NERC
Polaris House, North Star Avenue, Swindon, Wiltshire,
United Kingdom SN2 1EU
Telephone +44 (0) 1793 411500
Web http://www.nerc.ac.uk/

Large Grant PROPOSAL

Document Status: With Council
NERC Reference: NE/L013932/1

Large Grant NOV13

Organisation where the Grant would be held

Organisation	University of Edinburgh	Research Organisation Reference:	RiftVolc
Division or Department	Sch of Geosciences		

Project Title [up to 150 chars]

Rift volcanism: past, present and future

Start Date and Duration

a. Proposed start date	01 September 2014	b. Duration of the grant (months)	60

Applicants

Role	Name	Organisation	Division or Department	How many hours a week will the investigator work on the project?
Principal Investigator	Professor Kathryn Whaler	University of Edinburgh	Sch of Geosciences	7.5
Co-Investigator	Professor Ian Graham Main	University of Edinburgh	Sch of Geosciences	1.13
Co-Investigator	Dr Eliza Calder	University of Edinburgh	Sch of Geosciences	1.8
Co-Investigator	Dr Andrew Bell	University of Edinburgh	Sch of Geosciences	1.8

Technology

Is this project technology-led? No

Describe the type of technology being developed and its application to NERC science; an indicator of the level of maturity of the technology should be included (up to 500 characters).

Collaborative Centres

Please check the the appropriate button if this proposal is being submitted under the auspices of either NCAS or NCEO, and has been explicitly agreed with the centre administrator.

NCAS	
NCEO	
Neither	Yes

Objectives

List the main objectives of the proposed research in order of priority [up to 4000 chars]

We aim to improve the understanding of Rift Volcanism through three linked, multi-disciplinary work packages

Past: What has driven eruptions over geological timescales?(Objectives 1-3)

Present: What controls the active magmatic system and volcanic unrest?

(Objectives 4-5)

Future: What are the potential threats from future volcanic activity?

(Objectives 6-8)

We will focus our research on a target region in the central Main Ethiopian Rift (MER), where all the main features of rift volcanism are displayed, the volcanoes are a significant threat to local populations, and where the potential for geothermal exploitation is enormous.

Our specific objectives are:

O1: Constrain the timing and magnitude of Holocene to Recent volcanism.

O2: Understand magmatic controls on eruption style at the central volcanoes.

O3: Determine the links between eruption style and climate/hydrology.

O4: Define the role active rifting plays on magmatic plumbing systems and volcanism.

O5: Characterise the spatial and temporal variations in stress and strain associated with magmatic, hydrothermal and fault-related processes at the silicic volcanic centres.

O6: Quantify the state of unrest from geophysical data

O7: Develop probabilistic forecasting methods to fully characterise key volcanic hazards at a high risk central volcano.

O8: Develop a regional analysis of ash fall hazard and assess the long-term volcanic threat, incorporating the inherent uncertainty.

Outputs will include:

1) an integrated eruption catalogue for the central Ethiopian Rift including dates, magnitudes, eruption styles and compositional characterisation of major eruptions and associated flows and cones;

2) combined geophysical and geochemical models of the ascent and storage of melts through an active rift and the influence of along-rift variations in magma supply and tectonic setting;

3) characterisation and statistical analysis of the evolving stress, strain and fluid flow fields around the actively-deforming volcanic systems;

4) probabilistic hazard maps for a target volcano, with quantification of knowledge gaps and uncertainty associated with incomplete or sparse datasets leading to a new hazard analysis approach to be applied on a regional basis.

Collectively RiftVolc will deliver impact to local stakeholders through the provision or facilitation of advice and a legacy of tools that are of practical use in a developing, low-technology nation to determine optimum mitigation and resilience strategies. (Impact Summary)

Summary

Describe the proposed research in simple terms in a way that could be publicised to a general audience [up to 4000 chars]

Early explorers called it Africa's Great Rift Valley, a narrow strip that runs for thousands of kilometres from Djibouti to Mozambique and is perhaps most famous for the vast herds of the Serengeti, mountain gorillas and dramatic landscapes of high peaks and fertile plains. The mountains and valleys are the signs of a continent slowly tearing apart. Moving apart more slowly than your finger nails grow, the African continent will one day split into two, creating a new ocean. As the Earth's crust stretches and thins - like plasticine when you pull it - rocks melt, and the resulting magma rises to the surface. The resultant eruptions have had a dramatic and varied impact on the landscape: great lakes have filled the holes left by enormous eruptions; eruptions of volcanic glass have created a chain of peaks, and wide fields are filled with scattered cones and lava flows. This volcanic landscape is hazardous - a recent report for the World Bank ranked 49 of Ethiopia's 65

volcanoes in the highest category of hazard uncertainty. The high temperatures associated with magma in the Rift Valley make it a rich source of carbon-neutral geothermal power. Multi-billion dollar investments by development agencies are driving a ten-fold expansion in the geothermal infrastructure in East Africa over the next decade.

However, the majority of scientific research has focussed on volcanoes in other tectonic settings, such as Hawaii and Japan, leaving the volcanoes of the East African Rift largely a mystery. For many of them, we can't even say when the last eruption look place and there is no monitoring equipment to detect the early stages of an upcoming eruption. The eruption of Nabro volcano in 2011 was a timely reminder of the potential threats. Situated on the frontier between Ethiopia and Eritrea, the area is remote and sparsely populated, yet the eruption caused 32 fatalities, displaced >5000 people and disrupted regional aviation. Had this eruption originated from one of other 29 volcanoes with the same perceived hazard, but in densely-populated central Ethiopia, the humanitarian and societal cost would have been considerable.

RiftVolc will focus on the volcanoes of the Main Ethiopian Rift in central Ethiopia. The aim is to understand their past behaviour, look for subtle signs of present-day activity and assess the threat posed to the infrastructure and people on and around them. RiftVolc will involve scientists from many disciplines working together to produce an integrated view of the past, present and future of the volcanoes in this region and compare it to other parts of East Africa and volcanoes elsewhere. Together we will spend several months out in Ethiopia, collecting samples, mapping the geology and deploying geophysical instruments, before returning to the lab to use analyse the data and create computer models of the results. Petrologists and geochemists will look at the lavas and ash to figure out the timing, size and style of past eruptions. Geophysicists will look for tiny earthquakes, changes in gravity, the passage of electrical currents and movements of the Earth's surface to understand the plumbing system feeding the volcanoes today. Finally, experts in hazard assessment will model possible scenarios and create a long-range eruption forecast for Ethiopia. We will work with our colleagues in the University of Addis Ababa and the Geological Survey of Ethiopia to ensure our findings are appropriate communicated to the government, industry and people of Ethiopia and with international groups such as the Global Volcano Model to communicate our results to development agencies such as the UN and the World Bank.

Academic Beneficiaries

Describe who will benefit from the research [up to 4000 chars].

RiftVolc will focus on volcanism in active continental rifts, using the central Main Ethiopian Rift (MER) as a type location and developing methods and results that are of interest to a wider academic community. All our findings will be presented at international meetings and in peer-reviewed journals and the datasets archived (see ODMP). At the end of the project, we will host an international meeting in Ethiopia to disseminate results amongst the wider community and foster future research collaborations. We expect interest from the following academic groups:

1. Scientists working on East African Rift. Information from our target region to the rest of the East African Rift will enable us to define along-axis variation associated with changes in extension rate and melt supply, and produce hazard assessments on a regional scale. Some of this information exists in past NERC grants (EAGLE, ARC) and many scientists still work on these rich datasets. At the present time, the NSF-funded GeoPRISMS Rift Initiation and Evolution programme (RIE) has nominated the East African Rift System as its primary target. They will study activity at a rift-scale along with two primary focus areas, which lie south of the MER. Integration of our two data sets will greatly enhance their value to the scientific community and one of our annual science meetings with be held jointly with GeoPrisms.
2. Scientists working on other extensional settings: Understanding active continental rifting has implications for other tectonic settings. Comparisons with Iceland, through projects like FutureVolc, enables us to distinguish the role of extensional tectonics and the impact of a mantle plume. Continental rifts are the early stages of mid-ocean ridges and passive margins and have the advantage of being accessible on land. Interested parties involve both academic (e.g. Interridge) and industrial (e.g. hydrocarbon) communities
3. Scientists studying volcanic and seismic hazards in Ethiopia. We will work closely with Addis Ababa University (AAU), the national organisation providing geophysical monitoring data and advice to government during seismic and volcanic unrest and eruptions, and on petrology, geochemistry and the character of past eruptions. Through our Pathways to Impact plan,

we will enable these academics to engage with other experts (e.g. from the Ethiopian Geological Survey) and government representatives responsible for responding to crises. This will lead to improved delivery of and action on the advice.
4. Scientists studying volcanic and seismic hazards in developing countries. Improving resilience to disasters is increasingly a global issue: for example the World Bank has doubled its investments in disaster risk management to $2.3 billion per year and investments in prevention and preparedness for natural hazards now comprise 2/3 of new lending. RiftVolc will link with NERC-ESRC programmes such as Streva and EwF which are conducting research into resilience to eruptions and earthquakes, and with the Global Volcano Model, which is responsible for preparing the volcano component of the bi-annual UN Global Assessment of Risk.
5. African Scientists: This proposal is only possible because of a strong, two-way relationship with AAU, developed through more than 30 years of collaboration, most recently on the Afar Rift Consortium (ARC) project and the rapid response to the Dabbahu seismo-volcanic crisis. We propose to strengthen the collaboration by supporting established scientists and PhD students for extended visits to the UK, and by hosting an international meeting in Addis Ababa.
6. The next generation: The project will provide training for at least 4 UK doctoral students, 5 PDRAs and MSc/MSci students. In addition, several Ethiopian PhD students will be involved in our field programmes, learning to use the most up-to-date instrumentation and being exposed to new techniques, and will make use of the data in their projects.

Impact Summary

Impact Summary (please refer to the help for guidance on what to consider when completing this section) [up to 4000 chars]

Beneficiaries
National Government (Devolved Government & Government Agencies)
- The Institute of Geophysics, Space Science and Astronomy (IGSSA) at Addis Ababa University is the national organisation providing geophysical monitoring data and advice during unrest and eruptions, and the School of Earth Sciences advises on the character of past eruptions. There are no trained volcanologists in Ethiopia so they collectively provide scientific advice to the Ministry of Agriculture's Disaster Risk Management and Food Security Sector (DRMFSS), the Civil Aviation Authority and Ethiopian Pilots Association during an eruption.
- The Geological Survey of Ethiopia's geoscience data, advice and services contributes to the sustainable development of the agricultural, industrial, infrastructure and other sectors of the Ethiopian economy.
International Organisations and Agencies.
- The IAVCEI Commission on Hazards and Risk links academic research to decision-makers, to reduce the impact of volcanic hazards.
- The Global Volcano Model (GVM) is an international network creating an information platform on volcanic hazard and risk, and is responsible for the volcano component of the biennial UN Global Assessment Report on Disaster Risk Reduction.
Commercial Sector (Public and Private Geothermal Energy)
- Reykjavik Geothermal Limited develops high enthalpy geothermal resources and will construct Africa's largest (1 GW, $4billion) geothermal power plant in our study area.
- Ethiopian Electrical Power Corporation (EEPCO) currently operates a 7MW geothermal power station in our study area, which they are expanding to 70MW.

We will deliver benefit by:
National Government
- Assist Ethiopian scientific partners to build institutional capacity and a volcano monitoring strategy for observations of, and response to, future unrest and eruptions based on information on past eruptions, the processes driving current unrest, and priorities for potential impacts. Enable IGSSA to establish real-time seismic and geodetic monitoring.
- With in-country partners involved in science advice, monitoring, aviation, national and regional administration, and civil protection, ensure our research responds to the needs of all sectors, and make recommendations for the future.
- Research outputs and methodologies supporting effective decision-making under conditions of uncertainty will assist with policy development to strengthen the resilience of people and assets exposed to volcanic hazards. Deliver to local stakeholders advice and a legacy of tools that are practical for use in a developing, low technology nation to determine optimum mitigation and resilience strategies, supporting Ethiopia's national response to the Hyogo Framework for Action

international policy for disaster risk reduction. Enable DRMFSS to incorporate volcanic hazards into the local disaster risk profiling exercise.

International Organisations and Agencies

- Through organisations such as the GVM and IAVCEI commission, disseminate our results, share experience and practice applicable in a developing nation, and consult over the development of methodologies to underpin future global-scale analyses of volcanic risk.
- Transfer knowledge and contribute to policy through interaction with the UK Cabinet Office Civil Contingencies Secretariat and input to the National Risk Register.

Commercial Sector

- Collaborate with Rekjavik Geothermal and EEPCO to exchange data that inform geothermal exploration and production, and incorporate hazard analyses specific to rift volcanism to mitigate against potential future economic losses resulting from volcanic activity.

Activities detailed in the Pathways to Impact document will improve monitoring for early warning, facilitate science into policy supporting planning to build resilience, contribute to global data sets and volcanic risk modelling, increase the resilience of industry to support economic development, and facilitate better communities.

Summary of Resources Required for Project

Financial resources

Summary fund heading	Fund heading	Full economic Cost	NERC contribution	% NERC contribution
Directly Incurred	Staff			80
	Travel & Subsistence	205430.00	164344.00	80
	Other Costs	109884.00	87907.20	80
	Sub-total			
Directly Allocated	Investigators			80
	Estates Costs	60198.00	48158.40	80
	Other Directly Allocated	5906.00	4724.80	80
	Sub-total			
Indirect Costs	Indirect Costs	117789.00	94231.20	80
Exceptions	Staff	47565.00	47565.00	100
	Other Costs	13398.00	13398.00	100
	Sub-total			
	Total	**854617.10**	**695886.28**	

Summary of staff effort requested

	Months
Investigator	19.75
Researcher	30
Technician	0
Other	12
Visiting Researcher	0
Student	42
Total	103.75

Joint Proposals

Complete this section if more than one organisation is submitting a NERC proposal form for this project.

Is this part of a joint proposal ?	
Are you the lead RO ?	
Joint reference	
Total number of proposals	

Other Support

Details of support sought or received from any other source for this or other research in the same field.

Awarding Organisation	Awarding Organisation’s Reference	Title of project	Decision Made (Y/N)	Award Made (Y/N)	Start Date	End Date	Amount Sought / Awarded (£)

Staff

Directly Incurred Posts

			EFFORT ON PROJECT							
Role	**Name /Post Identifier**	**Start Date**	**Period on Project (months)**	**% of Full Time**	**Scale**	**Increment Date**	**Basic Starting Salary**	**London Allowance (£)**	**Super-annuation and NI (£)**	**Total cost on grant (£)**
Researcher	RA TBA	01/01/2015	30	100						
Other Staff	Project Administrator	01/09/2014	60	20						
									Total	

Applicants

Role	Name	Post will outlast project (Y/N)	Contracted working week as a % of full time work	Total number of hours to be **charged** to the grant over the duration of the grant	Average number of hours per week **charged** to the grant	Rate of Salary pool/banding	Cost estimate
Principal Investigator	Professor Kathryn Whaler	Y	100				
Co-Investigator	Professor Ian Graham Main	Y	100				
Co-Investigator	Dr Eliza Calder	Y	100				
Co-Investigator	Dr Andrew Bell	Y	100				
						Total	

Exceptions

Role	**Post Identifier**	**Start Date**	**London Allowance (£)**
Project Student	Project Student	01/10/2015	No

Travel and Subsistence

Destination and purpose		Total £
Outside UK	International Conferences for 4 investigators	6000
Outside UK	International Conference for PDRA	4500
Within UK	UK Meetings for 4 investigators	2400
Within UK	UK Meetings for PDRA	600
Outside UK	MT Fieldwork	57030
Within UK	2 UK Annual Science Meetings (4k impact)	16000
Outside UK	1 Annual Science Meeting in Iceland (7.5k impact)	15000
Within UK	1 Annual Science Meeting in US (GeoPrisms)	15000
Outside UK	Final Science Conference in Addis Ababa (5k impacts)	50000
Within UK	Management Committee Meetings	900
Within UK	Fieldwork Committee Meetings	900
Within UK	T&S for hazard mapping workshop (Impact)	1000
Within UK	Ethiopia - 'Women in Science' Day (Impact)	2000
Outside UK	2 x 3 week secondments for AAU staff (Impact)	4000
Outside UK	3 x 3 week secondments for AAU staff (Science)	6000
Within UK	PhD Student Meetings	5000
Within UK	UKRC training events in UK for PhD student 3*£200	600
Within UK	Two 3-day visits each to project partners in Bristol & Southampton for PhD student 4*600	2400
Within UK	Research visit to IMO Iceland to discuss access to data and visit selected analogue field sites over 1 week	1800
Outside UK	Two international conferences (years 2 and 3) for PhD student EGU - £1000 + AGU £1500	2500
Within UK	Attendance at BGA/VMSG meetings in UK for PhD student 3*£600	1800
Within UK	Final Hazards workshop (Impact)	10000
	Total £	205430

Other Directly Incurred Costs

Description	Total £
GEF costs (geomagnetic equipment and solar panels) for 2 field seasons of 2.5 months	7800
Magnetotelluric equipment hire at reduced rate through Project Partners	27000
Air freight, 1100 kg for two field seasons at £5/kg each way	11000
Fieldwork training (including first aid) for all participants	14000
12 sealed batteries for fieldwork @£75 each	900
Fieldwork peripherals (augers and other digging equipment, salt, bentonite, mobile phones, etc)	500
6 'core years' high performance computing time and 1 TB storage for 2 years on University of Edinburgh Eddie cluster	1684
Storage in Addis Ababa	2000
Sub-Contract to Addis Ababa University (2k translation for impact)	40000
Expert Elicitation	5000
Total £	109884

Other Directly Allocated Costs

Description	Total £
Infrastructure Technicians	5906
Total £	5906

Research Council Facilities

details of any proposed usage of national facilities

Name of Facility	Proposed Usage
Geophysical Equipment Facility (GEF) - Edinburgh	GEF costs (geomagnetic equipment and solar panels) for 2 field seasons of 2.5 months

Project Partners: details of partners in the project and their contributions to the research. These contributions are in addition to resources identified above.

