Emplacement mechanism of igneous sheet intrusions: A case study in the Malargüe Fault and Thrust Belt and analogue modeling

Benitez, A.[1,2], Vigide, N.[2], Winocur, D.A.[1,2] and Yagupsky, D.L.[1,2]

[1] *Universidad de Buenos Aires, FCEYN. Depto. de Ciencias Geológicas. Pabellon II, Ciudad Universitaria, CABA, Argentina*
[2] *Instituto de Estudios Andinos Don Pablo Groeber (IDEAN)- (UBA-CONICET).*

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The occurrence of intrusive bodies such as dikes and sills in sedimentary basins has been documented worldwide. In the northern sector of the Neuquén Basin in Mendoza, Argentina, intrusive bodies are recognized, preferably emplaced in shales, sandstones and limestones of the Cuyo and Mendoza groups and in the continental sedimentary rocks of the Neuquén Group.

The case study of this work corresponds to a sector of the Malargüe fold and thrust belt, in the south of Mendoza between 35º00' and 35°30' LS, where excellent outcrops of intrusive bodies are exhibited. We have recognized punched laccoliths up to 500 meters thick, which have elongated morphologies and are linked to linear structures, i.e. thrusts faults or large anticlines. There are also smaller igneous sheet intrusions corresponding to dikes and sills. The dykes are up to 20 meters thick, while the sills are up to 50 meters thick and 1000 meters long. In Los Blancos anticline core, shales and carbonates of the Cuyo Group are intruded by a sill ranging between 30 and 60 meters thick and 1400 m long (Fig. 1).

Fig. 1 – Field photograph of the transgressive sill emplaced in Cuyo Group.

Host rocks are mainly limestones (mudstones and wackestones) and shales. Limestones were previously fractured, so these rocks behaved as purely linear elastic solid. Magma propagated through some of these fractures, resulting in the irregular body in Figure 2a. On the other hand, inelastic deformation affected shale beds during sill intrusion. In some cases, the propagating magma seems to have pushed the host rock ahead like an indenter with a rectangular tip (Fig. 2b). These field observations suggest that the rheology of different host rocks defines the sill or dike geometry and the dominant intrusion mechanism.

Thus, factors such as differences in Young's module between successive layers control, at least partially, the intrusion mechanism. This is in good agreement with theoretical works (Kavanagh et al., 2006; Barnet and Gudmundsson, 2014). However, other mechanical aspects of the host rock can condition the propagation of sheet intrusions. In order to understand the influence of rock cohesion during the intrusive sill emplacement, simple analogue models were carried out.

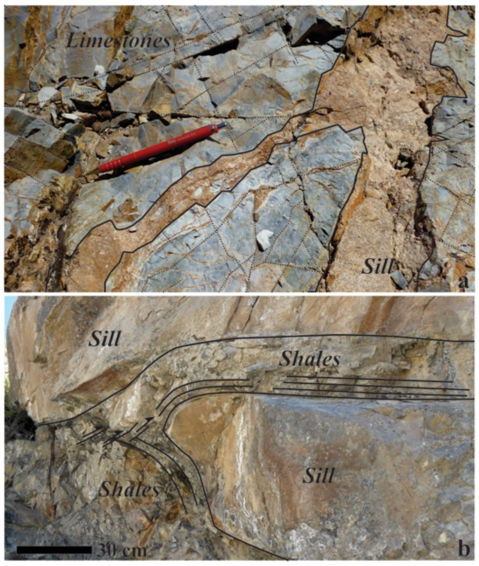

Fig. 2 – Close up photographs of the contacts between sills and different host rocks.

Glass microspheres (GM) and silica powder (SP) were used as interbedded host rocks analogue, given their contrasting cohesion (low and high respectively). GM with grain diameters of 70 µm have a density in a range of 1.5 – 1.9 g.cm^{-3}, a cohesion between 64 – 173 Pa, and an internal friction angle of 20º (Schellart, 2000). SP has grain diameters of 40 µm, a density of 1.3 g.cm^{-3}, cohesion of 38 Pa and an internal friction angle of 38º (Galland et al., 2006; Abdelmalak et al., 2016). Vegetal oil (VO) was used as magmatic analogue. This material can be injected as a viscous fluid, and it solidifies under the 32ºC. The used commercial vegetaline has a density of 0.9 g.cm^{-3} and a viscosity of 2x10-2 at 50ºC (Galland et al., 2006).

