Saucer-shaped sills and magma chamber establishment beneath calderas, with application to Chile

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Summary

The Central Andes host some of the largest calderas and deforming areas in the world (Fig.1). Crustal deformation is often associated with the propagation of magma along sills and/or the development of magma chambers. The mechanisms of these magma emplacements in the crust are not well understood (Fig.2).

Field observations have shown that several volcanic centres in Chile exhibit large scale inflation of the crust, as recently documented by InSAR data for the areas of Uturuncu (Bolivia), Laguna del Maule (Chile) and the Lazufre volcanic area (Chile-Argentina) (Fig.3). Different concepts and hypothesis exist for explaining the magma sills and chamber formation beneath.

Aim of this work is to investigate the effect of topography and loading for dike arrest, sill formation, saucer-shaped sills, and generation of crustal uplift. Here we present preliminary results of analogue experiment, aimed at studying the dike propagation below a topography simulation of a caldera.

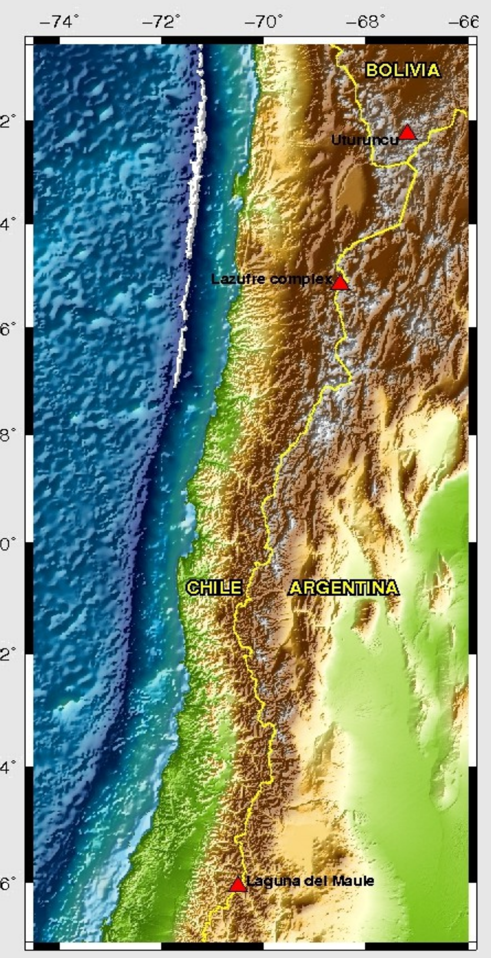

Figure 1: Map showing the location of Uturuncu, Laguna del Maule and Lazufre unloading areas.

