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Implications of incremental emplacement of magma bodies for magma differentiation, thermal aureole dimensions and plutonism–volcanism relationships

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ABSTRACT

Field observations and geophysical data indicate that many igneous bodies grow by amalgamation of successive magma pulses that commonly take the shape of horizontal sheets (sills). Emplacement styles and emplacement rates of magma bodies have fundamental implications on magma differentiation, country rock metamorphism and assimilation, and for the formation of large magma chambers in the upper crust.

When a magma body begins to grow by slow accretion of sills, each successive intrusion solidifies before the injection of the next one. When the system is thermally mature, sill temperatures equilibrate above the solidus, melts accumulate and older sills can re-melt. The time needed for each magma injection to cool down and equilibrate with its surrounding is short relatively to the total emplacement time of the body. The transition from a mafic crystal-poor magma to a partially molten rock that retains a highly differentiated melt is fast, whereas the resulting evolved residual melt can reside in the crust for protracted periods. As long as temperatures in the system are relatively low, highly differentiated melts are generated, which may explain the bi-modal character and the absence of intermediate compositions in some magmatic provinces.

The level of emplacement of successive magma pulses controls the shape of the thermal anomaly associated with the magma body growth. Metamorphism, partial melting and assimilation of the country rock are favoured if successive magma sheets are emplaced at or close to the country rock–magma body boundary. If the magma emplacement rate is low, the size of the thermal aureole is controlled by the size of one pulse and not by the size of the entire igneous body.

Understanding emplacement of magma bodies is fundamental for our understanding of the plutonism–volcanism relationship. Magma emplacement rates of several centimetres per year are needed for a magma body to evolve into a large magma chamber able to feed large silicic explosive eruptions. The time-averaged emplacement rates of plutons are lower than this critical emplacement rate. Eruptions of 100s to 1000s cubic kilometres of silicic products show that such high volumes of magmas can accumulate in the upper crust. This suggests that the emplacement of magma bodies is a multi-timescale process with the development of large magma chambers corresponding to the highest magma fluxes.

Because they control magmatic processes and the impact of magma intrusion on the country rock, future studies should focus on magma emplacement rates and on magma emplacement geometries. These studies should integrate field observation on plutons and geophysical data on active magmatic systems, coupled with laboratory experiments and numerical simulations.

1. Introduction

Many models (conceptual, petrological, numerical, etc.) that address cooling, crystallisation or differentiation of large magma bodies consider a single magma intrusion that was emplaced in the crust quasi-instantaneously (e.g. Barboza and Bergantz 1996; Bohrson and Spera, 2001; Huppert and Sparks, 1988). However, a growing body of evidence indicates that many igneous bodies are the result of the agglomeration of discrete smaller intrusions. The injection of magma in the crust and the growth of - plutons may be comparable to the successive eruptions of volcanic products on the Earth's surface and to the growth of volcanic edifices. For equivalent magma volumes, repeated injections in the crust of small magma intrusion induce a thermal evolution and result in temperature distributions that are fundamentally different from those resulting from the quasi-instantaneous emplacement of a single large magma body. In this paper, I will describe the implications of incremental intrusion in terms of magma differentiation, growth of thermal aureoles and plutonism–volcanism relationships. The present paper is based on a series of recent numerical studies involving heat transfer calculations in systems where magma bodies grow by accretion of discrete intrusions. Results of these studies are reported on Figs. 1 to 7. Although the numerical methods are not described here, interested readers are

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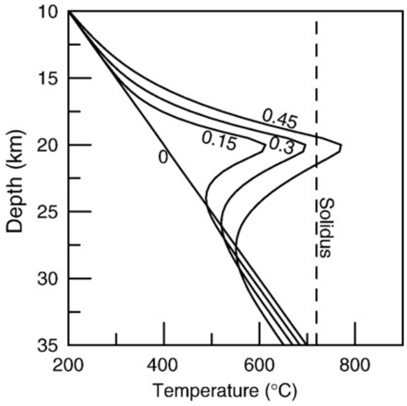

Fig. 1. Temperature evolution of the crust. Mafic sills are emplaced at 20 km depth. One 50 m thick sill is emplaced every 10,000 years resulting in an average emplacement rate of 5 mm/year. Curves are shown for times 0, 0.15 Myr, 0.3 Myr and 0.45 Myr. The dashed vertical line marks the magma solidus temperature. Details on the numerical model can be found in Annen et al. (2006a).

