit wall caused by the gas slug rising within the stagnant magma (Figure 4.3a). The second component is linked to the shear stress acting at the interface between the conduit wall and the magma. The shear stress is associated with the downward flow of viscous magma film around the slug (Nogueira et al., 2006a), and with the upward migration of the magma located above the slug as a consequence of its length expansion (Figure 4.3b). The total tilt is finally calculated by differentiating the sum of the two vertical component ($U_\sigma + U_\tau$) with respect to the radial distance r :

$$Tilt = -\frac{d(U_\sigma + U_\tau)}{dr}, \quad (4.10)$$

Figure 4.3. Model of surface deformation related to an ascending gas slug within stagnant magma in an open conduit. (a) The ascent of a gas slug perturb the initial pressure gradient causing the deformation of the conduit wall b , outward in the region above the slug (z_1 to z_2), and inward in the region below the slug (z_3 to z_4). (b) Shear stress on the conduit wall relates to the slug rising in the conduit at time $= t_n$. As the slug is rising we can identify two main region where the shear stress is acting: an upper region (z_2 to z_1) where the shear stress component T_m is acting upward due to the uplift of the magma surface from the slug expansion. And a lower region (z_3 to z_2) where the

shear stress component T_s is acting downward due to the liquid flowing around the slug. Computing the elastic Green's function we obtain the surface vertical deformation U recorded at a certain distance r from the conduit (eq. 4.8 and 4.9).

From the modelled tilt, the Bayesian inversion is then applied to get an estimate of the parameters controlling the behaviour of the observed natural system (Anderson & Segall, 2013; Segall, 2013). Considering that some parameters are fixed between events (σ , ρ , G , r_c , c), here we applied the Joint Bayesian Inversion (JBI) described in section 2.3.1.2, which consists in the application of the inversion technique simultaneously on different signals ($d_1, d_2, \dots, d_n$) with curves generated with the same set of fixed parameters and n independent gas masses and slug lengths ($m_1, m_2, \dots, m_n$). With this approach, the likelihood is given by the sum of the single likelihoods obtained from the fitting of the n different signals and the n curves generated with the model. In this study, the set of key parameters include density (ρ) and viscosity (μ) of the magma, the conduit radius (r_c), the initial length of the slug (L) and initial level of magma (c) in the conduit, since they control the spatial and temporal variation of the stress component within the conduit. Another important parameter controlling the deformation is the shear modulus of the host rock (G). Therefore our set of model parameters is expressed as:

$$\mathbf{m} = [G, \rho, \mu, r_c, c, L]. \quad (4.11)$$

The best fitting model will correspond to the maximum of the Probability Density Function (PDF) given by the combination of model parameters $\mathbf{m}$. To find the combination that gives the best fit we use a sampling technique known as Markov Chain Monte Carlo (MCMC) (Mosegaard & Tarantola, 1995) based on the Metropolis-Hastings rule (Hastings, 1970; Metropolis et al, 1953). Moreover, to further reduce the risk to be stuck in a local maximum of probability we combined the MCMC with the Simulated Annealing technique (Mosegaard & Tarantola, 1995). For each parameter, we evaluated the error between the best fitting and measured value as:

$$Error = \frac{(Estimated\ value - Real\ value)}{Real\ value} \cdot 100. \quad (4.12)$$

4.3 Results and discussions

The experimental results are shown in Table 4.2, which presents the slug characteristics and corresponding displacement magnitude and velocity. It also presents a summary of the experimental conditions including sampling rate, the size of the conduit, and the physical properties of the fluid analogues of the magma.

Table 4.2. Experimental results.

Exp #	Slug #	frame range	Frame rate	r_c	Fluid medium	Slug length	Slug Volume	Slug mass	V_{obs}	PVD	Surface displacement velocity
			(fr·s ⁻¹)	(m)		(m)	(m ³)	(kg)	(m·s ⁻¹)	(m)	(m·s ⁻¹)
1	1	40 - 299	24	0.025	Water	0.12	$2.1 \cdot 10^{-5}$	$1.7 \cdot 10^{-5}$	0.359	$-2.0 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$
1	2	400 - 672	24	0.025	Water	0.05	$8.8 \cdot 10^{-6}$	$7.2 \cdot 10^{-6}$	0.213	$-3.6 \cdot 10^{-5}$	$4.1 \cdot 10^{-5}$
1	3	70-210	24	0.025	Water	0.04	$6.7 \cdot 10^{-6}$	$5.5 \cdot 10^{-6}$	0.190	$-3.1 \cdot 10^{-5}$	$3.1 \cdot 10^{-5}$
1	4	365-520	24	0.025	Water	0.10	$1.9 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$	0.235	$-1.4 \cdot 10^{-4}$	$7.8 \cdot 10^{-5}$
1	5	600 - 899	24	0.025	Water	0.09	$2.2 \cdot 10^{-5}$	$1.8 \cdot 10^{-5}$	0.228	$-1.3 \cdot 10^{-4}$	$8.9 \cdot 10^{-5}$
2	1	0 - 459	24	0.015	Water	0.20	$1.4 \cdot 10^{-5}$	$1.2 \cdot 10^{-5}$	0.942	$-8.5 \cdot 10^{-5}$	$8.5 \cdot 10^{-5}$
2	2	620 - 864	24	0.015	Water	0.06	$4.2 \cdot 10^{-6}$	$3.4 \cdot 10^{-6}$	0.098	$-1.0 \cdot 10^{-5}$	$2.7 \cdot 10^{-6}$
2	3	130 - 407	24	0.015	Water	0.10	$8.7 \cdot 10^{-6}$	$7.2 \cdot 10^{-6}$	0.129	$-2.6 \cdot 10^{-5}$	$9.2 \cdot 10^{-6}$
2	4	516 - 851	24	0.015	Water	0.08	$5.4 \cdot 10^{-6}$	$4.5 \cdot 10^{-6}$	0.166	$-1.7 \cdot 10^{-5}$	$7.0 \cdot 10^{-6}$
3	1	0-148	24	0.025	Oil	0.12	$1.5 \cdot 10^{-5}$	$1.2 \cdot 10^{-5}$	0.845	$-1.1 \cdot 10^{-4}$	$4.4 \cdot 10^{-4}$
3	2	240-360	24	0.025	Oil	0.10	$1.2 \cdot 10^{-5}$	$9.6 \cdot 10^{-6}$	0.783	$-1.1 \cdot 10^{-4}$	$3.8 \cdot 10^{-4}$
3	3	360-748	24	0.025	Oil	0.04	$2.8 \cdot 10^{-6}$	$2.3 \cdot 10^{-6}$	0.111	$-1.6 \cdot 10^{-5}$	$4.7 \cdot 10^{-5}$
3	4	950-1180	24	0.025	Oil	0.05	$3.9 \cdot 10^{-6}$	$3.2 \cdot 10^{-6}$	0.364	$-2.8 \cdot 10^{-5}$	$8.4 \cdot 10^{-5}$
3	5	400-510	24	0.025	Oil	0.10	$1.1 \cdot 10^{-5}$	$8.6 \cdot 10^{-6}$	0.837	$-1.2 \cdot 10^{-4}$	$4.0 \cdot 10^{-4}$
3	6	635-800	24	0.025	Oil	0.07	$6.6 \cdot 10^{-6}$	$5.5 \cdot 10^{-6}$	0.432	$-5.5 \cdot 10^{-5}$	$8.3 \cdot 10^{-5}$
3	7	855-1000	24	0.025	Oil	0.09	$8.5 \cdot 10^{-6}$	$7.0 \cdot 10^{-6}$	0.682	$-7.8 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$
4	1	0-148	24	0.015	Oil	0.12	$4.0 \cdot 10^{-6}$	$3.2 \cdot 10^{-6}$	0.365	$-1.5 \cdot 10^{-5}$	$7.1 \cdot 10^{-5}$
4	2	220-399	24	0.015	Oil	0.13	$3.2 \cdot 10^{-6}$	$2.6 \cdot 10^{-6}$	0.260	$-1.3 \cdot 10^{-5}$	$2.8 \cdot 10^{-5}$
4	3	540-720	24	0.015	Oil	0.13	$3.1 \cdot 10^{-6}$	$2.5 \cdot 10^{-6}$	0.163	$-1.1 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$
4	4	860-1100	24	0.015	Oil	0.16	$7.2 \cdot 10^{-6}$	$5.9 \cdot 10^{-6}$	0.561	$-3.0 \cdot 10^{-5}$	$4.4 \cdot 10^{-5}$
4	5	30-190	24	0.015	Oil	0.16	$5.3 \cdot 10^{-6}$	$4.3 \cdot 10^{-6}$	0.346	$-9.1 \cdot 10^{-6}$	$1.5 \cdot 10^{-5}$
4	6	350-520	24	0.015	Oil	0.15	$4.4 \cdot 10^{-6}$	$3.6 \cdot 10^{-6}$	0.264	$-1.2 \cdot 10^{-5}$	$1.8 \cdot 10^{-5}$
4	7	790-990	24	0.015	Oil	0.15	$4.2 \cdot 10^{-6}$	$3.4 \cdot 10^{-6}$	0.228	$-1.8 \cdot 10^{-5}$	$2.4 \cdot 10^{-5}$

4.3.1 Parameters influencing the surface deformation

We evaluated the effects of the variation of viscosity and conduit diameter on the amplitude and duration of the tilt signal. As expected, we observed that the size of the slug is proportional to the amplitude of the vertical surface displacement, which is in line with the observations made at several natural systems reporting proportionality between volume of gas ejected and the recorded

geodetic signals (Genco & Ripepe, 2010; Iguchi et al., 2008; Kamo & Ishihara, 1989; Lyons et al., 2012; Nishi et al., 2007; Nishimura et al., 2012; Wiens et al., 2005).