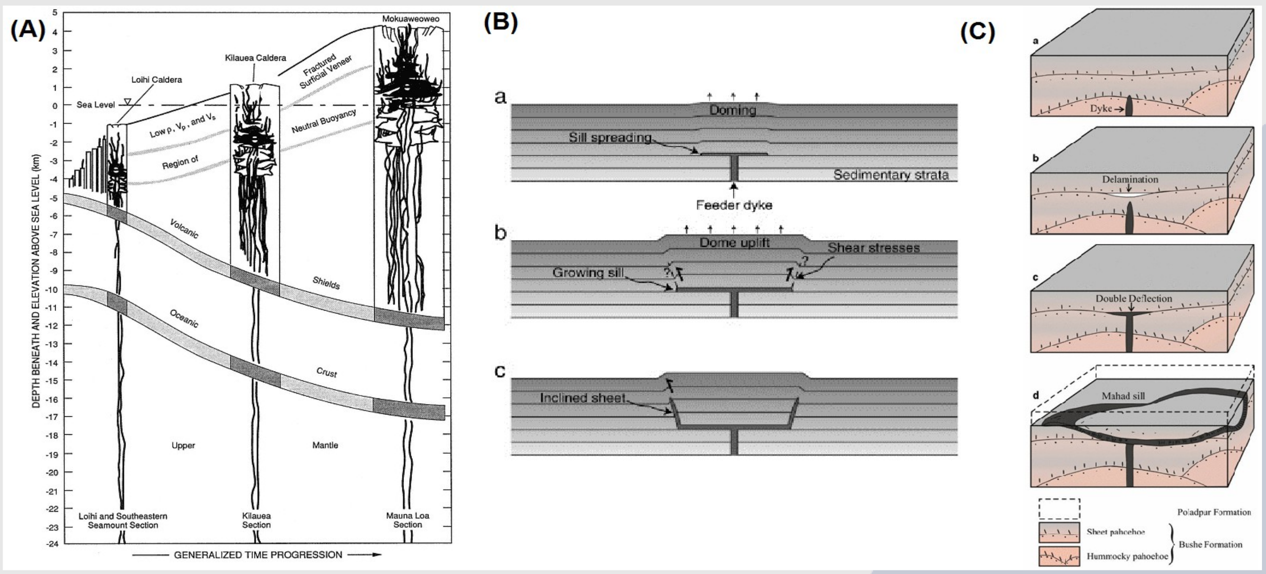

***Figure 2:** Three different hypothesis about the emplacement of saucer shaped sills. **(A) Level of neutral buoyancy**, where magma may accumulate to form magma chambers (Ryan, 1987b). **(B) Heterogeneity** controlled by layering (Galland et al., 2009). **(C) Delamination** produced by the stress at the tip of dike (Duraiswami et al., 2013).*

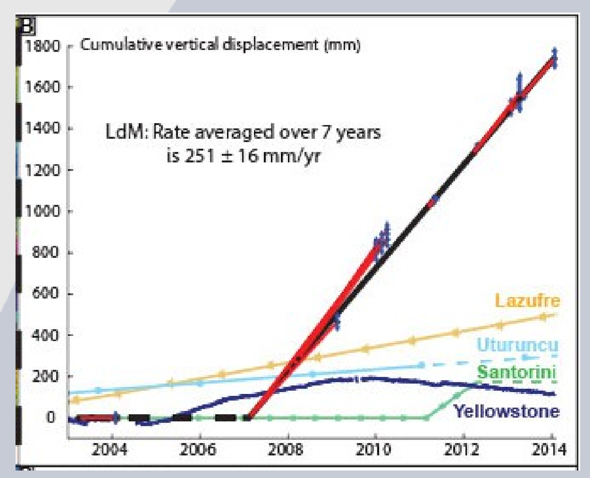

Figure 3: Time series of vertical uplift of Laguna del Maule calculated from InSAR models. Other curves are estimated from GPS and InSAR results at Lazufre and Uturuncu (Singer et al 2014).

Method

In the analogue experiments, we use gelatin to represent the Earth's crust (Kavanagh et al., 2013). It needs to be scaled geometrically, kinematically and dynamically.

Gelatin is a viscoelastic material that has an elastic and/or viscous behaviour during deformation. Like any homogeneous and isotropic solid, gelatin has properties like Young's modulus E~800 Pa and Poisson's ratio v=0.5.

Experimetal set-up

In a first approach we analyse the influence of topography upon dike propagation path. To test it, we prepared gelatin at different concentration (2 to 3 %wt.) and it was put in the fridge for several hours to solidify. The topography simulates a caldera and it was made using a small container filled with water.

To run the experiment a needle was inserted in the bottom of the gelatin and water was injected using a pump at a ratio 17 ml/minute. Three cameras take pictures simultaneously each 5 seconds (Fig.4).

