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Description of new dry granular materials of variable cohesion and friction coefficient: Implications for laboratory modeling of the brittle crust

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ABSTRACT

Cohesion and friction coefficient are fundamental parameters for scaling brittle deformation in laboratory models of geological processes. However, they are commonly not experimental variable, whereas (1) rocks range from cohesion-less to strongly cohesive and from low friction to high friction and (2) strata exhibit substantial cohesion and friction contrasts. This *brittle paradox* implies that the effects of brittle properties on processes involving brittle deformation cannot be tested in laboratory models. Solving this paradox requires the use of dry granular materials of tunable and controllable brittle properties. In this paper, we describe dry mixtures of fine-grained cohesive, high friction silica powder (SP) and low-cohesion, low friction glass microspheres (GM) that fulfill this requirement. We systematically estimated the cohesions and friction coefficients of mixtures of variable proportions using two independent methods: (1) a classic Hubbert-type shear box to determine the extrapolated cohesion (C) and friction coefficient (μ), and (2) direct measurements of the tensile strength (T_0) and the height (H) of open fractures to calculate the true cohesion (C_0). The measured values of cohesion increase from 100 Pa for pure GM to 600 Pa for pure SP, with a sub-linear trend of the cohesion with the mixture GM content. The two independent cohesion measurement methods, from shear tests and tension/extensional tests, yield very similar results of extrapolated cohesion (C) and show that both are robust and can be used independently. The measured values of friction coefficients increase from 0.5 for pure GM to 1.05 for pure SP. The use of these granular material mixtures now allows testing (1) the effects of cohesion and friction coefficient in homogeneous laboratory models and (2) testing the effect of brittle layering on brittle deformation, as demonstrated by preliminary experiments. Therefore, the brittle properties become, at last, experimental variables.

1. Introduction

Cohesion and internal friction have been used as the main parameters for scaling brittle deformation in most laboratory modeling studies (e.g. Hubbert, 1937, 1951; Ramberg, 1981; Merle and Borgia, 1996; Schellart, 2000; Bureau et al., 2014; Galland et al., 2014, 2015). Many materials of different cohesions and friction coefficients have been used in laboratory studies, spanning from cohesion-less, low friction sand (e.g. Malavieille, 1984; Krantz, 1991; Mourgues and Cobbold, 2003; Graveleau et al., 2012) to strongly cohesive, high friction fine-grained silica flour (e.g. Galland et al., 2006; Abdelmalak et al., 2012; Galland, 2012; Bureau et al., 2014; Galland et al., 2014). The deformation regimes in these materials depend on their brittle properties (Galland et al., 2015). For instance, faulting (i.e. shear failure) only accommodates deformation in cohesion-less dry sand (e.g., Malavieille, 1984; Huiqi et al., 1992; Schellart, 2000; Lohrmann et al., 2003; Mourgues and Cobbold, 2003; Panien et al., 2006; Schreurs et al., 2006; Cubas et al., 2013; Maillot, 2013). In contrast in cohesive materials, both open fractures and faulting accommodate deformation (e.g. Galland et al., 2006; Holland et al., 2006; Galland et al., 2007, 2009; van Gent et al., 2010; Abdelmalak et al., 2012; Kettermann and Urai, 2015).

Brittle properties are commonly not experimental variables, as most existing homogeneous laboratory protocols are based on one model rock material and are therefore only designed for testing the effects of many other experimental variables (geometry, boundary conditions, magma viscosity, etc.), but not those of cohesion and rarely those of internal friction (Graveleau et al., 2012, and references therein). In addition, a few published brittle experiments considered layers of qualitatively different brittle properties, but the mechanical contrasts

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between the layers were either not known (Mastin and Pollard, 1988; Alsop, 1996) or poorly variable (Rossi and Storti, 2003; Teixell and Koyi, 2003; Bernard et al., 2007; Schmatz et al., 2010; van Gent et al., 2010; Konstantinovskaya and Malavieille, 2011).

Rocks in nature, however, range from cohesion-less to strongly cohesive, and strata exhibit substantial and variable cohesion contrasts. The internal friction of rocks is also variable (Schellart, 2000, and references therein). One can notice that there is a trend between the cohesion and the internal friction: more cohesive rocks are also those with the highest friction, whereas low cohesion rocks exhibit lower friction (Schellart, 2000). The effect of brittle layering has rarely been studied in laboratory models (Rossi and Storti, 2003; Galland, 2005), although field observations evidence the role of brittle layering on deformation patterns (Fig. 1; Teixell and Koyi, 2003; van der Zee et al., 2008; van Gent et al., 2010; Walker et al., 2012; Roche et al., 2014). It has been also demonstrated that the emplacement of igneous sills (Fig. 1) and laccoliths is controlled by the layering of their host rock (Kavanagh et al., 2006; Menand, 2008; Thomson and Schofield, 2008; Galland et al., 2009; Walker, 2014). To date, the effects of (1) brittle properties and (2) contrasts in brittle properties on brittle deformation processes cannot be studied in a quantitative manner in laboratory models. There is therefore a *brittle paradox* between, on one hand the established fundamental aspect of brittle properties on rock deformation and scaling of laboratory models, and on the other hand the incapacity of quantifying the effects of brittle properties on deformation processes.