1	**Name of partner organisation**	**Division or Department**		**Name of contact**	
University of Florence		Earth Sciences Department		Professor Marco benvenuti	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment		
equipment/ materials	Sharing of expertise and samples		staff time	Engagement in collaborative meetings, provision of advice	
secondment of staff			other		
other			Sub-Total		
Sub-Total				Total Contribution	

2	**Name of partner organisation**	**Division or Department**		**Name of contact**	
Dublin Institute for Advanced Studies		School of Cosmic Physics		Professor Alan jones	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment	MT instrumentation at a fraction of commercial hire rate	
equipment/ materials			staff time	technician for training; Prof Jones	
secondment of staff			other		
other			Sub-Total		
Sub-Total		0		Total Contribution	

3	**Name of partner organisation**	**Division or Department**		**Name of contact**	
University of Leeds		School of Earth and Environment		Professor Timothy Wright	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment		
equipment/ materials			staff time	3 PDRAs and Prof Wright contributing	
secondment of staff			other		
other			Sub-Total		
Sub-Total		0		Total Contribution	

4	**Name of partner organisation**	**Division or Department**		**Name of contact**	
Global Volcano Model		none		Professor Robert Sparks	
Direct contribution to project			**Indirect contribution to project**		

	Description	Value £		Description	Value £
cash			use of facilities/ equipment		
equipment/ materials			staff time	to attend meetings, workshops etc	
secondment of staff			other	travel and subsistence for staff	
other			Sub-Total		
Sub-Total				Total Contribution	

5	**Name of partner organisation**	**Division or Department**		**Name of contact**	
Reykjavic Geothermal		Geophysics		Dr Hjalmar eysteinsson	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment		
equipment/ materials			staff time	Ethiopian field logistics; meeting in Iceland	
secondment of staff			other	Data sharing	
other			Sub-Total		
Sub-Total				Total Contribution	

6	**Name of partner organisation**	**Division or Department**		**Name of contact**	
University of Bristol		Chemistry		Professor Richard Pancost	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash	Travel and subsistence for meetings		use of facilities/ equipment	Stakeholder conference attendance	
equipment/ materials			staff time		
secondment of staff			other	Communicating with the geothermal industry	
other	Paying for professional document writer		Sub-Total		
Sub-Total				Total Contribution	

7	**Name of partner organisation**	**Division or Department**		**Name of contact**	
ETH Zurich		Institute of Geophysics		Professor Andy Jackson	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment		
equipment/ materials			staff time		

secondment of staff			other	Provision of data	
other			Sub-Total		
Sub-Total				Total Contribution	

8	**Name of partner organisation**	**Division or Department**		**Name of contact**	
University of Brest		UNLISTED		Professor Pascal Tarits	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment	Equipment loan	
equipment/ materials			staff time	Prof Tarits, Dr Hautot and PhD student	
secondment of staff			other	Use of proprietary inversion code	
other			Sub-Total		
Sub-Total				Total Contribution	

9	**Name of partner organisation**	**Division or Department**		**Name of contact**	
Addis Ababa University		Geophysical Observatory IGSSA		Dr Getnet Mewa	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment		
equipment/ materials			staff time	Research, fieldwork, meetings, pathways to impact	
secondment of staff			other	Import bond relief; equipment import-export, rock export	
other			Sub-Total		
Sub-Total				Total Contribution	

10	**Name of partner organisation**	**Division or Department**		**Name of contact**	
Geological Survey of Ethiopia		Grants Admin Office		Mr Hundie Melka	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment		
equipment/ materials			staff time	Consultation; workshop & training attendance; fieldwork	
secondment of staff			other	Access to datasets, permissioning	
other			Sub-Total		
Sub-Total				Total Contribution	

Total Contribution from all Project partners	£920000

Project Students Appendix

Project Student 1

1. a. Proposed start date 01/10/2015 b. End date 01/04/2019

2. Name (if known): Project Student

3.Project Title

Models for forecasting volcanic activity from geophysical data in active continental rifts

4. Proposed supervisors

Supervisor 1: Dr Andrew Bell
Supervisor 2: Professor Ian Graham Main

5.Project Summary

In active continental rifts, crustal deformation is driven by a combination of magma accumulation and movement, tectonic processes, and the migration of non-magmatic fluids. The resulting patterns of seismicity and surface deformation (measured by GPS and InSAR) associated with unrest are therefore more complex than those at volcanoes where magmatic processes dominate. For example, seismicity in these settings frequently includes combinations of accelerating sequences, mainshock-aftershock sequences, and less-systematic earthquake swarms. Consequently, it is more difficult to distinguish signals associated with the approach to eruption, and hence determine probabilities of future volcanic activity.

The student will develop new methods to analyze seismicity and surface deformation data in active rifts, and formulate forecasting models to provide probabilities of different types of eruptive activity in the presence of magmatic and tectonic processes. The work will involve three main components: 1) using, developing, and optimizing state-of-the-art earthquake cluster methods to identifying distinct, causally-related spatial-temporal clusters; 2) characterizing and classifying individual clusters and integrating these signals with surface deformation data from InSAR and GPS surveys; and 3) developing physical and empirical models to link deformation characteristics to physical processes and the probability of eruptive activity. The work will be based on regions with extensive monitoring data, including Iceland, Hawaii, New Zealand, Japan, and Italy, but the resulting methodologies and models will be applicable to other active rift settings.

1) There are a growing number of earthquake cluster identification methods (e.g., van Stiphout et al., 2012; Zhuang, 2002; Gardner and Knopoff, 1974). Many of these methods are based on empirical triggering statistics associated with tectonic seismicity (e.g. Omori's law), which are not necessarily applicable in active continental rifts where, in addition to classic earthquake-earthquake interactions, there is a strong influence of aseismic triggering processes (e.g. magma migration and fluid flow). The student will compare the performance of different cluster identification techniques in rift environments. They will develop new cluster identification methods based on formal discrimination from the standard stationary Epidemic-type aftershock sequence (ETAS) model, and use methods based on model-independent interevent-time and distance statistics (Talbi et al., 2013; Jacobs et al. 2013), and other physical and statistical models for earthquake triggering. They will benchmark the performance of different approaches using synthetic datasets, and test them on data from a range of volcano-tectonic regions.

2) The space, time, and magnitude properties of earthquake clusters are indicative of the physical processes underlying them. Tectonic clusters have different rate, magnitude, and inter-event statistics compared to swarms triggered by magmatic and non-magmatic fluids, for instance. This component of the project will identify key cluster metrics and produce a quantitative cluster characterization procedure for active continental rifts. These metrics will then be analyzed in combination with surface deformation data from GPS and InSAR surveys to allow quantification of factors such as the seismic to aseismic deformation ratio and the proportion of seismic triggering.

3) Once clusters have been characterized, it is necessary to link their occurrence to the probability of volcanic activity. This component of the project will develop quantitative physical and/or empirical models to link properties of seismicity and surface deformation to the probability of different volcanic phenomena. The work will build on established volcanic hazard methodologies, such as BET_EF, and direct probabilistic forecasts of the timing of eruption will be issued where possible.

6. Please describe how the student's project will contribute to the work of the project as a whole, justifying the importance of their inclusion within the wider project. What arrangements are there for the supervision and support of the student?

This studentship will develop new methodologies for analyzing seismicity and surface deformation data in active continental rifts. The work will be based on geologically analogous areas to the MER that are rich in monitoring data. These methodologies will inform the analysis of MER seismicity in Objective 5, providing better insight into the processes driving seismicity and its links to surface deformation. The new forecasting models will be formulated for operation in the MER and will feed in to the model testing work proposed in O6. This will enable a comparative study to be done with results of the analysis of the MER data described in the main proposal, thereby enhancing the interpretation of both.

The studentship will be supervised in Edinburgh, and the student will visit project partners in Bristol (InSAR, GPS), the British Geological Survey (volcanic hazard), and Southampton (seismicity).

Classification of Proposal

(a) Scientific Area (mandatory)

Assign % relevance (in multiples of 5) to one or more areas, totalling 100%.

Scientific Area	%
Atmospheric	5
Earth	90
Freshwater	5
Marine	0
Terrestrial	0
	Total = 100%

(b) Secondary Classification

Assign % relevance (in multiples of 5) to any areas that are relevant. Otherwise, leave blank.

Scientific Area	%
Co-funded	
Cross-Research Council	
Earth Observation	15
Polar North	
Polar South	
Science Based Archaeology	

(c) ENRI (mandatory)

Assign % relevance (in multiples of 5) to one or more ENRIs, totalling 100%.

Scientific Area	%
Biodiversity	0
Environmental Risks and Hazards	80
Global Change	0
Natural Resource Management	20
Pollution and Waste	0
	Total = 100%

OTHER INFORMATION

Nominated Reviewers

1	Name	Organisation	Division or Department	Email Address

Nominated Reviewers

2	Name	Organisation	Division or Department	Email Address

Nominated Reviewers

3	Name	Organisation	Division or Department	Email Address

Nominated Reviewers

4	Name	Address	Town	Email Address

Proposal Classifications

Research Area:

NERC’s ‘primary’ Research Areas (2nd level) are listed here (Science classification), but other Research Areas can be selected which may relate to other Research Councils. No more than 5 Research Areas should be chosen, with % attributions totalling 100.

To add or remove Research Areas use the links below

Subject	Topic	Indicator %	Keyword
Geosciences	Earth Resources	5	
Geosciences	Geohazards	30	
Geosciences	Hydrogeology	5	
Geosciences	Tectonic Processes	30	
Geosciences	Volcanic Processes	30	

Qualifier:

Qualifiers are terms that further describe the area of research. Please ensure you complete this section if relevant. To add or remove Qualifiers use the links below.

Type	Name
Geographic Area	Africa

Free-text Keywords:

Free-text keywords may be used to describe the science within your application in more detail. These will facilitate reviewer-matching and may form the basis of a more detailed classification in the future.

Add freetext keywords below (50 character max per keyword):

Part 1 - RiftVolc Track record

1. Previous Research Projects

The **Afar Rift Consortium (ARC)**, a £2.5M NERC consortium (2007-2013) carried out the first modern geological, geophysical, and geochemical analyses of the on-land portion of the Red-Sea rift in Ethiopia, in collaboration with US and French research teams. ARC was able to (i) measure and model the deformation and seismicity that occurred during the first major rifting episode of the modern era, building on the successes of NERC urgency funding; (ii) image the magmatic plumbing system that feeds the rift and understand its complex temporal behaviour; (iii) image the detailed structure within mantle beneath Afar and understand its relationship to surface rifting. ARC researchers have published more than 35 papers to date, including 9 in the Nature family. 7 investigators on this project were co-Is or researchers on ARC (*Wright, Whaler, Stuart, Kendall, Keir, Blundy, Pyle*). BGS was a Project Partner (*Vye-Brown*).

By a combination of passive and controlled source seismology, magnetotellurics and gravity, linked to US co-funded geochemical and geophysical research, the NERC-funded **East Africa Geoscientific Lithospheric Experiment (EAGLE)** (2001-3) demonstrated that magma-assisted rifting dominates the evolution of the northern main Ethiopian rift and Afar. Other key results were an asymmetry in structure of the adjacent plateaux, with a ~10km underplate layer beneath the Nubian plate. EAGLE was one of the largest seismic projects ever undertaken by a group of UK Universities. Four investigators on this project were researchers on EAGLE (*Whaler, Kendall, Keir, Stuart*). 27 papers have been published on the project, which have been cited about 1000 times to date.

In recent years, a series of smaller projects have focussed on the central Main Ethiopian Rift making use of NERC facilities and supporting studentships. Geophysical equipment has been provided by **SEIS-UK** (*Kendall*), **GEF-GPS** (*Biggs, Kendall*), **ARSF** (*Pyle, Biggs, Keir*) with **PhD studentships** to William Hutchison (NERC, Oxford, supervised by *Pyle, Mather, Biggs*); Raffaella Fusillo (ERC, Bristol, supervised by *Blundy*) and Matthew Wilkes (EPSRC, Bristol, supervised by *Kendall*).

The success of these projects is in a large part down to the input of Addis Ababa University (IGSSA and Earth Science Department) and Geological Survey of Ethiopia as project partners. Their contribution to the science, impact and logistics is invaluable.

2. Ongoing research projects

The investigators are involved in a wide range of projects that bring added value to the RiftVolc proposal: **Looking into the Continents from Space (LICS)** is a NERC-funded large grant (2013-2018) that will provide high-resolution strain maps for East Africa using radar data from Sentinel-1 satellite (*Biggs, Hooper, Wright*). NERC-funded work with **SERNAGEOMIN** (Chilean Geological Survey) has improved understanding of past volcanic activity in Chile (*Mather, Pyle*). The Oxford group has also contributed to the management of volcanic unrest in Greece (via the Greek Special Scientific Committee for the Monitoring of Santorini Volcano), and advanced understanding of the risks of future Icelandic eruptions to the UK (for the UK Cabinet Office). **VHub** is cyberinfrastructure (VHub.org), which provides knowledge transfer in critical high-priority areas such as hazard assessments (*Calder*). The **Global Volcano Model, GVM**, is a growing international network that aims to create a sustainable, accessible information platform on volcanic hazard and risk (*Loughlin, Vye-Brown, Biggs*). **Streva** is a NERC-ESRC thematic programme researching resilience to volcanic hazard (*Pyle, Loughlin, Mather, Biggs, Smith*). **FutureVolc** is a 26-partner FP7 project, addressing the integration of space and ground based observations for improved monitoring and evaluation of volcanic hazards (*Loughlin, Vye-Brown, Hooper, Ilyinskaya*). **EVOSS** is a consortium of data providers, academic institutions and government bodies whose aim is to develop techniques allowing the monitoring of volcanic hazards on a global scale (*Loughlin, Vye-Brown*)**. PURE** is a NERC thematic programme designed to improve the assessment and quantification of uncertainty and risk in Natural Hazards by developing new methods, demonstrating their applicability and stimulating good practice (*Main, Bell).* **Exploring Failure Forecasting in Real-Time (EFFORT)** developed a real-time forecasting portal for streaming data from volcano observatories in Iceland and El Hiero (*Main, Bell*).

Part 2 - Rift Volcanism: Past, Present and Future [RiftVolc]

1. Summary

Volcanoes display a diverse range of eruptive styles of varying magnitudes, intensities, and frequencies. A key control on eruptive processes is tectonic setting, which determines how magma is generated, the pathways by which it reaches the Earth's surface and the characteristics of eruptions. Although most regional studies of volcanism have been performed on subduction zones, approximately 10% of the world's volcanoes lie in continental rifts (Siebert et al., 2010) mostly in the East African Rift (EAR) System. Despite on-going scientific debate regarding the influence of rift dynamics on volcanism (e.g. Ferguson et al, 2013; Wadge & Burt, 2011; Rooney et al, 2011) and a large exposed population, the EAR volcanoes are under-studied in comparison to their subduction zone counterparts.

RiftVolc will focus on the type example of a continental rift, the central Main Ethiopian Rift (MER), which includes volcanism that ranges from focussed silicic centres, to large basaltic fields (Abebe et al, 2007; Corti, 2008). Recent satellite studies have identified four volcanoes that experienced periods of deformation in the last decade, raising important questions regarding the processes occurring at volcanoes that were previously believed to be quiescent (Biggs et al, 2011; Fig. 1). This knowledge gap suggests two scientific priorities for studies of high-risk volcanoes in populated areas of the EAR: 1) geological, geochemical, petrological and geochronological studies to establish recent volcanic history and 2) geophysical investigations of unrest (Aspinall et al., 2011).

RiftVolc will provide the first record of past and present volcanic behaviour in a continental rift. We will use these observations to determine the factors that control magmatic processes and eruptive styles during rifting, and to develop new methods to assess the associated hazard. The proposal is timely, as complementary international research projects are funded, and major expansions of geothermal power generation capacity are currently underway in the MER. RiftVolc will provide a unified view of volcanism in a rift setting that we expect to set the scientific agenda for decades to come. The development of new methodologies to assess the future hazard associated with such volcanoes will have significant and wide-reaching societal and economic impact and we have detailed our plans to exploit the results with a range of stakeholders.

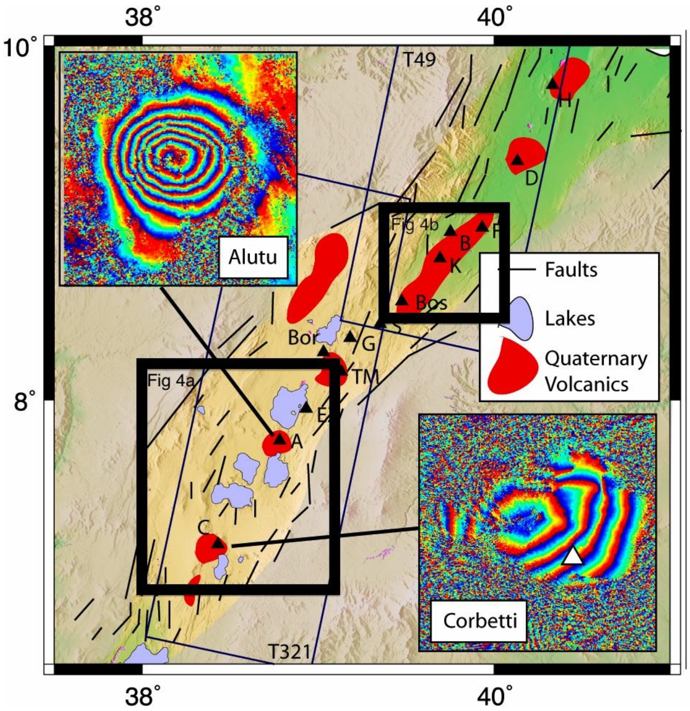


Fig 1: Main Ethiopian Rift. Triangles are volcanoes. Black boxes are locations of RiftVolc activities and are shown in more detail in Fig. 4. H, Hertali; D, Dofen; F, Fentale; B, Beru; K, Kone; B, Boset; S, Sodore; G, Gedemsa; Bor, Bora Berricio; TM, Tulla Moje; EZ, East Ziway; A, Alutu; C, Corbetti. Insets show example interferograms for uplift at Alutu and subsidence at Corbetti. After Biggs et al, 2011.

