Advances in Volcanology

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Editors

Physical Geology of Shallow Magmatic Systems

Dykes, Sills and Laccoliths

Springer

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Foreword

The intersection between surface volcanic rocks and their feeder systems has a fascinating history. What is the volcanic-plutonic interface telling us about the spatial, temporal and thermal evolution of sub-volcanic magmatic systems? Do they preserve information of use in forecasting future volcanic hazards? What is the link to deeper-level magmatism and the geochemical evolution of Earth's continental crust? Are there extra-terrestrial counterparts?

Mostly these questions are not new. Some of the greatest names in the development of igneous geology including Bowen, Cloos, Daly, Geikie, Harker, Holmes, Iddings, Mercalli, Sapper and Tyrrell embraced this topic. Between them they agreed the defining feature of high-level igneous intrusions (injected bodies) is that they are visibly enclosed by surrounding country rock with the exception of the magma feeding channel. However, the position regarding plutons and batholiths was far less clear. Were these subjacent rocks, apparently downwardly enlarging, magma intrusions at all, given the lack of observational evidence for a floor or base? If not, how did plutons relate to chemically associated volcanic rocks, often found in conjunction? And should large mafic intrusions be treated the same way?

Looking back through geological literature on the forms and structures of igneous rocks in the first 50 years of the 20th century makes fascinating reading. The conclusion by many of his contemporaries that batholiths were indeed injected bodies is rejected by R. A. Daly in the 1933 edition *Igneous Rocks and the Depths of the Earth* as "premature". This comes despite the relaxed acceptance that in places including Dartmoor, England, "extensive granites, formally called batholiths, have been shown to be of sheet-like, laccolithic, phacolithic or lopolithic nature". To those familiar with contemporary views of batholith formation, the freshness of this statement is striking—confirmation that there really is nothing new under the sun. Yet the ease by which two opposing points of view on the origin of batholiths can be accommodated seems odd—surely there should be one consistent truth? It seems these great minds could slip easily between rival interpretations of how intrusive rocks came to be.

One reason could be that early debate on high level intrusions revolved mostly around definitions to describe and classify their shape and geometry as opposed seeking a coherent view on underlying processes. Descriptive terms abound. Some of them, including Bysmaliths, Entmoliths, Sphenoliths, Akmoliths and Harpoliths, sound like monsters from a Harry Potter novel! The overriding sense is that of a community deliberately seeking out small differences which become amplified into conflicting theories about origins and meaning. From small beginnings these debates unchecked proliferate into so-called controversies, which, as happened with granites, are a sure sign of a subject area becoming moribund.

Luckily, understanding how magmas move about in the near sub-surface has improved significantly in the last 50 years. The realisation that shape and form are largely viscosity-related means that magmatic systems can be seen from a physical perspective as a continuum between differing compositions. In this system-wide view, arguments about intrusion geometry are understood to be manifestations of a deeper, dissipative and self-similar process.

That is why the integrated, systems-level approach put forward in this book is the right one. The science of shallow-level magmatic systems has entered a new and exciting mature phase. The editors both have long and distinguished track records in researching the origins and emplacement of shallow igneous intrusions, most notably sills and laccoliths. They have published research papers and edited special volumes on this topic for several decades now and the knowledge gained form multidisciplinary studies by international teams of geologists, geophysicists and petrologists has been distilled cleverly into this welcome and timely book.

Northampton, UK Nick Petford
November 2017

Preface

History, Design and Aims of This Book

The origins of intrusive rocks have been widely discussed for a couple of centuries, and the ways volcanoes work have attracted scientists and laymen since the dawn of mankind. However, shallow igneous intrusions, representing the obvious link between the hidden plutonic kingdom and the fiery volcanic realm, have not received the attention they deserve, leading to some shortcomings in the communication between "plutonic" and "volcanic" researchers. This book is an effort devoted to heal this breach and should also serve as a reference in the field of subvolcanic systems for master- and Ph.D. students, geo-scientists and professionals. At the same time, we hope that future research in the field will be sparked by its publication.