Interestingly, at the laboratory scale the vertical displacement and tilt results to have a negative trend, which is the opposite of the trend associated to slug burst observed in the natural system, as noticeable in Figure 4.4a. This figure shows the comparison between tilt measured in experiment 4 at 30 cm of distance from the conduit on the left, (around 200 m of distance at the volcano scale), and the tilt prior a Strombolian explosions recorded in Stromboli volcano, Italy, from station CPL located around 250 m from the vent (from Genco & Ripepe, 2010) on the right. Considering that the distance from the vent is proportional, we believe that the opposite gradient is related to pressure differences existing between the laboratory and the natural scale. The natural pressure gradient within the conduit is larger compared to the one observed in the analogue model as the initial gas pressure of the slug P_0 , is equal to the magma-static pressure related with the above column of magma, and the atmospheric pressure P_{atm} . This leads to a large bubble expansion due to the large decompression to which the slug is exposed during its rise. Consequently, the tilt component related to normal stress becomes more prominent at the natural scale (Figure 4.4a). Moreover, as numerically demonstrated in previous studies (Kawaguchi and Nishimura, 2015), the shear stress displacement component is found to be several orders of magnitude smaller than the normal stress component. On the contrary, at the laboratory scale, the shear stress becomes more important than the pressure gradient as the slug expansion observed is negligible (Figure 4.4a).

To support our hypothesis, we numerically simulated the conditions observed at the laboratory scale and at the natural system by using the model previously described in section 4.2.5. Figure 4.4b shows the comparison between the two synthetic tilt signals (green lines) with laboratory and natural parameters and the respective shear (red line) and normal (blue line) components. While the lab synthetic signal shows a negative gradient similar to the one recorded during the experiments, the volcano synthetic tilt is completely dominated by the normal stress component resulting in a positive gradient similar to the data recorded at Stromboli volcano. Despite the differences between the pressure gradient observed at the laboratory scale and the pressure gradient existing in real volcanic conduits, we believe that this experimental setup can still provide important insight on the dynamic of the slug in an elastic conduit, which is not function of the

pressure. Moreover, by neglecting the deformation related to the normal stress variation, the proposed analogue simulation also allows to improve our knowledge on the deformation driven by shear stress acting on the conduit wall.

Figure 4.4. Comparison between displacement data and synthetic signals. (a) On the left tilt data recorded during experiment 4, and on the right tilt data recorded at Stromboli volcano, Italy (source Genco & Ripepe, 2010) (b) Synthetic tilt signals generated using the numerical model described in Chapter 2. On the left, the synthetic tilt obtained using parameters mimicking the laboratory scale. On the right side the Synthetics obtained using a set of parameters that closely reproduce Stromboli volcano. Vertical dashed lines represent the time of the slug burst.

We observed that variations in the slug volume can lead to changes in the slug dynamic, with the formation of super slugs above a certain volume threshold which is dependent on the viscosity and conduit geometry as described in Chapter 3. The super slug is characterized by a rising velocity higher than the theoretical one and a tapered shape with a diameter that decreases from the head of the slug to the tail to the slug. In silicon oil, this condition becomes more evident as the slug acquired a particular streamlined shape. Figure 4.5a shows the comparison between slugs of similar length observed during the experiments in the large conduit for the two different fluid mediums.

Figure 4.5. (a) Photographs of slugs of similar lengths (around 10 cm and 4 cm in the top and bottom rows respectively) observed during experiments in the large conduit filled with silicon oil (left), and water (right). (b) Relationship between the Peak Vertical Displacement (PVD) measured at 20 cm from the centre of the conduit and slug length. (c) Relationship between PVD and slug volume. Experiments in water are represented by large and small red circles respectively for large and small conduits (Experiment 1 and 2). Experiments in silicon oil are represented as large and small grey circles respectively for large and small conduits (Experiment 3 and 4).

We can see that for the considered size, the slugs display the streamlined shape in silicon oil. On the contrary, the same lengths are not sufficient to affect the shape of the slug in water due to the lower viscosity, as we see the classic features of a regular slug as typically described in the literature. We speculate that to reach the super slug condition a slug in water needs to have a larger volume compared to a slug in oil. Figure 4.5b shows the relationship between the slug length and the amplitude of the vertical displacement (PVD), measured at 20 cm from the centre of the conduit, for the four tested conditions. As expected, deformations similar to the ones observed in

a large conduit can be achieved by longer slugs in the small conduit. For both conduits, slugs rising in silicon oil resulted in smaller PVD compared to slugs with similar length rising in water, despite the fact that they cause greater forces on the conduit walls, as described in Chapter 3, where we observed a greater deformation region above the head of super slugs compared to regular slugs. For instance, in Experiment 1, a slug with a length of ~ 12 cm produced a PVD of $20\text{ }\mu\text{m}$ while in Experiment 3 a slug of the same length produced a PVD of $11\text{ }\mu\text{m}$. To test whether this result is associated with the particular form of super slugs, which results in a smaller volume compared to the ones observed in water, we analysed the relationship between the volume of the slug and the vertical displacement. Figure 4.5c shows how the two metrics are positively correlated, in line with observations made in natural systems, which show a proportion between the amplitude of the deformation signals and gas volume emitted during gas explosions (Nishimura et al., 2012). The results show that super slugs induce a larger PVD compared to normal slugs with the same volume, which is a direct consequence of the larger conduit deformations described in Chapter 3.

Figure 4.6 shows the effect of slug volume (represented by the size of the symbols) on the relationship between displacement velocity, and the ratio between measured slug velocity and theoretical slug velocity (V^*) for slugs in the big conduit (Figure 4.6a) and small conduit (Figure 4.6b). The figure shows that as the slug volume increases, its rising velocity also increases entering the so-called super slug regime, this condition leads to faster surface deformation for both conduits. We can also see that in high viscosity fluid, the super slug regime is reached earlier and with smaller volumes of gas compared to experiments in low viscosity fluid. For example, in Figure 4.6a we can see that a slug in water with a volume of 8.7 cm^3 induces a surface displacement velocity of $40\text{ }\mu\text{m/s}$, while a slug of similar volume (8.5 cm^3) in oil induces a larger displacement velocity of $170\text{ }\mu\text{m/s}$. These results suggest that in natural systems more explosive events which are normally linked to rapid deformation of the surface can be related to a slug that has entered the super slug regime rising the conduit with a velocity higher than expected, in addition, this condition can be reached earlier as the viscosity of the magma increases. This can be the case of events observed at Santiaguito volcano, Guatemala (Johnson et al., 2014), and Stromboli volcano, Italy (Del Bello et al., 2012), which exhibit two distinct behaviors, i.e. low-energy “puffers” (slow inflation) and explosive events (fast inflation).

Figure 4.6. Relationship between surface displacement velocity and normalized slug velocity V^* , for a 15 mm conduit (a) and 25 mm conduit (b). The size of the marker is proportional to the volume of the slug. Red markers are related to experiments where water was used as magma analogue. Grey markers are related to experiments where silicon oil was used as magma analogue. The background colour highlights the transition from normal slug to super slug. This condition is linked to the increase of the slug rising velocity compared to the theoretical one velocity.

From Figure 4.6b we can identify an exceptional explosive event in the small conduit filled with water for the slug having the largest volume of 14.4 cm^3 , which is sufficient to generate forces acting on the conduit wall that cause the conduit to experience dilation at the slug nose, and compression at the slug base. The analysis of the video shows that the slug has a velocity 7 times higher than the theoretical one and the shape of a super slug. Unfortunately, with the setup used in this study, we were not able to generate normal slugs in experiment 4, due to lack of precision while injecting small volumes of gas in the conduit. Consequently, we cannot precisely determine the minimum slug volume that leads to the appearance of super slugs for a specific medium viscosity. A future study is planned to address this limitation.

The main implications of the results described so far are that the numerical model has been designed considering the ascent within the conduit of slugs behaving according to the Taylor bubble dynamics in rigid conduit, meaning with velocity and shape mainly controlled by the diameter of the conduit and viscosity of the fluid. On the contrary, our experiments show that in an elastic conduit the slug velocity is strongly controlled by the volume of gas and that for

relatively high viscosity the volume required to reach the status of super slug is lower compared to a low viscous fluid. The following section reports the limitations of the numerical model.