Outputs

1) the first integrated eruption catalogue for a continental rift, detailing dates, magnitudes, mechanism and chemical characterization of major eruptions and associated flows and cones;

2) combined geophysical and geochemical models of the ascent and storage of melts through an active rift and the influence of along-rift variations in magma supply and tectonic setting;

3) characterisation and statistical analysis of the evolving stress, strain and fluid flow fields around actively-deforming volcanic systems, and comparison with quiescent volcanoes;

4) novel probabilistic analysis of the hazards associated with rift volcanism at both volcano-specific and regional scales, and new statistical methods to assess regional volcanic threat

2. Background and Motivation

2.1 Rift Structure and Magma Supply**:** The Ethiopia-Afar Geoscientific Lithospheric Experiment (EAGLE; see track record) and co-funded projects imaged 3-D variations in crust and upper mantle structure, and characterised the distribution of strain and magmatism across this transitional rift sector thereby providing a snapshot of the lithosphere immediately prior to separation (Fig. 2). Pre-existing models of continental break-up showed that rifting is achieved through a combination of mechanical weakening of the lithosphere by stretching and intrusive heating, and dynamic processes within the asthenosphere (White & McKenzie 1989), but their relative importance was uncertain. EAGLE demonstrated clearly that magmatism-dominated dynamic processes helped to localise strain from a >50 km-wide rift to a ~10 km wide seafloor spreading centre that marks a new plate boundary. EAGLE found abundant evidence of partial melt in the crust and upper mantle, but the series of Recent-Quaternary magmatic segments (QMS) marking the along-axis segmentation was characterised by *higher* seismic velocities and positive gravity anomalies, interpreted as dykes and mafic intrusions fed at depth (rather than by shallow crustal magma chambers) (e.g. Keranen et al., 2004). Although EAGLE provided a regional perspective on the rift itself, the lack of focus on volcanoes and volcanic plumbing systems means fundamental questions remain regarding the shape and extent of the high velocity, high density bodies and their interaction with current and future magma movement, the locus and timescales of magma migration and storage through the lithosphere, and the interaction between magmatic and hydrothermal systems in the upper crust. We also lack constraints on the thickness of the lithosphere, as well as how the mantle lithosphere responds to extension and intrusion by magma.

Key Questions: How and where does magma migrate and accumulate through actively rifting lithosphere? What controls the along-rift variations in rates and amount of magmatism?

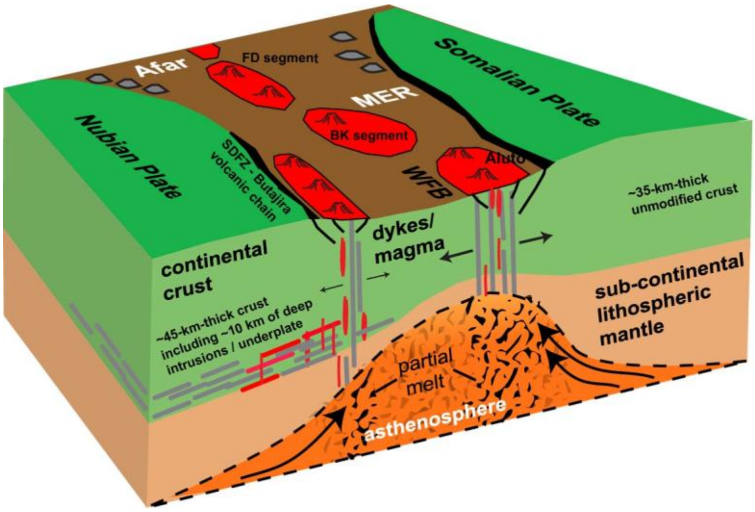


Fig. 2. Structure and processes of the MER as constrained by EAGLE. Strain in the rift over the last ~2 my, focused in the QMS, is accommodated by magma intrusion, both seismically and aseismically (Keir et al., 2006), consistent with predictions from geodetic data. Low velocity anomalies in the asthenosphere are generally offset towards the rift flanks suggesting a control on melting imposed by Miocene – Quaternary lithospheric thinning. After Rooney et al (2011).

2.2 MER Volcanism**:** The MER is the ideal location to explore magmatic rifting as it exhibits a variety of volcanism, ranging from large silicic calderas to basaltic fissure swarms, and from monogenetic cones to off-axis volcanic fields (Abebe et al., 2007; Siebert et al, 2010). Rhyolitic central volcanoes are regularly spaced along the rift axis, and are often located at the intersection with older tectonic structures, especially E–W faults (Acocella et al., 2003). Basaltic volcanic fields (cinder cones and fissures) cover more than 2900 km^2 and include 750 mapped vents (Abebe et al, 2007). Importantly, eruptive histories of the silicic central volcanoes and rift-fed volcanic fields appear to be linked, with mafic volcanism becoming more frequent and less evolved with time as the silicic centres cool and become faulted, allowing basalts to pass through the volcanic edifices and erupt along their flanks (Abebe et al, 2007). Abundant scoria cones and maars occur in linear chains along the western margin of the rift, for example, forming the Silti-Debre Zeyit Fault Zone (SDFZ) (Fig. 2). The associated basalts originate by deep (0.5 GPa) fractionation and are probably transported to the surface through poorly developed magmatic pathways (Rooney et al, 2011).

The spatial and temporal variability of rift magmatism may provide insight into an enduring fundamental question concerning the compositional diversity of erupted magma types. As seen in many rift settings, the central MER volcanoes erupt bimodal magma compositions: basalt and peralkaline rhyolite (Rampey et al., 2010; Rooney et al., 2012). As fractional crystallization of basaltic parents produces a continuum of compositions, the paucity of rocks of intermediate composition - commonly called the Daly gap - has puzzled petrologists for almost a century (e.g., Bonnefoi et al, 1995). This bimodal volcanism, with one mode corresponding to basalt and the other to felsic magmas, contrasts with that of composite volcanoes in the Afar region, which show continuous compositional evolution from basalt to rhyolite via trachyte (e.g. Field et al, 2013). Possible explanations for this difference include variations in magma supply rate, the fertility of the pre-existing crust or the H_2O content of the parent magmas (Melekhova et al, 2013). One objective of our work is to examine the possible control of rifting parameters on the temporal and spatial evolution of compositional diversity along the MER in comparison to other rifts, including Afar and the Kenyan parts of the EAR system.

Key Question: What controls magma composition, and what conditions promote accumulation of large volumes of silicic magma that could fuel major explosive eruptions?

2.3 Eruption and Unrest in the MER: The MER volcanoes have no explicit eruptive history (Siebert et al, 2010) and no permanent monitoring infrastructure (Aspinall et al., 2011). Although there have been several recent eruptions in the Afar region (Nabro in 2011 - Pyle, 2012; Alu-Dalafilla in 2008 - Pagli et al 2012; Dabbahu in 2005-2009 – Ferguson et al, 2010), the only documented, historical eruptions in the MER occurred at either Kone and/or Fentale in the 1820-1830s (Gibson, 1970, Rampey et al, 2010). However, signs of unrest have been observed in the MER using satellite data and temporary networks of seismometers. A satellite survey of the MER spanning 1997-2010 detected deformation at 4 volcanoes: Alutu, Corbetti, Haledebi and Bora (Fig. 1), but from the deformation pattern alone it is not possible to determine if the source is magmatic or hydrothermal. During 2001-2003, the EAGLE project network (Fig. 5) detected 42 local earthquakes ($0.7 \le M_L \le 2.9$) around Alutu (Keir et al. 2006) and in 2011-2012 a dense seismic network focused on Alutu detected > 1000 events ($0.8 \le M_L \le 3.5$) (Kendall et al unpublished data). These observations suggest a shallow (<10 km), frequently replenished zone of magma storage beneath volcanic edifices within the rift axis and add to the growing body of observations that indicate shallow magmatic processes operating on a decadal timescale are widespread.

Key Questions: How is magma interacting with the crust, hydrothermal systems and groundwater on its way to the surface, and what are the results of this interaction? Why are some volcanic edifices in a state of unrest and others not? Is the unrest warning us of magma movement and an imminent eruption in this populous region?

2.4 Hazard and Exposure. The volcanic threat analysis of Simpson et al. (2011), which ranks volcanic threat according to a series of discrete categories, was recently extended to Ethiopia (Aspinall et al, 2011). A high level of uncertainty was assigned to the 49 Ethiopian volcanoes (Fig. 3) that lack eruptive histories, including five in the RiftVolc area (Table 1). The population exposure of many of these volcanoes is also high: forty million people live within 100 km of a volcano (roughly half of the total population of Ethiopia), one million live within 10 km and, to give an example of a specific hazard, ~4 million people live in regions at risk from pyroclastic flows. Multi-billion dollar investments from organisations such as the World Bank are driving a 10-fold expansion in the geothermal industry in the EAR over the next decade. In Ethiopia, the 7MW plant at Alutu-Langano (Fig. 1) is expanding to 70MW, and a 1000MW plant has just been commissioned at Corbetti volcano (see Project Partner Letter). However, locating major infrastructure on volcanic edifices poses inherent risks. In Iceland, geothermal drilling intercepted shallow magma, and water re-injection, like fracking, can trigger earthquakes (Brodsky and Lajoie, 2013).

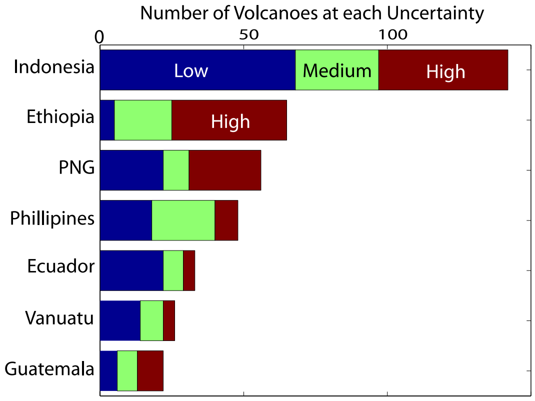


Figure 3: Number of volcanoes at each uncertainty level (Aspinall et al, 2011). Almost all of Ethiopia’s volcanoes fall in the highest uncertainty level (red, 3), and Ethiopia has almost as many high uncertainty volcanoes as Indonesia.

The 2011 Nabro eruption serves as a timely reminder of both the lack of information and potential risks of volcanic activity in this region. Situated on the Ethiopia – Eritrea border, the area is remote and sparsely populated, yet the eruption caused 32 fatalities, displaced >5000 people and disrupted regional aviation. Previous eruptions from Nabro have neither been dated nor subject to any detailed petrological study, despite a prominent caldera and associated ignimbrites (Wiart and Oppenheimer, 2004). The regional network detected a brief period of heightened seismicity before the eruption, but the volcano itself had no monitoring programme. Had this eruption originated from one of the broadly similar target volcanoes in the densely populated MER, the humanitarian and societal cost would have been considerable.

Key Questions: What triggers an eruption? Which monitoring parameters are required for effective and timely short-term forecast? What is the best approach to make effective long-term volcanic hazards forecasts at different scales? What is the susceptibility of hydrothermal systems to destabilisation by drilling and/or water extraction?

2.5 Target region: East Africa is the type example of a continental rift, and at this time, the central MER (Figs. 1, 4) is the ideal location to study rift volcanism because:

1) It lies at the transition between rift basins with isolated volcanic systems and focussed magmatic segments, and displays a wide range of magmatic and volcanic behaviour from silicic centres to basaltic fields (Abebe et al, 2007).

2) The area is densely populated; each of the 9 volcanoes in the area is estimated to threaten >300,000 people (Table 1; Aspinall et al, 2011).

3) Satellite studies have identified unrest at several volcanic centres, motivating ground-based investigation of the processes responsible (Biggs et al, 2011).

4) Ethiopia’s nascent geothermal industry is rapidly expanding with new geothermal wells being drilled at 2 volcanoes, both of which are in a state of unrest.

5) We have strong a track record of research in Ethiopia and a good regional knowledge base. Invaluable collaborations, detailed in the track record, include our Ethiopian project partners, international consortia, industry links, and existing data and results from previous NERC-funded projects. NSF is just beginning a major complementary research programme in the EAR.

6) The area has good transport and infrastructure, and is one of the most secure in Ethiopia, enabling us to conduct a safe and cost-effective field programme.

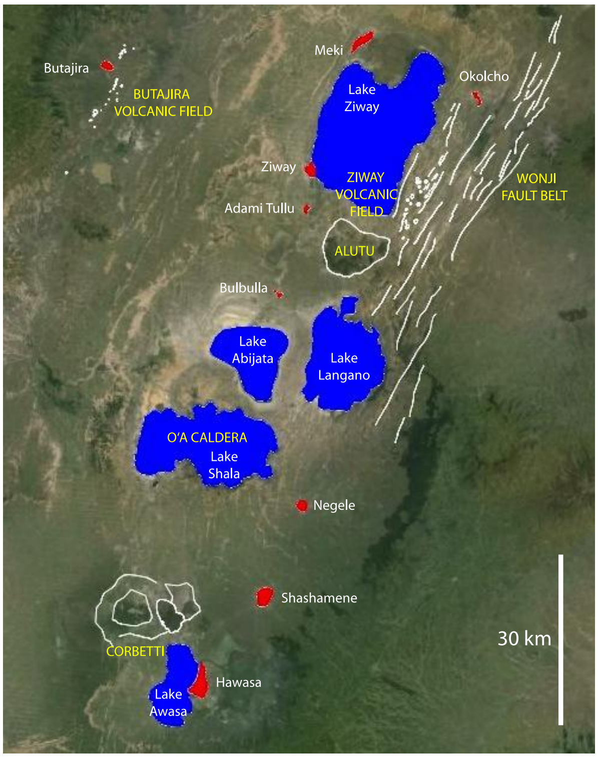
7) There is an existing research framework on which we can build. Widespread melt supply in the mantle was documented by the EAGLE project (Bastow et al, 2011), and RiftVolc will focus on the magmatic pathways through the lithosphere and crust and their relationship to eruption mechanism. Dating of Hominin fossils has provided a detailed chronology for eruptions in the age range of 1-6 Ma (e.g. Beyene et al., 2013); RiftVolc will focus on the eruption record from the last <1 Ma, which is of greater relevance for hazard assessment.

	Alutu	**Corbetti**	**E. Zway**	**O’a**	**Butajira**	**Kone**	**Boset**	**Fentale**	**Beru**
Hazard	Medium	Medium	Low	Medium	Medium	Medium	Medium	Low	Low
Uncertainty	High	High	Medium	High	Medium	High	High	Medium	Medium
Population	High	High	Medium	High	High	High	High	High	Medium
Monitoring	Zero	Zero	Zero	Zero	Zero	Zero	Zero	Zero	Zero

Table 1: The hazard, uncertainty, population exposure and monitoring levels at the volcanoes of the central MER (after Aspinall et al, 2011).

Fig. 4a shows the RiftVolc primary focus area: Alutu and Corbetti are actively deforming silicic volcanic centres (Fig. 1) composed of abundant obsidian lava flows, pyroclastic-flow and pumice-fall deposits with structurally-controlled cinder cones, lava domes, tuff cones, phreatic explosion craters, and thermal springs. East Zway and Butajiri-Silti volcanic fields are composed of hundreds of structurally-controlled basaltic cinder cones, and lava flows. The petrological and eruptive characteristics of the Butajiri-Silti field on the western flank are strikingly different to those on the rift floor, suggesting a deeper magma origin (Rooney et al, 2011).

Satellite images of the area to the north (Fig. 4b) show no signs of deformation (Biggs et al, 2011), but a combination of seismology, magnetotellurics (MT) and gravity during the EAGLE project documented partially molten, gabbroic bodies beneath Boset (Cornwell et al., 2006, Whaler and Hautot, 2006), and Fentale and Kone erupted in the early 19th century (Rampey et al, 2010), providing further evidence for the complex relationship between past eruptions, current unrest and future hazard. Boset is a composite rhyolitic-to-trachytic volcano with very recent pantelleritic obsidian fissure-fed lava domes and flows. Fentale is a large stratovolcano constructed of rhyolitic obsidian lava flows; the Kone volcanic complex comprises a series of silicic calderas, accompanied by ignimbrite outflow sheets and young basaltic cinder cones and lava flows. Regional comparison will be achieved through existing studies (e.g. Afar Rift Consortium (ARC)), new international projects (e.g. GeoPRISMS, Intercontinental Drilling Program) and PhD projects (linked and external). Additionally, as insight into active tectonic and volcanological processes is often advanced by responding to events as they evolve, we aim to keep the flexibility to react to changing situations in the region, and would apply for additional support from urgency grants if appropriate (for example, dyking events in Afar, new unrest or eruptions).



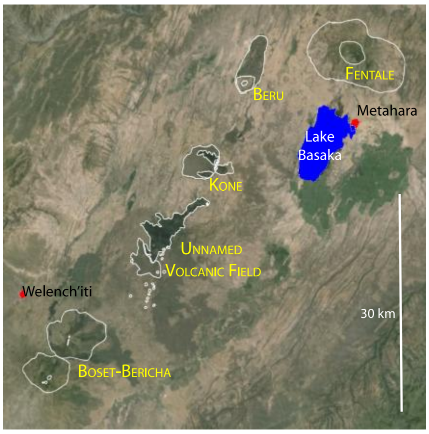


Figure 4a) (Left) The RiftVolc primary area, which includes two large silicic centres (Alutu and Corbetti), Ethiopia's largest caldera (O'a), and both on-axis and off-axis monogenetic fields (East Zway and Butajira). b) (Right) The RiftVolc extended area, which includes the 19th century eruptions at Fentale and Kone, basaltic volcanic fields and the partially molten gabbroic body under Boset (Cornwell et al., 2006, Whaler and Hautot, 2006). See Fig 1 for box locations.

3. RiftVolc Aims and Objectives

Aims

1) *High-quality observations.* We will produce the first eruption history of volcanism in a magmatic continental rift, detailing the timing, magnitude, style and composition of Holocene - Recent eruptions and the current state of activity of volcanic systems.

2) *Processes and mechanisms*. We will integrate geophysical, geochemical and structural information to differentiate between competing models of magma movement through rifted lithosphere and the diversity of eruption styles as magma moves past and along faults and through the water table to the surface.

3) *Hazard assessments and forecasts*. As our understanding of past eruptions, current behaviour and the processes responsible grows, we will develop methodologies for short and long-term forecasting at volcano and regional scales.

4) *Economic and societal impacts.* With stakeholders we will establish likely future unrest and eruption scenarios and design tools to aid decision-making under uncertainty.

To achieve this, we have brought together a team of scientists, international collaborations and industry partners that can make significant impact alongside major international initiatives such as the NSF-funded GeoPRISMS. We propose three linked, multi-disciplinary work packages:

Past*:* What has driven eruptions over geological timescales?

