Figure 2. Numerical tests (free surface, large strain, visco-elasto-plastic code) of the stability of a continental collisional system using various possible failure envelopes. The figure shows a snapshot at 5 Myr of the structural styles that develop after 300 km of shortening. Insert to right of case C₁ shows zoom of first 200 km in depth, with the effective shear stress (top) and plastic brittle strain (bottom). Note that despite high mantle strength, no brittle (seismic) deformation occurs below Moho depth except subduction channel.

ANALOGUE SIMULATION OF MAGMA RHEOLOGY DURING DIKE EMLACEMENT: A PRELIMINARY STUDY BASED ON FIELD OBSERVATIONS AND RHEOLOGICAL DETERMINATIONS OF MATERIALS

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Summary
The Tuzantla-Tiquicheo-Nanchititla swarm of mafic dykes represents a natural laboratory to study different rheology conditions of magma emplacement presumably producing variable and complexes geometries of dykes, which are cutting a stratified sedimentary host rock, under a tectonic scenario represented by an important shear tectonic influence and pre-existing tectonic structures. We focus in observations of crystal content and its distribution in order to infer a general rheology behavior of magma in these dykes through their textures. Inferred rheologies will constrain scaling of analogue materials as we will discuss.

Introduction
Previous analogue modelling of magma emplacement through dykes consider a relatively simple linear rheology of magma and consequently the usage of Newtonian analogue magma materials. From these early models some geometric analogies among structures obtained in laboratory and structures observed in field have been established (Takada, 1989; Corti et al., 2005; Menand and Tait, 2001). Using analogue approximations made possible to calculate velocity of magma transported through fractures and their interaction with other neighboring fractures (Takada, 1990). Furthermore, geometries of analogue dykes developed in laboratory are consistent with geometries expected from a theoretical perspective (Maaløe, 1987) based on the theory of fracture formation by fluid entrance in cracks (hydraulic fracturing), which can predict the development of dykes and their first order geometrical characteristics by using the concept of apparent viscosity of fluid and neglecting other factors related to magma rheology. Theoretical and analogue models viscosities are conceived with no variations in time (apparent viscosities) as shear strain
evolves; however, rheological measurements of real magma in laboratory conditions suggest variations of viscosity with increasing shear rate describing a non-Newtonian rheology, largely influenced by the content and size of crystals (Shaw, 1969; Ryerson et al., 1988; Lejeune and Richet, 1995). The geometries of contacts of non-Newtonian viscous fluids within a host are also influenced by rheological contrasts between these two materials. Indeed, dike intrusions can be controlled and/or influenced by a large number of mechanical and thermal processes interacting at different scales of time and space, but in this work we focus on the dynamics of non-Newtonian materials that seems to introduce also important effects on the intruding flow, which have not been studied with detail neither theoretically, nor experimentally. Detailed field observations in a dyke swarm in southern Mexico suggest that, at the outcrop scale, magma interacts actively with the brittle hosting rock during hydraulic fracturing and understanding its rheological behavior is of primordial importance. We analyze the isothermal rheological behavior of diverse analogue materials and discuss their suitability to model magma flow in the Tuzantla-Tiquicheo-Nanchtitlita dyke swarm by constraining the magma rheology of these dykes.

Rheology of magmas

Besides other factors, rheology of magmas is largely influenced by content and size of crystallized material (Shaw, 1969; Pinkerton and Stevenson, 1992; Lejeune and Richet, 1995). Adding a content of around 30% in volume of equal shape crystals to an originally Newtonian magma will modify its dynamics to a non-Newtonian rheology. The percentage of crystal content for this change can dramatically decrease until 5 or 10 % only if crystals are of different shape or size (Ryerson 1989, Ishibashi 2007). Magma could potentially present a wide range of behaviors including Bingham at low stress, pseudo-plastic or shear thinning, and shear thickening. These rheologies can be described by flow curves relating shear stress ($\tau$) and shear strain ($\gamma$) (Weijermars and Schmeling, 1986). In particular, shear thinning and shear thickening can be described by a power law function ($\dot{\gamma} = A\tau^n$), where A is a material constant and n is the power-law exponent. For $n=1$ the flow is Newtonian, whereas for $n > 1$ magma is showing a shear thickening rheology and for $n<1$ magma show a shear thinning rheology. Bingham rheology is attributed to magmas with high content of crystals (> 50%) in which a yield stress is necessary to start flow, and once started the material behaves as power-law fluid. Shear thickening is related with the availability of crystal suspensions to form conglomerates (polymerization) as shear rate increase; in contrast during shear thinning crystals reorganize and align in order to make viscosity decrease as shear rate increase. In Newtonian rheology, crystals are expected to trace and align with flow, in this way it is usual to find symmetrically imbricat ed crystals or phenocrystals near the dyke walls. The fabric and crystal distribution along transversal sections (perpendicular to dyke walls) crossing textural domains allows to recognize crystal clustering shear thickening. Since dilatancy is a concept related with shear thickening, an increase of randomly oriented crystal concentration (clustering) between neighbors crystal fabric domains indicates a local dilatancy (as well as shear thickening) as crystals moved past one another during shearing (Smith, 1997). The opposite physical effect occurs in shear thinning fluids, even with a high value of viscosity and significant concentration of particles (up to 30%) if the shape and size of the particles allow them to evolve to a state in which they align as shear strain increase it can produce a decrease of viscosity (thixotropy). However there are not experiments with shear thinning fluids in which neither specific arrangements of particles are demonstrated nor the contribution of thixotropy to magma flow in dykes.

