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Volcanic hazards in Tanzania

Volcanology Team, Earth Hazards and Observatories

Open File Report OR/14/005

BRITISH GEOLOGICAL SURVEY

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Mt Meru from the west, October 2013.

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) to summarise: the current knowledge, monitoring and management of volcanic hazards in Tanzania; a preliminary fieldwork visit to Mt Meru to investigate opportunities for more detailed characterisation of Holocene volcanic activity; and scope out opportunities for research and collaboration on volcanic hazards in Tanzania.

Whilst monitoring of activity, analysis of past activity, and characterisation of volcanic hazards and risk is being conducted in high-resolution in some countries, there are many which have little available data or resource to conduct such research. The East African Rift is one such example. This is a record of our first data collation for Tanzania to capture the current monitoring situation, knowledge of past eruptive activity and unrest, and in-country capacity for volcanic hazard management. The data has been collated for analysis and inclusion in the next Global Assessment Report to be published by the United Nations International Strategy for Disaster Reduction (UNISDR) in 2015 (GAR15). The data summarised here will be presented as the Tanzanian Country Profile as part of the contributory papers for the GAR15 report.

We present the Mt Meru example here as a case study for potential research that BGS could conduct prior to the next GAR report due in 2017. This would have merit both as a blue skies research project, as Mt Meru hosts one of the largest debris avalanches on Earth, and as an applied hazard project supporting capacity development, as Meru shows recent volcanic activity that poses a threat to the large local population living in and around the volcano and tourists who visit this area in large numbers every year.

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We would like to acknowledge the assistance and collaboration of the Geological Survey of Tanzania, particularly Prof Abdul Mruma, Yokbeth Myumbilwa, and Gabriel Mbogoni, for sharing data and experiences of monitoring and responding to volcanic eruptions and enabling the logistics for our fieldwork. Fieldwork assistance from Melania Maqway from the Geological Survey of Tanzania enabled sample collection from Mt Meru and facilitated access with local communities around Mt Meru. We thank the Director General and staff of TMA, particularly Hazla Masoud, for meeting with us and discussing the role, capacity and involvement of TMA in volcanic hazard management. Finally, we thank the Arusha Regional Government for providing census data and for permission to access and collect samples for analyses.

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Summary

This report presents the results of a pilot study on volcanic hazard analysis in Tanzania with a case study on Mt Meru to investigate potential future research needed to improve our knowledge of past and present volcanic activity in Tanzania and the inherent risks. This work was conducted alongside the Geological Survey of Tanzania by the BGS Volcanology Team to investigate potential collaborative research projects for the future. Existing data is compiled on volcanoes, volcanic hazards and population statistics within Tanzania as well as in-country monitoring and hazard management methods to evaluate the relative risk posed by volcanic activity. Outputs from this work are being compiled as the volcano contribution to the Global Assessment Report for 2015 (GAR15) published by the United Nations International Strategy for Disaster Reduction (UNISDR) alongside profiles for all countries hosting active volcanoes.

Initial research was conducted on Mt Meru as a case study of a potentially active high risk volcano, identified as a hotspot due to it's proximity to a major population centre. Members of the BGS Volcanology Team conducted interviews with the Geological Survey of Tanzania and the Tanzanian Meteorological Agency to build an understanding of monitoring, communication, science advice and data flow for hazard management. Analysis of the Smithsonian Institution's Global Volcanism Program and the LaMEVE (Large Magnitude Explosive Volcanic Eruptions) databases provide an overview of the distribution, occurrence and character of volcanic hazards in Tanzania. New data from Mt Meru provides an overview of past eruption history and first order analyses of volcanic risk. Finally, we provide a series of recommendations for integrating efforts to facilitate real-time monitoring and develop plans to enable effective response to volcanic eruptions.

1 Introduction

The United Nations Office for Disaster Risk Reduction (UNISDR) has invited the BGS/Bristol - led Global Volcano Model (GVM) to work with the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) to provide an assessment of global volcanic hazard and risk for the 2015 Global Assessment of Risk Report (GAR15). The GAR programme evaluates risk and identifies global challenges with reports released every two years to implement the Hyogo Framework for Action (HFA) that aims to substantially reduce disaster losses by 2015 by building the resilience of nations and communities to disasters. Volcanism along the East African Rift (EAR) varies hugely in terms of spatial and temporal variability as well as eruptive styles and products. However, there are limited data available on the EAR to characterise and define the potential hazards based on past events or to consider the future consequences of such hazards.

This report presents the results of a pilot study on volcanic hazard analysis in Tanzania with a case study on Mt Meru. The aim of the study was to establish science-based evidence for volcanic hazards and their impacts in Tanzania to provide a case study example for the GAR15 report that could be expanded and applied to the rest of Africa in the future. Data requirements for such analysis include:

- understanding the in-country monitoring capacity
- identifying needs for capacity development
- communication and response to volcanic eruptions and unrest
- assistance for hazard management
- how to support the integration of volcanic hazards into the Tanzanian Disaster Risk Reduction (DRR) programme.

There is no dedicated or mandated volcano observatory in Tanzania, however the Geological Survey of Tanzania (GST) have the responsibility for providing advice on the character and impact of volcanic eruptions. The Tanzanian Meteorological Agency (TMA) liaises with the regional Volcanic Ash Advisory Centre (VAAC) in Toulouse to provide information on the dispersion of ash. This report considers the current situation and infrastructure as part of an assessment of volcanic hazard and risk and in collaboration with both GST and TMA makes recommendations for future work.

1.1 TANZANIAN VOLCANOES

There are ten active Holocene volcanoes listed in the Global Volcanism Program (GVP) database for Tanzania (Figure 1). These form two clusters in the northern and southern parts of the country marking the southern portion of the East African Rift Valley. The northern volcanoes are Mt Kilimanjaro, Mt Meru and Ol Doinyo Lengai, while the southern volcanoes are clustered around Rungwe Volcanic Province. Of Tanzania's Holocene volcanoes, only the carbonatite volcano of Ol Doinyo Lengai is known to be currently active. However, at the time of writing, the lack of volcano monitoring in proximity to any of these volcanoes means that any state of unrest is unreported and the potential for an eruption may be underestimated.

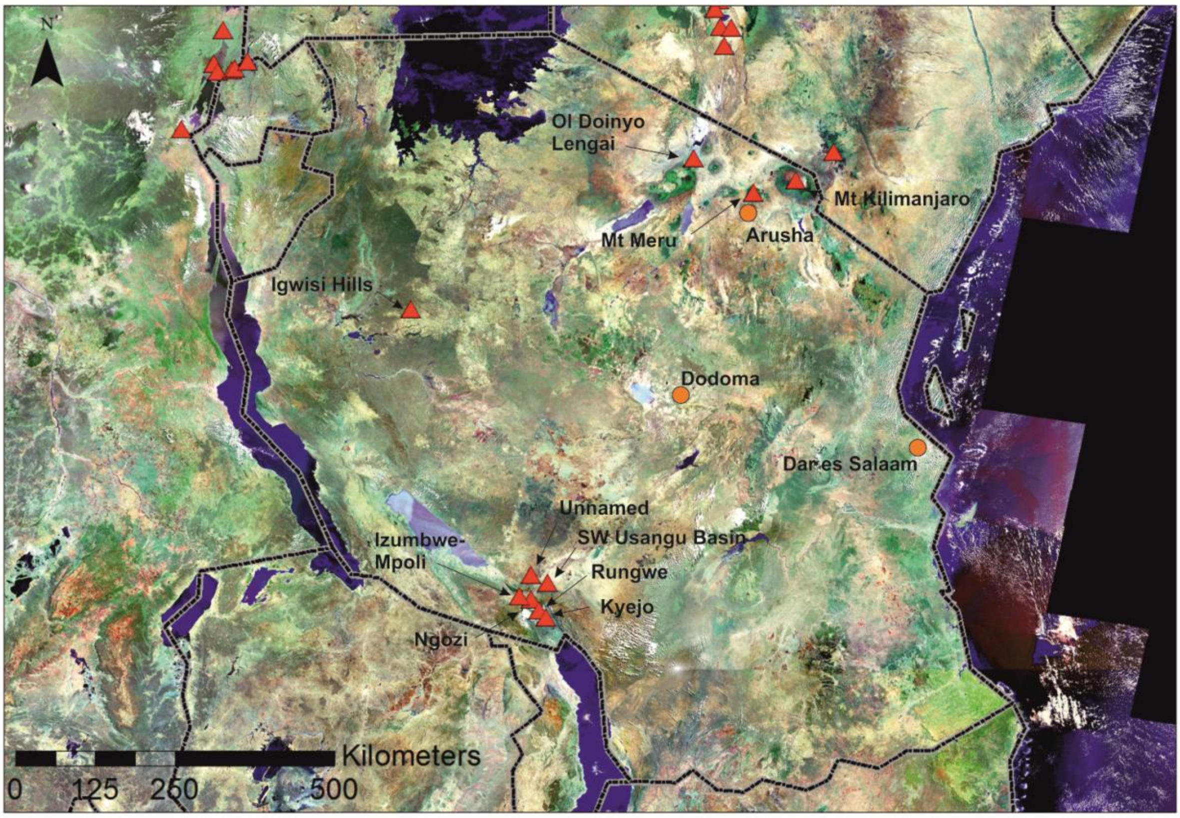


Figure 1 Location map of Tanzania's active volcanoes. Data from the Smithsonian Institute GVP.

The majority of Tanzania's Holocene volcanoes are explosive in nature, with effusive lava dome growth and lava flows. The three northern volcanoes (Mt Meru, Mt Kilimanjaro and Ol Doinyo Lengai), and Mt Rungwe and Mt Kyejo in the south, are stratovolcanoes characterised by pyroclastic cones and lava domes. Mt Kilimanjaro and Mt Meru also have craters resulting from edifice collapse. Three of the southern volcanoes (Igwisi Hills, Izumbwe-Mpoli and an unnamed volcano) are pyroclastic and tuff cones. Mt Ngozi is a shield volcano with a summit caldera. Only SW Usangu Basin is entirely effusive, characterised by lava dome growth.

Although Tanzania's largest cities are situated more than 30 km from the volcanic centres, the prevalence of numerous rural communities in Tanzania mean that seven of the Holocene volcanic centres have more than 100,000 people living within a 30 km radius. Of these, two have more than 300,000 people within a 10 km radius (Source: Smithsonian Institute GVP 2013).

There is no record of fatalities as a result of volcanic activity although there are reports of injuries and loss of livestock associated with the 2007 eruption of Ol Doinyo Lengai. The Disaster Management Unit (DMU) of Tanzania wrote a report to the Prime Minister's Office in response to this eruption, recommending a series of restrictions on access, regulation of official local guides, first aid stations and shelters be implemented on Ol Doinyo Lengai. At the time of writing those recommendations have yet to be actioned. The lack of fatalities known as a result of past eruptions may be due to recording and epistemic uncertainty that requires consideration when analysing the impact of past eruptions.