4.3.2 Limitations of the numerical model

To support the ability of the numerical model previously described in Chapter 2, we applied the Joint Bayesian Inversion (JBI) technique on different signals recorded during the four experimental conditions described in the previous section. The tilt signals related to a total of 23 slugs, with length ranging from 3 cm to 20 cm, were used to estimate their volumes and masses, and the parameters that could not change across within the same experiment (i.e. density and viscosity of the magma analogue, the conduit radius, the initial level of fluid in the conduit, and the shear modulus of the gelatin). This test allowed us to have a direct comparison between the estimated parameters and the measured ones. Considering that the analogue experiments here described are scaled versions of a natural system, the approach will serve as a benchmarking test to understand the limitations of the model and to evaluate its uncertainties.

Figure 4.7. Best fitting model obtained by applying the JBI on tilt data recorded in relation to the 5 slugs observed during experiment 1. (a) Pictures of the 5 slugs analyzed in experiment 1. (b) Measured tilt signals in grey, and the best fitting models, in green, obtained applying the JBI.

Figure 4.7a depicts the slugs analysed in Experiment 1 (water as magma analogue and a conduit diameter of 2.5 cm), with lengths of 12, 5, 4, 10 and 9 cm from left to right respectively. Figure 4.7b shows the best fitting model (green line) obtained by applying the JBI to data associated with the five slugs recorded in experiment 1. As previously discussed, the normal stress component of

the surface displacement was less relevant at the laboratory scale compared to the natural system, resulting in a vertical displacement with a negative slope, which is controlled by shear forces (see Figure 4.4b). Consequently, also the calculated tilt results in a negative increase of the signal that reaches the minimum value when the slugs burst at the surface. As described in Chapter 2 the JBI is based on the principle that within the same volcanic system the parameter linked to physical and geometrical properties of the volcano should not change between explosions. Based on this concept, we applied the JBI simultaneously on the five tilt signals recorded in experiment 1, and among the model parameters showed in equation 4.11, we allowed only the length of the slugs to change between events (Figure 4.7b). The good fitting obtained with the JBI confirms the observation in section 2.3.2 that by only changing the mass of gas, the model can explain different magnitudes of eruptions recorded at Semeru volcano, Indonesia, further supporting the theory that the mass/volume of gas is a major controlling parameter.

Despite the good fitting obtained, the errors in the best-estimated parameter show inconsistencies for experiments 1 and 2, where water was used to simulate the magma. Figure 4.8 shows the error plots for the fixed parameters (in light blue) and length of the slugs (in light red) obtained after the application of the JBI on the five different signals recorded during Experiment 1 (top) and four different signals during Experiment 2 (bottom). The best fitting model results in errors that are greatest for the estimation of viscosity, which was overestimated for both experiments with an error of around $5 \cdot 10^5$ %. As expressed by Newton's viscosity law, the shear stress T , on the conduit wall is a function of both viscosity, and the velocity gradients in the liquid film around the slug:

$$T = -\mu \frac{dV}{dr} . \quad (4.13)$$

Accordingly, we should expect from experiments in low viscous fluids, such as water, a small shear stress component, which implies also small surface deformation. On the contrary, Experiments 1 and 2 exhibit large negative surface displacements that considering the low viscosity of water can be only justified with a high velocity of the liquid film surrounding the slugs.

Figure 4.8. Box plots of the normalized errors for each parameter for inversion on tilt signals recorded during experiment 1 (above) and 2 (below) obtained applying the JBI. The blue boxes represent the fixed parameter, the red boxes represent the lengths of the slugs. Green horizontal lines represent the true value which corresponds to zero error. Rectangles span the first to the third quartile. Whiskers indicate the distribution range corresponding approximately to 2.7 times the standard deviation. Red crosses represent outliers considered as extreme values that are 1.5 times the interquartile range away from the top or bottom of the box, and diamonds represent the value obtained for the best inversion.

To support this hypothesis, in Figure 4.9a we compared a synthetic signal obtained using the real values of the parameters recorded during the rise of slug number 5 in experiment 1 (grey), with the related tilt measured at the surface. (red is the shear stress component and blue is the normal stress component). The amplitude of the shear stress component is very small compared to the measured tilt signal. Nevertheless, if we boost, the value of the downward velocity of the liquid film around the slug by a factor of two, the shear stress component becomes more important and the fitting improves (Figure 4.9b).

Figure 4.9. Comparison between tilt data recorded during experiment 1 in relation to slug number five and a synthetic signal generated using the proposed numerical model generated using : (a) The values of parameters measured in the experiment. (b); the same values for the parameter and increasing the downward film velocity of a factor of 2.

According to Nogueira et al. (2006a) and Brown (1965) for rigid conduit the liquid film velocity around the slug can be written as follow:

$$V_{film} = \frac{\rho g}{\mu} \left[\frac{r_c^2 - r^2}{4} - \frac{r_s^2}{2} \ln \left(\frac{r_c}{r} \right) \right], \quad (4.14)$$

By substituting and differentiating, the shear stress gradient can be written as:

$$T = -\rho g \left(\frac{r_s^2}{2r_c} - \frac{r_c}{2} \right), \quad (4.15)$$

In this form, the viscosity term is cancelled out disappearing from the equation. Nevertheless, it is still indirectly part of the equation by controlling the radius of the slug r_s , which as mentioned in section 4.2.4 is a function of the thickness of the liquid film $\lambda = (6 \cdot Fr / N_f)^{1/3}$ (Llewellyn et al., 2011). By substituting for equation 4.1, and 4.4 the radius of the slug can be recast as follow:

$$r_s = r_c \cdot \sqrt[3]{12 \frac{V_b}{\rho} \mu r_c^2}, \quad (4.16)$$

By substituting r_s in equation 4.15 with the formulation derived in equation 4.16, the shear stress becomes exclusively a function of the radius of the conduit, viscosity, and velocity of the slug, which itself is also a function of viscosity.

The theoretical considerations show two shortcomings with the numerical model: firstly, the only way to increase the shear stress is to increase the conduit radius or the viscosity, and secondly, the model does not allow us to directly control the velocity of the liquid film surrounding the slug. Considering these shortcomings, the large errors in the viscosity best estimate can be justified with the model trying to increase the shear stress component by increasing viscosity. . The existence of high downward velocity is related to the formation of super slug. As mentioned in the previous section, super slugs deform the conduit creating a difference in diameter between the region above the slug and the region below the slug, this phenomenon is not taken into account by equation 4.14 which considers a constant diameter. According to Bernoulli's equation, in a pipe the reduction of the diameter causes the water to move faster causing a pressure drop compared to the regions where the diameter is larger and the water is moving slower causing a pressure increase. The model here proposed does not take into account this effect and for this reason, failed to justify the large shear stress observed.

Another interesting result is that regardless of the errors in slug lengths estimation, for both experiments in water the best values of length obtained were proportional to the measured one. We believed that the high range of slugs dimensions analysed encompasses different slug dynamics that the model could not capture. Slugs with a small volume generate smaller deformations of the conduit and for this reason, they rise with the expected theoretical velocity. On the contrary, larger volumes, by deforming the conduit, acquired the condition of super slug following different dynamic not explained by the model currently used.

Figure 4.10. Same as Figure 4.7 but for experiment 3 (above) and 4 (below).

When we used silicon oil as magma analogue, almost all the slugs behaved as super slugs. The viscosity estimate was about two times smaller than the real one, showing a much closer estimate compared to the results of the inversion on Experiment 1 and 2. Contrary to the results in water, where errors were $\pm 100\%$, we can see that in silicon oil the errors in the length estimate display a greater range of values, with a peak of 300% for slug 4 in Experiment 3, which had a length of 5 cm. Moreover, the best values of slug length obtained are not proportional to the measurements and the viscosity was underestimated. These results can be related to a tentative of the model to explain the rapid displacement velocity linked to the super slugs, by reducing the viscosity of the fluid to increase the velocity. Figure 4.11a shows the comparison between the tilt recorded during Experiment 3 for slug number 6, and the synthetic tilt generated by using the measured values for the parameters. The model, again, fails to fit the measurements, in particular, the rapid deformation observed just before the slugs burst. Nevertheless, the amplitude of the PVD is well captured.

Figure 4.11. Comparison between tilt data recorded during experiment 3 in relation to slug number six and a synthetic signal generated using the proposed numerical model generated using : (a) The values of parameters measured in the experiment; (b) the same values for the parameter plus using the measured velocity of the slug.

Figure 4.11b shows the fitting when the initial velocity of the slug, computed following equation 4.6, increases so that the slug reaches the final values measured during the experiment. As a result, the fitting of the model drastically improves.

Our results suggest that the model can be improved by considering the velocity of the film around the slug and improve the estimation of the shape of the tilt signal. Several models do not consider the mechanical interaction between the magma analogue and the elastic conduit walls. In the work of D'Auria and Martini (2011), the authors consider the effect of the motion of the walls on the slug flow as negligible as the length/thickness ratios of their model was lower than 10. The interaction dynamics between the slug, magma, and host-rock are complex and their accurate analysis is left for future study.

