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A Pendulum of Innovations and Challenges: Technological System and Industrial Heritage of Sulphur Mining in Northern Chile (1887–1993)

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ABSTRACT

Located at the Bolivian border in the Antofagasta region, Ollagüe saw the emergence of industrialisation and capitalist expansion through sulphur mining activities during the 20th century. This article presents both an historical synthesis and the industrial heritage of Ollagüe to show how the innovations in the sulphur mining technological system go hand in hand with the global economic context of the last century. Archaeological industrial heritage is approached here in terms of continuity and ruptures; in other words, as a constant pendulum movement of technological innovations and production challenges.

KEYWORDS
sulphur mining; Chilean industrialisation; aerial ropeway; Ollagüe

Introduction

The aim of this article is to present an historical synthesis of the available information regarding the sulphur industry of Ollagüe, in the Antofagasta region, northern Chile.[1] Ollagüe is a municipality and village situated close to the Bolivian border. It comprises an area of 2,912km^2 and is located at 3,660m above sea level (Figure 1). The Antofagasta region went through important economic changes related to the development of mining exploitation (mainly silver, saltpetre and copper) and to the construction of the railway from Antofagasta to Bolivia in 1873, linking the Pacific port with the Bolivian highland mines.[2] Based on the abandoned sulphur mining camps located in this area, this article seeks to make visible a currently little-known mining activity (sulphur) and to highlight the importance of modern material culture associated with the installation and operation of mining industries in Ollagüe during the 20th century.

Historical sources regarding the sulphur deposits in this area, although abundant, are mostly technical reports produced by engineers and geologists, and were made with the aim of understanding and evaluating geological characteristics and economic potential.[3] Referring to the capitalist motivations behind such accounts, historical sources are generally dispersed and technical in nature. They deal with modes of sulphur production, extraction technology, cost/benefit calculations and exploitation recommendations.[4] These technical reports were either intended to nourish the interests of a Chilean ministry or state department (*eg* the Corporación de Fomento de la Producción, hereinafter CORFO), or those of foreign institutions (*eg* the United States Geological Survey, hereinafter USGS).

By presenting and synthesising in a diachronic and coherent way the body of data from these scattered and mostly technical bibliographic sources, an economic overview is offered, which allows an understanding of the specificities of sulphur exploitation in northern Chile and, particularly, in Ollagüe. In order to draw attention to this specific period and area of mining activities, the geological data that pre-dates the 20th century and that refers to the properties and exploitation of sulphur in other mining regions of Chile are not considered here.[5]

Properties and uses of sulphur: Some generalities

Sulphur is a non-metallic chemical element (S), widely distributed throughout the earth's crust in its native state and in chemical compounds. It can also be recovered from gases, furnaces and the waste of several industries.[6] In the 17th century, there were unclear ideas about the properties of sulphur. Its combustible properties were particularly highlighted, and it was believed that all flammable bodies contained sulphur to some degree. In Diderot and d'Alembert's *Encyclopédie*, it is defined as 'a solid but friable substance of a light yellow when it is pure, highly flammable, and that upon burning expands a bluish flame accompanied by a penetrating and suffocating smell'.[7] The Catholic priest and metallurgist Alvaro Alonso Barba noted that:

> Sulphur is a Mineral the most universally known of any. It is made of an Earthy unctuous substance, and very hot, to that degree, that it is esteemed to be nearest of kin to the Element of fire, of any compounded substance.[8]

The dispersion of sulphur on the planet can be found in two states. The first, natural or elemental, is the most scarce. The state of combination, on the other hand, is the most frequent in nature and is the state in which sulphides and sulphates predominate.[9] Sulphur is obtained from two main sources: it is mined, and it is acquired from natural and industrial gases. Mining sites are related to the extraction of what is commonly called native sulphur. In this state, it is found in two types of deposits, those of sedimentary origin and those of volcanic origin, such as in Ollagüe.[10] In Chile, sulphur deposits are widely dispersed geographically but confined to specific areas of the summits of the high Andes.

Four groups of deposition formations can be distinguished. Sulphur deposition came from reactions between sulphur gases that emanate from volcanic magma. Some deposits are formed by metasomatic replacement. Deposits formed by a combination of these two processes are the most common and are found in all Chile's sulphur-bearing regions. Finally, some deposits are mantles of high-grade molten sulphur. They are formed by an eruption in which the pressure exerted by gases and lava attempting to escape produces heat. The heat of the lava and ashes melts the sulphur, which then runs along the slopes of the volcano. When solidified, this sulphur forms new deposits that are covered by new ash blankets. Such deposits include those of the Aucanquilcha and Santa Rosa volcanoes in the Ollagüe area, which are the focus of this article.[11]

While it has multiple uses (black powder, vulcanisation of rubber, insecticide and fungicide, *etc*), most sulphur is used in the manufacture of sulphuric acid, a powerful water-soluble acid with strong exothermic properties. Sulphuric acid is highly corrosive and can attack metals, salts, as well as organic bodies such as wood, cotton and, of course, meat.[12] It is used in large quantities in metallurgy, in chemical industries, in petroleum refining and in the manufacture of fertilisers, explosives and glucose, among others. Due to these uses, a country's sulphuric acid consumption

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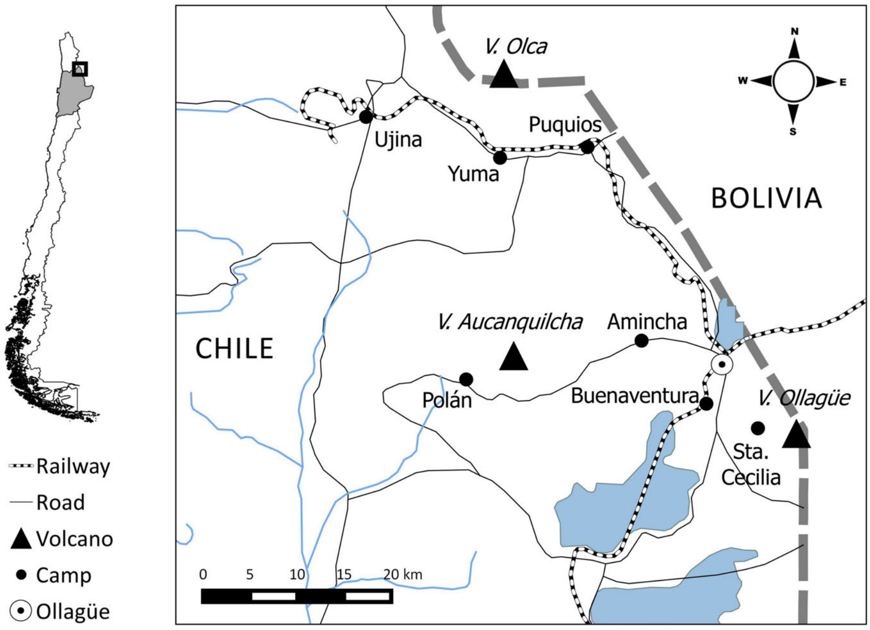

Figure 1. Map of the Ollagüe area. © Proyecto Arqueológico Alto Cielo.

has generally been considered as an informal index of its industrial activity, some even asserting that 'sulphuric acid is the golden key that opened the door of modern industry'.[13]

Production of sulphur in the world

The American engineer Robert Ridgway wrote, in 1930, that almost all the sulphur produced worldwide came from Italy, the United States, Japan, Spain and Chile.[14] Historically, it was the Italian exploitation sites of Sicily that provided most of the sulphur used in the world.[15] However, with the discovery and exploitation of the enormous deposits of elemental sulphur on the coast of the Gulf of Mexico in the United States, as well as with the improvement of the exploitation system conceived by Herman Frasch in 1903, the United States increased their output, which in 1930 represented 85% of world production.

