Nature Around the ALMA Site – Part 1

Michel Grenon
(Geneva Observatory, Switzerland)

The natural environment around the ALMA site, its flora, fauna and landscape morphology, are presented and interpreted in terms of combined geological and climatic evolution with, in parallel, the necessary biological adaptions.

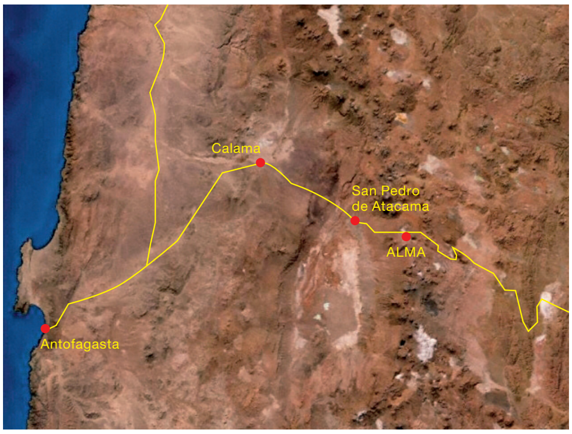

Figure 1: ALMA is located inside the high volcanic range in the Central Andes, east of San Pedro de Atacama, close to the road to Argentina through the Jama Pass.

The ALMA site morphology results from the long-term evolution of the Andes, governed by plate tectonics. The associated volcanic activity, the climate evolution and oscillations, the erosion by ice, water and wind, are factors which converge to build up the exceptional landscape as we may observe it now, adequate to host the ALMA installations.

The present-day vegetation pattern and composition, the plant adaptations to various, and often extreme, conditions, and the local fauna, are testimonies and, by the way, key indicators of the complex past history of this singular site. After a summary of the geological history of the area, representative examples of life adaptations around the site will be given, mainly in the field of geobotany which is by far the most sensitive approach, having the highest spatial resolution to reveal tiny macro- and microclimatic effects.

The local altiplano history

A striking feature of the landscape at ALMA is the presence of a nearly flat surface, made of pale yellow to pink material, culminating at about 5 100 m, capped with several volcanic cones and structures, reddish to black, depending on their origin, age and chemistry.

These structures are direct consequences of the peculiar volcanic activity prevailing in the Central Andes. The whole area is being uplifted due to the compression by two tectonic plates, a continental one, the South-American plate, moving westwards, a distant response to the slow opening of the South Atlantic Ocean, and an oceanic one, at the west, the Nazca plate, moving towards South America at the highest known velocity in tectonics 10.4 cm/yr. The Nazca plate is subducted in the Pacific trench, about 80–100 km west of the Atacama coast, with a depth of 8 064 m in front of Antofagasta. The subducted material, oceanic crust and sediments, travels along an inclined plane. It is metamorphosed when the partial melting point is reached, at a depth of about 200 km. Carbonates turn into silicates, CO_2 is restored to the atmosphere through volcanos, together with other volatiles as H_2O, SO_2 and salts such as NaCl, plus rarer ones involving Lithium and Boron.

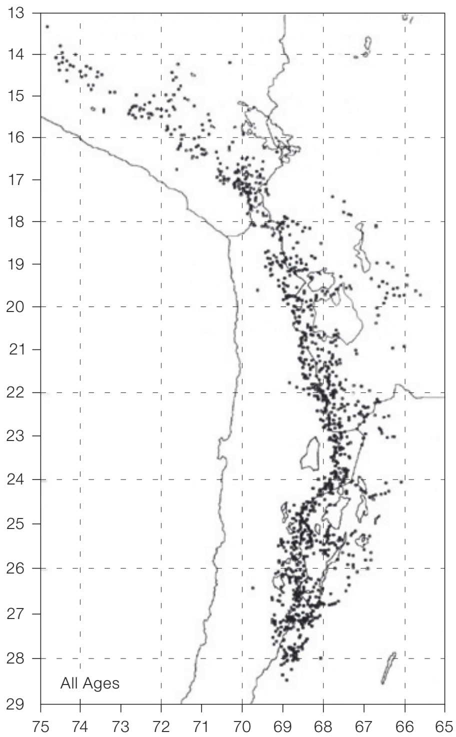

Figure 2: The distribution of 1113 late Tertiary and Quaternary volcanoes in the Andes. The distance between the volcanoes and the coast is maximum at the Chajnantor latitude (23S) (from de Silva and Francis 1991).

