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GHOSTS OF THE ATACAMA: THE ABANDONMENT OF NITRATE MINING IN THE TARAPACÁ REGION OF CHILE

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ABSTRACT: *The Atacama Desert of South America contains the world's only naturally occurring nitrate deposits. With the development of synthetic nitrate in Germany during WWI, Chile's nitrate mining industry found itself overcapitalized and suffering from the effects of overproduction. By the end of the 1940s the industry had all but collapsed. This paper will illustrate the impacts that over-reliance on primary exports has had on the desert landscape in the Tarapacá Region of northern Chile. Based on data compiled from the field and photo-interpretation a conservative estimate is that about 5-7% of the desert (≈103,000 acres) has been directly impacted by nitrate mining, nearly 174 million cubic yards of waste material generated, and over 100 processing plants abandoned. While the impacts on the landscape are substantial, the abandoned remains of the industry constitute an important cultural resource and offer a glimpse into the long-term effects of this failed economy of dependency.*

Keywords: *Chile, Nitrate, Mining landscapes, Atacama Desert*

INTRODUCTION

Between northern Chile's coastal mountains and the Andes lies a landscape whose immense size and desolation seem to defy any attempt at human habitation. Surface water is nonexistent and the intense dryness saps away any hint of moisture. In the Atacama Desert there may be decades between rainfalls. This near absence of rain has allowed nitrates of soda found in the groundwater to accumulate in layers called *caliche*. Nowhere else in the world are natural nitrates found in quantities sufficient for mining, and from 1880 and 1930 the *salitrera* (saltpeter or nitrate mines) of Chile's Tarapacá Region were home to tens of thousands of miners or *rotos*[1] who scratched a meager living from the desert. So valued was the nitrate that at the turn of the twentieth century over 100 processing facilities operated in the region and the taxes collected on exports accounted for the bulk of the Chilean government's revenue. British, American, and Chilean entrepreneurs flocked to the northern Atacama, hauling in millions of pounds of equipment, building hundreds of miles of railroad, and turning-over more than 100,000 acres of desert in search of the mineral. By the close of WWI and the advent of artificial nitrates, Chile's monopoly on nitrate production was broken and the country's key industry entered a long period of decline.

As with many extractive economies, especially those dependent on mining, the nitrate region of Tarapacá was heavily capitalized. In order to gain scale economies the equipment used to extract and separate the nitrate was large and expensive. The region was remote and completely lacking in transport infrastructure, all of which had to be purpose-built. The coastal mountain range here drops steeply to a thin, rocky shoreline with few natural harbors, and moving the nitrate down this escarpment proved difficult and expensive. This whole system, devised solely to export nitrate, was viable only as long as demand was high and there was no competition that would lower prices. Once these conditions were no longer met, the system experienced substantial contraction, which meant—given the high cost of dismantling—abandonment. The goal of this paper is to first provide some historical context to that abandonment process, and then provide a survey of its scope within the region based on field measurements and aerial photo-interpretation.

REGIONAL SETTING

The northern extension of the Atacama Desert, called the Pampa del Tamarugal, is roughly 25 to 35 miles wide, 120 miles in length, and varies between 2,500 to 3,000 feet in elevation (Figure 1). The region consists of three major physiographic units: the coastal mountain range, the longitudinal depression, and the Andes Mountains (Rich, 1941). The coastal range is a series of unconnected mountain masses whose elevations rarely exceed 4,000 feet. To the east the Andes rise to an average elevation of some 13,000 feet, with peaks topping 17,000 feet. Between these two ranges lies the longitudinal depression, known locally as the *pampa* (plain). The northern section of the *pampa* consists of extensive alluvial flats, while the south section contains several large *salars* or salt flats. Rainfall in this region is almost non-existent: yearly precipitation amounts on the coast at Iquique average 0.6 mm (0.024 in) (Clarke, 2006), but even this measurement is somewhat misleading. Between 1946 and 1972 Iquique recorded a total of 20 mm (0.79 in) of rain, yet this miniscule amount of precipitation fell in 1957 and 1958—no rainfall was recorded for the remaining 25 years (Pinto et al., 2006). Few plants can survive such hyper-arid conditions, and with the exception tracts of *tamarugo* trees planted by the Chilean government as part of a reforestation program (Robertson, 1980), the desert is almost completely devoid of vegetation (Figure 2).

