Moab and Mount Hillers (Utah, USA)
22-26 September 2010

from Gilbert (1877)

Abstracts

Sven Morgan - Central Michigan University, Mount Pleasant, MI, USA
Eric Horsman - East Carolina University, Greenville, NC, USA
Michel de Saint Blanquat - CNRS and University of Toulouse, France
Basil Tikoff - University of Wisconsin, Madison, WI, USA
LASI 4 Conference

Physical Geology of Subvolcanic Systems: Laccolith, Sills and Dykes

Conveners:

Sven Morgan - Central Michigan University, Mount Pleasant, MI, USA
Eric Horsman - East Carolina University, Greenville, NC, USA
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LASI 4 Conference

Physical Geology of Subvolcanic Systems: Laccolith, Sills and Dykes

General Program

Wednesday, 22 September
Arrive in Salt Lake City. 2 pm leave on motorcoach bus to Red Cliffs Lodge (www.redcliffslodge.com), Moab, Utah. Icebreaker, dinner, and accommodations at lodge.

Thursday, 23 September
Oral presentations and accommodations at Red Cliffs Lodge.

Friday, 24 September
Oral presentations. Leave after dinner for Hanksville, Utah. Stay in local motels.

Saturday, 25 September – Field trip
AM - In the morning we will visit exposures of the Maiden Creek sill composed of two stacked sheets with a complex map view geometry and discuss emplacement history, magma flow patterns, etc..

PM - In the afternoon we will examine the Trachyte Mesa laccolith and consider how intrusion construction processes (multiple sheet injection) seen in the sill relate to those preserved in the Trachyte Mesa.

Sunday, 26 September – Field trip
AM - In the morning we will examine a complete cross section through a mature elongate laccolith (Sawtooth Ridge) and use excellent views of a nearby bysmalith (Black Mesa) to discuss growth of these intrusions, and how they may have evolved from sills and laccoliths.

PM - In the afternoon we will visit one superb outcrop of the outer margin of the main Mt Hillers intrusive center (Gold Creek exposures). Specific features to examine will likely include subvertical sedimentary beds, concordant sills, discordant dikes, and the main intrusive body. These exposures will serve as catalysts for discussion of the possible relationships between the range of intrusion geometries examined, and for the growth of complex shallowly emplaced igneous bodies in general. Return to Salt Lake City with stop in Richfield Utah for people going on the post-meeting trip.

Monday, 27 September – Post Meeting Field trip
## Thursday September 23

09:00 Welcome and introduction

### Session 1: Emplacement Processes - Chair: Michel de Saint Blanquat and Allen F Glazner

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<tr>
<th>Time</th>
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<tr>
<td>09:10</td>
<td>Christopher D. Henry, David A. John, and Joseph P. Colgan</td>
<td>Calderas, subjacent plutons, and lacco- or loppoliths? A perspective from geologic mapping of calderas of the ignimbrite flareup in Nevada</td>
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<tr>
<td>09:40</td>
<td>Basil Tikoff, and Paul R. Riley</td>
<td>Structural and tectonic controls on emplacement of Mammoth Mountain magmatism</td>
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<tr>
<td>10:00</td>
<td>Cristina de Ignacio, Mercedes Muñoz, and Juana Sagredo</td>
<td>The mafic-ultramafic, Montaña Blanca-Esquinzo subvolcanic intrusion: roots of Miocene volcanism in NW Fuerteventura, Canary Islands, Spain</td>
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<tr>
<td>10:20</td>
<td>Alexander Cruden and Andrew Bunger</td>
<td>Emplacement dynamics of laccoliths, sills and dykes from dimensional scaling and mechanical models</td>
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<tr>
<td>11:00</td>
<td>Sergio Rocchi, Laura Bracciali, Gianfranco Di Vincenzo, Andrea Dini, and Simone Vezzoni</td>
<td>Dikes and mega-dike in the Morozumi Range (Antarctica)</td>
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<tr>
<td>11:10</td>
<td>Francesco Mazzarini, Giovanni Musumeci and Alexander R. Cruden</td>
<td>Sill geometry and fabrics in the syn-tectonic contact aureole of the Porto Azzurro pluton, eastern Elba Island, Italy</td>
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<tr>
<td>11:50</td>
<td>Francesco Mazzarini, Ilaria Isola and Alexander R. Cruden</td>
<td>Thickness distribution of felsic sills in the upper brittle crust, eastern Elba Island, Italy</td>
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### Session 1: Emplacement Processes (suite) - Chair: Basil Tikoff and Sandy Cruden

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<tr>
<td>14:00</td>
<td>Emanuele Roni, Sergio Rocchi, Andrea Dini, David Scott Westerman and Carl Stevenson</td>
<td>Magma flow in laccoliths (Elba island): results from fabric analyses</td>
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<tr>
<td>14:20</td>
<td>David S. Westerman, Andrea Dini, Sergio Rocchi, Emanuele Roni and Ethan J. Thomas</td>
<td>Waves-ropes-lobes, fluidization and deformation at laccolith-host contacts (Elba Island, Italy)</td>
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<tr>
<td>14:40</td>
<td>Craig Magee, Carl Stevenson, Brian O’Driscoll and Tim Reston</td>
<td>Emplacement mechanisms of cone sheets: A case study from Ardnamurchan, NW Scotland</td>
</tr>
<tr>
<td>15:00</td>
<td>Carl Stevenson, Brian O’Driscoll, and Craig Magee</td>
<td>Revisiting classic emplacement mechanisms in the British and Irish Palaeogene Igneous Province</td>
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<td>15:20-15:50</td>
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16:10 Nicolle Schulz, Peggy Hielscher, Christoph Breitkreuz and Bodo-Carlo Ehling

3D GOCAD modeling of an intermediate sill complex in the Late Paleozoic Halle Volcanic Complex, East Germany

16:30 Discussion?

17:00-18:00 Posters session

### Posters Session

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<td>Benoit-Michel Saumur, Alexander R. Cruden and Dawn Evans-Lamswood</td>
<td>The Mesoproterozoic Voisey’s Bay Intrusion: Laccolith or Loppolith?</td>
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<tr>
<td>Jason Luke, Eric H. Christiansen, R. Keach</td>
<td>3D-Seismic Images Reveal the External Structure of Igneous Intrusions, Taranaki basin, off-shore western New Zealand: Hints for Emplacement Mechanisms</td>
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<tr>
<td>Sverre Planke</td>
<td>Presentation of the LASI 5 in the Karoo basin</td>
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<td>David hacker et al.</td>
<td>Presentation of the Iron Axis laccoliths</td>
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## Program

### Friday September 24

### Session 2: magmatic processes - Chair: Eric Horsman and Sergio Rocchi

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<th>Time</th>
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<tr>
<td>09:00</td>
<td>Allen F. Glazner, John M. Bartley and Drew S. Coleman</td>
<td>Reconciling incremental emplacement with the apparent homogeneity of plutonic rocks</td>
</tr>
<tr>
<td>09:30</td>
<td>Sven Morgan, Jeremy Conner, Taryn Serwatowski, James Student, Eric Horsman and Michel de Saint Blanquat</td>
<td>Internal contacts in the Henry Mountains satellite intrusions: Not just shear zones!</td>
</tr>
<tr>
<td>09:50</td>
<td>Catherine Annen</td>
<td>Intrusions incremental emplacement and thermal aureoles</td>
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<tr>
<td>10:10</td>
<td>Mélanie Barboni and François Bussy</td>
<td>Quantitative constraints on the thermal evolution of incrementally built &quot;sill on sill&quot; magma reservoirs in the shallow crust</td>
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<tr>
<td>10:30-11:00</td>
<td><strong>Coffee break</strong></td>
<td></td>
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<tr>
<td>11:00</td>
<td>Andrea Dini, Sergio Rocchi and Simone Vezzoni</td>
<td>Porphyry dikes and skarn pockets filled by mafic magma at Temperino mine (Campiglia Marittima, Italy)</td>
</tr>
<tr>
<td>11:20</td>
<td>Ingrid Aarnes, Sverre Planke, Henrik Svensen, Yuri Y. Podladchikov, Mikal Trulsvik, Stéphane Polteau</td>
<td>Gas generation during emplacement of Large Igneous Provinces – implications for global climate and petroleum systems</td>
</tr>
<tr>
<td>11:40</td>
<td>Karina Fernandes, Stephen M. Jones, Nick Schofield and Geoff Clayton</td>
<td>North Atlantic Igneous Province sills: Did they trigger or maintain Paleocene-Eocene Thermal Maximum global warming?</td>
</tr>
<tr>
<td>12:00</td>
<td>Sverre Planke, Stéphane Polteau, Fernando Corfu, Henrik Svensen, and Ariano Mazzini</td>
<td>Rapid emplacement of the Karoo Basin sill complex during the Toarcian carbon isotope excursion revealed by U-Pb dating of zircons.</td>
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<tr>
<td>12:20-14:20</td>
<td><strong>Lunch</strong></td>
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### Session 2: magmatic processes (suite) - Chair: Sven Morgan and Sverre Planke

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<tr>
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<tr>
<td>14:20</td>
<td>Eric H. Christiansen</td>
<td>Cenozoic Magmatic Overview of the Basin &amp; Range/Colorado Plateau</td>
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<tr>
<td>14:50</td>
<td>Eric Horsman</td>
<td>A review of Henry Mountains geologic thought, 1869 - 2010</td>
</tr>
<tr>
<td>15:20</td>
<td>Laura Renaudin, Michel de Saint Blanquat, Michel Grégoire, Mathieu Benoît, Guillaume Delpech, Jean-Louis Paquette, Eric Horsman and Sverre Planke</td>
<td>Origin, evolution and emplacement of Mount Hillers diorites</td>
</tr>
<tr>
<td>15:40</td>
<td>Jean-Louis Paquette, Michel de Saint Blanquat, Guillaume Delpech, Eric Horsman and Sverre Planke</td>
<td>LA-ICPMS U-Pb zircon dating of Mount Hiller laccolite and satellite intrusions: short-length emplacement and large Proterozoic inheritance.</td>
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<tr>
<td>16:00-16:30</td>
<td><strong>Coffee break</strong></td>
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<tr>
<td>16:30-17:00</td>
<td><strong>Final discussion?</strong></td>
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Talks are 15' + 5' questions  
Keynotes are 25' + 5' questions
Gas generation during emplacement of Large Igneous Provinces – implications for global climate and petroleum systems

Ingrid Aarnes1, Sverre Planke1,2, Henrik Svensen1, Yuri Y. Podladchikov1, Mikal Trulsvik2, Stephane Polteau2

1 PGP, University of Oslo, Norway – ingrid.aarnes@fys.uio.no
2 VBPR, Oslo Innovation Center – planke@vbpr.no

Keywords: contact metamorphism, multiple sills, sediment degassing

Organic maturation during contact metamorphism is well known, although most studies are concerning the localized effects of one intrusion only. Large scale fluid generation can occur when a sedimentary basin is intruded by multiple igneous sills during formation of Large Igneous Provinces (LIPs), like the Vøring and Møre basins, offshore Norway (~55.5 Ma) and the Karoo Basin, South Africa (~182.6 Ma). The LIP-formation coincides in time with global carbon cycle perturbations, warming of the climate and mass extinctions. The proxy records from these events are best explained by a massive release of isotopically light carbon gases, such as methane, to the atmosphere.

In this study we aim at quantifying the generation potential of organic and inorganic devolatilization reactions during LIP emplacement in sedimentary basins. Geochemical data from boreholes intruded by multiple sills are used to constrain our model.

Both depth and thickness of the intrusions are important parameters in determining the hydrocarbon yield. Modeling also illustrates an essential dependence on the background temperature of the sediments. In the case of multiple sills, the distance between the intrusions and the relative emplacement timing are key parameters. Fig. 1 shows that multiple sills can increase the hydrocarbon yield with up to 35 % (Aarnes et al., in review). The organic-rich formations are commonly located at the base of a sedimentary basin, which coincides with the intrusion level of the thickest sills (>100 meters) and the warmest parts of the basin. Hence, conditions are favorable for large-scale contact metamorphism of the sedimentary rocks.

Our model is applied to borehole data from the Voring Basin and the Karoo Basin to get realistic estimates of the fluid generation in the shales. We show that for the Utgard sill complex in the Voring Basin, consisting of two ~100 m thick sills intruded into relatively poor source-rocks with ~1 wt. % TOC, the total gas generation potential equals that of the Troll field (10 Gt CH4), the largest producing gas-field offshore Norway. The sills in the Karoo Basin intrudes organic-rich shale formations, with TOC contents locally up to 15 wt. %, and the total generation potential of the whole basin lies between 3000 – 16 000 Gt of CH4 (Aarnes et al., accepted).

These gases could have rapidly reached the atmosphere through numerous (>1000) vents mapped in the Vøring, Møre and Karoo basins. The vents are vertical pipe structures shown to originate in the contact aureoles of the heavily metamorphosed shales (e.g. Svensen et al, 2007). From derivation of new analytical solutions, we show in Fig. 2 that the pressure buildup from devolatilization reactions is large enough to cause fracturing and vent-formation (Aarnes et al., subm.).

Release of the potent greenhouse gas methane to the atmosphere can explain the global carbon cycle perturbations and warming events associated with the emplacement of these and other Large Igneous Provinces (e.g. Svensen et al., 2004). Still, if less than 1% of the generated gases were to be trapped in a reservoir, it would result in a substantial gas field.

Fig. 1 – a) Organic maturation (%Ro) as a function of increasing vertical separation between two sills. b) Total CH4 generation in a vertical column with area 1 m2 above and below the sill. The generation of methane from multiple sills is up to 35 % higher than from two separate sills due to thermal interaction, and a larger total volume of sediments affected. Figure from Aarnes et al., (in review).
Acknowledgements

We would like to thank James A. D. Connolly for great assistance during the development of the model.

References


Fig. 2 – Expected vent formation resulting from CH$_4$ generation around the sill intrusion, as a function of depth and permeability of the host-rock contoured for different wt. % total organic carbon (TOC). The green field represents the condition where venting can be expected in the case of 5 wt. % TOC, and higher wt. % increases this field. In the Karoo Basin, the level of sill intrusion is about 2-3 km, and the permeability of unfractured shales is about 10$^{-18}$ m$^2$, which is compatible with vent formation from devolatilization reactions. Figure from Aarnes et al. (subm.)
Intrusions incremental emplacement and thermal aureoles

Catherine Annen

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Keywords: contact metamorphism, pluton growth, incremental growth.

For a given depth and initial country rock temperature, heat transfer calculation shows that the size of a thermal aureole, induced by an intrusion that is rapidly emplaced, is proportional to the size of the intrusion (fig. 1). However, in nature, thermal aureoles are sometimes larger (e.g. Westphal et al., 2003) and often smaller (e.g. Guillot et al., 1995) than predicted by simple thermal models. For a given depth and country rock composition, aureole relative sizes (size of aureole/size of intrusion) can vary over several orders of magnitude (Barton et al., 1991). Fluid circulation can affect the size of the aureole. A larger than predicted thermal aureole can also be explained by a sustained long lasting magma flux during intrusion but a smaller than predicted aureole is more difficult to understand.