Tuzantla-Tiquicheo-Nanchtitlita (TTN) swarm of dykes, a case of bimodal rheology of magma

TTN swarm of mafic dykes is located in the central part of the Sierra Madre del Sur, southern México. The TTN swarm of dykes was emplaced in the late Eocene along a long-lived shear zone (characterized by left lateral faults) mainly oriented NW-SE. The swarm is exposed to the west of a ~400 km alignment of Eocene and Oligocene plutonic and volcanic centers outlined in the same orientation, and east of the Tzitzio Anticline, a major shortening structure of southern Mexico (Fig. 1). The dikes were classified as basaltic-andesitic and basaltic (Serrano-Durán, 2005), and show an important number of porfidic textures containing plagioclase phenocrystals from 0.5 to 2.5 cm in size that are considered magma flow tracers. Different rheology conditions of magma during emplacement presumably produced variable and
complexes geometries of dykes, which are cutting a stratified sedimentary host rock, under a tectonic scenario represented by shearing along pre-existing tectonic structures. Two modes of magma emplacement are clear in the swarm: a) dykes with tabular geometries of host-rock wall and b) dykes with an irregular geometry of host-rock wall (Fig. 2b).

Dykes can also be classified by the presence or absence of phenocrystals and their percentage. We focus our observations in crystal content and its distribution in order to infer in a general way the rheology of the dykes through their textures, following the criterions mentioned above. Inferred rheologies will constrain scaling of analogue materials as we will discuss in the next section. If the percentage of phenocrystals was higher than 25%, a Non-Newtonian rheology of magmas was assumed for the magma. From 80 dykes observed, 40 dykes satisfied a non-Newtonian rheology, and around 60 dykes have phenocrystals above 10% in volume. An example of irregular and complex wall geometry possibly attributed to the non-Newtonian rheology of magma and its mechanical contrast with the host rock, is shown in figure 2. A zone of higher content of phenocrystals is observed near the left wall of dyke (to the left of the dashed line in figure 2a). Due to tight clustering of irregular shape phenocrystals, magma needs to expand to allow displacement of crystals providing us with a good example of what can be a shear thickening effect. High viscosity bubbles are observed immersed in magma with lesser phenocrystals content in which plagioclases orient freely with flow without much interaction among them (right side of dashed line in figure 2a). Irregular geometries of dykes have been used as evidence of flow during shearing (e.g., Hallot, 1996). Our observations suggest also an important contribution of rheology contrasts between magma and host rock, and the tendency of emplacement of magma in a shear thickening fashion. However, more systematic and quantitatively analysis of fabric are needed to confirm this process.
Scaling: reaching the dynamic, geometric, and cinematic similarity in analogue materials
The concept of similarity or scaling is attributed to the proportional conservation of some variables as length, velocity, mass, and force between model and natural magmatic system. Achievement of similarity in models able us to give a real sense to the results and make useful interpretations. To evaluate the similarity and scaling conditions of models it has summarized a set of dimensionless numbers including: Reynolds number (characteristic force ratio), Schmoluchowski number, Stokes number, and Ramberg number; which depend on variables such as $v, l, \rho, \eta, g, \Delta p$ that are velocity, length, density, viscosity, gravitational acceleration, and pressure difference; respectively. Reynolds number in geologic flows seems to be low ($Re < 10^{-20}$), in such way that Reynolds numbers around this value are required in analogue flows to satisfy dynamic and geometric similarity under the same broader conditions. However, in these non-dimensional numbers only the apparent viscosity is considered and its non-linear behavior with time is omitted for simplicity. The variability of viscosity with time (or the non-linearity of the relation shear stress and shear strain) indicates that for the same non-Newtonian magma fluid different values of Reynolds numbers will be obtained, implying that this parameter is not the most appropriate to be consider as a base to scaling of analogue materials. To capture the complex behavior of viscosity it is more suitable the usage of flow curves of the fluids we want to model as the departure point for the scaling of our materials. Flow curves are constructed by plotting the resulting shear strain of the fluid subjected to a shear stress in which the changing slope of the curve represents the variable viscosity. Furthermore, if both natural and analogue flows have the same shape of curve a dynamic similarity can be assured (Weijermars and Schmeling, 1986), and both analogue and natural no-Newtonian flows curves can be approximated by a power-law function ($\dot{\gamma} = A \dot{\varepsilon}^n$); to achieve a rheological similarity it is necessary that the exponent $n$ be the same for both natural and model power-law approximated functions (Weijermars and Schmeling, 1985; Boutelier, 2007). The challenge is to know the rheology of the natural material and the value of $n$ of the power-law function that better approximates the curve flow in order to find a material with the same approximated flow-curve and to achieve the best scaling. Composition of magma as well as content and distribution of crystal can be indicative of the prevalent rheology of magma during emplacement and a departure point for assumptions about rheology and further scaling of analogue materials. On the other hand it is also valid to obtain some inferences about magmas from experimentation with known Newtonian analogue materials in which we can study the effect of interacting particles in suspension of different content, size, and aspect ratio. In this work we measure the shear strain, shear stress, and viscosity of PDMS silicon with different percentage in volume of quartz grains suspensions. The results of this measurements and their analogy with the TTN swarm dykes rheology are presented in the next brief discussion.
Magma emplacement of the TTN swarm of dykes: Lessons obtained from the rheology of analogue materials