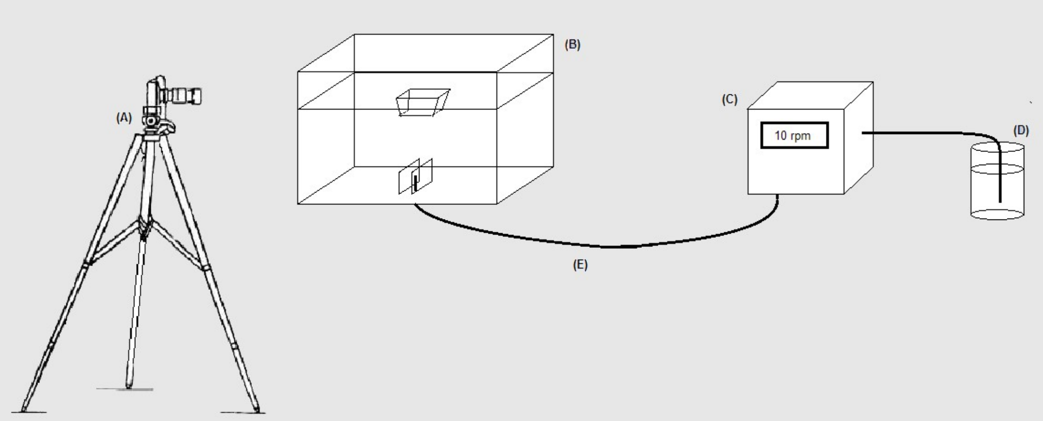

***Figure 4:** Experimental set-up. (A) Cameras record the experiment. (B) Container filled with gelatin. On the bottom a needle is inserted between 2 transparent sheets. The sheets control the dike direction. Topography was included, it simulates a caldera (C) Pump injects water at ratio of 10 rpm (17 ml/min).*

Results

Here we show two experiments with a topographic basin, in the first experiment a saucer shaped sill and uplift of the basin was created and in the second experiment a dike that is slightly deflected. The only difference between these two models was the concentration (stiffness) of the gelatin.

