Earth and Planetary Science Letters 331–332 (2012) 120–127

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Salt lake deformation detected from space

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ARTICLE INFO

Article history:
Received 27 September 2011
Received in revised form 8 February 2012
Accepted 2 March 2012
Available online 5 April 2012

Editor: P. DeMenocal

Keywords:
InSAR
central Andes
salar
salt flat
halite
ground deformation

ABSTRACT

To investigate the spatiotemporal evolution of salars in the Atacama Desert in Chile (24–26°S), we use a deformation time series retrieved by applying satellite radar interferometry techniques for the period from 2003 to 2008. We find that all 12 salars surveyed are actively deforming, with displacement rates from −1.4 to 1.5 cm/yr in the satellite line-of-sight direction. Displacement rates are mostly confined to the salars themselves, and are generally constant in time and space. To understand the reason for this displacement signal, we further compare these observations with LANDSAT imagery and field observations. Relationships between these observations suggest that the most rapid uplift regions indicate subsurface material accretion. A variety of saline sedimentary processes related to the salar hydrology can explain this accretion, the most likely being capillary halite precipitation within and below surficial salt crusts. We further propose that salars, whose dynamics are dependent on the presence of brine and resurging saline groundwater, may be used as potential indicators of water resource evolution in the central Andes, and in similar water-limited regions elsewhere on earth.

1. Introduction

Dry lakes and saline lakes are common geomorphologic features in arid regions and are known to be reliable indicators of hydrology using both field and remote sensing technologies. Morphologically, saline hydrologies accumulating bedded salts typically occur in hydrographically-closed depressions or saline pans, which are infrequently water covered, but act as continual groundwater sumps, even when the salar surface is subaerial (Warren, 2010). Sedimentologically, within a broad range of saline depressions worldwide, salars define a particular style of saline sump where halite precipitates near the upper surface of the groundwater system, via the evaporation of groundwater brines (Jordan et al., 2002; Lowenstein et al., 2003).

Elevation changes at salar surfaces have been observed using InSAR in the central Andes (Pritchard, 2003), however, no clear explanations have been yet provided to explain the deformation mechanisms. The present study utilises an InSAR time series across a number of salars to show that the ground surface within a salar is subject to variable displacement rates tied to specific sedimentary units and their inherent hydrological processes.

1.1. Climatic and sedimentologic framework

Altiplano Puna encompasses substantial portions of the hyperarid Atacama Desert; one of the driest regions of the world with an average elevation of 3750 m (Fig. 1a, Strecker et al., 2007). A hyperarid desert, by definition, experiences a number of consecutive years with no rain. Salts are accumulating in various forms and geometries across the Atacama Desert, for example: 1) as a suite of sodium-nitrate salts in pedogenic horizons; 2) as calcium-sulphate mantles on newly formed volcanic cones, and 3) as thick beds of salar halite in intermontane groundwater sumps (Warren, 2006). Hereafter we concentrate on this third group. During the Mid-Holocene period, the Altiplano Puna plateau underwent rapid regional climatic change, with many areas shifting from vegetated regimes, subject to more frequent rainfall, to inhospitable hyperarid desertic environments (Betancourt et al., 2000; Núñez et al., 2002; Placzek et al., 2006; Quade et al., 2008). In response to the desertification, the regional water table was lowered and many former perennial intermontane saline lakes desiccated into salars (Bobst et al., 2001; Lowenstein et al., 2003).

The term salar describes a groundwater sump where the sediments are typically subaerial and halite-rich, with intrasediment salt-growth textures driven by capillary evaporation of near-surface hypersaline groundwaters (Fig. 1b; Lowenstein and Hardie, 1985; Alonso et al., 1991; Warren, 2006, 2010). In a salar centre (depression), the hypersaline water table is less than a metre beneath the halite-encrusted salar

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doi:10.1016/j.epsl.2012.03.009