North American sulphur was extracted by means of the Frasch System, which, from the time of its implementation, reduced the costs of extraction. Broadly speaking, this process consists of introducing superheated water to underground sulphur deposits by means of pipes. This water, at a temperature higher than that of sulphur fusion point, melts the sulphur, which is forced up to the surface by pressurised hot air introduced via a concentric tube located inside the pipe. This process yields in a single operation a product of high purity without the costs associated with mining, lowering the cost of sulphur. It is important to note that this transformed the means of production at a global level. A 1954 report by ECLAC (United Nations Economic Commission for Latin America and the Caribbean) stated that:

> The increase in the relative importance of elemental sulphur since the United States began to work large deposits of the salt dome type by the Frasch method is one of the most noteworthy recent developments affecting this substance. The low-cost sulphur obtained in substantial tonnages by this method has flooded the world market. This has provided a considerable spur to consumption. At present so-called Frasch sulphur forms 90 per cent of the world production of elemental sulphur which in turn amounts to 50 per cent of all output.[16]

In short, the world industry was based on the price and availability of sulphur obtained using the Frasch System, which radically transformed the modalities of supply.

Sulphur production in Chile

In Chile, sulphur began to be exploited around 1887, in parallel with the production of saltpetre in the Antofagasta region, as sulphur was necessary for the manufacture of gunpowder needed for the saltpetre mining industry.[17] Santiago Macchiavello states that 'the Indians of Puquintica and other interior regions, before the railroads to Bolivia were built, sold sulphur to the saltpetre works'.[18] However, throughout the end of the 19th century, sulphur production continued unevenly due to price fluctuations on the international market.

In 1903, the engineer Alberto Herrmann, who worked for the National Mining Society (SONAMI), and actively participated in their *Boletín Minero* (Mining Bulletin), published a cardinal book containing the available data for the period. He mentions the importance of the Ollagüe volcanic deposits as well as the production's destination towards the saltpetre camps of the Antofagasta region.[19] For Herrmann, production levels were not yet high enough for export, exploitation therefore focusing only on domestic consumption 'except for very small quantities shipped to Bolivia, Peru and the United States as a sample'.[20]

Almost ten years after Herrmann's work, Carlos Avalos, also a member of the National Mining Society, published a short article in the Society's *Bulletin*. In this text, the author gives an account of the situation of production worldwide, thus evaluating the needs and economic policies that were necessary in the country to allow the full development of the sulphur industry. He wrote:

> We do not participate in the current opinion that affirms that the soil of Chile is privileged by nature, in such a way that our country possesses for that only chapter an exceptional, extraordinary wealth, compared with that of other nations. On the contrary, we believe that our natural riches, exception made of the saltpetre, are of a medium value, and that we will only arrive at a truly outstanding situation by means of work and industry.[21]

For Avalos, a new territory rich in mineral resources was not enough. (It must be underlined that this was in 1912, only 30 years after the end of the war with Peru and Bolivia.) Rather, for the author it was necessary to encourage mining exploitation and the introduction of capital, stressing the need to develop this nascent industry. It is interesting to note that this development of the sulphur industry would increase state interests at a time when the exploitation of sulphur resided essentially with private initiatives financed with State loans.

In the 1920s, US geologist Herbert Officier argued that Chilean deposits could compete successfully with the sulphur exploitation of the coasts of the Gulf of Mexico, on the condition of them being conveniently funded to provide the industry with the facilities and administrations appropriate for the challenge.[22] In 1934, the *Boletín*

Minero reported that most of the production (12,000–16,000 tonnes per year) was used in the country and that only a small balance was exported, almost entirely to Great Britain.[23] In order to increase international competitiveness and reduce costs, three essential aspects for the sulphur industry of Ollagüe were to be considered: improving the exploitation system, modernising and changing the transport system (from trucks to aerial ropeways) and improving the refining system.[24] Likewise, the falls in sulphur production have to do with the crises that arose in the saltpetre industry in 1920–1, in 1924–6 and in 1931–2, the latter being the most intense.[25] The excessive dependence on external market fluctuations and the absence of adequate technology to reduce production costs characterised the Chilean sulphur industry at that time.

In the second half of the 1940s, production remained at an average of 12,500 tonnes per year, an amount that corresponds to domestic consumption. Due to a world production deficit, exports began to grow in 1950. During that decade, Chilean production reached an average of about 32,000 tonnes per year. However, despite favourable numbers, the ECLAC economic reports stated that 'the fall in prices in 1953 halted exports and forced the closure of part of the mines'.[26] For the experts of the time, the sulphur production industry, privileged by its natural abundance in the territory, was constantly fighting against the lack of capital, the absence of good means of transportation, the lack of technology and of adequate and modern facilities. For this reason, in its Economic Report of 1953, ECLAC stated that:

> [i]n order to solve temporarily the crisis of the sulphur industry, the government is studying the possibility of granting a special exchange rate that favours exports. For their part, the companies are striving to reduce production costs through greater mechanisation of work and the introduction of new methods of profit.[27]

Figure 2 shows the annual quantities produced from 1887 to 1993. It is interesting to note, first, the increase in production in 1916, which is related to the beginnings of copper exploitation in the mining centre of Chuquicamata (Chile's main mining centre) and, second, the decrease in production observed in 1931. The latter decline was not caused by the exhaustion of sulphur reserves, but by the lack of capital needed to maintain production and to compete with the United States' sulphur production. This challenge is recurrent throughout the 20th century. Likewise, two large increases in production are observed in the early 1970s, followed by a dramatic fall in 1973, due to the *coup d'état* of dictator Augusto Pinochet and the subsequent breakdown of mining work. At the beginning of the following decade, production regained its vitality, but gradually declined during the following years. In 1992, the Amincha plant, the last active sulphur centre, finally ceased its operations. From 1993 onwards, native sulphur exploitation in Chile has been non-existent, although it is still produced as sulphuric acid or as a derivative of other geochemical processes.