An increasing series of evidence indicates that many large and apparently coherent igneous bodies were built up by the addition of smaller intrusions (e.g. Michel et al., 2008). In the present paper, numerical simulation is used to determine the size of thermal aureoles induced by an incrementally growing igneous body. The igneous body is assumed to grow by addition of low aspect ratio magma sheets and heat transfer is calculated in 1D. The accretion of 10 sheets, 100 m thick, is modeled resulting in an igneous body with a final thickness of 1km. A series of models are run with time intervals between two intrusive increments (recurrence times) ranging from 10 yrs to 1 My corresponding to a range of emplacement rates from 100 m/yr to 1 mm/yr. For each run, the crust is left to thermally relax during 500,000 yrs after the last intrusive episode. Profiles of the maximum temperatures reached in the country rock are recorded.

For a tabular body instantaneously emplaced in a country rock with a homogenous temperature, the temperature profiles on each side of the body are similar. For a growing body, where each sheet is added at the boundary between the growing body and the country rock, the temperature profiles differ on each side of the body. If we assume that the sheets are horizontal sills and the body grows from top to bottom (under-accretion), the temperatures reached in the aureole at the top of the body (aureole 1 in fig. 2 and 3) are lower than the temperatures in the aureole at the bottom of the body (aureole 2 in fig. 2 and 3). Conversely, if the body grows from bottom to top (over-accretion), the highest temperatures are in the top aureole.

Fig. 1 – Size of contact aureoles for an instantaneously emplaced sheet-like magma body as a function of the magma body thickness. Size of aureoles is represented as the distance to contact where the maximum temperatures are 550 and 625°C. Initial temperature of country rock is 350°C, intruded magma temperature is 990°C and magma crystallization latent heat is 350,000 J/kg.

Fig. 2 – Maximum temperatures reached in the country rock related to intrusion of 10 sheets 100 m thick with a recurrence interval of 1000 years, as a function of the distance to contact. Aureole 1 is for the contact that is opposite to the locus of injection. Aureole 2 is for the contact where successive intrusions are added. Distances are normalized to the final thickness of the igneous body (1
km). Non dimensional temperature is $T - T_0 / T_m - T_0$, with $T$ the maximum temperature, $T_0$ the initial country rock temperature and $T_m$ the equivalent magma temperature corrected for latent heat.

The simulations show that the shape of temperature profiles and thus the size of thermal aureoles are controlled by emplacement rates, i.e. the thickness of successive intrusions divided by the recurrence time. The top aureole (assuming under-accretion) is always thinner than it would be in the case of instantaneous emplacement of a body of the same size and it decreases with increasing recurrence times (decreasing emplacement rates) (fig. 3). In contrast, the bottom aureole (again assuming under-accretion) that develops in the country rock that is close to the locus of intrusions first increases with increasing recurrence times and is larger than the aureole induced by an instantaneously emplaced body (fig 3). After a maximum is reached, the relationship between aureole size and recurrence times reverses. For long recurrence times (low emplacement rates), the bottom aureoles is thinner than the aureole induced by an instantaneously emplaced body. For very long recurrence times, the relationship between aureole sizes and recurrence times breaks down and both top and bottom aureole sizes become constant. For low emplacement rates, because the crust has time to thermally relax between intrusions, the size of the thermal aureole is controlled by the size of one increment and is independent from the size of the whole igneous body.

Emplacement rate is an important parameter for understanding the development of large magma chambers and the relationship between plutonism and volcanism because large volumes of magma can only accumulate in igneous bodies emplaced at high emplacement rates of several centimeters per year (Annen, 2009). In some igneous bodies that are believed to be emplaced incrementally the contact between intrusions is cryptic. In this context, studies of thermal aureoles may provide constraints on the emplacement rate of plutons and on the size of the intrusive increments that built them.

References


Fig. 3 – Size of thermal aureoles as a function of recurrence interval. The size of aureoles is represented as the distance to contact where the non dimensional maximum temperature is 0.2 (c.f. fig 2). The distance to the contact is normalized by the result obtained for an instantaneously emplaced intrusion with a thickness equivalent to the final thickness of the growing body. The non dimensional recurrence interval is $t \kappa / L^2$, with $t$ the recurrence interval, $\kappa$ the diffusivity and $L$ the thickness of the intrusive increments. Aureole 1 is for the contact that is opposite to the locus of injection. Aureole 2 is for the contact where successive intrusions are added.
Quantitative constraints on the thermal evolution of incrementally built "sill on sill" magma reservoirs in the shallow crust

Mélanie Barboni and François Bussy

Institute of mineralogy and geochemistry, University of Lausanne, Switzerland - melanie.barboni@unil.ch

Keywords: Shallow emplacement, sill, in-situ differentiation, thermal constraints.

Understanding the emplacement and growth of intrusive bodies in terms of mechanisms, duration, thermal evolution and rates are fundamental aspects of crustal evolution. Recent studies show that many plutons grow in several Ma by in situ accretion of discrete magma pulses, which constitute small-scale magmatic reservoirs. The residence time of magmas, and hence their capacities to interact and differentiate, are controlled by the local thermal environment. The latter is highly dependant on 1) the emplacement depth, 2) the magma and country rock compositions, 3) the country rock thermal conductivity, 4) the rate of magma injection and 5) the geometry of the intrusion (Annen et al., 2006; Annen, 2009).

In shallow level plutons, where magmas solidify quickly, evidence for magma mixing and/or differentiation processes is considered by many authors to be inherited from deeper levels (e.g. Galzner et al., 2004). We show however that in-situ differentiation and magma interactions occurred within basaltic and felsic sills at shallow depth (0.3 GPa) in the St-Jean-du-Doigt bimodal intrusion, France. This intrusion emplaced ca. 347 Ma ago (IDTIMS U/Pb on zircon) in the Precambrian crust of the Armorican massif and preserves remarkable sill-like emplacement processes of bimodal mafic-felsic magmas. Field evidence coupled to high precision zircon U-Pb dating document progressive thermal maturation within the incrementally built laccolith. Early m-thick mafic sills (eastern part) form the roof of the intrusion; they are homogeneous and fine-grained with planar contacts with neighbouring felsic sills (Fig.2a). The system gets warmer within a minimal 0.5 Ma time span in the western part of the pluton. Sills are emplaced by under-accretion (in the sense of Annen et al., 2006) under the old eastern part, interact and mingle (Fig.2b). A striking feature of this younger, warmer part is in-situ differentiation of the mafic sills in the top 40 cm of the layer (Fig.1), which suggests liquids survival in the shallow crust.

We performed rheological and thermal models, in order to establish the conditions required to allow the observed in-situ differentiation-accumulation processes. Strong constraints such as total emplacement duration (ca. 0.5 Ma, TIMS date) and pluton thickness (1.5 km, gravity model) allow a quantitative estimation of the various parameters involved (injection rates, incubation time, ...). Our results show that in-situ differentiation may be achieved in less than 10 years at such shallow depth, provided that:

Fig. 1 – Example of in-situ differentiation at the top of the mafic sills in the western "warm" part with mineralogical evolution to the top.

1. The differentiating sills are injected beneath consolidated, yet still warm basalt sills, which act as low conductive insulating screens (eastern part formation in the SJDD intrusion). The later are emplaced in a very short time (800 years) at high injection rate (0.5 m/y) in order to create a "hot
"zone" in the shallow crust (incubation time as defined by Annen et al., 2006). This implies that nearly 1/3 of the pluton (400m) is emplaced by a sustained magmatic activity in a short time span at the very beginning of the system.

2. Once incubation time is achieved, our calculations show that a small hot zone is created at the base of the sill pile, where new injections stay above their solidus T°C and may interact and differentiate. Extraction of differentiated residual liquids might eventually take place and mix with newly injected magma as documented in active syn-emplacement shear-zones within the "warm" part of the pluton.

3. Finally, the model shows that in order to maintain a permanent hot zone at shallow level, injection rate must be of 0.03 m/y with injection of 5m-thick basaltic sills every 130y, implying formation of a 15 km-thick pluton, which is unrealistic in SJDD considering the thickness constrained by gravimetric data (1.5 Km). It also largely exceeds the average thickness observed for many shallow level plutons. Consequently, we rather infer that there was no permanent hot zone (or magma chamber) at such a shallow level, but formation of small, ephemeral (10-15yr) reservoirs (Reid, 2003) which represent only small portions of the final size of the pluton. Thermal calculations show that such ephemeral reservoirs could form in SJDD if 5m-thick basaltic sills emplaced every 1500y. The reservoirs correspond to the coalescence of a few individual sills in a mushy state, which can briefly interact and differentiate.

Acknowledgements

We have very much appreciated the stimulating discussions and support offered by Catherine Annen (University of Bristol) about the thermal models. We also thank Urs Schaltegger, Maria Ovtcharova (University of Geneva) and Blair Schoene (University of Princeton) for their help in the TIMS dates acquisition. This ongoing study was funded by the Swiss National Science Foundation, grant 200021-116705.

References


Fig. 2 – A. Bimodal sills in the early eastern "cool" part showing planar boundaries. This part was built during the incubation time of the system. B. Bimodal sills in the younger western "warm" part with mingling processes indicating liquid state magmatic interactions. This part emplaced once the system was warm enough to allow liquid survival in the shallow crust.
Emplacement dynamics of laccoliths, sills and dykes from dimensional scaling and mechanical models

Alexander Cruden\(^1\)\(^3\) and Andrew Bunger\(^2\)

\(^1\) University of Toronto, Canada – cruden@geology.utoronto.ca
\(^2\) CSIRO Earth Science & Resource Engineering, Melbourne, Australia – Andrew.Bunger@csiro.au
\(^3\) Monash University, Melbourne, Australia

Keywords: laccoliths, sills, dykes.

Tabular intrusions are characterized by a spectrum of length (\(L\)) and thickness (\(T\)) values (Fig. 1) that can be described by a range of power-law scaling relationships for different types of intrusive structures (Cruden and McCaffrey 2006). The empirical power-law scaling of tabular intrusions is:

\[
T = bL^a
\]

(1)

where \(a\) is the power-law exponent and \(b\) is a constant (McCaffrey and Petford 1997). The exponent \(a\) differentiates between growth behavior in which the aspect ratio \(L/T\) is increasing (\(a < 1\), “lateral spreading”) and decreasing (\(a > 1\), “uplifting”). For laccoliths, the growth regime favors uplifting with \(a > 1\). Indeed, when applied to individual provinces, \(a\) has been observed to be as large as 1.5 (Rocchi et al. 2002). In contrast, plutons, large mafic sills, mafic dykes and felsic sills favor lateral spreading with \(a < 1\). This contribution focuses on new and previously compiled dimensional data and scaling relationships for laccoliths, mafic and felsic sills, and mafic dykes (Fig. 1).

Current research is aimed at understanding the mechanical basis for these scaling relationships along with some of the observed geometric characteristics such as the classical flat-topped morphology of laccoliths. To this end, we first consider intrusions which do not interact with Earth’s surface. These include most dykes as well as sills for which the radius is much smaller than theemplacement depth. Under conditions where the magma pressure is spatially uniform and the growth of the intrusion is implied by \(K_I = K_{Ie}\), where \(K_I\) is the mode I stress intensity factor and \(K_{Ie}\) is the mode I fracture toughness of the rock, LEFM predicts (e.g. Olsen 2003):

\[
T = \frac{K_{Ie}(1-v^2)}{E} \sqrt{\frac{8}{\pi}} \sqrt{L}
\]

(2)

where \(E\) is Young’s modulus and \(v\) is Poisson’s ratio. The exponent of the \(L-T\) scaling for mafic dykes (Delany and Pollard 1981; Olsen 2003; Schultz et al. 2008a,b) and small mafic and felsic sills (this study, see Fig. 1) is therefore consistent with this LEFM prediction. However, as noted in previous studies, \(K_{Ie}\) values 10 to 1000 times laboratory values are required to fit the different data sets (Delany and Pollard 1981; Olsen 2003; Schultz et al. 2008; Cruden et al. 2009). For example, best fit curves that bracket the dyke and sill data in Fig. 1 are computed for values \(E = 100\) GPa, \(v = 0.3\) and \(K_{Ie} = 300\) to 3000 MPa m\(^{1/2}\) whereas typical laboratory rock toughness values range from 0.5 to 2 MPa m\(^{1/2}\). If large effective \(K_{Ie}\) values can be accounted for by scale effects, fracture network branching or cooling/solidification at fracture tips (viz., tip screen out) then LEFM accounts satisfactorily for the scaling of these intrusion types. Furthermore, this model is favored relative to the LEFM model under conditions of uniform magma pressure, which is at odds with the data because it predicts \(a \sim 1\) (Olsen 2003). Furthermore, this model is favored relative to models that consider viscous flow to be predominant because the magma viscosity range required to bracket the data is implausibly high (Cruden et al. 2009).

While the data for intrusions that do not interact with the surface can be explained, at least to some extent, through application of existing LEFM models, current theories do not fare as well for laccoliths and large mafic sills. Such intrusions almost always attain a radius that is similar to, or in many cases, much larger than the emplacement depth. Elastic plate theory (e.g., Pollard and Johnson 1973) predicts bell-shaped thickness profiles, which is at odds with the observed flat-topped thickness profiles of these intrusions. Nor can plate theory account for the \(L-T\) scaling of large mafic sills. The classical punch model of Gilbert (1877) and the laminar-sliding plate theory of Koch et al. (1981) are consistent with flat-topped thickness profiles (essentially as a result of the models assuming this shape \textit{a priori}), but fail to make appropriate predictions of the \(L-T\) scaling for either laccoliths or large mafic sills. In an effort to provide a model that is more consistent with the data, we have revisited elastic plate theory in light of the fact that previous elastic plate-based predictions have not taken into account an appropriate fracture propagation
condition, fluid flow in the growing intrusion, and, importantly, the influence of the weight of the magma on intrusion growth (Bunger and Cruden 2010). We present a model for the growth of circular intrusions that accounts for all of these factors. The model predicts the appropriate geometry for both laccoliths and large mafic sills. The predicted thickness-to-length relationships are also consistent with field data. Hence, while it may sometimes be appropriate, there is in general no fundamental need to appeal to large scale rock plasticity in order to explain observed intrusion geometries and it may in fact be appropriate to understand the growth of laccoliths and large sills in light of a single underlying mechanical model.

References


Porphyry dikes and skarn pockets filled by mafic magma at Temperino mine (Campiglia Marittima, Italy)

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Skarn deposits commonly result from the metasomatic alteration of a carbonate-rich rock by infiltration of hydrothermal fluids. Most skarns have an intimate spatial relationship with igneous intrusions, although in some instances magmatic hydrothermal fluids migrate considerable distances to produce skarns well outside contact aureoles, without any obvious link with magmatic intrusions. In those cases where favourable exposures allow direct observation of the skarn in contact with an igneous intrusion, a mineralogical zoning of the metasomatic masses has been described.

The area of Campiglia Marittima (Fig. 1) is characterised by a structural high made up of carbonatic formations (Falda Toscana) and bounded by N-S striking extensional faults. A peraluminous monzogranite intrusion emplaced at 5.7 Ma at the base of Falda Toscana Unit producing widespread contact metamorphism and foliation. Later (around 4.5 Ma) mafic and acidic porphyritic dikes emplaced concurrently with the formation of several skarn bodies showing a variable content of Cu-Fe-Pb-Zn sulfides (Corsini et al., 1980). In spite of the numerous studies, chronological relationships between monzogranite, porphyries and skarns have never been defined (Barberi et al., 1969).

