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Research Paper

Magma chamber growth models in the upper crust: A review of the hydraulic and inertial constraints

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ABSTRACT

Finite volumes of magma moving in confinement, store hydraulic potential energy for the generation, control and transmission of power. The Pascal's principle in a hydraulic jack arrangement is used to model the vertical and lateral growth of sills. The small input piston of the hydraulic jack is equivalent to the feeder dike, the upper large expansible piston equivalent to the magmatic chamber and the inertial force of the magma in the dike is the input force. This arrangement is particularly relevant to the case of sills expanding with blunt tips, for which rapid fracture propagation is inhibited. Hydraulic models concur with experimental data that show that lateral expansion of magma into a sill is promoted when the vertical ascent of magma through a feeder dike reaches the bottom contact with an overlying, flat rigid-layer. At this point, the magma is forced to decelerate, triggering a pressure wave through the conduit caused by the continued ascent of magma further down (fluid-hammer effect). This pressure wave can provide overpressure enough to trigger the initial hydraulic lateral expansion of magma into an incipient sill, and still have enough input inertial force left to continue feeding the hydraulic system. The lateral expansion underneath the strong impeding layer, causes an area increase and thus, further hydraulic amplification of the input inertial force on the sides and roof of the incipient sill, triggering further expansion in a self-reinforcing process. Initially, the lateral pressure increase is larger than that in the roof allowing the sill to expand. However, expansion eventually increases the total integrated force on the roof allowing its uplift into either a laccolith, if the roof preserves continuity, or into a piston bounded by a circular set of fractures. Hydraulic models for shallow magmatic chambers, also suggest that laccolith-like intrusions require the existence of a self-supported chamber roof. In contrast, if the roof of magmatic chambers loses the self-supporting capacity, lopoliths and calderas should be expected for more or less dense magmas, respectively, owing to the growing influence of the density contrast between the host rock and the magma.

1. Introduction

The intrusion of magmatic bodies plays a major role on the growth of the continental crust and has remained a source of debate since the recognition that plutonic rocks derive from the freezing of largely molten systems. For this reason, the development of magmatic bodies has been addressed by a plethora of works that discuss the influence of different chamber evolutions, among which the formation of punched laccoliths (Corry, 1988), the roles of diapirism versus ballooning (Pitcher, 1993), the subsidence of the pluton floor (Cruden, 1998; Cruden and McCaffrey, 2001; Cruden and McCaffrey, 2002) or the stoping of xenoliths from the roof (Glazner and Bartley, 2006) stand out. The varied crustal levels and geological settings in which intrusions are emplaced suggest that a diverse range of processes contribute to the construction of a pluton. Chief among such processes is the way an intrusive body thickens, a process that is closely interwoven with the three-

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dimensional shape of the body. In this regard, although the identification of intrusions with sub-horizontal floor goes back to the 19th century for laccoliths emplaced in brittle, shallow crustal levels (Gilbert, 1877), evidence that flat-lying sheeted geometries are also common for plutons and batholiths emplaced at deeper ductile levels is much more recent and possibly does not account for all such bodies (Saleeby et al., 2003). Based on field data and a large gravity data set, McCaffrey and Petford (1997) and Petford et al. (2000) found empirical power-law relationships demonstrating that most plutons and batholiths take the shape of flat-lying sheets. This result is in accordance with analogue models of intrusions in multi-layered media, where mainly sheeted intrusions develop controlled or assisted by the horizontal anisotropy of the overburden (Roman-Berdiel et al., 1995; Kavanagh et al., 2006; Mathieu et al., 2008).

In shallow brittle crustal levels, magma ascent through dikes is plausible (Clemens, 1998; Petford et al., 1993; Vigneresse and Clemens, 2000; Weinberg and Regenauer-Lieb, 2010). Alternatively, diapiric ascent is restricted to the ductile, deeper continental crust where high temperatures establish long-term viscous conditions required to keep the Rayleigh-Taylor instability active (Weinberg and Podladchikov, 1994).

The buoyancy of magma depends of the density contrast between magma and host rock. Hydrostatic equilibrium for lateral intrusion at shallow crustal levels such as laccoliths and sills at the neutral buoyant zone is considered to play a major role (Gilbert, 1877; Holmes, 1944; Willam and McBirney, 1979; Corry, 1988). Francis (1982) suggested that basaltic liquids can reach the neutral buoyancy at depths of 10 km or less, where the density of the sediments become less than that of the basaltic magma.

From the variety of forms an intrusion can take - dike, sill, laccolith, lopolith, spherical or tear-drop-there is a growing perception that most sub-horizontal intrusive igneous bodies start as thin sills that propagate by lateral spreading and then thicken by the amalgamation of successive sill intrusions (Jackson and Pollard, 1988; Coleman et al., 2004; Glazner et al., 2004; Menand, 2008; Michel et al., 2008; Morgan, 2008; Currier and Marsh, 2015). Besides, mafic sill complexes consist of networks of interconnected sills, where many sills are linked to each other by means of inclined bridges (Francis, 1982; Magee et al., 2016).