Import, export and consumption

Chilean sulphur exports began slowly, in 1901, with a significant increase in 1917, probably driven by global raw material demands arising from the economic crisis generated by the First World War (Figure 3). However, the sulphur produced in Chile could not be exported to European markets, due to the scarcity and cost of transportation.[28] On the other hand, this beginning and later increase to almost double in 1918 is observed in relation to the abrupt drop in imports. The same phenomenon has been observed in the 1930s, with a notable increase in exports and a drop to almost zero import levels. Exports suffered a new decline, which can be attributed to the economic crisis of 1929.[29]

Due to this crisis, Chilean mining exports collapsed from 1930 onwards. The mining production index, 'set at 100 in 1929, dropped to 26.2 in 1932, without ever recovering its 1929 value in the next two decades'.[30] One of the causes has to do with the devaluation of the dollar, which in 1933 put the sulphur produced in the United States in a more favourable situation in world markets. This was an economic strategy with respect to its European competitors, especially the Italians, who were severely affected by the low prices resulting from the fall of the dollar. Santiago Macchiavello tells how, in August 1933, Italian producers invited Americans to a conference in Paris to seek an agreement to raise the world price of sulphur. However, 'the Americans did not accept the proposal, because they considered that a high price would lead to the promotion of the pyrites industry'.[31] The economic war for the control of the world's sulphur market between the two largest producers, the United States and Italy, was declared.

Ollagüe's sulphur industry

In the 17th century, in his famous work *Historia del Nuevo Mundo*, the Spanish Jesuit priest Bernabé Cobo noted the presence of sulphur in Peru's volcanoes:

> The abundance of sulphur is very great in all the Indies […] not only in the volcanoes that launch fire, but in innumerable minerals […] A kind of sulphur stone is stirred up with earth, which has to be benefited to purify it; and other mines there are like this, of whole hills, so pure and stony, that there is no need to make it any benefit; and this second one is of colour of gold very shining and almost transparent.[32]

The author also emphasised the uses of sulphur made by the indigenous communities for the care of their herds of llamas, as well as the use that the Spaniards themselves made of it, referring to the

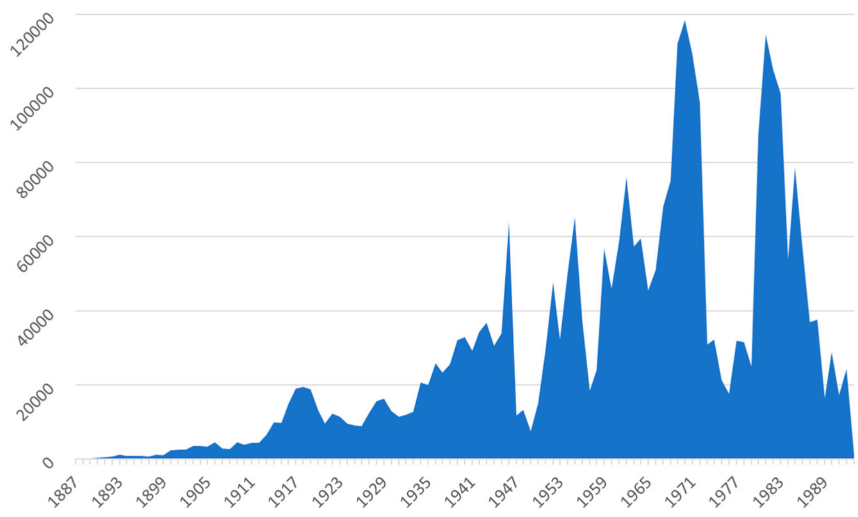

Figure 2. Sulphur production in Chile (tonnes) between 1887 and 1993 (based on Chilean and foreign yearly economic reports). © Proyecto Arqueológico Alto Cielo.

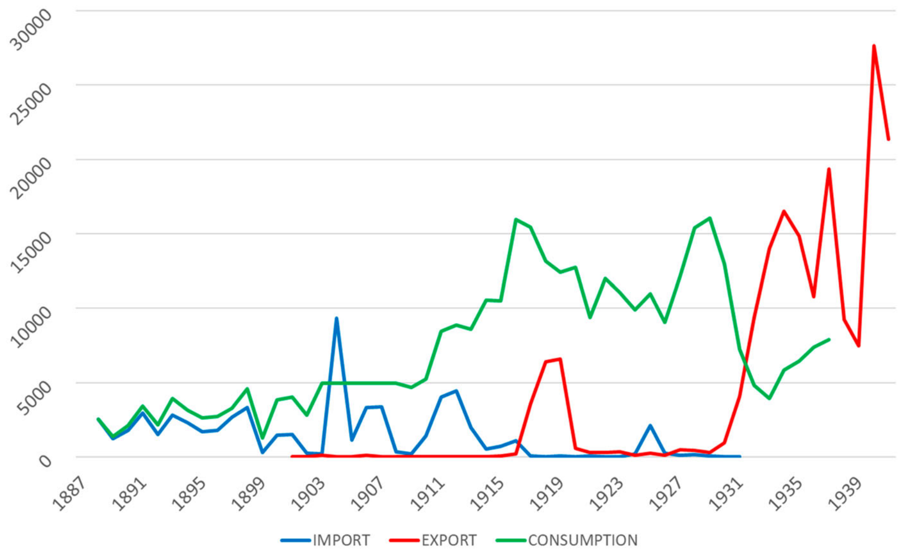

Figure 3. Import, export and consumption of sulphur in Chile (tonnes) between 1887 and 1941 (based on Chilean and foreign yearly economic reports). © Proyecto Arqueológico Alto Cielo.

knowledge that they had brought from Europe, and reproduced in the Americas.[33] At the same period, Alvaro Alonso Barba mentioned the presence of sulphur in the regions of Lípez in Bolivia, and in the current regions of northern Chile (Arica-Parinacota and Tarapacá).[34]

In the 19th century, in his famous voyage through the Atacama Desert, the German scientist Rodolfo Philippi reported on sulphur deposits on the summits of the Llullaillaco volcano in the Antofagasta region. Although his expedition did not reach the Ollagüe highlands, his descriptions of the current regions of Antofagasta and Atacama are notable for their descriptive and comparative value so characteristic of 19th-century scientific expeditions.[35]

Despite these earlier descriptions of explorers and travellers, it was only in the 1920s that Herbert Officier first calculated the sulphur reserves of the northern districts of Chile. For the author, the district of Ollagüe had smaller sulphur deposits than other parts of the Andes, that is, Tacora, but with a much better grade mineral.[36] In the Ollagüe mining district there are three large zones for which there is abundant geomorphological information: the Aucanquilcha, Polán and Ollagüe volcanoes. Officier described the deposits of the latter:

> The area of the sulphur-bearing ground is about forty-two acres [17ha]. The hillside is steep, averaging about 35 deg. The deposit is overlain by from two to six metres of overburden, but this does not interfere seriously with mining. The sulphur beds conform to the slope of the hill. The thickness of the bed is from one to three meters, and the average grade probably around 75 per cent.[37]

In 1913, Juan Carrasco began mining operations in what would become the famous sulphur exploitation of the Aucanquilcha volcano (Figure 4), also building in the Ollagüe village the first autoclave, a technology hitherto unknown in Chile. Later, in 1933, the Sociedad Industrial Azufrera Minera (SIAM Carrasco) was founded.[38] In this period, one of the most notable catalysts for the development of the sulphur mining industry was the construction of two refineries, one in the camp of Amincha (Figure 5) and another in the town of Ollagüe (Figure 6).