Investigate by establishing an eruption chronology, identifying the petrological drivers of the diverse eruption styles, and examining historical archives (Objectives 1-3)

Present: What controls the active magmatic system and volcanic unrest?

Investigate by an extensive field programme quantifying the geophysical and geochemical parameters relevant to present-day unrest, identifying the active processes and their relationship to magmatic and geothermal activity, and undertaking numerical modelling of coupled magmatic and hydrothermal systems (Objectives 4-5)

Future: What are the potential threats from future volcanic activity?

Test short-term eruption forecasting through analysis of past and present monitoring data. Develop probabilistic hazard methodologies and assessments at a specific volcano centre and at a regional scale. Use novel statistical methodologies to analyse the revised Holocene eruption history and establish the effect of uncertainty on long-term eruption forecasts (Objectives 6-8)

Specific Objectives
O1: Constrain the timing and magnitude of Holocene to Recent volcanism.
O2: Understand magmatic controls on eruption style at the central volcanoes.
O3: Determine the links between eruption style and climate/hydrology.
O4: Define the role active rifting plays on magmatic plumbing systems and volcanism.
O5: Characterise the spatial and temporal variations in stress and strain associated with magmatic, hydrothermal and fault-related processes at the silicic volcanic centres.
O6: Quantify the state of unrest from geophysical data.
O7: Develop probabilistic assessment methods to fully characterise key volcanic hazards at a high risk central volcano.
O8: Develop a regional analysis of ash fall hazard and assess the long-term volcanic threat, incorporating the inherent uncertainty.

4. Past: *What has driven eruptions over geological timescales?*

As discussed above, the MER is the most extensive continental volcanic field in the world. The rift's numerous large silicic calderas must have erupted multiple times during the late Quaternary (Pyle, 1999; Rampey et al, 2010) and it contains extensive fields of young cones and lava flows, as well as craters produced during violent phreatomagmatic eruptions. However, little is known about the eruption histories of these volcanoes over the past million years (Siebert et al, 2010). This work package will build on our current projects developing initial geological maps of Alutu and Corbetti (Hutchison and Fussillo PhDs in collaboration with scientists from Addis Ababa University (AAU)), using field surveys and NERC ARSF overflight data (November 2013), to deliver a step change in our understanding of the eruptive history of MER volcanoes. Previous work (e.g., Rampey et al., 2010; Rooney et al., 2012) has also identified some intriguing features of the geochemistry of the products of MER volcanism with hazard implications. This is both in terms of the compositional Daly Gap outlined above and the origin and eruptive style of the unusual peralkaline rhyolite magmas that characterize large explosive eruptions in this region. In this region past climates may also have played a key role in terms of determining eruptive style (e.g., extent of phreatomagmatic activity). Combining a new determination of the geological record of MER volcanism over ~1Ma with an understanding of the processes controlling eruption will allow this work package to make significant scientific advances in our basic understanding of rift volcanism as well as a powerful contribution to understanding future volcanic hazards in the MER in the context of RiftVolc.

Objective 1: Constrain the timing and magnitude of Holocene to Recent volcanism

Previous work on ancient tephra deposits in the EAR has focused on the age range of 1-6 Ma, because these deposits are interstratified with the rift sediments that contain Hominin fossils and frequently contain fresh sanidine (K-feldspar) crystals that can be precisely dated. As a consequence, there is a detailed chronostratigraphy for some parts of the rift (including parts of the Awash valley at the northern end of the MER, from 0.7 – 3.5 Ma; and parts of southern Ethiopia, from 0.7 – 2 Ma; Pyle, 1999; Campisano and Feibel, 2008; Beyene et al., 2013). No attempt has been made, however, to link individual tephra units to their volcanic sources, neither is there a chronostratigraphy for the volcanic units along the MER. In contrast, glass chemistry and age have been used successfully to correlate Plio-Pleistocene (1 – 2 Ma) tephra deposits from the Konso, Omo and Turkana basins (WoldeGabriel et al., 2005) to the south of our study area. The compositions of distal tephras from this region overlap with the compositions of products erupted from the MER caldera volcanoes (including Alutu, Gademota and Awasa), but the individual distal tephra layers cannot be related to proximal eruptive deposits without improved knowledge of the ages and eruptive histories of these volcanoes (e.g., Rooney et al., 2012). There are virtually no constraints on other eruption-related hazards from this area, including the frequency and extent of pyroclastic flows associated with silicic explosive eruptions, the occurrence of phreatomagmatic explosions, or the nature of associated effusive activity.

We will carry out targeted fieldwork to establish the eruptive history of major MER caldera volcanoes between Corbetti and Fentale, and their distal tephra. We will acquire suites of samples of peralkaline rhyolite from the large caldera volcanoes - Gedemsa, Kone and Fantale - where shallow, large-volume magma chambers exist. Analysis of airborne and satellite hyperspectral images and digital elevation models, combined with whole-rock geochemical analyses will enable us to calculate areas (and volumes) of different extrusive compositions. Together, this will provide important information about the temporal and spatial variability of ash, gaps in the stratigraphic record caused by burial or erosion, and the potential for any one location to be affected by ash fall from a number of volcanoes. Field observations will constrain inundation areas, volumes, thicknesses, and lengths for both pyroclastic density currents (PDCs) and lava flows. We will assess the relationships between PDCs and topography and map their welding characteristics, and preservation. Lava flows will be mapped by vent location; the spatial extent of individual lava flows will provide information on effusion rates, emplacement mechanisms, cooling, and channelization (e.g. Hon et al, 1994; Keszthelyi and Self, 1998; Cashman and Mangan, in press). We will apply empirical models (e.g. Sparks 1986) and inversion techniques (e.g. using TEPHRA2: Connor and Connor, 2006) to derive and test eruption parameters. This will allow us to produce a fully-quantitative eruption database with, for example, magnitude, grain size distribution, column height, flow runouts and associated uncertainties. This in turn means we will be able to run numerical and analytical models under O7, in contrast to the global eruption catalogue (Siebert et al, 2010) which relies on qualitative, text-based information and semi-quantitative measures such as Volcano Explosivity Index (VEI).

Objective outputs:

- The first age model for Holocene-Recent eruptions in a continental rift based on correlation between distal tephrochronology horizons and proximal deposits using geochemical characterisation and Ar-Ar dating of key eruptive units.
- Quantification of eruption magnitudes and determination of frequency-magnitude relationships for explosive eruptions from volcanic centres in the MER.
- A quantitative database of eruptions and their products, and source parameters and uncertainties on which to base analytical modelling (objectives 7 & 8).

Objective 2: Understand magmatic controls on eruption style at the central volcanoes

Existing evidence suggests that Pliocene to Quaternary volcanism in the MER has been dominated by the eruption of silicic magmas from central volcanoes with large summit calderas (e.g., Gedemsa, Kone and Fantale), with associated ignimbrites and pumice- and ash-fall deposits (Rampey et al., 2010). Effusive eruptions are less common and basaltic products are volumetrically subordinate. The peralkaline rhyolites (pantellerites and comendites) that drive the large explosive eruptions in this region are extremely rich in iron, alkalis and halogens (Rooney et al., 2012). These unusual compositions are frequently observed in continental rift settings and are thought to be derived from basalts by extreme (>95%) fractional crystallization (e.g. Scaillet and Macdonald, 2003). Their composition gives them unusual rheological properties - high density and a viscosity more than 3 orders of magnitude lower than calc-alkaline rhyolites (Di Genova et al., 2013) - that, along with the total volatile content, determines eruptive style.

A key goal of this objective is to explore conditions that could generate a large eruption from a central MER volcano. To address this problem, we will (1) constrain conditions of magma storage using petrologic methods and melt inclusion analysis (e.g., Blundy and Cashman, 2008; Putirka, 2008), (2) address conditions of magma ascent and gas evolution by analyzing both crystal and vesicle textures of previously erupted material, and (3) relate both sets of observations to the volume and extent of the products of past eruptions. Of particular interest are eruptions of low viscosity pantellerite magma. There has been no opportunity to observe an explosive eruption involving pantellerite magma and so we have little understanding of how such an eruption might be triggered, how it might develop, and the accompanying volatile release. The magmas are rich in volatiles (e.g. Neave et al., 2012) and a large eruption is likely to be associated with significant gas release, which has potential for regional or global climate effects. Associated pyroclastic and lava flows will have unusual rheomorphic properties that will affect the style of both transport and deposition and the resulting areas of inundation.

By integrating field observations, petrology and geochemistry (from the literature and O1 and O2 outputs) with tectonic information and thermal models using approaches that we have applied in the Afar (e.g. Field et al., 2012, 2013; Ferguson et al., 2013), we shall assess critically the different possible causes of compositional bimodality seen in the MER (e.g. Melekhova et al, 2013). Insights from melt inclusion geochemistry will be particularly valuable for identifying whether compositionally intermediate liquids exist.

Objective outputs:

- Characterisation of magma sources and ascent conditions in a magmatic rift based on the major, trace and volatile elements of melt inclusions. New insights into geochemical variations of magma composition along the rift by comparison with existing data from Afar and the Kenyan Rift.
- New models of the fragmentation of silicic peralkaline magma based on the physical characteristics of pyroclasts using a combination of porosity and grain size distributions, SEM analysis of clast shapes and surface textures, and detailed 3-D analysis using high resolution X-ray tomography.
- Reconstruction of the conditions of pre- and syn-eruptive degassing and crystallization from combined textural and geochemical data.

Objective 3: Determine the links between eruption style and climate/hydrology

The central MER hosts several significant lakes, including Ziway, Langano and Shala, which lie close to the central volcanic edifices of Alutu and Corbetti. These lakes developed during the late Pleistocene, and are closed basins that show considerable variations in lake level (~40 – 80 m) and areal extent through the late Pleistocene and Holocene (Gillespie et al., 1983; Benvenuti et al., 2002, 2013) because of changes in climate (rainfall), tectonics (faulting), magma supply and eruptive deposition. Lake chemistry shows the strong imprint of volcanic degassing and hydrothermal exchange (in Sr, O and H stable isotopes; e.g. Rango et al., 2010), and the temporal record of these interactions can be extracted from the compositions of lacustrine shells preserved in ancient strandlines, raised beaches and lake sediments (Benvenuti et al., 2013). Since climate fluctuations control the areal extent of lakes, and by extension, the probability that distributed volcanic vents will intersect either surface or shallow groundwater, we would expect both the likelihood of explosive phreatomagmatic eruptions also to be strongly climate-controlled. The history of these interactions in the past will be preserved in both the age and distribution of tuff rings and cones within the MER, and in tephra records of the lacustrine sediments. If we can demonstrate links between past climates and phreatomagmatic activity, then future hazards from phreatomagmatism may be deduced from regional-scale climate models.

We will sub-sample lacustrine sediments at high resolution to identify visible and cryptotephra tephra layers produced by small to medium-scale late Pleistocene and Holocene eruptions; for example, a 12.6 m core from Lake Abiyata spans 13,000 years and contains at least 9 tephra layers (Chalié and Gasse, 2002). We will determine magma fragmentation conditions (i.e. phreatomagmatic or not) using 2-D and 3-D SEM analysis to define external pyroclast shape and internal texture; quantitative shape analysis and surface area measurements will be made using Mex Software (e.g., Mills and Rose, 2010).

Objective outputs:

- A new tephrostratigraphy for the rift based on analysis of deposits from selected tuff cones and lacustrine sediments.
- Evaluation of the relationship between phreatomagmatic activity and climate fluctuations based on magma fragmentation conditions over time.

5. Present: *What controls the active magmatic system and volcanic unrest?*

EAGLE and associated projects provided an excellent definition of the structure, properties and evolution of the crust (e.g. Mackenzie et al., 2005), and upper mantle at depths of below ~75 km (Bastow et al., 2005, 2008; Benoit et al, 2006; Hammond et al., 2013). Alutu and Corbetti are the sites of recent geophysical investigations including: Seismic networks on Alutu and Corbetti (M. Kendall; Seis-UK); GPS networks on Alutu and Corbetti (J. Biggs; GEF); MT on Alutu (A. Jackson; ETH-Zurich) and Corbetti (Reykjavik Geothermal); and a soil-CO_2 study of Alutu (W. Hutchison, Oxford PhD student). However, our knowledge of structure, deformation style, melt volumes and magma pathways in the mantle lithosphere between the base of the crust and melt generation zone in the asthenosphere at ~75 km is poor and little is known about the activity of the shallow magmatic and hydrothermal systems beneath the volcanoes; 'bridging these gaps' will be a focus of our investigation.

Objective 4: Define the role active rifting plays in magmatic plumbing systems and

volcanism

The lithospheric structure of the tectonically and magmatically active MER is a critical starting point for understanding the drivers, controls and processes involved in its volcanism. Previous geophysical and geochemical studies have defined some of the key features, such as the relative importance of magmatic and tectonic strain in localising extension (Ebinger and Casey, 2001; Keir et al., 2006; Rooney et al., 2011) and weakening the lithosphere (Ebinger and Hayward, 1996, Ebinger, 2005). We will deploy a network of seismometers and carry out an electromagnetic survey in the MER. By combining geophysical and petrological results, including those from legacy data, we will constrain independent physical parameters that indicate composition, amount and arrangement of melt, and how, and how quickly, it migrates from where it is generated to crustal reservoirs. In addition, analyses of variations in stress and strain at zones of tectonic faulting and magmatism conducted for O5 will help characterise the interaction between extensional processes and magmatism.

We will use the LiCS strain rate map (see track record) produced from Sentinel-1 satellite data by the method of Wang & Wright (2012) to define the rift-scale plate velocity field and to quantify the extent to which strain is localised on either the border faults or magmatic centres. We will deploy a network of 25 seismic stations at 10-15 km station separation covering major rift axial fault and aligned cone systems, as well as border faults (Fig. 5). Local earthquake arrival times will be used to invert jointly for earthquake locations and the seismic velocity structure of the mid-upper crust (e.g. Daly et al., 2008). Specifically, the velocity of P-waves as well as the ratio between P- and S-wave speeds (Vp/Vs) will help us to interpret spatial variations in rock composition and fluid content caused by, for example, magmatic intrusion (e.g. Daly et al., 2008). Ambient noise, and teleseismic surface (Rayleigh) - wave tomography will constrain S-wave velocities in the crust and mantle to depths of ~75 km, providing key constraints on magma pathways from the melt zone through to the crust (e.g. Wang et al., 2009). Modelling of teleseismic receiver functions will also constrain Vp/Vs of the crust and will supplement modelling of azimuthal variations in speed of local to regional surface (Rayleigh and Love) waves to constrain type and orientation of anisotropic fabrics through the lithosphere (e.g. Bastow et al., 2010), and thereby help distinguish melt arrangements such as sills or dykes.

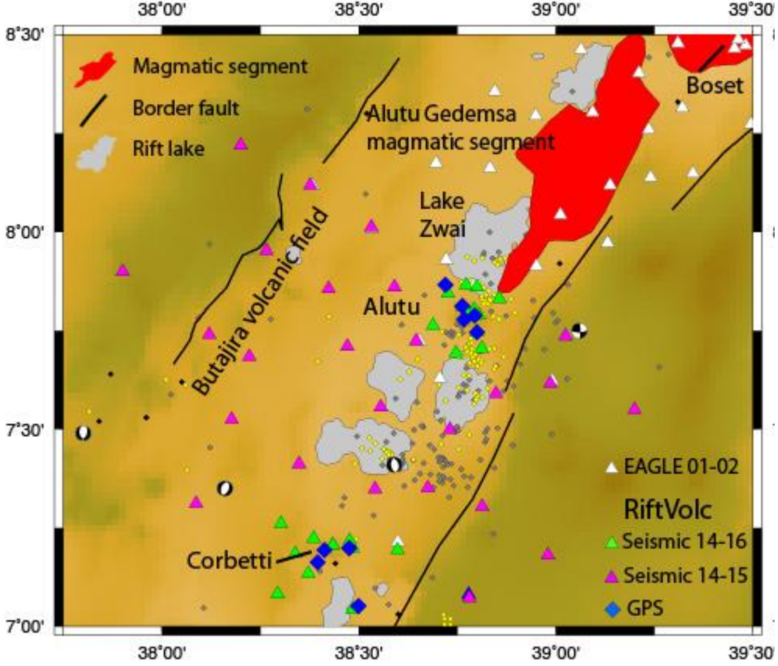


Fig 5. RiftVolc Field Deployment. Purple triangles: seismic stations deployed 2014-2015 (20 x Guralp ESPs & 5 x 6TDs). The green triangles form two nested arrays surrounding Aluto and Corbetti volcanoes and will be deployed 2014-2016 (25 x Guralp 6TDs), with four of the stations set up to transmit data real-time to the existing seismic hub in Addis Ababa. Blue diamonds: GPS stations for 2014-2019. Project Partners have carried out MT surveys at Alutu and Corbetti, and RiftVolc will deploy additional sites co-located with the seismic stations. Quaternary-Recent magmatic segments are red, rift lakes are grey and border faults are black lines.

We will collect broadband magnetotelluric (MT) and vertical component magnetic field (i.e. MT/GDS) data and transient electromagnetic (TEM) data, co-located with or near to the broad deployment seismic stations, and at higher density over the Butajira volcanic field/SDFZ and Wonji fault belt, supplementing the focussed MT surveys at Alutu and Corbetti and the EAGLE MT profile to the north (Whaler and Hautot, 2006). The ~40 new broadband sites will probe to the uppermost mantle; in addition, long period data, penetrating to magma generation depths, will be collected at

~10 sites. The MT/GDS data will be robustly processed (e.g. Chave and Thomson, 1989), and analysed for dimensionality and directionality on a site-by-site and period-by-period basis. Basic indications of sub-surface resistivity structure (e.g. GDS induction vectors point towards conductors, here expected to be associated with magma reservoirs and migration, geothermal fluids, and geothermal alteration of clay) as a function of period (a depth proxy) will inform 2-D and 3-D (possibly anisotropic) resistivity modelling of the MT/GDS data, with TEM data constraining distortion (Sternberg et al., 1988). Petrological analyses performed under O1 will provide the compositional data needed to determine melt conductivity to interpret resistivity models in terms of partial melt fractions and total melt volumes. Combined petrological modelling, and imaging S-wave velocity variations of the upper 75-km, will constrain the link between lithospheric thinning, mantle potential temperatures and degree of melting.