Lavas emitted in this context, the andesitic basalts, are richer in SiO_2 than those issued directly from the Earth's mantle, such as the Galapagos or Hawaiian lavas. A higher content in SiO_2 dramatically increases the lava viscosity, leading to a very explosive volcanism. The Lascar volcano, about 40 km south-east of the ALMA site, is a well-known example of such behaviour.

The volcanic activity is impressive with 1113 volcanoes active or extinct between latitudes 14S to 28S, as counted from Landsat satellite images (Figure 2). The amount of emitted material has been enormous, raising the Andes to very high altitudes (the altitude difference between the Pacific trench and the Cerro Llullaillaco volcano is no less than 14.8 km!).

The Central Andes area, at ALMA latitude, is characterised by major silicic volcanic systems, at the origin of paroxysmal explosions in the past. The injection of pyroclastic material, as incandescent ash clouds, up to the stratosphere is followed by its deposit on the ground, filling all landscape depressions such as valleys or even gorges. If close enough to the emission centre, ashes are hot enough (above 600 °C) to glue as a compact rock, the tuff, also called ignimbrite.

Ignimbrite deposits constitute the flat basement of the ALMA site. Around ALMA, major emission centres are Cerro Pastos Grandes, Cerro Guacha and La Pacana.

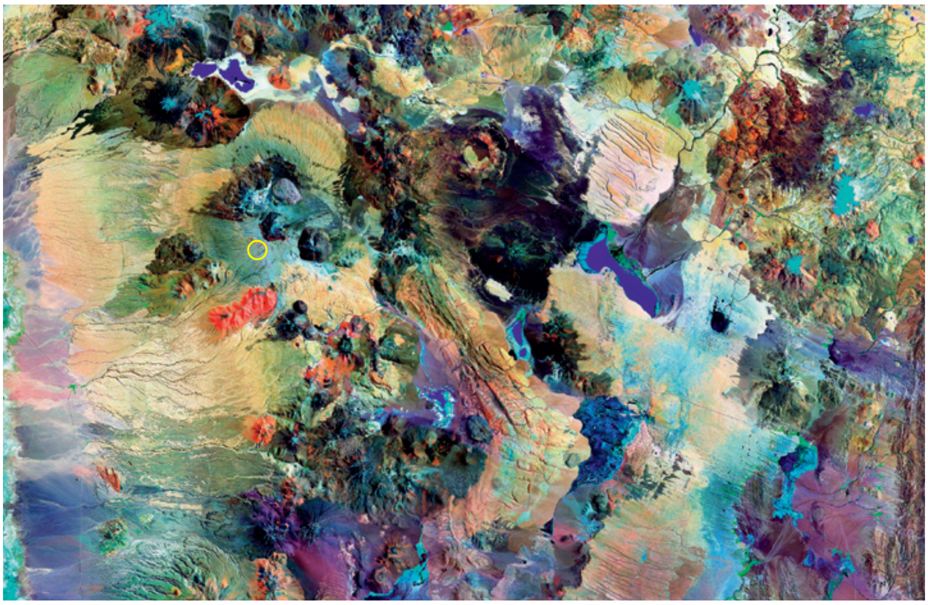

Figure 3: Satellite image showing the area around ALMA (yellow circle). Surfaces covered by ignimbrites are yellowish. Fresh lava is brown to black. Hills with hydrothermal alteration appear orange-red because of the presence of iron oxydes. Alluvions are grey, turning to bluish, pink or purple depending on the amount of Mn and Fe in minerals. Snow appears as turquoise, as does the salt in the Atacama Salar (left side). Some volcanic structures are very recent, such as the Licancabur, 5916 m, close to the twin Laguna Verde, capped with snow (upper left corner), showing recent fluid lava flows over the ignimbrite. In the image centre lies the faulted zone of the Cerro La Pacana caldera (Landsat, S-19-20 2000).