In early years of tectonic and magmatic models dynamically scaled, it was assumed that natural magmas were Newtonian resulting in a selection of simple Newtonian magma analogue materials. Because of the simplistic conception of magma rheology and its first order approximation to the geometry of modeled dykes, usage of non-Newtonian rheology materials has been poorly explored and in consequence its usage in analogue model is still scarce. Some PDMS Silicons have been extensively used as good analogue simple Newtonian fluid. We have introduced a non-Newtonian effect in the silicon by adding several kinds of particles, and we have explored the effect of 4 different concentrations in the rheology of this material. Measurements of shear stress and shear strain were obtained using an AR 1000-N (AT Instruments) rheometer of double plate and the flow curves were plotted for each case. In figure 3 a, b, c, and d the plot of flow curves in a log-log axis are shown for silicon and silicone-sand mixture with 30%, 50%, and 90% volume of particles and fitted to a power-law distribution. The non-Newtonian rheology of the silicones with particles in suspension is clearly observed but most of all the pseudo plastic or shear thickening tendency of the curve, evident also by the value of $n$ in the power law function, which is in both cases higher than 1 (Boutelier, 2007). In these results we observe the influence of crystal content in original Newtonian fluids, and envisage good analogy with inferred shear thickening rheology as the case of the dyke 50 in the TTN swarm dykes zone. Furthermore, there is a fine variability of $n$ as particle content increase indicating the importance of the specification of phenocrystals content in the magma to be model. There is a value of $n$ beyond which the flow can trigger the formation of irregularities and complex geometries of intrusions as viscous fingering founded in some natural magma and other experimental fluids (Hallot 1996). These geometries do not adhere completely with the general model of hydraulic fracturing of host rock by dykes emplacement, but it is possible that this theory is not predicting such complex geometries because it does not considers the non linear effects of viscosity.

Figure 3. Flow curves calculated for PDMS silicon with particles volume concentration of 30%, 50% and 90%. The line in red is the power-law approximated function.
**Conclusions**

Detailed field observations of the geometry and fabric distribution of dykes warn us about the importance of specifying the magma rheology for analogue models and the finding of the right analogue materials. The irregularities developed by the non-Newtonian behavior of fluids have to be noted and taken in account for future magmatic systems models to a better understanding of the magma dynamics. In the case of TNT swarm dykes the usage of analogue materials with now Newtonian rheology could explain not just the irregular geometries of the dyke, but it will be useful tool to find insights about the role of magma rheology and its relations of other factor in the emplacement of these dykes.

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**ARCHEAN GRANITE-GREENSTONE DOME-AND-KEEL STRUCTURE DEVELOPMENT BY SHORTENING OF HETEROGENEOUS CRUST**

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**Summary**

We present results of isothermal 3D analogue and 2D numerical experiments that test an alternative hypothesis for the structural development of Archean granite-greenstone belts. The hypothesis invokes non-cylindrical bucking of spaced, competent tabular granitic intrusions and the corresponding response