These new refineries were built to counter the negative effects of a decrease in the ore grade, forcing mining companies to change their production strategies. This inevitably increased the costs, considering the difficulties of high-altitude exploitation, transportation and the harsh climate. Indeed, from 1935 to 1939 the Carrasco company went through a period of great financial difficulties, which required the help of a loan from the Caja de Crédito Minero.[39] These difficulties resulted from the instability and fluctuations of the international markets, as well as difficulties in competing in them, which resulted in irregular and intermittent production. An ECLAC report mentions that this is the reason why state institutions like the Caja de Crédito Minero:

> devoted great efforts in the 1930s to the study of the sulphur industry and installed a flotation plant to concentrate the minerals, in order to allow the efficient use of those of lower grades and facilitate the extraction of blocks of ore without selecting.[40]

The exploitation of Ollagüe volcanic sulphur deposits, on the other hand, began in 1899 when two private entrepreneurs, Francisco Caralps Ribot and Federico Lesser, submitted the first application for mining ownerships. In 1916, they installed a refinery in the camp of Buenaventura (Figure 7). Later, Luis Borlando, son-in-law

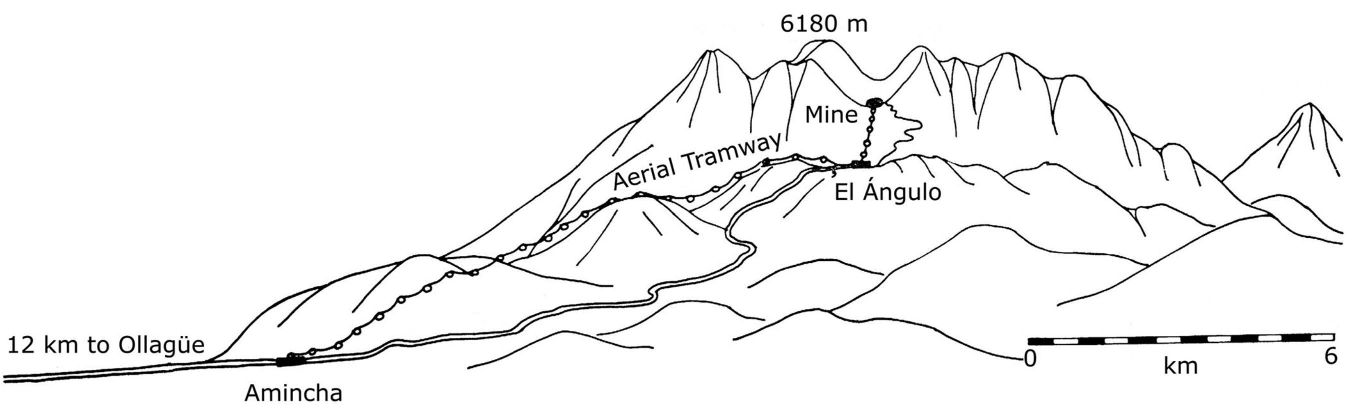

Figure 4. Sketch of the Aucanquilcha volcano exploitation. (Modified from Keys, Ancel, 'The Physiology of Life at High Altitudes', *The Scientific Monthly* 43.4 (1936): 289–312.)

Figure 5. Amincha plant ruins today. © Proyecto Arqueológico Alto Cielo.

Figure 6. Ollagüe refinery ruins today. © Proyecto Arqueológico Alto Cielo.

of Caralps, acquired 43% of the property and operated under a labour agreement between 1932 and 1936, assuming afterward the control of most of the interests of Francisco Caralps's company.[41] Benjamin Leiding, in his report on the exploitation of the volcano, points out that 'there is only an average of 50 workers between the Mine and the Plant (Buenaventura), which maintains a very small exploitation'.[42] The Buenaventura site is located 5km south-west of Ollagüe and 6.9km from the Chile–Bolivia border, at an altitude of 3,730m above sea level (21°16′ 3.40″ S, 68°16′ 23.41″ W). It is one of the major industrial sites of the region and is composed of a total of eight sectors with 12 architectural structures defined by their location and their primary function (labour, administrative, domestic and public).

Leiding was one of the experts who arrived to Ollagüe to describe and evaluate its sulphur economic potential. The extension of the ten properties owned by the Compañía Azufrera de Chile (Borlando's company) in the Ollagüe volcano is shown in Figure 8. This company also owned two properties on the Bolivian side of the volcano (Carmen and Constancia). According to Leiding, all the mining properties contained important sulphur deposits, although the Isabel, Josefina and Chilena mines had a special value due to their large sulphur deposits, which 'are known as the oldest in the whole region and have been exploited although in a very small proportion for many years'.[43]

Exploitation systems and technology

The history of sulphur exploitation in Chile and Ollagüe shows the close relationship between import, export and consumption. For Officier, the sulphur industry in Chile in 1923 was 'in its infancy, and as yet production is comparatively small. It is amply protected by tariff and is already a profitable business'.[44] Similarly, an anonymous article published in the *Boletín Minero* in 1934 noted that:

> The construction of the railroads from Arica to La Paz and from Antofagasta to Bolivia, which both pass near important deposits of sulphur, stimulated the industry of this metalloid and allowed practically all the consumption of Chile to be covered with the production, and still there is certain exportable excess.[45]

For ECLAC economists, due to high production costs in Chile and because of the type of deposits, 'exports are only possible at remunerative prices when the relationship between the exchange rate