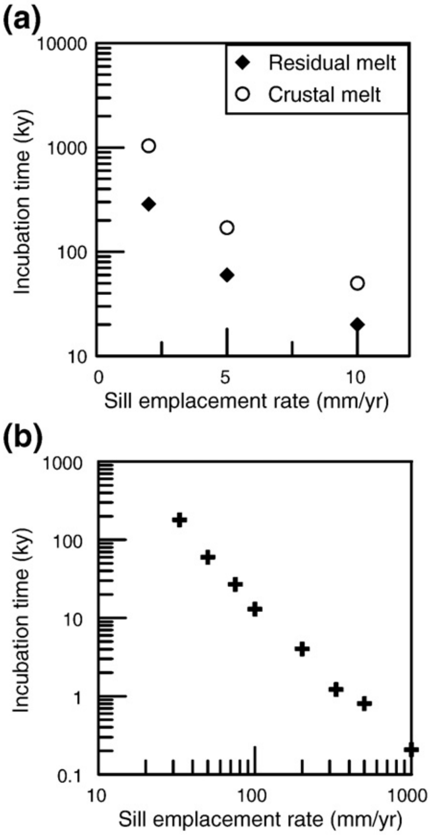

Fig. 3. Relationship between incubation times and emplacement rates. (a) Sills of basalt are emplaced at the base of the lower crust (30 km) by over-accretion. Black diamonds show incubation times needed to accumulate residual melt generated by incomplete crystallisation of the basalt. White circles show incubation times needed to partially melt the country rock if its composition is amphibolitic. (b) Sills of silicic andesite are emplaced in the upper crust (from 5 to 15 km) by under-accretion. Incubation times are for the accumulation of mobile eruptible magma ($T \geq 875$ °C). Details on the numerical model can be found in Annen et al. (2006b, 2008).

invited to consult the relevant publications referred to in the text and figure captions.

1.1. Evidence for incremental magma emplacement in the upper crust

Geochronological, geophysical and field studies indicate that many igneous bodies emplaced in the upper crust result from the amalgamation of several, discrete magma pulses. Several million years separate the top and bottom of some plutons and batholiths that are several kilometres thick (Coleman et al., 2004; Harrison et al., 1999; Matzel et al., 2006). Because this timescale largely exceeds the cooling time of such volumes of magma, it has been inferred that these plutons were built up by addition of several discrete pulses. Plutons 3D reconstruction based on field relationships and geophysical investigations shows that most plutons are tabular or wedge-shaped (Cruden, 1998, Vigneresse et al., 1999) which supports a model of pluton emplacement by accretion of sheet intrusions (Menand, 2009-this issue). Limits between the successive intrusions are often cryptic and cannot be readily observed in the field (Miller et al., 2009-this issue). However, in some cases that cover a range of compositions from basalts to leucogranites, successive intrusions are distinguishable. Examples include the Himalayan Leucogranites (Searle, 1999, 2003), the Adamello granite in Italian alps (John and Blundy, 1993), the Torres del Paine granite in Chile (Michel et al., 2008), the Ox Mountain granodiorite in Ireland (McCaffrey, 1992), the diorite black Mesa pluton, in the Henry Mountains, Utah, USA (de Saint-Blanquat et al., 2006), and the basalt laccolith associated with the Stardalur volcano in Iceland (Pasquarè and Tibaldi, 2007). More examples are presented in this volume (Allibon et al., 2009-this issue; Gudmundsson, 2011-this issue; Miller et al., 2009-this issue; de Saint-Blanquat et al., 2009-this issue).

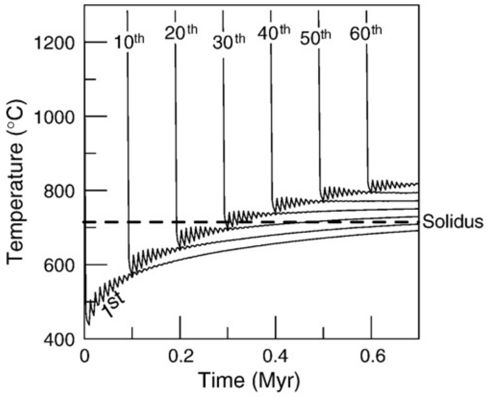

Fig. 2. Temperature evolution of successive mafic sills. Sills are emplaced at a depth of 20 km by over-accretion. One 50 m thick sill is emplaced every 10,000 years (average emplacement rate of 5 mm/year). Curves show temperatures of every 10th sill. Each sill is emplaced at 1285 °C. Sills' very rapid cooling is followed by temperature fluctuations due to emplacement of later sills. Eventually sills thermally equilibrate with their surroundings. The whole crust segment heats up with time resulting in increasing equilibration temperatures. The horizontal dashed line marks the H_2O-saturated solidus. After an incubation time of about 0.35 Myr, newly emplaced sills equilibrate at temperatures higher than the solidus and retain residual silicic melts. Details on the numerical model can be found in Annen et al. (2006a).

1.2. Evidence for incremental magma emplacement in the lower crust

Observations also indicate that large mafic magma bodies emplaced within or at the base of the lower crust (underplating) result from the accretion of successive magma pulses. Some of these deep bodies were exhumed by tectonics during orogenic events and individual pulses of magma can be directly observed in the field. This is the case for the Ivrea mafic body in the Alps (Quick et al., 1994). Seismic profiles of the lower crust show a layering that has been interpreted as due to the presence of sills (Franke, 1992; Fuchs et al., 1987; Wenzel and Brun, 1991). The cyclic fluctuation of sea level identified in the sediment records of the North Sea are thought to

