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Salt rims and blisters: peculiar and ephemeral formations in the Atacama Desert (Chile)

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with 13 figures and 1 table

Abstract. During a field trip in November 2007 at San Pedro de Atacama (Chile) several centimetre-scale white rims and blisters were observed on the salt crust floor in the famous Valle de la Luna (moon valley). These curious features are composed entirely of pure white salt and have been encountered in a limited area of about 15,000 m^2. A total of 35 of these small structures, named here "salt rims" and "salt blisters", have been located and measured. Their average plan dimensions are 6.5 x 5.5 cm for a mean height of 3.6 cm. Almost 60% of these structures have an opening on top (salt rims), sometimes on their flanks, typically smaller than their diameters. The biggest features always have an opening, being the closed structures, named blisters, normally less than 3 cm in diameter.

A tube-like opening continuing underground for at least a decimetre, mostly deeper than 20 cm, is clearly visible in the inside of the salt rims. The rims perfectly match the edges of these holes. In some cases salt crystals grow on the inner walls of the rims forming curving filaments.

The salt blisters and rims are very similar to homonymous (sam-name) speleothems and form by condensation-evaporation processes after very sporadic rainy episodes. Rainfall (average annual rainfall is < 20 mm), occurs very rarely and enables infiltration of salty water through openings in the salt crusts. This water is conveyed underneath the impervious salt crust presumably in a network of interconnected fissures and underground cavities containing airborne fine sediments and in which moist air flows. According to our genetic model these underground aerosols can escape under the form of vapour only through cracks or openings when outside temperature drops below underground temperature (e.g. during the night). Evaporation processes occur when the vapour exits the holes leading to the formation of a salt rim on the side. When the airflow decreases gradually the rim can get smaller in diameter and eventually closes completely forming a salt blister. Salt rims and blisters are generally seasonal features that are doomed to dissolve by rain, but some appear to be able to survive several years building up a thick salt crust that can reach almost 1 cm.

Keywords. Atacama, condensation, evaporation, salt, secondary deposits

Introduction

Atacama Desert is one of the driest places on earth with mean annual rainfall below 20 mm y^{-1} and often null during several subsequent years (Houston & Hartley 2003, Sesiano 2006). Close to the village of San Pedro de Atacama, North of the Salar de Atacama basin, there is an important outcrop of Oligo-Miocene evaporites known as Cordillera de la Sal. This low mountain range is composed of a succession of marls, gypsum and salt beds forming a NNE-SSW trending anticlinal ridge. Despite the hyperarid climate the evaporites in this range have been karstified by occasional rains and show a subterranean karst drainage network (De Waele et al. 2009, Fryer 2005, Maire & Salomon 1994, Padovan 2003, Sesiano 2006). Also surface karst landforms are well developed, including extremely sharp

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and deeply cut rillenkarren often isolating salt pinnacles of up to 15 m in height. The roofs of the salt caves often collapse forming a series of collapse-dolines aligned along the cave direction.

This contribution presents a geomorphological analysis of some very peculiar micro-forms, named salt rims and blisters, found in a flat area of the Cordillera de la Sal with the aim of understanding the mechanisms involved in their formation and evolution.

Description of the study area

Salt blisters and rims have been found in a very restricted area of the Cordillera de la Sal, at about 12 km southwest of San Pedro village, a small distance west of the famous Valle de la Luna (Moon Valley) (Fig. 1). The salt blisters and rims are scattered over an area of about 15,000 m^2, close to and below an abandoned quarry where salt used to be mined. This quarry is located in the ridge that forms the southern boundary of a large flat salt plain, on the south side of the road that connects the Valle de la Luna with the Llano de la Paciencia. Several gypsum heaps (called hoodoos by other authors, e.g. Fryer 2005) stick out in linear-shaped arrays along the salt plain, a set of which are known under the name "las tres Marias" (The three Marys). These gypsum heaps are constituted of large crystals that seem to have grown along fractures, rising from the plain for up to 10 meters (Fig. 2). These structures are most probably active morphologies that continue rising slowly from the plain due to recrystallisation processes in the subsurface along joints and fractures.

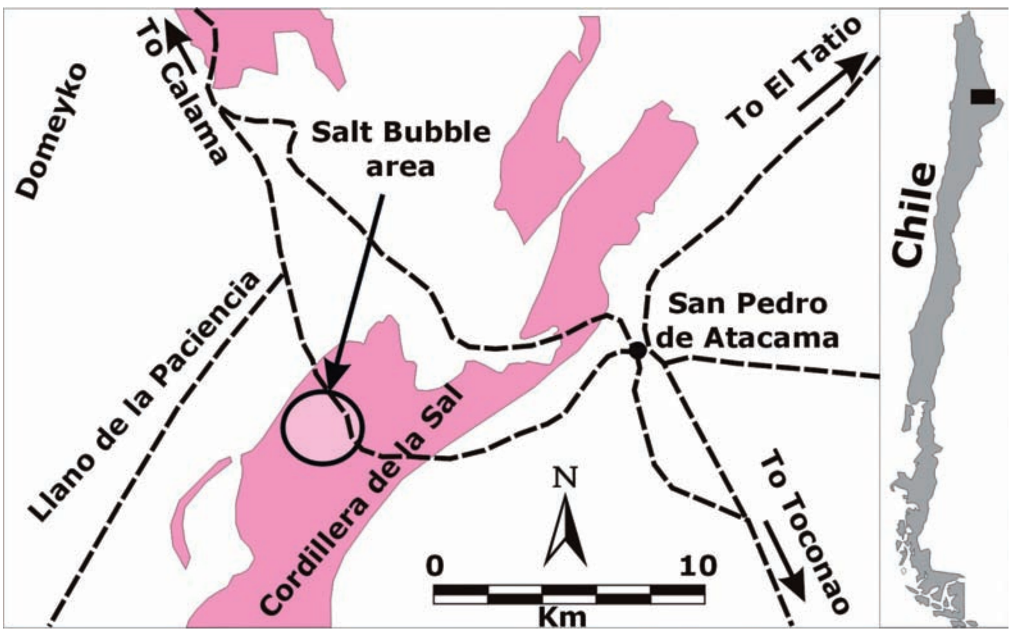

Fig. 1. Location of the study area. Shaded areas represent the Oligocene-Miocene evaporite sequence.