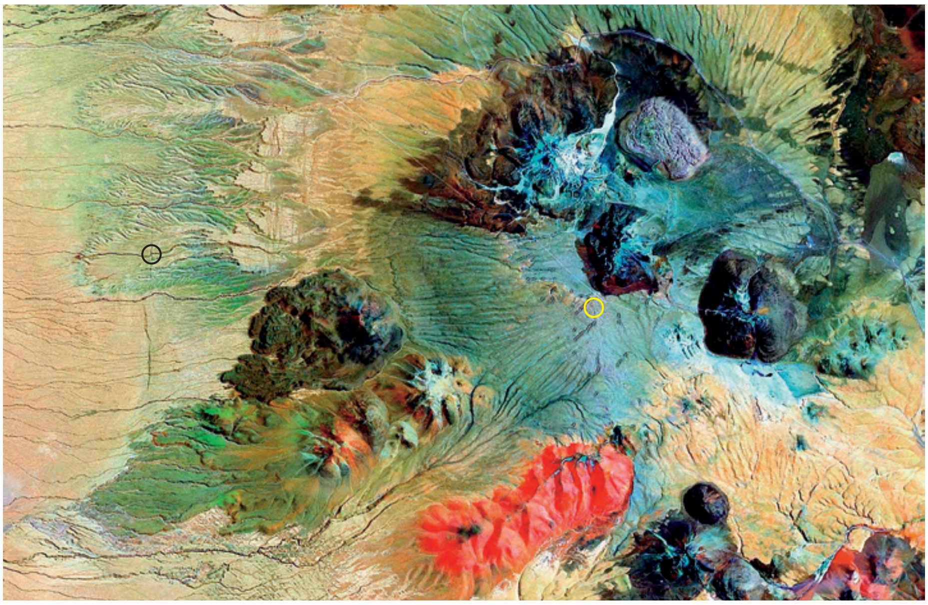

Figure 4: The ALMA site is located on an ignimbritic dome, the Purico ignimbrite. The crested edge of terraces at the upper left corner marks the limit between two consecutive deposit layers. ALMA is surrounded by a wide variety of volcanic structures. Immediately N and E of ALMA, two young volcanoes, made of black and viscous lava, show flow ridges (ogives) rapidly solidified. The grey structure to the north is a silicic dome, with a wavy 'elephant skin' texture, the terrestrial counterpart of the 'pancakes' discovered on Venus. North of ALMA, the old volcano Toco Toco shows whitish flows due to sulfur exploitation around the summit. To the south, in red, are hills with soil alteration by hydrothermal circulation. Thin NS lines to the west reveal a network of tectonic faults. One of them has recently shifted a river bed (black circle), an indication that deformations are still going on. (Landsat, S-19-20 2000).

Plinean eruptions occur when a volcanic system is mature, i.e. reaching an altitude above the ground level such that the next magmatic rising will be unable to find its path across the cone. Tensions accumulate until the whole structure explodes, cutting at minimum the upper part of the volcano. Truncated volcanoes are locally named *Descabezado*, the decapitated. When the magmatic chamber shrinks, it leaves an ellipsoidal depression, a caldera. Calderas around ALMA are among the largest in the world. La Pacana caldera, immediately East of ALMA, has an extent of 70 × 35 km, with ejecta covering about 17000 square km. The volume emitted in the last 5.6 Myr is about 3000 km^3.

The last Ice Age and after

During the last Ice Age, the Würm, the climate was altered not only at high latitudes, but also in the intertropical zone. In the Atacama, the alternation of a warm and dry climate during the interglacial episodes, such as the present one, with a colder and more humid climate, as during the glaciations, started at the Lower Pleistocene epoch, about 2.4 Myr ago. The present climate on the Chilean side of the Andes is characterised by an extreme aridity, nearly the most extreme reached up to the present.