Mechanical properties for both, granular and viscous materials, are appropriate to simulate and scale different host rocks and low viscosity magmas (see Galland et al., 2006 for experimental scaling complete analysis).

The experiments dimensions were 40 cm x15 cm x 4cm. Model 1 consists of a single homogeneous layer of glass microspheres (Fig 3a), and model 2 consists in four successive thin layers (0.3 cm) of GM-SP mix, interbedded with thicker (between 0.2 and 0.5 cm) SP layers. Melted VO was injected by a volumetric pump at a rate of 10 cm^3min^{-1}. After the vegetal oil gets cold, the granular material was extracted to recover the resultant intrusive body, allowing its tridimensional analysis.

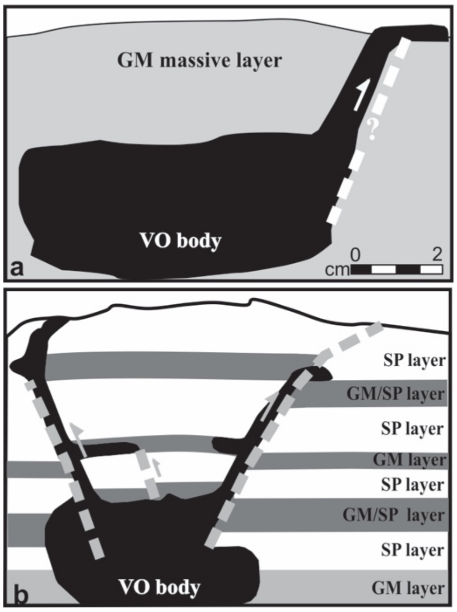

Fig. 3a.b. – Photographs and corresponding drawing of cross-sections of the experiments Models 1 and 2.

In the not layered model (1), the VO accumulates at the base of the model, pushing upwards the host material until a branch propagates through, reaching the surface. This results in an oblate spheroid basal body, with an arm plunging from the surface towards the body margin (Fig. 3a). The low cohesion of the GM volume allows a remarkable propagation of the viscous material both laterally and vertically.

In the layered model (2), the basal layer of GM allows the formation of a spheroidal body that pushes the sequence upwards. VO raises along reverse faults, forming dykes (Fig 3b). Sills propagate laterally from these dikes through the interfaces between GM-SP mix layers and SP layers.

Our experiments show that the intrusion geometry is conditioned by the existence of layers with different rheological properties. In a homogeneous medium of GM, i.e. a low cohesion material, massive lacoliths are formed, as previously suggested by Schmiedel et al. (2017). In contrast, the SP layers are elastically fractured by the stresses resulting from the propagation of the VO, generating annular dikes or cone sheets. The existence of interfaces with less cohesive layers (GM or GM-SP mix) favors the formation of sills that extend from the dykes towards the interior of the cone in the deep levels, while they extend outwards in the upper levels.

These results constitute an approximation to understand the intrusion geometry of tertiary volcanic rocks in southern Mendoza. Sills and dikes are formed between units or layers with rheological contrast, as in the Los Blancos anticline. There, sills are emplaced in shale layers or in the interfaces between shales and limestones, in good correlation with results of model 2. On the other hand, punched laccoliths described in La Valenciana anticline are emplaced in a ~700 m thick shales sequence, with subordinate limestones and silty sandstones. Well data in the Altiplano del Payun and Los Cavaos oil fields located south of the Rio Grande Valley show similar intrusion geometries, affecting shales of the Mendoza Group (Rodriguez Monreal et al., 2009; Witte et al., 2012). Model 1 results present a good correlation with this prototype, being the massive and low cohesive host material a determining factor to the intrusion mechanism and the resulting body shape.

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