1.2 VOLCANIC HAZARDS AND DISASTER RISK REDUCTION STRATEGIES

UN ISDR is the lead organisation for global governance of Disaster Risk Reduction (DRR) and so has great influence on policy development, international collaboration among nations and decision-making on priorities and actions by nations. UN ISDR and the GAR reports are also highly influential among NGOs, other international agencies (e.g. the World Bank, the European Space Agency) and the private sector.

GVM and IAVCEI (the international volcanology body – International Association of Volcanology and Chemistry of the Earth's Interior) have been jointly commissioned by UNISDR to produce the volcano chapter for the GAR15 study. Volcanoes have not been considered in previous GAR reports so this is a unique opportunity for the international volcanological community to make a broad global assessment of volcanism in the context of DRR and to present the state-of-the art in volcanic hazards and risk assessment. The volcano model will complement other models in the report on: earthquakes, floods, cyclones and extreme weather, tsunamis, exposure and risk. GAR13 was launched in May 2013. It looks at how public regulation and private investment shape disaster risk. GAR15 will be launched at the World Disaster Programme meeting in 2015 and will develop "Ready to use risk data". The GAR15 task force has been tasked to produce the assessment of volcanic hazard and risk by April 2014.

We are building on the methodology employed in the World Bank funded GFDRR report (Aspinall et al. 2011) to evaluate volcanic risk and are working in collaboration with volcanologists worldwide to build this model. This methodology is being modified by a GVM task force on volcanic indices. Volcano data from key databases, such as the database of Smithsonian's Global Volcanism Program and VOGRIPA, will be used to provide a synoptic assessment of global volcanism from a hazard and risk perspective. The products of the GAR15 study will include a general synoptic document for a non-technical readership, and a more detailed technical report which gives the evidence that supports the global assessment, including: global, regional or local analysis on volcanoes and volcanic hazards, case studies that are through to be illustrative of key issues, good practice or methodologies in hazard and risk assessment. References to key publications and authoritative web sites, specialised background papers and data collation forming individual country profiles will also be presented and digitally accessible. The reported work in Tanzania will form the basis for one of these country profiles and is the first profile to be completed for the GAR15 report.

2 Volcanic hazards

The following provides a description of the products of volcanism and the variety of volcanic hazards and their impacts in Tanzania that pose a risk to proximal and distal populations in terms of infrastructure, health, environment, livelihoods and well-being in Tanzania and specifically relating to Mt Meru. Although the volcanoes of Tanzania can generally be characterised in terms of their predominant magma chemistry, size and dominant eruptive style, each has some distinctive characteristics. The following accounts for the principal volcanic hazards in Tanzania and examples of where these are of concern.

2.1 DEBRIS AVALANCHES AND LANDSLIDES

Debris avalanches and landslides are common and are not necessarily related to active volcanism. Destabilisation may result from inherent instability or changing state such as regional tectonic earthquakes, extreme weather or triggered by volcanic activity resulting in failure of a volcanic edifice or a flank.

The large size of many central volcanoes in Tanzania means that volumetrically significant debris avalanches and landslides may pose a risk to large populations. Sector collapses resulting in debris avalanches are reported from Mt Meru as well as vents in the Rungwe Volcanic Province. The collapses of Mt Meru are believed to be amongst the largest debris avalanches in the world with deposits reaching the foothills of Kilimanjaro.

2.2 PYROCLASTIC DENSITY CURRENTS

Pyroclastic density currents (PDCs) are turbulent clouds of hot ash, gases and particles that flow along the ground from the collapse of an eruption column, lava dome or lateral blast of a volcano edifice. PDCs typically flow down valleys away from the vent whilst surges can spread widely irrespective of undulations in the landscape. PDCs flow at speeds of up to 100 metres per second and travel up to 30 km from the vent. PDCs are lethal and responsible for thousands of deaths in individual eruptions, e.g. 29,000 deaths associated with PDCs from the 1902 eruption of Mt Pelée in Martinique.

PDCs are associated with the central volcanoes in northern Tanzania and thick deposits have been found on the southern flanks of Mt Meru. PDCs have been suggested to be absent from the Rungwe Province in the south (Fontjin et al., 2012).

2.3 LAHARS AND FLOODS

Lahars are flows consisting of volcanic debris and water which may be hot or cold depending on their genesis. Lahars can occur as a result of: interaction of an eruption with ice or snow generating large amounts of meltwater moving down river valleys carrying large amounts of debris; heavy rains on loose volcanic deposits cause a mass movement; or failure of the walls of a crater lake resulting in a catastrophic draining of the lake. Lahars have been a major cause of fatalities in historic times e.g. 23,000 deaths from the 1985 Nevado del Ruiz lahar in Colombia. Fatalities and injuries from lahars can be avoided if communities are evacuated in a timely manner to high ground.

Deposits interpreted to have resulted from lahars are often also cited as debris avalanche deposits, although there are clear differences between the characteristics of the emplacement these flows. This includes the interpretation of flows deposited on the north-western and northern flanks of Mt Meru (Wilkinson et al. 1983; Delcamp et al. 2013).

2.4 TEPHRA HAZARDS

Tephra describes ash, rock and magma ejected from an explosive eruption into the atmosphere that can be transported hundreds of kilometres from the vent. Tephra is erupted from the vent to form an eruption column that may rise up to 55 km into the stratosphere. Eruption column heights can be used to measure eruption intensity as it relates to the mass eruption rate. Dispersion of tephra from an eruption column occurs as a combined result of the eruption rate and the meteorological conditions at the time of the eruption. Tephra falls and is deposited from this plume with coarser particles, including pumice, deposited near the vent and finer ash deposited further afield. By capturing data on the dispersal and fragmentation of tephra deposits from past eruptions we can constrain the explosive character of the eruption and height of the eruption column to provide essential data into hazard models. Tephra deposits are hazardous in different ways; it can accumulate on roofs causing collapse, inhalation of ash by animals and humans is a health hazard, and volcanic ash is a major hazard to the aviation industry. Ballistics (also referred to as blocks or bombs) are rocks ejected during volcanic explosions. They are typically several centimetres to a couple of metres in size. In most cases the range of ballistics is a few hundred metres to perhaps a couple kilometres, but they can be thrown to distances of up to 5 kilometres in the most powerful explosions. Fatalities, injuries and structural damage result from direct impacts.

Thick tephra fallout deposits have been found in the Rungwe volcanic province, in southern Tanzania. Fontijn et al. (2010) constructed the stratigraphy of Holocene eruptions, and discovered a major Plinian eruption c. 10 ka, and at least five sub-Plinian to Plinian explosive eruptions occurred in the late Holocene. Ol Doinyo Lengai experienced major ash eruptions in 1917, 1926, 1940, 1966 – 1967 and 2007 – 2008 (Dawson, 2008). Local communities reported ashfall in 2007, and three villages were evacuated (Prof Mruma, pers. Comm.).

The western slopes of Mt Meru are blanketed in tephra fallout, and reworked deposits. River gullies expose thick (>2.7 m) pumice-rich fallout deposits, up to 10 km west of the summit of Mt Meru. The age of these eruptions are unknown.

2.5 LAVA FLOWS

Lava flows usually advance sufficiently slowly to allow people and animals to self-evacuate but anything in the pathway of a lava flow can be damaged or destroyed. including buildings, vegetation and infrastructure.

Lavas rank as a volcanic hazard of lower concern than those already mentioned as the impact is lower. However, the emission of lava flows can accompany significant gas emissions and lava flow emplacement has been prevalent in the East African Rift in the past. Known Holocene activity suggests that volumetrically significant lava flows may be associated with volcanic systems in southern Tanzania, especially the Rungwe Province and are usually small with a relatively limited footprint in northern Tanzania.

2.6 GAS EMISSIONS

Gases and aerosols are dissolved in magma at depth in the subsurface but escape during reduction in pressure as the magma reaches the surface. Whilst the main component of gaseous release during an eruption is water vapour (60-99%), there are many other volcanic gas species and aerosols released. These may include: carbon dioxide (up to 10%), sulphur dioxide and sulphates (up to 15%), halogens (including fluorine and chlorine, up to 5%) and various metals such as mercury and lead (trace amounts) (Symonds et al, 1994).

The impact of volcanic gases varies widely and depends on the amount of gas emitted, the level it is injected into the troposphere or stratosphere and the meteorological conditions at the time. Emissions are known to have adverse effects on agriculture and health (human and animal) leading to fatalities in high concentrations, cause volcanic fogs and air pollution, result in acid rain, and lead to environmental changes including variations in temperature. Gas emissions are a known hazard in the East African Rift due in part to the 1986 Lake Nyos disaster in Cameroon in which 1,700 people suffocated in a CO_2 cloud. In 2011 the eruption of Nabro on the Eritrea-Ethiopia border produced the most SO_2-rich eruption observed in satellite history.

The peralkaline composition of many central volcanoes in the East African Rift mean that they have the potential to produce eruptions that are rich in sulphur gas species and aerosols, fluorine / fluoride and chlorine / chloride. Fluoride in particular has implications for secondary hazards as it bonds to ash particles in the eruption column and is associated with the deposition of ash. Therefore, high levels of fluoride and fluorosis poisoning are found in areas of thick accumulations of ash over both historic in geologic timescales. Due to the composition of Ol Doinyo Lengai there is clear potential for CO_2 to be a major gas hazard. However, there is no gas monitoring to detect the baseline gas emissions from Holocene volcanoes in Tanzania so any increases, or the potential of any one volcano to emit high levels of gas, are currently unconstrained.

3 Monitoring and management of volcanic hazards

There are no dedicated volcano observatories or ground-based monitoring system for volcanoes in Tanzania. The Geological Survey of Tanzania (GST) and the Tanzanian Meteorological Agency (TMA) together provide scientific advice to the Prime Minister’s Office through representation on the DMU during sustained volcanic unrest and eruptions.

The GST maintain a broadband network of 12 seismometers that are downloaded every 3 months during a field visit from the GST seismologist. These are not telemetered in real-time although there is a possibility to develop this for the future and for the funding for this to be sought within Tanzania. Scientific advice from volcano seismologists is required to enable purchase and installation of an appropriate telemetering system as well as a data analysis and management system on receipt of the data in the GST head office in Dodoma. The seismic stations are currently dispersed around the country to capture information on tectonic and regional events.

GST is one of the users of the EVOSS (European Volcano Observatory Space Services) system, providing pre-processed satellite products for ash, sulphur dioxide and thermal signatures. In the event of an eruption the EVOSS system would enable management of the eruption through characterisation of the eruption flux, changes in character of the eruption, height of an eruption column and dispersion of products. EVOSS does not currently offer a deformation service that may aid in the identification of volcanic unrest; however, this capability does exist and will be possible once the SEVIRI satellites are engaged.

The TMA receive models for the dispersion of volcanic ash from the Toulouse VAAC to support advice to the Disaster Management Unit (DMU) and any necessary evacuations. TMA are supported by the UK Met Office and the World Meteorological Office in their modelling and it is understood that capacity development and training for the TMA is currently in progress.