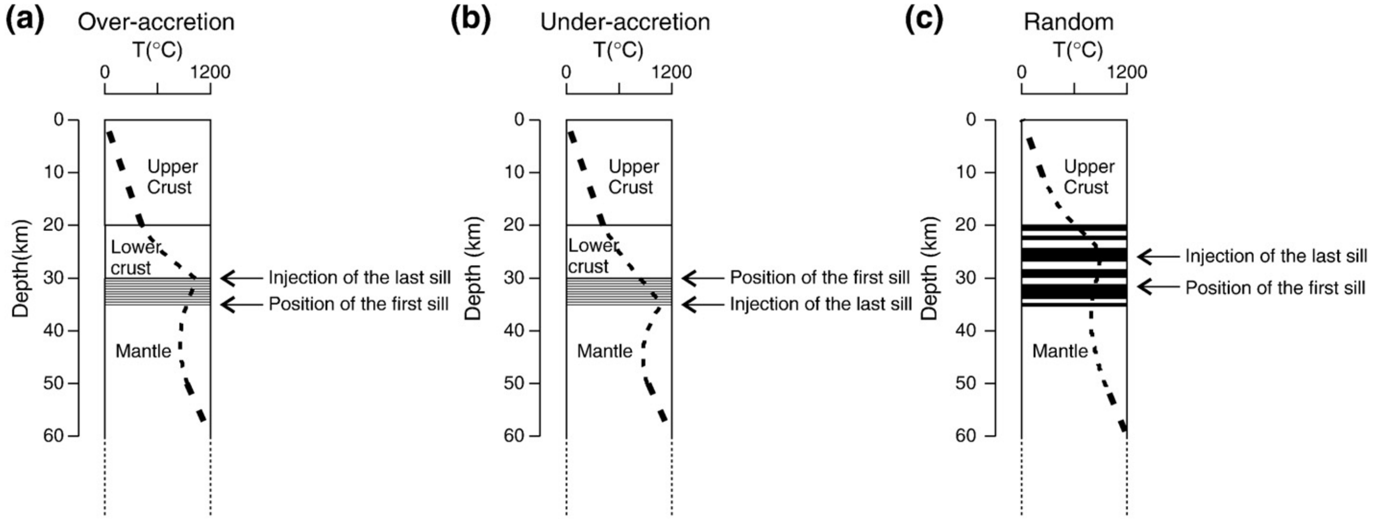

Fig. 4. Sill emplacement geometries and the resulting temperature distributions. Dashed lines show the shape of the temperature anomaly induced by each type of emplacement geometry. In these examples sills of basalt are emplaced at the mantle–lower crust interface. (a) Emplacement is by over-accretion and the highest temperatures are at the top of the growing intrusive body; (b) emplacement is by under-accretion and the highest temperatures are at the bottom of the growing intrusive body; (c) sills are randomly distributed within a segment of crust and temperatures form a broad anomaly within the crust. Details on the numerical model can be found in Annen et al. (2006b).

correspond to cycles of magma injection and solidification at the bottom of the crust (Maclennan and Lovell, 2002).

2. Thermal evolution of magma bodies and of the surrounding crust

2.1. Magma bodies emplaced instantaneously

The thermal evolution of a single magma body emplaced instantaneously into the crust is controlled by magma and crust initial temperatures, by the magma body size and shape, by country rock conductivities and by the possible occurrence of magma convection within the intrusion and of hydrothermal convection within the country rock. Because direct field observations and geophysical studies show that many plutonic bodies are tabular in shape (Cruden, 1998; Vigneresse et al., 1999; Petford et al., 2000; Cruden and McCaffrey, 2001) I will only discuss here the thermal evolution of sill-like bodies. A sill-like magma intrusion cools down from the walls toward the centre. If heat transfer by convection and latent heat produced by crystallisation are ignored, the cooling timescale can be estimated with the diffusivity equation

$$t \approx b^2 / \kappa \tag{1}$$

where b is the half dimension of the magma body and κ is the thermal diffusivity. According to this scaling, a magma body 1500 m thick with thermal diffusivity of 5×10^{-7} m^2/s would cool down on timescales of 3.6×10^4 years.

The solidification of the body proceeds from the wall to the centre. The solidification time for a non-convecting sill or dyke that releases latent heat during crystallisation is given by Turcotte and Schubert (1982):

$$t_s = \frac{b^2}{4\kappa\lambda^2} \tag{2}$$

λ is a dimensionless constant and:

$$\frac{L\sqrt{\pi}}{c(T_m - T_0)} = \frac{e^{-\lambda^2}}{\lambda(1 + erf\lambda)} \tag{3}$$

where L is latent heat, T_m is magma temperature at emplacement, T_0 is the initial temperature of country rock before emplacement and c is specific heat. For $L = 300$ kJ/kg, $T_m = 1000$ °C, $T_0 = 500$ °C and $c = 1.3$ kJ/kg, $\lambda = 0.564$, a 1500 m thick body would solidify in 2.8×10^4 years. This solution assumes that solidification is instantaneous below T_m. Most magma however crystallise over a range of temperature. As the magma crystallises, the residual melt chemically evolves with time and follows the normal trend of magma differentiation (Bowen, 1915).