During the last glacial maximum, about 22000 Before Present (BP), precipitations around ALMA were more intense by at least a factor of two. The increased cloudiness, combined with a fall of temperature by 6–7 °C, allowed a significant extension of the local glaciers. In the El Tatio area, NW of ALMA, most summits were ice covered with glacial tongues going down to 4300–4200 m. The volcanoes, not active since the ice retreat, show conspicuous glacial features as lateral and front moraines (Figure 5). The snowline was lowered by about 1000 m, as in parallel the altitude of the vegetation belts. Today's high mountain plants could have expanded over wide areas, forming nearly continuous populations. Now, all of that zone, including that of the high Cerro Llullaillaco (6739 m), is totally devoid of ice.

Nowadays, volcanic spring waters and meteoric waters accumulate in closed depressions. Waters are saturated in salts, crystallising on the shores and at the bottom of the so-called *salares*. The residual lake sizes are self-regulated, a result of a balance between water accumulation and evaporation. During Ice Ages, the water supply was sufficient to fill nearly all basins with fresh water and salts emitted by the volcanoes were removed continuously by the rivers.

The precipitation regime

The ALMA climate is quite distinct from that of the coast where precipitation occurs mainly during the southern winter, in phase with, or just preceding major El Niño events. The occurrence of rainfall is irregular; rains are separated by long-duration droughts reaching typically 5–8–12 years, thus the scarce vegetation, if any, has to develop highly specialised adaptations.

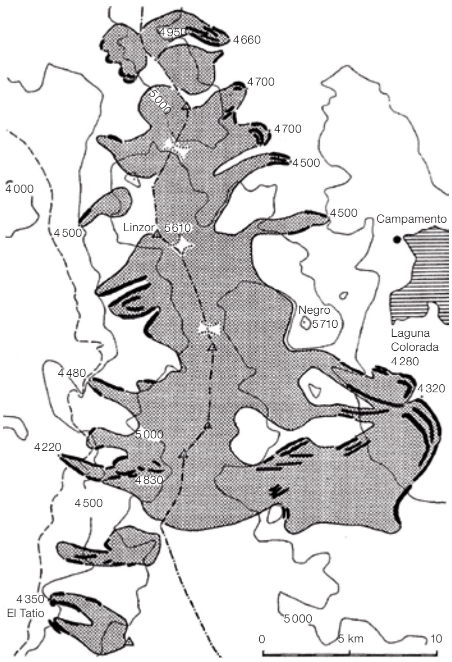

Figure 5: At the maximum extent of the Würm glaciation, 22000 years ago, all areas in grey were covered by ice. The old front and lateral moraines (thick lines) are still conspicuous in the landscape (from Graf 1991).

Around ALMA, precipitation is much more regular, in phase with the Bolivian winter, with an interannual variability not exceeding ~ 65 %. The amount of precipitation depends strongly on the local landscape morphology. The compact mountain ranges extending NS and reaching nearly 6000 m such as the Linzor (5610 m)-Sairecabur (5971 m) range, NW of ALMA, and the Miñiques (5913 m) range S of ALMA, act as barriers and convection centres, where the humid air pumped over the Pacific as a sea breeze, heated over the Atacama desert, reaches the dew point at about 6100 m. The resulting thunderstorm activity produces fine grain hail in amounts sufficient to cover the whole landscape, as shown in Figure 7. Due to the very low air humidity and temperature in the morning, the hail turns into vapour, the sublimation process leaving little liquid water to moisten the soil and plants.

On the west side of the Andes, the amount of precipitation increases quadratically with altitude: 10 mm/year at 2100 m, 50 at 3300 m, 200 at 4300 m, 350 at 5000 m. On the contrary, the evapotranspiration – the water layer evap-

Figure 6: Laguna Leija, south of ALMA, with the Lascar volcano (5641 m) at left and Aguas Calientes (5924 m) at the centre, is a typical example of an altitude lake saturated by salts of volcanic origin. Its brackish waters host one of the highest colonies of Chilean flamingos. By the end of the afternoon, strong SW winds form balls of foam, rolling over the waves, up to the shore (Source, see footnote).

Figure 7: The road to ALMA after a thunderstorm in mid-December 1993. At left, the Licancabur (5930 m), at right the Juriques (5704 m).