Objective Outputs:

- 3-D structure and compositional variations of an active magmatic rift based on spatial patterns of seismic P-wave velocities (Vp).
- Identification of the locus of melting and quantification of melt-volumes in a magmatic rift based on S-wave velocities (Vs), Vp/Vs, and electrical resistivity, which are all sensitive to fluids.
- New geophysical insights into variations in magma location, storage and transport along the rift by comparison with existing data from Afar and the Kenyan Rift.

Objective 5: Characterise the spatial and temporal variations in stress and strain associated with magmatic, hydrothermal and fault-related processes at the silicic volcanic centres

Deformation has been observed at many of the silicic centres of the MER (Fig. 1), but the processes driving it are unclear (Biggs et al, 2011). Although volcanic deformation is often linked to eruption, shallow magma storage can also lead to unrest. Spatial and temporal variations in seismicity, deformation and gravity are key to understanding the evolving stress, strain and fluid flow fields. We will deploy 25 broadband seismometers in focussed networks at Alutu and Corbetti volcanoes for 2 years. Ambient noise will enable measurement of temporal variations in Vs caused by the evolving magmatic and hydrothermal systems (Brenguier et al, 2008). Earthquake locations, moment tensors, magnitudes and magnitude-frequency relationships, shear-wave splitting, and their variations through time will characterise the stress field (e.g. Miller and Savage, 2001; Roman et al., 2008). We will apply earthquake cluster identification methods based on model-independent inter-event time and distance statistics (e.g. Jacobs et al., 2013) and analyze the diagnostic metrics such as rate, magnitude, inter-event, and moment tensor statistics of clusters. The results will be used in O6 as the underpinning of seismicity-based time-dependent models of unrest.

We will deploy 9 cGPS stations clustered at Alutu and Corbetti to give a daily 3-component position vector at each site, and combine with time series analysis of InSAR images from the TerraSAR-X and Sentinel-1 satellite missions to give a detailed spatial map of the deformation pattern (e.g. Biggs et al, 2010). Microgravity will be measured at 6 monthly-intervals at ~10 benchmarks across Alutu covering the region of active deformation. Residual gravity changes will be inverted to deduce mass and density changes occurring at Alutu. This will provide insights into the nature of processes behind the deformation and will allow us to discriminate between magmatic and aqueous drivers of unrest (e.g. Battaglia et al, 2008). We will re-occupy two of the quietest MT sites from the existing survey at Alutu. If the phase data and the shape of the apparent resistivity data curves shows evidence of temporal variability that could be associated with magmatic processes (e.g. Aizawa et al., 2011), we will run the sites continuously for the duration of the field programme.

The seismic analysis will be integrated with the outputs of the deformation studies to determine the ratio of seismic to aseismic deformation and identify any viscoelastic contributions to the deformation field (e.g. Newman et al, 2006). Spatial variations in Vp and Vs will be used jointly with seismic anisotropy and resistivity structure to quantify locus, shape, and volumes of fluids (e.g. Dessisa et al., 2013; Keranen et al., 2009). From subsets of the MT/GDS data with consistent and well-defined directionality (McNeice and Jones, 2001), we will compare electrical and seismic anisotropy. Petrological and thermal models (e.g. Annen et al. 2006) will be combined to assess the role of phase changes associated with cooling and crystallisation of the magmatic system (Carrichi et al, in review). Models of steady-state fluid flow in a porous medium above a heat source will be perturbed by changes in source temperature, local and regional permeability and topography to assess the spatial and temporal response of the hydrothermal system to magma input, dissolution and exsolution of hydrothermal minerals, deformation and extraction (e.g. Wicks et al, 2001). Fluid flow along fractures alters the stress field and causes slip on the fractures themselves (Hooper et al, 2011). Boundary element models will be used to test the interactions between pressure sources and fractures and the combined contribution to the overall deformation. The parameter space for these forward models will be defined using the geophysical and petrological observations from O1-5, and the outputs, namely the spatial and temporal response of the stress and strain fields, will be compared to the detailed patterns of deformation and seismicity.

Objective outputs:

- A 4-D characterisation of the evolving stress, strain and fluid flow fields around the actively-deforming rift volcanoes based on detailed temporal and spatial patterns of seismicity (location, magnitude, focal mechanism), deformation, resistivity and gravity changes.
- Testing of conceptual models of the spatial and temporal response of the magmatic and hydrothermal systems to perturbations against detailed observations using a variety of modelling approaches.

6. Future: *What are the potential threats from future volcanic activity?*

Current understanding of volcanic hazards and risk is largely derived from our knowledge and experience of activity in arc and intra-plate oceanic settings. Continental rift settings, where both effusive and explosive volcanism occur from fissure swarms, volcanic fields, calderas and stratovolcanoes, pose a suite of challenges, such as determining the threat posed by large magnitude explosive eruptions and their associated hazards in rift settings, particularly in the EAR (Aspinall et al. 2011). Towns and cities in the volcanic EAR areas are rapidly being developed with little knowledge of, and no regard for, the long-term risks posed. An improved understanding of the evolution of volcanic systems in the MER obtained through O1-5 will provide the foundation on which probabilistic methods to assess and forecast volcanic hazards will be based. Assessments will be required at different scales: short- and long-term; from volcano-specific to regional to national; and from high-risk central volcanoes to active rift segments and volcanic fields. There are clear elements that the setting provides, such as dominant structural controls and unusual compositions, that will enable a unique set of hazard assessment and forecasting approaches to be developed.

Objectives 6-8 will address critical science questions in four areas: 1) quantification of the state of unrest and effective short-term forecasting based on geophysical data, 2) development and investigation of a fully probabilistic multi-hazard methodology and long-term forecasts at a single volcano-scale, 3) investigation and sensitivity analysis of probabilistic ash fall hazards assessments at MER and national-scale, and 4) use of statistical methods, analogues and elicitation in assessing uncertainty in volcanic eruption datasets, hazards assessments and forecasting.

Objective 6: Quantify the state of unrest from geophysical data

Changes in the spatial and temporal patterns of seismicity and deformation are key indicators of the state of volcanic unrest, and provide a primary basis for short-term forecasts of volcanic activity (Marzocchi & Bebbington, 2012). Using central MER volcanoes as case studies and using data collected in previous objectives, we will characterise the background hazard rate and its fluctuation, and develop objective methods for separating tectonic and volcanic processes. We will develop algorithms for identifying objectively the state of unrest as anomalous relative to this background, based on past data from the MER, as well as on synthetic data (Bell et al., 2013, Biggs et al, in review). This will include a retrospective analysis of the Alutu region, already identified as being in a state of unrest, as well as examples of periods of unrest that ended without an eruption (e.g. Corbetti 1997-2000, Biggs et al, 2011). We will integrate several kinds of time-dependent data and associated modelling – including identifying earthquake clustering (Jacobs et al., 2013), defining triggering probability (Amitrano & Helmstetter, 2006), and testing the power of failure-forecast models to detect and explain any periods of accelerating strain (Voight, 1988). We will examine data from the dense, temporary seismic network to demonstrate the potential of such monitoring capabilities, but also look at ways of quantifying unrest from satellite data and regional networks. By comparing summed seismic moment tensors with InSAR and GPS data, we will be able to quantify changes in the ratio of seismic to total strain associated with periods of unrest. This will be done in 'pseudo-forecasting' mode in the web portal being developed in the NERC ‘EFFORT’ project, so that the system is also ready operationally within or after the project for application during any future period of unrest. This will include quantification of uncertainty in the assessed probabilistic hazard, informed by the NERC 'PURE' programme.

Objective Outputs:

- Statistical forecasting models for volcanoes experiencing decade-long unrest without eruption.
- Algorithms for identifying objectively anomalous behaviour based on definitions of 'background state' from on geophysical monitoring.
- Tests of multiple hypotheses for forecast probability and associated forecast quality.

Objective 7: Develop probabilistic forecasting methods to fully characterise key volcanic hazards at a high-risk volcano

Simulation tools can be applied stochastically to characterise and assess specific hazards including lava flows, PDCs and tephra fallout (IAEA 2011; Connor et al 2012). We will develop probabilistic multi-hazard assessment methods for both central volcanoes and volcanic fields. We select volcanic centres that have high population exposure, recent activity (eruptions, deformation or hydrothermal activity; Biggs et al 2011), and represent contrasting styles of historical activity to optimise probabilistic forecasting methodologies for a range of eruptive scenarios. We will focus on *Corbetti* to develop probabilistic multi-hazard assessment methods at a peralkaline volcanic centre; the *Butajira* volcanic field to develop models of lava flow inundation, computation of the probability of a vent opening and the occurrence of phreatomagmatic activity, and the Manda-Hararo rift segment for the spatial relationship of fissure vents in a rift setting (Vye-Brown et al 2012; Ebinger et al., 2010). Fieldwork and analysis in O1 will be used to define the probability distributions such as frequency-magnitude relationships for each hazard required for computer models (such as Tephra2, Connor and Connor, 2006; TITAN2D, Patra et al,. 2005.). Uncertainty in vent/fissure location for future eruptions can be estimated using random sampling of a spatial density model given the location of past eruptive activity (Connor et al 2012). This approach will be adapted for rift settings, where linear structures influence vent distribution and vent geometry (e.g. Mazzarini et al., 2013). For Butajira volcanic field we will produce scenario-based maps of the susceptibility to lava flow inundation, based on topography, vent locations and phreatomagmatic behaviour.

We will develop fully probabilistic hazard maps by adapting a recent method that uses a combination of computer modelling, Bayesian statistical approaches, and extreme-event probability computation (Bayarri et al., 2009). The method has been tested for PDC modelling, but its generic nature means it will now be adapted for the analysis of relevant hazards at Corbetti. In this approach, statistical emulators are used to rapidly and efficiently approximate the output of simulation tools, allowing coverage of a larger parameter space than would otherwise be feasible using computational modelling on its own (Bayarri et al, 2009). Emulators can be used to account for uncertainties in the source parameters, model input parameters, wind fields, and/or digital elevation models, all of which are important in the context of MER volcanism.

Objective Outputs:

- Development of statistical emulator methodologies to produce fully probabilistic hazard maps for single hazards at a given volcano.
- A probabilistic multi-hazard map for Corbetti volcano, the first assessment to account for multiple hazards of a peralkaline continental rift volcano.
- Lava flow susceptibility maps of Butajira volcanic field, and assessments to account for rift-controlled vent distributions.

Objective 8: Develop a regional analysis of ash fall hazard and assess long-term volcanic threat and the inherent uncertainty

In order to assess the likelihood of future eruptions of different magnitudes, extreme value models using a combination of a point process model (for occurrence of events) and a continuous statistical distribution (e.g. the generalized Pareto distribution) can be applied (e.g. Mendoza-Rosas and de la Cruz-Reyna, 2008; Sobradelo et al., 2011). The focus on large events makes these models robust to some level of uncertainty in the event catalogue. In order to carry out a systematic evaluation of uncertainty, we will analyse a high data-quality 1000 year record from an analogous setting (the Iceland Volcanic Catalogue). We will elicit error distributions to represent the uncertainty of event dates (which will vary with time) and the probability of detection of events of different magnitudes (again, time varying) for Iceland and the MER database from O1. Using these distributions, the Iceland catalogue can be degraded stochastically to generate multiple realizations of a lower-quality (MER) database. By fitting extreme value models to the degraded catalogues, and comparing model parameters, event probabilities and derived hazards assessments with those fitted to the original Iceland catalogue, we will be able to quantify the uncertainty in assessments made from the MER data, based on different event thresholds. This will allow us to assess the robustness of the methodology, and to indicate the implications of data uncertainty for our assessments (Marzocchi and Zaccarelli 2006; Song et al., 2012).

Based on the new frequency-magnitude data and eruption database from O1, we elicit uncertainties on source parameters from the RiftVolc community. We will combine them with an appropriate analytical sedimentation model calibrated against field data (e.g. python-ASHFALL3D: Bear-Crozier, 2012) to produce a probabilistic ash fall hazard assessment at MER scale. We will develop existing methodologies that assign volcanoes to discrete levels of hazard and uncertainty (e.g. Aspinall et al. 2011, Simpson et al. 2011) to rank threat in the MER, and produce event trees for key volcanoes (Newhall and Hoblitt 2002). Reliable ash fall hazards assessment is dependent on comprehensive characterisation of tephra deposits (O1-3) and critical and synergistic application of models with different levels of sophistication (Bonadonna and Costa, 2013) and ash fall thickness exceedances (the output of the probabilistic approach) at MER scale due to the possibility of ash fall from multiple sources at any given site (e.g. Jenkins et al 2012). Both eruption characteristics and winds are highly variable, so sensitivity analysis and investigation of scaling issues are required for a robust solution.

Key outputs:

- The first rift-scale probabilistic assessment of ash fall hazards with a full and critical sensitivity analysis.
- Quantification of the uncertainties in magnitude-frequency relationships in regions with incomplete datasets using degradation of analogue data and expert elicitation.
- Revised threat analysis methods designed and adapted for regions with sparse datasets, including ranking systems and event trees.

7. Further Consideration:

7.1 Justification of Large Grant Approach. The RiftVolc project goals are extremely unlikely to be achievable with multiple standard grants, and the synergies would not fully be exploited. We will follow a multi-disciplinary approach similar to that underlying ARC's success, in which, for example researchers (1) combined geodetic, seismic and modelling methods to track dyke injection and deduce magma volumes (Ebinger et al., 2010), (2) used petrological and geochemical data on magma source and storage depths together with magnetotelluric and seismic data to determine magma availability to feed the dykes and build new crust (Desissa et al., 2013), and (3) demonstrated that constraints from geodesy and petrology required a system of stacked sills beneath Dabbahu volcano (Field et al, 2012). Our three work packages are inter-dependent, and the data obtained will be applied to multiple aims. A large grant would provide a single point of contact with GeoPRISMS, and, as with EAGLE and ARC, allow optimum configuration of sensor deployments and mapping and sampling strategy.

7.3 Associated collaborations and co-funding: For both EAGLE and ARC, close links with the Geophysical Institute (IGSSA) and School of Earth Sciences at AAU, and the Geological Survey of Ethiopia (GSE) were vital to achieving the scientific objectives. RiftVolc will act in full partnership with them (see project partner letters) and it would not be possible to organise the logistics of a large fieldwork-intensive project without their support. They also provide the contacts to stakeholders essential for our research to have a local and regional impact, and advise us on end-user needs. EAGLE and ARC both benefited from contemporaneous NSF-funded projects; combining results significantly enhanced the scientific achievements and impact of the research. We will link with the ~$25M NSF-funded GeoPRISMS program that has recently chosen the EAR as its primary site for studying rift initiation and evolution, with the MER/Afar being one of two collaborative foci. Other Project Partners provide reduced cost access to equipment, or access to previously collected data and information (for research, or for training and capacity building), or with whom we wish to liaise over our research programme and its pathways to impact.

7.4 Timeliness: RiftVolc is informed and motivated by recent major NERC-funded investigations in the EAR, as detailed in the track record and, although we tackle new scientific questions in a new region of Ethiopia, RiftVolc also acts as timely continuation of our long-standing and productive collaboration with our project partners there. An investment by NERC now would enable us to link with the NSF-GeoPRISMS at the start of its EAR programme, greatly increasing the viability, visibility and impact of both initiatives (see accompanying letter of support). The ICDP Hominin Sites and Paleolakes Drilling Project, with AAU Project Partner staff Principal Investigators, is obtaining sediment cores from Ethiopian and Kenyan lake sites important for hominid fossils and artefacts, including some potentially affected by MER volcanoes. A recent development in Ethiopia is the significant investment being made in the geothermal energy industry, including the expansion of the Alutu geothermal plant and the commissioning of a new plant, to be the largest in Africa, at Corbetti. This renewed interest in the volcanoes of the central MER will contribute to the RiftVolc scientific objectives though logistical support and access to exploration datasets, and ensures that our results will have significant economic and societal impact

7.4 Risk and Mitigation Strategies. The RiftVolc objectives are necessarily inter-dependent such that problems or delays with one would adversely affect others. The Management Committee will oversee progress on a regular basis, and aim to ensure all objectives remain on track. The inter-dependencies provide all investigators and PDRAs with opportunities to work closely together, thus minimising the disruption should a PDRA leave. RiftVolc includes a significant fieldwork component, which always requires careful preparation in a developing country. We will ensure that thorough risk assessments precede each field campaign based on the extensive experience the RiftVolc investigators have working in Ethiopia. The field area is a few hours drive from Addis Ababa on good tarmac roads, but access to field sites, especially on volcanoes, involves slow journeys over rough terrain. Our vehicles will be rented from reputable companies with experienced off-road drivers. The region has not been subject to civil unrest or strife, nor does it suffer from extreme temperatures. In the unlikely possibility that fieldwork were delayed, existing datasets would allow some research to start on almost all objectives. Inflation in Ethiopia averaged 20% over the last 7 years, and there was a sharp devaluation against the US dollar in 2010. We will transfer funds into local currency on an as-needed basis to protect its value. Prices when calculated against ‘hard’ currencies have tended to increase at rates comparable to those in the UK.

References

Aizawa, K, et al, 2011. Temporal changes in electrical resistivity at Sakurajima volcano from continuous magnetotelluric observations, *J. Volc.. Geotherm. Res.*, **199**, 165–175

Abebe, B, et al, 2007. Quaternary faulting and volcanism in the Main Ethiopian Rift. *J. African Earth Sciences,* **48(2),** 115-124.

Acocella, V et al, 2003. Elliptic calderas in the Ethiopian Rift: control of pre-existing structures. *J. Volc. Geotherm. Res*., **119(1),** 189-203.

Amitrano, D & Helmstetter, A, 2006. Brittle creep, damage, and time to failure in rocks, *J. Geophys. Res*., **111**, B11201,

Annen, C, Blundy, JD & Sparks, RSJ, 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. *J. Petrology,* **47(3),** 505-539.

Aspinall, W, et al., 2011. Volcano hazard and exposure in GFDRR priority countries and risk mitigation measures. NGI Report 20100806.