The scientific staff within both GST and TMA have some experience of responding to volcanic eruptions as a result of the eruption of Ol Doinyo Lengai in 2007. There is only one fully trained seismologist in GST. TMA staff have no direct experience of volcanism and there is one volcanologist currently in training in Tanzania. In past eruptions, international assistance and scientists from USGS have rapidly mobilised to visit eruption sites, analyse ash and provide advice on the hazards, impacts and risk of eruptions in-country.

4 Mt Meru Case Study

Mt. Meru is a 4565m high stratovolcano in northern Tanzania, approximately 70 km west-southwest of Kilimanjaro. It is Africa’s fourth highest peak and is historically active, with its last eruption occurring in 1910 from the summit ash-cone. The summit of Mt Meru is just 14 km from the centre of the city of Arusha, which has a permanent population of just over 400,000 (2012 census). Arusha city lies in the Arusha region which has a population of approximately 740,000. It is estimated that 75% of the total number of tourists entering Tanzania, pass through the Arusha region which is on the Northern Circuit tourist route (Mwunga Pers. Comm.).

4.1 PREVIOUS WORK

The first study of Mt Meru was carried out in 1953 as part of the Sheffield University Expedition to Kilimanjaro (Guest and Leedal, 1953). The authors climbed to the summit of Mt Meru and made observations and some interpretations of the geological features. They also described the recent volcanic activity and observed two main areas of fumaroles within the crater. Wilkinson et al. (1983) produced a detailed geological map of Mt Meru and a description of the geology. Through whole-rock K-Ar dating of lava flows and stratigraphic correlation, Wilkinson et al. (1986) published a volcanic chronology for Mt Meru and Mt Kilimanjaro.

Further detailed work was carried out by Roberts (2002) who studied the geochemical and volcanological evolution of Mt Meru for his PhD. No other work has been carried out on Mt Meru.

4.2 GEOLOGICAL SUMMARY

Mt. Meru sits on a faulted terrain of flood basalts associated with the Neogene Rift Valley volcanic province (Wilkinson et al., 1986; Roberts, 2002). These flood lavas have a thickness of several hundred metres and overly the Usagaran basement gneisses (Wilkinson et al., 1986). In the northwest of the Meru-Kilimanjaro area, faulting has a west-northwest – east-southeast trend; and in the southwest of the area, the trend is north-south (Wilkinson et al., 1986).

K-Ar dating of volcanic rocks from the area reveal the flood lavas were erupted approximately 2.37±0.11 Ma (Wilkinson et al., 1986). Lavas, which overflow the fault scarps, have been dated at 1.71±0.06 Ma therefore bracketing the faulting to between 2.37 and 1.71 Ma (Wilkinson et al., 1986). Volcanic activity at Mt. Meru commenced approximately 1.5 Ma (Wilkinson et al., 1986).

4.2.1 Volcanic Evolution of Mt Meru

Mt. Meru is the main volcanic centre, with the smaller centres of Meru West and Little Meru on its flanks, and small parasitic cones and craters on the lower slopes and surrounding plains (Dawson, 2008). The earliest activity of Mt. Meru was the extrusion of nephelinite lava flows at Meru West approximately 1.5 Ma (Wilkinson et al., 1986). Due to subsequent ash and lahar deposits, the extent and relationship of these lavas to the main volcanic centre is unknown (Wilkinson et al., 1986).

Alkaline lava flows and clasts from volcanic breccia from the lower north-western slopes of Mt. Meru yield K-Ar dates of between 0.28±0.05 and 0.38±0.009 Ma (Wilkinson et al., 1986). Wilkinson et al. (1986) therefore suggested that at around 0.35 Ma extensive alkaline lavas accumulated to the northwest of the current cone, and that much of the northern part of the volcano is underlain by these lavas. The date of 0.28 Ma is from an angular lava block typical of those from Little Meru. Little Meru is on the north-eastern flank of Mt Meru, and is a steep-sided symmetrical volcano with a height of 3800m (Roberts, 2002). Wilkinson et al. (1986) suggested that this block represents the lavas on which Little Meru is constructed; however, Roberts (2002) noted that this block is characteristic of volcanic breccias that dominate Little Meru and therefore proposed that this age likely represents the age of Little Meru. Little Meru is constructed from moderately to poorly sorted volcanic breccias overlain by lava flows near the summit. Roberts (2002) proposed that the construction of Little Meru was through numerous strombolian explosive events, with a final phase of lava extrusion.

A date of 0.17±0.01 Ma from one of the cones on the volcano's northern flank is thought to represent one of the earliest events in the construction of the main volcanic cone of Mt. Meru (Wilkinson et al., 1986). This age is much younger than that of Little Meru, therefore the activity at Little Meru ceased well before the construction of Mt Meru.

Exposure of the main Mt Meru cone is limited due to densely vegetated lower slopes, and later lahar and pumice deposits on the middle and lower slopes (Roberts, 2002). The main cone deposits are exposed in the walls of the crater and comprise intercalated lava flows and volcaniclastic tuffs and breccias (Wilkinson et al., 1986; Roberts, 2002). Roberts (2002) estimated a ratio of 70:30 for the volcaniclastic deposits to lava flows, showing that Mt Meru had a largely explosive history with intermittent effusive lava flows.

Roberts (2002) divided the main cone deposits into three groups: the Lower Group; the Mid-cone Group and the Summit Group. The Lower Group comprises a series of sub-horizontal lava flows at the bottom of the western wall of the crater, which Roberts (2002) suggested could have resulted from a series of lava lake flows. The Mid-cone Group form about 800m of the 1400m crater wall, comprising mainly volcaniclastic deposits (Roberts, 2002). The ages of these deposits range from approximately 0.111 to 0.102 Ma (Wilkinson et al., 1986). Intruded into the Mid-cone Group are numerous, vertical to near horizontal, cross-cutting dykes, estimated to be 3 to 20 m thick (Roberts, 2002). Mid-cone Group lavas are also exposed between Little Meru and Mt Meru (Roberts, 2002).

The Summit Group consists of interbedded volcaniclastic breccias, tuffs and lava flows and represents the final phase of construction of the Mt. Meru cone (Roberts, 2002). The Summit Group deposits erupted between ~0.08 and 0.067 Ma (Wilkinson et al., 1986). The dominance of breccias and tuffs suggests the final constructive phase was explosive, comprising strombolian and sub-plinian eruptions (Roberts, 2002).

4.2.2 Superficial Eruption deposits

4.2.2.1 LAHARS

Four major lahar deposits were initially identified on the north, south and eastern flanks of Mt. Meru by Wilkinson et al. (1983). Roberts (2002) identified further lahar deposits on the western and north-eastern slopes of Mt Meru, and describes the lahars as being dominated by angular to sub-angular blocks of nephelinite and phonolite up to 3 m in diameter, supported in a pale-brown ash and/or clay matrix which contains lapilli-sized vesicular phonolite. He observes no internal structures in the deposits and describes the surface of the lahars as undulating.

The two lahars on the northern flank of Mt Meru are confined to drainage valleys and spread out laterally onto the plains. The flow fronts are lobate, comprising multiple pulses (Roberts, 2002). The thickness of the lahars, near their termini, is approximately 20-30 m (Roberts, 2002). As this is where the lahars have spread laterally, their thicknesses, where confined to the river valleys, should be greater; therefore Roberts (2002) estimated 20-30m to be a minimum thickness. Roberts (2002) estimated the minimum volume of the north-western and north-eastern lahars as 1.9 to 2.9 km^3 and 2 to 3.1 km^3, respectively, based on the minimum thickness and aerial extent.

A lahar deposit to the east of Mt Meru has been described as the main Meru lahar (Wilkinson et al., 1983; Roberts, 2002). It has an estimated aerial extent of ~1500 km^2, and extends as far as the base of Mt. Kilimanjaro, 60 km distant (Wilkinson et al., 1983; Roberts, 2002). Based on the absence of well-preserved flow termini, Roberts (2002) suggested that this lahar was more fluid than those on the northern flanks of Mt. Meru. Such a fluid flow would produce a thinner flow (Roberts, 2002). The only thickness estimate of this deposit comes from a river exposure near the base of Mt. Meru. The lahar thickness here is 20 m; however, the base of the lahar is not observed; therefore this is a minimum proximal thickness (Roberts, 2002). The deposit volume could not be measured as there is no measured thickness; however, based on the assumption that the flow was fluid and therefore thinner than the northern lahar deposits, and taking the aerial extent into account, Roberts (2002) estimated that for a thickness of 3m the volume would be ~4.5 km^3, making it one of the biggest lahars ever described. Roberts (2002) does however concede that this may be a series of lahars rather than one massive deposit.

Roberts (2002) suggested that the lahar deposits resulted from the presence of an ice cap on Mt Meru during the Last Glacial Maximum (~21 ka), either by melting of the ice, or indirectly by hydrothermal water. Hydrothermal systems can develop on glaciated volcanoes, and result in hydrothermal alteration at the summit (Vallance, 2000), which in turn results in an increase in porosity, trapping water in the edifice.

Although there are abundant unconsolidated tephra deposits blanketing the slopes of Mt Meru, Roberts (2002) suggested that the likelihood of future lahars has been reduced as a result of the collapse of the edifice to the east, which lowered the summit to below the permanent snow/ice level.

4.2.2.2 PUMICE AND ASH DEPOSITS

Pumice and ash deposits blanket much of the western slopes, and to a lesser extent, the northern and southern flanks of Mt Meru (Wilkinson et al., 1983; Roberts, 2002). They consist of a sequence of pumice fall, ash fall and reworked pumice and ash deposits (Roberts, 2002). The pumice and ash fall deposits are visible in drainage valleys where rivers have cut through the overlying reworked ash and soil layers (Roberts, 2002).

Roberts (2002) divided the pumice and ash deposits into three groups: near-vent/block facies pumice deposit; early/proximal pumice fall deposits; and the main pumice fall deposits. The near-vent/block facies pumice deposit is described at one locality, ~9 km north of the summit of Mt Meru. The deposit is ~20m thick comprising poorly bedded, clast-supported units of sub-angular to sub-rounded pumice and lithics (Roberts, 2002). The lithic clasts are phonoloite, nephelinite and black obsidian, and comprise ~15 vol. % of the deposit. The pumice and lithics are comparable in size, with maximum diameters of 30 and 25 cm, respectively (Roberts, 2002). Due to the comparable clast sizes, and the clast-supported nature of the deposit, Roberts (2002) suggested that this deposit is associated with the initial stages of the Mt Meru pumice forming eruptions i.e. vent widening.

The early/proximal pumice deposits are also only described at one locality, on the west-southwest slope of Mt Meru. This sequence is exposed in an inaccessible river valley, and comprises at least six pumice fall units interbedded with dark-grey reworked units (Roberts, 2002). The bases of the reworked units are erosional.

The main pumice deposits are widespread, with exposures over 23 km west of Mt Meru (Roberts, 2002). The main pumice deposits are a sequence of four primary pumice fall units (A, B and C) and one ash fall unit (F) interbedded with reworked units (Roberts, 2002). The pumice fall deposits comprise angular pale-grey pumice with amphibole, sanidine and nepheline phenocrysts (Roberts, 2002). Clast sizes vary depending on the thickness of the deposit, with the thicker deposit (A) containing the larger clasts (up to 6.5 cm; Roberts, 2002).