4.4 Summary

This chapter presented a series of analogue experiments to simulate short-time surface deformation cycles observed in relation to the rise of slugs in an elastic deformable volcanic conduit. In chapter 3, we have already described the effects of slugs on an elastic conduit in gelatin by applying PIV

techniques to measure both displacements in the fluid and the surrounding elastic medium. In this chapter, we extended this analysis to the surface deformation data by applying a photogrammetry technique vertical displacement and tilt. The results confirmed the observation made in the previous chapter, that in an elastic conduit the slug volume mainly controls its rising velocity, as the volume increases above a certain threshold the slug becomes a super slug. We found that small volumes are also linked to a small deformation rate of the top surface, while large volumes induce fast deformation rates similarly to the natural system where we observe both low-energy “puffers” (slow inflation) and explosive events (fast inflation) (Johnson et al., 2014; Del Bello et al., 2012).

Moreover, the analogue simulations were used as a benchmark to evaluate the numerical model described in Chapter 2. Despite the close fitting between the recorded data and the model, the results show inconsistency in the best values obtained for the controlling parameters. Results show that the model struggles to estimate the viscosity of the fluids. The obtained error for the experiments in water was $+10^5\%$, and for the experiments in silicon oil was -100% . The errors can be linked to a different slug dynamic observed during the experiments that may cause the slug and the liquid around it to accelerate, in contrast to classic formulations. Nevertheless, the numerical model showed the ability to distinguish the relative size variation between simulated slugs confirming the potential ability of the proposed numerical model to be applied for estimating the size of future explosive events. The results suggest that the dynamic of the super slug in elastic conduit have to be taken in to account in the model formulation to be able to better estimate the time of large explosive events, which may be linked to this particular type of slugs.

Chapter 5

Correlation between GNSS-TEC and eruption magnitude supports the use of ionospheric sensing to complement volcanic hazard assessment

Despite the importance of monitoring and early warning systems in consideration of the disastrous impacts that large-scale eruptions can have, many active volcanoes still lack ground-based instrumentation, precluding the application of the technique presented and validated in the previous chapters. Here we present a study on new satellite-based remote sensing techniques for volcano monitoring. We first test the potential use of a new metric related to the energy of atmospheric disturbances, called Total Electron Content Intensity Index (TECII), to provide additional information to complement the existing monitoring system. We then evaluate the relationship between the TECII and several well-known metrics obtained by seismology and satellite remote sensing to test whether ionospheric monitoring can provide information about the magnitude of a volcanic eruption, opening an exciting new avenue for volcano remote sensing based on GNSS-TEC analysis.

5.1 Total Electron Content Index (TECII) as a measure of power of an event

As discussed in Chapter 1, volcanic surveillance relies mainly on seismic and geodetic networks, and in-situ volcano monitoring has been recently complemented with techniques based on remote sensing. When the necessary conditions for these techniques are not present, their application is limited, and new methodologies should complement the current set of tools available to quantify the power of volcanic events. A promising method is based on the observation that powerful blast, including volcanic eruptions, strong earthquakes or even nuclear explosions, generate acoustic-gravity waves that propagate upward in the atmosphere and perturb the ionospheric plasma density. The perturbation is visible in the ionospheric total electron content (TEC), which

represents the number of electrons integrated along the ray-path between the GPS satellite and the ground based station.

Perturbations in TEC have been observed for a number of large earthquakes (e.g., Calais & Bernard, 1995) and more recently for tsunami (e.g., Artru et al., 2005; Occhipinti et al., 2006); the ionospheric signatures of those events have been detected (Occhipinti et al., 2013) and explored to estimate the seismic magnitude (Occhipinti et al., 2018). The analysis of TEC has also revealed perturbations after volcanic eruptions at Pinatubo Volcano (Cheng & Huang 1992, Igarashi et al., 1994), Asama Volcano (Heki, 2006), Soufriere Hills Volcano (Dautermann et al., 2009) Calbuco Volcano (Shultz et al., 2016) and Kelud Volcano (Nakashima et al., 2016). However, the relationship between the TEC perturbation induced by the volcanic acoustic gravity waves and the corresponding magnitude and explosiveness of the eruption has not been analysed yet.

In this chapter, we evaluate the relationship between TEC perturbations, measured with a new metric called TECII, and volcanic eruption characteristics, to determine the feasibility of using ionospheric sounding techniques to infer volcanic eruptions characteristics. The TECII metric represents the ratio between the maximum level of power spectral density of the TEC perturbation during the volcanic event and the mean background level. We believe that, as this metric is related to the entire spectrum of energy of the acoustic gravity waves at the epicentre, it is consequently more appropriate than the TEC amplitude estimation used by previous authors, and that could be affected by frequency pass-band filtering. The next section describes the computation of the metric and its validity for the estimation of the power of an event.

As a case study, we analyzed whether the TECII was able to discriminate between two Mw 7.8 earthquakes (Figure 5.1) that occurred in 2010 along the Sunda megathrust (Indonesia): The 6 April Banyaks earthquake (Feng et al., 2015; Morgan et al., 2015) and the 25 October Mentawai earthquake (Hill et al., 2012; Newman et al., 2011; Satake et al., 2013).

Figure 5.1. Main geological features of the Sumatran subduction zone and location of SuGAR stations available and the 29 stations used in the study.

The Banyaks earthquake ruptured a deeper portion (20-30 km) of the megathrust, producing relatively small uplift of the seafloor and thus only a small tsunami (max water height: 44 cm, max run-up: 6 m, source NOAA database). On the other hand, the Mentawai earthquake was a shallow event with estimated slip concentrated at depths of <6 km, no more than ~ 50 km away from the trench. Given the lower rigidity of the shallow sediments at this location, the Mentawai event generated considerably higher levels of slip (Hill et al., 2012; Yue et al., 2014) than the Banyaks event (Morgan et al., 2015) while maintaining the same moment magnitude. The reported shake intensity at 150km distance from the epicentre was MMI 5 and MMI 6 for the Mentawai, and for Banyaks event, respectively. The high slip at shallow depths resulted in seafloor uplifts of up to several meters, producing the outsize tsunami with a reported maximum run-up >16 m (Hill et al., 2012), which should lead to differences in the associated TECII.

5.1.1 Ionospheric Total Electron Content (TEC)

The TEC is the total electron content measured in TEC units ($1 \text{ TECU} = 10^{16} \text{ el/m}^2$). We calculated the TEC by applying a method similar to the one described by Calais & Minster (1995). To obtain a more accurate measure of the apparent distance between a satellite and receiver, we

used the carrier phase (L1 & L2), neglecting the less precise pseudo-range measurements (P1 & P2):

$$TEC = \frac{(L1 - L2)}{40.3} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \quad (5.1)$$

where, L1 and L2 are corrected for phase ambiguities using the program Ninja within the GPS-Inferred Positioning System and Orbit Analysis Simulation Software (GPSY-OASIS) developed at the Jet Propulsion Laboratory (JPL), California Institute of Technology (Blewitt, 1990, 2000; Lichten & Border, 1987) and f_1 and f_2 are the high and low GPS frequency values.

We considered the area located around the height of the maximum of ionosphere ionization (the F2 layer, fixed at an altitude of 300 km), as the main contribution to the observed TEC variations. Therefore, the observed perturbations are visualized at the ionospheric pierce point (IPP), which represents the intersection of the line of sight between each GPS satellite-receiver pair at F2.

In order to identify perturbations caused by the earthquake and the subsequent tsunami, we filtered all the initial TEC time series on a defined range of frequencies following the same methodology as Rolland et al. (2011). We applied a 1 to 10 mHz bandpass finite impulse response (FIR) Butterworth filter in order to remove the contributions from daily ionospheric variabilities, satellite motions, and instrumental biases.

We used the filtered signal to evaluate the TEC Intensity Index (TECII) as:

$$TECII = \frac{PSD_{MAX}}{MBL} \cdot 100, \quad (5.2)$$

PSD_{MAX} corresponds to the maximum level of power spectral density of the TEC recorded during the event, and MBL is the mean background level. This is defined as the average maximum level of PSD of the TEC recorded by the same satellite-station pair during a 2-hour window, starting from the event onset time, of the 6 days preceding the event. We averaged the maximum PSD by the number of days to further limit the effect of perturbations unrelated to the event.

5.1.2 Results and discussions

At the time of the Mentawai earthquake, 29 stations of the SuGAR network were in operation (Figure 5.2a), while 25 stations were operating at the time of the Banyak earthquake (Figure 5.2b).

Figure 5.2. (a) Map of the distribution of ionospheric piercing points (IPPs) for the pairs of 29 GPS stations and the four closest satellites at the time of the Mentawai earthquake (local time: 21:42:23 UTC +7). The IPPs are represented by four different symbols corresponding to different satellites; the symbols are located at positions along the trace of the IPPs corresponding to the event time. Note the bold traces highlighting the trajectory of the satellite-receivers pairs showed in Figure 5.3. The red star represents the epicentre of the earthquake. (b) Hodochrones of the TEC perturbation observed by GPS satellites PRN 21, 9, 14, and 29. (c) Insert with colour scale 5 times higher to highlight the gravity waves related to the IGWtsuna recorded by PRN 21. (d) Map of the distribution of ionospheric piercing points (IPPs) for the pairs of 29 GPS stations and the four closest satellites at the time of the Banyak earthquake (local time: 5:15:02 UTC+7). (e) Hodochrones of the TEC perturbation observed by GPS satellites PRN 2, 28, 5, and 10. Vertical

dashed lines represent the time of the event. The grey dashed lines show the speed of the AGWepi (800 m/s) and IGWtsuna (250 m/s).