The nitrate deposits are found primarily on the lower slopes of the Coast Range and along the western edge of the alluvial and salt flats. The *pampa* slopes almost imperceptibly toward the west and it is thought that the nitrate accumulates where the water table comes close to the surface (Rich, 1941). The movement of ground water through the alluvial material of the flats deposited the *salitre*

Figure 1. Northern Chile and the study area. Chilean regions are denoted with Roman numerals.

Figure 2. The Atacama Desert. A series of *geoglyphs* can be seen in the foreground on the hill slope, with the Andes just visible in the background. In the middle distance is the broad, flat expanse of the pampa. The remains of a nitrate plant and its tailings pile can be seen to the left.

(nitrate of soda), which then crystallizes as the water rises and evaporates. The crystallized salts fill in the interstitial spaces of the alluvium, cementing the material together to form the *caliche*. The incredible dryness of the desert is in all likelihood the reason that the nitrate beds have been preserved—nitrate is easily dissolved in water and any significant rainfall would wash away the nitrate beds. Although nitrate is found throughout the alluvium it is concentrated into a more easily extractable form in the *caliche*. The depth of the *caliche* layer ranges from just a few inches below the surface to several feet, and while averaging just a foot in thickness, can reach up to 12 feet thick (Whitbeck, 1931).

Few towns exist in this part of Chile, and those that do have seen their fortunes rise and fall with the nitrate industry. The principal port and largest city is Iquique (2002 population: 164,396), located on one of the few natural harbors along this section of the coast (Figure 3). Just west of Iquique, on the edge of the escarpment, is the town of Alto Hospicio (2002 population: 50,190), whose primarily Aymran population has migrated to the region from the north in search of jobs. North of Iquique are the abandoned ports of Junin and Caleta Buena which have no modern access. At the far northern end of

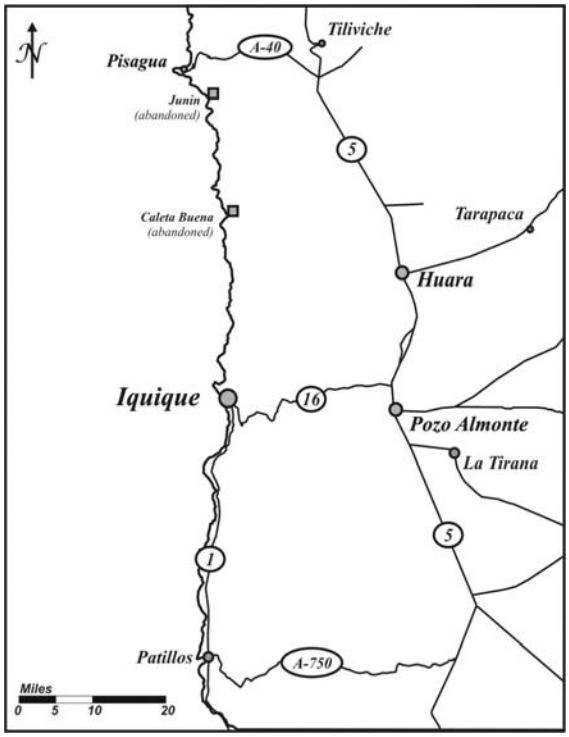

Figure 3. Modern towns and paved roads within the study area.

the nitrate region is the small port of Pisagua (Approximate 2002 population: 250), which was all but abandoned after the boom period. Inland are the towns of Pozo Almonte (2002 population: 6,384) and Huara (2002 population: 956), both of which lie on Route 5, Chile's major north-south highway. There are nearly 400 miles of paved roads in the study area, principally Routes 5 and 1. The majority of the roads here are unpaved but graded, yet since rainfall is almost non-existent, traffic on unpaved roads appears to be nearly equal to that occurring on the paved routes. That being said, traffic of any sort outside of Iquique is exceptionally light. Manufacturing and commercial services account for over 50% of the region's economic output, whereas mining in the region currently comprises only about 6% (Instituto Nacional de Estadísticas, 2002).