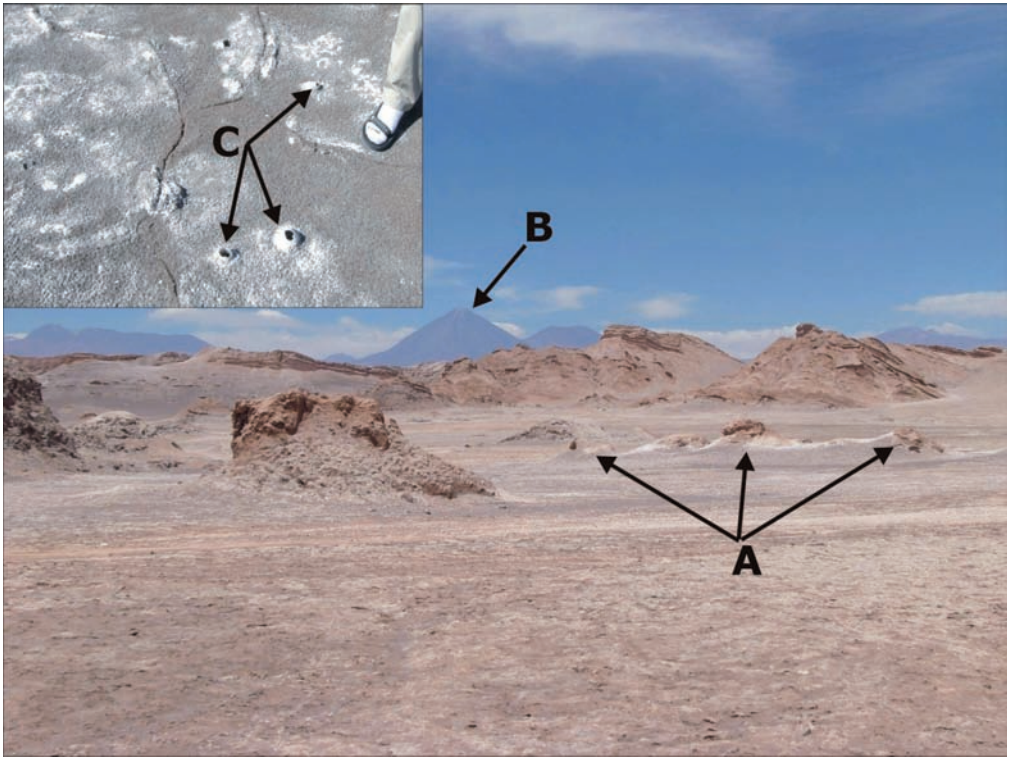

Fig. 2. The salt flat with the gypsum heaps alignments. A. Gypsum heaps; B. Licancabur volcano; C. Salt rims.

Probably these gypsum alignments have deep roots that form impervious barriers for horizontally flowing groundwater that flows from the higher ridges to the lower parts of the plain. Groundwater is forced to rise along these faults and evaporation processes lead to the formation and growth of gypsum crystals.

On the salt crust floor in between one of those hoodoo alignments and the southern salt ridge several centimetre-scale white rims and blisters have been observed. These curious forms are composed entirely of pure white salt and do not appear to be formed along preferential directions or alignments.

Salt rims and blisters

A total of 35 of these small structures, named here "salt rims" and "salt blisters", have been recorded and measured (see Table 1). Their major axes range between 1.5 and 15 cm (average 6.5 cm), their minimum axes between 1 and 12 cm (average 5.5 cm), their original height (some are broken to the floor) is comprised between 1 and 8 cm (average 3.6 cm). More

Table 1. Morphological characteristics of 35 salt blisters and rims. Measures are expressed in cm.

N°	**Base**		**Aperture**		**Height**	**Depth**	**Notes**
	Long axis	**Short axis**	**Long axis**	**Short axis**			
1	15	12	6	6	1	>20	
2	4	4	0	0	1	?	
3	4	4	3	3	3	>10	
4	5	5	5	5	6	>20	
5	6	5	0	0	2	?	
6	6	5	5	5	5	>15	
7	5	5	2	2	2	>10	
8	5	5	0	0	5	?	
9	4	4	0	0	4	?	
10	6	5	5	2,5	4	>10	
11	6	4	0	0	4	?	
12	6	6	0	0	3	?	
13	6	6	0	0	5	?	
14	3	3	0	0	5	?	
15	8	6	5	4	2	>20	
16	13	9	13	9	0	>20	Broken
17	8	6	8	6	6	>20	Broken
18	5	5	4	2	7	?	Side opening
19	5	5	2	2	6	>20	
20	8	7	3	2	5	>20	
21	5	5	4	4	1	>15	
22	5	5	3	3	3	>20	
23	3	3	0	0	2	?	
24	8	6	0	0	2	?	
25	10	8	4	2	8	>20	
26	7	5	0	0	3	?	Fissure opening
27	8	6	0	0	5	?	
28	10	8	2	2	6	>20	
29	4	4	0	0	3	?	
30	5	4	1,5	1,5	3	>20	
31	3	3	0	0	1,5	?	
32	11	5	10	3	3	>20	
33	7	7	0	0	3	?	
34	7	7	7	7	1	>20	
35	5	5	4	4	4	>20	
Total	226	192	96,5	75	124,5		
Mean	**6,5**	**5,5**	**2,8**	**2,1**	**3,6**		

than half of these structures have a perfectly circular section and display a cylindrical shape, the bigger rims being the most irregular ones (Fig. 3). These features tend to develop as cylindrical tubes from the early beginning, deviating their morphology from this perfect geometry only in rare occasions, corresponding to the formation of the bigger rims. Almost 60% of these structures have an opening on top (salt rims) (Fig. 4A), sometimes on their flanks, in average smaller than their diameters. The biggest always have an opening, being the closed structures, named blisters (Fig. 4B), normally less than 3 cm wide. The opening can have various shapes, from circular to triangular (Fig. 4C) up to a narrow fissure (Fig. 4D).