In both cases, more than 8 GPS satellites were visible in the sky, and we selected the four that better depicted the events. During the Mentawai event the TEC shows a perturbation related to the Acoustic-Gravity Waves (AGWepi) associated with the uplift (Figure 5.2) with a frequency signature between 1 and 7 mHz (Figure 5.3a) appearing 8 minutes after the main shock (21:42:23 local time, UTC+7) and propagating away from the epicenter at a horizontal speed of 600-800 m/s (Figure 5.2b). Later, a second weaker TEC perturbation at a lower frequency (~ 1.5 mHz), related to the atmospheric Internal Gravity Wave (IGWtsuna) linked to the oceanic internal gravity wave appears to travel at a horizontal speed of ~ 250 m/s, consistent with the tsunami speed of ~ 220 m/s observed by DART buoy 56001, located ~ 1600 km from the epicenter (Lay et al., 2011). The arrival time of IGWtsuna observed at a distance of 480 km from the epicentre (Figure 5.3a) is coherent with the tsunami propagation. A much smaller TEC perturbation followed the Banyaks earthquake (Figure 5.3b and Figure 5.2d, e), which generated a much weaker tsunami that did not cause any damage. As consequence of the integrated nature of TEC along the station-satellite line of sight, satellites at low elevation angle have a better detection capability (Occhipinti et al., 2013). Accordingly, to be able to compare the power spectral signature of the two events analyzed in this analysis, we select satellite-station pairs with similar angles and distances from the epicentre area (Figure 5.3).

Figure 5.3. Filtered ionospheric TEC time series and related spectrograms extracted by (a) observations of satellite PRN29 with respect to station BTHL at the time of the 2010 Mw 7.8 Mentawai earthquake and (b) observations of satellite PRN2 with respect to station BSIM at the time of the 2010 Mw 7.8 Banyak earthquake. Solid red and white vertical lines indicate the time of the events. Dashed vertical lines indicate the time of the first potential arrival of the AGWepi (8 min) and the minimum time of IGWtsuna observation (40 minutes) in the ionosphere. Horizontal dashed lines are the Brünt-Väisälä frequency that represents the limit between gravity and acoustic domains. In grey is indicated the elevation angle during the observation time for the two represented satellite-station pairs.

Spectral analysis (Figure 5.4) of observed TEC during the days before and after the Mentawai event reveals the unique characteristics of the AGWepi compared to the mean background level (MBL).

Figure 5.4. Spectrograms of the filtered TEC signal recorded by the pair of station PTLO and satellite PRN29 at the epicentre of the 2010 Mw 7.8 Mentawai earthquake over seven consecutive days. Horizontal dashed lines are the Brünt-Väisälä frequency that represents the limit between the gravity and the acoustic domain. Vertical lines in the central panel (d) indicate, respectively from left to right: the time of the event (solid line); the first potential arrival of the AGWepi (8 min, dashed line); the minimum time of IGWtsuna observation (40 min, dashed line) in the ionosphere. Green contour lines mark where the intensity of the signal is above a threshold value that represents the mean background level (MBL) calculated on the six days before the event.

The TECII for the Mentawai event was 14, as TEC observations revealed a perturbation 14% larger than the MBL (Figure 5.4). A comparable energetic signature related to external localized phenomena (e.g., plasma bubbles, travelling ionospheric disturbances) appeared on 22 October 2010 but this was not related to a seismic event and consequent tsunami early warning, showing the importance to couple ionospheric observations with conventional techniques. Weaker TEC perturbation followed the Banyaks earthquake approximately 5% of the MBL, confirming the

presence of a weaker tsunami ($TECII = 5$). The $TECII$ measured for the two events shows a correlation with the seafloor uplift, reported by Cahyadi and Heki (2014), by the United States Geological Survey (USGS, <https://earthquake.usgs.gov/earthquakes/>), and by Hill et al. (2012). Figure 5.5 supports the possibility of obtaining information on seafloor uplift and therefore the power of the event from ionospheric perturbation.

Figure 5.5. Relation between seafloor maximum volume displaced (V_{max}), coseismic TEC amplitude and $TECII$ for 17 events. Blue symbols represent earthquakes from the literature (Cahyadi & Heki, 2014). Red symbols represent the Mentawai and Banyak earthquakes discussed in this paper. The left axis represents the TEC coseismic amplitudes normalized by background vertical TEC estimated from Global Ionospheric Maps (GIM) as defined by Cahyadi & Heki (2014). The right axis represents the $TECII$ for the Mentawai and Banyak events. X symbols represent events that generated a very small tsunami that did not cause damage. O symbols represent events that do generated a tsunami and damage.

5.2 Relationship between ionospheric $TECII$ and current techniques for volcano monitoring

In this section, we compare the TEC perturbations observed during 22 different eruptive events to different parameters normally linked to the size of the eruption (i.e. reported VEI, plume height, reduced seismic amplitude). We investigate events that occurred at 12 different volcanoes, located at different latitudes, to include the effects of the magnetic field on the detection (Figure 5.6). The

results provide insight into the feasibility of using ionospheric sounding techniques to complement current volcano monitoring systems, especially in remote areas. The potential to remotely gain additional information can be especially valuable for isolated volcanoes where monitoring is limited or non-existent.

Figure 5.6. Map showing the location of the 12 volcanoes analyzed in this work. We chose volcanoes at different latitudes to consider the possible effects of the magnetic field on the TEC signals

5.2.1 Data analysis

Our dataset comprises the GNSS signals recorded during 22 volcanic events between 2003 to 2018 (Figure 5.7), as listed in Table 5.1. These include 5 events which are known to have induced perturbations in the ionosphere and can be found in the literature (Dautermann et al., 2009; Heki et al., 2006; Li et al., 2016; Nakashima et al., 2016; Shults et al., 2016). To identify variations in the TEC data recorded from the stations operating at the time of each eruption, we compare the TEC signal of 6 quiet days prior to the eruptions to the signal recorded at its onset.

Table 5.1. List of events discussed in this chapter

ID	Name	Date (dd-mm-yy)	Time (UTC)	Lat	Lon	GNSS network code	Number of GNSS available	Sampling rate (sec)	Seismic station code
AS01	Asama (Japan)	01-09-04	11:02:00 AM	36.41	138.52	IGS	1	30	IU-MAJO
AS02	Asama (Japan)	01-02-09	04:51:00 PM	36.41	138.52	IGS	1	30	IU-MAJO

CA01	Calbuco (Chile)	22-04-15	09:05:55 PM	-41.33	-72.61	CAP Andes	12	15	C-GO07
CA02	Calbuco (Chile)	23-04-15	04:08:00 AM	-41.33	-72.61	CAP Andes	12	15	C-GO07
CL01	Cleveland (Alaska)	29-12-11	01:12:00 PM	52.82	-169.95	PBO AVO	12 8	15 30	AV-OKSO
ET01	Etna (Italy)	03-12-15	02:30:00 AM	37.76	15.00	Calabria IGS	3 1	15 30	IV-NOV
ET02	Etna (Italy)	04-12-15	08:00:00 AM	37.76	15.00	Calabria IGS	3 1	15 30	IV-NOV
ET03	Etna (Italy)	04-12-15	09:00:00 PM	37.76	15.00	Calabria IGS	3 1	15 30	IV-NOV
ET04	Kelud (Indonesia)	13-02-14	03:46:00 PM	-7.94	112.31	SuGAR IGS	27 3	15 30	GE-UGM
KR01	Anak Krakatau (Indonesia)	22-12-18	01:34:00 PM	-6.10	105.42	SuGAR IGS	21 2	15 30	GE-BBBI
MA01	Mayon (Philippines)	13-01-18	08:21:00 AM	13.26	123.69	PHIVOLCS	2	15	MN-VMLH
MA02	Mayon (Philippines)	14-01-18	01:49:00 AM	13.26	123.69	PHIVOLCS	2	15	MN-VMLH
MA03	Mayon (Philippines)	14-01-18	03:43:00 AM	13.26	123.69	PHIVOLCS	2	15	MN-VMLH
MA04	Mayon (Philippines)	22-01-18	04:43:00 AM	13.26	123.69	PHIVOLCS	2	15	MN-VMLH
ME01	Merapi (Indonesia)	26-10-10	10:02:00 AM	-7.33	110.27	SuGAR IGS	33 5	15 30	GE-UGM
ME02	Merapi (Indonesia)	04-11-10	05:05:00 PM	-7.33	110.27	SuGAR IGS	33 5	15 30	GE-UGM
OK01	Okmok (Alaska)	12-07-08	07:43:00 PM	53.43	-168.13	PBO	17	15	AK-NIKH
SI01	Sinabung (Indonesia)	06-09-10	05:23:00 PM	3.17	98.39	SuGAR IGS	30 4	15 30	GE-GSI
SI02	Sinabung (Indonesia)	17-09-13	05:03:00 AM	3.17	98.39	SuGAR	30	15	GE-GSI
SI03	Sinabung (Indonesia)	17-12-16	02:33:00 AM	3.17	98.39	SuGAR	29	15	GE-LHMI
SH01	Soufrière Hills (Monserrat)	13-07-03	03:35:00 AM	16.72	-62.18	IGS	1	30	--
TO01	Tolbachik (Russia)	27-11-12	05:15:00 AM	55.83	160.33	IGS	3	30	IU-PET

The TEC time series for all the satellite-station pairs were filtered with a bandpass finite impulse response (FIR) Butterworth filter with a range of 2 mHz to 10 mHz, in order to remove the contributions from daily ionospheric variabilities, satellite motions, and instrumental biases.