New field, petrographic and mineralogical data on skarn and porphyries from the Temperino mining area were collected during a detailed survey both at the surface and in mine shafts and drifts. The geological survey in underground works allowed a three-dimensional control of the geometry and distribution of skarn mineral zones/textures and the mafic porphyry bodies. These observations were integrated with data provided by old mining surveys and drill logs. The bulk of data led to the reconstruction of a different history than previously thought.

After the emplacement of the monzogranite and development of contact metamorphism, ilvaite-hedenbergite skarns formed producing four main "en
echelon” tabular bodies. The mafic magma emplaced after formation of skarn bodies, forming dikes and filling metric-sized crystal pockets occurring in between already-formed hedenbergite-ilvaite spheroids (Fig. 3). Mafic magma exploited fractures and pockets of the skarn masses with limited injections into the marble host.

The net result of this process is the peculiar formation of isolated masses of mafic igneous porphyry that show the negative shape of the pockets where coarse, euhedral ilvaite crystals project (Fig. 3). The late intrusion of mafic magma produced thermal effects on the host skarn with prograde back-reaction transforming ilvaite into a hedenbergite-magnetite assemblage and promoting reversal chemical zoning of the hedenbergite crystals.

Later, acidic magmas emplaced forming two dikes that crosscut both skarn masses and mafic porphyry bodies. The two acidic dykes display systematic side-steps and bridges indicating emplacement controlled by a right-lateral transcurrent zone. The acidic porphyries have been strongly hydrothermally altered (sericite, adularia, epidote) but they are never related to significant sulfide concentrations.

In the Campiglia Marittima area the Mio-Pliocene Tuscan magmatism produced several intrusive units ranging in geometry from pluton to sub-vertical tabular intrusions, but the most peculiar emplacement geometry is represented by the skarn pockets filled by mafic magma found at Temperino mine.

This noticeable occurrence provides stimulating insights on relative timing of magma emplacement, ore fluids release and development of metasomatic processes, rising also questions on mechanisms and timing of magma transfer and emplacement.

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References
North Atlantic Igneous Province sills: Did they trigger or maintain Paleocene-Eocene Thermal Maximum global warming?

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Intrusion of North Atlantic Igneous Province (NAIP) sills has been suggested to generate most of the greenhouse gases that forced warming during the ~55.8 Ma Paleocene-Eocene Thermal Maximum (PETM) global warming event (Svensen et al. 2004). Organic geochemical analysis and numerical climate models suggest that methane was involved in forcing PETM warming (Pancost et al. 2007; Rensson et al. 2004). NAIP sills may have generated much of this methane by thermal maturation of organic material in the host rocks. Hydrothermal vents above sills have been observed on seismic reflection data (Fig. 1) and also by drilling. Such vents would have allowed the escape of greenhouse gases to the ocean and atmosphere.

Svensen et al. (2004) showed that the NAIP sills could have generated the total volume of methane required to explain the PETM. But this methane was not supplied at an even rate; atmospheric modeling shows that larger methane fluxes are required in the first few millennia to kick-start warming (Rensson et al. 2004). Nisbet et al. (2009) questioned whether the high fluxes required to trigger the PETM could be supplied by sill-vent complexes. They estimated that if all of the methane generated next to an individual sill was released explosively through a hydrothermal vent, the resulting warming would probably last for a few decades. The climate would likely return to its pre-existing state before the next sill intruded, making it difficult to explain initiation of sustained PETM warming. In this case, methane from NAIP sills would have helped maintain PETM warming, once initiated by some other mechanism(s).

Here, we explain how field observations of sills from Golden Valley, South Africa, together with seismic observations of vents, suggest that methane generated by NAIP sills is released even more slowly than estimated by Nisbet et al. (2009). We argue that methane from each sill is released in a two-stage process, illustrated in Fig. 2. In the first phase, only a small amount of the total methane generated by the sill escapes by explosive venting. The bulk of the methane seeps out slowly during the second phase.

The first key field observation is that a zone of fluidized country rock can be recognized adjacent to some sills (Schofield et al. 2010). We interpret that host-rock fluidization occurs by the same processes that drive venting to the surface. Boiling of pore water and thermal maturation begin as soon as a sill intrudes host-rock but the gases produced cannot reach the surface until a hydrothermal conduit forms. As the sill rim propagates laterally and upward, gas pressure in the boiling zone may become sufficient to fracture the host-rock and allow a hydrothermal conduit to propagate rapidly to the surface (Jamtveit et al. 2004). The combination of pressure-driven fracturing and rapid flux of escaping gas leads to fluidization of host-rock next to the sill and gas-supported flow within the conduit.

The second critical field observation is that host-rock fluidization does not occur next to the entire sill. Typically, the fluidization is localized within a few meters of certain inward-dipping (host-rock transgressing) sill margins (Schofield et al. 2010). These sill margins are also characterized by radially-trending upfield fronts. Magma may have advanced into the fluidized host-rock as a viscous fingering front, forming the lobe and finger structures that coalesced to form undulations. Irrespective of the details of sill emplacement, the volume of fluidized host-rock able to export gas rapidly up the hydrothermal conduit is much smaller than the final volume of the thermal aureole. Furthermore, the thermal aureole takes centuries to millennia to grow, while fluidization probably occurs within years of sill emplacement. Therefore, most of the gas that escaped explosively up the hydrothermal vent was probably water vapor, and only a small proportion of the total methane was exported explosively.

The third key observation is that seismic profiles show that hydrothermal vents often are topped by eye structures, each comprising a crater and a mound (Fig. 1). We interpret that the eye structures demonstrate a two-stage fluid expulsion history. At the initiation of venting, gas flux up the conduit is rapid enough to fluidize the pipe breccia and to form an explosive crater at the palaeo-surface. As pressure in the boiling zone adjacent to the sill is released, the flux of gas through the vent wanes and eventually ceases to support the vent rocks. At this stage, flow of gas and fluid through the vent is a Darcy flow through the static vent breccia. This
seeping fluid flow is associated with infill of the crater and construction of a mound. The bulk of the methane generated by thermal maturation would have been exported to the atmosphere during this phase.

Simple volumetric calculations based on typical fluidized zone dimensions suggest that roughly 0.1–1% of the total methane produced by NAIP sills was exported rapidly (Fig. 3). Without proper modeling of methane generation and expulsion rates, coupled with atmospheric modeling of the resulting climate forcing, it is too early to conclude that NAIP sills triggered the PETM.

Fig. 1 – 2D seismic image of a hydrothermal vent emanating from a sill tip. The vent is imaged as a poorly resolved conduit terminating at the palaeosurface in an eye structure comprising a crater and mound.

Fig. 2 – Illustration of the two-step release of gas produced by igneous sills.

Fig. 3 – Estimated volumes of gas released explosively (Fig 2a) from the fluidized zone (a band of thickness 1 m or more over 25% of the area of the sill) and slowly (Fig 2b) from the rest of the thermal aureole. Calculations are based on data from the Irish and Norwegian sectors of the North Atlantic Igneous Province.

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References


Reconciling incremental emplacement with the apparent homogeneity of plutonic rocks

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A growing body of geochronologic data (e.g., Coleman et al., 2004) indicates that many plutons were emplaced over time spans on the order of 10⁶ years rather than the ~10⁵ year times required to cool even huge magma bodies. Such data require the plutons to have grown in situ in small increments rather than to reflect the ascent of giant magma blobs as shown in textbooks (Glazner et al., 2004). The lithologic homogeneity and continuity of many plutons appears to conflict with this conclusion. If plutons grow in myriad small increments, where are the internal contacts?

Here we argue that the paucity of visible internal contacts is largely a product of post-emplacement textural modification. Crack-seal appears to be an important intrusive process over length scales from 10 cm to 10 km (Fig. 1; Bartley et al., 2008). However, the textural record of cyclic crack opening and magma injection is well preserved at the 10 cm scale in composite dikes, but lost at the 10 km scale in large plutons owing to pervasive recrystallization.

Evidence for such textural modification includes: (1) sharp internal contacts are uncommon even in plutons in which lithologic sheeting and/or in-situ enclosure of wall-rock screens indicate growth by amalgamation of dikes and/or sills (Fig. 1; Pitcher and Berger, 1972; Mahan et al., 2003); (2) mineral compositions typically have reequilibrated at low, nominally subsolidus temperatures; (3) plutonic textures, if interpreted with paragenetic criteria used in volcanic rocks, commonly indicate a highly improbable order of crystallization; and (4) field evidence is common for the presence large-magnitude focused ductile shear within plutons, yet microstructural products of such deformation are absent, suggesting that they were eliminated by pervasive recrystallization.

This view of pluton growth and plutonic textures implies a need to reconsider the basic notion of what a “pluton” is. Plutons are defined by field mapping of lithologic variations. The typical compositional range within a single pluton, combined with the relatively small overall range of granitic compositions, means that texture commonly is the principal mapping criterion. If plutonic textures are products of post-emplacement processes, then there may be little connection between mapped plutonic rock bodies and the bodies of magma from which the plutons grew.

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Fig. 1 — Magmatic crack-seal across length scales. A—Composite dike, Big Pine Creek, CA (Bartley et al., 2008); B—Interleaved dikes and wall-rock screens, McDoogle pluton, CA (Mahan et al., 2003); C—Wall-rock screens in the McDoogle pluton (Coleman et al., 2005); D—Sheet-like plutons with interleaved wall-rock screens, Mt. Pinchot Quadrangle, Sierra Nevada, CA (after Moore, 1963).

Fig. 2 — Stained slabs from the transition between non-megacrystic Half Dome Granodiorite (D) and megacrystic Cathedral Peak Granodiorite (E) in Yosemite National Park. Plagioclase is red, K-feldspar yellow, quartz medium gray, and mafic minerals black. This textural transition occurs smoothly, generally over 1-2 km but in places over only a few 100 m. The main textural change is coalescence of K-feldspar into large poikilitic crystals, although all phases coarsen. The pluton boundary has been drawn, arbitrarily, within this transition zone, but this transition reflects post-emplacement textural annealing, not a primary contact.
between distinct magma bodies. From Johnson and Glazner (2010).

Plutons are bounded by contacts with either non-plutonic wall rocks or texturally distinct plutonic rocks. Where a younger pluton intrudes a substantially older one (e.g., Late Cretaceous into Middle Jurassic), the contact is commonly sharp. However, where the plutons are of similar age, the contact is commonly subtle and gradational over length scales of 10-100 m. Even where the textures of the plutons are distinct away from the contact, the plutons commonly take on each other’s textural characteristics as the gradational contact is approached. In the Tuolumne Intrusive Suite of Yosemite National Park, California, one can walk from the outer contact to the central pluton, across 6 km of glacially polished slabs that expose products of 5 m.y. of intrusive history, without crossing a sharp intrusive contact. The plutons must be highly composite and yet the field relations do not show it. The internal anatomy of the plutons (in particular, the Half Dome Granodiorite) is locally intricate with complex zones of diking and schlieren, but all of the contacts between the mapped plutons—which are defined almost entirely based on textural differences—are generally gradational and subtle (Fig. 2).

This pattern is puzzling if the textures reflect the plutons’ distinct magmatic histories. It is readily understandable if the textures instead reflect their shared post-emplacement thermal history. The implication is that a mapped pluton records a degree of uniformity in post-emplacement thermal and crystallization history, but the map does not provide reliable information about the size, number, dimensions, or shapes of the magma bodies from which the pluton grew.

Mineral compositions in these plutons require significant, ubiquitous recrystallization. \(O_{K_0}\) K-feldspar (vs. \(O_{K_0}\) expected from the magma composition), magnetite that has completely exsolved its Ti component, and 3-feldspar assemblages with plagioclase compositions spanning the peristerite gap all require recrystallization down to ~400°C, likely in the presence of a small-volume pore fluid rich in H$_2$O, F, B, etc. Such volatile components depress the solids such that a small amount of leucogranitic pore melt persists down to temperatures normally associated with the upper greenschist facies (cf. Sirbescu and Nabelek, 2003). We hypothesize that such small-volume grain-boundary melts mediate pervas size recrystallization, which is further favored by an oscillating thermal history owing to incremental magmatic addition.

A major outstanding question in plutonic geology thus is how to see through textural patterns that have to date guided so much thought but mainly reflect post-emplacement processes, and thereby to discern a record of the actual processes by which a pluton was constructed.

References


Calderas, subjacent plutons, and lacco- or lopoliths?: A perspective from geologic mapping of calderas of the Ignimbrite Flareup in Nevada

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Keywords: calderas, plutons, laccoliths

Controversies and questions persist about the relationship of calderas to regional deformation (especially extension); whether calderas are underlain by—and sourced from—large chambers that form major plutons/batholiths, or from small chambers that erupt almost their entire magma volume; and what the geometry of underlying magma chambers is. A traditional view, now at least partly abandoned, is that magma chambers are spherical or steep-sided and thick, 10 km or more. Most current physical and numerical models treat magma chambers as generally flat, tabular bodies. Most geologists working on calderas show similar flat, tabular chambers beneath calderas but rarely discuss the space-making process and almost never mention laccoliths.

Although calderas of the Nevada Ignimbrite Flareup (mostly 35-22 Ma but ranging from ~45 to 7 Ma) are now exposed in the extensional Basin and Range Province, most formed in a near-neutral tectonic environment following an episode of moderate 40-38 Ma extension dominated by intermediate, effusive volcanism that formed few calderas. Several ~16 Ma, mostly peralkaline calderas that marked initiation of Yellowstone hotspot activity in northwestern Nevada were formed during the beginning of a major episode of extension that was ongoing elsewhere in the Basin and Range (Colgan and Henry, 2009), but the calderas themselves underwent little deformation during and after this period.

Calderas of the Ignimbrite Flareup formed in a region that had undergone multiple episodes of Paleozoic and Mesozoic shortening and crustal thickening, followed by Late Cenozoic normal faulting that locally ranges from negligible to extreme (>100% strain). This complex geologic history often makes interpretation of purely caldera-related structures difficult, but several features are relevant to the formation of calderas. Both the thick Neoproterozoic to Mesozoic sedimentary sequences that overlie crystalline basement and the regionally extensive bedding-parallel thrust faults provided subhorizontal horizons that favor tabular intrusions. The calderas formed on a high plateau or mountain range with significant relief, probably analogous to the modern Andean Altiplano. Caldera-collapse faults commonly exploited older structures, so calderas are often asymmetric and seldom perfectly circular.

Calderas were underlain by voluminous magma chambers, exemplified by the exceptionally well exposed, 33.8 Ma Caetano caldera in central Nevada (John et al., 2008). The Caetano caldera formed during eruption of ~1100 km³ of moderately zoned, high- to low- SiO₂ (78 to 72%) rhyolite tuff, which induced as much as 5 km of collapse. Collapse was quickly followed by magma resurgence and emplacement of granite intrusions that are chemically indistinguishable from the last-erupted tuff. Precise ⁴⁰Ar/³⁹Ar and U-Pb dating of multiple samples demonstrates that caldera-related magmatism occurred during an irresolvable time period at ~33.8 Ma; all activity probably occurred during less than 0.1 Ma. These intrusions, and the process of magma resurgence in calderas in general, demonstrate that substantial amounts of magma were still present following the main caldera-collapse eruption, either in the same chamber that generated the erupted tuff, or in a still-deeper chamber that fed the shallower one. Either interpretation requires a large source chamber.