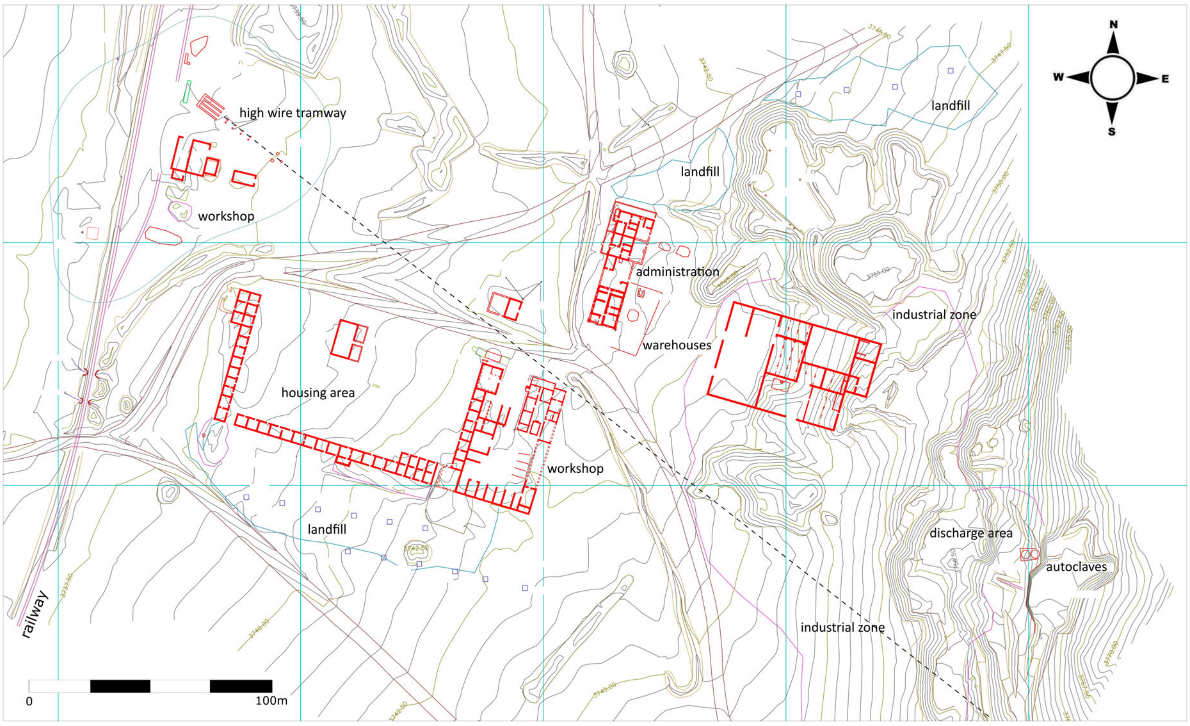

Figure 7. Site plan of the Buenaventura camp. © Proyecto Arqueológico Alto Cielo.

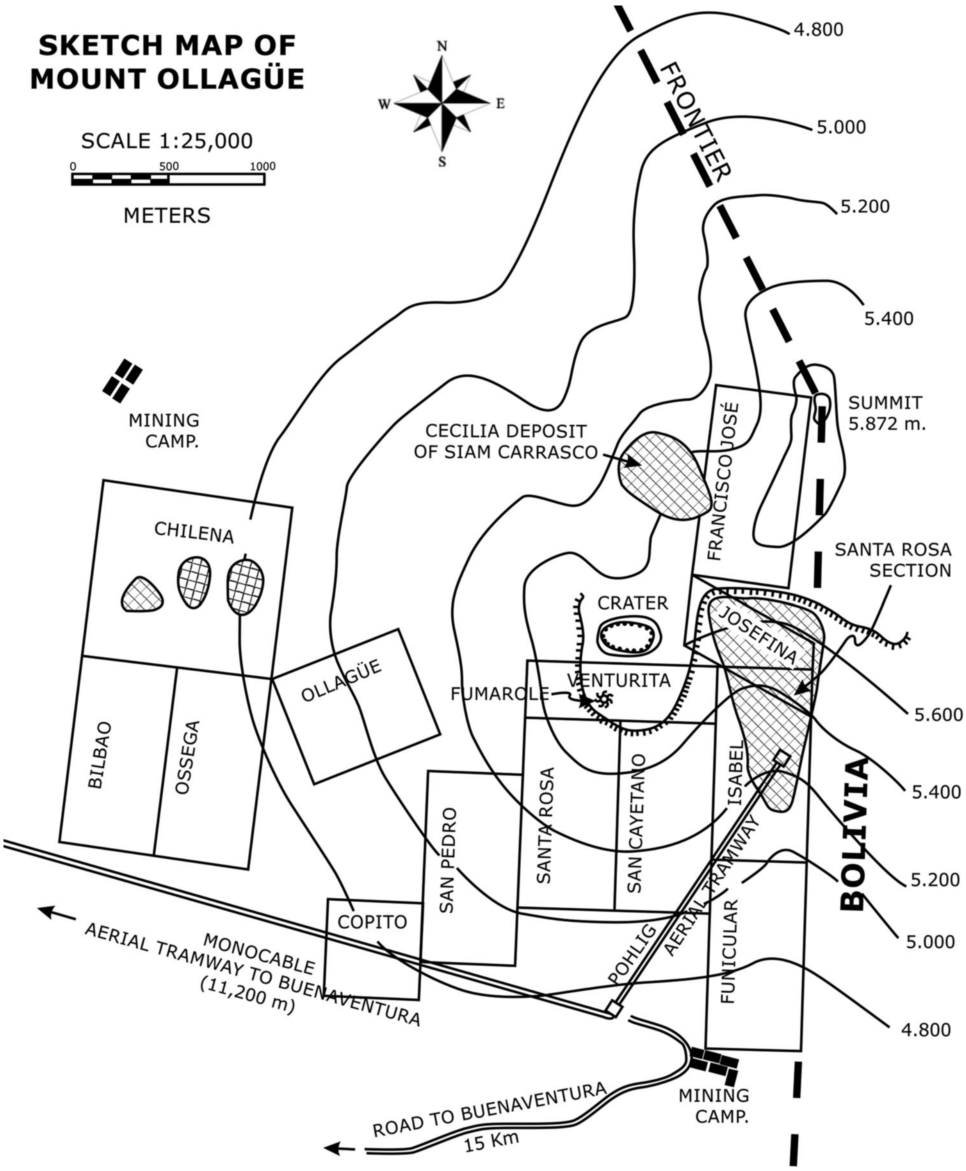

Figure 8. Distribution of mining properties on the Ollagüe volcano (Modified from de Wijs, *Reconnaissance of Sulphur Deposits in South America*).

and costs and wages favour the product'.[46] However, sulphur production was beginning to consolidate, but it depended to a large extent on production costs, on levels of domestic demand due to the development of other mining industries, such as copper, and especially on global political uncertainties and economic fluctuations in world markets. A 1950 report analysed the increase in sulphur demand in the United States, which did not depend solely on the armaments industry, but also on agriculture, and especially on the changes in industrial structures that were developing in post-war Europe.[47] For ECLAC, the reduction of costs would contribute to solving the fundamental problem of industry, which was considered to be a problem not of markets but of prices.