We selected among all the available TEC data obtained for each event, one signal for further analysis according to the following criteria: (1) presence of continuous-time signal during the event; (2) IPP distance from the source < 1000 km; (3) line-of-sight elevation angle between satellites and GNSS receivers between 10 and 70 degrees. If these criteria were met by the signals recorded from different satellite-station pairs, we visually inspected the data and chose the signal showing less background noise to limit the effect of meteorological perturbations. We then used it for the evaluation of the TEC Intensity Index (TECII) as described in eq. (5.2).

We collected information on several parameters related to the intensity of the eruptions from the literature. In particular, we used the Volcanic Explosivity Index (VEI), reported plume height, seismic Peak Ground Velocity (PGV). The events analyzed presented VEI values in the range from

2 to 4 as reported in the Smithsonian Institution's Global Volcanism Program (GVP, <http://www.volcano.si.edu>), with VEI 2 as default value for small scale events.

Another parameter used to characterize the explosivity of eruptions is the plume height. It can be measured by ground-based sensors including radars (Donnadieu et al., 2016; Schneider & Hoblitt, 2013; Valade et al., 2012), lidar, cameras, lightning detectors (Cimarelli et al., 2016) and infrasound. We used plume height values reported in the literature obtained from direct measurements as well as modelling (Corsaro et al., 2017; Cronin et al., 2013; Fee et al., 2010; Global Volcanism Program, 2012; Gunawan et al., 2017; Kristiansen et al., 2015; Marchese et al., 2012; Matoza et al., 2018; McCausland et al., 2017; NDRRMC, 2018; Senyukov et al., 2015; Shimbori et al., 2009; Shults et al., 2016; Surono et al., 2012; Voight et al., 2010). Plume height for the event SI03 volcano eruption is based on the report issued by the Volcanic Ash Advisory Center (VAAC) in Darwin.

Further, we collected and analyzed broad-band seismic data available from the GEOFON and IRIS data centres. For each event, we analyzed the data from a single seismic station with distances ranging from 32 km to 330 km (Table 2). Following Zobin (2012), we measured the amplitude of the PGV of the first arrival extracted from the vertical component of the sensors filtered between 0.5 and 8 Hz. PGV values were adjusted to a reference distance fixed to 10 km from the source, for which the attenuation caused by geometric spreading and the loss of energy due to the anelasticity of the medium were taken into account (Aki & Richards, 2002). The amplitude of the waves function of the epicentral distance r , is expressed following Battaglia and Aki (2003):

$$A(r) = A_0 \cdot \frac{1}{\sqrt{r}} \cdot e^{-Br}, \quad (5.3)$$

With

$$B = \frac{\pi f}{Q\beta}, \quad (5.4)$$

where, A_0 is the source amplitude, f is frequency, β is shear wave velocity, and Q is the quality factor. We use $f = 3.75$ Hz which represent the mean value of the frequency band 0.5–8 Hz filter applied to the data. We use a range of shear wave β velocity between 2 - 3 km/s. Quality factor have been chosen in the range of values obtained by Koyanagi et al. (1995) for Kilauea Volcano, and De Natale et al. (1987). For events measured at distance < 70 km we used $Q = 50$ which better

represents the highly fractured, and weakened volcanic edifice, and $Q = 300$ for the events recorded at distance greater than 70 km considering the presence of more competent rocks.

Therefore, the PGV measured at r was adjusted as:

$$PGV(@10) = PGV(r) \cdot \sqrt{\frac{r}{10}} \cdot e^{-B(r-10)}. \quad (5.5)$$

We used the available datasets to determine whether GNSS could be exploited to provide useful information to volcano observatories and the VAACs for mitigation of volcanic ash hazards.

5.2.2 Results and discussions

5.2.2.1 GNSS-TECII

For each event, we measured the TEC for all the satellites orbiting close to the volcano. We then selected the signals recorded by the satellite-station pair that satisfies the criteria for the analysis, and analyzed these signals in the time and frequency domains to better detect perturbations.

Table 5.2. List of all the volcanic events analyzed, with associated values of the parameters evaluated.

ID	Plume height (km)	VEI	Seismic PGV @ 10km (ms ⁻¹)	TECII	GNSS-satellite pairs	Line-of-sight elevation angle (degree)
AS01	4.5*	2	-4.71	-2.9	USUD-19	64
AS02	4.5 [†]	2	-5.28	-5.3	USUD-31	60
CA01	17°	4	-2.92	17.32	MHIN-23	67
CA02	21 [§]	4	-2.61	21.6	MHIN-28	64
CL01	5 [‡]	--	-4.74	5	AV06-9	47
ET01	11.8**	--	-4.23	-0.89	LUZZ-25	38
ET02	14.1**	--	-3.98	4.1	LUZZ-22	38
ET03	10.5**	--	-3.95	-4.8	CETR-12	50
KL01	17 ^{†‡}	4	-3.76	18.43	BAKO-20	40
KR01	15 ^{°°}	3	-3.10	4.35	BAKO-23	45
MA01	4.9 ^{§§}	--	-5.65	-3.17	BICA-16	30
MA02	N/A	--	-5.38	0.23	VRAC-20	30
MA03	N/A	--	-5.55	-2.34	VRAC-15	30
MA04	5 ^{§§}	--	-5.35	0.47	BICA-31	30
ME01	4.5 ^{‡‡}	--	-2.46	4.7	XMIS-2	13
ME02	17 ^{‡‡}	4	-0.95	12	NTUS-29	12
OK01	16 [▲]	4	-0.78	20.72	AC25-2	32
SI01	5 [▼]	--	-2.82	-4.25	UMLH-12	15
SI02	6 [▼]	2	-3.85	4.8	BTET-17	24
SI03	6 [□]	--	-3.18	-3.36	MREK-2	30
SH01	12.2 [■]	3	--	9.96	CR01-31	56

TO01	6[•]	--	-3.09	-4.29	PETS-4	60
<i>*, Marchese et al., 2012; †, Shimbori et al., 2009; °, Shults et al., 2016; §, Matoza et. al., 2018; ‡, GVP Bulletin 2012; **, Corsaro et al., 2017; ††, Kristiansen et al., 2015; ‡‡, Cronin et al., 2013; ▲, Fee et al., 2010; §§, NDRRMC; ‡‡, Surono et al., 2012; ▼, Gunawan et al., 2017; McCausland et al., 2017; □, Darwin VAAC report; ■, Voight et al., 2010; ♦, Senyukov et al., 2015</i>						

In Figure 5.7 we report an explanatory example of the analysis of the Anak Krakatau eruption on the 22nd December 2018. We analyzed data from a total of 23 GNSS stations (21 from SuGAR with 15-sec temporal resolution shown in Figure 5.7a, and 2 operating at 30-sec resolution from the IGS network) paired with 13 GPS satellites, in search of perturbations linked to this complex event. Among the satellites that satisfied the criteria for the analysis of TECII, we used the ones for which the TEC displayed higher perturbations (PRN 3, 7, and 23, shown in Figure 5.3a) to visualize the oscillation pattern in the hodochrone (Figure 5.7b). The time series and spectral analysis of the signal recorded by satellite PRN3 with respect to station LNNG (Figure 5.7c and Figure 5.7d) show the 2 different perturbations induced in the ionosphere which could be noted in the hodochrone: a first one travelling at a horizontal speed of ~ 1 km/s with origin time corresponding to the time of the flank collapse and a second one, appearing around 22:30 (local time) in conjunction with the second and stronger pulse at a similar speed (~ 1 km/s) but stronger in amplitude. The presence of an acoustic component in correspondence with the first perturbation coincides with the 5.1 Mw earthquake, with a NW-SE trending focal plane recorded at 20:55 (local time) on the regional seismic network triggered by flank collapse (GEOFON Program website). The stronger gravity component observed in relation to the second pulse can be attributed to the presence of a sustained plume in the atmosphere. Indeed, the rise of the eruptive plume, constituted by a mixture of hot gas and particles, can displace the atmospheric medium inducing the propagation of gravity-waves (De Angelis et al., 2011; Ripepe et al., 2010).

Figure 5.7. (a) Map of the ionospheric pierce points (IPPs) at the time of the event for three satellites (PRN 3, 7, and 23, depicted with different colours and shapes), in relation to 21 GNSS stations (hollow black circles) from the SuGAR network. Arrows show the 3-hour trajectories of the IPPs, starting 30 minutes before the event (b) Hodochrone of the TEC perturbation observed by the 63 GPS satellite-receiver pairs following the 22 December 2018 eruption of Anak Krakatau, which shows the perturbations in the ionosphere induced by the two phases of the event as colour bands. (c) Filtered ionospheric TEC time series and related spectrogram (d) extracted from observations of satellite PRN3 with respect to station LNNG. Dashed vertical lines represent the time of the 2 eruptive phases at 20:40 and 22:20 local time. The dashed red line indicates the time of the flank collapse at 20:55 local time. Horizontal dashed line in (d) corresponds to the Brünt-Väisälä frequency that represents the limit between gravity and acoustic domains. An acoustic component is visible in correspondence with the earthquake, a gravity component is observed after the second pulse, attributable to the presence of a sustained plume in the atmosphere.