Caldera-bounding faults and the floor of the Caetano caldera are locally well exposed. Along the northeast margin, collapse was accommodated by two subparallel normal faults that dip 55-65° inward and may have been reactivated from Paleozoic thrust ramps. The outward dipping reverse faults suggested by some modeling and geometric considerations are not exposed but could be buried by intracaldera tuff elsewhere in the caldera. The caldera floor (exposed along more than 4 km of strike in one area) is structurally intact, indicating piston-like collapse. Lack of disruption of the caldera floor suggests the area of the caldera was not greatly domed before ash-flow eruption.

Detailed geologic mapping, geochemistry, ⁴⁰Ar/³⁹Ar, and U-Pb zircon dating demonstrate that tuff eruption and resurgence of the Caetano caldera at 33.8 Ma was the culmination of ~6 Ma of silicic
migmatism in an ~60 x 30 km area (present day, post extension) (John et al., 2009). Zircon growth occurred in as many as 8 episodes, 4 of which can be correlated with emplacement of volcanic or shallow intrusive rocks dated by \(^{40}\)Ar\(^{39}\)Ar. The other four episodes are indicated only by zircon ages. Aeromagnetic data suggest several unexposed discrete plutons in the 60 x 30 km area but may only be probing the shallow subsurface. The data could be interpreted to indicate incremental growth of a single large pluton, but is equally compatible with a series of discrete plutons.

Similarly, the geometry of the underlying caldera magma chamber(s) is largely unknown, both for the Caetano caldera and Nevada calderas in general, because only the mid- to upper levels of caldera systems are exposed, and no diagnostic geophysical data are available. Although the structural complexity of pre-caldera rocks hinders identification of pre-caldera doming, the lack of major doming around most calderas of the Ignimbrite Flareup indicate few, if any, are the small, Solitario-type “laccocalderas” (Henry et al., 1997). However, many of the same data used to support tabular bodies beneath calderas and for the shape of major granitic intrusions in general still apply, and considerable additional evidence that large intrusions are tabular has accumulated in the last 15 years. Because the largest metaluminous calderas in Nevada are ~30 km diameter (the diameter of peralkaline calderas reaches 45 km), the diameter of the underlying intrusion must be at least 30 km. Thus, spherical or other high-aspect ratio plutons beneath the largest calderas would extend to depths well below the brittle-ductile transition and even into the upper mantle. We suggest that many calderas of the Ignimbrite Flareup are underlain by tabular intrusions that dominantly generated space by downwarping their floors rather than by doming their roofs (Fig. 1).

Fig. 1 – Conceptual model of caldera system underlain by a tabular intrusion emplaced at the basement – Neoproterozoic contact.

References


A review of Henry Mountains geologic thought: 1869 - 2010

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Keywords: Henry Mountains, history of geology.

The evolution of geologic thought concerning the Henry Mountains of southern Utah is uncommonly rich, despite a relatively short history of exploration. I present an historical review of highlights in the progress of geologic thought resulting from work in the Henry Mountains, with a focus on topics pertinent to the subject of the LASI conferences.

The Henry Mountains were first ‘discovered’ in 1869 during the first expedition down the Colorado River, led by J.W. Powell. As part of Powell’s subsequent Survey of the Rocky Mountain Region, G. K. Gilbert undertook the first geologic survey of the region 1875-76. This work resulted in a classic publication (Gilbert, 1877) in which Gilbert concluded that the igneous rocks of the Henry Mountains were actually intrusive and deform adjacent wallrocks, a groundbreaking thought at the time. He outlined a two-stage process of magma emplacement whereby the initial intrusion is sill-like, but with continued injection of magma, vertical growth is initiated and horizontal spreading ceases. The details of the growth of these intrusions have been debated ever since. This 1877 publication also introduced several fundamental concepts of geomorphology.

Hunt et al. (1953), after extensive detailed mapping on horseback in the Henry Mountains in the 1930s, produced the first comprehensive geologic maps of the region and reinterpreted the five main intrusive centers as discordant stocks rather than concordant laccoliths. Despite this disagreement, Hunt et al. (1953) concurred with Gilbert that the relatively small intrusions peripheral to the large intrusive centers were sills and laccoliths fed from the large central intrusions. This early detailed work also identified the ‘shattered zones’ at the center of the large intrusions, where igneous and sedimentary rocks are very complexly intermingled.

Johnson and Pollard (1973) and Pollard and Johnson (1973) applied dynamic analysis to the processes of sill and laccolith formation, elaborating considerably on concepts introduced by Gilbert (1877). These workers relied primarily on observations of deformed sedimentary strata to constrain models of stress evolution and intrusion development. These models make field-testable hypotheses about intrusion geometry.

The ‘laccolith-stock controversy’ was revisited by Jackson and Pollard (1988). Detailed mapping, structural analysis, and geophysical work led to an interpretation more in agreement with Gilbert (1877) than Hunt et al. (1953) – i.e. the five main intrusive centers are concordant ‘floored’ laccoliths and not stocks. Additionally, these workers established that early sills on the margin of one of the major intrusive centers cooled while still sub-horizontal and were rotated by subsequent underlying intrusions to their present sub-vertical orientation. Although earlier workers inferred that multiple....
magma pulses were required to construct each intrusive center, this observation provided the clearest example yet of the pulsed nature of assembly in the Henry Mountains.

Regional interpretations of the significance of magmatism in the Henry Mountains changed considerably when modern geochronology and geochemistry were applied to the rocks (Nelson et al., 1992; Nelson and Davidson, 1993). Revised ages of the intrusions made it clear that mid-Tertiary Colorado Plateau magmatism was part of voluminous regional magmatism in the North America Cordillera. Geochemical data demonstrated that the Henry Mountains magmas have arc-like affinities and that each intrusive center has a distinct isotopic signature.

Recent work has relied for the first time on detailed study on both the intrusive bodies and adjacent host rock. Results from this work provide constraints on the timing of pluton assembly (Saint Blanquat et al., 2006), evolution of space-making mechanisms (Morgan et al., 2008), and magma flow kinematics development during progressive intrusion growth (Horsman et al., 2009).

Ongoing work is designed to address, among other topics, 4-d growth of intrusive centers, the significance of the ‘shattered zone,’ and magma rheology.

References


The mafic-ultramafic, Montaña Blanca-Esquinzo subvolcanic intrusion: roots of Miocene volcanism in NW Fuerteventura, Canary Islands, Spain

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Keywords: mafic-ultramafic rocks, emplacement, Fuerteventura

Among the whole range of volcanic islands worldwide, there are just a few where the roots of volcanic edifices crop out, so that relations between intrusive bodies and the volcanism they may have fed can be studied. The island of Fuerteventura, in the eastern part of the Canary archipelago, is one of such islands. In its NW sector, the Oligocene-Miocene (25-26 Ma, de Ignacio et al., 2002), Montaña Blanca-Esquinzo intrusion crops out in a 9 km length and 3 km width strip trending NE-SW. Within this intrusive body three zones can be distinguished, each characterized by a specific lithological association (Figure 1). The inner zone (Milocho Unit) is made up by olivine-rich clinopyroxenite and gabbro, with syn-plutonic dykes of alkaline-olivine basalt; the intermediate zone (Blanca Unit) is, in turn, formed by amphibole and nepheline rich clinopyroxenite and gabbro crosscut by nepheline-rich syenitic differentiates and alkaline lamprophyre dykes. The outer zone (Esquinzo-Agua Salada Unit) is made up of perovskite-rich, ultramafic and mafic lithologies, nepheline-syenites and, carbonatites. This work focuses on the Milocho and Blanca Units, due to their larger extension of outcrop and more common mineralogy and geochemistry.

To the west, the Montaña Blanca-Esquinzo intrusive body gets into contact with a dense (80-90% of outcrop), mafic dyke swarm trending NE-SW (N25°-40°) with 70-80° dips (Fig. 1, label A). The host rock to this dyke swarm is a submarine volcanic tuff that can be observed locally passing upwards into a subaerial agglomerate. Therefore, these outcrops may represent the submarine stage of growth of a major volcanic edifice in this NW sector of the island, the Miocene Tetir edifice, the geometry of which was reconstructed by Ancochea et al. (1996). To the NE, the Montaña Blanca-Esquinzo intrusion shows a tectonic contact with the volcanic materials of the Tetir edifice, which are represented by brecciae of volcanic fragments that most probably formed during collapse episodes (Fig. 1, label B).

Internal structure features of the Montaña Blanca-Esquinzo intrusive body are essentially conditioned by consolidation and magmatic evolution processes giving rise to ultramafic and mafic cumulates that are crosscut by differentiated lithologies derived from crystallization of residual melts. Structures observed in the field mainly include: preferential concentration of olivine in the Milocho Unit by flow differentiation, defining a 2 km long corridor (Fig. 1, C) interpreted as a feeder channel for the primitive magmas giving rise to the Milocho and Blanca Units and, features of the different compositional layers in each unit indicating formation by in situ crystallization.

The Blanca Unit is more alkaline and volatile-rich than the Milocho Unit. Contacts between both are transitional, conditional on modal variation. The latter involves progressive disappearance of olivine from Milocho to Blanca Unit coupled with extensive occurrence of amphibole in the latter. This indicates the importance of volatiles in magmatic differentiation of the Montaña Blanca-Esquinzo intrusion. Whole-rock geochemistry of the Milocho and Blanca Units indicates that both are related by fractional crystallization, coupled with accumulation or, in a broad sense, local concentration of some mineral phases. Application of aluminium-in-clinopyroxene thermobarometer (Nimis, 1999) yielded higher crystallization pressures (4-2 Kb) for the Milocho Unit than for the Blanca Unit (1-2 Kb). This could reflect polybaric crystallization of a single batch of magma that would concentrate volatiles upon decompression, giving rise to olivine destabilization and amphibole oversaturation in the Blanca Unit. Amphibole crystallization at an early stage in the Blanca Unit involves reaction of previously formed olivine + clinopyroxene with the melt, which consumes SiO2 from the liquid leading to magma undersaturation and increase in alkalinity in the Blanca unit differentiates. The latter (Fig. 1, 2, orange) crystallized from evolved melts derived from formation of ultramafic and mafic cumulates. These melts would have been expelled from the crystal mush because of the prevailing extensional
stress field and, injected as dykes, veins and lobe-shaped impregnations. Locally, they brecciate their host pyroxenite or gabbro by volatile (mainly H\textsubscript{2}O) overpressure.

Differentiation trends and geochemistry of the Milocho and Blanca Units match two different evolution paths in Miocene volcanic materials belonging to the Tetir edifice, thus supporting the interpretation that they represent the subvolcanic chambers feeding this volcanism.

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Sub-volcanic intrusives of Kudamkulam, India  
- a ground magnetic characterization of sub-surface structure

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Keywords: ground magnetic survey, horst-graben, mafic plugs

Introduction

The area in and around Kudangulam, where India's largest nuclear power complex is being built, has an unique geology compared to the rest of the south-east coast of India. The terrain is transected by mafic bodies cutting into the granulite grade of metamorphic rocks and are overlain by limestones, kanker and Pleistocene sand bodies. The mafic bodies intrude into the country rock as plugs and rarely as dykes towards the west, while they acquire the form of dyke swarm towards the east, in the region. Despite the noted occurrence and structural characteristics, their importance in understanding the upper continental characteristics in and around Kudangulam and the Gulf of Mannar (a deep water body located towards the east) has not yet received detailed attention.

Ramaswamy (1987,1991,1995) and Ramaswamy (1993) have reported carbonatites and associated rocks with a few evidences of late Cenozoic volcano-tectonic deformation in Kudangulam. Ramasamy and Balaji (1995) brought out a few direct evidences of Pleistocene tectonics in the region. Therefore, a systematic study of these shallow intrusives - their structures, emplacement, chemical characteristics and mineral assemblages would help to grasp the behaviour of the crust mantle interface beneath continents. Emplacement related thermal characteristics and crustal dynamics can be deduced from them.

To study the configuration of sub volcanic intrusives in plain land having a surface relief limited to 1m, needs geophysical aids. To achieve this goal, a ground magnetic survey was undertaken in and around Kudangulam. Blakely (1995) asserts that by using ground magnetic signals, the sources of magnetic anomalies in the subsurface can be isolated and thereby enhance geological interpretations. In the present work, the ground magnetic data and its transformations are used to corroborate the structural characteristics of the sub volcanic intrusives.

Geochemical Signatures

The lithochemical data have been collected for dykes and mafic plugs in and around Kudangulam. The dykes record important information concerning the tectonic and magmatic evolution in the south eastern extent of Proterozoic Achankovil Shear zone and that of Gulf of Mannar, immediately east to Kudamkulam. The mineralogy and chemistry of mafic bodies along with the parameters like Mg#, alkaline ratios, D.I, norm and mode confirms that the rocks belong to varieties of basalt, rich in olivine, both in mode and in norm. Hypabyssal emplacement of olivine rich basalts in continents signal temporal and special event of thinning of lower crust by a primitive mantle melt by modification through fractional crystallization of olivine, pyroxene and, lastly, plagioclase. The trace element systematics of representative samples of the plugs and dykes display very little deviation from that of lower crust-mantle interface chemistry. It display high values of Cr, Ni and Mg# and significant depletion in the most incompatible trace elements (Th, U, La) and high-field strength elements (Nb, Zr, Ti). A possible explanation for these trends is that the rocks are less differentiated or assimilated since its primitive stage till its emplacement.

Ground Magnetic Survey

As the geochemical studies suggest that the intrusive are basaltic in nature, it is expected that they would have distinctive magnetic signatures. A ground magnetic total field intensity survey was therefore conducted in the Kudankulam region over an area of 30sq.km, with an average of 7 data points per sq. km. Interpretation of magnetic data has allowed to map the concealed bedrock lithology and structure in detail.

The anomaly map from which the effect of the main field (IGRF) and the external field was removed showed several interesting features. The anomaly map is dominated by EW and NW-SE
trends broadly in line with the trend of the charnockitic country rock. The abundance of bipolar and circular anomalies suggests that the terrain is traversed by several subsurface intrusive implying extensional tectonic regimes. The analytic signal map (Figure 1) shows that most of these intrusives are shallow. Several intrusive are found in dug wells at an average depth of 15-20m. One conspicuous feature in the map, which is also evident in the tilt derivative, is the EW trending anomaly running almost entirely from east to west in the northern part of the map. A similar but disseminated anomaly is seen parallel to coast as well. It is inferred that the region under study is composed of SE-NW trending horst and graben structure. The analytic signal map shows that the bigger dykes are intruded into the horst structures while smaller dykes into the graben. These dykes are more or less vertical, with a slight tilt of $5^\circ$ to $10^\circ$ degrees to south-east. The faults/lineaments and dykes / mafic plugs within the graben extend to an average depth of 150m while those that are emplaced in the horst extend to 110m, only. Using the Euler’s equations, the depth of the graben structure was found to be extending to 200m.