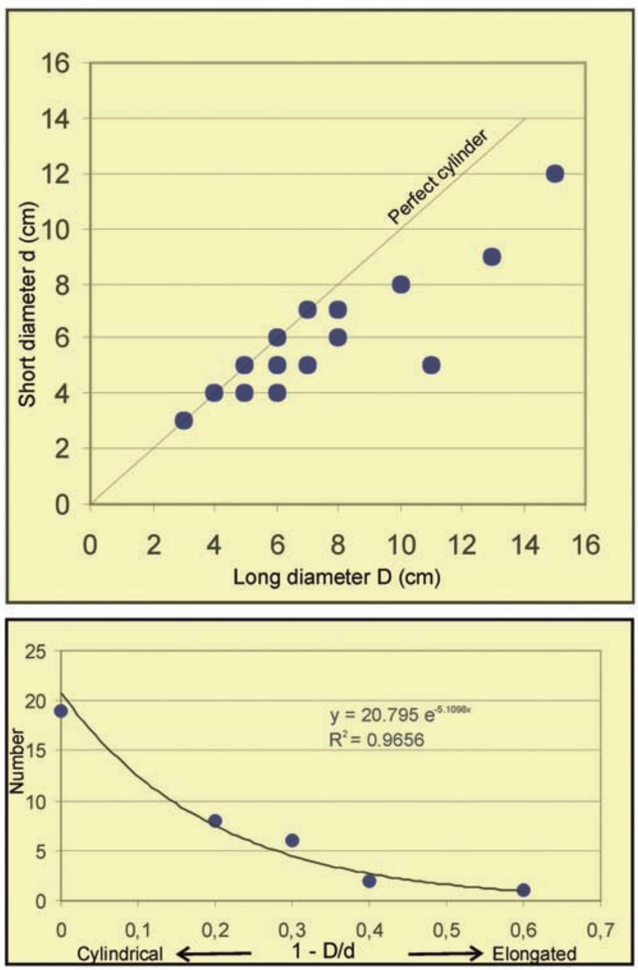

Fig. 3. Graphs showing the relationship between the major and the minor axes of the recorded salt rims and blisters (see text for explanation).

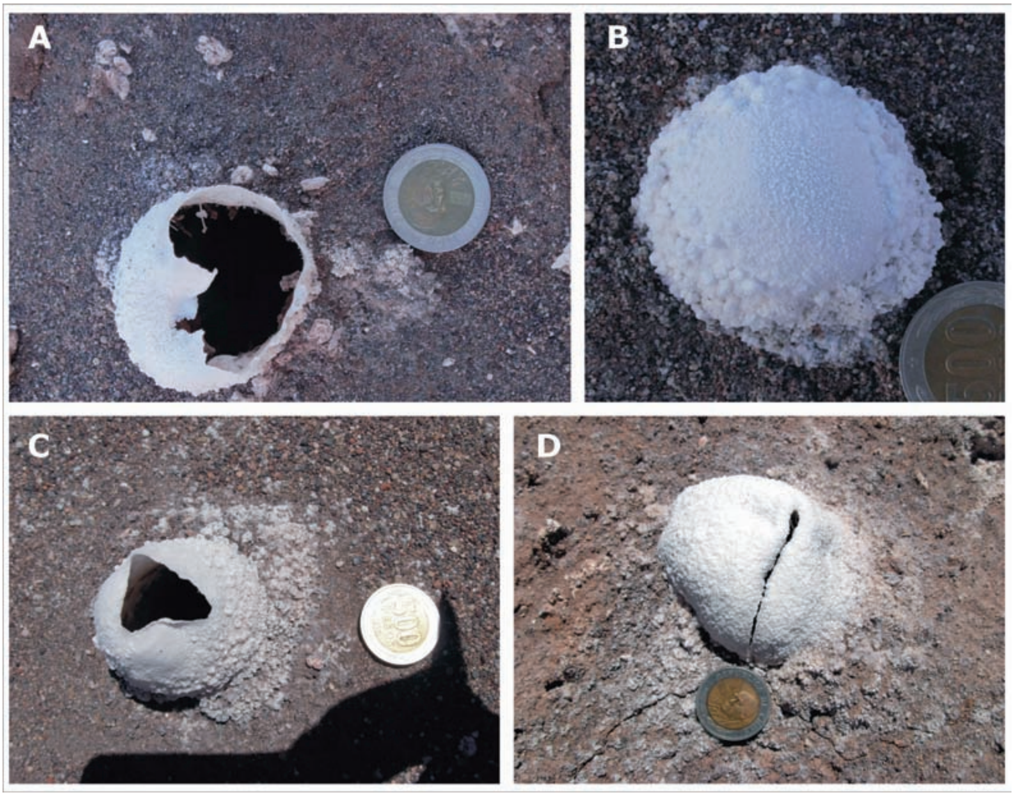

Fig. 4. Salt rims and blisters: A. Rim with acicular salt crystals growing on the inside wall; B. Salt blister with popcorn-like deposits (at the base); C. Salt rim with triangular opening and popcorn-like precipitates along its foot; D. Salt rim (almost a blister) with fissure opening. The coin is 2.6 cm in diameter.

XRD-analysis has shown that blisters and rims are composed of pure halite. The rims are usually composed of a very thin and fragile salt veil (thickness of some tenths of mm), but in some cases the rims (or blisters) can be thicker, up to 1 cm, and show a succession of pure white salt layers. The inner side of the rims has a smooth surface, sometimes showing fine reddish clay particles embedded in the white salt, especially close to the bedrock upon which they grow. In some cases salt crystals grow on the inner walls of the rims forming curving filaments (Fig. 5A). A tube-like opening continuing underground for at least a decimetre, mostly deeper than 20 cm, is clearly visible observing the inside of the salt rims in detail (Fig. 5B). The rims perfectly match the edges of these holes. The outside has a much less regular surface, often covered with popcorn-like salt deposits (Figs. 4B and 4C).