In Eqs. (1) and (2) heat transfer by convection is not taken into account. A magma injected as a sill is expected to convect as long as its melt fraction is above a critical value of about 40–60% (Lejeune and Richet, 1995). Below this critical value, crystals form a connecting network and the magma is not mobile anymore. Convection increases heat transfer and accelerates cooling. Convection also mixes and homogenizes the magma. Huppert and Sparks (1988) analyzed heat transfer between a cooling, turbulently convecting basaltic sill and the country rock. They found that a 1500 m thick basalt sill emplaced in a crust at 500 °C needs only 270 years to crystallise to 60% crystals (934 °C) and stop convecting. Further cooling is by conduction and

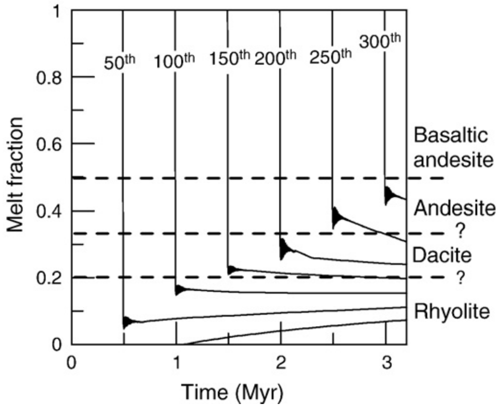

Fig. 5. Evolution in melting degree of successive mafic sills. Sills are emplaced at the boundary between the lower and the upper crust by over-accretion. Curves are shown for every 50th sill. One 50 m thick sill is emplaced every 10,000 years resulting in an average emplacement rate of 5 mm/year. Because sill equilibration temperatures increase with time (Fig. 2), melting degrees of successive sills also increase with time resulting in compositions that become less differentiated. Details on the numerical model can be found in Annen et al. (2006a,b).

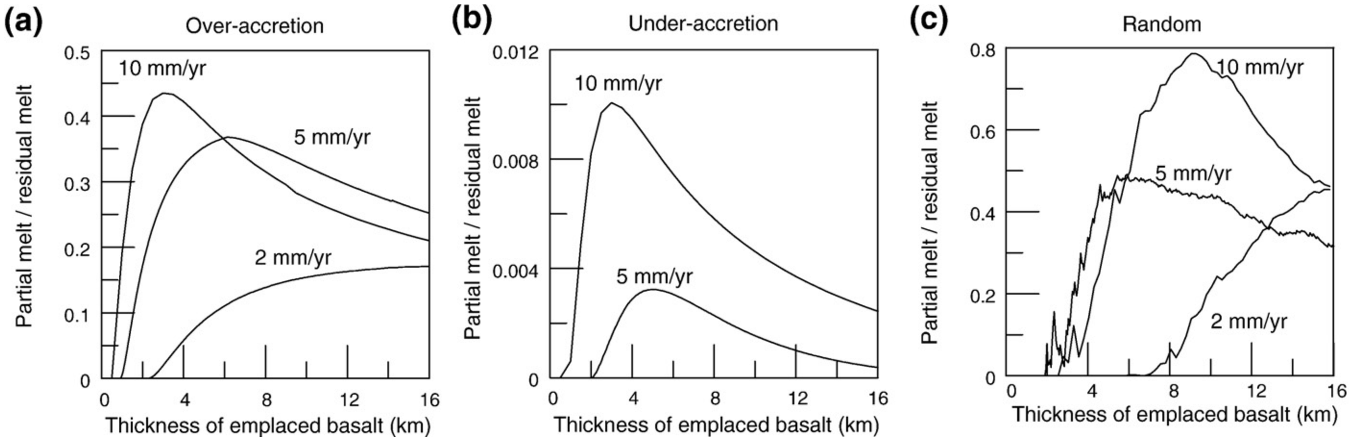

Fig. 6. Ratios of thicknesses of melt produced by partial melting of an amphibolitic crust over thicknesses of melt produced by incomplete crystallisation of a mafic magma. A mafic body is growing at the boundary between the mantle and the lower crust by (a) over-accretion; (b) under-accretion. In (c) mafic sills are randomly distributed over a 20 km thick segment of lower crust. Note changes in scales between diagrams (a), (b), and (c). Results are shown for emplacement rates of 2, 5, and 10 mm/year. In case of under-accretion (b), an emplacement rate of 2 mm/year does not result in any partial melting of an amphibolitic crust. Details on the numerical model can be found in Annen et al. (2006b).

much slower. According to their model, the heat transferred from the basalt to the crust results in melting of the crust over a thickness of 870 m.

2.2. Magma bodies emplaced incrementally

As for instantaneously emplaced magma bodies, the thermal evolution of incrementally emplaced magma bodies depends on initial magma and country rock temperatures, on country rock conductivities and on the possible occurrence of hydrothermal circulation in country rocks. In addition, emplacement rate and emplacement geometry of successive intrusion are parameters specific to incremental emplacement and exercise a strong control on the thermal evolution of the system.