Experimental studies have investigated the feeder dike to sill transition (Pollard, 1973; Rivalta et al., 2005; Kavanagh et al., 2006; Menand, 2011; Hansen, 2015). These experiments suggest that sill formation and propagation in layered elastic media, having discontinuities such as rigidity contrasts, can control the formation and dynamics of sills at the interfaces separating an upper, rigid layer from a lower, weaker layer. They also assume a vertical ascent of magma through dikes, the feeder dike being just located below the flat-lying intrusion.

Cruden and McCaffrey (2001) suggested, by analogy with natural and experimental subsidence phenomena, that plutons grow by vertical inflation of a thin sill.

Available thickness-width data for sub-horizontal, felsic-intermediate igneous intrusions in the range from 1 m to 600 m, suggest that thickness increases with increasing width, with a maximum slope at around a width of 1 km, suggesting the increasing ability of shallow intrusions to lift their roofs as their horizontal area increases (Petford et al., 2000; McCaffrey and Cruden, 2002). Limiting factors on vertical growth include host rock elastic properties, the driving pressure and the emplacement depth (Kerr and Pollard, 1998; Zenzri and Keer, 2001; Kavanagh et al., 2006; Bunger and Cruden, 2011).

The contrasting methodological approaches outlined above reflect that the vertical growth of a magma chamber relies in a wide variety of physical and geological factors. For this reason, the works attempting to clarify this issue are often simplified models that examine only a limited number of factors. Following this way of working and in order to contribute to the debate about the growth of sills and the formation of the different morphologies of igneous bodies, we here focus on the feeder dike-magma chamber system and how it operates as a hydraulic jack. In the model proposed here, we discuss the fluid mechanics of magmas that are rapidly transferred from a narrow dike to a wider overlying chamber as they reach contrasting rigid zones in the brittle crust, providing enough energy to support chamber growth. Moreover, the influence of the self-supporting ability of the magma chamber roof, as well as the influence of the density relation between host rock and magma on the resultant morphology of the igneous body is also discussed.

2. Dike-sill arrangement: A geologic hydraulic jack–Pascal's principle and Newton's first and second law of mechanics

Magma behaves as a *moving mass of fluid* that follows the Pascal's principle during its migration through the upper crust. According to this principle a pressure change occurring anywhere in a confined incompressible fluid is transmitted throughout the fluid such that the same change occurs everywhere. The moving mass of fluid is also constrained by Newton's first and second laws of mechanics (*inertial* force and *net* force). The magma in its source is initially static and accelerates (a>0) by buoyancy forces. The net force that the accelerated magma mass (m) develops in the conduit is $\boldsymbol{F_1} = \mathbf{m} \cdot \mathbf{a}$, where acceleration (a) is ultimately dependent on the final constant velocity along the conduit, a function of the extent and width of the conduit, the density contrast between magma and surroundings, and magma viscosity. For simplicity, we assume that the magma reaches constant velocity by the time it reaches the upper crust. Under constant velocity, the net force is conserved as the inertial force. For magma to keep movement, the inertial force has to overcome the fracture strength of the host-rocks in order to open a conduit, and the friction between the moving magma and the dike walls.

Under adequate confinement arrangement of the conduit with respect to the chamber wall-rocks (Fig. 1), the inertial force F_1 in the conduit can be multiplied in the chamber using the Pascal's principle ($P_1 = P_2$), resulting in a force $F_2 >> F_1$ (the hydraulic jack principle).

Eq. (3) in Fig. 1A indicates that the input force (F_{inp} in Fig. 1B) required by the small piston in the narrow conduit to lift the large piston in the chamber depends on the area ratio between the small input area (A_1) and the large output area (A_2). Thus, the output force (F_2) must rise to the point it will be capable of lifting the chamber roof by increasing the large piston area of the chamber with respect to the small section of the piston conduit. Since in the shallow upper crust magmas are close to hydrostatic equilibrium, the force (F_2) needed to lift the roof is mainly to break the tensile/compressive strength of the roof with respect to its side walls (not the roof weight).

For simplicity of the models in Fig. 1, the following constraints are assumed:

Conduit (feeder dike) is the non-deformable pipeline for magma transport. The area (A_1) of the conduit section remains constant. The moving magma has an inertial force F_{inp} as it achieved constant velocity by the time it reaches the upper crust. Chamber is the deformable recipient space for the incoming magma. The areas of the roof and/or side walls (A_2) increase as more magma is continuously forced into the chamber by the inertial input force F_{inp}. Two hydraulic jack designs can be used to model the magma chamber growth: a vertical piston jack and a lateral expanding ring jack (Fig. 1B,C).