Results

The configuration of sub volcanic intrusives in and around Kudangulam, deems a horst-graben structure criss-crossing the E-W trend of the coast. We suggest the presence of an anomalous body at a depth of 110-200m, whose surface expressions are marked by these sub-volcanic bodies. They have bisected the near surface crust in the form of plugs to the west and in the form of dyke swarms to the east, indicating severe crustal dilation to the east.

The intrusive identified by the magnetic method may be considered to be of lower crustal origin, as is seen from the geochemical studies as well. The incidences of primitive geochemistry of these sub-volcanics credit lower crustal characteristics to the anomalous body. Therefore, we suggest a crustal thinning and mantle upwelling along the southeastern tip of peninsular India, leading to the emplacement of mantle hybrid rocks as dykes and plugs, near (200m deep) sub-surface.

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3D-Seismic Images Reveal the External Structure of Igneous Intrusions, Taranaki basin, off-shore western New Zealand: Hints for Emplacement Mechanisms

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Several off-shore volcano-plutonic complexes are imaged in a detailed 3D seismic survey acquired by Pogo New Zealand/Plains Exploration. The new data provide insight into the sizes, shapes, and wall rock deformation associated with the emplacement of plutons. The seismic survey, conducted in 2005, covers 1700 km² and was processed with modern techniques used in hydrocarbon exploration. The images and structures have to be interpreted with care because of distortions caused by “velocity pull ups” created by the large seismic wave velocity contrast between sediment and igneous rock.

The magmatic rocks may be part of the Mohakatino Volcanic Centre (15 to 1.6 Ma) that intrudes and partially fills the Taranaki graben, which began to form in the Cretaceous. Imaged plutons range from less than 1 to as much as 12 km across. The intrusions are steep-sided and do not resemble sills, but their bases are poorly resolved. The top of the largest complex is sharply delineated and marked by multiple apophyses as much as 2 km across and hundreds of meters high. Deformation along the sides of the intrusion is dominated by highly attenuated dipping strata with apparent dips of 45° or higher. Dips decrease rapidly away from the intrusion but doming extends several hundred meters from the margins.

A series of high-angle faults fan out from the margin of the pluton and cut the folded strata along the margin. These faults terminate against the margins of the intrusion, extend as much as 1 pluton diameter away from the margin, and then merge with “regional” faults that are part of the Taranaki graben. Offset along these radiating faults is on the order of a few hundred meters.

Strata on the top of the complex are thinned but are deformed into a faulted dome with an amplitude of about 1 km. Steep, dip-slip faults form a semi-radial pattern in the roof rocks but are strongly controlled by the regional stress field as many of the faults are sub-parallel to those that form the graben. The longest roof faults are about the same length as the diameter of the pluton and cut through approximately 1 km of overlying strata, but offset gradually diminishes vertically away from the top of the intrusion.

The pluton appears to be composite and formed from multiple, steep-sided intrusions as evidenced by the complex margins, roof roof, and multiple apophyses. Small sills are apparent several hundreds of meters above the top of the main complex. Multiple episodes of deformation are also indicated by a series of unconformities in the sedimentary strata around the complex. In fact, doming appears to have generated a series of channeled turbidite deposits that fan out around the intrusion.

The intrusion lies in a relay zone between two NE-trending en echelon normal faults. Little oblique-slip has occurred and space for the intrusion may have been created by doming and floor subsidence; stoping may have occurred, but stoped blocks are not apparent in the seismic images.

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The seismic survey was acquired by Pogo Producing New Zealand. Pogo Producing was recently acquired by Plains Exploration & Production Company which has agreed to allow us to use this survey. Software was provided by Landmark/Halliburton.

Fig. 1 – Seismic images of composite intrusion in Taranaki basin of western New Zealand.

(A) Standard processing emphasizes the structure of the sedimentary beds and reveals folds around the intrusions.

(B) Semblance processing of the same data brings out the small faults (shaded scarps) related to the intrusions as well as the larger regional faults that are not directly tied to the emplacement of the magma. In addition, the meandering channels of turbidites—all buried now by several kilometers of younger sediment—are apparent.
Fig. 2 – Vertically exaggerated block diagram through the 3D seismic volume showing the deformation that surrounds the submarine intrusion. The “cube” of seismic data has been cut horizontally along the front and base to show the structure in map view and vertically along the back to show a cross section view of the plutons walls and interior. Complexly folded sedimentary strata show up as “rings” around the intrusion. The same beds are seen in the cross section to be steeply domed against the intrusion. In addition, a multitude of normal faults cut the domed strata across the top of the intrusion.
Emplacement mechanisms of cone sheets: A case study from Ardnamurchan, NW Scotland

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Keywords: cone sheets, Ardnamurchan, AMS.

Inclined concentric sheet intrusions (ring dykes and cone sheets) are key elements of the intrusive framework of sub-volcanic systems (central complexes). The nucleus of volcanic centers are often identified by the focus of inward dipping cone sheets based on a fundamental assumption about how the geometry and disposition of the sheets relates to a (central) source. We aim to test this model by studying igneous fabrics, and consider the implications for sub-volcanic plumbing. Here we present preliminary evidence for magma flow and emplacement dynamics from the cone sheets of Ardnamurchan, NW Scotland, using anisotropy of magnetic susceptibility (AMS) measurements and structural field observations.

The British Paleogene Igneous Province (BPIP) preserves the roots of deeply eroded volcanic edifices, which formed between 62-55 Ma, during the opening of the North Atlantic. The central complexes, including Ardnamurchan, Mull and Skye, provide world class examples of cone sheet and ring-dike intrusions. The original field observations of inward and outward dipping sheets, with partially concentric strikes, by Bailey et al. (1924) and Richey and Thomas (1930), on the Mull and Ardnamurchan central complexes respectively, resulted in the classic emplacement model for cone sheets (Fig. 1) and ring dykes. In this model the build-up of magmatic overpressure, within a parabolic or spherical magma chamber, imparts a local stress field on the country rock, which favors the formation of inwardly inclined conical fractures focused on the central magma chamber source. Magma flows up and out, in a radial manner, from the source into the fractures, producing cone sheets and releasing the magmatic overpressure (Fig. 1; Anderson, 1936). Depletion of the magma chamber instigates instability in the roof rock, which eventually subsides along outwardly inclined fractures (~60°), along which magma passively intrudes, forming ring dykes. This model has been applied to volcanic complexes in Gran Canaria, Iceland, Mexico and Japan, forming the blueprint for our modern understanding of sub-volcanic emplacement.

Richey and Thomas’ (1930) original mapping of Ardnamurchan was based on three fundamental geometric elements of the cone sheet model: (1) a concentric pattern can be described for both individual sheets and cone sheet swarms; (2) the sheets dip inwards towards a common focus; (3) the average dip of the sheets steepens towards the centre. Ardnamurchan contains three sets of cone sheet swarms (some are further sub-divided), which dip toward three separate foci, suggesting three distinct sources separated both spatially and temporally (Fig. 2). The cone sheets are intruded into a variety of host rock lithologies including, Neoproterozoic Moine psammites, Mesozoic sediments (limestones and sandstones) and penecontemporaneous Paleogene intrusives and extrusives.

New field observations show host rock behavior during cone sheet emplacement can be linked to lithology; magma fingers (ductile) occur in poorly consolidates Paleogene volcanic and volcaniclastic rocks, broken bridges (brittle-ductile) occur in Mesozoic sediments, and angular xenoliths (brittle) occur in Proterozoic psammites. In well exposed coastal sections, cone sheets intruding Mesozoic sediments are observed parallel to bedding, transgressing up the sedimentary sequence and may be described as transgressive sills. At
Mingary Pier (NM 493 626) the transgression appears to be controlled by host rock fractures. This implies host rock structure and lithology, at least partially, controls cone sheet geometry. Given that there is little compositional variation between different cone sheets, the host rock lithology and structure needs to be considered before grouping them into separate geometric suites related to a central source.

AMS data from over 100 oriented block samples from the Ardnamurchan cone sheets reveals magnetic lineations, interpreted as parallel to primary magma flow, that are consistent with visible magma flow indicators, such as step and broken bridge axes. Flow directions vary from strike parallel to dip parallel and cannot be traced back in a simple way to a source. Flow direction data does not support flow from a centralized source. In fact the magnetic lineations reveal a consistent NW-SE trend with predominantly sub-horizontal plunges, suggesting lateral intrusion. The extensive regional dyke swarm of the BPIC strikes NW-SE providing a possible alternative source, with the inclined nature of the sheets possibly reflecting lateral intrusion into inwardly inclined fractures created by doming of the country rock by the pene-contemporaneous central complex.

Fig. 2 – Map of Ardnamurchan depicting three main sets of cone sheet swarm, each with a different focal source (star), defined as a centre, separated spatially and temporally. The Centre 1 cone sheets (purple) are the oldest. The Centre 2 cone sheets (brown) and are sub-divided into two swarms based on age relationships. The Centre 3 set (pink) is the youngest. Note the concentric strike of the sheets.

Fig. 3 – Base map of Ardnamurchan with cone sheet traces (thin black lines) separated into suites (dashed lines). The double-headed red arrows represent the general magnetic lineation trends for small areas, calculated using AMS, with the black arrow highlighting the average NW-SE trend. No radial pattern, as predicted by the classic emplacement model, is observed.

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References


Thickness distribution of felsic sills in the upper brittle crust, eastern Elba Island, Italy

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Keywords: sill thickness, distribution, eastern Elba Island

Displacement-length scaling from faults, joints, veins, dikes, shear and compaction bands is generally defined by a power-law \( d = cr^a \) where \( d \) is the maximum displacement (i.e. slip for a faults and thickness for dikes, etc.), \( r \) is the length, \( a \) the power-law exponent and \( c \) a normalization constant. Generally, two groups can be defined (Schultz et al., 2008): faults and shear bands having \( a \approx 1 \), and opening and closing structures (i.e. veins, dikes, deformation bands) with \( a \approx 0.5 \). According to Linear Elastic Fracture Mechanics (LEFM), Olson (2003) observed that \( a \approx 1 \) implies fracture propagation with constant opening driving stress \( \Delta \sigma = P_f - \sigma_\nu \) (where \( \sigma_\nu \) is the stress normal to the dike wall and \( P_f \) the fluid pressure), and \( a \approx 0.5 \) implies that fracture propagation is governed by fracture toughness \( (K_\nu) \).

The aspect ratio for opening mode fractures is defined as the thickness \( (t) \) to length \( (r) \) ratio and is defined as \( t/r = cr^{a-1} \), where \( a \) is the fractal power-law exponent and \( c \) a normalization constant, as above. Clearly, a constant aspect ratio is expected for \( a \approx 1 \), while a scaling of the aspect ratio with \( r^{-0.5} \) is expected for \( a \approx 0.5 \). The aspect ratio for tabular igneous intrusion varies greatly depending on emplacement processes and composition (e.g. Cruden and McCaffrey, 2006), and for dikes and sills is best represented by \( a \approx 0.5 \).

For sills and dikes the length \( r \) is the most difficult feature to measure because true diameters are often not observed in the field (e.g. Cruden et al., 2009). On the other hand, the thickness of tabular intrusions is best defined by direct observations. We model tabular intrusions (sills) as two parallel disks that meet at a rapidly tapering tip (Fig. 1). The tip region (b) is much shorter than the radius or any chord (c) of the sill (Fig. 1). In this model r or c >> b and any sampled thickness along a chord at a distance from the tip > b is very close to the true maximum thickness \( (t) \). According to this model, the volume of a sill is \( V \sim r^3 t \).

Applying thickness - length scaling laws the volume is \( V \sim pt^{2+a-3} \), where \( p = (\pi c^2 a^3)/4 \). For \( a \approx 0.5 \) volume scales with \( t^1 \). Applying again the same scaling laws, the aspect ratio of tabular intrusion scales as \( t/r = (1-a) d/\sigma \), and for \( a \approx 0.5 \) the aspect ratio scales with \( t^1 \).

Fig. 1 – Conceptual model for sill. Two parallel disks with radius \( r \) >> thickness \( t \). Thickness is nearly constant across a section along the diameter (dashed plane) or across any chord (c). The tip region (b) is very short compared to any diameter or chord.

Analysis of thickness distributions could therefore provide insights on sill volumes and aspect ratios as well as hydraulic transmissivity. We will also show that the computation of average thickness for a sill population is strongly dependent on the thickness distribution.

We analyzed the thickness distribution of tabular intrusions in a ~6 Ma old sill complex, eastern Elba Island, Italy (Mazzarini and Musumeci, 2008). The sills are well exposed on the eastern side of the Calamita Peninsula and are hosted by the strongly-foliated Calamita schists, the lowermost of two thrust units on Elba Island. Calamita schists are HT/LP hornfelses forming the contact aureole of the Porto Azzurro pluton (Fig. 2). The sills are discordant or paraconcordant to the main foliation in the host rock (Mazzarini and Musumeci, 2008; Cruden et al., 2009).

Within the Calamita Peninsula sills typically have parallel, straight walls and, when observed, the tip regions are very short and rapidly tapered. Thus the studied case fits the proposed model for sill geometry (Fig. 1) and observed thicknesses can be assumed to be very close or equal to the maximum sill thickness.
The observed thickness distribution for the Calamita sills is well defined by a power-law $n(>t) = \gamma t^{-D}$, where $n(>t)$ is the number of thicknesses greater than $t$, $D$ is the fractal exponent and $\gamma$ a normalization constant. For the Calamita sills (190) we derived $D=1.1942$, $\gamma=11.667$ and $R^2=0.9817$. The arithmetic average of thickness is 0.3 m.

The cumulative thickness distribution for the Calamita sills is defined between lower and an upper limits (the minimum value $t_m=0.003$ m and the maximum value $T_M=6.8$ m). The cumulative distribution derived for thickness can be generally defined as:

$$n(t) = \frac{TM}{\int_t^{TM} g(x)dx}$$

where $n(t)$ is the number of sills with thickness greater than $t$ and $TM$ is the maximum thickness in the population, and $g(t)dt$ is the number of sills in the interval $[t, t+\delta t]$ and $g(t)=-n'(t)$, where $n'(t)$ is the first derivative of $n(t)$. In terms of cumulative distribution $n(t)$ the number of sills in the interval $t, t+\delta t$ is $-n'(t)\delta t$ and the average sill thickness derived from the cumulative thickness distributions is:

$$\bar{t} = \frac{-\int_{t_m}^{TM} cDx^{-(1+D)}dx}{ctm^{-D} - cTM^{-D}} = \frac{D\int_{t_m}^{TM} x^{-(1+D)}dx}{(1-D)(tm^{-D} - TM^{-D})}$$

where $D$ and $c$ are the parameters of the power-law describing the thickness distribution.

For the Calamita sills the mean thickness of population is thus 0.01 m, less than the arithmetic average. This is consistent with the observed $D>1$ implying that the distribution is controlled by thin sills. Using the thickness distribution for the Calamita sills gives a maximum cumulative thickness of ~172 m. As discussed above, the volumetric scale as fifth power of thickness.