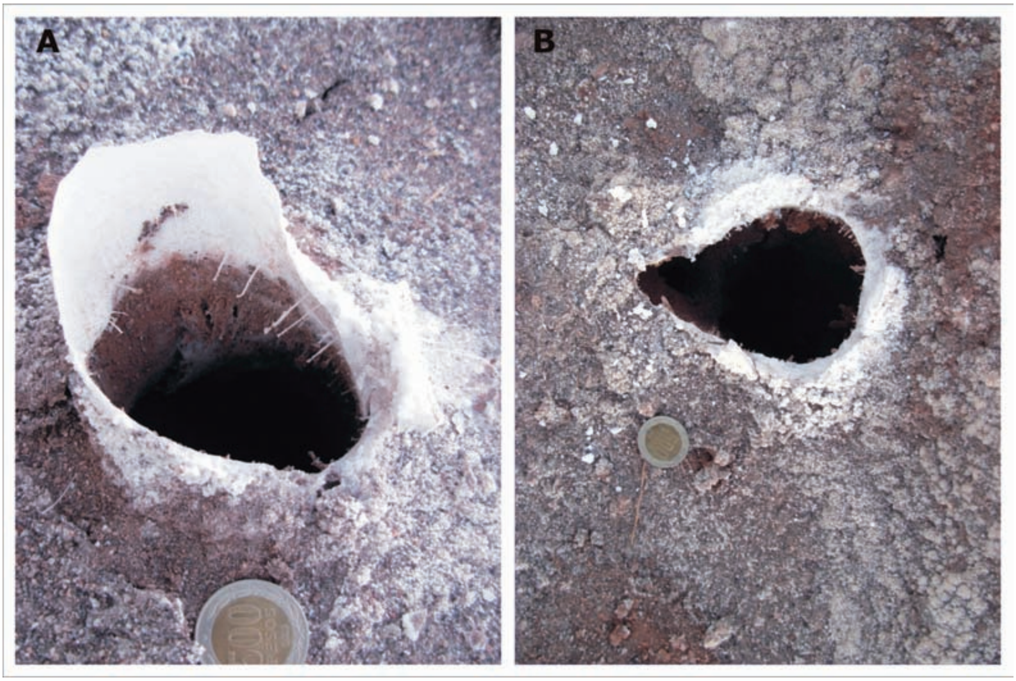

Fig. 5. Close-up views of salt rims: A. Acicular halite crystals in the inner face of the rim oriented radially towards the central axis of the rim; B. The rim perfectly matches a cylindrical pipe in the rock salt floor. Note rim thickness of several mm.

Genesis and evolution of the salt rims and blisters

The genesis and evolution of the halite rims and blisters are clearly controlled by a combination of circumstances that are rarely met in natural conditions. In fact, these forms are localized in an extremely small area in the Cordillera de la Sal and, to our knowledge, these features have been described only from another area where salt outcrops, along the edges of the Qarhan Salt Lake in the Qinghai Plateau in China (Yuhua & Lin Hua 1986). Similar morphologies, made of gypsum and of much smaller dimensions, have also been described from Patagonia in Argentina (Forti et al. 1993).

The climate plays a fundamental role in their development: all three regions, in fact, are characterized by an arid climate with extreme temperature ranges between night and day and very scarce rainfall. However, the fact that rims and blisters form in very small areas indicate that they cannot be explained by climate alone.

In order to analyse the factors that control the development of salt rims and blisters in the Atacama Desert, the conditions that allow the development of these forms in much more stable environments such as in caves will be summarized first. In fact, similar forms have been described in caves (Davis 1982, Green 1991, Hill 1984, Hill & Forti 1997, Klimchouk et al. 1995). Besides, since caves are very stable environments, it is also easier to define the meteorological and physico-chemical parameters that influence the formation and evolution of these rare speleothems.

The most important factor that allows the formation of rims is the existence of an intense and constant air flow escaping from a more or less narrow hole into a much bigger space. This situation is found for example when light air masses are situated below spaces with denser air. A good example of such a situation is a recently formed lava tube, in which fumarolic and very hot fluids (gases) enter into the cave through fractures (Forti et al. 1995) or when deep parts of an extensive thermal aquifer are in direct connection with higher cave levels containing much colder air (Hill 1984).

But air flow is not enough to give rise to a rim, because a sufficiently strong supersaturation of flowing air is also required. Moreover, this supersaturation must occur only after the narrow passage, otherwise the inner tube would rapidly be filled up.

The mechanism that can cause the fluid to become supersaturated is the sudden semi-adiabatic expansion of the gas at the precise moment it enters the big space. The sudden decrease in pressure (expansion) of the fluids causes their temperature to drop, and the same expansion causes enhanced turbulent flow just after the narrow hole, where the fluids are forced to reduce their velocity.

The temperature drop will induce a decrease in solubility high enough to produce supersaturation with respect to the mineral, thus giving rise to the development of a rim, while turbulence, which is highest along the hole edges, will produce the maximum of contact between the supersaturated fluid and the rock just there. This explains why the rims always develop as thin tubes only along the hole edges.

There is also another boundary condition that has to be met contemporaneously if rims are to develop; the presence of soluble compounds that can easily dissolve and be transported by an air flow under the form of aerosol. It is not surprising that in the speleological literature rims are reported to be composed of relatively soluble minerals, like calcite and aragonite, but as recently pointed out also frequently by more soluble compounds such as gypsum, thenardite and halite (Forti et al. 1996).

The increase in soluble compounds within the fluids occurs exactly where the air has to squeeze from a large void into a narrow tube. At that point, in fact the air is forced to undergo a semi-adiabatic compression. This causes a slight temperature increase, which enhances the solubility of the rock compounds. At the same time turbulence is induced by the increase of flow velocity just at the edges of the tube entrance, where, therefore, the maximum of contact between fluids and rock will occur.

The formation process of cave rims can thus be summarized as follows (Fig. 6A). The air that passes from a big space to narrow conduits and/or fissures undergoes a semi-adiabatic compression (increasing its turbulence and temperature). Both physical changes favour corrosion and dissolution of the rock walls. The air may become saturated with respect to the mineral and the solutes are transported under the form of aerosols and/or spray. When this saturated air escapes from the narrow void into a larger one the semi-adiabatic expansion causes turbulence and temperature fall enhancing deposition of the transported material.

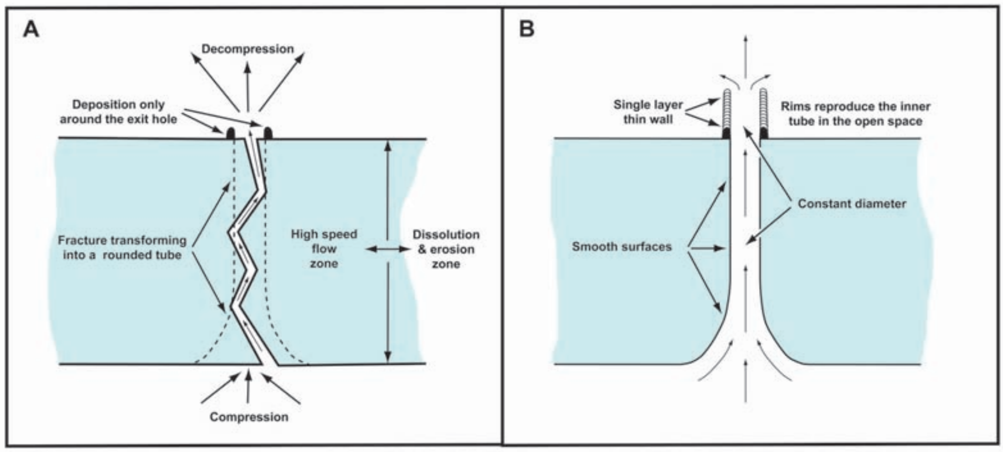

Fig. 6. Cartoon showing the formation process of a rim.