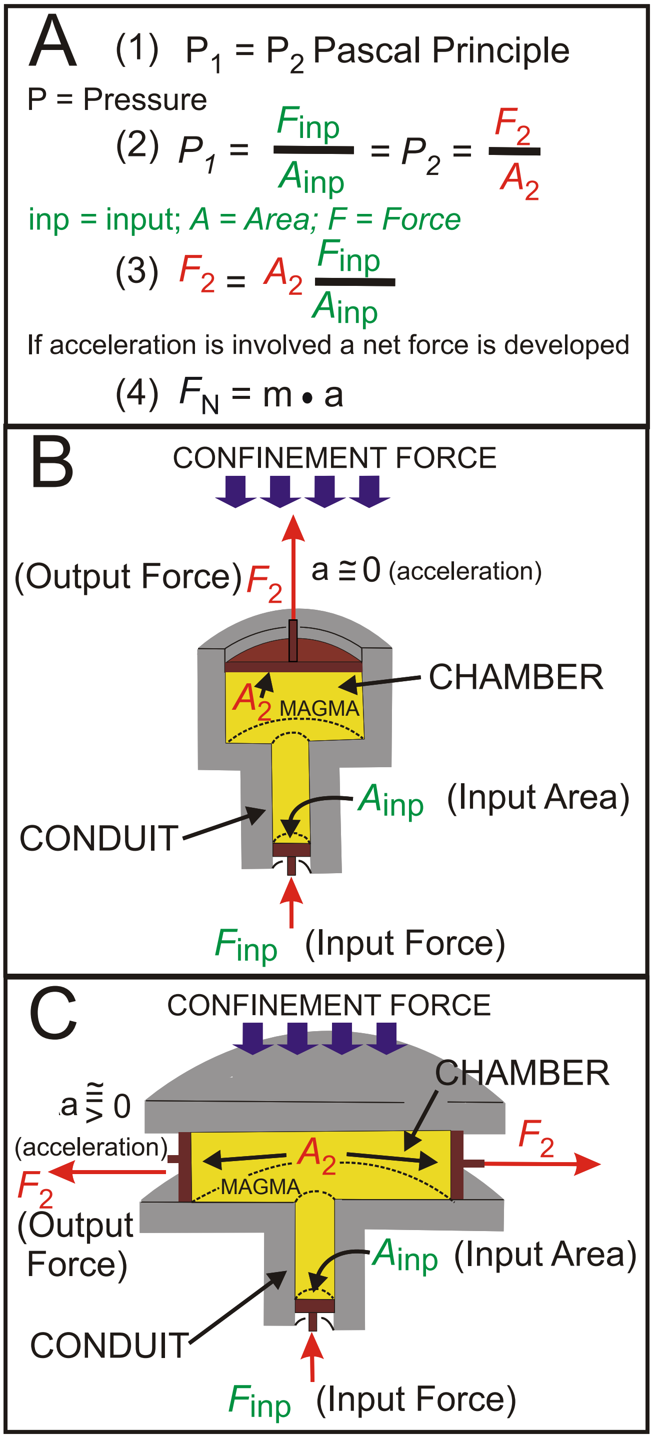

Figure 1. Pascal hydraulic principle and magma intrusion models with hydraulic jacks. (A) Equations that relate pressure ***P*** to area ***A***; force ***F***; mass ***m*** and acceleration ***a***, in a hydraulic two cylinder system. Notice in Eq. (3) that the input force $\boldsymbol{F_{inp}}$ is multiplied increasingly to an output force $\boldsymbol{F_2}$ as the area $\boldsymbol{A_2}$ increases with respect to the input area $\boldsymbol{A_{inp}}$. The two cylinder system is made of a conduit (not-deformable thin cylinder) and a chamber (wide cylinder in which deformation takes place). (B) Hydraulic jack geometry in which the roof area is deformable by hydraulic force $\boldsymbol{F_2}$. Notice that in this model the amount and rate of vertical growth is controlled by the magma input rate and time. (C) Hydraulic Jack geometry in which the ring side wall area is the deformable surface by hydraulic force $\boldsymbol{F_2}$. Notice that in this model the amount and rate of lateral growth may be favored by acceleration besides the magma input rate and time.

3. The fluid hammer effect

In the growth model the rising magma in the feeder dike (conduit) reaches a less rigid layer overlain by a more rigid layer (Fig. 2A). Then, when the front of the feeder dike intersects this rheological boundary, the propagation of the dike is stopped or delayed from crossing this interface boundary, but the mass of magma along the conduit before this interface is still moving, thereby building up pressure and a resulting pressure surge or wave (fluid hammer effect). The expression for the excess pressure due to fluid hammer effect is given by the Joukowsky equation:

$$\Delta P = QZ \quad (1)$$

In this expression, ΔP is the over-pressurization expressed in Pa; Q is the volumetric flow in m^3/s; and Z is the hydraulic impedance in $kg/(m^4 \cdot s)$.