Note: all pictures are from the author, except where specifically indicated.

orated per year from a surface maintained at 100% humidity – decreases with altitude, e.g. from 2200 mm/year at 3000 m, to 1400 mm at 5000 m. In all cases, the water deficit is huge.

The high evapotranspiration rate is due to very high insolation, low air humidity and moderate to high wind velocity. The combination of precipitation and transpiration effects leads to an increase of biodiversity with altitude, from the Atacama Salar level up to 3500–4000 m, where the maximum richness is observed (~ 45 different plant species), followed by a slow decline down to zero around 5000–5100 m, the local vegetation limit. Above 5350 m, the soil is permanently frozen to 50 cm depth.

Winter storms provoke snowfalls lasting several days. Strong winds associated with the transit of cold air masses may accumulate snow in ground depressions and at the lee side of mountain crests. Through melting-freezing cycles, the snow hardens and forms compact *névés* with a uniform surface. During spring, thanks to an erosion/sublimation process by the wind and the solar radiation, the surface becomes wavy, showing depressions like bowls. The dust brought by the wind accumulates in the depressions. Around the summer solstice, the solar radiation is maximum: the dust absorbs the radiation more efficiently than the crests and the snow sublimates faster in the holes. In deep holes, the higher water vapour pressure allows melting, whereas on the crests the sublimation alone is active. Since sublimation requires eight times more energy than melting, daily snow losses are eight times larger in the holes which deepen and finally reach the dark ground as shown in Figure 9, leaving a field of ice blades, the so-called 'Ice Penitents' or 'White Penitents' in memory of the 'White Penitents' procession during Holy Week, prior to Easter. From sunrise to sunset, solar rays draw an inclined plane aligned East-West, pointing to the Sun position at noon. The crest shadow prevents the sublimation of the adjacent ice in the EW direction, the alignment direction of penitents. At Chajnantor at the summer solstice, the Sun is close to the zenith at noon, penitents are thus vertical. Around Ojos del Salado, east of Copiapo, the penitent inclination towards the North reaches about four degrees. Penitents may be used as a natural compass providing the latitude of the site in addition to the EW direction.

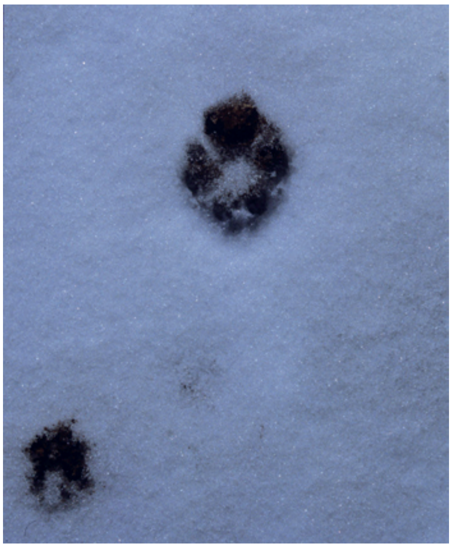

Figure 8: Hail may reveal the most discrete wild life presence, such as the puma footprint on the way to ALMA, NW of Cerro Toco-Toco.

The wind and temperature regimes

The ALMA area is under the influence of two wind regimes: an upper wind, blowing continuously from the west, above 4500 m during the night and 5200–5500 m during the day. This zonal circulation is driven by the South-East Pacific anticyclone, fed by high altitude air brought by the Hadley circulation from the intertropical convergence zone (ITCZ). This air, travelling at the lower limit of the stratosphere, is nearly free from water vapour and aerosol particles.

During the day, a convective boundary layer, driven by the intense solar radiation on the west flank of the Andes, travels across the Atacama desert, in a NE direction. Its thickness increases from about 600 m east of the Coastal Cordillera, to 1.5 km above the Atacama Salar. This anabatic wind (blowing uphill) reaches its maximum velocity, about 12 m/s at 5800 m, in late afternoon and stops around 10 p.m. in summer. The relative humidity follows a similar pattern and peaks between 7 and 8 p.m. at about 70% at 5800 m and 100% at 6200 m.