The present book is directly related to, and a result of, a series of five field workshops that occurred from 2002 to 2012 in various countries. The series of LASI[1] field workshops started in October 2002 in Freiberg (Saxony,

[1]LASI stands for Laccoliths, sills and dykes—Physical geology of shallow-level magmatic systems

Germany), where one of us (C.B.) and Alex Mock hosted 40 participants coming from 10 countries. A one-day field trip was undertaken to examine Late Paleozoic sill and laccolith complexes in eastern Germany (abstract and field guide volumes of LASI can be found on the LASI web site).[2]

LASI II followed in April 2006 on the Isle of Skye in NW Scotland, organized by Ken Thomson, Nick Petford and Donny Hutton, gathering 53 scientists from 16 countries. Of course, the mafic Cenozoic sill complex of that island was the topic of the field trip.

Weather conditions improved somewhat with the field workshops that followed. LASI III was held on Elba Island (Tuscany, Italy) in September 2008, where 44 participants from 17 countries gathered and examined the classical Christmas-tree laccolith complex and surrounding waters of the Tyrrhenian island.

LASI IV led to the mother of laccolith systems, the Henry Mountains in Utah (USA). There, in 1877 following two weeks of field work, Karl Groove Gilbert defined what a laccolith looks like. In September 2010, the team led by Sven Morgan made sure that 33 participants from 10 countries deeply enjoyed both seminars and outcrops. Connected to this, in a one-day field trip, David Hacker introduced the spectacular subvolcanic bodies and related landslides of the Iron Axis Mountains in SW Utah (Chapter "Catastrophic Collapse Features in Volcanic Terrains: Styles and Links to Subvolcanic Magma Systems").

In November 2012, LASI V was held in South Africa with 44 participants from 11 countries. A warm-hearted welcome, a smooth organisation and an interdisciplinary data set were the ingredients applied by the people around Sverre Planke and Henrik Svensen for a successful introduction to the magnificent saucer-shaped sill complex in the Karoo Basin (Chapter "Subvolcanic Intrusions in the Karoo Basin, South Africa" and parts of Chapter "Geochemical Fingerprinting and Magmatic Plumbing Systems").

A total of 350 geoscientists from 32 countries co-authored papers that were presented during the five LASI field workshops. The most prominent methods applied to subvolcanic systems were geometric and textural studies, geophysics (mostly 3D seismic and paleomagnetics), and analog and numeric modelling, as well as petrological/geochemical investigations. Silica-rich and —poor complexes, and deep-seated as well as shallow systems have been examined. Within plate tectonic settings, intra-continental rift and plume-related systems dominated.

During all five LASI events, Europe was the most prominent host of subvolcanic complexes described; LASI V boasted examples from the venue country, South Africa. Clearly, Mesozoic and Cenozoic subvolcanic complexes, being less altered and deformed, prevailed over Paleozoic and Precambrian examples.

A large number of papers authored by LASI participants have been published in the last 15 years, and have been widely cited in the present book. As a direct outcome of LASI conferences, two Special Publications

[2]https://people.unipi.it/sergio_rocchi/lasi/

of the Geological Society of London (Breitkreuz and Petford 2004; Thomson and Petford 2008), as well as a special issue of Geosphere (Rocchi et al. 2010), can be noted.

The series of LASI field workshops displayed the enormous range in size, emplacement depth and composition of subvolcanic systems. Fossil volcanic centres often have been eroded down to the subvolcanic level, exposing coherent weathering-resistant subvolcanic rocks (volcanic necks, paleo-magmatic arc successions). As a consequence, subvolcanic rocks are overrepresented in the geological record and their preservation potential is high compared to many volcanic rocks such as fallout or non-welded pyroclastic flow deposits. Understanding the geometry of subvolcanic complexes and "reading" the internal and external textures of these rocks enable geologists and geophysicists to distinguish subvolcanic complexes from volcanic counterparts. This distinction obviously bears importance for the lithostratigraphic and magmatic evolution of a particular lithospheric block.

This book, presented by experts in their respective fields, intends to summarize the wealth of knowledge about subvolcanic systems. The first part of the book (Chapters "Physical Geology of Shallow-Level Magmatic Systems—An Introduction"–"Sills in Sedimentary Basins and Petroleum Systems") collects comprehensive reviews on various aspects of subvolcanic systems. In the second part (Chapters "The Subvolcanic Units of the Late Paleozoic Halle Volcanic Complex, Germany: Geometry, Internal Textures and Emplacement Mode"–"Laccolithic Emplacement of the Northern Arran Granite, Scotland, Based on Magnetic Fabric Data"), case studies of important subvolcanic complexes are being presented.