The hydraulic impedance Z of the conduit, which determines the magnitude of the fluid hammer pulse, is defined as:

$$Z = \frac{\sqrt{\rho B}}{A} \quad (2)$$

In this expression: ρ is the density of the liquid in kg/m^3; A is the cross sectional area of the conduit, in m^2; and B is the equivalent modulus of compressibility of the liquid in the conduit in Pa, that depends on the elasticity of the wall rocks and the compressibility of the liquid, defined by its adiabatic compressibility modulus. Compressibility of degassed basalts at crustal depths is in the range between 0.4×10^{-10} and 2×10^{-10} Pa^{-1} (Spera, 2000). Replacing Z in Eq. (1):

$$\Delta P = Q\frac{\sqrt{\rho B}}{A} \quad (3)$$

Thus the high density and low-compressibility of magma related to a small sectional area of the non-deformable conduit favour the over-pressurization and development of a pressure surge or wave (fluid hammer effect). Nevertheless, since ρ and B can be considered constant, it is the Q/A relationship that will determine if the ΔP developed is large enough to trigger lateral flow. Thus, only dykes with large Q/A relationships (i.e. large volume flux through a small area) can trigger lateral flow and still have remnant *inertial force* to be used by the hydraulic jack system to continue lateral flow.

If the build up of ΔP cannot cause dike propagation break across the obstacle created by the more rigid layer, then, the pressure surge is transmitted backwards along the side-walls of the conduit, with an increased lateral area A_2 exposed to the surge (Fig. 2A). Thus, the pressure surge propagating backwards is more likely to promote lateral (sill) propagation, along the conduit, particularly if the magma is close to/or exceeded the neutral buoyancy zone (close to hydrostatic equilibrium), so this over-pressure does not have to be used to lift the roof, but to overcome the tensional-compression strengths below the impeding rigid layer.

As the sill propagates, the roof and side ring wall areas also expand (Fig. 2B). The roof (vertical piston jack) area increases with the square of the radius (exponential growth curve) while the side ring wall (lateral ring jack) area increases with the radius (linear growth line). The lateral expansion (area increase) causes a continuous amplification of the force on the sides and roof of the incipient sill (the hydraulic jack principle) triggering further expansion in a self-reinforcing process.

These two different area growth rates predict that, as the sill propagates, the roof area will become larger than the side walls area, and that the vertical piston jack will be able to eventually lift the roof. The area/radius growth diagram in Fig. 2B shows schematically that