HISTORICAL SETTING

Naturally occurring nitrate was an important component of early commercially produced fertilizers and was used extensively in the production of explosives (Jones, 1920). In the early part of the nineteenth century Peru held a near monopoly on the most readily available forms of nitrate—*guano* and *salitre*—and had become heavily dependent upon revenues from its export (Matthew, 1970). As Peru's *guano* deposits were exhausted and demand waned,[2] the government looked to its southern province to replenish its coffers. The world's only significant *salitre* deposits were located in the Peruvian province of Tarapacá and the Bolivian coastal region of Antofagasta. Unlike *guano*, *salitre* processing was capital intensive, requiring substantial British and Chilean investment (O'Brien, 1982). Following the recession of 1870, the Peruvian government adopted a policy of expropriation in the nitrate fields that left only British and Peruvian *salitreros* (nitrate mine owners) operating in Tarapacá. Most of the Chilean owned *salitreros*, which had limited capital and production capacity,[3] were put out of business (O'Brien, 1982). Chile's export dependent economy was in a precarious position: a long downward trend in the price of raw materials (principally copper and silver) and the loss of taxes levied on shrinking nitrate exports left the country deeply in debt with no means to raise revenue. In 1878 the Bolivian government imposed a tax on the Chilean nitrate operations in its territory in an apparent violation of an earlier treaty. When the Antofagasta Nitrate and Railway Company refused to pay the tax and Bolivia seized the property, threatening to auction it off, the conditions for conflict were in place (Ortega, 1984). Chile sent 2,000 troops on the day of the auction and took the city of Antofagasta without bloodshed. Bolivia and Peru, wary of Chile's intentions in the region, had signed the Defensive Treaty of 1873, creating a pact to oppose any expansionist actions by Chile. War was declared in early 1879, yet Peru and Bolivia were no match for the Chilean military. By 1883 Chile had expanded its territory as far north as Arica and was in sole possession of the Atacama nitrate beds.

Based on changes in production capacity, the nitrate era in Chile can be broken into three distinct periods: the period of steady growth from 1883 to 1914, the period of wildly fluctuating production during the First World War from 1915 to 1920 (Jones, 1927), and the period of decline and abandonment from 1920 to the present. Prior to the War of the Pacific, British capital was of limited importance in the development of nitrates. British concerns in the region produced 700,000 quintals[4] (≈ 31,500 tons) or about 20% of the total nitrate output of the 3,200,000 quintals (≈ 144,300 tons) mined in Tarapacá between 1870 and 1872, and British investors controlled less than 14% of the *salitreras* (Centner, 1942). Once under Chilean control, British interests in the nitrate region increased dramatically. By 1889 British joint-stock companies in Tarapacá

had invested £1,645,000 ($8,011,150[5]) in properties valued at £4,675,500 ($22,769,685), and British nitrate companies produced nearly 60% of the nitrates exported from the region. At the peak of their involvement there were 48 British *oficinas* (processing plants) operating in Tarapacá producing a total of 20,184,000 quintals (≈ 910,100 tons) of nitrate for export. To a Chilean government looking for a quick fix to its long term fiscal problems the boom in nitrate exports was a welcomed, if short term, relief. By the late 1880s over 50% of the government's revenue came from nitrate exports (Figure 4) and the cycle of dependency had become well entrenched. Not only did Chile depend ever more heavily on nitrate revenues, but this dependency had a trickle-down effect. The heavy machinery used to extract and transport the nitrate was either imported or built in Chile by foreign-owned companies. By 1902 Chile was importing over $5,000,000 in heavy machinery a year (Pfeiffer, 1952).