Bastow, ID et al, 2005. Upper-mantle seismic structure in a region of incipient continental breakup: northern Ethiopian rift. *Geophys. J. Int.*, **162**, 479-493,

Bastow, ID et al, 2008. Upper Mantle Seismic Structure Beneath the Ethiopian Hotspot: Rifting at the Edge of the African Low Velocity Anomaly. *Geochem. Geophys. Geosyst.*, **9**, *Q12022,*

Bastow, ID et al, 2010. Melt-induced seismic anisotropy and magma assisted rifting in Ethiopia: Evidence from surface waves. *Geochem. Geophys. Geosyst.*,, **11**, Q0AB05

Bastow, I.D, Keir, D & Daly, E, 2011. The Ethiopia Afar Geoscientific Lithospheric Experiment (EAGLE): Probing the transition from continental rifting to incipient seafloor spreading. *Volcanism and evolution of the African lithosphere*, Geol. Soc. Am. Sp. Papers, **478**, 51-76.

Battaglia, M., et al., 2008. 4D volcano gravimetry Geophysics **73(6)**: Wa3-Wa18.

Bayarri, MJ et al, 2009. Using statistical and Computer models to Quantify Volcanic Hazards, *Technometrics*, **4**, 402-413

Bear-Crozier, AN et al, 2012. Development of python-FALL3D: a modified procedure for modelling volcanic ash dispersal in the Asia-Pacific region, *Nat. Haz*., **64**, 821-838

Bell, AF, Naylor, M & Main, IG, 2013. Quantifying the limits of predictability of volcanic eruptions, *Geophys. J. Int***., 194,** 1541-1553,

Benoit, MH, Nyblade, AA & VanDecar, JC, 2006. Upper mantle P-wave speed variations beneath Ethiopia and the origin of the Afar hotspot. *Geology*, **34,** 329-332.

Benvenuti, M, et al 2002. The Ziway–Shala lake basin (Main Ethiopian rift, Ethiopia): a revision of basin evolution with special reference to the Late Quaternary. *J. Afri Earth Sci.*, **35(2),** 247-269.

Benvenuti, M, et al, 2013. Holocene lacustrine fluctuations and deep CO_2 degassing in the northeastern Lake Langano Basin (Main Ethiopian Rift). *J. Afri. Earth Sci.*, **77**, 1-10.

Beyene, Y, et al, 2013. The characteristics and chronology of the earliest Acheulean at Konso, Ethiopia. *PNAS* **110(5),** 1584-1591.

Biggs, J, et al, 2010, Magma flux at Okmok Volcano, Alaska, from a joint inversion of continuous GPS, campaign GPS, and interferometric synthetic aperture radar, *J. Geophys. Res*., **115**, B12401

Biggs, J, et al., 2011. Pulses of deformation reveal frequently recurring shallow magmatic activity beneath the Main Ethiopian Rift. *Geochem. Geophys. Geosyst.*, **12**, Q0AB10,

Biggs, J, Ebmeier, SK, Aspinall, WP, Lu, Z, Pritchard, ME, Sparks, RSJ, Mather, T, Global link between deformation and volcanic eruption quantified by satellite imagery. 2013. In review (second round). *Nature Comm.*

Blundy, J & Cashman, K, 2008. Petrologic reconstruction of magmatic system variables and processes. *Reviews in Mineralogy and Geochemistry,* **69(1),** 179-239.

Bonadonna C & Costa A, 2013. Modeling of tephra sedimentation from volcanic plumes. In: Modeling Volcanic Processes: The Physics and Mathematics of Volcanism. CUP, Eds: S.A. Fagents, et al.

Bonnefoi, CC, Provost, A & Albarède, F, 1995. The 'Daly gap' as a magmatic catastrophe. *Nature*, **378**, 270-272

Brenguier, F, et al, 2008. Towards forecasting volcanic eruptions using seismic noise, *Nat. Geosci.,* **1**, 126-130

Brodsky, EE & Lajoie, LJ, 2013. Anthropogenic seismicity rates and operational parameters at the Salton Sea Geothermal Field. *Science*, **341**, 543-546

Campisano, C. J., & Feibel, C. S. 2008. Depositional environments and stratigraphic summary of the Pliocene Hadar formation at Hadar, Afar depression, Ethiopia. *GSA Spec. Paper*, **446**, 179-201.

Caricchi, L.J, Biggs, C, Annen, C & Ebmeier, SK, in revision. The influence of cooling, crystallisation and re-melting on the interpretation of geodetic signals in volcanic systems. *Earth Planet. Sci. Lett.*

Cashman, KV & Mangan, MT, A century of studies of effusive eruptions in Hawai'i (in press, USGS Professional Paper)

Chalié, F & Gasse, F, 2002. Late Glacial–Holocene diatom record of water chemistry and lake level change from the tropical East African Rift Lake Abiyata (Ethiopia). *Palaeogeog., Palaeoclim., Palaeoecol*, **187(3)**, 259-283.

Chave, AD and Thomson DJ, 1989. Some comments on magnetotelluric response function estimation. *J. Geophys. Res.,* **94**, 14215-14225

Chernet, T et al, 1998. New age constraints on the timing of volcanism and tectonism in the northern Main Ethiopian Rift–southern Afar transition zone (Ethiopia). *J. Volcanol. Geothermal Res.*, **80**, 267–280

Connor, CB & Connor, LJ, 2006. Inversion is the key to dispersion: Understanding eruption dynamics by inverting tephra fallout, in Mader, H.M., Coles, S.G., Connor, C.B. and Connor, L.J., Eds., Statistics in Volcanology: Special publications of IAVCEI, 1, p. 231-242, Geological Society, London

Connor, LJ et al, 2012. Probabilistic approach to modelling lava flow inundation: a lava flow hazard assessment for a nuclear facility in Armenia, *J. Appl. Volcanol*., **1**:3,

Cornwell, DG, et al, 2006. Northern Main Ethiopian Rift crustal structure from new high-precision gravity data. In: Yirgu, G, Ebinger, CJ & Maguire, PKH (eds) The Afar Volcanic Province within the East African Rift System, *Geol. Soc. Lond. Sp. Pub.*, **259**, 269–291

Corti, G, 2008. Continental rift evolution: From rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa, *Earth Sci. Rev.,* **96**, 1-53

Daly, E, et al, 2008. Crustal tomographic imaging of a transitional continental rift: the Ethiopian rift, *Geophys. J. Int.,* **172**, 1033-1048

Desissa, M et al, 2013. A mantle magma reservoir beneath an incipient mid-ocean ridge in Afar, Ethiopia, *Nature Geosci.*, **6**, 861-865,

Di Genova, et al. 2013. The rheology of peralkaline rhyolites from Pantelleria Island. *JVGR.* **249**, 201-216.

Ebinger, CJ & Hayward, NJ, 1996. Soft plates and hot spots: Views from Afar. *J. Geophys. Res.* **101(B10),** 21859-21876.

Ebinger, CJ, & Casey, M, 2001. Continental breakup in magmatic provinces: An Ethiopian example. *Geology*, **29(6),** 527-530.

Ebinger, C, 2005. Continental break-up: the East African perspective. *Astronomy & Geophysics*, **46(2),** 2-16.

Ebinger, C, et al, 2010. Length and timescales of rift faulting and magma instrusion: The Afar rifting cycle from 2005 to present, *Ann. Rev. Earth Planet. Sci*., **38**, 437-464

Ferguson, DJ, et al., 2010. Recent rift-related volcanism in Afar, Ethiopia, *Earth Planet. Sci. Lett.,* **292**, 409–418,

Ferguson, DJ, et al., 2013. Melting during late-stage rifting in Afar is hot and deep. *Nature*, **499**, 70-73,

Field, L, et al., 2012. Magma storage conditions beneath Dabbahu Volcano (Ethiopia) constrained by petrology, seismicity and satellite geodesy. *Bull. Volc.*.**74**, 2251-2271.

Field, L, et al., 2013. Magmatic history of Dabbahu, a composite volcano in the Afar Rift, Ethiopia. *Geol. Soc. Am. Bull.,* **125**, 128-147,

Gibson, IL, 1970. A pantelleritic welded ash flow tuff from the Ethiopian Rift Valley. *Contr. Min. Petrol.*, **13**, 31–44

Gillespie, R, Street-Perrott, FA & Switsur, R, 1983. Post-glacial arid episodes in Ethiopia have implications for climate prediction. *Nature*, **306**, 680-683

Hammond, JOS et al, 2013. Mantle upwelling and initiation of rift segmentation beneath the Afar Depression. *Geology*, **41**, 635-638

Hon, K, et al, 1994. Emplacement and inflation of pāhoehoe 757 sheet flows: Observations and measurements of active lava flows on Kilauea Volcano, Hawaii, *Geol. Soc. Am. Bull.,* **106**, 351-370

Hooper, A, et al, 2011. Increased capture of magma in the crust promoted by ice-cap retreat in Iceland, *Nat. Geosci.,* **4**, 783-786,

IAEA 2011. Volcanic hazards in site evaluation for nuclear power plants. Draft Safety Guidance DS405. International Atomic Energy Agency, Vienna, Austria

Jacobs, KM, et al, 2013. Cumulative rate analysis (CURATE): A clustering algorithm for swarm dominated catalogs, *J. Geophys. Res.,* **118**, 553–569,

Jenkins, S, et al, 2012. Regional ash fall hazard I: A probabilistic assessment methodology, *Bull. Volc*., **74**, 1699-1712

Keir, D, et al., 2006. Strain accommodation by magmatism and faulting as rifting proceeds to breakup: Seismicity of the northern Ethiopian rift. *J. Geophys. Res*., **111**,

Keranen, K, et al., 2004. Three-dimensional seismic imaging of a protoridge axis in the Main Ethiopian rift. *Geology*, **32**, 949–952

Keranen, K, et al, 2009. Low lower crustal velocity across Ethiopia: Is the Main Ethiopian Rift a narrow rift in a hot craton? *Geochem. Geophys. Geosyst.*, **10**, Q0AB01

Keszthelyi, LP & Self, S, 1998. Some physical requirements for the emplacement of long basaltic lava flows, *J. Geophys. Res*., **103**, 27447-27464

Mackenzie, GD, Thybo, H & Maguire, PKH, 2005. Crustal velocity structure across the Main Ethiopian Rift: Results from two-dimensional wide-angle seismic modelling. *Geophys. J. Int.,* **162**, 994–1006

Marzocchi,W & Zaccarelli, L, 2006. A quantitative model for the time-size distribution of eruptions, *J. Geophys. Res.,* **111**, B04204

Marzocchi, W & Bebbington, M, 2012. Probabilistic eruption forecasting at short and long time scales,2013 *Bull. Volcanol*., **74**, 1777-1805.

Mazzarini, F, Keir, D & Isola, I, 2013. Spatial relationship between earthquakes and volcanic vents in the central-northern Main Ethiopian Rift. *J. Volc. Geotherm. Res.,* **262**, 123–133

McNeice, GW and Jones, AG 2001. Multisite, multifrequency tensor decomposition of magnetotelluric data. *Geophysics*, **66**, 158-173

Melekhova, E, Annen, C & Blundy, J, 2013. Phase equilibrium controls on the generation of compositional gaps in magmatic rocks. *Nature Geosci.,* **6**, 385-390

Mendoza-Rosas, AT & De la Cruz-Reyna, S, 2008. A statistical method linking geological an historical eruption time series for volcanic hazard estimations: applications to active polygenetic volcanoes. *J. Volc.. Geotherm. Res.*, **176**, 277–290

Miller, V & Savage, M, 2001. Changes in seismic anisotropy after volcanic eruptions: Evidence from Mount Ruapehu, *Science*, **293**, 2231-2233

Mills, OP, & Rose, WI, 2010. Shape and surface area measurements using scanning electron microscope stereo-pair images of volcanic ash particles. *Geosphere*, **6(6),** 805-811.

Neave, DA, et al, 2012. Melting, differentiation and degassing at the Pantelleria volcano, Italy. *J. Petrology*, **53(3),** 637-663.

Newhall, CG & Hoblitt, RP, 2002. Constructing event trees for volcanic crises. *Bull. Volcanol.,* **64**, 3–20

Newman, AV, Dixon, TH & Gourmelen, N, 2006. A four-dimensional viscoelastic deformation model for Long Valley Caldera, California, between 1995 and 2000. *J. Volcanol. Geothermal Res.*, **150**, 244-269

Pagli, C, et al., 2012. Shallow axial magma chamber at the slow-spreading Erte Ale Ridge**,** *Nat Geosci.,* **5**, 284–288,

Patra, AK, et al, 2005, Parallel adaptive simulation of dry avalanches over natural terrain, *J. Volcanol. Geothermal Res.*, **139**, 1-21

Putirka, KD, 2008. Thermometers and barometers for volcanic systems. *Rev. in Min. Geochem.,* **69,** 61-120

Pyle, DM, 1999. Widely dispersed Quaternary tephra in Africa. *Global and Planetary Change*, **21,** 95-112.

Pyle, DM, 2012. Small volcanic eruptions and the stratospheric sulfate aerosol burden. *Envi. Res.Lett.,* **7(3),** 031001.

Rampey, ML, et al., 2010, Caldera forming eruptions of the Quaternary Kone Volcanic Complex, Ethiopia, *J. Afri. Earth Sci.,* **58**, 51-66

Rango, T, et al, 2010. Geochemistry and water quality assessment of central Main Ethiopian Rift natural waters with emphasis on source and occurrence of fluoride and arsenic. *J. Afri. Earth Sci.*, **57,** 479-491.

Roman, DC et al, 2008. Patterns of volcanotectonic seismicity and stress during the ongoing eruption of the Soufriere Hills Volcano, Montserrat (1995-2007), *J. Volcanol. Geothermal Res.*, **173**, 230-244

Rooney, TO, Bastow, ID & Keir, D, 2011. Insights into extensional processes during magma assisted rifting: Evidence from aligned scoria cones. *J. Volcanol. Geothermal Res.*, **201**, 83-96.

Rooney, TO, et al., 2012, Peralkaline magma evolution and the tephra record in the Ethiopian Rift, *Contrib. Min. Pet.*, **164**, 407-426

Scaillet, B, & Macdonald, RAY, 2003. Experimental constraints on the relationships between peralkaline rhyolites of the Kenya Rift Valley. *J. Petrology,* **44,** 1867-1894.

Siebert, L, Simkin, T & Kimberly, P, 2010, Volcanoes of the World, 3rd ed. Berkeley: University of California Press, 568 pp.

Simpson, A, Johnson, RW & Cummins, P, 2011. Volcanic threat in developing countries of the Asia-Pacific region: Probabilistic hazard assessment, population risks and information gaps. *Nat. Haz.*, **57**,151-165

Sobradelo, R, et al, 2011. Volcanic hazard assessment for the Canary Islands using extreme value theory. *Natural Hazards Earth System Sci.*, **11**, 2741–2753

Song, Y, et al, 2012. Susceptibility assessment of earthquake-induced landslides using Bayesian network: A case study in Beichuan, China, *Computers & Geosciences*, **42**, 189–199

Sparks, RSJ, 1986. The dimensions and dynamics of volcanic eruption columns, *Bull. Volcanol.*, **48**,3-15

Sternberg, B, Washburne, JC & Pellerin, L, 1988 Correction for the static shift in magnetotellurics using transient electromagnetic soundings. *Geophysics*, **53**, 1459-1468

Voight, B, 1988. A method for prediction of volcanic eruptions. *Nature*, **332**, 125-130.

Vye-Brown, C, et al, 2012. Geological map of the Dabbahu (Manda-Hararo) Rift, North, 1:100,000 scale. British Geological Survey

Wadge, G, & Burt, L, 2011. Stress field control of eruption dynamics at a rift volcano: Nyamuragira, DR Congo. *J. Volc. Geotherm. Res.,* **207(1),** 1-15.

Wang, Y, Forsyth, DW & Savage, B, 2009. Convective upwelling in the mantle beneath the Gulf of California, *Nature*, **462**, 499-501

Wang, H & Wright, TJ, 2012. Satellite geodetic imaging reveals internal deformation of western Tibet. *Geophys Res.Lett,* ***39***,**(7)**, *L07303*

Whaler, KA & Hautot, S, 2006. The electrical resistivity structure of the crust beneath the northern main Ethiopian rift. In: Yirgu, G, Ebinger, CJ & Maguire, PKH (eds) The Afar Volcanic Province within the East African Rift System, *Geol. Soc. Lond. Sp. Publ*., **259**, 293-305

White, R & McKenzie, D, 1989. Magmatism at Rift Zones: The generation of volcanic continental margins and flood basalts. *J.Geophys Res.*, **94**, 7685-7729

Wiart, P & Oppenheimer, C, 2000. Largest known historical eruption in Africa: Dubbi volcano, Eritrea, 1861. *Geology*, **28**, 291-294

Wicks, CW et al, 2001. Steady state deformation of the Coso Range, east central California, inferred from satellite radar interferometry. *J. Geophys. Res.*, **106**, 13769-13

WoldeGabriel, G., Hart, W. K., Katoh, S., Beyene, Y., & Suwa, G. 2005. Correlation of Plio–Pleistocene Tephra in Ethiopian and Kenyan rift basins: Temporal calibration of geological features and hominid fossil records. *J. Volc.Geotherm. Res*., **147(1),** 81-108.

Part 3 - *RiftVolc Outline Data Management Plan*

This document outlines the data sets that will be produced as a result of the RiftVolc project and the corresponding local, national and international data repositories. All data sets will be offered to the relevant NERC Data Centre – the NERC Geoscience Data Centre http://www.bgs.ac.uk/services/ngdc/ (NGDC). This is a time of rapid change for NERC policy on data management and we look forward to setting up a full DMP with the NGDC at the start of the project.

We have allocated funds for 4 months of PDRA salary dedicated to Data Management, plus travel funds for the PDRA to spend one week in each institution. This will enable us to work with the NGDC to prepare the data and metadata for ingestion in accordance with the latest NERC guidance.

Rock samples. Will be catalogued and archived in the Research Collections of the University of Oxford Museum of Natural History. Samples will be searchable (online) and made available for use by other researchers after the end of the project.

Petrological and Geochemical Data. Will be published in open-access journals, uploaded to international datasets (e.g. GeoRoc for geochemical data), and full datasets will also be archived in the University of Oxford’s open access data repository, along with all appropriate meta-data.

Magnetotellurics: We will archive the raw MT/GDS time series and TEM data, and the robustly processed MT/GDS transfer functions, along with metadata (site coordinates, instrumentation, MT electrode separation, TEM loop size, comments on data quality, etc). Volumes will be Gb.