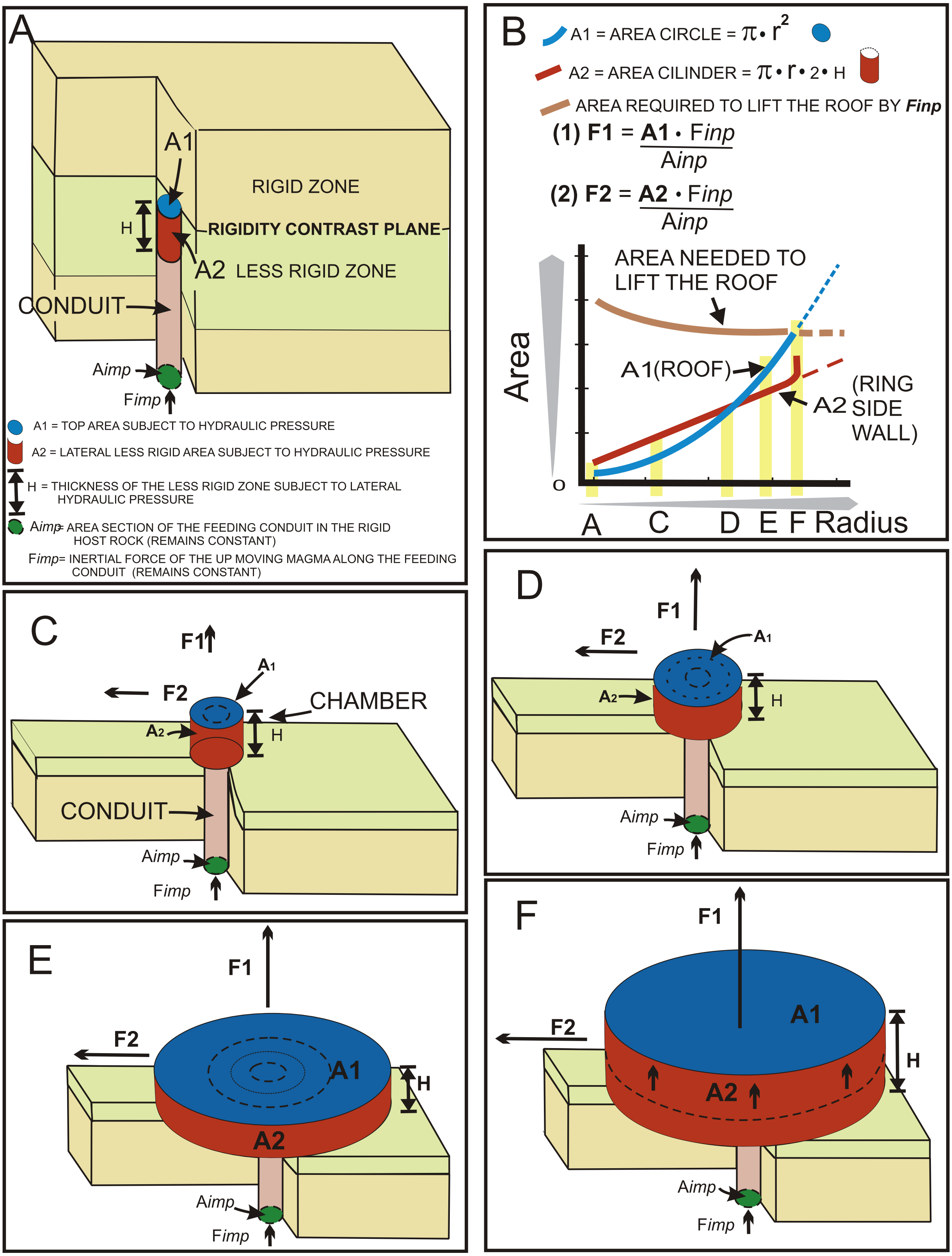

Figure 2. Schematic model for magma chamber growth using Pascals hydraulic principle in lateral and vertical hydraulic jack geometries. (A) Ascending magma in a conduit intrudes a less rigid zone (portion H) is prevented from continuing when reaching a more rigid zone that forces a lateral expansion and widening of the conduit and development of an incipient chamber. (B) Area/Radius growth diagram. For simplicity, the magma chamber growth is modelled using the expansion of a cylinder in the less rigid zone. The roof area is circular and shows an exponential growth curve with the square of the radius. The area of the lateral ring wall is that of a cylinder and increases linearly with radius. Since hydraulic force multiplication depends on the relationship between areas, this Area/Radius diagram predicts that deformation begins as lateral growth followed later by vertical growth. The brown line represents schematically the area that the sill roof should reach so that the hydraulic jack output force is capable of breaking the tensile/compressive strength that supports the roof to the side wall and lift the roof; thus, as distance between the side walls increases the tensile strength is the main force keeping the roof integrity. In

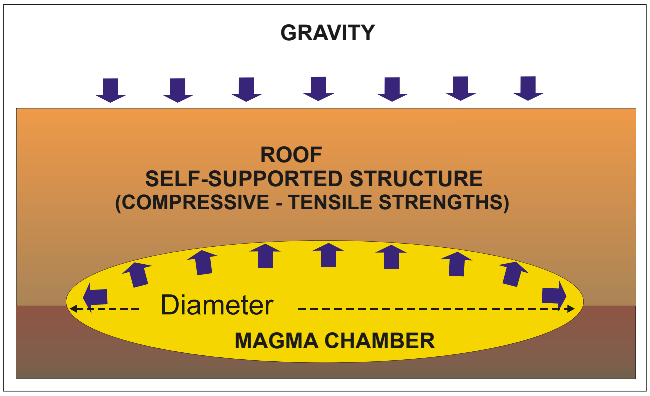

Figure 3. Schematic representation of the forces applied to the roof of a shallow magma chamber. In this model, the roof is a self-supported structure (roof = the portion of crust between the magma chamber and the surface) and is subject to downward-directed gravitational force and the upward-directed force applied by the magma in the chamber. The roof self-supported structure depends on the compressive–tensile strengths of its rocks, thickness of the roof, and the diameter of the chamber. This leads to two situations controlling the fate of the roof for a given roof thickness: (1) the diameter of the chamber allows the self support of the roof without it yielding, or (2) the increasing diameter of the chamber causes the roof to lose its ability for self-support, causing it to break and become supported by the magma.

the roof will be lifted when one of the two lines of the hydraulic jack systems intersects the line of the area required for the increasing input force (F_{inp}) to overcome the roof confining force (brown line in Fig. 2B). Fig. 2C–E shows the gradual sill like lateral growth of a sill-like sheet and finally, in Fig. 2F, the hydraulic force acting on the roof area exceeds the roof confining force and push up the roof.

4. The self-supporting capacity of the roof

The self-supporting capacity of the roof is yet another factor to be considered when evaluating the diameter of a magma chamber. Lateral expansion of the magma layer could exceed the self-supporting capacity of the roof before the sill reaches the roof area needed for vertical hydraulic jack lifting capacity. Thus, leaving the roof to collapse and float or sink in the magma layer.

This simplified model, considers that at the beginning of sill-like lateral magma emplacement, the magma chamber roof is a self-supported structure (Figs. 3 and 4). The stability of this self-supported roof depends on the compressive and tensile strengths of the roof rocks, the thickness of the roof and the distance between the lateral supports of the roof (diameter of the chamber). For example, if the roof thickness remains constant during the propagation of the sill, the increasing diameter of the chamber may jeopardise the stability of the roof, which would fracture and lose its side support (Fig. 5).