Applying a similar approach used for the mean thickness distribution, the volume scales as:

$$V = \int_{t_m}^{TM} cDx^{-(1+D)}dx \propto \left(\frac{tm^{-D} - TM^{-D}}{5-D}\right)^5$$

According to Olson (2003), Mazzarini and Musumeci (2008) and Cruden et al., (2009), $p$ is $\sim 10^3$ giving an emplaced total volume $V \sim 10^9$ m$^3$.

The thermal aureole of the Porto Azzurro pluton was therefore intruded by $\sim 1$ cubic kilometer of magma, giving a maximum cumulative thickness of $\sim 170$ m. Assuming a maximum actual thickness for the contact aureole of approximately 0.5 km gives a maximum volumetric strain of about 14%.

References


Sill geometry and fabrics in the syn-tectonic contact aureole of the Porto Azzurro pluton, eastern Elba Island, Italy

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Keywords: sill, texture, contact aureole, eastern Elba Island

The final geometry and fabrics of magmatic rocks emplaced during tectonic deformation (i.e. syn-tectonic intrusion) result from a competition between processes (deformation, cooling and magma input) operating at different rates (e.g. Paterson and Tobish, 1992; Musumeci and Pertusati, 2000).

We analyze the distribution of leucocratic sills intruded within the contact aureole of the ~6 Ma Porto Azzurro pluton in the Calamita peninsula of eastern Elba Island (Mazzarini and Musumeci, 2008). Throughout the contact aureole the metamorphic grade increases eastward and its highest grade innermost portion (pyroxene hornfels facies) crops out in the eastern part of the Calamita peninsula where hornfelses host leucogranite sills derived from the Porto Azzurro pluton (Mazzarini and Musumeci, 2008). The main foliation in the pelitic-psammitic hornfelses resulted from lower Miocene regional deformation subsequently overprinted by contact metamorphism (e.g. Mazzarini and Musumeci, 2008). Locally, meter to decameter thick high strain domains (e.g. Punta Bianca-Capo Calvo, Punta Rossa and Praticciolo) are characterized by development of mylonitic foliation with synkinematic growth of muscovite + andalusite + cordierite + biotite + K-feldspar mineral assemblages, dated at ~6.2 Ma (Di Vincenzo, personal communication).

As observed in the field, sills generally have discordant to para-concordant contacts with respect to the host rock foliation and their emplacement postdates peak metamorphic conditions. The Metamorphic foliation and the sills have share orientations that are consistent with a large (kilometer size) fold with a gently north plunging axis and a steeply dipping axial plane (Figs. 1a, b).

The sills have constant angular relationships with the host rock foliation foliation of about 20°. These observations strongly suggest that:

i) leucocratic sills did not exploit the main discontinuity (foliation) in the host rock, instead

Their orientations were controlled by fractures or shear zones at low angles to the main foliation;

ii) sill emplacement postdated the thermal peak;

iii) regional folding affected the contact aureole during the thermal and sill emplacement event (~6 Ma).

Cruden et al (2009) proposed that sills were emplaced into the forelimb and the backlimb of an actively growing anticline with a nearly N-S trending axis (Fig. 1c). This conceptual model accounts for the observed angular relationships between the sills and host rock structure (i.e. foliation) and highlights that the Porto Azzurro pluton is associated with a syn-tectonic contact aureole (Fig. 2a, b).

Three main mesoscopic scale fabric elements have been recognized. The most common fabric is a purely magmatic fabric, often marked by alignment of tourmaline and biotite grains. Locally this fabric is affected by brittle deformation (Fig. 2c).

The second fabric type is represented by a well
developed high-to low-temperature mylonitic foliation. This fabric is parallel to the foliation in the host rock and developed within decametre scale high-strain domains that affect both metamorphic and magmatic rocks (Fig. 2d).

The third fabric type is a low-temperature purely brittle cataclastic fabric, partitioned in local meter-scale high-strain domains. In these domains magmatic fabrics are preserved as centimeter to decimeter thick lenses enveloped by a dark fine-grained matrix (Figs 2e, f).

The fabrics represent three types of relationship between deformation and magma emplacement in the Porto Azzuro contact aureole.

The purely magmatic fabric (i.e. the most common fabric in the field) characterizes sills emplaced within low strain domains and exploited favorably oriented structures (shear zones and fractures).

The mylonitic and cataclastic fabrics indicate that sill emplacement within high-strain domains was distributed heterogeneously within the contact aureole.

The mylonitic and purely brittle cataclastic fabrics are associated with fault zones that developed contemporaneously and after emplacement and cooling of the sills.

This study highlights the structural complexity of a syntectonic contact aureole.

References


Internal contacts in the Henry Mountains satellite intrusions: Not just shear zones!

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Keywords: shear zone, contact, laccolith.

Construction of satellite intrusions in the Henry Mountains has been interpreted to occur through the emplacement and stacking of magma sheets (Horsman et al., 2005; Saint Blanquat et al., 2006; Morgan et al., 2008). Magma sheets have been interpreted to exist based on the observation of thin (~1 cm thick) brittle-ductile shear zones (Fig. 1) which are planar and horizontal and also on the bulbous geometry of the margins of the intrusions. Shear zones are observed every 50 cm to 2 m beginning near the base and moving to the top of the outer margin of the Trachyte Mesa laccolith (TML) and are also observed along the margins of the Maiden Creek sill (MCS). The question remains as to whether these shear zones actually represent contacts between individual sheets of magma which are involved in the construction process or are the results of processes solely developed at the margins of intrusions. We suggest that although shear zones are only developed or preserved near the margins of intrusions, shear zones are the locations of boundaries between sheets which can be traced into the interior of intrusions using geochemical, magnetic, and structural data.

Fig. 1 – Shear zone between sheets on the margin of the Trachyte Mesa intrusion.

At the western margin of the TML, the top margin is defined by a sheet-like geometry. The top-most sheet is 50 cm thick, has a vertical front face, flat top, shear-zone boundaries, and the flat top can be traced for over 30 m into the interior. 1.2 m deep oriented cores were drilled down through this top sheet at 1m, 2m, and 3m from the front margin of the sheet. No shear zones were observed along these cores although Anisotropy of Magnetic Susceptibility data and magnetite chemistry suggest a contact exists. At approximately 40 cm depth, foliation rotates, Susceptibility (Km) doubles, and Anisotropy (P%) decreases. SEM EDS spectrum on magnetite reveals that crystals from higher in the cores have significant titanium contents and exhibit little to no exsolution. In the deeper part of the cores, magnetite and ilmenite exhibit significant exsolution (Fig. 2) and SEM EDS spectrum taken from magnetite reveal no titanium present. A pure end-member magnetite appears to be exsolving out of a more titanium rich magnetite-ulvöspinel solid solution. The exsolution of a pure magnetite from deeper in the core may be the cause of the higher Km values found there. Pure magnetite has Km values 3X-4X higher than a Ti-rich titanomagnetite (McElhinney and McFadden, 2000). Exsolution of titanomagnetite into a pure end-member magnetite and either an ulvöspinel or ilmenite is believed to the result of slow cooling at high temperatures.
Therefore we interpret the magnetite data to indicate that the magma in the lower half of the core cooled more slowly because it was insulated by a top sheet. In this model, the top sheet is emplaced first and acts as a thermal blanket for a later, lower sheet which also allows the top sheet to cool more rapidly.

The MCS was interpreted as being constructed through stacking of two sheets, both sheets sharing the same outer margins (Horsman et al, 2005). This interpretation is based on the geometry of the margin, which has a double bulge from top to bottom and also on the observation of a horizontal shear zone dividing the top and the bottom (Fig. 3).

Near the terminus of the MCS, a meter thick layer of Entrada Sandstone is observed between the top and bottom sheets. This sandstone layer thins toward the interior and where it terminates, a brittle-ductile shear zone is observed. This shear zone decreases in intensity towards the interior of the intrusion and evolves into a cm scale zone of cataclastic bands/micro-faults. This summer we drilled 30 cores across the shear zone, along a 10 m vertical traverse to detect any changes associated with this possible contact. Preliminary AMS data indicate a very abrupt 10X increase in Km across the shear zone. Other magnetic, structural, and geochemical data from these cores are currently being processed and will be available at the time of the meeting.

The last intrusion we have studied in detail is the Black Mesa intrusion (BMI) which is much larger than the TML or the MCS and may represent a more evolved stage in the pluton-construction process. The outer margin of the BMI exhibits m-scale zones of cataclastic bands at 10-20 m intervals.

We suggest that although shear zones are only preserved/developed near the outer margins of these intrusions, they are located at contacts between sheets and these contacts can be defined by structural, magnetic, and geochemical data in the interior of these intrusions. Models for sheet emplacement will be discussed that take into account the disappearing, interior shear zones.

References


LA-ICPMS U-Pb zircon dating of Mount Hiller laccolite and satellite intrusions: rapid emplacement and large Proterozoic inheritance.
Jean-Louis Paquette, Michel de Saint Blanquat, Guillaume Delpech, Eric Horsman and Sven Morgan

The Mount Hillers intrusive complex (Colorado Plateau, Utah) consists of a large central laccolith and many smaller satellite intrusions (Hunt et al., 1953; Jackson and Pollard, 1988). The map pattern shows that the majority of the satellite intrusions emanate from the central intrusion, similar to volcanic lava flows connected to their volcano. Our recent work has shown an episodic and very rapid construction of the satellite sheeted intrusions by vertical stacking of magma pulses (Horsman et al., 2005; St Blanquat et al., 2006; Morgan et al., 2008). The goal of the present work is to characterize the emplacement time for the satellite and central intrusions, to try to identify age variations from the bottom to the top of single intrusions and to date inherited zircons if any.

The zircon crystals are euhedral, light pink colored and moderately elongated. Their morphology and inner structure are similar in all the samples from the central intrusion and the satellites. Most crystals are composed of large, irregular and U-enriched cores, surrounded by sector-zoned rims (Fig. 2). The boundaries between core and rim domains have complex shapes suggesting the replacement of an older generation of zircon with younger material.

Fig. 1 – U/Pb and Pb/Pb ages measured on the zircon cores in the Mount Hiller intrusions.

The ages measured on the concordant and sub-concordant zircon cores range between 1.2 and 1.8 Ga in the concordia diagram (Fig. 1). The histogram frequency of $^{207}$Pb/$^{206}$Pb apparent ages (inset in Fig. 1) shows a major peak at 1.4 Ga, with smaller peaks at 1.3 Ga and 1.6 Ga and minor occurrences at 1.95 Ga and 2.45 Ga. The very large number of Paleo to Mesoproterozoic zircon crystals suggests the strong reworking of a zircon-enriched fertile component. Consequently, the mixing of mafic magmas with one or several metasedimentary end-members during magma formation seems likely.

The ages of all the intrusions are concentrated in a very narrow range at 24.75 ± 0.50 Ma (Fig. 2). This implies means the zircon crystals most probably recrystallised during a single event in a large magma chamber. The magmas emplaced in a short time-span in both central intrusion and satellites, as demonstrated by the sub-equivalent U/Pb ages in all the samples. No significant age difference can be distinguished between the central intrusion and the satellites or between the top and the bottom of individual intrusions (i.e. Black Mesa or Sawtooth Ridge).

Our results are in good agreement with published fission track 21-29 Ma ages on zircon and sphene from the same Mount Hillers laccolith (Sullivan, 1997). In contrast, our in-situ U/Pb zircon results are significantly younger than the 29.35 ± 0.33 Ma reported by Nelson (1997). Nevertheless, that author emphasizes the presence of excess argon and xenocryst contamination which could be responsible for this difference between results. Interestingly, the U/Pb zircon age of 24.75 ± 0.50 Ma obtained in Mount Hiller samples is similar to the $^{40}$Ar/$^{39}$Ar ages measured on the neighboring Mount Pennell intrusive center (Nelson, 1997). The consistency between the high temperature U/Pb ages and low temperature fission track ages on similar zircon crystals from the Mount Hillers intrusive center demonstrates that the 24.75 ± 0.50 Ma age can be
interpreted as the crystallisation age of the zircons during or very close to magma emplacement.

Fig. 2 – Top left: $^{238}$U/$^{206}$Pb vs. $^{207}$Pb/$^{206}$Pb diagram (Tera & Wasserburg, 1972) of Saddle Pass intrusion. Top right: weighted average of mean $^{206}$Pb/$^{238}$U ages of Mount Hiller samples. Bottom from left to right: cathodo-luminescence images of zircons crystals with large, medium and small-size inherited core. The last grain do not display any inherited core. (pseudo) Sector-zoned rims are well visible.

References


Rapid emplacement of the Karoo Basin sill complex during the Toarcian carbon isotope excursion revealed by U-Pb dating of zircons.

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Keywords: Karoo, U/Pb, Toarcian.

Volcanic basins are formed when large volumes of magma intrude sedimentary basins. Well-known volcanic basins include the Karoo Basin in South Africa, the Voring and More basins offshore mid-Norway, and the Tunguska Basin in Siberia. Such basins contain complex and interconnected networks of sheet intrusions (i.e. sills and dykes) that are surrounded by contact aureoles of thermally matured sediments. Devolatilization reactions of organic matter and carbonate minerals in the contact aureoles cause rapid gas generation. The gases may either be trapped to form hydrocarbon accumulations or be released into the atmosphere to affect the global carbon cycle.

However, accurate dating of the sill complexes and the carbon isotope excursions is required to firmly establish a causal link between past global carbon cycle perturbations and contact metamorphism. In this study, we have completed a basin scale U/Pb geochronology study of zircons from dolerites in the Karoo Basin. In addition, we have dated the carbon isotope excursion in the Neuquen Basin in Argentina.

We sampled 48 pegmatites (see Fig. 1) found in thick sill intrusions from different parts of the 550,000 km\textsuperscript{2} Karoo basin. The samples are separated by as much as 1000 km (see Fig. 2). From fifteen selected samples, thirteen contained fresh euhedral and inclusion-free zircons suited for high resolution dating. The mean age is 182.7 Ma, with a range from 182.3 to 183.0 Ma. All thirteen U/Pb ages overlap within the uncertainty (average of \pm 0.4 Ma), suggesting that the dated sills were emplaced very rapidly, or even simultaneously, in the basin, regardless of their geographic or stratigraphic position.

The formation of the Karoo sill complex is synchronous with a short-period global carbon cycle perturbation, the Toarcian Oceanic Anoxic Event (TOAE). We have sampled and dated the TOAE in a shale sequence in the Neuquen Basin in Argentina. The shale sequence includes tuff layers with zircons. New U/Pb dating of the zircons provides constraints on the age and duration of the TOAE event. The age overlap with the sill ages in the Karoo Basin. Our new high-precisions dates strengthen the hypothesis that sills in volcanic basins may trigger global warming by massive production and release of greenhouse gases into the atmosphere.
The geological map of the Mount Hillers intrusive complex (Hunt et al., 1953; Jackson and Pollard, 1988; our work) shows a large circular intrusion centered on the Mount Hillers summit, surrounded by numerous satellite intrusions connected or not with one another, and/or with the central intrusion.

Our recent structural studies have shown an episodic and rapid construction of the satellite sheeted intrusions by vertical stacking of magma pulses (Horsman et al., 2009).