I will describe here the case where the successive intrusions that build up an igneous body are horizontal (sills) because this is a geometry often observed in nature (Searle, 1999; Searle et al., 2003; de Saint-Blanquat et al., 2006; Michel et al., 2008), that explains well plutons tabular shape (Cruden, 1998; Vigneresse et al., 1999; Menand, 2008). Moreover, the thermal history of an igneous body that grows by addition of sills is not fundamentally different from the thermal history of an igneous body that grows by addition of dykes (Annen et al., 2008). The first emplaced sills are in contact with a cold country rock and they cool and solidify rapidly. In the earliest stage of the igneous body growth, unless the time interval between intrusions is very small, each successive sill crystallises before the next one is emplaced. Sills, when cooling down and crystallising, transfer their sensible and latent heat to the country rock that progressively heats up (Fig. 1). With time, successive sills thermally equilibrate with their surrounding at progressively higher temperatures (Fig. 2). After an incubation time that depends on the emplacement rate, the temperature of the system is high enough for new sills to equilibrate above their solidus temperature (Figs. 1 and 2) and retain residual melt. As intrusions proceed, temperatures continue to increase and an increasing volume of melt is present in the system as the melting degree of newly intruded sills increases and older sills re-melt. If the solidus of the crust is reached, more melts are generated by crust partial melting. If temperatures become high enough for melt fractions to exceed a critical threshold of about 40–60% (Lejeune and Richet, 1995) the magma can convect. Michaut and Jaupart (2006, 2009-this issue) showed that if the cooling of the first sills is fast enough for the magma to quench, the progressive heating of the system eventually leads to devitrification, sudden release of latent heat and rapid re-melting of previously emplaced sills.

2.2.1. Role of emplacement rates

If the successive sills (or dykes) aspect ratio is low, most heat is transferred through the walls and the heat loss at the tips is insignificant (Annen et al., 2008). The sill emplacement rate (i.e. the sill accretion velocity) corresponds to the sill thickness divided by the time interval between two sill injections. As long as the time interval between two injections is short in comparison with the total duration of the igneous body emplacement and the cooling rate is low enough for the sills not to quench (Michaut and Jaupart, 2006, 2009-this issue), the thermal evolution of the system depends on the average emplacement rate and not on the exact sill thickness and intrusion frequency (Annen and Sparks, 2002). Several incubation times can be defined in a system where an igneous body is emplaced incrementally: the incubation time before residual melts start to accumulate (Annen and Sparks, 2002; Dufek and Bergantz, 2005; Annen et al., 2006a,b; Michaut and Jaupart, 2006), the incubation time before country rock starts to partially melt (Petford and Gallagher, 2001; Annen and Sparks, 2002; Dufek and Bergantz, 2005; Annen et al., 2006b), and the incubation time before the magma starts to convect and mix (Annen and Scaillet, 2006; Annen et al., 2006c). These incubation times strongly depend on intrusion emplacement rates (Fig. 3). If the sill emplacement rate is low, heat has time to diffuse

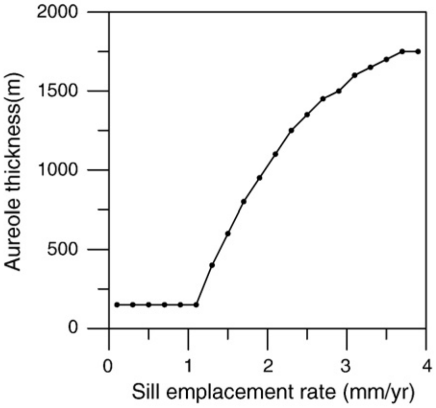

Fig. 7. Thickness of the top thermal aureole (defined as the thickness of country rock above 400 °C) associated with the growth of a 5 km thick leucogranite pluton. The thickness of the thermal aurole is shown in relation with different pluton emplacement rates. The depth of the pluton–country rock upper boundary is 10 km. The pluton grows by sills under-accretion so that the magma injection level moves with time down and away from the top pluton boundary. Below a critical emplacement rate, the size of the thermal aureole is independent of the emplacement rate and is controlled by the size of the first sill. Details on the numerical model can be found in Annen et al. (2006c).

through the crust between intrusions and heat cannot accumulate. In this case, incubation times for magma accumulation exceed the lifetime of the intrusive system. The magma volumes present at any time in the system do not exceed the volume of a single intrusion. Scales of convection and differentiation are limited to the scale of one intrusion and successive pulses cannot mix.

If incubation times are exceeded and magma can accumulate, the amount of magma that is produced and the respective quantities of melt generated by differentiation of the intruded magma and by partial melting of country rocks also depend on the emplacement rate (Petford and Gallagher, 2001; Dufek and Bergantz, 2005; Annen et al., 2006b).

2.2.2. Role of emplacement geometries

Emplacement geometries of the successive intrusions determine the thermal impact of the growing igneous body on the surrounding rocks. Successive intrusions of randomly oriented dykes intruded at the base of the crust have been modelled by Dufek and Bergantz (2005).