Deposition occurs where the expansion starts at the exact point where air leaves the narrow holes or fissures and enters the open space. Thus a thin ring will start to precipitate on the edges of these small outlets. As deposition proceeds the ring will transform gradually into a cylindrical tube (a rim) that will tend to have a constant diameter, determined by the size of the hole from where the air escapes, unless airflow changes (Fig. 6B).

If deposition would make the hole narrower, the increased compression of the air would cause dissolution. Conversely, with increasing diameter decompression would start earlier inside the tube favouring deposition. The process is absolutely conservative in respect to the dimension of the rim. A cylindrical geometry minimises turbulence and optimises the laminar and regular flux of the gas.

All these processes can also explain the evolution from rim to blister. If the air flow diminishes, and considering that all the other factors remain constant, the deposition of airborne material would start earlier, along the inside of the cylindrical rim, causing the progressive narrowing of the outlet feature and keeping air flow speed constant. This would prevent pressure rise and dissolution of the rim walls. If this process progresses gradually the rim will eventually be completely closed and transform the rim into a blister. If air flow stops the rim will simply interrupt its growth. This seems to be the most frequent situation in caves where rims very rarely develop towards closed forms. This mechanism is able to explain the development of rims in caves, where these forms are characterised by extremely thin walls (some tens of mm).

To ascribe the development of salt rims and blisters of Atacama to this genetic mechanism two questions have to be answered:

- Is there a fairly strong ascending air flow from beneath the salt floor and where does it come from?
- How can we explain the thick walls of the rims and blisters and the presence of popcorn-like formations on their outer walls?

Given the diapiric nature of the area and the morphological situation in which the rims and blisters have developed, the presence of large underground cavities developed on different interconnected levels with entrances at various altitudes, thus triggering the development of strong air currents, can be excluded a priori. This, for instance, was the situation encountered for the gypsum rims found in Argentina (Forti et al. 1993). In the case of Qarhan salt lake the cavities that allowed air circulation were related to the dissolution at the base of the salt formations by the waters of the lake that increased their levels up to half a metre during rainy periods (Yuhua & Lin Hua 1986).

In the Cordillera de la Sal there are no lakes and because of the diapiric structure of the salt ridge, only shallow caves can develop. There has to be another mechanism that induces air circulation through the salt bedrock. The excavation of some rims has allowed us to examine some fractures, less than 10 cm wide, that project downwards into the rock salt often creating a network of interconnected openings. These fractures are clearly in relationship with the gypsum heaps that are also aligned according to prevailing tectonic directions. In an area extending some tens of meters from the gypsum heaps the salt crusts are also broken in separate slabs with the edges between slabs welded together, thus forming an impervious blanket. The sides of these slabs are distorted because of continuous small lateral and vertical movements, and in the first meter of thickness they often show hollows subparallel to the surface. Both vertical fractures and hollows are interconnected composing a network of voids, often partially filled with fine-grained aeolian sediments. Most probably this network of interconnected voids and fractures partially filled with fine sediments that make up the ideal environment for the formation of the rims and blisters on the surface (Fig. 7).

Another very important factor is the extreme climate of Atacama, with a very high temperature range between day and night, that may exceed 30°C (Sesiano 2006). Conversely, the temperature inside the network of subterranean voids is more or less stable because of the poor connection with the atmosphere through small holes and the insulating capacity of the salt. During the day (Fig. 8A) the outside temperature is much higher than the temperature inside the network inhibiting exchange between the two air masses because of the density stratification. During the night this situation reverses, with the air mass inside the rock salt much warmer and lighter than the outside air, creating an upward airflow (Fig. 8B). For rims to develop there has to be enough humidity in the air mass of the subterranean network to dissolve the rock salt in the cavities and deposit salt around the outlet.

The humidity of the air masses inside the fractures and voids may partially come from occasional rainfall, although Atacama is known to be one of the driest areas of the world. Average rainfall was 0.4 mm y^{-1} in the period 1996–2004 at San Pedro de Atacama, and 2.7 mm y^{-1} in the period 1904–2001 at the coastal city of Antofagasta (Sesiano 2006). Very probably condensation plays an important role in the hydrology of this desert area, and may provide most of the humidity in the subsurface voids at least in some periods of the year, as has been demonstrated in other arid karst regions (Calaforra et al. 1993). The fine-grained sediments accumulated in the subsurface cavities could hold most of the accumulated humidity and release it gradually in order to maintain the rim growth process constant and for a long enough time span.