We applied the same approach to analyze all the eruptions reported in Table 5.1. List of events discussed in this chapter, and the analysis of the available GNSS signals revealed that 13 events out of 22 induced clear perturbations in ionospheric TEC as reported in Table 5.2. List of all the volcanic events analyzed, with associated values of the parameters evaluated. For these events, the table reports also the measure of the TECII index as well as the IPPs and angles of the best station-satellite pair used to compute the corresponding index. TECII ranged from -5.3 (AS02 in Table 5.2. List of all the volcanic events analyzed, with associated values of the parameters evaluated) to 21.6 (CA02 in Table 5.2. List of all the volcanic events analyzed, with associated values of the parameters evaluated). Figure 5.8 shows the spectrograms of the TEC signal of the week preceding

the Kelud eruption in 2014, where it is possible to see how, in comparison to the quiet days, the eruption is marked by a high-energy anomaly within frequencies ranging from 2 mHz to 10 mHz. As reported by Nakashima et al. (2016) oscillations in the ionosphere are visible from 24:00 to 2:00 (local time).

Figure 5.8. Spectrograms of the filtered TEC signal recorded by the pair of station BAKO and satellite PRN20 at the time of Kelud eruption over seven consecutive days starting on 7th February 2014. The signal is filtered with a bandpass Butterworth filter with a range of 2 mHz to 10 mHz. Vertical solid line in the lower panel indicates the time of the event. The eruption is marked by a

high power and a frequency component ranging from 2 mHz to 10 mHz, between 24:00 to 02:00 on the day of the event.

Interestingly, it was possible to remotely detect the Cleveland volcano eruption CL01 (Alaska). In this region, where many active volcanoes are not monitored by ground-based instrumentation, the use of remote techniques is crucial. Regional-scale seismic and infrasound observation have been already reported in the literature (De Angelis et al., 2012), showing the potential of infrasound detection in this remote region about 50 minutes after the eruptive activity began (Figure 5.9a). We have also shown that the ionospheric TEC is capable of detecting the event as early as 40 minutes after the eruption started (Figure 5.9b), confirming the potential of ionospheric TEC monitoring as a complementary technique to the existing early warning system. Another interesting result is the detection of the 2008 Okmok eruption, Alaska (OK01) supporting the observation of gravity waves induced by the rising plume also detected AS A ultra long-period (ULP) signal at OKFG seismic station (De Angelis et al., 2011).

Figure 5.9. (a) Infrasound detection of the 29th December 2011 Mt. Cleveland explosion, Alaska made at the DLL array (from De Angelis et. al., 2012). (b) Filtered ionospheric TEC time series and related spectrogram (c) extracted by observations of satellite PRN9 with respect to station AV06 at the time of the volcanic explosion. Solid red and white vertical lines indicate the time of the events. The TEC data shows the detection of the event with a timing of 40 minutes after the explosion consistent with the infrasound detection.

As shown in Table 5.2, for some of the listed events the detection has been limited due to different factors. The strongest influence is given by the network availability: a small number of GNSS stations can drastically reduce the possibility to detect an event, as in the case of Asama Volcano, for which we had a single station available for both the events analyzed in this study (AS01, AS02). The dynamics of the eruption, in addition to an unfavourable observation geometry of the satellites, further reduce the possibility of detecting ionospheric perturbations related to the events. Particularly, for the Tolbachik volcano eruption in 2012, the TEC analysis does not reveal a peak of intensity related to the onset of the event. The eruption at Tolbachik Volcano was likely less

energetic at the onset (27th November 2012) and gained intensity at the time when associated infrasound are first recorded at the IS44 array (between late 28th and early 29th November).

Figure 5.10. Relationship between TECII and VEI (a), plume height (b), and seismic amplitude of the first arrival at 250 km of distance from the epicentre (c). Horizontal dashed represent the zero level. The horizontal solid grey line in (a) represent the separation between different VEI values. The regression (black lines) show a linear correlation between the different parameters and the TECII.

5.2.2.2 TECII and VEI index

The Volcanic Explosivity Index (VEI), proposed by Newhall and Self (1982), is a practical and widely used metric for categorizing the scale of explosive eruptions and accounts for both eruption magnitude (volume) and intensity (plume height). For the event discussed in this chapter, we used values of VEI as reported by the Smithsonian Institution's Global Volcanism Program (GVP). For some of the events analyzed in this chapter, the VEI was not reported because considered part of a sequence of explosions and are therefore excluded from the figure. The relationship between this metric and the TECII is shown in Figure 5.10a, where it is possible to notice a strong positive correlation (Pearson's $r = 0.82$; $p < 0.001$). Interestingly, the 2 events displaying a $VEI = 2$ show a negative perturbation compared to the average daily variability normally present in the

ionosphere. The two eruptions are very different in terms of PGV (Figure 5.10c) and all have an associated small plume, with a maximum height of 5 km (Figure 5.10b).

Further, the analysis showed that all the most powerful events considered ($VEI = 4$) produced strong TEC perturbations apart from the Tolbachik Volcano. While this might be surprising at first glance, the low TECII can be explained in consideration of the fact that the event was likely less energetic at the onset as mentioned in the previous section. Indeed, seismic data recorded at 17:15 (local time), shown in Figure 5.10c, suggests that the event was not energetic enough, also confirmed by the analysis of infrasound data, revealing why the acoustic signals did not propagate at large distances (Fee & Matoza, 2013).

In optimal conditions, with favourable geometry of the network available and sufficient number of satellite-receiver pairs, the TECII metric can be used to estimate the VEI based on ionospheric monitoring: if $TECII < 0$, it is more likely that the event has $VEI = 2$, while a TECII between 4.5 and 10 might suggest a $VEI = 3$ event, and finally $VEI = 4$ when $TECII > 10$. A more precise threshold estimate can be validated with additional observations, which will be the subject of future study.

5.2.2.3 TECII and Plume Height

Another important parameter that can provide information about the power of an explosive eruption is the plume height, which can be estimated by ground-based sensors including radars (Donnadieu, 2012; Donnadieu et al., 2016; Schneider & Hoblitt, 2013), LIDAR, cameras, lightning detectors (Cimarelli et al., 2016) and infrasound (Caplan-Auerbach et al., 2010; Taisne et al., 2019).

Figure 5.10b shows the correlation between the TECII and the plume height (Pearson's $r = 0.81$, $p < 0.001$). From the figure, two groups of events can be distinguished: those with small associated plumes (height < 6 km), clustered at the left of the plot, and the remaining 10 events producing a greater plume and presenting a wider range of TECII values. Given the dependency of the VEI on the plume height, it is not surprising to see how the TECII can provide information about explosive eruption products, as a positive correlation can be noticed. However, among the second group mentioned earlier, we observe that despite the considerable altitude reached by the emitted ash,

the Etna eruptions caused limited perturbations (Figure 5.11) compared to the ones visible the week before, and two of these events display a negative TECII.

Figure 5.11. Comparison between filtered ionospheric TEC and related spectrograms for the three explosive events occurred at Mt Etna, Italy, between the 3rd and 4th December 2015. The observations of (a) satellite PRN25 with respect to station LUZZ at the time of ET01 event, (b) satellite PRN22 with respect to station LUZZ at the time of the ET02 event and (c) satellite PRN12 with respect to station CETR at the time of ET01. Despite the important altitude reached by plume during these events (12, 14, and 10 km respectively) no considerable perturbations are visible in ionospheric TEC probably due to their deep seismic activity. Solid red and white vertical lines indicate the time of the events and horizontal dashed lines are the Brünt-Väisälä frequency that represents the limit between gravity and acoustic domains.

Mt. Etna volcano is one of the major degassing volcanoes in the world (Allard et al., 1991), and the events in this study are part of a rapid sequence of summit eruptive episodes observed in December 2015. The high-energy events, or paroxysms, were characterized by Strombolian activity followed by high lava fountaining and abundant tephra emission (Corsaro et al., 2017). Electromagnetic perturbations were also expected in the upper atmosphere, especially for the ET01 event, which was accompanied by lightning activity, linked to electrostatic discharges in the ash plume as the eruption columns can carry significant electrical charge (James et al., 2000; James et al., 1998; Mather & Harrison, 2006). In addition, this event happened at night, during which the optimal conditions for the detection of ionospheric disturbances are found (Rozhnoi et al., 2014). However, these events were all accompanied by a low seismic activity, with the ET01 event characterized by lowest PGV (Figure 5.10c), suggesting that this event did not emit strong acoustic-gravity waves detectable in the ionosphere as compared to ET02.