By the second half of the 20th century, the country had reserves of sulphur that many experts considered abundant enough for self-sufficiency. They would have been available for export if extraction, transport and processing conditions had been adequate. In 1956, the Chilean parliament approved the 10 December Convention of 1954 modifying the exchange and investment treatments accorded to saltpetre companies, which had important consequences for sulphur producers. Although there were no changes in the tax rates, the modification of the cost calculation base, which granted greater allocations for amortisation, reduced tax burden. As ECLAC reports, 'a further investment incentive was provided by a more liberal import duty exemption on machinery, spare parts, accessories and chemical materials for production processes'.[48] These decisions were mainly based on the well-known 'Import Substitution Industrialisation' economic strategy promoted in the 1950s.

However, the reality was more intricate. According to CORFO statistics, during 1968 Chile had a deficit in sulphur production that prevented the state from being self-sufficient. This was mainly caused by three factors: climatic (low temperatures), geographic (high altitude) and human (labour shortage):

> The climate imposes a certain human quality on the individual, since it is necessary to have workers capable of resisting a height above 6,000m and therefore the technical personnel are only sporadic and minimal. In addition, because of a limited technical preparation of the operator, adding to this its scarce culture, the production has a low yield. Contributing to this, the machinery suffers a rapid and excessive deterioration.[49]

The problem was also due to, and mainly about, the low recovery rate in the refining processes. Added to it all was the problem of transport, especially bad roads, which made the use of trucks and railways more expensive.[50] Given the geographical location at high altitude, transport was undertaken with llamas and mule-drawn carts, trucks being introduced a few years later.[51] Many experts considered it was not profitable to build roads to reduce transportation costs. For them, the most beneficial solution consisted of the installation of modular plants within the extraction sites. Amongst the other factors that impacted the development of the industry due to the high cost of exploitation was the scarcity of water next to the deposits, which was available only in the rainy periods, from March to April and June to August. High costs caused by the lack of state intervention and an absence of an economic and high-yield procedure for extracting sulphur from its minerals made it impossible to compete with the international markets, with the United States and Italy as the main producers.

The modification of the traditional systems of exploitation stimulated the development of sulphur production. Moves towards more modern technological systems were promoted, thus bringing about general changes in the planning of the industry. The Sociedad Azufrera Aucanquilcha Company (formerly SIAM Carrasco), for example, incorporated in its plants the so-called Japanese autoclave, which had, according to experts, satisfactory results (Table 1). Improvements in technology represented a partial solution to production difficulties, although it was considered that these modifications would have an impact on final costs if sulphur ore of lesser quality was exploited.[52] This raw sulphur ore

Table 1. Operating data of autoclaves by Carrasco and Borlando companies in 1942 (from de Wijs, *Reconnaissance of Sulphur Deposits in South America*, 52.)

	Operator and Plant Site	
	Carrasco Ollagüe	Borlando Buenaventura
No. of autoclaves	6	1
Capacity per autoclave (tonnes)	1.2	4.8
Average grades		
% sulphur	52%	56%
% *caliche* rejects	40%	45%
% brimstone	99.3%	99.3%
Recovery (%)	38.5	34.0
Ratio *caliche*: brimstone	5: 1	5: 1

is known as *caliche*; this is different from *Costra*, which is the barren or lean overburden of sulphur deposit, and different from *Manto*, which is the bed of sulphur ore parallel to the surface.

Most Chilean deposits were exploited by the open pit system: 'first, it is necessary to dislodge the sterile overload that covers the *caliche* mantle. Once this task is done, the caliche is removed with manual tools or appropriate machinery'.[53] The processing systems differed according to the characteristics of the mineral and, of course, the technology used in each site. One of the most common processing systems was that of sublimation by heating the ore gently in a retort. The purpose of this retort system was to refine the sulphur already processed by other systems, and it was mainly intended to treat rich ores: 'they consist of a closed cast iron bucket and an adjacent masonry chamber where sulphur vapours condense'.[54]

Another processing system was the 'fixed and rotary autoclave fusion'. In it, it was necessary to use autoclaves, devices of cylindrical form, constructed of cast iron with a height that was twice as long as their diameter. The autoclave treatment consisted of the extraction of sulphur from the *caliche* by means of a liquefaction process, through the direct action of water vapour subjected to pressure. However, this system had some deficiencies, the most important being 'the low recovery rate that forces the use of large amounts of caliche to obtain refined sulphur, which is uneconomical and produces premature depletion in reserves'.[55]

At the Buenaventura site, the two best-known refining systems were used to treat *caliche*. These were the 'refining system by direct fire in retorts' and the 'steam refining in special autoclaves' (Figures 9–13). The following detailed description of the characteristics and operation of both systems is provided by the Chilean engineer Benjamin Leiding:

> Retorts are cast iron with a capacity for two and a half tonnes of *caliche* in 24 h. Two or three retorts are installed with the same chamber and cooling or precipitation chamber. The fuel used is *yareta* [a plant, *Azorella compacta*, that grows in the highlands of the Andes, which was used for drying and smelting of minerals] in a proportion of more or less 200kg for each 1,000kg of *caliche* treated. With this system they can obtain at will Refined Sulphur in bulk or Refined Sulphur in powder called Sulphur Flower, both of 99.5% purity. (…) The autoclaves are made of cast iron with a variable capacity of about 25 tonnes. of caliche in 24h. They use steam as heat, having a consumption of 90kg of *yareta* and 35kg of water for every 1,000kg of caliche treated. With this system it is possible to obtain only Refined Sulphur in bulk which if desired is ground to powder in special mills obtaining what is called Ventilated Sulphur; both of 99.5% purity.[56]

At the Buenaventura site, the refining plant's capacity could treat 300 tonnes of sulphur *caliche* per month.[57] However, experts found that its autoclaves were not designed to work with a finely ground load. Studies made in Chile with the Japanese autoclave allowed many aspects of the ore processing to be improved. The Ministry of Mining also reported in the early 1960s that the Sociedad Azufrera Aucanquilcha had installed a Japanese autoclave at its Amincha plant to refine concentrates. According to the reports, the yields 'have been satisfactory, obtaining in open circuit recoveries of 83%, which will improve when the autoclave operates in closed circuit with flotation'.[58]