1) 2 %wt. concentration of gelatin

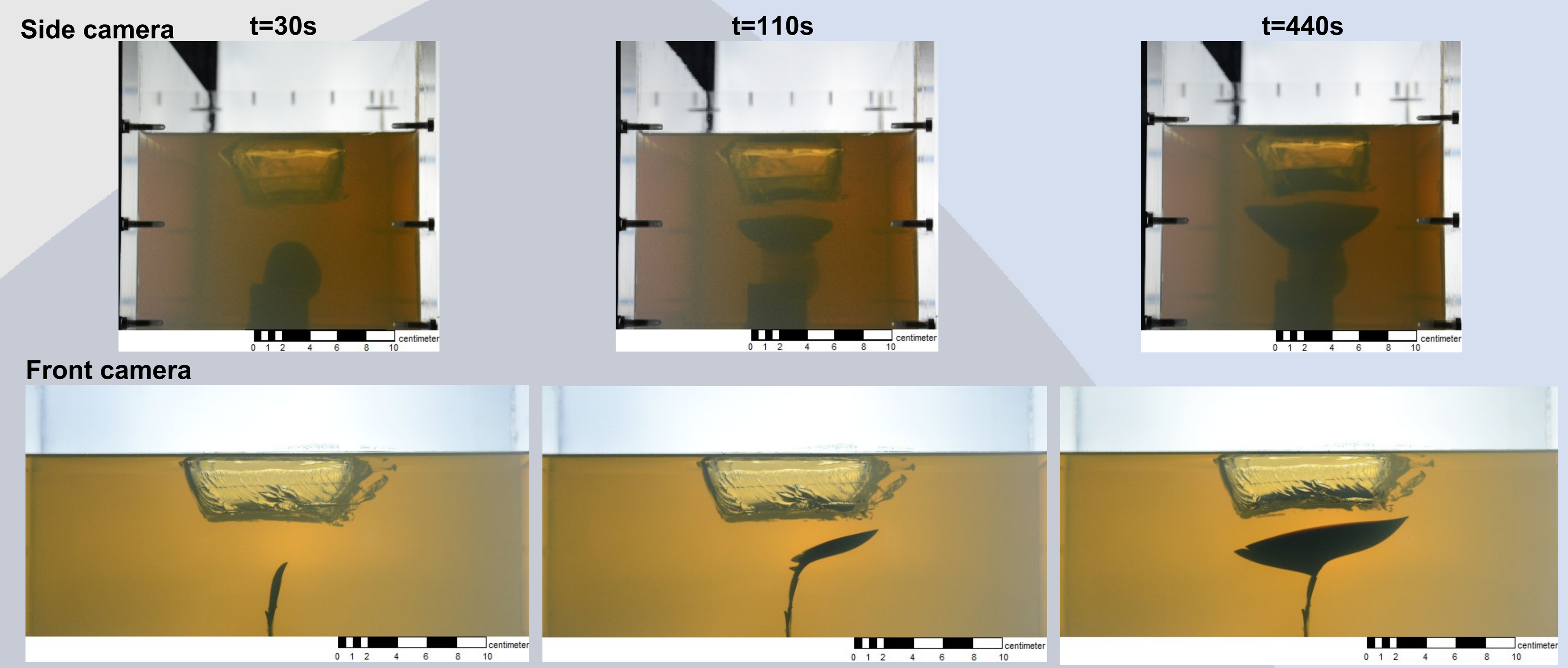

***Figure 5:** Gelatin concentration of 2 %wt. It shows the process of dike formation and posterior lateral propagation. Finally, it forms a saucer-shaped sill around the caldera. Pictures were taken with a front and side camera at different time steps.*

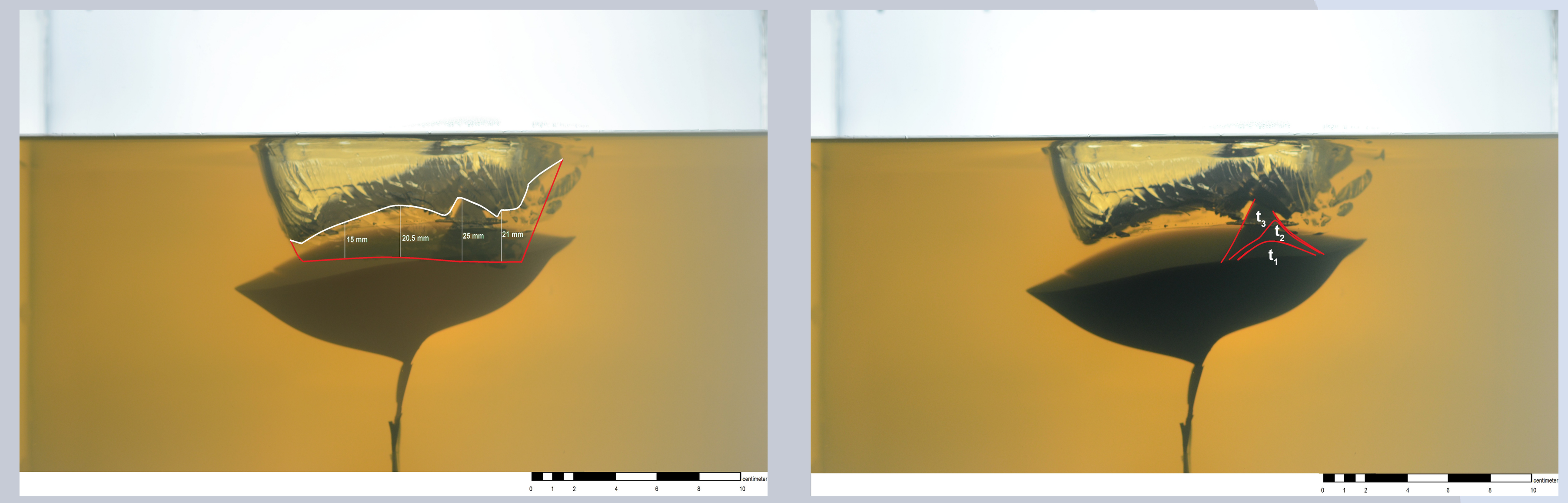

***Figure 6:** Gelatin concentration of 2 %wt. Left: Uplift produced by the overpressure caused by the injection of water (diference between surface at t=0s (in red) and t=1085s (in white)). Right: In red, formation of chamber. A small magma chamber begins to develop from the saucer-shaped sill and produces high deformation upon one side of the caldera(at t_1=985s, t_2=1065s and t_3=1085s). Finally, it erupts.*