Roberts (2002) interpreted the main pumice deposits to represent the fallout from two explosive events: the first producing the ash fall deposits of unit F; and the second producing the sequence of pumice fall deposits of units A, B and C. Based on the eruption volume calculations of Pyle (1989, 1999) and Fierstein and Nathenson (1992), Roberts (2002) estimated an eruption volume of 2.1 km^3 for the second explosive event which produced units A, B and C. Using maximum clast size data and the model of Carey and Sparks (1986), Roberts (2002) also estimated a maximum column height of the eruption of 23 km.

4.2.2.3 Debris avalanche deposit

The Mt Meru debris avalanche deposit resulted in the 5 km wide and 8 km long horse-shoe shape crater open to the east (Wilkinson et al., 1983). The collapse occurred approximately 8600 yrs BP (calibrated ^{14}C; Hecky, 1971; Wilkinson et al., 1983, 1986), and produced a deposit covering an area of ~390 km^2. Initially, this deposit was thought to have formed from a lahar (Wilkinson et al., 1983); however, the hummocky nature of the deposit and the horse-shoe shape crater are characteristic features of a debris-avalanche deposit (Roberts, 2002). Roberts (2002) estimated the volume of the debris-avalanche deposit, based on the volume of the missing sector, to be 28 km^3, making it one of the largest ever recorded (Socompa was ~36 km^3, and Mt Shasta was 26 km^3). There is no clear evidence for the cause of the collapse which resulted in the Mt Meru debris-avalanche (Roberts, 2002).

Wilkinson et al. (1983, 1986) proposed that the pumice and ash deposits were associated with the collapse event. However, based on field evidence (no young pumice deposits inside the Meru crater) Roberts (2002) suggested that the pumice and ash deposits preceded the collapse event. There is no reliable dating for these deposits. Roberts (2002) obtained Ar-Ar ages from sanidine phenocrysts from unit A pumice of >1 Ma. Roberts (2002) suggested that significant atmospheric argon affected the dating.

4.2.2.4 Post-collapse Deposits

Volcanic activity that occurred after the collapse has been confined to inside the crater, and included the ash-cone, a lava dome and lava flows (Roberts, 2002). The ash cone is ~1.5 km wide at its base, rises 200 m above the crater floor and comprises dark ash and vesicular pumiceous blocks up to 30cm in diameter (Roberts, 2002). The dominant style of eruptive activity is thought to be strombolian due to the wide range in clast sizes.

At the western base of the ash cone is a nephelinite lava dome, which is 350 m in diameter and ~70 m high (Roberts, 2002). Numerous later lava flows originated from the lava dome, and flowed down the collapse scar extending up to 7 km distant (Roberts, 2002). The most recent flows were in 1877 and 1886 (Padang, 1954; IAVCEI Catalogue of Volcanoes; referenced by Roberts, 2002).

Roberts (2002) suggested that these lava flows represent effusive activity in between explosive strombolian activity associated with variations in dissolved gas content.

The most resent eruption of Mt Meru was in 1910 with explosions on 26th October and 13th, 18th and 22nd December (Roberts, 2002). The explosions resulted in much of the crater being filled with ash. Since 1910, fumarolic activity has been recorded in the ash cone (in 1911, 1926, 1936 and 1953; Guest and Leedal, 1953). Although no activity has been recorded since 1953, Roberts (2002) reported that in the last few years several local guides working in the Arusha National Park have reported smelling sulphur whilst walking along the north crater wall. In March 1999, a 20cm wide, 100 m long fissure opened on the southern slopes of Mt Meru and emitted steam for about a week (Roberts, 2002). This was attributed to the result of heated ground water as it occurred in the wet season.

4.3 EXPOSURE

The population of the area surrounding Mt Meru is concentrated in Arusha town located on the southern flanks of the volcano although there is a distributed rural population on all the flanks with the exception of the National Park boundaries on a sector of the eastern flank. Population is lowest in the arid western flank which coincides with the area inundated by tephra deposits from the most recent Holocene eruptions of Meru. Whilst the population figures provided by the Arusha Regional Government in the September 2013 census (Table 1) capture the permanent residents in the area, there are a significant number of tourists that use Arusha as a base for safaris and expeditions to Meru prior to an ascent of the neighbouring Kilimanjaro. There is also a significant expatriate community that reside in Arusha and who may not be captured in the current census data.

Population by District	*Households*	*Male*	*Female*	*Total*
Arusha Jiji	97540	199524	216918	416442
Arusha V	72150	154301	168897	323198
Karatu	42469	117769	112397	230166
Longidp	23494	60199	62954	123153
Meru	59499	131264	136880	268144
Monduli	31903	75615	83314	158929
Ngorngoro	33815	82610	91668	174278

Table 1 Population data for the Arusha Region.

Of the population data available, there is limited information about the age distribution of the population. However, the distribution and number of schools within the Arusha Region (Table 2) suggests that a significant proportion of the population is under 16.

Schools by District	Preparatory	Primary	Secondary
Arusha City	108	111	47
Arusha V	108	116	48
Karatu	103	103	31
Longidp	36	41	8
Meru	138	138	55
Monduli	44	60	19
Ngorngoro	64	64	11
Total	601	633	219

Table 2 Number and type of school in the Arusha Region.

Information was provided on the water sources for the Arusha Region (Table 3). Water access is not a particular problem in the region due in part to the rains induced by the topography of Mt Meru and Kilimanjaro. However, a significant number of surface water storage and schemes that use surface runoff of meteoric waters may be subject to contamination in the event of an eruption through ash deposition.

Water sources by District	Shallow boreholes	Deep boreholes	Dams	Surface water storage	Gravity schemes (source from rivers)
Juli Arusha	0	17	0	4	2
Arusha District	2	10	16	15	48
Karatu	16	9	10	50	18
Longido	2	13	10	37	39
Meru	7	17	3	32	45
Mondoli	6	18	68	158	17
Ngogoto	2	13	53	7	25
TOTAL	35	97	160	303	194

Table 3 Type of water sources in the Arusha Region.

If further work to assess the volcanic hazard and risk is conducted this data may be used to provide population exposure indices. Further information on the location of critical services and infrastructure such as hospitals and medical facilities will be sought.

4.4 GIS AND REMOTE DATA

A GIS (Geographic Information System) was built in ArcGIS 10.1 using vector and raster data acquired for the whole of the Mt Meru and surrounding area. This system enables comparative analysis of datasets as well as providing a better understanding of the spatial and topological context of features within the study area.

4.4.1 GIS Vector Data

A series of vector shapefiles was obtained from a free-of-charge online source (www.diva-gis.org) for the whole of Tanzania. The files provided spatial and contextual information on the following types of features:

- point features: named places (e.g. town, village, city, suburb, etc..) and other point features
- linear features: railways (e.g. used, disused, abandoned, etc...), roads (e.g. dirt road, track, primary, etc...) and waterways (e.g. stream, river, drain, etc...)
- polygon features: buildings (e.g. church, industrial, residential, etc...), landuse (e.g. farmland, landfill, reservoir, etc...) and natural features (e.g. water, riverbank, forest, etc...)

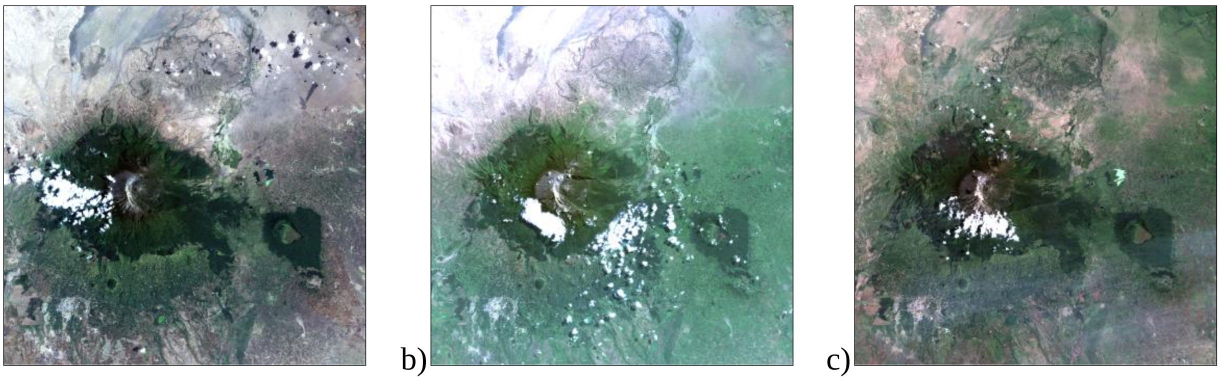
4.4.2 Remote Sensing Image Data

Remote Sensing image data were obtained from the USGS Global Visualisation Viewer (http://glovis.usgs.gov) when minimal cloud conditions prevailed over Mt Meru and the surrounding area. This data source provides global image data free-of-charge from specific satellite sensors, such as the TM (Thematic Mapper) onboard the Landsat-4/-5 satellite platforms and the ETM+ (Enhanced Thematic Mapper Plus) onboard the Landsat-7 satellite platform. These are spectral imaging sensors that measure the amount of solar radiation reflected by the ground surface across specific spectral wavebands. Data from both sensors were used in this study and their spectral and spatial characteristics are detailed in Table 4.

Sensor	Band	Spectral Characteristic (μm)	Spectral Region	Spatial Resolution (m)
Landsat TM	1	0.45-0.52	VIS	30
	2	0.52-0.60	VIS	30
	3	0.63-0.69	VIS	30
	4	0.76-0.90	NIR	30
	5	1.55-1.75	SWIR	30
	6	10.40-12.50	TIR	120
	7	2.08-2.35	SWIR	30
Landsat ETM+	1	0.450-0.515	VIS	30
	2	0.525-0.605	VIS	30
	3	0.630-0.690	VIS	30
	4	0.750-0.900	NIR	30
	5	1.550-1.750	SWIR	30
	6	10.400-12.500	TIR	60
	7	2.090-2.350	SWIR	30
	8	0.520-0.900	PAN	15

Table 4: Spectral and spatial characteristics of the Landsat TM and ETM+ sensors (from http://landsat.usgs.gov/band_designations_landsat_satellites.php).