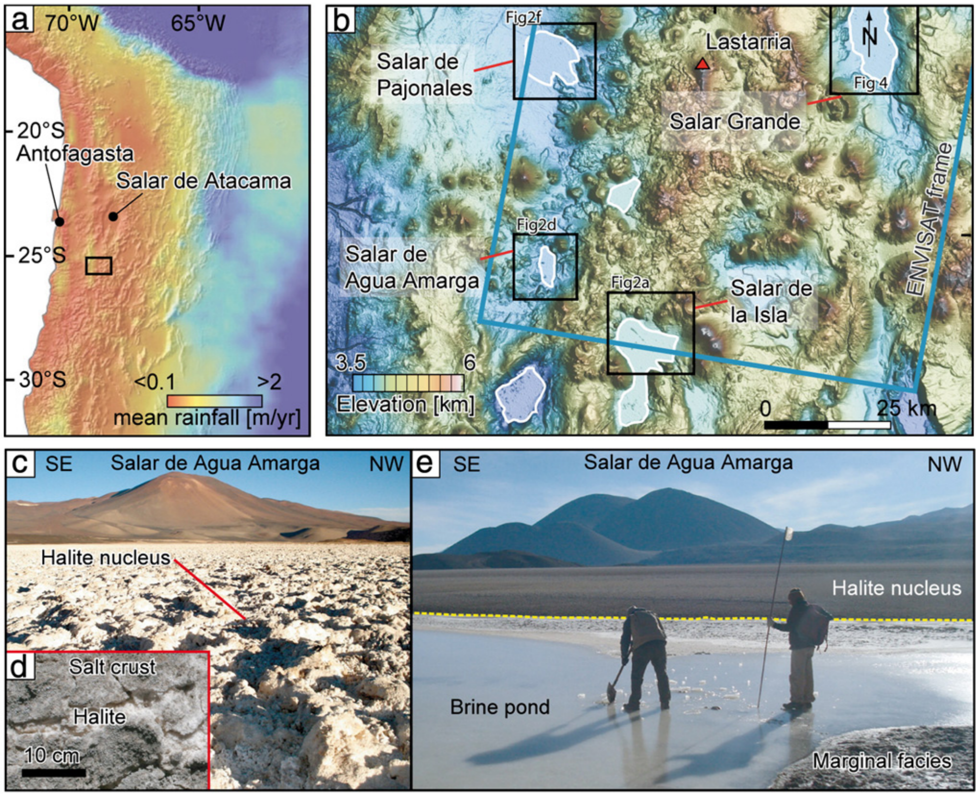

Fig. 1. The studied salars are located ~200 km south of Salar de Atacama and 250 km SE of Antofagasta city. a) Shaded relief map of the central Andes overlain by annual rainfall; the black rectangle indicates the position of the study area. b) DEM of the South Puna Plateau with salar locations, thick light grey boundary outlines the area covered by the InSAR time series, small black boxes delineate the studied areas of Figs. 2 and 4. Surface geology photographs at Salar de Amarga that show c) irregular hummocky surface of the halite nucleus facies, and d) flat surface of marginal facies (partially covered by frozen brine) with the transition to the more elevated surface of the halite nucleus.
Panel a: modified from Strecker et al. (2007).

surface and the associated halite bed is typically metres to ten or more metres thick. In plan view, a salar's hydrologically-controlled sediment system consists of two principal parts: a halite nucleus and a marginal salt flat zone (Fig. 1c–d), with respective proportions of the two varying from one salar to another (Houston, 2006; Lowenstein et al., 2003; Warren, 2006). Compared to the marginal zone, the surface of the halite nucleus is hummocky and rugose, it defines the region in the salar's central sump that is somewhat higher (tens of cm) than the immediately surrounding margin facies (Fig. 1c–e). This elevated halite nucleus facies is very rarely covered by a water sheet. This is unlike portions of the salar edges, where saline brines seep to the surface and can form brine-filled ponds and pits.

Directly below its surface (first few cm below), the halite nucleus facies is composed of an aggregated set of dry silty-cemented solution-etched salt encrustations. Below this, numerous mm–cm scale halite crystals are precipitating from capillary pore brines in a permeable halite mass. Solar-driven evaporation (not cryogenic concentration) drives an ongoing supply of brine to the nucleus, fed from the shallow water table and brought to the near surface by capillary forces. Salt etching in the uppermost layer of the halite nucleus is a response to occasional fogs and mists, which in this hyperarid desert can constitute the main mode of fresh water influx to the elevated salar nucleus facies (Diaz et al., 1999). However, in terms of salar's solute budget, most of the ions precipitated as salts in the nucleus unit are groundwater-derived; this is why lithium salts can be recovered economically from pore brines in the halite nucleus facies across a number of Andean salars (Warren, 2010).

Adjacent marginal facies are made up of varying combinations of silty mudflats, saline pan crusts and brine ponds, with elevated proportions of gypsum and carbonate minerals in the underlying sediment, but with a sediment surface that for much of a year is still covered by fluffy white halite-rich efflorescences and thin salt crusts (Fig. 1d). Occasional storm floods and alluvial sheet flood processes carry in much of the terrigenous mud and silt sediment found in the marginal facies. When flooded, the salt efflorescences capping the marginal flats dissolve back into the covering brine sheets. With desiccation, this recycled salt can reform as a thin salt crust covering the lower parts of the surface in the marginal facies belt.

Small perennial brine ponds (lagunas and *ojo de diablo*) are brine-filled zones of salt dissolution (salt sinkholes), which are typically interspersed within the marginal facies of many Andean salars. In less-saline salar systems, or in zones of fault-controlled stronger groundwater resurgence, these perennial brine ponds and pits can occur also in the more central parts of a salar (Lowenstein et al., 2003; Warren, 2006).

2. Salar surface deformation analysis

To analyse the surface deformation, we use an interferometric synthetic aperture radar (InSAR) dataset acquired by the ENVISAT satellite composed of 21 images in descending orbit spanning from March 2003 to January 2008. By processing the phase difference (interferogram) between SAR image pairs separated in time, we obtain temporal and spatial surface displacements projected in the LOS (satellite line-of-sight) direction (e.g. Massonet and Feigl, 1998). We computed a total of 153 interferograms characterised by spatial baseline values smaller than 500 m. We applied the SBAS algorithm (see for details Berardino et al., 2002) to obtain mean deformation velocity maps and time series. The average standard deviation of the technique is generally 0.1–0.2 cm/yr for the velocity and 0.5–1 cm for the time series (Casu et al., 2006). Note that radar signal acquisition of superficial water (i.e. brine ponds and perennial lakes) will result in incoherence. This