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A simple theoretical approach to the thermal expansion mechanism of salt weathering

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ABSTRACT

The traditional plate theory in solid mechanics is used to estimate the thermal stress caused by a superficial salt layer on a rock substrate. This preliminary investigation theoretically demonstrates that the thermal expansion of superficial salt layers is difficult to result in rock breakdown during the process of salt weathering.

Weathering is essential to the landscape development in arid environments (Cooke and Warren, 1973; Laity, 2008; Smith, 2009; Viles, 2011; Goudie, 2013), mostly because this natural phenomenon can produce substantive clasts and fascinating landforms over long time periods. In the long history of weathering research (Turkington and Paradise, 2005; Goudie, 2013), various processes resulting in rock breakdown, *e.g.* insolation weathering, frost weathering, salt weathering, and biological weathering *etc.*, were proposed and frequently investigated (McGreevy, 1982; Jenkins and Smith, 1990; Chen et al., 2000; Doehne, 2002). Salt weathering often occurs in desert and coastal environments. Three well-recognized mechanisms involved in this process are crystallization, hydration, and thermal expansion (Cooke and Smalley, 1968; Laity, 2008). It is obvious that salt weathering is principally controlled by rock strength and state of stress. The stresses generated by crystallization and hydration in porous materials can be quantitatively evaluated (Rodriguez-Navarro and Doehne, 1999; Scherer, 1999; Charola, 2000; Doehne, 2002), whereas analogous expressions or equations for thermal stress are scarce (Johannessen et al., 1982). A very recent literature review showed that most considerations on thermal expansion were not beyond the conceptual level, and that the opinions were often contradictory (Gonçalves and Brito, 2016). It is necessary to accurately understand the role of thermal expansion in salt weathering process, although this mechanism was previously thought to be less effective than the other two (Laity, 2008).

The methods of weathering research include field monitoring, laboratory testing, dating, and modeling. As pointed out by Viles (2011), an advantage of modeling is that it can address questions at any temporal and spatial scale. For instance, the growth of tafoni due to crystallization has been simulated under the condition of wetting/drying cycles (Huinink et al., 2004). In the current study, a simple model was established by using the traditional plate theory in solid mechanics to estimate the thermal stress caused by a superficial salt layer on the rock substrate.

Salt weathering is common in the arid region of northwestern China. Fig. 1 shows the tafoni at $(40^{\circ}3'12''N, 100^{\circ}8'20''E)$ in the southwestern margin of the Badain Jaran Desert. These typical cavernous weathering features, which form on sandstones, cover an area of 1200 km^2 approximately. The diameters and depths of tafoni can change from a few centimeters to several meters, see Fig. 1(a). Similar to those found in the Atacama Desert of Chile (Viles, 2011), salt deposits also occur within most tafoni in the Badain Jaran Desert, see Fig. 1(b). The widely distributed saline playas in this region are being subjected to active aeolian processes (Wang et al., 2013). Some previous studies discovered that aeolian sediments on the ground or in the air could contain remarkable salts (Abuduwaili et al., 2008; Wang et al., 2008; Zhu et al., 2012). Therefore, aeolian deposition of saline dust is an evident source of the superficial salt layers in the study area. Another possible source is the salt concentration associated with water migration and evaporation in rocks.

Phenomenological models describing the processes of salt weathering and tafoni evolution can be established, according to the geometrical, thermal and mechanical properties of materials and the

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Fig. 1. Tafoni in a sandstone in the southwestern margin of the Badian Jaran Desert, northwestern China: (a) large boulder showing the characteristic landscape of the study area; (b) salt deposits within a tafone ≈25*cm* wide, ≈10*cm* deep.

principles of solid mechanics (Hetnarski and Eslami, 2009; Eslami et al., 2013). Most substances, including rocks and salt layers in this study, deform when their temperature changes. For a wide range of temperatures, this deformation is proportional to temperature change. The coefficient of linear thermal expansion α is thus defined as the length change of a bar of unit length per unit temperature change. A simplified model for the thermal deformation of a superficial salt layer within a tafone is illustrated in Fig. 2. To estimate the thermal stress acting on the rock substrate, we made two assumptions as follows: (1) The salt layer and rock are completely composed of homogeneous elastic and rigid materials, respectively. This assumption is based on the fact that many common desert salts deform to a much greater degree than those of rocks which are subjected to the same temperature change (Cooke and Smalley, 1968; Goudie, 2013). Consequently, salt deposits within a tafone can be modeled by an elastic material restricted by a rigid body, as shown in Fig. 2(a). (2) The thickness h of the salt layer is small compared with its diameter $2a$. Field measurements suggest that $h/a<10$. This geometrical characteristic suggests that the mechanical behavior of salt layers can be well described by the plate theory in solid mechanics.

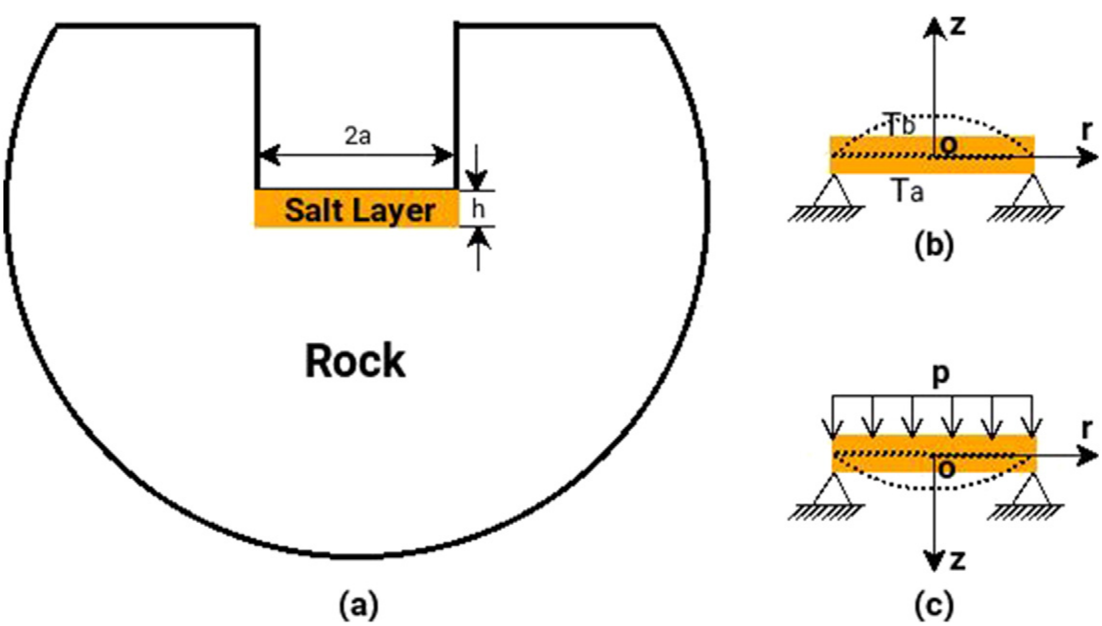

Fig. 2. Modeling the deformation of a superficial salt layer within a tafone: (a) a deformable circular salt layer restricted by a rigid rock, where h and $2a$ denote the thickness and diameter of the salt layer; (b) upward deflection induced by a thermal load, where T_b and T_a are the temperatures at two faces of $z=h/2$ and $z=-h/2$; (c) downward deflection induced by a uniform mechanical load p. The arrows of **or** and **oz** represent a cylindrical coordinate system. The resulting deflection of the salt layer is the sum of two deflections occurring in the cases of (b) and (c).