Level 1G terrain-corrected TM data were obtained for scene Path 168/Row 062 for 25 February 1987 (NASA, 1987a), 1 June 1987 (NASA, 1987b) and 17 February 1993 (NASA, 1993). Level 1G terrain-corrected SLC-on (Scan Line Corrector-on) ETM+ data were obtained for the same scene for 14 September 1993 (NASA, 1999) and 21 February 2000 (NASA, 2000). A series of images were required in order that the peak and flanks of Mt Meru were fully exposed at some point during the time series as well as to minimise vegetation cover for mapping purposes (Figure 2).



a) b) c)

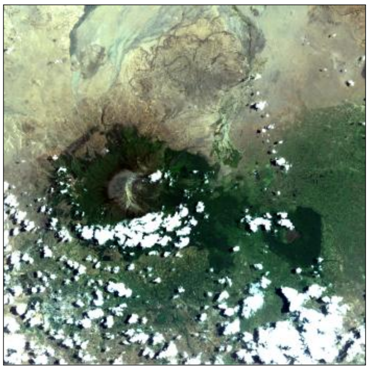
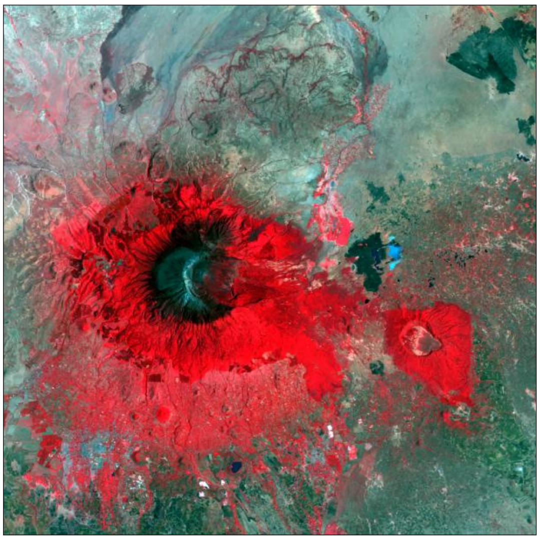
d)  e) 

Figure 2: Overview natural colour composite imagery for calibrated Landsat Path 198/ Row 062 scenes for a) 25/02/1987, b) 01/06/1987, c) 17/02/1993, d) 14/09/1999 and e) 21/02/2000. Data available from the U.S. Geological Survey.

These images were pre-georeferenced to UTM zone 37-South projection, with WGS84 horizontal datum. Each spectral band of TM and ETM+ data were converted from DN (digital number) to spectral radiance using the Landsat Calibration Pre-processing utility in ENVI Version 4.7 software (EXELIS Visual Information Solutions). This process uses published post-launch gains and offsets specific to the sensor for the user-defined date of image acquisition, in conjunction with parameters on sun elevation angle, band minimum DN value and band maximum DN values, each of which are specified in the associated image metadata file.

Digital image processing was performed on each calibrated scene to highlight particular surface features. A series of images were generated using specific RGB display channel band combinations with histogram manipulation in order to enhance visualisation of the study area. RGB band combinations visualised (Figure 3) were the natural colour composite 321 (similar colouring to that observed through a digital camera) and the false colour-composites for 432 (healthy vegetation appears red), 742 (exposed lithologies appear in blue hues), and 457 (enhances variations in exposed lithologies). All image enhancements were exported as GeoTIFF files and incorporated into the GIS for future analysis.

a)  b) 

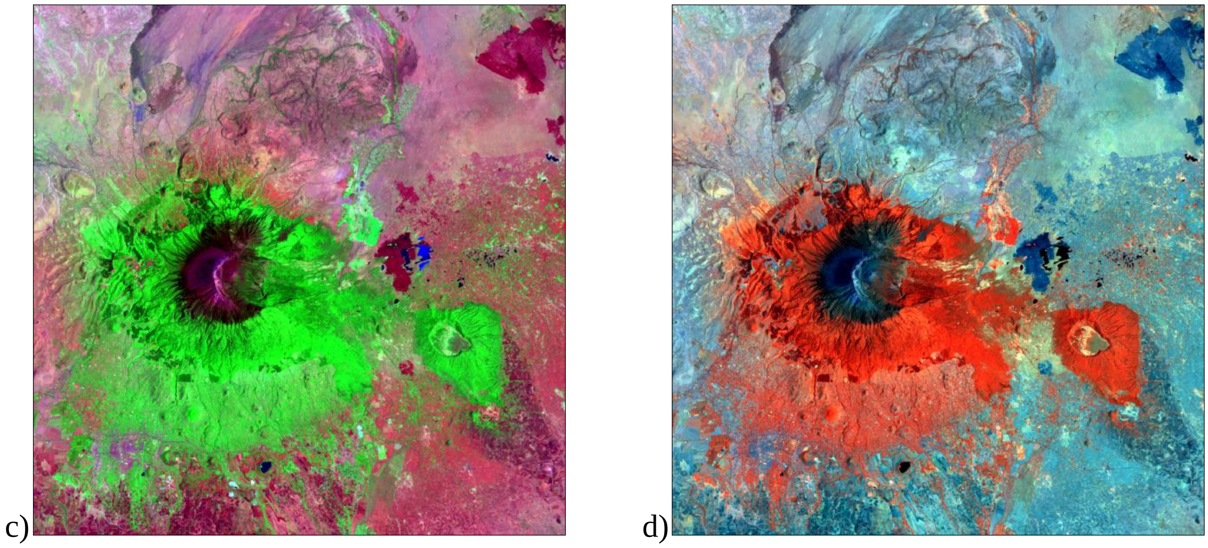


Figure 3: RGB band combinations for calibrated Landsat scene from 21 February 2000 a) 321, b) 432, c) 742, and d) 457.

The calibrated TM and ETM+ data can be further manipulated in future work to help distinguish specific surface compositions and thus enhance mapping.

4.4.3 Topographic Data

Topographic data was obtained from the USGS Earth Explorer online facility (http://earthexplorer.usgs.gov) over Mt Meru and the surrounding area. This data source provides remotely sensed image data free-of-charge, including topographic data from the SRTM (Shuttle Radar Topography Mission) as used in this study. The SRTM was flown on the Endeavour Space Shuttle during February 2000 acquiring C-band (5.6 cm) radar data from which to create a near-global data set of land elevations.

A 3-arc-second (90m) resolution GeoTIFF tile for 036°-037°N and 001-002°S (SRTM3S04E036V2) was downloaded from Earth Explorer. The elevation data was reprojected to the UTM zone 37-South projection, with WGS84 horizontal datum, and a hill-shade generated to enhance visualisation of topographic features (Figure 4). Both elevation images were incorporated into the GIS.

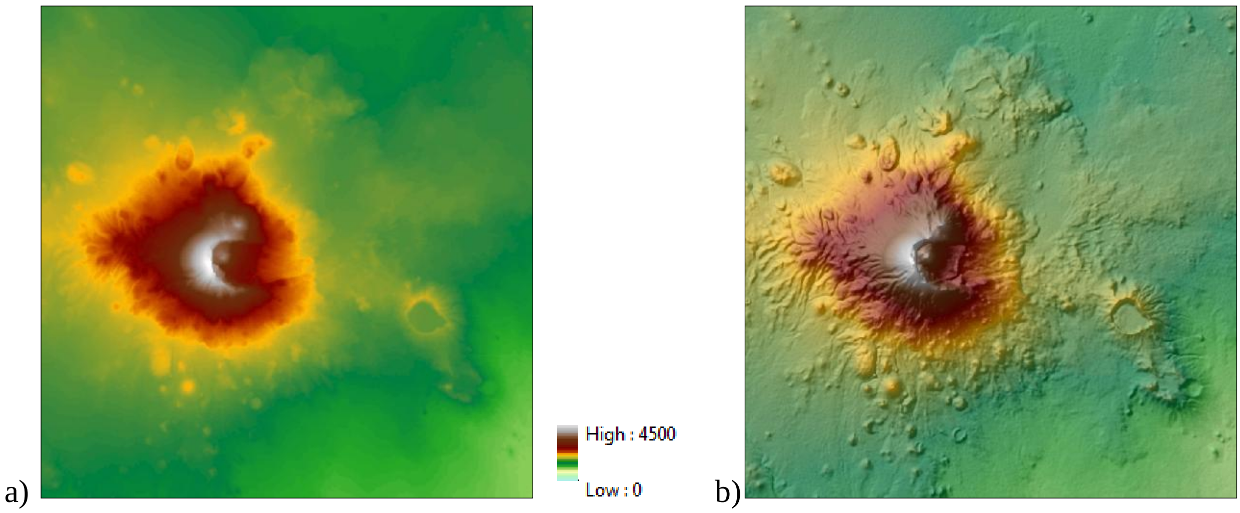


Figure 4: SRTM a) colour-coded elevation for tile SRTM3S04E036V2 over the Mt Meru study area and visualised b) draped on hill-shade image. Data available from the U.S. Geological Survey.

4.5 FIELD STUDY

A day was spent in the field looking at the tephra fall deposits described by Roberts (2002), to the west and northwest of Mt Meru. In northern Tanzania, the prevalent wind direction is from the east, therefore tephra fallout deposits occur on the western slopes of Mt Meru, and beyond. Roberts (2002) reported the locations of exposures of tephra fallout deposits (Figure 5). The aim of the day was to validate his observations, explore potential exposures along river gullies, and to sample pumice from fallout units to determine the ages of the eruptions. Dating of the pumice fallout deposits has been attempted; however, Ar-Ar dating on a sanidine-bearing pumice fall deposit yielded an age of 1 Ma, and was discarded (Roberts, 2002). Through improved dating techniques, we hope to accurately determine the ages of these large explosive eruption.

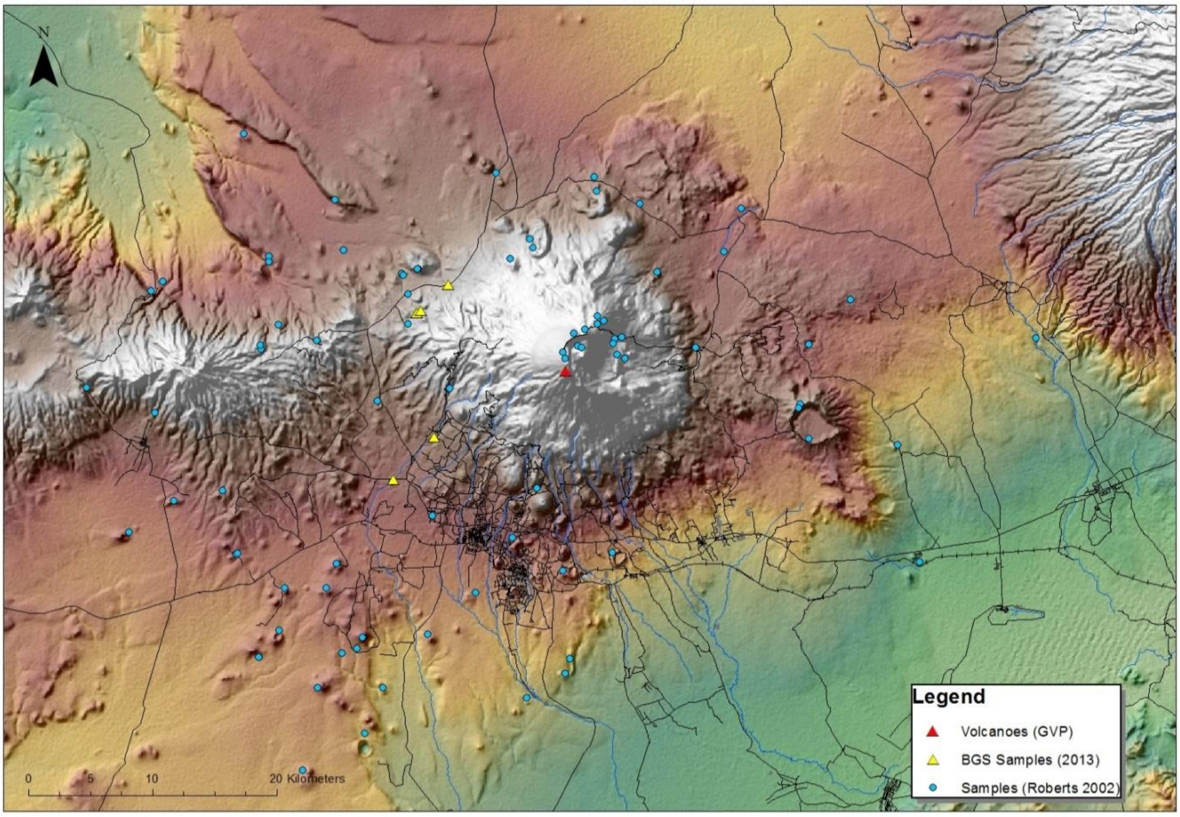


Figure 5 Mt Meru sample location map.