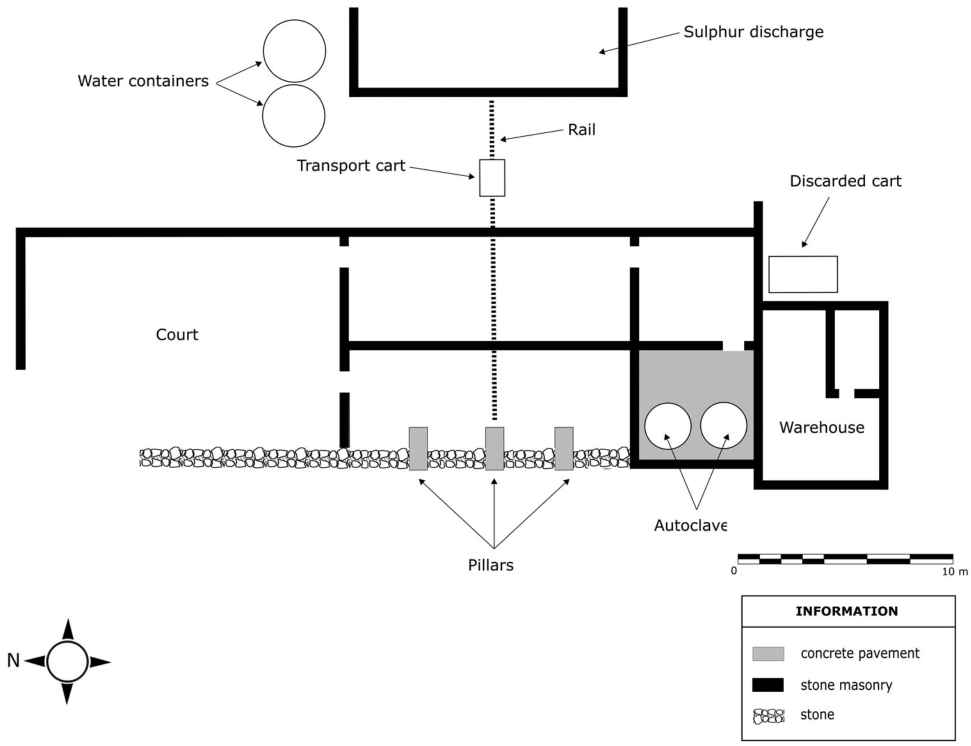

Figure 9. Plan of Buenaventura's sulphur treatment sector. © Proyecto Arqueológico Alto Cielo.

Figure 10. Structure surrounding the autoclaves at the Buenaventura site. © Proyecto Arqueológico Alto Cielo.

A third, commonly used treatment system was 'carbon disulphide leaching'. It is a method that achieves high recovery rates and very good quality sulphur, although with a high level of solvent losses and high fuel consumption. Finally, another system was the 'Simpson system', which uses solvent extraction at high temperatures.[59]

Sulphur refining was a topic of extensive debate, as well as the subject of important technological innovations. In the 1920s, Officer observed that

> with one exception, all refiners use the same process. This consists of placing a charge of sulphur ore in a cast-iron retort, excluding air, and by applying external heat evaporating the sulphur in the charge. The vapours pass to a condensing chamber, where they yield the finely divided amorphous powder known as flowers.[60]

This phase of the process is important, because the final products varied in quality and, therefore, in its final market price. In the refining process, two products are obtained: flowering sulphur and granulated sulphur. The first is used, among other things, to disinfect vineyards, and has a higher price on the market than equally pure granulated sulphur. Refiners therefore wanted to produce as much of the flowering sulphur as possible.

High-wire ropeways

An important and highly visible material remains on Ollagüe's landscape that has to do with the technology associated with the transport of ore. In addition to autoclaves and retorts, the sulphur industry in Ollagüe explored a series of technological innovations

Figure 11. Japanese autoclave TAMAGAWA at the Buenaventura site. © Proyecto Arqueológico Alto Cielo.

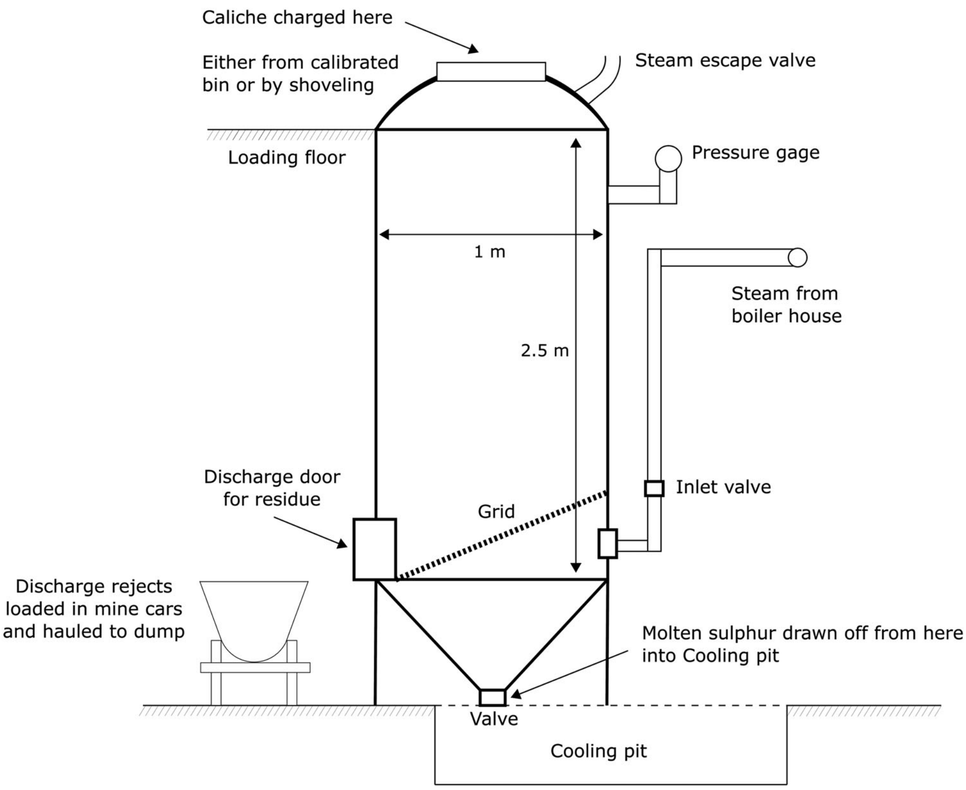

Figure 12. Sketch of autoclave in Buenaventura (Modified from de Wijs, *Reconnaissance of Sulphur Deposits in South America*).

that were quickly integrated in the activities of exploitation and transport, forming an important part of the material assemblage of the sites. Aerial ropeways were a fundamental innovation for the transportation of ore from the extraction sites to the processing centres. They also became one of the material heritage symbols of the sulphur industry, and one of the most visible and valuable archaeological remains in the industrial landscape.

Two large aerial ropeways were installed for the transport of sulphur: one that connected the Ollagüe volcanic deposits belonging to the Borlando company with its plant in Buenaventura, and another that transported sulphur from the Aucanquilcha volcano, belonging to the SIAM Carrasco Company (Figure 14). Carrasco installed a Pohlig-type dual-cable wire and an angular station, known as 'El Ángulo', at 5,100m high (Figures 15–18). It reached the plant of the company located in Amincha (Figures 19–20), where sulphur was loaded to be sent to the port of Antofagasta by train.