Because of the very low vapour content above 5000 m, and of the reduction of the column density of CO_2 by a factor of two at 5200 m, the greenhouse effect is extremly low by night at high altitude. The ground surface cools down rapidly through unblocked radiation towards space. At Sairecabur (5820 m), at ground level, the temperature may reach +40 °C in the early afternoon, fall below freezing point around 4 p.m. and reach –15 °C before midnight. The thermal amplitude at the ground surface is huge, 39 °C in July, 52 °C in January (Schmidt 1999). Such amplitudes put enormous stress on the vegetation, which has to develop highly specialised strategies to survive. If we notice that the yearly 0 °C isotherm is located at 4850 m, we can easily understand that very few species may develop above 5000 m outside well-protected biotopes.

During the night, the air layer in contact with the ground, which is colder and denser, flows down by gravity, giving birth to a katabatic wind (blowing downhill), a land breeze, blowing towards the SW until about 8 a.m. when the solar heating restarts the convection.

West winds, zonal and anabatic, fall as cascades on the east flank of the mountains immediately at the back of the ALMA site. The air compression lowers the relative humidity and provides an extraordinary dessicating power to this Föhn-like wind (Figure 11).

References

Graf K. 1991, Bamberger Geographische Schriften, Band 11, 139
de Silva S. L. and Francis P. W. 1991, Volcanoes of the Central Andes, Springer-Verlag
Schmidt D. 1999, Dresdener Geographische Beiträge, Heft 4, 1

Part 2 of this article, on flora, fauna and animal life in the ALMA area, will appear in the next issue of *The Messenger*.

Figure 9: Field of white penitents at 4500 m above Laguna Verde, east of Copiapo, in December 1992.

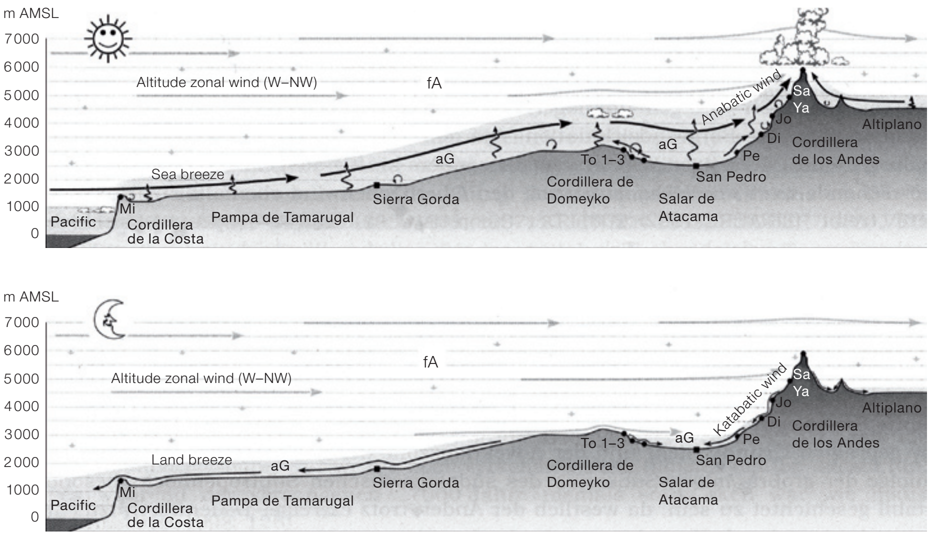

Figure 10: The air motions in the lower troposphere at the ALMA latitude. The sea breeze (day) and the land breeze (night) develop under an altitude zonal wind, blowing from the west. Above massive mountain ranges, the boundary layer associated with the sea breeze forms convective clouds, leading to thunderstorm activity in summer. In between the high mountain ranges, the boundary layer merges with the zonal wind and flows towards the east side of the Andes. During the night, the boundary layer disappears and a slower katabatic wind flows down to the sea, jumping over the Paranal site (from Schmidt 1999).

Figure 11: To the east of ALMA, strong katabatic winds generate ripples, amplified by the vegetation which traps blown soil parcels. A graminaceous herb is the only plant able to survive in this harsh environment, forming vegetal dunes, linear or half-moon shaped.