Acknowledgements

In times of demanding publication efforts in high-impact journals, preparedness of authors to contribute to such a book is supremely acknowledged. We thoroughly enjoyed working closely with high-level scientists to finally produce this hopefully useful piece of work.

At the same time, we really have to thank the reviewers for their outstanding effort to improve the scientific quality of every chapter. We acknowledge reviews by Valerio Acocella, Olivier Bachmann, Eric H. Christiansen, Alexander Cruden, Christopher Henry, John P. Hogan, Eric Horsman, Nina Kukowski, William P. Leeman, Craig Magee, Julian Marsh, Nick Petford, Nick Schofield, Lee Siebert, David S. Westerman, and Paul Wignall.

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Freiberg, Germany — Christoph Breitkreuz
Pisa, Italy — Sergio Rocchi
September 2017

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The original version of the book was revised: Incorrect chapter DOIs and Copyright Year information for all chapters have been updated and the series subtitle has been included. The erratum to the book is available at https://doi.org/110.1007/11157_2018_2005

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About the Editors

Chris (right) and Sergio (left) enjoying the overview of the Golden Valley saucer-shaped sill in Karoo during LASI V

Christoph Breitkreuz

Born 1955 in Berlin, Christoph Breitkreuz studied geology at TU Berlin. At the same university he completed PhD in 1982 with a topic on Mesozoic plutons in the Coastal Cordillera in northern Chile. Also at TU Berlin, 1986 he obtained habilitation with a revision of Paleozoic volcanosedimentary successions in northern Chile.

After a research stay at University of Kansas (1992-1994), Christoph Breitkreuz received a Heisenberg Fellowship (1995-2000) which he spent at GFZ Potsdam. This was also the start for research on Late Paleozoic volcanic and subvolcanic systems in central Europe – a topic that forms focus of his activity until today. Since 2000 Christoph Breitkreuz is full professor at the TU Bergakademie Freiberg. There, he established a Centre for Volcanic Textures with more than 3000 samples.
http://tu-freiberg.de/geo/sedi/team/cbreitkreuz

Sergio Rocchi

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Author of over 100 publications in peer-reviewed scientific journals.
http://people.unipi.it/sergio_rocchi/

List of Acronyms (only non-geographical)

AFC	Assimilation fractionation crystallisation process
AFTA	Apatite fission track analysis
AMS	Anisotropy of magnetic susceptibility
AVO	Amplitude versus offset
CFBP	Continental flood basalt province
CSD	Crystal size distribution
CSEM	Controlled-source electromagnetic survey
DIC	Digital image correlation
DSI	Discrete smooth interpolation
EC-RAFC	Effects of concurrent eruption, recharge, variable assimilation and fractional crystallization (EC-E’RAχFC)
FS-DFA	Forward stepwise-discriminant function analysis
GEOROC	Geochemistry of rocks of the oceans and continents (database)
GPS	Geopositioning system
ICP-AES	Inductively coupled plasma atomic emission spectrometry
ICP-MS	Inductively coupled plasma mass spectrometry
InSAR	Interferometric synthetic aperture radar
LASI	Laccoliths, sills and dykes—Physical geology of shallow-level magmatic systems (series of field workshop)
LEFM	Linear elastic fracture mechanics
LIP	Large igneous province
LNB	Level of neutral buoyancy
LOI	Loss on ignition
MME	Mafic microgranular enclave
MPS	Maximum particle size
NAIP	North Atlantic Igneous Province
NAVDAT	North American volcanic and intrusive rock database
PAST	Paleontological statistics software package
PCA	Principal component analysis
PDMS	Polydimethylsiloxane
PETM	Paleocene-Eocene thermal maximum
PM	Primitive mantle
REE	Rare earth element
RMA	Reduced major axis regression
RTV	Room temperature vulcanization silicone
SDP	Spatial distribution pattern
SLI	Shallow-level intrusions
SPO	Shape-preferred orientation

TAS	Total alkali silica (plot)
TIMS	Thermal ionisation mass spectrometry
TOC	Total organic carbon
VPDB	Vienna Peedee Belemnite standard
VR	Vitrinite reflectance