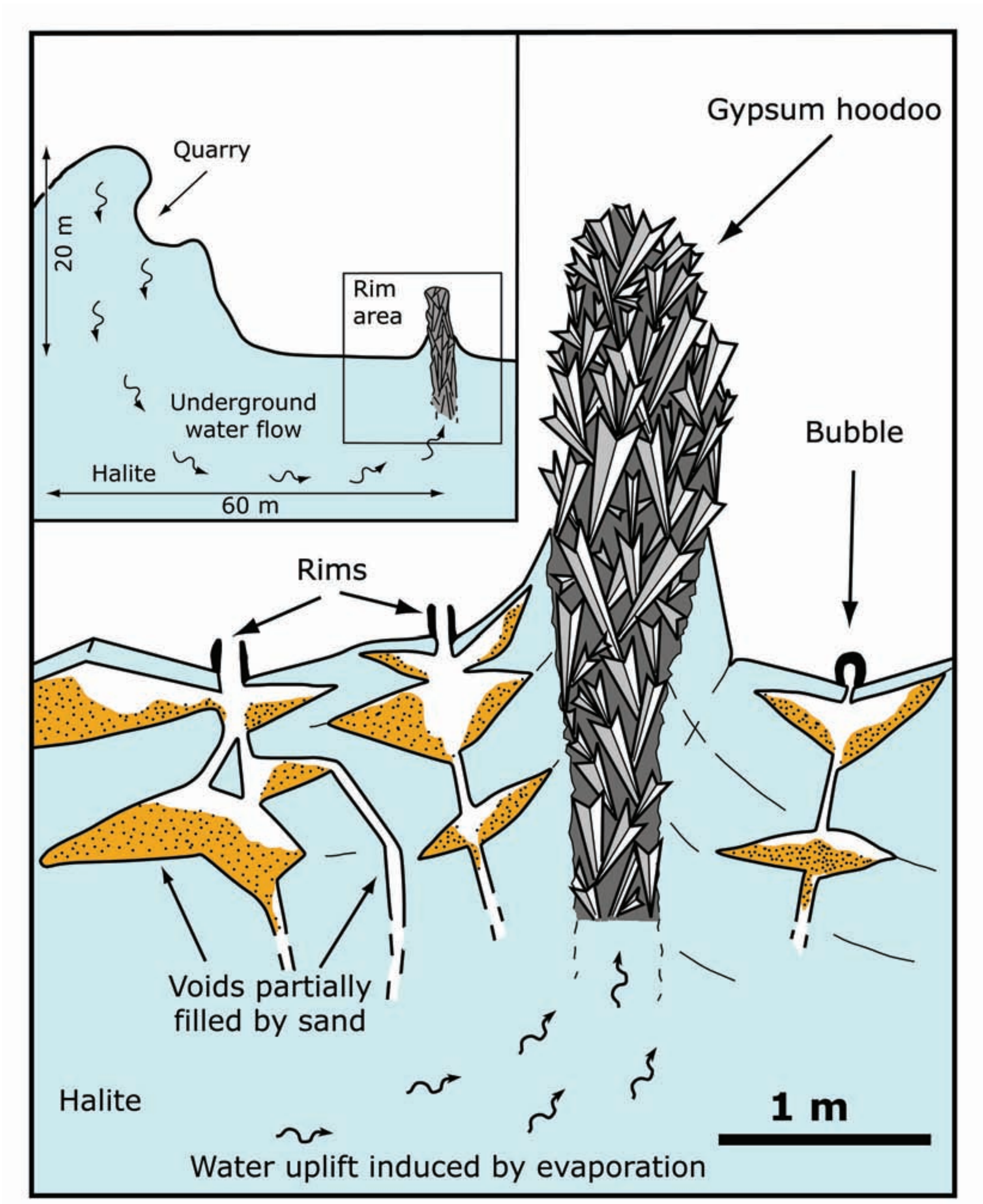

Fig. 7. Cartoon showing the physical environment in which rims and blisters develop in the Cordillera de la Sal of Atacama.

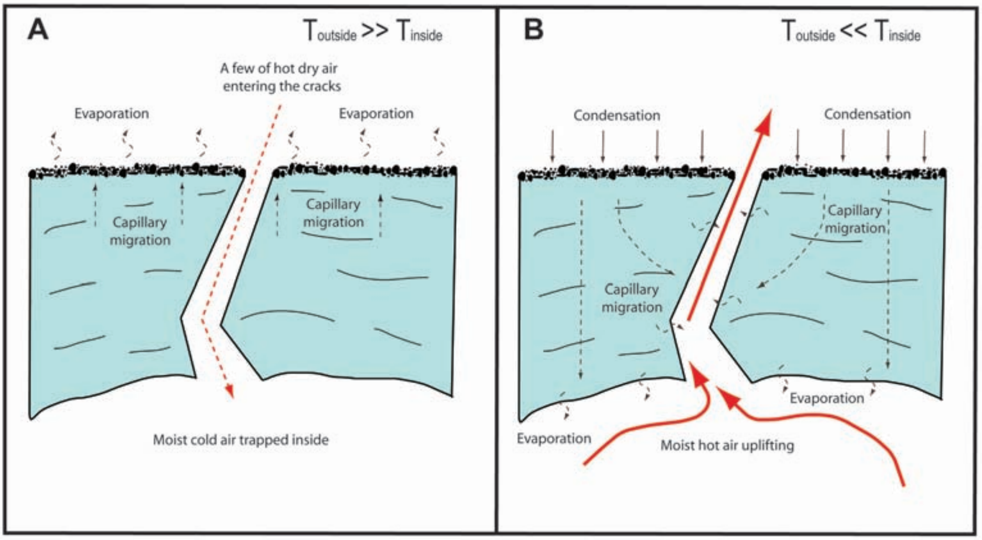

Fig. 8. Conditions for rim development in the Atacama desert: A. During the day air current is weak and directed downwards; B. During the night air current is important and directed upwards.

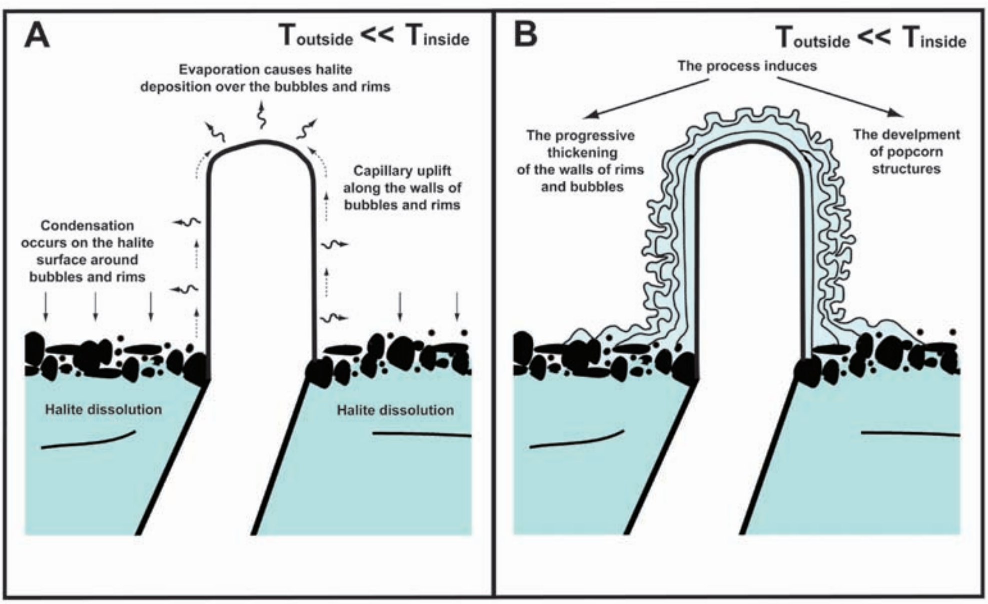

Fig. 9. Blister wall thickening due to condensation-evaporation processes occurring when outside temperature is much lower than temperature inside the subterranean voids partially filled with sediments.