If the successive intrusions are sills and are fed by dykes, the level of sill emplacement is the level at which dykes reorient to spread horizontally and form sills. The factors that control this level and how the first emplaced sills can influence the emplacement level of later sills are discussed in this volume by Gudmundsson, Menand, and Vigneresse. Several types of emplacement geometries can be envisaged (Fig. 4). In case of over-accretion, each sill is emplaced above the former one so that the younger sill is at the top of the igneous body (Fig. 4a) and the body grows from bottom to top. In case of under-accretion (Fig. 4b), each sill is emplaced below the former one so that the younger sill is located at the bottom of the igneous body and the body grows from top to bottom. Another possibility is that each intrusion is emplaced in the middle of the former one (intra-accretion). The sills can also be distributed through a segment of crust (Fig. 4c) which results in screens of country rock being sandwiched between intrusions. In this last case, a coherent igneous body will only form if the melting degrees in the screens of crust and in the intrusions are high enough for large-scale magma mixing. Field observation suggests that newly injected magma intruding a magma chamber spreads at the interface between the mushy, partially solidified part of the magma chamber and the overlying mobile highly molten magma (Wiebe and Collins, 1998). It has been shown numerically that this emplacement mechanism results in a magma body growing from top to bottom and that the resulting temperature distributions are quite similar to those associated with under-accretion sensu-stricto (Annen et al., 2008). Accretion of sills induces a temperature peak that develops at the level of intrusion emplacement. In the case of over-accretion, the highest temperatures are at the upper interface between the body and the country rock (Fig. 4a), in the case of under-accretion, they are at the lower interface (Fig. 4b) and in the case of intra-accretion, the temperature peak is in the middle of the magma body. Thus the location and size of thermal aureoles and the degrees of country rock melting depend on the emplacement geometry. Emplacement geometries are especially important if the magma is trapped by a geological interface and if the rocks below and above the igneous body are of different compositions and fertilities. If the intrusions are distributed through the crust, the heat they advect is also distributed resulting in a broad unfocused thermal anomaly (Fig. 4c). The consequence is that incubation times depend on the degree of sill dispersion but are significantly longer than in the case of focused magma emplacement (over-, under- or intra-accretion) (Annen et al., 2006b).

3. Implications of incremental emplacement

3.1. Generation of silicic melts

Numerical simulations were used to model the thermal effect of repeated mafic intrusion in the lower crust (Petford and Gallagher, 2001; Annen and Sparks, 2002; Dufek and Bergantz, 2005; Annen et al., 2006a,b). All these studies showed that if the composition of the crust in contact with the mafic intrusions is amphibolitic, partial melting of the crust is very limited. However, large quantities of silicic melts can be generated by incomplete crystallisation of the intruded mafic magma (Dufek and Bergantz, 2005; Annen et al., 2006a,b). For any given cumulated intrusion thickness the amount of silicic melt residual from the mafic magma strongly depends on the emplacement rate. Because temperatures increase with time and with successive intrusions, melting degrees also increase and the melt is expected to become less differentiated with time (Fig. 5). Thus the chemical evolution of the residual melt composition is the reverse of the chemical evolution predicted by fractionation in a large cooling magma chamber. If the emplacement rates are low (a few mm per year or less) and the temperatures in the system stay relatively low, only highly silicic melts are produced by crystallisation of the mafic magma. It must be noted however that the essence of an incrementally emplaced body is to be an open system. If the differentiated residual melts mix with the new mafic magma coming from the mantle, intermediate compositions can be produced.

If a mafic magma crystallises at depth, the H_2O it contains concentrates in the residual melt and the solidus corresponds to a wet rhyolite solidus. The solidus temperature of the mafic magma is lower than the dehydration melting temperature of the country rock even if the country rock is fertile. The first differentiated melts generated in the system are melts residual from the intruding mafic magma (Fig. 3a). The time needed to partially melt pre-existing crustal rocks depends on their fertility and if the emplacement geometry of the mafic magma results in a temperature increase at the contact with the crust (Annen et al., 2006b). For example, if mafic magma is emplaced at the mantle–lower crust boundary, partial melting of the crust is possible if emplacement is by over-accretion (Fig. 6a) but is very limited if emplacement is by under-accretion (Fig. 6b). As noted before, random emplacement is associated with long incubation times but once solidus temperatures are reached this geometry produces more partial melting of the crust than focused intrusions (Fig. 6c). If the melting degrees are high enough for the magma to convect, the successive injections and possibly the melt generated by melting of the crust can mix and homogenize forming a MASH zone as described by Hildreth and Moorbath (1988).

3.2. Thermal aureoles

For an instantaneously emplaced magma body, the size of the associated thermal aureole depends on initial crust temperatures, on the size of the magma body, and on country rock conductivities. For an incrementally growing igneous body, in addition to initial temperatures and country rock conductivities, the thickness of the thermal aureole depends on the igneous body emplacement rate and emplacement geometry (Fig. 7) (Annen et al., 2006c; Barker, 2007). The relative thicknesses of the top and bottom thermal aureoles are controlled by emplacement geometry. The top aureole is larger if emplacement is by over-accretion and the bottom aureole is larger if emplacement is by under-accretion. The thermal aureole close to the level where magma is preferentially emplaced is larger than the aureole that would be produced by an instantaneous emplacement because high temperatures are maintained at this level by repeated injection. For very low emplacement rates, the contact with the country rock that is the furthest away from where intrusion is focused (i.e. the top contact in case of under-accretion or the bottom contact in case of over-accretion) cools down after the injection of the first pulse. It becomes isolated from later intrusions by the first magma pulses and does not reheat significantly during the igneous body construction. The aureole that develops at this contact depends on the size of the first magma pulses and does not depend on the emplacement rate anymore (Fig. 7) (Annen et al., 2006c). Incremental emplacement explains easily the occurrence of thermal aureoles that are either smaller or larger than predicted by heat transfer models that only consider the size of the associated intrusion and assume instantaneous emplacement of the whole igneous body.