The goal of the present work is to characterize and compare the petro-geochemical fingerprint of the Mount Hillers central intrusion and its satellites, in order to understand the origin of the dioritic magmas and their evolution, but also to provide new data about the similarities and differences between all the intrusions which will help to produce a detailed construction model at the Mount Hillers scale.

The intrusive rocks of the Mount Hillers are microgranular porphyritic diorites emplaced into Permian to Mesozoic horizontal sandstone and shale dominated formations. Our recent in-situ LA-ICPMS U-Pb zircon dating of 10 samples from the Mount Hillers central intrusion and satellites give ages concentrated in a narrow range of 24.75 +/- 0.50 Ma with no differentiated ages between satellite and central intrusions (see Paquette et al., this volume). We have conducted mineralogical, textural, major and trace elements (whole-rock and in-situ) and isotopic (Sr and Nd) analysis from 58 samples, 56 diorites, among which 9 are from the central intrusion and the rest from 9 satellite intrusions, plus 2 mafic xenoliths (one cumulate and one metabasalt, see Fig. 1 for the spatial repartition of samples).

The main conclusions we can extract from our dataset are:

1/ The samples are composed of 30-55% of phenocrysts (20-40% plagioclase, 5-20% amphibole, 1-5% accessory minerals like epidote, clinopyroxene, titanite, oxides, quartz, apatite, calcite) drowned in a microgranular matrix mainly composed of plagioclase and amphibole.

2/ detailed thin section analysis of accessory minerals show that magmatic epidote and clinopyroxene never coexist in the same sample. This defines at least three types of magma: one with epidote, one with clinopyroxene, and one without epidote and clinopyroxene. Each satellite intrusion is composed of a single mineralogical family, but the central intrusion displays the three families. The epidote-bearing family is the most abundant. This confirms and completes our preliminary study (Bankuti et al., 2008).

3/ Whole-rock compositions are at first order homogeneous (SiO₂ between 58 and 65 wt%), and display a bulk medium- to high-K calc-alkaline flat trend with high alkali and CaO content (Na₂O+K₂O between 5.5 and 8.5, CaO between 3.5 and 7.5 wt%). In the TAS diagram, epidote-bearing satellite intrusions fall in the calc-alkaline field (diorite), and cpx-bearing intrusions fall in the high-K calc-alkaline field (monzodiorite). The central intrusion shows a wider range of composition, covering these two fields, independently of the sample mineralogy.

4/ trace elements analysis shows also at first order a great homogeneity between all the samples. LREE are more enriched than HREE, which show a flat spectra around 10 times chondrite. The cpx-bearing family is slightly more enriched than the epidote-bearing family. The multi-element pattern is compatible with an arc origin for the magmas with spikes in Ba, La, and Sr and troughs in Nb and Ti.

5/ in-situ trace element analysis on plagioclase, amphiboles, epidote and cpx show a difference between the two mineralogical families, the amphiboles in the cpx-bearing intrusions being more enriched in REE. In each family, the complimentary peaks and troughs of the multi element pattern of amphibole versus epidote or cpx shows a contemporaneous crystallisation of these minerals.

6/ isotopic Sr and Nd analysis show that the samples from the epidote- and cpx-bearing satellites intrusions have distinct signatures and define two group. Again, the central intrusion shows a wider
range of isotopic composition, independently of the sample mineralogy. A crustal signature with a weak sedimentary contribution is evidenced, with a relatively homogeneous low $^{87}\text{Sr}/^{86}\text{Sr}$ ratio between 0.7042 and 0.7052, and a negative and more variable $\varepsilon_{\text{Nd}}$ between -5 and -10. On a Sm/Nd isochron diagram, the data distribution is consistent with 2 magmatic events, a young one around 25 Ma defined by the "flat" trend of each group of satellite intrusions, and one around 1.6 Ga defined by the preferred alignment of all the samples. The position of the xenoliths in this diagram shows that they could be interpreted as the residue(s) of the melting event(s) which produced the diorites.

The presence of magmatic epidote, the absence of plagioclase fractionation process (no Eu anomaly), and our barometric data, all suggest a deep magma source(s) and a fast magma migration.

Our preferred model for the genesis of the Mount Hillers diorites involve the melting of one heterogeneous or two distinct mafic sources located in the lower part (below 20 km) of the Colorado plateau crust. Given the intermediate composition of Mount Hillers diorites, this/these source(s) are compatible with metabasalts produced by an older (proterozoic ?) magmatic event in an active continental margin setting. The question of the heat source remains which originated the ∼25 Ma melting event.

References

Dikes and mega-dike in the Morozumi Range (Antarctica)

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Keywords: dike, Ross Orogeny, Antarctica.

The Morozumi Range Intrusive Complex (Fig. 1) was emplaced at mid-upper crustal levels during the early Paleozoic Ross Orogeny, linked to the convergence and subduction of the Paleo-Pacific plate below the continental margin of Gondwana in Antarctica (Goodge, 2002; Rocchi et al., 2009).

The Morozumi Range Intrusive Complex is comprised of a main intrusive body (the Morozumi Granite) and a variety of minor intrusive units which have complex geometric, chronological, and geochemical relationships with the main granite. All the intrusive units were defined in the field and further validated and constrained on the basis of their petrographic and geochemical features.

The Morozumi Granite, that constitutes the central part of the complex, is a porphyritic monzogranite with K-feldspar megacrysts (up to 5 cm), in places defining an igneous foliation, set in a medium-grained matrix with 10-15 vol% biotite and rare primary muscovite. The Morozumi Granite stretches for 16 km in N-S direction, while its E-W width is 1 to 6 km. The subvertical contacts against the metagreywacke host rock give the intrusion the overall appearance of a mega-dike (Fig. 2).

The other intrusive units of the complex are the Jupiter Granite, a muscovite-bearing, peraluminous granite body; the small Morozumi Granodiorite, a network of minor irregular bodies crosscutting the Morozumi Granite with sharp contacts, and the Morozumi Diorite, a set of mafic stocks and dikes showing diffuse contacts and mingling relations with the Morozumi Granite.

Fig. 1 – Geological sketch map of the Morozumi Range Intrusive Complex.

Fig. 2 – Morozumi Range, helicopter view from the east. North-south elongation in this view is approximately 15 km. Light brown on the ridge top is the Morozumi granite; dark grey in the lower part of the wall is the metagreywacke host rock; lighter stripes within the metagreywackes are the eastern, subvertical dikes.
The most striking geometric and intrusive relationships within the Morozumi Range are shown by a set of tabular intrusions of metric to decametric thickness, developed on both the eastern and western side of the Morozumi Granite and intruding also its summit part. All these tabular bodies are collectively described as dikes owing to their overall steep dip, even though some of them (those cropping out the east), intrude conformably the foliation of the host metagreywackes.

Tabular intrusion to the east of the main granite (Fig. 2) are interlayered with their metagreywacke host (Fig. 3) and consist of medium-grained foliated tonalites and granodiorites with 5 to 10 vol% biotite ± muscovite. In the western side of the complex, W-dipping dikes (fine-grained foliated tonalites with about 15 vol% biotite) intrude the Morozumi Granite at high angles with the granite igneous foliation. Some of these tabular bodies have leucocratic apical portions of fine-grained leucosyenogranite. The summital part of the range is characterized by gently W-dipping dikes, crosscutting the poor igneous foliation of the Morozumi Granite. These dikes are fine- to medium-grained leuco-monzogranites to leucogranodiorites with less than 5 vol% biotite and minor muscovite.

The lithological complexity of the Morozumi Range Intrusive Complex is confirmed by the large chemical spread, that rules out simple evolutionary genetic relationships among the intrusive units. Mingling-mixing relations between the main granite and the diorite are supported by both field and chemical evidence, while peraluminous granites seem not to have interacted with the main granite magma on the basis of the whole rock chemistry.

The dikes are calcalkaline tonalites, grading into more evolved products. Isotopic and geochemical data clearly indicate a separate origin with respect to the main granite-diorite magma. The geochemical trends suggest an interaction between dike magma and a peraluminous material, possibly the metasedimentary country rock, as suggested by the break-down and tearing off of metagreywacke slices within the eastern dikes that can be observed both at the outcrop (Fig. 3) and the microscope scale. Field relationships indicate the dikes were emplaced late in the intrusive sequence, yet zircon in-situ LA-ICP-MS U-Pb data indicate emplacement in a short time span of a few Ma.

Overall, the observed chemical variability suggests the occurrence of multiple magma pulses derived from different crustal and subcrustal sources. All the pulses were emplaced in a rather short time interval under the interplaying constraints of the host rock anisotropic structure and the regional stress within the active continental margin.

Acknowledgements

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References


Magma flow in laccoliths (Elba island): results from fabric analyses

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Keywords: tabular intrusions, magma flow, AMS.

Shallow igneous intrusions provide a link between plutonic and volcanic processes. Detailed study of the emplacement of intrusive bodies can help to explain the evolution of felsic magma chambers (Bachmann et al., 2007). The aim of this study is to test current understanding of feeding and growth mechanisms of shallow-level intrusions (less than 3-4 km deep) using magma flow markers. The study area includes the Late Miocene San Martino multilayer porphyry laccolith and its large subvertical feeder dikes (Elba island, Italy; Fig. 2; Dini et al., 2002). These intrusive bodies are composed of monzogranite and are characterized by prominent sanidine megacrysts set in an aphanitic groundmass. Emplacement depths averaged roughly 1900 m with estimated filling times on a scale of <100 years, Rocchi et al. (2002), Westerman et al. (2004).

Magma flow can be studied by the analysis of flow markers such as the preferred orientation of K-feldspar megacrysts (Fig. 1) and biotite phenocrysts. Analyses and heating experiments have shown that biotite is a significant iron-bearing phase and may carry the magnetic signal.

Spatial orientation of K-feldspar megacrysts can be measured directly in the field while the attitude of biotite phenocrysts can be reconstructed using anisotropy of magnetic susceptibility (AMS) measurements. Petrographic studies, SEM-EDS analyses and heating experiments have shown that biotite is a significant iron-bearing phase and may carry the magnetic signal.

Fig. 1 – Typical outcrop of San Martino laccolith with preferred orientation of K-feldspar megacrysts.

Fig. 2 – Geological map of central Elba (from Dini et al. (2006)); San Martino laccolith is intruded in Cretaceous flysch. Blue dots represent sites sampled for AMS; red dots represent group of stations in which K-feldspar attitude were measured (200-300 m each other far).

The preliminary K-feldspar data on 25 sites (1500 measurements; Fig. 2) reveal a well defined
foliation with no discernible lineation (Fig. 3). AMS data on 40 sites (400 measured cores; Fig. 2) reveal a foliation, that is parallel to the feldspar foliation but additionally also reveals a well-defined lineation (Fig. 3).

Both sets of data show local variability of lineation and foliation, probably reflecting local variations of flow direction (perhaps magma lobes or magma fingers?; Rocchi et al., 2010; Stevenson et al., 2007). Foliation-lineation markers and their interpretations provide strong constraints to the feeding and filling model being developed for the San Martino laccolith.

Acknowledgements

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References


The Mesoproterozoic Voisey’s Bay Intrusion: Laccolith or Lopolith?

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Keywords: mafic layered intrusion, magmatic sulfide deposit, Labrador.

The ca. 1333 Ma Voisey’s Bay Intrusion (VBI) is a kilometer scale layered mafic intrusion consisting dominantly of troctolite with minor gabbro and norite. It is one of many plutons forming the 20,000 km² Mesoproterozoic Nain batholith, northern Labrador, which coincides with a major Paleoproterozoic suture between the Churchill and North Atlantic Cratons (Ryan 1998). Various tectonic regimes have been proposed for the time of batholith emplacement, including anorogenic conditions (Ryan 1998) and regional sinistral transtension (Myers et al. 2008). Estimates on the depth of emplacement of the batholith range between 6.5 and 13 km (e.g., Morse 1982).

The VBI hosts a producing world-class Ni-Cu-Co massive sulfide deposit, discovered in 1994. Research has since focused on the geology, geochemistry and genesis of the intrusion and its mineralization. Our work focuses on the geometry and kinematics of the VBI, with the goal of elucidating external tectonic and internal igneous processes during emplacement.

The geology and structure of the VBI has been documented by fieldwork, over 500 km of diamond drill core, and more recently by surveying new and historic bore holes with acoustic and optical televueer probes. The intrusion consists of several magma chambers and a complex network of dykes: here we focus on the components east of the Discovery Hill Zone (Fig. 1). The Ovoid Dyke is a roughly E-W striking, subvertical, of variable thickness (10-100m), and its geometry is strongly controlled by brittle wall-rock structures. The Ovoid is a 100m scale body of massive sulfide located where the dyke dramatically increases in width (Fig. 2a). It is roughly bowl shaped, with a steeply dipping northern wall and relatively shallow dipping floor. The Ovoid is thought to represent either a swell within the Ovoid dyke (Evans-Lamwood et al. 2000) or the base of an eroded magmatic chamber (e.g., Li and Naldrett 1999).

Further east, the km-scale Eastern Deeps Chamber (EDC) is essentially “bathtub” shaped, with steep northern and southern walls and a shallowly E-dipping stepped (normally faulted?) floor (Fig. 2b). The walls of the chamber were likely active faults during emplacement, which were reactivated during post-emplacement deformation. Primary layering in the EDC is observed in outcrop and in drill-core, and generally strikes ESE to E and dips 40 to 60°S. The chamber was fed by the subhorizontal Eastern Deeps Feeder, and significant mineralization is located at the zone of entry of this feeder into the chamber. This subhorizontal feeder connects with the subvertical Ovoid dyke in a structurally complex zone known as the South East Extension (Fig. 1). A second feeder, known here as the “Failed Feeder”, is located structurally above the Eastern Deeps Feeder, and pinches out towards the west and north but thickens towards the east. The Chamber was invaded by the ca. 1305 Voisey’s Bay Granite, which intruded along mechanical anisotropies such as the contact between the Failed Feeder and host gneiss, and south dipping internal layering within the chamber.

The VBI is considered to have been fed by two or more magmatic pulses (e.g., Li and Naldrett, 1999), with strongly mineralized magma pulses representing the last magmatic inputs (e.g., Cruden et al., 2008). Based on the geometry of the intrusion, it is thus attractive to consider that the upper troctolitic portions of the EDC were fed by the Failed Feeder, and the Ovoid and the lower strongly mineralized portions of the EDC were fed by the Ovoid and Eastern Deeps feeders respectively.

Geometrical features of the Ovoid and EDC (i.e., steeply dipping walls, shallow floors, strong syn-emplacement brittle structure control), albeit at different scales, are similar to those observed in laccoliths and lopoliths. Hence, we hypothesize that emplacement of the VBI may be related to one or a combination of chamber roof uplift and floor subsidence. Growth of the EDC by asymmetrical roof uplift (north side up, pole of rotation towards the south) and progressive accumulation of magma inputs would be consistent with the observed south dipping layering of the EDC. However, the inferred depth of emplacement of the VBI is somewhat problematic, since laccoliths are thought to form at depths < 3 km (e.g., Cruden 1998).