These mechanisms explain the genesis of the Atacama salt rims and blisters but do not yet explain the fact that they are composed of thick crusts with an external irregular surface covered with popcorn-like forms. The condensation that participates in the formation of the rims and blisters is the only possible mechanism that is able to make the walls of these forms much thicker than the similar speleothems. During the night the condensation water deposits on the entire external surface of the salt crusts and is able to dissolve part of the salt. The water condensed close to rims and blisters can rise by capillary forces ultimately generating salt precipitates by evaporation and making the crusts gradually thicker (Fig. 9). The popcorn like deposits that decorate the rims and blisters are typical of evaporation processes (Hill & Forti 1997).

The water rise by capillary forces is demonstrated by the fact that close to the rims some stainless steel pegs fixed on a vertical wall in the rock salt for the purpose of denudation measurements with the micro erosion meter, were covered with a millimetre-sized crust of newly deposited salt (De Waele et al. 2009) (Fig. 10).

The effect of condensation on the salt rims and blisters is not always constructive through the thickening of the walls, but can also lead to the destruction of blisters and

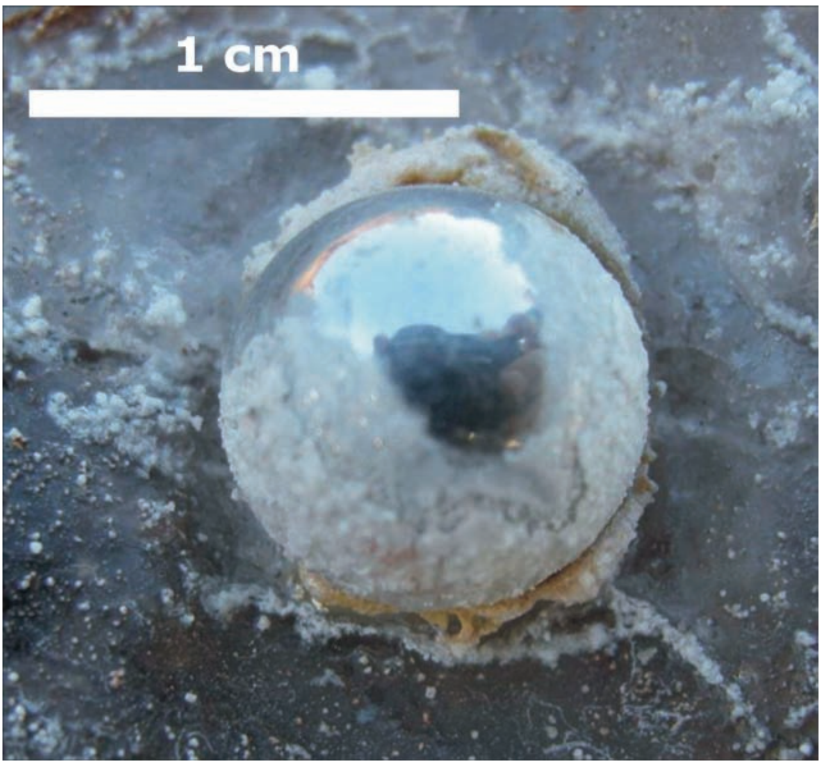

Fig. 10. Stainless steel peg (support of a MEM station) with white crust of salt deposited by condensation processes between October 2007 and March 2008.

their transformation back into rims. This happens when the amount of water that condenses on top of the blister exceeds the water that evaporates. This condensation water dissolves part of the salt on the upper part of the rim or blister and, before it evaporates, is driven by gravity towards lower parts where dissolved salt may precipitate giving rise to the growth of fibrous salt crystals (Fig. 12A). These fragile fibrous crystals never occupy the entire inner space of the rim since their tips are dissolved where the rising air current passes. The condensation-corrosion process gradually leads to the thinning of the upper part and can, in some cases, lead to the opening of a blister that is thus transformed into a rim.

More often dissolution is caused by direct rainfall that is rarely important enough to enable the total destruction of the forms, but is responsible for the changes observed in blisters over a period of a couple of months (Fig 11), including its transformation into rims. Poor rainfall is also responsible for the recharge of the sediment-filled fractures and voids and allows the process of rim and blister formation to start again, with a further vertical growth of the rims and the reopening, because of condensation-dissolution of their summits, of the blisters, thus transforming blisters into rims (Fig. 12B).

The complete destruction of the forms with the reset of initial conditions happens only in occasion of heavy thunderstorms. The process will restart again as soon as arid conditions are restored, especially because the sediment hosted in the subsurface voids will release the stored water again. Based on the available meteorological data it seems reasonable to believe that blisters and rims of the Cordillera de la Sal may reach ages of 20 years at most, depending on where heavy rainfall comes down.

Figure 13 reports the main processes and factors that influence the development and evolution of salt blisters and rims at Atacama.

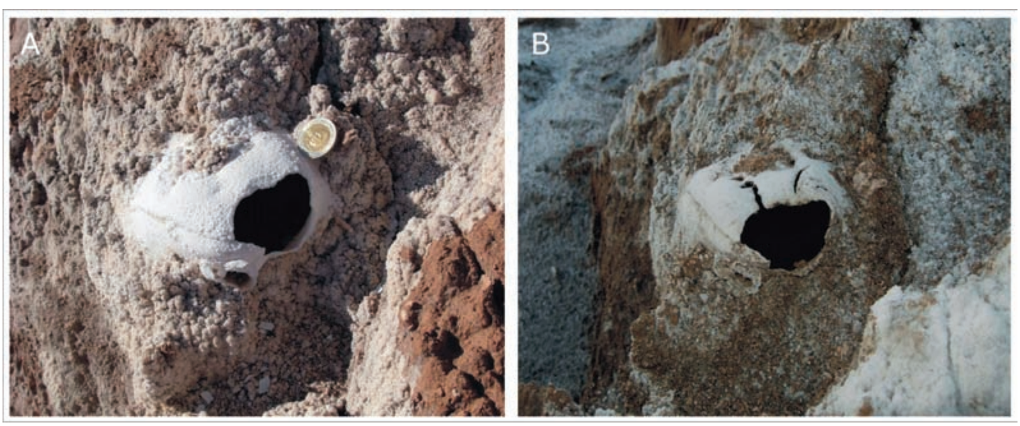

Fig. 11. Morphological changes in one of the greater salt rims on the flank of a gypsum heap. A. October 2007; B. March 2008.