Yellow triangles show the locations of samples collected by BGS on October 2013 as part of this study. Blue circles are sample locations from Roberts (2002).

Roberts (2002) proposed that the tephra fallout deposits form part of a large 'climatic' eruption, based on the similarities in field characteristics of the deposits, and the whole-rock geochemistry. When plotted on a TAS diagram the deposits reveal a clear fractionation trend, which Roberts (2002) interpreted as the emptying of a large, fractionated magma chamber. He calculated the volume of such an eruption, taking the combined thicknesses of the units, as 2.1 km^3.

4.5.1 Tephra Sections

As part of this study, tephra deposits were described and samples were collected at five localities to the west of Mt Meru (Figure 5). Locality 1 is in a dry river bed at the village of Kiushian, just off the main Arusha – Nairobi road. Within the dry riverbed, a ~1.5 m thick consolidated ash deposit with abundant pumice and lithics is exposed (Figure 6). Average clast sizes are between

1 and 5cm, with rare larger clasts up to 30 cm. The deposit has internal structure with layers of more concentrated lithic and pumice fragments.

Figure 6 Field photographs of Locality 1 and Locality 2.

Locality 2 is further up the same riverbed towards Mt Meru. The river valley is much deeper here (~5 m). Exposed near the top of the channel walls is a ~50cm thick, unconsolidated ash-supported deposit that contains abundant rounded cream pumice fragments. Overlying this deposit is a ~1.5 m thick reworked deposit, possibly a lahar, with very large blocks (up to 1 m) of lithics and consolidated pyroclastic flow material (Figure 6).

Figure 7 Field photographs of Locality 3: the road-cut reveals numerous interbedded ash-rich reworked, and pumice fall deposits.

Locality 3 is on the edge of the north-western slope of Mt Meru, through a Masaai village just south of the main Arusha-Nairobi road. A series of tephra fallout and reworked pyroclastic deposits are exposed in a road-cut through a topographic high (or mound) (Figure 7). It appears as though the pyroclastic material is draping a topographic feature such as a monogenetic cone, of which there are many surrounding and on the flanks of Mt Meru. At least three tephra fall deposits were identified, all of which are pumice-supported with abundant lithics (Figure 7). The pumice is very light grey / cream in colour, and up to 2 cm along the long-axis. These deposits are all between 10 and 15cm thick. Interbedded between the pumice fall deposits are ash-supported, pyroclastic flow deposits with reworked pumice and lithic fragments. These deposits vary in thickness from <1 m to > 2 m.

Locality 4 is in a steep-sided river valley, ~50 m along the road from Locality 3. The gorge is ~20 m deep with clearly visible grey tephra fall deposits interbedded with yellow and pale cream ash-rich units (Figure 8). Near the top of the gorge is a rubbly a'a lava flow. The lava comprises a very dark glassy groundmass with abundant phenocrysts of feldspar, quartz and hornblende.

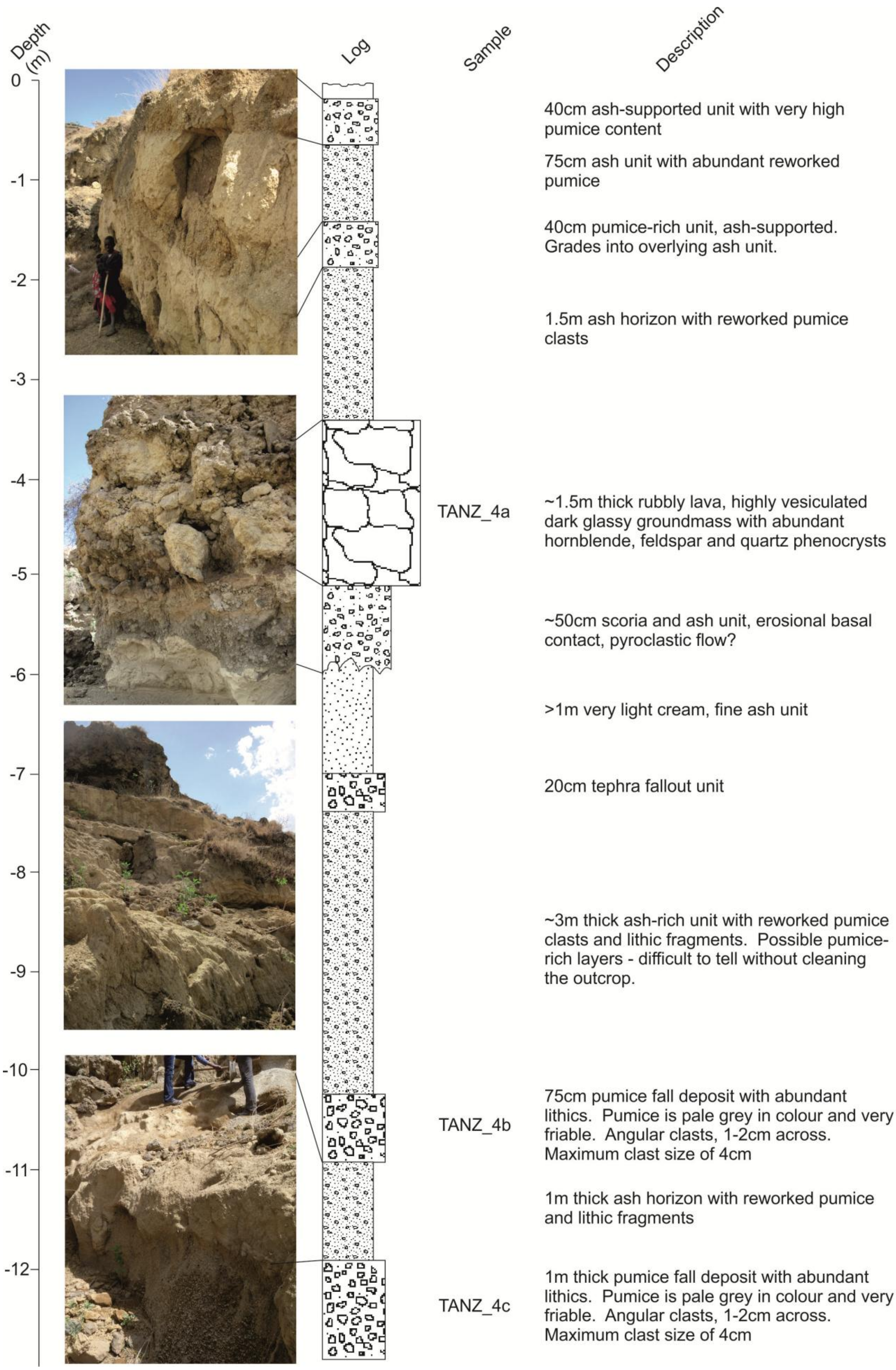


Figure 8 Locality 4 stratigraphic section with field photographs. Sample descriptions are in Table 1.

The final locality, 5, is located on the main Arusha-Nairobi road in another river gorge. The gorge is ~10 m deep, and exposes a thick (>2.7 m) tephra fallout deposit, overlain by a series of tephra and ash fall layers (Figure 9). These are then overlain by a ~70 cm thick pumice-rich deposit. The thick fallout unit is clast-supported with predominantly light-grey pumices. The deposit is lithic-poor. Phenocrysts are clearly visible in the pumice clasts. Clasts are typically 3 cm, with common clasts up to 5 cm across.

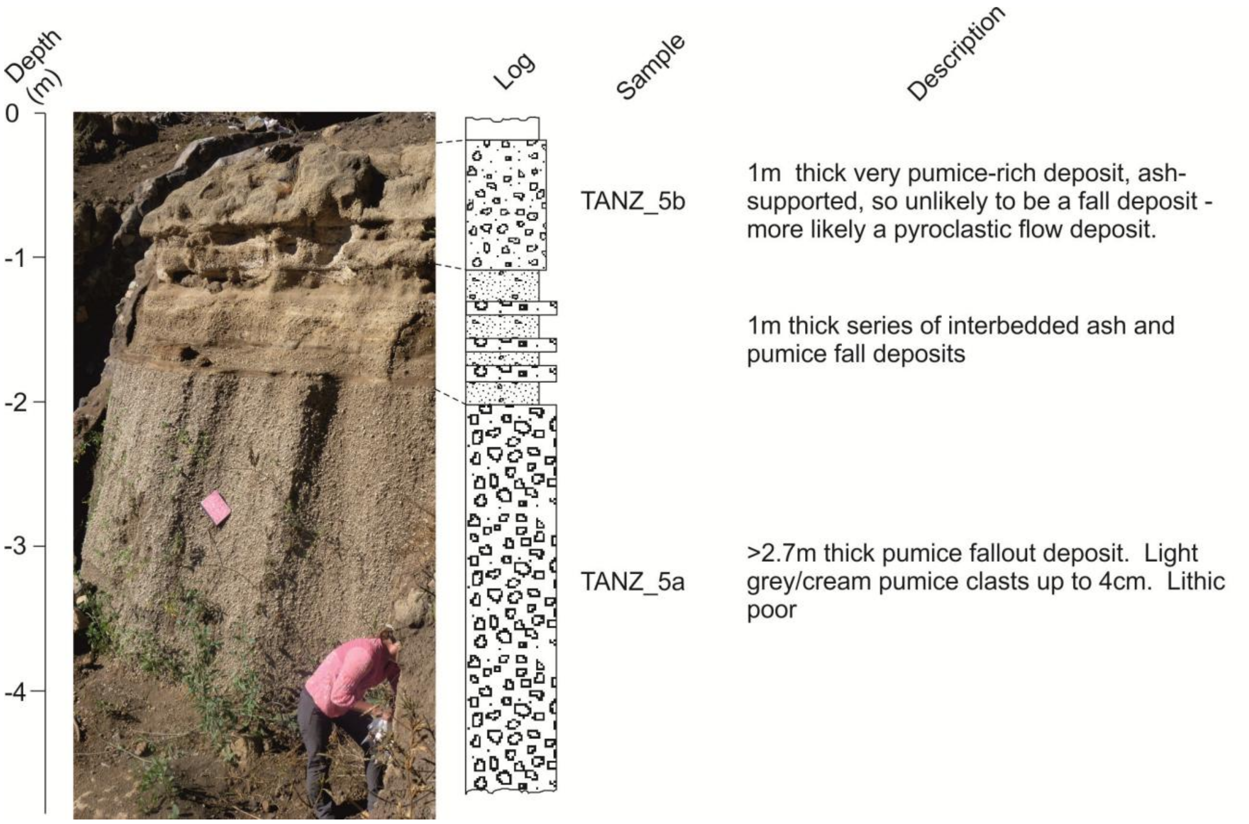


Figure 9 Locality 5 stratigraphic log with field photographs. Sample descriptions are in Table 1.