4.1. The self-supported roof

The sill roof area is large enough to enable the vertical hydraulic jack piston to deform the self-supported roof (Fig. 4). For this case there are two possible end cases depending on the rheological

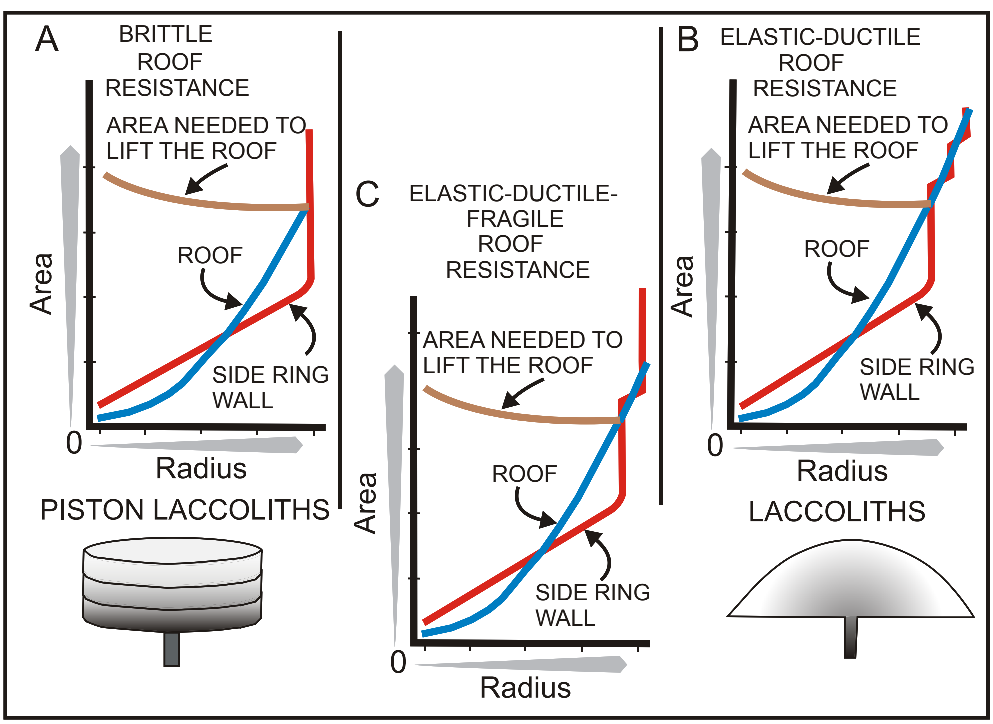

Figure 4. Schematic representation of hydraulic growth in a laccolith: the intrusion begins as a lateral thin layer in an elastic medium. After lateral growth, the roof area is large enough to be deformed by the hydraulic force. This model is related to self-supported roofs and magmas with intermediate to high viscosities. The brown line represents schematically the area that the sill roof should reach so that the hydraulic jack output force is capable to deform the roof. (A) The roof is brittle, deformation generates ring fractures and the laccolith grows upward as a piston. (B) The roof is elastic and/or ductile. Deformation caused by the intrusion is concordant to the planes of weakness in the country rock and the chamber grows as a blister. (C) The roof starts with elastic and/or ductile deformation until it reaches a critical value and yields in a brittle fashion.

the radius axis, the growth stages of figures A, C, D, E and F are shown as yellow bars. (C) Once the feeder dyke reaches the rigidity contrast plane, the lateral ring wall area is larger (height H of the cylinder) than the roof area (circular) and the magma forces a lateral expansion of the chamber beneath the rigidity contrast plane. (D) At this point, the lateral and top areas reach equal size, but the force amplification at the roof is insufficient to lift it. (E) Further increase of the chamber radius causes the top area to become larger than the lateral area, force amplification remain insufficient to lift the roof. (F) Finally, the top area is large enough to amplify the input force so that is able to break the tensile/compressive strength that supports the roof to the side wall and lift the roof.