To carry the ore down from the Ollagüe volcano, the Borlando company built a Pohlig-type aerial ropeway that carried the sulphur from the bottom of the deposit located at 5,254m altitude, to an intermediate recharging station at 4,747m altitude. From this recharging station, sulphur was transported on a single-cable wire to the Buenaventura plant and station. There, it was loaded onto trains, which went down to the port of Antofagasta, to be finally shipped abroad.

This new technology facilitated the expansion of the industry to meet growing demand. The old methods (transport with llamas)

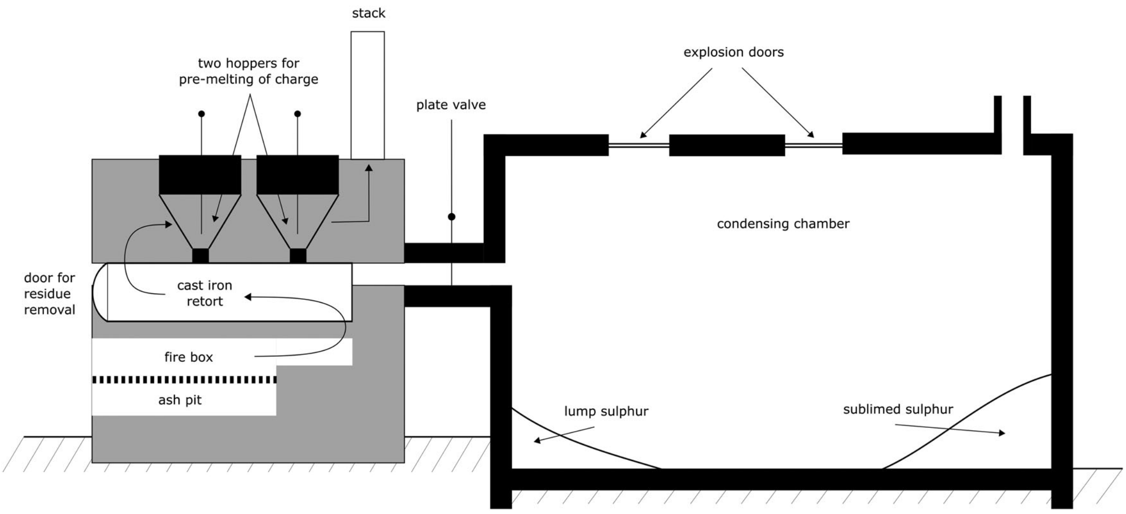

Figure 13. Sketch of Chilean retort (Modified from de Wijs, *Reconnaissance of Sulphur Deposits in South America*).

Figure 14. Aerial ropeway on the Aucanquilcha volcano in 1945. © Museo Histórico Nacional, Santiago. Photo by Robert Gertsmann reproduced with permission.

Figure 15. 'El Angulo' site. © Proyecto Arqueológico Alto Cielo.

Figure 16. Aerial ropeway tower on the Aucanquilcha volcano in 2017. © Proyecto Arqueológico Alto Cielo.

Figure 17. Aerial ropeway structure on the 'El Angulo' site. © Proyecto Arqueológico Alto Cielo.

Figure 18. Aerial ropeway structure on the 'El Angulo' site. © Proyecto Arqueológico Alto Cielo.

Figure 19. Discharge station on Amincha camp. © Proyecto Arqueológico Alto Cielo.

Figure 20. Aerial ropeway carriage remains on the Amincha discharge station. © Proyecto Arqueológico Alto Cielo.

had proven incapable of transporting large quantities of ore, due to weight and distance. Improvements of aerial ropeway technology started in the 1850s in the iron, coal and limestone mining sites in the United States.[61] This technology prospered from the 1870s to the 1920s, following the expansion of the so-called 'industrial frontier'.[62] However, its use declined until it disappeared, mainly due to the 1929 crisis, when many mines had to close their operations. In Chile, aerial ropeways were in use until the middle of the 20th century, when they were finally replaced by trucks, changing the mechanisation model of the Andean territory.[63]

Aerial ropeways are part of the history of technological innovations and machinery that were invented, improved and implemented in mining, in addition to the general process of industrial expansion, in the framework of the development of capitalism in peripheral areas. They are part of a whole series of material vestiges that can be found in industrial sites, among which are also the new artefacts of mineral extraction, electricity supply and installations for large-scale production.

In a region such as the mining district of Ollagüe, filled with streams and natural barriers, ropeways were an important alternative to transportation by constantly eroded roads and high-cost railroads. Through straight lines, aerial ropeways avoided the obstacles imposed by the natural environment.[64] The costs were also much lower, and ropeways were less prone to the difficulties of the Ollagüe region's characteristic climatic conditions, such as snow and summer rains. Likewise, the ropeways worked not only for the transport of minerals, but also for the transport of workers, with all the risks that this implies (and that today would be unthinkable).[65]

Conclusions

Innovations and the application of new technology in different phases of the productive process, from extraction to transportation and processing, were promoted by a state policy that sought to stimulate the sulphur industry in Ollagüe. At the end of the 1960s, Joaquín Sánchez emphasised the imbalance between 'the growing scarcity of sulphur' and CORFO's policies to boost its industry to supply domestic demand and reach the long-desired export stage.[66] The author thus echoed the words of capitalists who prayed for a complete study of Chile's sulphur resources in order to increase production levels, for example during the prosperous years of the Second World War.[67]

Exploitation strategies and technological systems aimed at stimulating and promoting the sulphur industry. These strategies must be understood within global economic cycles and the relationship between the state and private enterprises, developed in the mining-industrial context of Ollagüe. William Rudolph, full of optimism, believed that '[I]f the engineer succeeds at his task, Chile will have a product to equal or surpass its copper and nitrate and to provide that which neither copper nor nitrate can furnish, the foundation for a full-scale industrialisation'.[68] What the privilege of the perspective of time offers us is the possibility of evaluating the author's erroneous prediction. Sulphur exploitation could not face price fluctuations and competition in international markets to build the bases of industrialisation so long awaited by the state's modernising utopia. What it did, however, was to leave material traces and memories that are still present in the mining landscape of Ollagüe's community.

Notes

1. This research is part of the Alto Cielo Archaeological Project: www.altocielo.cl
2. Before the so-called Pacific War or Saltpeter War (1879–83), this region was part of Bolivia with the name of Departamento del Litoral. The Treaty of Peace and Friendship signed in 1904 between Chile and Bolivia ratified the definitive annexation of this territory.
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43. Leiding, *Informe sobre las azufreras del volcán Ollagüe*, 3.
44. Officier, 'Sulphur Resources of Chile', 999.
45. Anon., 'Producción de azufre en 1933', 651.
46. ECLAC, *Estudio económico de América Latina 1950*, 136.
47. ECLAC, *Estudio económico de América Latina 1950*.
48. ECLAC, *Economic Survey of Latin America 1956* (United Nations Department of Economic and Social Affairs, 1957), 103.
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