2) 3 %wt. concentration of gelatin

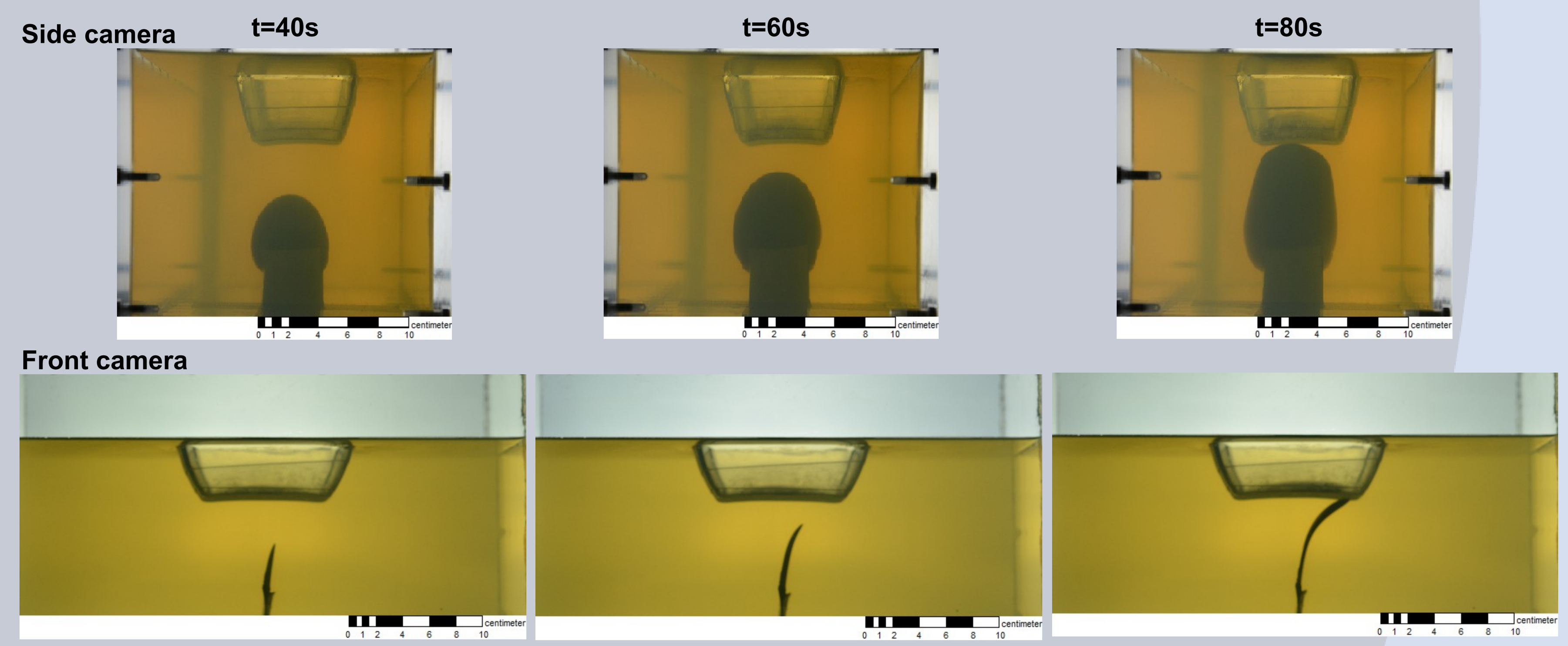

***Figure 7:** Gelatin concentratin at 3 %wt. It shows the process of dike formation and posterior vertical propagation. This concentration of gelatin allows for a vertical propagation only, in this case the dike breaches the surface much faster than in the other experiments. Pictures were taken with a front and side camera at different time steps.*

Discussion and conclusion

The topography is known to influence the propagation of dikes (Maccaferri et al., 2014). As we show here, also the arrest of dikes and development of reservoirs can result from interaction with topography.