Seismology: Following each field campaign the seismic data will be archived in miniseed format on the SEIS-UK computer system. Upon completion of all the fieldwork the full volume of miniseed data will then also be archived on the IRIS Data Management System (DMC) and remain password protected for three years after the date on which the SEIS-UK instrument loan terminated. Once the data exclusivity period expires, all data will be publicly available on the IRIS DMC.

Geodesy and Gravity: In the first instance, the GPS data will be archived the University of Addis Ababa and at Bristol, then to the appropriate national archive (NGDC) and finally to the international repository (UNAVCO). We understand that a NERC archive system for GPS at the NERC-GEF is under discussion, but if available, the data will be archived there as well as at the NERC Geoscience Data Centre. InSAR data will be collected in collaboration with the NERC large grant, LiCS, and BGS-COMET so will be automatically archived and distributed using their system at the CEMS.

Hazard models and maps. Will be archived at the NERC Geoscience Data Centre (NGDC) at BGS and provided to the Geological Survey of Ethiopia for integration with the in-country hazard maps. Further dissemination of new tools and models arising from WP3 research will be facilitated through use of the VHub cyberinfrastructure (www.vhub.org) so that our novel approach can be applied to other areas by the volcanology community.

Eruption database. Detailing a collation of existing and new data on the occurrence, character, frequency and magnitude of eruptions will be archived at the NERC Geoscience Data Centre (NGDC) and provided to the Global Volcanism Program of the Smithsonian Institution for integration into the global database of volcanoes and their eruptions.

Regional volcanic threat assessment. The methodology developed and the output assessment will be archived at the NERC Geoscience Data Centre (NGDC) and the assessment will be delivered in Ethiopia to the DRMFSS and to the United Nationals International Strategy for Disaster Reduction for integration in the subsequent Global Assessment Report on risk.

Part 4 - Rift Volcanism: Management Plan

Project management: The project's eight objectives are grouped under three interlinked themes: Past Eruptions; Present Magmatic System and Future Potential Impacts. One investigator is responsible for each of the objectives (see Table in Justification of Resources). The project has two PIs; ***Whaler*** (Edinburgh) will be responsible for the overall budget, project meetings, reporting and supervising the project administrator, and ***Biggs*** (Bristol) will oversee all fieldwork campaigns, and be responsible for data management. ***Whaler*** and ***Biggs*** have extensive experience of successful large projects, including COMET+, STREVA, EAGLE, Geospace and ARC. ***Vye-Brown*** will oversee Impact activities.

Management Committees: A project Management Committee, consisting of one investigator from each institution (***Whaler, Biggs, Mather, Keir, Vye-Brown, Edmonds***), will meet every 6 months to track progress of the project and to ensure that the separate strands of the project are working together. These committee members will have responsibility for managing their individual institutional budgets. The Fieldwork Committee ***(Biggs, Pyle, Keir, PDRA1-4*** once they are appointed) will meet prior to the field seasons (twice in Years 1 and 2, and annually thereafter) to co-ordinate logistics, fieldwork ethics and safety, and first aid training.

Project Science meetings: The full project team, including representatives from our Ethiopian Project Partners, will meet annually for two days to review results and progress, and strengthen inter-disciplinary working links. The PDRAs and PhD students within the project will be expected to report back on their progress. Time will be dedicated to establishing methodologies and tasks required to tackle the over-arching research questions. Each meeting will have a theme:

Yr 1: Launch event, Edinburgh
Yr 2: Linked with US GeoPRISMS
Yr 3: UK Field Event in a volcanic location such as the Isle of Skye
Yr 4: Iceland, linked with Geothermal Industry.
Yr 5: Open Conference, Addis Ababa.

Some of these meetings will have Impact activities such as Workshops associated with them, and one will include an Expert Elicitation, associated with Objective 8.

Advisory Board: The PIs and Management Committee will be guided by an Advisory Board, which will meet three times during the course of the project, in years 1, 3 and 4. We will invite a member of the ARC Advisory Board and of the GeoPRISMS Steering and Oversight Committee, and others of similar international standing and calibre. We will include a member with experience in hazards, to advise on the impact objectives of the project.

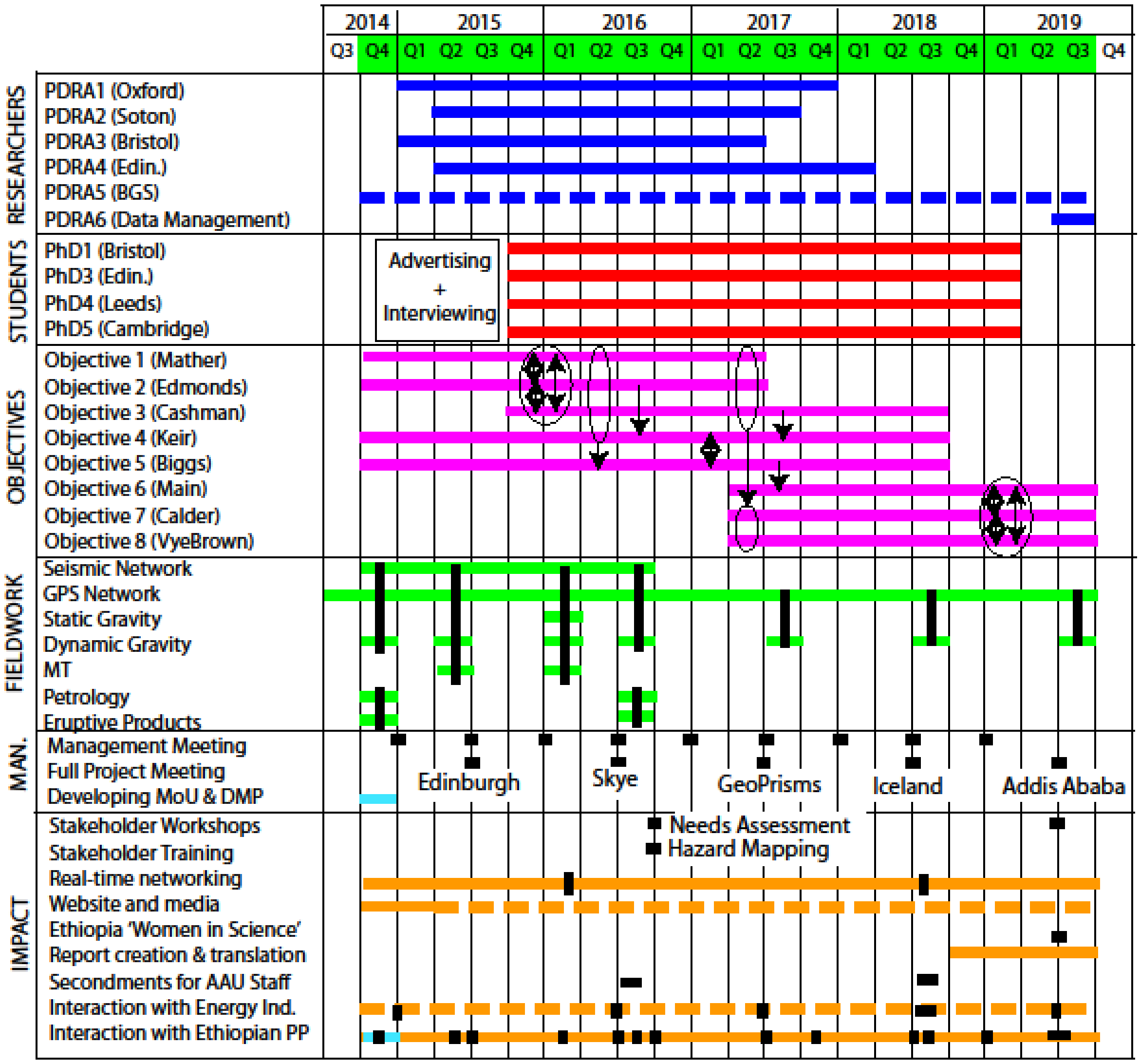
Recruitment and appointments: The PDRAs will be interviewed by a committee that consists of one of the PIs, the co-I who will be managing the PDRA, and an independent assessor from the host institution. PhD students will be advertised broadly, and selection will take place through the standard procedures in place in each institution.

Management of PDRAs and PhD students: Although multiple investigators are associated with every PDRA and PhD student, each will have a primary supervisor (see table in Justification of Resources), responsible for managing their progress. In addition, the relevant PI will keep an overview of progress, and each staff member/student will report back to the full project team at the annual meeting. Any major changes of direction or supervision will be referred to the Management Committee. A full breakdown of the time plan for the project is given overleaf.

Resources for project management: The primary resource requirement for managing the project will be investigator time. In addition, the project administrator at Edinburgh will be responsible for organising project meetings, maintaining the website, arranging travel, and writing up minutes/reports. Funds for travel to management and full project meetings, including Advisory Group members and Project Partner representatives, will be held centrally (see Justification of Resources).

Interactions between objectives: Although annual Science Meetings will be the major forums for interaction between and integration of the objectives, Objective leaders will also coordinate with each other, particularly at key points where information, data and results are shared (see progress chart overleaf). They will also liaise frequently with Vye-Brown, who leads the Impact Objectives. Funds have been set aside for project members to meet and work together in pairs or small groups for short periods (see Justification of Resources) to maximize these interactions.

Diagram illustrating work plan and timelines



Rift Volcanism: Justification of Resources

1. Personnel The Rift Volcanism proposal brings together investigators from seven institutions (6 Universities and BGS). They combine the breadth of expertise, summarized in Table 1, required to cover the diverse aspects of rift volcanism – from characterizing past eruptions, understanding current processes and analyzing future risk. The project will be led jointly by ***Whaler*** and ***Biggs,*** who will be responsible for managing and overseeing it. We have budgeted a nominal 20% FTE for ***Whaler***, 15% FTE for ***Biggs*** and 8% FTE for 5 years for each other institutional lead and up to 8% FTE for 3 years for all other investigators (with the exception of ***Blundy, Cashman, Loughlin*** and ***Wright*** who will contribute hours from existing projects/national capability funding, and ***Crummy***, whose contribution is combined with PDRA5 to give 3 years FTE). Many investigators will be able to devote a considerably greater effort to the proposed research. The responsibilities of the investigators are described below by research strand and objective (and on an individual basis in the table at the end), as well as the roles of the proposed PDRAs.

O1 - establish chronology. ***Mather*** will lead this objective with assistance from ***V.Smith***. **PDRA1** will be responsible for mapping eruption deposits in the region and collecting samples for geochemical and petrological analysis and dating. S/he will also be responsible for undertaking the subsequent analysis and correlation to identify the tephrostratigraphy with input from ***V Smith, Pyle and Mather.*** Field characterisation of lava flows, pyroclastic density currents and tephra will be delivered by ***Vye-Brown, Calder*** and ***Crummy*** to provide eruption parameters and spatial density models as inputs to O7 and O8 modelling**.**

O2 - magmatic controls on eruption. ***Edmonds*** will lead this objective with assistance from ***Cashman***. ***Edmonds*** will be responsible for collection of samples of explosively erupted peralkaline rhyolites and their petrological analysis. ***Cashman*** will be responsible for the physical characterization of the pyroclasts and both ***Edmonds*** and ***Cashman*** will be responsible for developing new models of silicic peralkaline eruptions. **PDRA 1** will be responsible for combining the new geochemical data from O1 and O2 with that from the literature and undertaking thermal modelling to further understand along rift compositional trends with guidance from ***Mather***, ***Pyle*** and ***Blundy***.

O3 - links to hydrology/climate. ***Cashman*** will lead this objective with assistance from ***Mather***. ***Cashman***, ***Mather***, ***V Smith***, ***Pyle*** and ***PDRA1*** will all be responsible for mapping and analysing deposits from selected tuff cones associated with target MER volcanic centres and sampling outcrops of lacustrine sediments. ***Cashman*** will be responsible for pyroclast shape, grain size and compositional analysis.

O4 - magmatic plumbing systems. ***Keir*** will lead this objective with assistance from ***Whaler***. ***PDRA2*** will be responsible for the collection, processing and analysis of seismic data with input from ***Kendall, Baptie, Luckett*** and ***Stuart. PDRA4*** will be responsible for collecting, processing and analysing magnetotelluric data with input from ***Whaler*** and for rift-scale modelling of magmatic systems with input from ***Whaler, Keir, Kendall*** and ***Blundy***. ***Wright*** and ***Biggs*** will link with the LiCS project to provide rift-scale strain rate maps.

O5 - stress and strain at silicic volcanoes. ***Biggs*** will lead this objective with assistance from ***Keir***. ***PDRA3*** will be responsible for the processing and analysis of GPS and gravity data with input from ***Biggs, Stuart*** and ***Gottsman*** and responsible for the integrated modelling with input from ***Biggs, Whitaker,*** and ***Hooper***. ***Biggs*** and ***Wright*** will be responsible for the processing and analysis of InSAR data, in conjunction with LiCS. ***PDRA2*** will be responsible for the processing and analysis of seismic data with input from ***Kendall, Stuart, Luckett, Main*** and ***Bell. PDRA4*** will be responsible for identifying time-varying MT signals with input from ***Whaler.***

O6 - eruption forecasts from monitoring data. ***Main*** will lead this objective with assistance from ***Bell.*** They will produce statistical eruption forecasting models tailored for MER volcanoes suitable for web-based verification based on seismicity, and quantification of their forecasting power and quality.

O7 - characterise volcanic hazards at a high risk centre. ***Calder*** will lead this objective with assistance from ***Vye-Brown. PDRA5*** will work on tephra and pyroclastic clastic density current modelling with ***Calder, Crummy*** and ***Loughlin***, on lava flow modelling and susceptibility mapping with ***Vye-Brown, K Smith*** and ***Cashman*** to produce probabilistic multi-hazard maps for short and long timescales. ***Murray*** and ***Loughlin*** will create a multi-hazard event tree with conditional probabilities derived from an expert elicitation.

O8 - regional analysis of ash fall hazard and long-term volcanic threat. ***Vye-Brown*** will lead this objective with assistance from ***Loughlin***. ***Loughlin, Lark*** and ***Vye-Brown*** will generate a new database of volcanoes, eruptions and hazard parameters for the MER/Ethiopia; an analysis of uncertainty using **s**tatistical models, analogues and expert elicitation**;** an assessment of the likelihood of future eruptions of different magnitudes

Justification of Resources

and styles over different time scales. ***Crummy*** will produce a regional probabilistic ash fall hazard assessment with ***PDRA5, Baptie*** and ***Loughlin*** and a sensitivity analysis of the methodology.

2. Postdoctoral Researchers: The project depends on a significant commitment to new field data acquisition (with lengthy field seasons and equipment servicing required), analysis and modelling that needs dedicated personnel at Post-Doctoral level to achieve. Experience gained through this and being embedded in a large, inter-disciplinary project should greatly enhance the PDRAs' career development.

PDRA1 – Petrology and geochemistry will work with ***Mather, V Smith*** and ***Pyle*** to establish a detailed tephrostratigraphy of the area and to establish size-frequency characteristics for the explosive activity of the major volcanic centres. They will work on petrological and geochemical characterisation of pyroclasts in order to aid unit correlation and also, in combination with other literature data and modelling, to understand the along-rift variation in compositional modality, from the MER to Afar. They will also work with ***Cashman, Mather, V Smith*** and ***Pyle*** to map and analyse deposits from selected tuff cones associated with target MER volcanic centres and sampling outcrops of lacustrine sediments.

PDRA2 - Seismology will work with ***Kendall*** and ***Keir*** to develop an automated migration algorithm to detect and locate volcanic tremor as well as high-frequency volcano-tectonic (VT) earthquakes, tested against manual picking, 1-D and 3-D seismic velocity models from local tomography, waveform cross-correlation and double difference relocation. methods. Earthquake magnitude determination will be automated and used to constrain both spatial and temporal variations in seismic energy release and magnitude-frequency relationship (b-value). Cross-correlation will be used to classify earthquake families.

PDRA3 – Geodesy will work with ***Biggs***, ***Gottsman***, ***Stuart*** and ***Wright*** to process the cGPS and gravity data. Initially the PDRA will use analytical solutions, inverse models and Monte Carlo approaches to model time-varying source volume, mass and density and predict the stress field for comparison to the seismic location, rates and focal mechanisms. The PDRA will then work with ***Hooper*** to incorporate more realistic geophysical constraints from the seismic and MT imaging. The PDRA will use petrological and thermal models to assess whether the deformation can be attributed to phase changes associated with cooling and crystallisation with input from ***Biggs*** and ***Pyle***, and conceptual fluid-flow models to assess the response of the hydrothermal system to perturbations in temperature, permeability and uplift with ***Whitaker*.**

PDRA4- Magnetotellurics will work with ***Whaler*** and Project Partners to process, analyse and model the TEM and MT/GDS data. The electrical anisotropy and geoelectric strike direction will be compared with seismic anisotropy. 2-D and 3-D models provide magmatic fluid location, pathways, and volumes, and directional dependence of electrical properties may indicate pathways along which fluids migrate; both may inform geothermal resource exploration. Data collected previously (by ETH, Zurich) and long time series broadband MT/GDS data will be analysed for temporal variability. The PDRA will carry out a joint inversion of MT/GDS and seismic data to provide more robust definition of high melt regions/paths.

PDRA5 - Hazards will work with ***Calder, Vye-Brown, Loughlin and Crummy*** to develop a new methodology based on a combination of computer modelling, statistical modelling, and extreme-event probability computation to generate fully probabilistic hazard maps for different volcanic hazards and scales. Field and historical data for lava flows, pyroclastic density current deposits and tephra fall is needed to determine the associated frequency-magnitude distributions used to compute the probabilities and conduct susceptibility mapping. Computer model approximations (statistical emulators), will then be employed to improve efficiency of the modelling tools over the large parameter spaces required.**.**

PDRA6 - Data Management (4 months) see ODMP.

3. Studentships: We have included 4 PhD student projects, with funds for fieldwork programmes attached to the main field campaigns, sample preparation and analyses, computing resources, training and conferences (up to £10k per student). We anticipate we will use funding from other sources (e.g. DTPs, institutional or overseas scholarships) for additional studentships associated with the project – these additional students will participate in the overall project. The students will be allocated £5k (in Edinburgh budget) to hold their own science meetings and social events and to take a leading role in communicating the project. Please note that due to a problem in the Je-S software, the stipend for the students is incorrect as it is at 2013/14 rates of £13,590 while it should be at the rate for 2014/15 which is £13,726.