The TECII positively correlates with the cloud column heights for the eruptions at Mt Etna. This behaviour is also observed at Calbuco and Merapi: in the first case, the two events analyzed were characterized by a plume height of 17 km (CA01) and 21 km (CA02) and we measured a TECII of 17.3 and 21.6 respectively; for Merapi, the two plumes reached an altitude of 4.5 km (ME01) and 17 km (ME02), and the corresponding TECII was 4.7 and 12. A specific relationship between TECII and ash plume seems to characterize the volcanic activity and further studies are warranted to identify the individual correlation between eruption plumes at different volcanic systems and to unveil the physical and chemical properties controlling the amplitude of ionospheric disturbances.

5.2.2.4 TECII and Peak Ground Velocity (PGV)

We evaluated whether the energy transferred by the events to the ionosphere, quantified using the TECII, is proportional to the PGV measured for the vertical component of the broad-band seismic station, which is linked to the power of the eruptions. The relationship between TECII and the log value of PGV is shown in Figure 5.10c. The regression analysis showed a moderate correlation between the two metrics in a linear scale, as confirmed by the Pearson's $r = 0.6$ ($p = 0.004$).

An inspection of the events that did not cause greater ionospheric perturbations than the disturbances related to normal fluctuations in TEC ($\text{TECII} \leq 0$), showed an unexpected trend for the three events recorded at Sinabung, a stratovolcano awakened in 2010 after 1200 years of quiescence (Gunawan et al., 2017). SI01 refers to one of the first activities recorded after the initial small phreatic eruption of 28 August 2010 that marked the beginning of his active state. Among the events analyzed at this volcano, SI01 has the greatest PGV, recorded during an ash explosion that followed a volcano-tectonic earthquake swarm (Gunawan et al., 2017), but the lowest TECII. SI02 is part of the second episode of small explosions that began on 15 September 2013 which, however, is associated with the highest TECII and the smallest PGV.

As shown in Heki (2006), an important factor for the detection of ionospheric disturbances is the incidence angle of the line-of-sight vector into the acoustic wavefront, and therefore we tested whether the negative relationship found could be caused by a poor relative position of the transmitter and receivers that hindered the possibility to detect the perturbation caused by SI01. Figure 5.12 shows how the zenith angles and distances between IPPs and vent are similar across events, demonstrating that differences between TECII cannot be attributed to observation geometry of the satellites, which were optimal for all the events.

Figure 5.12. Time evolution of (a) elevation angles of the satellite-receiver line of sight and (b) epicentral distances of the IPPs relative to the Sinabung eruptions: SI01 (black), SI02 (orange) and SI03 (green). Vertical dashed lines represent the time of the events. Zenith angles and distances between IPPs and vent are similar across events, indicating that the differences between TECII cannot be attributed to the observation geometry of the satellites.

A difference between the Sinabung events is that SI01 was accompanied by mainly deep volcano-tectonic earthquakes, that were absent during the SI02 event. The SI02 event was characterized exclusively by shallow volcano-tectonic earthquakes (Gunawan et al., 2017). The greater TECII of SI02 can be related to the evidence that TEC is especially influenced by shallow earthquakes, which lead to disturbances in the sensitive F2 layer of the ionosphere (Shah & Jin, 2015), and it has been shown that seismo-ionospheric disturbances related to a shallow hypocenter cause greater disturbances as compared to deep hypocenter earthquakes (Kon et al., 2011; Lin, 2013; Liu et al., 2006).

Another surprising result is that similar PGVs are accompanied by a large variation of TECII. This is especially visible when comparing CL01, KR01 and SI03, which have a TECII of 17.3, 4.4 and -3.4, respectively, despite a range of PGV between 0.7 and 1.2 mm/s. The relationship between the two metrics seems more complex compared to the other measurements discussed, as seismic

data are affected by many parameters. The nature and amplitude of the ground motions at a certain distance from the epicentre depend on the tectonic regime, magnitude, magnitude-dependent attenuation, style of faulting and differences in crustal structure, to cite a few. Further, a more rapid attenuation of amplitudes with distance is observed at volcanoes displaying shallow crustal seismicity (McVerry et al., 2006). For these reasons, a more precise relationship between seismic information recorded during volcanic eruptions and ionospheric TEC could be established by taking into account more variables such as earthquakes magnitude, duration and wave profiles.

5.3 Summary

In this chapter, we aimed at evaluating the possibility to exploit remote sensing techniques based on ionospheric seismology to complement volcanic surveillance. To this end, we investigated the relationship between the Total Electron Content Intensity Index (TECII), a validated metric that captures the magnitude of the ionospheric perturbations, to several parameters that are commonly used to quantify the volcanic explosive energy. We found that the metric strongly correlates with the Volcanic Explosivity Index (VEI) and the ash plume height, allowing a quick assessment of the hazard. A deeper examination is required to understand the link between the Peak Ground Velocity (PGV) and Total Electron Content (TEC) variations. The results confirmed the potential of the proposed tool to be applied to complement the existing monitoring techniques. The proposed method showed an efficient applicability in remote areas such as the Aleutian volcanic arc, Alaska, and in tropical regions, such as the Sunda volcanic arc, Indonesia, where harsh weather conditions and an almost persistent clouds coverage can limit the applicability of the existing satellite-based techniques. Further examination of the relationship between TECII and other parameters used to quantify explosive energy such as mass eruption rate and infrasound will be carried out to support the applicability of ionospheric monitoring to remotely access the magnitude of large explosive events.

Conclusions and future work

Volcano surveillance relies on the application of diverse monitoring techniques to record and interpret geophysical signals linked to processes happening in volcanic systems. Despite advancements in technology, explosive eruptions still pose significant threats to the wealth of the world population and the development of modern society.

In this thesis, we proposed two different approaches aiming to contribute to the existing monitoring techniques for small Strombolian-like eruptions and for large-scale explosive eruptions. We showed that by using a new model that links tilt data recorded at a single station to the volcanic system parameters, we could forecast the time and magnitude of Strombolian-like eruptions. The method, called Joint Bayesian Inversion (JBI), consists in the tilt data inversion that constrains the range of values for parameters that are believed to remain constant across events, i.e. density and viscosity of the magma, the elastic modulus of the host-rock, and radius of the conduit. These estimates, refined with time as new events are recorded, were obtained for three different scales of explosions at Semeru, Indonesia, and were comparable to the parameters found in the literature. The estimated fixed parameters can be used to forecast timing and amplitude of an upcoming event up to 58 s before it occurs and with 1% error on amplitude estimation. The results show the potential of this tool for real-time application to support the current monitoring techniques.

Further, this thesis aimed at validating the numerical model with a series of analogue experiments to simulate the dynamics of slugs rising in an elastic deformable volcanic conduit. For the first time, the effect of slugs on an elastic conduit was analyzed by applying PIV techniques to measure both displacements in the fluid and the surrounding elastic medium. Close-field photogrammetry techniques were then used to measure the deformation at the top surface. We observed a different type of slug, here called “super slug”, characterized by a shape that varies from bullet shape with a truncated cone body, to streamlined shape accordingly to the viscosity of the fluid and displaying a higher rising velocity compared to classic slugs described in the literature. The experimental setup allowed us to visualize and quantify the presence of three different stress regions in the conduit characterized by an over-pressure above the slug, a transitional region along the slug length and an under-pressure below the slug. This structure of the conduit stress has been hypothesized and numerically modelled, and is now being visualized in this experimental study. Interestingly, we have found that while the rising velocity of regular slugs is mainly controlled by the viscosity

of the fluid, and by the diameter of the conduit, the velocity of super slugs is linked to their volume. The dynamic of the two types of slug has also different effects on the magnitude and rate of the displacement observed at the surface. While “regular slugs” have low velocity and cause slow deformation of the surface, “super slugs” rise at higher velocity resulting in a fast surface displacement and more energetic explosions. These observations could be key to discriminate passive degassing from explosive events, hinting towards the potential of using such observations as a monitoring tool to forecast the explosive style. To quantify the uncertainties of the numerical model, we applied the JBI on the surface displacement data recorded during the experiments. Despite the good fitting between the recorded data and the model, the results show inconsistency in the best values obtained, which can be linked to the slug dynamic observed during the experiments that differ from the formulations used as direct model. These results suggest that future work is required to improve the numerical model by including the effects of the rising of super slugs on the wall displacement and its velocity.

Finally, the new method based on ionospheric GNSS-TEC monitoring can be used to remotely detect and quantify the size of large explosive eruptions, allowing the surveillance of volcanoes located in underfunded and remote regions. The new metric called Total Electron Content Intensity Index (TECII), which captures the magnitude of the ionospheric perturbations, is the Volcanic Explosivity Index (VEI) and the ash plume height, providing essential knowledge for volcano surveillance. This new method can provide useful information to support the existing monitoring techniques allowing a quick risk assessment.

Future work will aim at validating and determining the limitations of the proposed forecasting method by using raw tilt data. Improvements in the methodology will also lead to the reduction of the computational time necessary to infer the time and size of future events. This will allow creating a tool that can be used in real-time and on real case scenarios. The numerical model will be modified to take into account the presence of super slugs. Finally, the next step to validate the use of ionospheric monitoring will aim at a better understanding of the link between the TECII and Peak Ground Velocity as well as metrics from other techniques such as infrasound.

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