How do sills and magma chambers develop? The hypothesis discussed in the literature focus on either the level of neutral buoyancy (Ryan et al., 1987b), or on the presence of stress barriers associated with lithology contrasts and layering (Galland et al., 2009, Duraiswami et al., 2013). We explored here the effect of a caldera-scale depression, and find that dikes develop into saucer-shaped sills, which then thicken. We found that the diameter of the basin and the concentration of the gelatin are important parameters to define the shape of magma pathways.

Low concentration of gelatin (≤2 %wt.) allows for a lateral propagation before the eruption. The lateral propagation encircles the caldera and forms a saucer-shaped sill. We further find that only when it is completely closing, the sill begins to thicken and a chamber begins to develop. This chamber is often asymmetric and is formed on one side of the saucer-shaped sill. It causes the maximum uplift in the model.

Higher concentration of gelatin (>2 %wt.) allows for only vertical propagation. In this case, the dike breaches the surface before it can propagate laterally around the caldera.

Future work

- Applying our models to a few volcanic areas in South America (Fig.8).
- Scaling the model dimensions using the appropriate scaling parameters in the experiment.
- Investigating the key parameters that control the establishment of magma bodies.

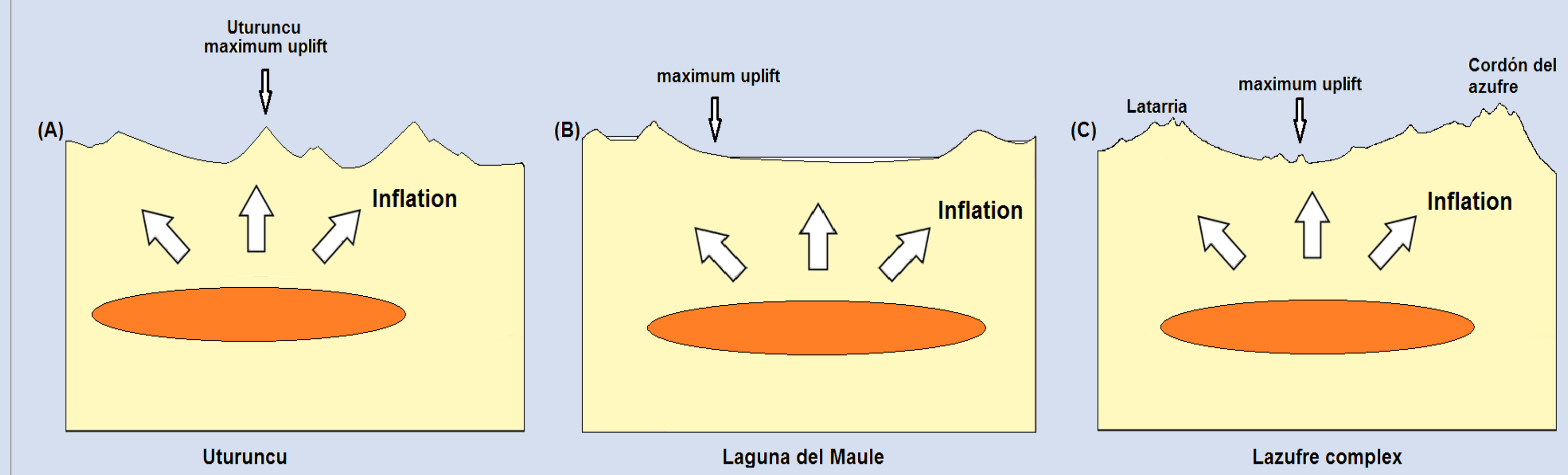

***Figure 8:** Sketches of the topography of Uturuncu, Laguna del Maule and Lazufre volcanic area. All of them are large unloading areas surrounded by volcanoes and mountains. Recent studies have shown that in (A) the maximum uplift occurs in the centre where Uturuncu volcano is located, (B) a high uplift on the SW border of theLaguna del Maule and (C) in Lazufre the maximum uplift occurs in the surface between Lastarria and Cordón del Azufre. Our results suggest that the inflation of the crust below these three areas may be associated with a saucer-shaped sill and its interaction with the topography (caldera).*

Acknowledgements

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