4.5.2 Tephra Samples

Pumice clasts were collected at each locality in order to try to date the large magnitude eruptions that produced the tephra fallout deposits. Roberts (2002) previously tried to date a sanidine crystal from a pumice fall deposit; however, the results were questionable. Based on field evidence and whole-rock geochemistry, Roberts (2002) described the fall deposits as resulting from one, climatic, plinian eruption. Dating of individual deposits would enable this hypothesis to be tested.

In total 12 samples were collected. The sample descriptions and locations are presented in Table 1. Nine of the samples comprise pumice clasts, while samples TANZ_2b and 2c are lithic fragments from a reworked lahar(?) deposit, and sample TANZ_4a is taken from the rubbly lava flow at Locality 4. Samples are labelled with the country (TANZ) followed by the locality and a letter (a, b, c) depending on the number of samples taken at a single locality.

Sample	Locality	Easting	Northing	Description
TANZ_1	1	236029	9631733	Pumice fragments from consolidated ash-supported deposit
TANZ_2a	2	239314	9635172	Reworked rounded pumice fragments from lower ash-rich deposit
TANZ_2b	2	239314	9635172	Block of consolidated pyroclastic flow material. Light grey colour with lithic and pumice fragments. Overlying TANZ_2a
TANZ_2c	2	239314	9635172	Lithic block from same unit as 2b.
TANZ_3a	3	237963	9645158	Pumice from lower fall deposit
TANZ_3b	3	237963	9645158	Pumice, very similar to TANZ_3a. From fall deposit higher up section
TANZ_3c	3	237963	9645158	Pumice from fall deposit near the top of the road-cut
TANZ_4a	4	238268	9645325	Vesicular lava, very dark glassy groundmass with abundant phenocrysts of hornblende, feldspar and quartz.
TANZ_4b	4	238268	9645325	Pumice is pale grey in colour. Very friable - possibly highly altered. Angular clasts, average size 1-2cm, max 4cm.
TANZ_4c	4	238268	9645325	Very similar to TANZ_4b from a fall unit below.
TANZ_5a	5	240467	9647438	Pumice from thick fall deposit
TANZ_5b	5	240467	9647438	Pumice from upper pumice-rick deposit

Table 5 BGS sample descriptions.

4.5.3 Fieldwork Recommendations

There are common drainage gullies along the north-western slopes of Mt Meru. In many of these, tephra fallout deposits are exposed. Clear variations in thickness can be seen between the exposed deposits in the river gullies, therefore a useful exercise would be to map along the gullies and correlate the deposits between the gullies. This would enable detailed study of the lateral continuity of the deposits, which would feed in to tephra dispersion modelling and enable estimations of eruption volume and column height (i.e. Pyle, 1989; Carey and Sparks, 1986; Connor and Connor 2006). If no dates can be yielded from the phenocryst phases in the pumice samples, detailed mapping and investigation of the individual units would lead to a better understanding of the relationship between these units.

In order to determine eruption recurrence rates, the volcanic stratigraphy must be well understood. Detailed stratigraphic logging would enable this work to be carried out.

If exposure is limited, it may be possible to dig some trenches on the western slopes of Mt Meru. This would give a better spatial distribution of sample sites which reduces the uncertainty of tephra dispersal modelling.

5 Fieldwork Logistics

5.1 FIELD ACCESS

Fieldwork was arranged by staff at the GST in discussion with BGS. Letters of introduction were provided to the Regional Administration of Arusha to request permission to access Mt Meru and the surrounding land. Within Tanzania there is a permit for non-Tanzanian researchers that is administered by COSTECH (The Tanzania Commission for Science and Technology). This requires arrangement in advance with payment made to the administering authority per visiting researcher. Prof Mruma, Director of GST informed us that we did not require a COSTECH as BGS were assisting GST with their work for the public-good in Tanzania. Whilst this was not problematic in the Regional Administration, the National Park would not grant us access without this permit. Although this could have been resolved as part of a longer fieldtrip, there was insufficient time to arrange communications between the National Park and the director of GST.

5.2 SAMPLE SHIPMENT

Collection and export of samples from Tanzania requires particular permission. There is a high sensitivity about sample export due to the highly lucrative mineral and crystal industry, in particular the Tanzanite, Emerald and Sapphire extraction in the Arusha Region. Following sample collection, permission to export was sought from Zonal Mines in Arusha. An accompanying letter from GST was required, as well as an interview with the Director of the regional Zonal Mines office to explain the sample collection and export reason. Following this, samples were individually checked, scanned for mineral content, and sealed in sample boxes. The cost of the permit was $100 US for samples for scientific (not for profit) research purposes only. The seals were wax and we needed to demonstrate that the seals were intact as the hold luggage were processed through Arusha International Airport for transfer to Dar es Salaam before we left Tanzania to return to the UK. The permit, evidence of payment, and letter of permission from GST also needed to be shown to demonstrate that the seal was official.

6 Recommendations for future work

A number of recommendations for future work were realised during discussions with both GST and TMA. The details of these discussions can be found in Appendices 1 and 2.

6.1 CAPACITY BUILDING ACTIVITIES

Monitoring – Monitoring of volcanoes in Tanzania in real-time is sought by both GST and TMA to enable response. The current seismic array provides regional information but does not provide real-time information and is not sufficiently dense to enable volcano monitoring. Information and experience is sought from international colleagues on equipment, installation, telemetry and data processing. GST are working with collaborators to link seismometers deployed by research projects such as the NSF GeoPrisms project in Rungwe Volcanic Province to real-time data delivery to the office in Dodoma.

Training – Knowledge exchange is sought in the areas of scientific advice in hazard management and communication during a volcanic crisis and further collaboration with the international volcanological community to gain experience in these fields.

Hazard and risk assessments - Further research is needed to establish the past activity and behaviour of volcanism in Tanzania in order to discern the likely future activity, recurrence intervals and likelihood. Such data will enable the production of realistic hazard and risk assessments in-country.

6.2 COLLABORATIVE RESEARCH OPPORTUNITIES

A number of opportunities for further research and collaboration were identified by BGS, GST, TMA and Dr Shukrani Manya, Head of Earth Sciences at the Dar es Salaam University:

- Assessment of the current state of volcanic activity at Mt Meru – initially using a seismometer(s) installation within a school or the national park headquarters on the eastern side of Mt Meru to investigate any magmatic activity.
- Volcanic history of Mt Meru - geochemistry, evolution and mapping.
- Regional geochemistry and volcanology of northern Tanzania to look at the evolution and influence of the main rift and conjugate structures on magmatism.
- Baseline geochemistry and volcanic history to investigate the origin of fluoride responsible for the high incidence of fluorosis in northern Tanzania.

Many of these would provide the essential knowledge to enable the preparation for an updated GAR assessment due for reporting in May 2016 and publication by the UN in May 2017.

Appendix 1 Geological Survey of Tanzania (GST)

A meeting was held at the offices of the Geological Survey of Tanzania in Dodoma on the 18th October 2013 with Professor Abdul Mruma (GST), Dr Charlotte Vye-Brown (BGS) and Dr Julia Crummy (BGS) to gather information on monitoring and management of volcanic hazards in Tanzania and work alongside GST to conduct fieldwork on the Mt Meru case study.

AIM

To understand current arrangements for the provision of scientific advice and monitoring of volcanic unrest and activity in Tanzania.

THE GEOLOGICAL SURVEY OF TANZANIA

The Geological Survey of Tanzania (GST) aims to: “provide high quality and cost effective geoscientific data and information to stakeholders in order to enhance the knowledge and use of earth resources, thereby contributing to national poverty alleviation knowledge of geo-hazards and their mitigation, protection of environment, life and property” and to: “become one of the leading Customers oriented Geo-scientific Centre of Excellency in Africa in providing national geoscientific data and information by the year 2025.”

The role of GST is to provide geological information, data and advisory services, and to carry out geological hazard assessments. The GST produce, maintain, archive and disseminate national geological data and information. They also conduct environmental studies including mining effects, pollutions and waste disposal, and carry out assessments of geological hazards i.e. earthquakes, volcanoes and landslides, and their risks and mitigations.

GST is part of the Tanzanian Government’s Ministry of Energy and Minerals, and was first declared in December 2004, and inaugurated in June 2005. GST finds a third of its funding through commercial work and is funded by the Ministry of Finance for the remaining two thirds. The GST has 153 employees, of which 56 are geologists, 59 are technicians and 38 are support staff. The geologists train with GST to become specialists in different areas of expertise i.e. seismology. At present there is only one volcanologist in training at GST. The GST collaborate with the University of Dar es Salaam, University of Dodoma and the Nelson Mandela Research Centre in Arusha on research into natural hazards.

MONITORING CAPACITY

Regional seismometers are installed all over Tanzania. Initially there were 5 or 6 non-real-time seismometers installed by Uppsala University. During a campaign to set-up all African countries with base-line seismicity monitoring, African Array installed 12 seismometers and GST received the software to download and process the data. The resources and intent of Africa Array is to provide base-level monitoring of seismicity, but this is not in real-time. Due to increased theft of the original solar panels and seismometers, GST and African Array decided to install the new seismometers in prisons across Tanzania to protect the array. Data are typically downloaded from field locations once a month; however, during the 2007 eruption of Ol Doinyo Lengai, data was downloaded every 3 days.

The GST do have access to real-time remote sensing and satellite data for monitoring through Earth Volcano Observation System Science (EVOSS) and the preparatory Commission for the comprehensive nuclear Test Ban Treaty Organisation (CTBTO).

ERUPTION MANAGEMENT

During an eruption, there is a clear hazard management procedure in Tanzania. GST reports to the government's Disaster Management Unit (DMU) at the Prime Minister's Office. The DMU is a committee including Prof. Mruma representing GST, officials from the Commission of Science and Technology, Tanzanian Meteorological Agency (TMA), the police, the Army and other first responders, and other officials representing the government office. The DMU responds to all types of disasters. The Army are the first responders in an event such as a volcanic eruption, and carry out any necessary evacuations.

In mid-2013 the EVOSS monitoring system was delivered to GST. There hasn't yet been an eruption during which EVOSS could be implemented. Therefore the following is based on eruptions prior to 2013, the last of which was in 2007.