Growth by asymmetric floor subsidence may explain the late stages of growth of the Eastern Deeps and the Ovoid, represented by the late strongly mineralized pulse, and would be consistent with normal faulting observed at the base of the EDC and high temperature normal shear zones within troctolites near the base of the chamber.

Alternatively, lopolithic growth could account...
for the growth of the entire EDC. If the chamber was emplaced by several magmatic pulses, this would require inputs from feeders structurally above the Failed Feeder: any significant chamber floor drop would be associated with a new active feeder, and previous feeders would be closed or abandoned. Such subhorizontal feeders may have been intersected by drilling north of the EDC, but their relationship with the chamber has yet to be clearly defined. Feeders are also not limited to the north side of the EDC and may be located elsewhere. In any scenario, the Eastern Deeps Feeder became active at the expense of the abandoned Failed Feeder structurally above.

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This work would not have been possible without the contributions of past and present Vale geologists and staff to the Voisey’s Bay knowledge database.

References


Figure 1: Simplified map of the Voisey’s Bay Intrusion. Sections O-O’ and E-E’ in Figure 2 are indicated.

A) OVOID
B) EASTERN DEEPS

Figure 2: N-S Profiles of components of the Voisey’s Bay Intrusion (refer to Fig. 1). The legend is identical for both sections. A) O-O’ section of the Ovoid. Vertical Scale is elevation in meters (V.B. datum, sea level + 5000 m). B) E-E’ section of the EDC. Boreholes for which televiewer data was available for section construction are indicated with asterisks: the apparent dips (in a N-S plane) of geological contacts obtained from televiewer data were plotted on the section and were used to define the geometry of the units, including the jagged pattern (normal faults) at the northern base of the EDC.
3d GOCAD modeling of an intermediate sill complex in the Late Paleozoic Halle Volcanic Complex, East Germany

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Keywords: structural control, conglomeratic host, Late Variscan perimontane basin.

Precursory to the evolution of the voluminous rhyolitic rocks of the Halle Volcanic Complex (Schwab 1970, Mock et al. 2005, Breitkreuz et al. 2009), an intermediate sill complex (ISC) emplaced in the Wettin Subformation and the overlying Halle Formation of the Saale Basin. The latter is a NE-SW-trending Late Variscan perimontane basin controlled by transtension (Schneider et al. 2005).

Based on well data, Siegert (1967) differentiated the ISC into four phases, and assumed an effusive origin. Romer et al. (2001) classified the ISC rocks, which often show signs of magma mingling, as trachybasalts, trachyandesites and trachydacites. The Halle Formation starts with a prominent conglomerate (called “Kieselschiefer-Quarzit-Konglomerat”, KQK), with a maximum thickness of 150 m.

We evaluated data of 1200 drill holes and a pre-Cenozoic fault trace file and selected a 58 km² area, located north of the city of Halle, for a 3d modeling of the ISC and the KQK with the Paradigm GOCAD® software. Seven sill units were modeled belonging to the ISC phases 3 and 4, the largest unit reaching 3600 m length, 290 m thickness and a volume of 0.68 km³. Geometry of ISC sills displays partially saucer shape (Thomson and Hutton 2004), with one to possibly three feeding conduits (Fig. 1b, e, f).

Sill geometry is strongly controlled by pre-existing NW-SE trending faults. NNW-SSE and N-S trending faults, which were active synchronously to the emplacement of the phase 4 sills, displaced phase 3 bodies implying syn-magmatic tectonics.

In two locations, phase 4 sills penetrated through and emplaced above phase 3 units (Fig. 1d). The GOCAD model proves the intrusive nature of the ISC, since some sills initiated and/or pierced through the KQK in at least nine locations (Fig. 1a). Presumably, the then unconsolidated conglomerates served as preferred pathways during sill initiation (Thomson and Schofield 2008).

Thickness variation and vertical displacement of KQK indicates uplift of a WNW-ESE trending horst during and after KQK sedimentation, but prior to ISC evolution. Fig. 1c displays a maximum vertical displacement of c. 300 m. This uplift structure of unknown origin apparently controlled the emplacement location of ISC units (Compare Fig. 1b with c) since they are preferable located on both flanks of the structural high.

References


Fig. 1 – 3d GOCAD modeling of the ISC and the KQK: a) Isopach model of KQK showing an area of reduced thickness in the centre, red dots = wells used for the model, white areas = region were ISC sills pierced the KQK; b) distribution of ISC bodies in the modeled area, body An3b is hidden below An4e; c) NNE-SSW section through the model (see line A-B in b); d) section showing the stacking of two sills of phases 3 and 4 (see line C-D in b); e) and f) lateral and map views of bodies An3a below An4a and An4d, respectively, displaying possible magma flow patterns; margins of sill bodies have been cut off due to restrictions of the data base and of the modeling software.
Revisiting classic emplacement mechanisms in the British and Irish Palaeogene Igneous Province

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Keywords: BIPIP, laccolith, AMS, cauldron subsidence

The 62 – 55 Ma British and Irish Palaeogene Igneous Province (BIPIP) part of the North Atlantic Large Igneous Province (NALIP) (Fig. 1) is where many of the traditional long standing subvolcanic emplacement models were developed, principally by J. E. Richey and co-workers form the British Geological Survey in the early 20th century (e.g. Richey, 1928; Bailey et al., 1924; Richey and Thomas, 1930).

The outcome of the classic BIPIP work has influenced studies all over the world and forms the blueprint for our modern understanding of the architecture of volcanic systems. The traditional textbook view of the magmatic system is of a series of vertically stacked intrusions linked by vertical (dikes) to a directly subjacent source (Fig. 2a).

This paper reports recent and ongoing work on key BIPIP centres that is challenging these long held models. The central approach to this body of work is in the application of anisotropy of magnetic susceptibility measurements that reveal subtle igneous fabrics which can be interpreted in many cases as recording magma flow. We review the key findings from work on the Ardnamurchan centre (O’Driscoll et al., 2006; Magee et al., this volume), Mourne and Slieve Gullion centres (Stevenson et al., 2007, 2008) and preview new and ongoing work on the Mourne and related centres (Fig. 1).

In each case, new AMS fabric data has warranted a revision of the accepted emplacement model (ring-dike, cauldron subsidence or cone sheet) favouring instead a generally laccolithic type emplacement model. In many cases the emplacement sense is lateral, precluding a source from a subjacent magma chamber and supporting a degree of lateral magma transport. These findings are providing new information about crustal scale magmatic pathways in this region. The traditional view of a vertically stacked system where the igneous body or volcanic edifice directly overlies its source may no longer apply (Fig. 2b).

The new laccolithic-style emplacement models applied in the BIPIP are more akin to the original work of Gilbert (1877). Perhaps this form of emplacement was not obvious in the often highly deformed terranes in NW Scotland and Ireland (see Stevenson et al., 2007), even though forceful doming and shouldering of host rocks was noted at each centre in the BIPIP in the early work (see Emeles and Bell 2004 for a review) it was not considered important. This bears similarities to the so called ‘laccolith-stock controversy’ in the Henry Mountains (cf. Jackson and Pollard, 1988).

Lateral movement of magma is not a new concept, e.g. McKenzie dyke swarm (Ernst and baragar, 1992). However the implications of significant lateral emplacement in individual centers (Case 2, Fig. 2b) are that the location of volcanic centers and intrusions bears no observed relationship to the location of magma generation at the base of the crust. This is controlled instead by the structure

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Fig. 1 – A) The NALIP after Bell and Emeleus (2004). B) Location of the major intrusive centres, dyke swarms and extrusions of the BIPIP. Only the intrusive centers are labelled; S&C – Slieve Gullion and Carlingford, M – Mourne, Ar – Arran, Mu – Mull, A – Ardnamurchan, R – Rum, Sk – Skye, K – St. Kilda, B – Blackstones.

Fig. 2 – Considering traditional vertical magma transport in the crust (A) and with significant lateral transport in the upper crust (B).
and dynamics of the lithosphere. In the traditional model (Case 1, Fig. 1a) the location of volcanic centers and intrusions is controlled fundamentally by mantle processes. Our findings highlight the influence of lithospheric structure on the distribution, transport and storage of magma. This concept provides a physical model that can be used to test or tune geochemical, petrogenetic and geophysical models which link the composition and evolution of igneous and volcanic rocks to mantle processes.

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Fig. 3 – View of the Ardnamurchan Central complex, NW Scotland.
Mammoth Mountain, California, is situated on the southwestern margin of the Long Valley Caldera, rising more than 750 m above the surrounding landscape. Geographically it is linked to the caldera and the Mono-Inyo volcanic chain, but its magmatism is geochemically distinct from other Pleistocene/Holocene magmatism in the area (Fig. 1; Hildreth, 2004). Mammoth Mountain is comprised of a stack of ~30 trachydacite and alkali rhyodacite lava flows that dominantly formed between 68 and 57 ka (Mahood et al., 2010). This stack of lava flows, ~7 km in diameter, is situated within a larger (~16 km diameter), more dispersed field of mafic vents that both pre- and post-date the Mammoth Mountain stack. Based on the geochronology and geochemistry, it is clear that the 68-57 ka rhyo- and trachy-dacites that formed Mammoth Mountain had a magmatic plumbing system distinct from other recent volcanic events. In addition, events younger than Mammoth Mountain extend along a north-trending linear trend (i.e., Mono-Inyo chain) and do not consist of repeated eruptions at the same geographic location. This pattern differs from Mammoth Mountain, where repeated, localized eruptions occurred over a small spatial area.

With respect to other Pleistocene magmatism, Mammoth Mountain occupies a unique structural position. It is situated directly on top of the mid-Cretaceous Rosy Finch Shear Zone (RFSZ), a lithospheric-scale feature that recorded dextral, transpressional fabrics (Fig. 2; Tikoff and St. Blanquat, 1997). The RFSZ is an otherwise continuous feature that extends to the northwest and southeast of Mammoth Mountain. We propose that the 30 localized eruptive events occur at Mammoth Mountain because magmatism was focused along the shear zone. Magmatism was apparently also focused by a series of north-striking normal faults, presumably related to Basin and Range extension, which intersects NNW striking normal faults related to the eastern edge of the Sierra Nevada block.

Pleistocene magmatism may also be interconnected with faulting in the Long Valley Caldera area. On the western edge of the Long Valley Caldera, recent magmatism has a NS-oriented, linear trend from Mammoth Mountain through the Mono-Inyo chain. On the eastern edge of the caldera, recent magmatism extends southward, also defining a NS-oriented, linear trend. The NS-oriented dikes north of Long Valley that feed the magmatism lie at a low, but distinct, angle to the eastern rangefront of the Sierra Nevada. South of the caldera, a series of NNE-oriented earthquake swarms record non-dipole moments, suggesting NNE-oriented magma injection. Connecting these two trends of magmatism is an
EW-oriented, right lateral fault that occurs along the S side of the caldera (Hill, 2006). The orientation of this right-lateral fault is kinematically incompatible with the overall movement of the Sierra Nevada block relative to the Basin-and-Range and the left-lateral movement on faults associated with the nearby Mina deflection. We propose that this section of the Sierra Nevada front has decoupled from the rest of the Sierra thrust front, accommodating the divergent motion in a different way. Here, dike swarms accommodate the extension, rather than the faults, in a direction consistent with relative motion of the Sierra Nevada block relative to the crust immediately E (Note that the right-lateral eastern California shear zone is located eastward of this location). The right-lateral fault on the south side of the Long Valley caldera, between the zones of inferred dike magmatism, acts essentially as a transform fault, accommodating the motion between the two. The extent to which the crustal magma chamber below Mammoth Mountain results from its emplacement in a dilational area caused by the strike-slip faulting versus being controlled by the Cretaceous shear zone is unresolved.

To the north and south, extension (with a small right-lateral component) is accommodated by normal faults.

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References


Fig. 2 – Tectonic model of the magmatic injection in the Long Valley Caldera. In the area around Mammoth Mountain, divergent movement is accommodated by two zones of dike injection; these areas are joined by a right-lateral fault, which acts as a transform fault. Magma concentration at Mammoth Mountain (red blob) is attributed to the presence of the inactive Rosy Finch shear zone (yellow curved lines) which acted as a lithospheric conduit.
Waves-ropes-lobes, fluidization and deformation at laccolith-host contacts (Elba Island, Italy)

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Emplacement of shallow intrusions produces a variety of contact features both in the igneous rock and in its host. Marginal features of such intrusions have been studied primarily while examining the larger question of emplacement and growth, and discussions have focused on magmatic flow structures and solid-state deformation within the outermost skin of the igneous rock (Horsman et al., 2005; Morgan et al., 2008; Saint-Blanquat et al., 2006). Careful descriptions of marginal features such as ropy flow structures in vesicles (Liss et al., 2002) as well as fingered margins and fluidization structures (Schofield et al., 2010) are scattered and related only to mafic intrusions.

Felsic porphyritic multilayer laccoliths of the Elba Island Miocene igneous complex (Dini et al., 2002) offer a wide range of examples of contact features, many of which provide constraints on magma flow direction. The Portoferaio laccolith in central Elba intruded ~8 Ma at an average depth of about 2.6 km (Rocchi et al., 2002) into Jurassic serpentinites and overlying Cretaceous flysch (dark shale, feldspathic sandstone, marly limestone) that make up the top two complexes of a thrust stack assembled by about 20 Ma. The three main layers of the megacrystic San Martino laccolith were emplaced ~7.4 Ma at an average depth of 1.9 km, within the Cretaceous flysch (Rocchi et al., 2010).

Contact features for the Portoferaio and San Martino laccoliths have been separated into two sets. The first set consists of specific geometric shapes defined by the external morphology of the intrusive surface. Wave structures (Fig. 1) are seen with geometries ranging from rounded crests and V-shaped troughs, through sinusoidal, to “fully-developed” with breaking crests. Scales range from centimetric to metric, often with smaller waves on surfaces of larger waves. “Pahoehoe” rope structures represent a unique style of wave in which rounded crests tend to override the adjacent rope with formation of triple points (Fig. 2). Decimetric lobate structures occur both on the intrusion floor and on steeper, ramp-like surfaces connecting offset floor segments (Fig. 3). In the former case, they exhibit structures reminiscent of load casts or lava pillows, with superimposed fine-scale waves and weak lineations on their surfaces, while in the latter case they appear as tightly bent, rounded wave crests.

Fig. 1 – Wave crests (parallel pencil) with perpendicular lineations of stretched phenocrysts indicating flow direction.

Fig. 2 – “Pahoehoe” rope structures on upper surface of porphyry intruded below serpentinite.

A second set of contact features is characterized by deformation and/or disruption of materials on one or both sides of the contact. Most common are solid-state stretching lineations made from quartz and feldspar phenocrysts (Fig. 1) that experienced either ductile or brittle deformation. Deformation style is related to distance from contacts, with ductile strain...
These relationships suggest that when the host material has a high water content, it can become fluidized, setting up a condition in which two fluids of differing viscosity are in contact. It is at this interface that waves and their derivatives (lobes and ropes) develop, along with solid-state strain at the chilled margin. The orientations of these features preserve evidence of magma flow direction along the contact surface, which can be compared with results from the interior of the intrusive bodies. Additionally, wave fronts can evolve during magma advance, by folding in screens of host material to form laminations that simulate multiple thin sheets.

References

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