Testing the effects of brittle properties and contrasts in brittle properties on tectonic deformation and magma emplacement requires the design of model materials of tunable and controlled cohesion and friction coefficient. In this paper, we present quantitative measurements of cohesion, tensile strength and angle of internal friction of dry mixtures of a cohesive fine-grained silica powder (SP) and fine-grained

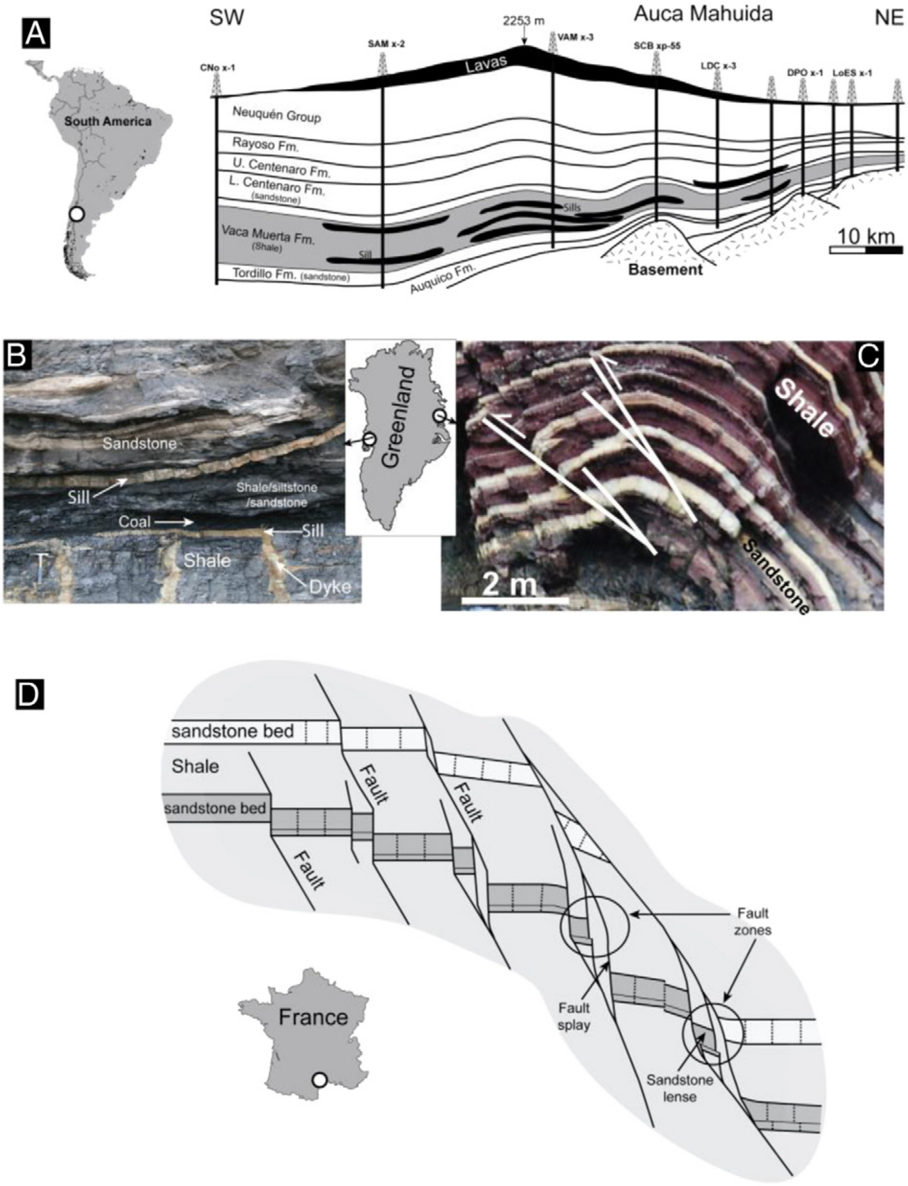

Fig. 1. Characteristic examples of the effects of brittle layering on geological systems. A. Geological cross section of the Auca Mahuida volcano, Neuquén Basin, Argentina (modified from Rossello et al., 2002). It shows that most sills preferably intruded into shale formation (Vaca Muerta Fm.) rather than in sandstone formations (e.g. Tordillo and Centenaro Fms.). B. Field photograph of a dyke-to-sill transition in western Greenland (north coast of Nuussuaq) at the interface shale/coal layers. C. Field photograph of a folded and faulted layered formation (eastern coast of Greenland in the Kaiser Franz Josef Fjord) [http://www.geol-alp.com/0_geol_gene/__tecto_photos/Faille-inverse-plissee-Sptzb_5.jpg (original photograph is provided by Mr. Bernard Couturier)]. D. Geological cross section showing the complex normal fault pattern affecting a multilayer shale/sandstone formation, Lodève Basin, Southern France (van der Zee et al., 2008). The section qualitatively highlights the effect of layering on faulting pattern.