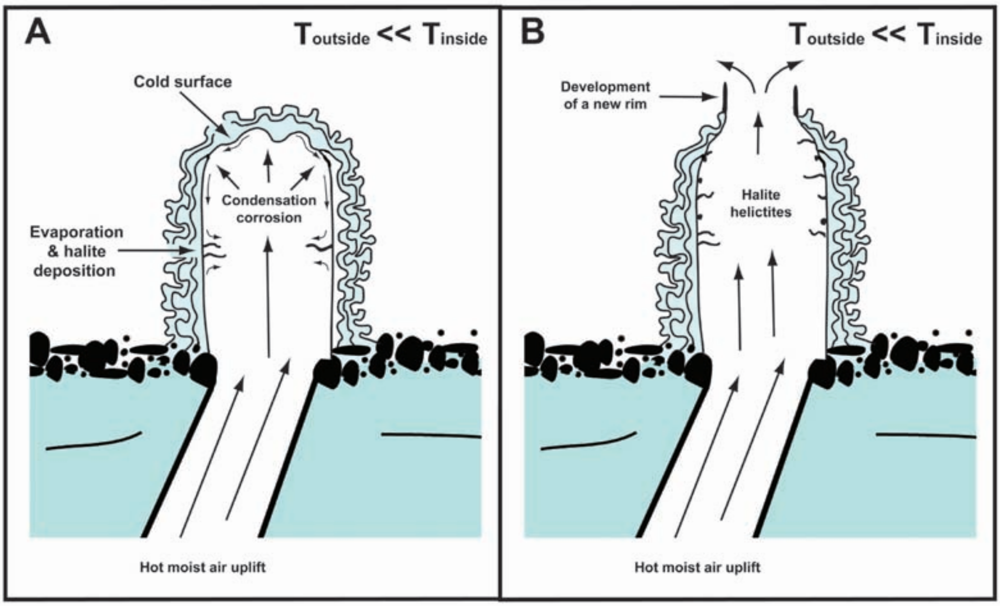

Fig. 12. Transformation of a blister into a rim.

Conclusions

Salt blisters and rims are centimetre-scale formations that develop in very peculiar situations on the salt crust of the Atacama Desert. These formations are located in small areas close to gypsum heaps. Their genesis is related to condensation-evaporation processes occurring at small orifices at the contact between the salt surface and the atmosphere during periods immediately after small rain events. Humidity is stored in fine airborne sediments hosted in a subcutaneous network of voids and fractures in which air circulation is driven by density differences between underground and external air masses. Subcutaneous aerosols and sprays saturated with respect to salt are released when outside temperature drops (during the night) and halite is deposited along the borders of the orifices. This leads to the formation of a salt rim, similar to the rims known from caves, and when airflow decreases gradually the rims can transform into closed structures (salt blisters) thus temporarily stopping the process. Rain events and further condensation can partially dissolve the summits of these structures transforming blisters into rims again, reactivating the process.

These small formations can change their shape in a few days or hours, and their survival depends on the rainfall pattern. Important rain events, occurring once every ten years or so, will eventually completely dissolve the rims and blisters, but recharge the subcutaneous network with water again, thus reactivating the whole process.

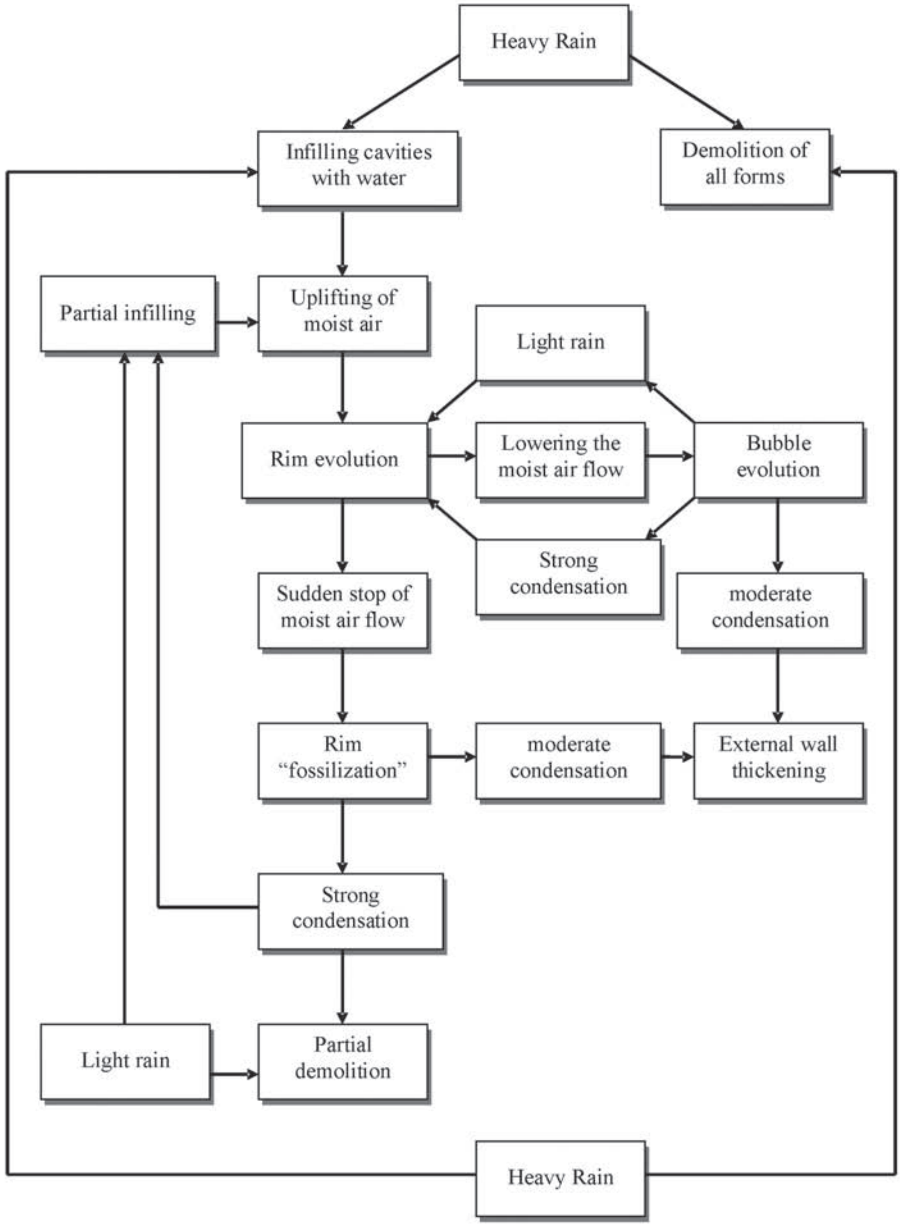

Fig. 13. Factors controlling the evolution of the salt rims and blisters.

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