4. Equipment:

GPS: The NERC Geophysical Equipment Facility (GEF) has a maximum loan time of 2 years. NERC have approved our suggestion to purchase the necessary equipment and provide it to GEF at the end of the 5 year deployment. GEF will contribute to construction, training and testing (see Facilities). Each GPS site requires a receiver (£5.5k) and a 36W solar panel (£200), a regulator (£370 inc £190 GEF facilities), a pelican

Justification of Resources

(£100), battery (£100) and assorted cables (£306). GEF Facilities costs include £400 training and £60 testing per instrument. *Gravity*: We will make use of gravimeters from Addis Ababa University (AAU) and the University of Bristol which can be taken to Ethiopia as hand-luggage. *Magnetotellurics (MT)*: We will use solar panels and TEM equipment in the GEF, supplemented by 6 long period and 4 broadband MT systems, coils and electrodes at a fraction of commercial hire rates from Project Partners (£27k). Peripherals (augers, bentonite, etc) (£500) and batteries (£900). Soil-CO_2 instrument (£6k).

5. Fieldwork:

WP1 will require 2 x 3 week field seasons (£44.9k held in Oxf.); WP3 will require 2 x 4 week field seasons (£51.4k held at BGS). The MT will require 2 x 5 week field seasons with 2 vehicles, plus equipment transport (£57k held in Edin.); the seismic deployment will require 4 trips with 30 vehicle-days for deployment, 20 for service runs and 15 for retrieval (£65.6k held in Soton.); the GPS and dynamic gravity will require 10-day visits, initially timed with the seismic service runs, and annually thereafter; the static gravity will require an additional 15 field days (£73k held in Bristol).

We have fixed the field costs across all work packages at: flights (inc. visas, insurance etc) £1000; Accommodation and Subsistence in Addis Ababa £75 per person per day; Field Accommodation and Subsistence £40 per vehicle per day; AAU staff £50 per day; guards £10 per site per month (long term), £2 per site per 24 hours (short term); car rental £150 per day; Fuel £50 per day; Shipping at £5 per kg. Mobile phone coverage is good in field region and we budget £20 per trip for SIM cards & calls. Medication at £500 per person for 10 investigators, 5 PDRAs and 4 PhDs; Fieldwork & First Aid training at £500 per person for 5 PDRAs and 4 PhDs and £500 for refresher days for some investigators.

Collaboration with Addis Ababa University (AAU) is vital to ensure the success of the field-based and impact components of this proposal and their scientific expertise with contribute across all objectives (see track record). We have allocated £40k to support these activities: assist with organising the final meeting in Addis Ababa and associated fieldtrips, organising temporary import and export permits and liaising with customs; maintaining field-based equipment (fieldwork costs, spares etc), establishing links between RiftVolc equipment and national networks (e.g. absolute gravity, seismic and GPS networks) and UK visa applications to visit the UK (e.g. annual science meetings). To protect against inflation, the budget will be held in Edinburgh and transferred as needed.

6. Facilities and other directly incurred costs

NERC-Facilities: *GEF/GPS:* £3.4k for building regulators, equipment testing and training. *GEF/MT:* £7.8k equipment costs. *SEIS-UK:* £291k; *NERC Radiocarbon Labs:* 30 radiocarbon analyses [£9k]; 19 Ar-Ar dates [£33k Oxford, £19.8k BGS]. *NERC IMF*: 120 hours: £15k.

Other Facilities, analytical costs and related consumables (directly-incurred): MT equipment from project partners £41.5k; 100 rock analyses, XRF (Major elements), Leicester, [£2.28k]. Instrument/SRF Time, Oxford [£19k] including 14 days Electron Probe Analysis (SRF) 10 16 days SEM analysis, (SRF); 4 days Trace Element ICP-MS (SRF), 2 days thin section lab (SRF); and laser-ablation ICP-MS of single grains [Dublin, £1.23k]. Consumables for grain size analysis, tephra extraction, polishing and gas analysis [£4.5k]. High performance computing time and data storage [£2k] for running complex geophysical hazard models (e.g. TITAN2D). Analytical costs, Cambridge [13.46k], including 10 days Electron Probe Analysis, 5 days Scanning Electron Microscopy and 10 days Manchester X-Ray Imaging Facility, thin section and grain mount manufacture.

7. Administrative Assistance We have included 12 months p.a. time in Edinburgh for administrative assistants for the PIs. Responsibilities include organising and minuting meetings, arrangements for visitors, compiling annual performance measures and maintaining project web pages and other communication media, outreach, and liaison with project partners and companies.

8. Meetings and Other Travel

Project Meetings There will be one science meeting per year over 2 full days. The first will be in Edinburgh (£12k + £4k impact), the second in the US with GeoPRISMS investigators (£15k), the third on Skye (£12k + £4k impact) will be extended for 2 days for the expert elicitation (£5k), and the fourth in Iceland (£7.5k + £7.5k impact). The final 3 day meeting will be in Addis Ababa (£50k), with an associated 2 day stakeholders workshop (£10k - impact). Costs are based on similar meetings for the Afar Rift Consortium. There will also be 2 management committee meetings per year for one investigator per institution, one of these meetings being coincident with the science meeting. We have budgeted £900 on the assumption there will be 2 in Edinburgh, 1 in Bristol, and 1 each in Leeds and Southampton, and that travel can be completed on the day. Advisory Board meetings will coincide with science meetings and costs are included. Fieldwork Committee

Justification of Resources

meetings will coincide with science meetings, and with additional meetings at Southampton and Oxford (£900). We have assumed a ‘typical’ off-peak rail fare for UK meetings, plus air fares for Project Partners and Advisory Board members.

Travel for collaboration and facilities: Investigators, PDRAs and students will interact at the annual science meetings. In addition, we have included a small amount of UK travel to enable individuals in different institutions collaborating closely on research objectives to meet, and to interact with project partners, on the assumption of 16 trips with one night’s overnight accommodation. We also budgeted for 5 extended visits by Ethiopian Project Partners (3 for science, 2 for impact) in association with the science meetings (10k). We intend to supplement from other international exchange funds (e.g. Royal Society International Exchanges, Royal Society of Edinburgh). Cambridge requests 1.15k for 2 x 1 week trips to the NERC IMF facility, and to the MXIF facility at Harwell.

Conferences We have budgeted one international conference for each investigator and one per year for the PDRA. Actual costs for AGU, EGU, International Association (IAVCEI, IASPEI, IAGA) and others (e.g. Goldschmidt) are variable, but as most are in locations outside Europe we have assumed £1.5k. For PDRAs we budgeted one international meeting per year. We also budgeted 2 UK science discussion meetings per individual over the project assuming these would be for 2 days with 1 night’s accommodation and food (@£150 including registration).

9. Consumables: Miscellaneous peripherals, mobile phones, computers and data storage are required to support fieldwork (£5k, Southampton). The seismic deployment will require 50 batteries, the MT deployment 12 batteries, at £75 each. Satellite images: (SPOT, ASTER, TSX, CSK) £15k.

Note: Costs for impact-related activities are detailed in the Pathway to Impact.

		Contribution	Obj	PDRA	Stu.
Kathy Whaler	Ed	Project management, MT	4,5	**4**	
Juliet Biggs	Br	Project management, Geodesy	**5,** 4	**3**,**6**,	
Brian Baptie	BGS	Seismic interferometry, Monte Carlo simulations	4,6	2,5	
Andrew Bell	Ed	Eruption forecasts from monitoring data	**6,**4,5		*
Jon Blundy	Br	Igneous petrology: field observations & mineral chemistry.	4	3	*
Eliza Calder	Ed	Probabilistic Hazard Analysis	**7**,8	5	
Kathy Cashman	Br	Volcanic deposits, specifically tephra & links to eruption styles.	**3**,1,2,	1,5	*
Julia Crummy	BGS	Tephra fieldwork, probabilistic analysis of ash fall	1,7, 8	1,5	
Marie Edmonds	Cam	Sampling peralkaline rhyolites and their petrological analysis	**2**	-	*
Jo Gottsmann	Br	Static and dynamic gravity fieldwork, processing and analysis	5	3	
Andy Hooper	Le	Boundary Element Modelling in deforming systems.	5	3	*
Derek Keir	So	Seismic data fieldwork, processing and analysis.	**4**,5	**2**,3,4	
Michael Kendall	Br	Seismic data fieldwork, processing and analysis.	4,5	2,4	
Murray Lark	BGS	Statistical modelling & elicitation of expert opinion	7,8	5	
Sue Loughlin	BGS	Eruption and hazard database, frequency-magnitude probabilities	1, 3, 7,8	1,5	
Richard Luckett	BGS	3D seismic velocity model, real time seismic monitoring	4,5,6	2	
Ian Main	Ed	Eruption forecasts from monitoring data	**6**,4,5		*
Tamsin Mather	Ox	Volcanic degassing, regional eruption rates and forcings.	**1**,3	**1**	
David Pyle	Ox	Petrological analysis; trends in rift composition.	1,3	1	
Kay Smith	BGS	Hazard susceptibility maps	1,7, 8	1,5	
Victoria Smith	Ox	Chemical characterisation & radiometric dating of tephra deposits	1,3	1	
Graham Stuart	Le	Seismic data fieldwork, processing and analysis; static gravity.	4,5	2,3,4	
C.Vye-Brown	BGS	Lava flow hazard modelling; regional volcanic threat	**8**,1,7	**5,** 1	
Fiona Whitaker	Br	Fluid flow modelling.	5	3	
Tim Wright	Le	Strain mapping, Deformation, Comparison to Afar.	4,5	3	*

Numbers in **bold** represent the lead on this objective or PDRA supervision; final column indicates project student supervisors**.**

Pathways to Impact for ‘Rift Volcanism: Past, Present, and Future’ (RiftVolc).

1. Who and How?

RiftVolc results will be used to integrate volcanic hazard and risk into policies for short-term emergency management and long-term planning. This will build resilience and reduce losses across all three of NERC’s key impact areas: 1) *fostering global economic performance* through the geothermal energy industry; 2) *increasing the effectiveness of public services and policy* through the relevant international and national organisations and 3) *enhancing quality of life and health* by increasing resilience to natural hazards, and supporting the renewable energy industry in a developing country. The PP letters are testimony to our strong track record and long-standing collaborations with the relevant end-users, and we have involved them in the proposal development from its inception. During the Afar Rift Consortium (ARC) hazards workshop held in Addis Ababa in 2012, in recent UN reports, during the NERC urgency response to the 2011 Nabro eruption and during a NERC Impact Accelerator Geothermal Workshop we have comprehensively identified the end-user benefits and targeted RiftVolc impact at specific end-user needs.

The ***Institute of Geophysics, Space Science and Astronomy*** at **Addis Ababa University *(AAU)*** is the national organisation providing geophysical monitoring data and advice during volcanic unrest and eruptions. The ***School of Earth Sciences*** at AAU provides advice on petrology, geochemistry, structural geology and the character of past eruptions. There are no trained volcanologists in Ethiopia but collectively these departments provide scientific advice to the Disaster Risk Management and Food Security Sector, Civil Aviation Authority and Ethiopian Pilots Association during an eruption (see below). ***RiftVolc*** *will make use of BGS’ expertise in real-time monitoring and provide the equipment to assist AAU in establishing the first real-time seismic and geodetic monitoring in Ethiopia. This is a key step towards delivering an operational capacity that the UN highlighted as a key weakness in its ‘Hyogo Framework for Action (2011-2013)’ report.*

The ***Geological Survey of Ethiopia (GSE)*** is the national institution producing geoscience data, advice and services that contribute to the sustainable development of agricultural and industrial infrastructure and other sectors of the Ethiopian economy to improve living standards. **RiftVolc** *will work with GSE’s Natural Hazards and Geothermal Divisions to ensure our outputs can be embedded into existing systems and provide training in volcanic impacts and hazard modelling*.

The ***Disaster Risk Management and Food Security Sector (DRMFSS)*** in Ethiopia is the government department responsible for civil protection and managing risks resulting from natural hazards. In the last year the DRMFSS have moved from reactive crisis management to proactive disaster risk management and launched the Woreda Disaster Risk Profiling (WDRP) Programme that adopts the Hyogo Framework for Action in order to strengthen community resilience. Through the Intergovernmental Authority on Development, Ethiopia is the lead for Disaster Risk Management on a regional scale, undertaking assessments to understand risks across international borders. ***RiftVolc*** *will work with WDRP to inform and advise on analysis of regional volcanic hazards and risk and will contribute to regional risk assessments through data and knowledge exchange with DRMFSS.*

Ethiopia Civil Aviation Authority (ECAA) needs timely scientific advice during volcanic eruptions to manage Ethiopian airspace (including closures) and advise the ***Ethiopian Pilots Association (EPA)*** in order to minimise disruption (e.g. caused by the Nabro 2011 eruption) and ensure safety. **RiftVolc** *will characterise the likelihood of future volcanic eruptions and their impacts and lay a foundation for improved response and real-time information flow during a volcanic crisis.*

The ***United Nations International Strategy for Disaster Reduction*** **(UNISDR)** is undertaking a global analysis of risk, the ***Global Assessment Report (GAR)*** and the global-scale analyses of volcanic risk is co-authored by BGS. ***RiftVolc*** *will build on existing links with these major international initiatives to contribute experience and practice in a developing nation and engage with these initiatives to co-ordinate research on a global scale.*

The ***UK Cabinet Office Civil Contingencies Secretariat*** and the ***National Risk Register*** have identified a strategic need in the UK and across Europe to increase our understanding of rift volcanism and their hazards and impacts to support planning. ***RiftVolc*** *will ensure knowledge transfer through BGS interactions so that research contributes to policy in the UK and investigates transferability of science between the EAR and Iceland.*

The ***Global Volcano Model*** (Co-Led by Co-I Loughlin) is the global platform for volcanic hazards and risk, and the project will update global databases to support international policy and risk modelling. The ***IAVCEI Commission on Hazards and Risk*** (led by Co-I Calder) is dedicated to applied volcanology linking academic research and decision-makers to reduce the impact of volcanic hazards. ***RiftVolc*** *will share outcomes with the international community through GVM and the IAVCEI commission to increase our impact with a broad set of global stakeholders.*

Reykjavik Geothermal Limited is develops high enthalpy geothermal resources for utility scale power production and, in October 2013, signed an agreement with the Ethiopian government to construct Africa's largest (1,000 MW) geothermal power plant at Corbetti volcano in the Main Ethiopian Rift. ***Ethiopian Electrical Power Corporation (EEPCO)*** currently operate a 7MW geothermal power station at Alutu Volcano in the Main Ethiopian Rift, which they are expanding to 70MW. Bristol's **Cabot institute** maintains extensive links with private, public and third sector organisations and with policymakers, particularly in the areas of energy and natural hazards**.** ***RiftVolc*** *will work with the Cabot Institute to ensure the project connects effectively with these and other similar research initiatives and international stakeholders in the energy industry.*

2. What? Activities to engage end-users.

Experience gained during ARC and in discussion with our PPs has been used to ensure the activities below are appropriate to the research, likely to generate significant impact and ensure a lasting legacy. In each case, we identify the timing, personnel, and finance required.

***Workshops*:** A stakeholder workshop with DRMFSS, ECAA, EPA, GSE and AAU partners will assess need, identify knowledge gaps and discuss policy formulation. [*Year 2; Vye-Brown and Loughlin; £13k*]. An impact workshop for all stakeholders will be held alongside the final science workshop in Addis Ababa *[Year 5; Vye-Brown & All; £20k].* A portion of the budget for each science meeting has been set aside for PP T&S *[All years; PPs; £16.5k].* RiftVolc will participate in Cabot workshops on 'Energy and infrastructure in an uncertain world' and invite relevant Cabot Institute members to attend RiftVolc meetings *[All years; Cabot; £6k].*

Training: PPs and Riftvolc scientists at all levels will collaborate on fieldwork, science meetings and workshops *[All years; All; No additional cost]*. Specific training for AAU and GSE staff in volcanic hazard mapping methodologies, forecasting and modelling using the VHub cyberinfrastructure and the EFFORT portal *[Year 2, Bell & Calder; £1k]*. Two 3-week secondments to the UK for AAU staff *[Year 4; AAU; £4k].*

Establishment of **real-time monitoring capacity**: Data from AAU stations and temporary project stations will be telemetered back to AAU for real-time data delivery with training in maintenance. *[Years 2 & 4; Luckett; Equipment £16k; Training £7k T&S + £12k facilitation time].*

***Public engagement*:** The RiftVolc website will detail project objectives, progress, results, blogs, non-technical summaries, and schools' information. *[Set-up Year 1; maintained throughout; Project Administrator; £3k].* New developments will be rapidly communicated through social media *[All Years; Cabot + all personnel; No additional cost].* We will visualise volcanic hazards for outreach and communication with non-specialists using science animation production company Vivomotion *[Year 3; Vye-Brown & Vivomotion; £4.2k].* RiftVolc investigators currently have at least 5 active blogs, 8 tweet with >3,500 followers, and there have been >16,000 viewings of the ARC video and volcano animations over the last 3 years. The project findings will be show-cased at Open Days and Science Festivals across the UK *[All years; All investigators; £2k].* In Ethiopia, we will support development goals with 'Women in Science' days for high school girls *[Year 5; All; £2k]*.

Stakeholder Communication: *Cabot's* professional science writers will be used to create documents targeted at the energy industry *[Years 4-5; Kendall & Cabot; £4k];* Outputs and reports will be translated into Ethiopia's official language, Amharic, to ensure uptake *[All years; AAU; £2k].*

3. Milestones and measures of success

- Improvements in long-term planning & short-term emergency management of volcanic risk
- Incorporation of the RiftVolc outputs in the UNISDR-GAR and other international initiatives
- Capacity building through training in operational, policy and research work
- Establishment of Ethiopia's first real-time monitoring capability
- High readership of websites, blogs and twitter and high attendance at events
- Impact workshops in years 2 and 5 and strong attendance by PPs at science meetings
- Interaction between RiftVolc scientists at all levels and PPs during fieldwork and secondments

4. **Summary of Resources** Workshops £55.5k; Training £5k; Building real-time capacity £35k; Public Engagement £11.2k and Stakeholder communication £6k; . **Total £102.7k**