3.3. Generation of large shallow silicic magma chambers and relationship between volcanism and plutonism

The finding of differences in ages of several millions years within plutons led to questions about the relationship between plutonism and volcanism (Coleman et al., 2004; Glazner et al., 2004). Because this timescale is much larger than the cooling time of the plutons, the plutons cannot have been at any time a single giant magma chamber of corresponding volume that eventually solidified. In addition, seismic studies do not detect any current large volumes of magma molten enough to be mobile and eruptible. These observations led Glazner et al. (2004) to postulate that large magma chambers are rare and ephemeral and maybe unconnected to pluton growth. Lipman (2007) contested this view on the basis of field observations and reaffirmed the likely existence of the link between large magma reservoirs and plutons.

Numerical simulations of incremental emplacement of silicic magma show that emplacement rates of several centimetres per year are required to accumulate large volumes of eruptible magmas (Hanson and Glazner, 1995; Yoshinobu et al., 1998; Annen et al., 2008) (Fig. 3b). This value is conservative because the numerical models neglect thermal convection in the magma chamber and possible hydrothermal circulation in the country rock that both accelerate cooling. The minimum emplacement rate needed to generate a large magma chamber is significantly higher than the average emplacement rate of plutons (a few millimetres per year) inferred from geochronological data (Crisp, 1984; Coleman et al., 2004; Matzel et al., 2006). The emplacement rates required for fast devitrification melting as modelled by Michaut and Jaupart (2006, 2009-this issue) are also higher than time-averaged pluton emplacement rates. It can be inferred from these results that either large magma chambers are unrelated to pluton growth as suggested by Glazner et al. (2004), or that they are associated with rare episodes of exceptionally high magma fluxes.

Recent high precision geochronology shows transient increase in magma fluxes during pluton emplacement (Matzel et al., 2006; Burgess and Miller, 2008). The emplacement rate of shallow laccoliths like the Torres del Paine (Chile) (Michel et al., 2008) or the Black Mesa pluton (Utah, USA) (de Saint-Blanquat et al., 2006, 2009-this issue) was one to several orders of magnitude faster than the average emplacement rate of large plutons. In the central Andes, current magma fluxes inferred from ground surface uplift detected by INSAR interferometry (Sparks et al., 2008) are one order of magnitude larger than time-averaged magma accumulation rates (de Silva and Gosnold, 2007). This suggests that igneous bodies are not only incrementally emplaced but that their emplacement rates can vary in time over several orders of magnitude (de Saint-Blanquat et al., 2009-this issue).

4. Discussion and conclusions

4.1. Incremental growth of magma body: a “paradigm shift”?

Many models of plutons and magma chambers evolution are based on the assumption that a large volume of magma was somehow instantaneously emplaced into the crust and differentiated during cooling. The recognition that many large igneous bodies grow by addition of smaller intrusions has far reaching implications and give us a new perspective on magmatic processes and on the way magma intrusions interact with country rocks. Thermal evolution and temperature distribution in an incrementally growing magma body are fundamentally different from those of an instantaneously emplaced similar volume of magma. The heat advected by successive pulses of magma is partly dissipated between magma injections by conduction, possibly aided by hydrothermal circulation, and the molten part of many igneous bodies may have never exceeded the size of one magma pulse. The presence of large volumes of mobile magma associated with pluton incremental emplacement requires either that compaction and/or deformation separates a low degree melt from its crystal matrix and concentrates it to form layers or pockets of melt (Jackson et al., 2003; Bachmann and Bergantz, 2004) or that thermal maturation of the system and transient high magma emplacement rates result in temperatures high enough for melting degrees to exceed the critical melt fraction. In any case, thermal models suggest that the generation of a large reservoir of mobile magma is restricted in space and time so that the presence of large volumes of mobile magma in the crust may be the exception rather than the rule. A corollary of these results is that large-scale convection, fractionation and mixing are probably limited in many upper crustal plutons (Coleman et al., 2004; Glazner et al., 2004; Miller, 2008).