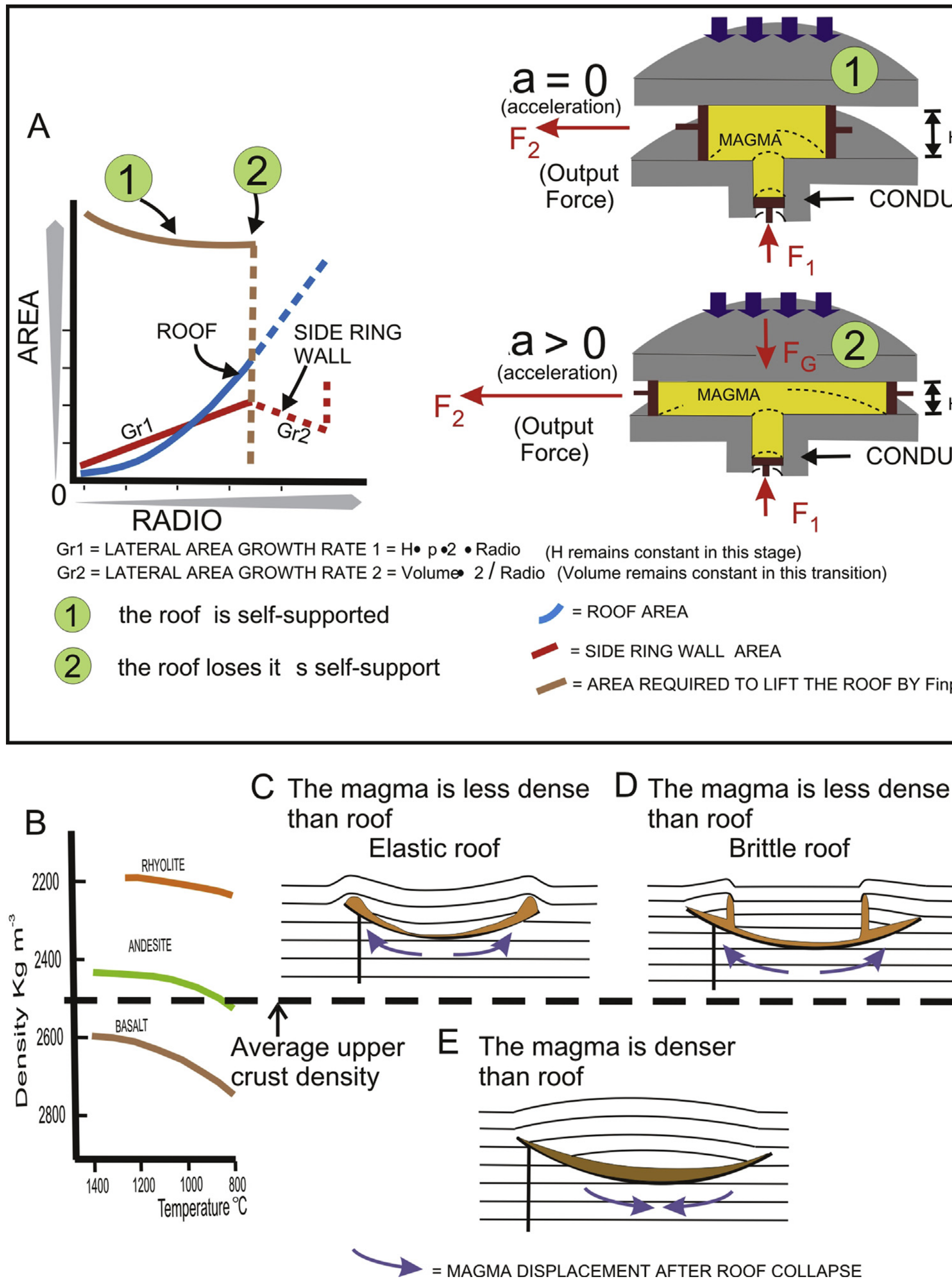

Figure 5. The roof loses its ability for self-support before the magma has the ability to lift it; Continuous lateral growth of chambers for magmas with low viscosities. (A) For large laminar intrusions, the roof eventually loses its self-support ability at which point yields and becomes supported by the magma. The additional pressure introduced by the roof on the magma promotes magma lateral flow (a > 0), thus lateral intrusion rate increases rapidly or promotes eruption. If eruption is avoided, the potential lateral extent that this system can reach is determined by the volume of magma stored in the chamber before self-support is lost. (B) Density-temperature diagram for basaltic, andesitic and rhyolitic magmas, compared to the average upper crust density (stippled line) (modified from Murase and McBirney, 1973). Notice that, after self-support is lost, the roof flotation response depends on the density relation between roof rocks and magma. (C) If the magma is less dense than the ***elastic*** roof rock, then the roof sinks gradually into the magma chamber generating a sagged structure. (D) If the magma is less dense than the ***brittle*** roof rocks, then the fractured roof sinks as a piston into the magma chamber. (E) If the magma is denser than the roof rocks, then, the magma accumulates in the deeper level of the chamber, pushing the roof upward as a lopolith.

properties of the roof: (1) a brittle behaviour of the roof would promote its uplift as a disc, leading to a piston-type laccolith (Fig. 4A), and, (2) If the roof behaves in an elastic or visco-elastic way, the in-coming magma will bend the roof to form a laccolith (Fig. 4B).

4.2. The roof loses its self-support – Archimedes buoyancy principle

This case favours the collapse of the roof (Fig. 5) and adds pressure to the magma confined in the chamber due to loading by the sinking roof. This can accelerate the lateral expansion of the magma or trigger an eruption. When this situation is reached, the roof floats or sinks in the magma controlled by the density relation between roof rock and magma (Fig. 5B). The roof of a large reservoir of rhyolitic magma would tend to sink when it loses its self-support ability. Under such conditions, the magma is forced to migrate outwards and upwards and caldera-like structures are expected (Fig. 5C,D). The opposite situation is that of the large mafic sills in which basaltic magma is denser than the upper crust. As the roof loses its self-support ability, the floating capacity of the roof depends of the Archimedes buoyancy principle: the buoyancy force imposed by the magma on the floating roof is equal to the weight of the magma displaced by the roof. Therefore, the roof will sink until its weight is balanced by the buoyancy force (iceberg effect), and the magma accumulates in the deepest part of the sill as it pushes the roof upward in that place (Fig. 5E) (lopolith like structures are expected).