Notification of unrest or an eruption usually occurs as GST receive calls from local people notifying them of tremors and/or ash as there is currently no real-time monitoring of volcanic activity. GST checks the USGS website for earthquakes magnitudes, and then sends geologists to make field observations. If the activity is confirmed, GST notify the DMU. The geologists, often Prof. Mruma himself, make an assessment of the hazard based on field observations i.e. the area covered by ash fall and impact on the livelihood of locals. In Tanzania, this assessment is the Impact Analysis. There are not set protocols for an analysis so that it can be tailored to the circumstance on a case by case basis. This report is presented to the DMU who then assess the level of risk, the danger to local people, and how and when to evacuate if required. During an eruption, where information is available, GST provide daily updates to the DMU, based on a combination of observations of the eruption by GST scientists and the public. The DMU are responsible for passing on official information to the media. Through the DMU, GST inform the public, using local meetings and the media.

During an eruption GST becomes focussed on enabling a response; however, there are limited resources available to support this activity. GST are responsible for contacting various authorities including the local district and regional government and Civil Aviation Authority (CAA). Prof. Mruma advises the CAA in Dar Es Salaam, on the level of activity, character of the eruption, and the area of impact at ground level. The CAA are the central hub for further information to the Tanzanian regional airports etc. The CAA restricts airspace, which in the past has resulted in flights being re-routed slightly, and tourist charter flights cancelled (i.e. 2007 eruption of Ol Doinyo Lengai). The GST has never had any contact with the Volcanic Ash Advisory Centre (VAAC), which for Africa is the Toulouse VAAC. GST also interacts with the Tanzanian Meteorological Agency to share information.

2007 OL DOINYO LENGAI ERUPTION: A CASE STUDY

The eruption was reported by the local authority who informed GST. In response, GST sent geologists to make physical observations in the field and a seismometer was relocated from Arusha to a location closer to Ol Doinyo Lengai. The GST started monitoring the activity and communicated the hazard to the DMU. During the early part of the eruption data from the seismometer was downloaded every day and latter data was downloaded every three days.

As the event continued, Prof. Mruma was made the director of the DMU. Prof. Mruma made an impact assessment and recommended the relocation of three villages while the eruption continued. These villages were to the west of Ol Doinyo Lengai, in the direction of prevailing wind. The DMU advised the local authority to close access to Ol Doinyo Lengai; however, it is known that some people still climbed the active volcano. One injury is known as a visitor stepped on the cooled crust of a lava flow which gave way to the molten core and resulted in a leg amputation. There are no rescue measures in place on Ol Doinyo Lengai. The DMU have since recommended that access be restricted and emergency facilities including gas detectors and face masks be provided at the summit in close proximity to the overnight camp locations for visitors. These recommendations have not yet been agreed.

During the eruption, the United States Geological Survey (USGS) sent scientists to work with GST on Ol Doinyo Lengai. USGS produced a detailed geological map and took samples for research purposes but results from these could not be processed in time to support the eruption response.

The eruption is reported to have had a big impact on tourism. Many chartered flights to Ngorongoro crater were cancelled due to ash, and safaris were stopped. The eruption also had an impact on the environment with reports of deaths of many flamingos due to the proximity of Lake Ngorongoro which is a breeding ground.

Health impacts from the eruption were revealed by medical assessments attributing the death of many cattle from inhaling ash, and many local people reported difficulty breathing and itchy skin. Cattle were moved away from the areas affected by ash and returned when the ash had washed away and new shoots could grow from 2009 onward.

RECOMMENDATIONS AND SUMMARY

GST is not run operationally 24/7 and is not currently mandated to monitor or respond to natural hazards. At the present time there is one seismologist on the staff at GST and one volcanologist in training. An eruption puts strain on the resources and trained staff are not always available to respond. However, Tanzania is in need of a dedicated operational monitoring agency to handle geophysical hazards and GST could be well positioned to provide such a service if supported by resource investment and capacity development.

To reduce disaster risk, early-warning systems are needed in Tanzania. Real-time monitoring is sought including seismometers, gas detectors (CO_2 and SO_2) and thermal imaging. GST have the essential infrastructure in place for real-time data collection i.e. broadband internet connection and a back-up generator in case of power cuts.

GST particularly seek to increase their capacity to monitor unrest and forecast eruptions to provide early warning and improve hazard management. In order to deliver this it is known that further work is required on eruption history and magmatic processes of volcanoes in Tanzania to calculate eruption recurrence rates, frequency and cyclicity. At the moment, there are too few detailed studies of historical activity to enable this. GST is keen to work with international collaborators to facilitate this and to compile a database in country of the emerging research results. GST do not have access to journal publications in restricted-access journals; therefore, dissemination of information from international research is essential to increase awareness of impacts of natural hazards.

Appendix 2 Tanzanian Meteorological Agency (TMA)

A meeting was held on the 25th October 2013 between staff of the TMA and BGS at the TMA office, Ubungo Plaza, Dar es Salaam on 25th October 2013 to discuss further work on Disaster Risk Reduction to help with the TMA Severe Weather Forecasting Demonstration Project (SWFDP)

AIM

To understand the work programs, capability, areas of interest and responsibility of BGS and TMA to investigate planning for effective management and response of volcanic unrest and eruptions in Tanzania and potential areas for future collaboration.

PARTICIPANTS

1. Dr. Hamza Kabelwa - Director of Forecasting Services (DFS)
2. Dr. Ladislaus Chang'a - Director of Research and Applied Meteorology (DRA)
3. Dr. Charlotte Vye-Brown - BGS Volcanologist
4. Dr. Julia Crummy - BGS Volcanologist
5. Mr. Augustine Kanemba - Manager of Marketing and Public Relations (MMPR)
6. Mr. Wilberforce Kikwasi - Analyst Incharge (ANI)
7. Mr. J. Loning'o- MCC - Manager of Climatology and Climate Change
8. Mr. Wilbert Timiza - Acting Manager of International Affairs (Ag. MIA)
9. Ms. Hazla Masoud - Meteorologist - International Officer (MIO)

Director General of TMA and PR of Tanzania with WMO, Dr. Agnes Kijazi: Prior to a group meeting with interested parties, BGS met with the Director General of the Tanzania Meteorological Agency who gave approval and encouragement for her staff to talk openly with BGS to investigate potential future collaboration.

TMA

TMA is the National Early-Warning Centre for meteorological-related hazards in Tanzania and it is mandated to provide daily information and updates on natural hazards to the public. TMA run a 24/7 operational service but would like capacity development in several areas. TMA are looking to establish a MoU with the Geological Survey of Tanzania in order to provide better information to the public and link real-time observation points for data exchange.

ORGANISATIONAL STRUCTURE OF TMA

- Director General Division
- Forecasting Services Division
- Research and Applied Meteorology Services Division
- Supporting Services Division
- Technical Services division
- Zanzibar Office Division

1. Forecasting Services Division

Under this division there are Networking Operations, the Central Forecasting Office, and the Marine and Aviation Sections. This division covers issues relating to natural hazards including tsunamis, offshore extreme weather, earthquakes (marine services) and volcanic ash. Work is delivered through the network operations group (national observing stations), central forecasting office, (producing short and seasonal forecasts), with GTS and global networks.

2. Research and Applied Meteorology Division

This division includes the: Manager of Environment and Research (MER), Manager of Agricultural Meteorology (MAM) and Manager of Climatology and Climate Change (MCC). The division covers research and environmental issues aiming to enhance collaboration both within and beyond Tanzania in the areas of climatology, climate change (including historical weather) and applied meteorology. This section undertakes training of students from higher education institutions to short training courses to provide students with practical operational experience.

3. Supporting Services Division

This division deals with human resources, finance and administration.

4. Technical Services Division

Under this division there are Technical Services, Information and Computer Technology (ICT) Sections. The division undertakes all meteorological equipment maintenance including one RADAR in Dar es Salaam and another which is currently being installed in Mwanza. The divison is also responsible for Information Technology for TMA.

KEY AREAS OF CONSIDERATION FOR MONITORING NATURAL HAZARDS

Marine Service

Information about earthquakes and Tsunami in the region is delivered by 3 regional Tsunami service provides:

- Inter-governmental Oceanographic Commission - IOC – tsunami program service provider
- Regional undersea Earthquakes and Regional Tsunami Service Providers - RTSPs (Australia, India and Indonesia)
- TMA as the National Early Warning Centre for undersea earthquakes and generated tsunamis has responsibility for the evaluation, modelling and delivery of information on the occurrence of earthquakes in the Indian Ocean, and for tsunamis (including wave arrival time, wave height, run-up and inundation areas) impact on the Tanzania coastline.

Information on earthquake and tsunamis occurrence from the other RTSPs is delivered to TMA through the WMO Global Telecommunication System (GTS) through fax, mobile phones, e-mails and RTSPs websites. Information on earthquakes is delivered within 5 minutes of occurrence and updates on tsunami potential delivered within 10 minutes after an earthquake.

Earthquakes

TMA is aware that understanding the location of earthquakes is also important both inland and in the ocean. The Indian Ocean is geologically a challenge and TMA are interested in ways to get seismometers to provide real-time monitoring to get forecasting capability for both tsunamis potential and volcanism to enable provision of process-based information to the aviation industry, public, private industry, and the Disaster Management Unit (DMU) in the Prime

Minister's Office. TMA would like sensors to provide observation points around the Indian Ocean and the Tanzanian coastline to facilitate immediate response.

Volcanic Ash

There are protocols for reporting volcanic ash for aviation with provision of models and data from the Toulouse VAAC to chart the development and dispersion of volcanic ash. In the case of an eruption TMA alert Toulouse VAAC who run ash dispersion models and validate the eruption with satellite data. The VAAC provide the information and advisory notes to TMA using the WMO GTS system so that information can be passed on to the aviation industry (including the Civil Aviation Authority) and the public through TMA. The GTS system is used as the primary mode of communication. The VAAC model outputs provided to TMA do not include resolution and uncertainty information. This mode of operation does not work for early-warning but to facilitate emergency response for aviation and provision of information.

During the Ol Doinyo Lengai 2007 eruption TMA followed the systematic operating procedures established by ICAO with daily updates from Toulouse VAAC and collaboration and coordination between TMA, GST and the DMU to provide information and advice on evacuation areas.

RECOMMENDATIONS AND SUMMARY

- TMA would like to increase their capacity in seismology and volcanology for early-warning products.
- The Global Atmospheric Watch – Gabriel Mohr – provides some observation through air pollution monitoring. However, there are no observing systems in Tanzania. TMA is interested in equipment that might be of use to provide information on areas susceptible to earthquake and volcanic activity.
- TMA is in need of a dispersion model for monitoring volcanic ash and for any early-warning of ash and associated volcanic gases.
- Information exchange on the status of volcanic activity between TMA and Comoros Islands is needed.
- Routine information exchange on seismic and volcanic activity between GST and TMA and international collaborators is needed to develop a comprehensive observing system in Tanzania.
- TMA is expecting an MoU with GST to provide a 24/7 system for observation and early warning of earthquakes and volcanic activity.
- TMA requires an enhanced communication infrastructure with seismic and volcanic observation points to establish a monitoring centre between TMA and other early-warning components (TMA, DMU, Media and Community at risk) in order to provide information in real-time.

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