Because magmas emplaced at shallow levels in the upper crust cool rapidly, unrealistically large volumes of mafic magma would be needed either as parental magma or as a heat source to generate silicic melts by fractional crystallisation or by crust partial melting (Annen et al., 2006a). This suggests that most silicic melt generation happens within the lower crust or at the mantle–lower crust boundary where temperatures are higher and where mafic cumulates produced by fractionation can be recycled in the mantle by delamination (Ducea and Saleeby, 1998; Jull and Kelemen, 2001; Zandt et al., 2004). For an instantaneously emplaced magma reservoir, magma residence timescales, cooling timescales and differentiation timescales are similar. In contrast, if mafic magma is repeatedly injected in the lower crust, magma residence times depend on the body emplacement duration after the system was mature enough to accumulate melt (10^6 years) whereas differentiation times scale with the time each magma pulse takes to equilibrate with its environment (10^3 years) (Annen et al., 2006a). As a result of rapid differentiation and thermal equilibration of the individual magma pulses, the presence of intermediate compositions related to fractionation is very limited in time and space, which could explain the occurrence of bi-modal magmatism. However, as discussed in Section 3.1, intermediate compositions can be generated by mixing between the differentiated residual melt and new mafic magma. Intermediate compositions can also be obtained when the system has matured enough for high equilibration temperatures to allow storage of high melting degree melts.

The impact of an incrementally growing igneous body on country rocks in terms of metamorphism, partial melting and assimilation depends on the body emplacement rate and emplacement geometry. Thus the size of a thermal aureole or the extent of crust partial melting cannot be inferred from the size and depth of the igneous body only. However, if other parameters can be estimated, the size of a thermal aureole can be used to put limits on the emplacement rate of an igneous body (Annen et al., 2006c).

4.2. Future work and challenges

Because many, if not all, igneous bodies grow by repeated addition of smaller intrusions, a better understanding of magmatic processes depends on our ability to (see also Cruden and McCaffrey, 2001):

(1) Quantify emplacement rates and magma fluxes and understand the physics that are behind rate fluctuations;
(2) Determine shapes and sizes of the intrusions that are the building blocks of the igneous bodies and understand how these intrusion dimensions and shapes are controlled;
(3) Determine how successive intrusions are emplaced relative to each other.
(4) Evaluate the possible differences in emplacement rates, intrusion shapes and sizes, and emplacement geometries for different magma compositions (mafic to silicic) and emplacement depths (deep lower crust to shallow upper crust).

Emplacement rates control the volumes of mobile magma that can be stored in the crust, the melting degrees and composition of the melts, the possible partial melting and assimilation of country rocks, and the size of thermal aureoles. Current magma fluxes in the crust are estimated on the basis of ground deformations measured with radar interferometry (e.g. Pritchard and Simons, 2004; Sparks et al., 2008). High precision geochronology is currently providing us with new exciting data on pluton assembly times (Coleman et al., 2004; Matzel et al., 2006; Michel et al., 2008). Age resolutions of the order of 10^4 years that can now be achieved (Michel et al., 2008) are close to the timescales for which a large mobile magma chamber may develop if the system is not cooled down by hydrothermal circulation. In the future, high precision geochronological data on large magmatic systems will hopefully provide us with new data on the fluctuation of magma fluxes. Magma fluxes may be controlled by dynamics of the magma source at depth, and by interactions between the timescales of magma generation, melt segregation and ascent. Because of the complexity of these processes, modeling such interactions is challenging and laboratory experiments, analytical models and especially numerical simulations that integrate different processes will be needed to understand how magma fluxes are controlled.

In case of low emplacement rates and/or shallow emplacement and/or enhanced cooling by hydrothermal circulation, the volume of any mobile magma chamber associated with the growth of an igneous body does not exceed the volume of one magma pulse. In this case, the volumes of the eruptions and the scale of magmatic processes such as fractionation and convection are directly related to the dimension of the individual pulses, hence the importance of determining the dimension of these pulses. For most plutons, contacts between pulses are cryptic. Moreover, contacts drawn on the basis of rock mineralogy or texture do not necessarily correspond to the original boundaries between pulses (Gray et al., 2008). The dimensions of active magma chamber can be estimated on the basis of geophysical data. The intrusions that agglomerate to build up a pluton are often sills and the mechanics and dynamics of sill intrusions are still poorly known (Menand, 2008). The dimension of magma pulses may be controlled by the volumes (or fluxes) the deep source can provide and by the volumes (or fluxes) the crust can accommodate. More laboratory experiments and mathematical analysis are needed to understand the parameters that control the size of intrusions. Once these parameters are known and the physics are understood, numerical simulations would provide insight on the way successive intrusions may evolve in size in the context of a growing body and of a heating crust.

The way successive intrusions are emplaced relative to each other controls the thermal impact an igneous body has on the country rock. Menand (2008, 2009-this issue) reviews the possible processes that control sill emplacement (see also Gudmundsson, 2011-this issue). In particular, the finding that dykes convert to sill when they abut a more rigid layer (Kavanagh et al., 2006) can lead to different styles of emplacement (under-accretion, over-accretion and mid-accretion) depending on the relative rigidities of country rocks and of formerly emplaced sills that form the growing igneous body (Menand, 2008). In several cases, the top of plutons is older than the bottom (Coleman, 1998; Harrison et al., 1999; Coleman et al., 2004; Michel et al., 2008) indicating a top to bottom emplacement, i.e. under-accretion. If rigidity controls successive sill emplacement, the emplacement style may vary with the pluton temperature distribution and with emplacement rates. More field observations and laboratory experiments possibly complemented by numerical simulation are needed to understand emplacement geometry. In addition to geochronological data and structural observations, the dimension of thermal aureoles can be used as indicator of emplacement geometries.

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