TOPOGRAPHIC DATA, PETROGRAPHY AND SAMPLE GEOCHEMISTRY AS PROXIES TO CONSTRAIN LAVA FLOW RHEOLOGY: THE CASE OF THE ALTIPLANO PUNA VOLCANIC COMPLEX MARS ANALOGUE SITE.
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Introduction: Terrestrial analogues have been used to constrain geological processes on other planetary surfaces which are mostly studied by remote sensing data. One of its main applicability has been to test and constrain the orbital interpreted data with ground truthing data from fieldwork. A range of geological phenomena has been studied based on Earth analogues, e.g., astrobiology, tectonic, eolian, volcanic, and igneous processes [1]. Volcanism is one of the main geological processes that shape most of planetary surfaces (e.g., Venus, Mars, Moon) and has been one of the main focuses of research in planetary sciences. The morphological and compositional volcanic diversity of each planetary surface results from complex processes associated with the style of eruption, where intrinsic (e.g., mainly viscosity related to chemical composition, degassing, and crystal fraction) and extrinsic parameters (e.g., slope surface, gravity) are involved. On Mars, the most prominent volcanic features are shield volcanoes constructed by long lava flows [2]. Their composition is settled as tholeiitic basaltic, however, more evolved magmatic rocks (e.g., andesite, trachyte, dacite) have been recognized locally, from a combination of data (e.g., SNC Martian meteorites, Mars rovers and orbiters) [3]. In this study we propose to use the Altiplano Puna volcanic Complex (APVC) within the Atacama Desert of Chile, as a terrestrial analogue site for Mars volcanic features, by testing the rheology of lava flows of diverse compositions between the two planetary surfaces.

Lava flow rheology: Rheology is related to the study of *fluid dynamics* [4] and mostly considers two types of fluid: either Newtonian (zero stress required to initiate a flow) or Bingham (an energy threshold should be overcome to initiate a flow). A lava flow is considered as a Bingham fluid with plastic behavior, controlled by two rheological parameters: the Yield strength (τ) Pa and Viscosity (η) Pa s. In planetary sciences, the latter has been used to infer the composition of a lava (silica content). First approaches to calculate viscosity include the 3D morphology of flows [η_{App} 5, 6]. As an alternative, thermodynamic models based on parameters such as the chemical composition (χ) and temperature (T) [η_{melt} 7,8] were proposed. Lastly, others [9,10] have analyzed the effect of crystal content, their shape and size by petrographic analysis. The viscosity of a lava can therefore be seen as a non-unique parameter but as a transient value that can vary according the geochemical, 3D morphology and petrography of lava flows. Here we calculate the viscosity based on two different rheological models proposed and compare the values obtained by the morphology versus the geochemical approach.

The analogue site: Our study area, the APVC, is within the Central Andes volcanic zone (22°-24°S). This volcanic complex highlights as an excellent analogue site for its diversity of volcanic features, low erosion rates, and a hyper arid climate [11], preserving most of the pristine lava flows. It gathers more than 1100 lava flows [12], as part of Pleistocene-Holocene composite volcanoes, scoria cones and domes. Here we analyze blocky and lobate lava flow units by sampling 32 rock samples along 10 lava units. TAS chemical compositions range between basaltic andesite to trachydacites (54.7 wt.% to 64.03 wt.%).

Methodology

Calculation of Apparent viscosity (η_{app}) and yield strength (τ) from topographic data. We determined the 3D geometry of lava flows by measuring length (L), Width (W), levee distance (w), thickness (H) in meters, slope surface (α) [°], from a 12.5 m/pixel Alos Palsar and a 12 m/pixel TanDem-X DEM. The data was collected in a *GIS* using Arcgis Desktop and Qgis 3.14.16. We use the Hulme's equation [4] for Bingham fluid (1) with ρ set to 2500 kg/m^3 [13] and g of 9.80665 m/s^2 to determine the apparent viscosity and yield strength(2).

$$\eta_{app} = \frac{w3\tau\sin2\alpha}{24n} \quad (1)$$

$$\tau = \rho g(W-w)\sin^2\alpha \quad (2)$$

Calculation of Melt viscosity (η_{melt}) from geochemical data We use a thermodynamic model (Rhyolite-Melt 1.2.0, [14]) to reproduce the liquid line of descent of the studied magmatic series, and to eventually characterize the viscosity of the related volatile-bearing melts [15] as a function of T(°C), H_2O (wt. %) and major oxides composition. We then apply the Giordano model based on the VFT (3) equation for non-Arrhenius temperature dependence with 2 compositional variables C, B and A as the highest temperature (high-T limit) to estimate melt viscosities.

$$\log(\eta_{melt}) = A + \frac{B}{T(K)-C} \quad (3)$$

Chemical analyses used as in input were obtained by ICP-MS analyses carried out at SARM, France.

Merging the two approaches - The relative viscosity (η_r) The **(η_r)** is defined by the ratio of apparent and melt viscosities , (4) [15] and by the Shaw rheological model [9] using the Einstein-Roscoe (5) eq., where the ϕ value (Packing fraction) takes theoretical maximum values of 0,74 for saturated crystals flows, while $\phi<0.74$ are considered not saturated crystals flows. Hence, the ratio of the **(η_{app})** to the **(η_{melt})** is known to increase with the presence of crystals.

$$\eta_{App} = \eta_{melt}\eta_r \quad (4)$$

$$\eta_r = (1-1.35\phi)^{-2.5} \quad (5)$$

Results

η_{app} values are in order of 10^6 to 10^{12} Pa.s, τ from 10^3 to 10^5 Pa, η_{melt} are in order of 10^3 and 10^8 Pa.s, η_r are in order of 10^1 to 10^7 Pa.s, with ϕ values between 0.57 to 0.74.

Discussion of the models and Conclusions

The η_{app} calculated with the Hulme's eq. fluctuates with andesitic/trachyte terrestrial lava flows viscosities, with values ranging from 10^9 Pa s to 10^{13} Pa s [16]. The lowest values of η_{melt} correlate to terrestrial basaltic andesite from the TAS diagram, whereas the highest η_{melt} are found for dacites and trachydacites [15]. However, the high η_r values still highlight a discrepancy between the two different approaches, and the resulting η_{app} and η_{melt} values. Highest η_r values correlate to packing fractions (ϕ) of (0,71-0,74), which are close to the theoretical maximum, and hence, suggest that the effect of crystals on the viscosity is not negligeable. Petrological analyses confirm that a selection of high silica rocks (59-64%) contain high phenocrystal abundances comprised between 28.6 and 39.5 %vol while a percentage of lava flows of basaltic andesites composition (54.7-57.1 wt.%) show lower crystals fraction between 7.7 to 11.7 %vol and hence, crystal fraction cannot be the sole responsible for this gap in viscosities. Before potential applications to Mars, we need to understand which factors can explain the discrepancy between the viscosity values obtained with the different approaches and implement correction factors. Our combined approach should allow us to survey the properties of Mars lava flows and bring clues to their possible composition and evolution over time, as well as to identify more differentiated flows than the globally basaltic surface based on their remote physical parameters.

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