5. Discussion

Previous work has shown that tabular igneous intrusions are characterized by a power-law scaling relationship between the vertical thickness and the horizontal length, for tabular igneous intrusions (Cruden and McCaffrey, 2002; Bunger and Cruden, 2011; Cruden et al., 2017; and references therein). These size-related trends show that when the length exceed 500 m, a clear distinction can be made between laccoliths and mafic sills trends, since roof lifting dominates in laccoliths whereas horizontal lengthening dominates in sills. These authors suggest that these trends are unrelated to differences in emplacement depth or composition, density or viscosity, but rather relate to the combination of magma productivity and the rates of magma supply and solidification. This is in agreement with our models that also suggest that magma supply rate (Q) and the cross sectional area (A) of the feeder conduit, are the main constrain for triggering lateral growth (Q/A ratio Eq. (3); fluid hammer effect), and to sustain a hydraulic jack system (Fig. 1; Eqs. (3) and (4)).

Our models deal with a magma moving in a non-deformable feeder dike (conduit) connected to a deformable chamber where lateral expansible ring and vertical piston hydraulic jack geometries are possible. These models are in agreement with experimental works in layered elastic media (Kavanagh et al., 2006), which shows the formation of sills at the interface separating an upper, rigid layer from a lower, less rigid layer, suggesting over-pressurization by the fluid hammer effect.

The magmatic hydraulic jack system is highly dependent on the input-output area ratio (Eqs. (1) and (2) in Fig. 2B). Its efficiency is favoured by a small input area and a non-deformable conduit. Feeder dikes that reach the upper brittle crust meet both conditions.

Sills are regarded as flat-lying bodies with contacts concordant with the country rocks and wedge-shaped peripheral margins. As long as crystallization does not reach the critical threshold, the magma behaves as a fluid and its input force is transferred to the tips of the expanding sills causing fracturing and opening of the layer contacts along the wedge-shaped margins, leading to space generation that allows magma emplacement. The wedge-shaped tips become blunt edges as soon as the magma stars to crystallize, because the smaller thickness of the wedge tip favours a fast thermal decay due to the higher temperature contrast with the country rocks. This situation, promotes the fluid hammer effect and the activation of the lateral expansible ring hydraulic jack. This will occur when the lateral contact between the feeder dike and the lower hard layer is large enough (height H in Fig. 2), so that the fluid hammer overpressure is transmitted to a large area of the expansible lateral ring in the hydraulic jack system.

The vertical growth of the hydraulic jack system is achieved when the roof area of the sill is large enough so that the vertical hydraulic piston can amplify the input force to a value above the confinement force. This is in agreement with the observation of the increasing ability of shallow intrusions to lift their roofs as their horizontal area increases (Petford et al., 2000; Cruden and McCaffrey, 2001; McCaffrey and Cruden, 2002).

Roof lifting and lateral expansion becomes easier as magma gets closer or exceeds its hydrostatic equilibrium with respect to the country rocks, as the roof column is supported by the magma column (Gilbert, 1877; Holmes, 1944; Willam and McBirney, 1979; Francis, 1982; Corry, 1988).

When evaluating the lateral growth of a magma chamber, the self-support capacity of the roof is another important factor to be considered. The lateral expansion of the magma layer can exceed the self-support capacity of the roof and cause it to collapse as a brittle or an elastic-ductile crust layer that floats or sink in the magma layer depending on the density contrast (magma/crustal rocks). Large collapse calderas of rhyolitic magma have laterally extended chambers that are likely to lose the self-support of the roof before eruption. If the density of the rhyolitic magma is lower than that of the upper crust the roof sinks, and the outwards and upwards expulsion of magma results in a ring shape of the chamber and probably an eruption (Fig. 5C,D). The opposite situation is that of the large mafic sills complexes in which basaltic magma is denser than the upper crust. When self-support is lost, the roof behaves like an iceberg, the roof will reach equilibrium with the basaltic liquid. If more basaltic liquid is fed into the sill system, it flows downward and the sill complex becomes thicker in its deepest emplacement part (lopolith), as it pushes the roof upwards (Fig. 5E).

6. Concluding remarks

A finite portion of magma moving in confinement has hydraulic conditions for the generation, control and transmission of power in the elastic/brittle upper crust. The models for magma chamber growth using Pascal's principle in alternating vertical/lateral hydraulic jack arrangements are useful to explain the initial lateral growth of sill-like intrusions that would eventually reach conditions for subsequent vertical growth.

In these hydraulic jack arrangements, the feeder dike plays the role of the small piston that pushes magma into the chamber. Two large expansible pistons, one vertical and the other a lateral ring, alternate in the deformation of the host rock and the growth of the chamber. The argument to explain why lateral expansion starts is the presence of a rigidity contrast boundary. When the propagating dike reaches a more rigid layer that delays or stops dike propagation, the sustained supply of ascending magma along the dike generates an overpressure on the overlying rigid layer and side walls (pressure surge or fluid hammer effect), that may trigger sill propagation. The lateral expansion underneath the strong impeding layer develops a continuous increase of the area and thus, continuous amplification of the force on the sides and roof of the incipient sill, triggering further expansion in a self-reinforcing process. It is remarkable that the smaller the input area of the feeder dike, the greater is the fluid hammer effect (Eq. (3)) and the hydraulic expansion effect in the chamber (Fig. 1).

Acknowledgments

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