Nitrate Mining and Production

The earliest method of nitrate mining in Tarapacá involved digging or drilling holes in the desert floor to determine the extent of the nitrate bed to be mined. Maps would be drawn depicting the likely nitrate distribution and a series of blast-holes dug into these areas. Charges of black power or dynamite placed into these holes would fracture the *caliche* and remove the overburden. The *caliche* would then be loaded by hand into horse carts and taken to the processing location, where the ore would be further crushed and dissolved in heated water. The nitrate-rich liquid was then placed in large drying pans where the nitrate crystallized (McConnell, 1935). Over time this simple system was mechanized in what became known as the Shank's system, in which a tremendous amount of the nitrate was lost. Typically only the highest grade of ore was mined, with moderate and low grade ores left behind as spoils. This inefficient process could only be maintained as long as Chile had a near monopoly on production and the price of nitrate remained high (Whitbeck, 1931).

Given such wasteful conditions and the government's heavy reliance on nitrate revenues it was necessary to mine large areas in order to remove the highest grade *caliche* and to process large volumes of ore. Horse carts and small boiling vats were replaced with railroad and steam powered boilers. All operations at the *oficinas* increased in size to take advantage of scale economies. Giant steam powered ore crushers were installed to grind the *caliche* into a finer material, speeding up the leaching process. To increase the productivity of the actual mining operation, nitrate beds were laid out with a grid pattern that were accessed by portable railroad tracks (Platt, 1936). Narrow gauge railroads were built to connect the mines to the processing plants, and the processing plants to the port towns. Obviously this increase in capitalization and efficiency led to increased production (Figure 5) and a lowering of costs.

In 1926 a further refinement in the nitrate extraction process was introduced in an attempt to resurrect the industry in Chile. The "Guggenheim process", named for American capitalists Murray and Sol Guggenheim who financed construction of the new processing plants, further increased mechanization at the *oficinas* (Glaser-Schmidt,

Figure 4. Percentage of governmental revenue derived from nitrate exports, 1880-1929.

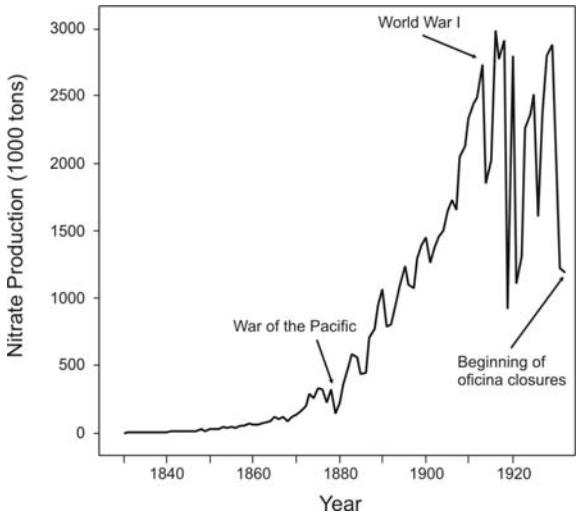

Figure 5. Nitrate production in the Tarapacá Region, 1830-1932.

1995). The extraction method was only economical at very large processing volumes, and once again, all operation at them were scaled up. Steam shovels loaded the ore into awaiting rail cars and hauled it to the processing plants. Larger and heavier crushers were used, the pulverized material was moved via conveyor belts to larger steam boilers, and compressed ammonia cooled the precipitation vats. The increase in nitrate recovery jumped from 60% for the Shank's process using high grade ores to 90% using the Guggenheim process and ores containing as little as 15% nitrate (Whitbeck, 1931). One of the major drawbacks of the process was its cost. For example, the Pedro de Valdivia plant using the Guggenheim process cost approximately $30,000,000, while the Chacabuco plant which used the Shanks process cost about $5,000,000 (McConnell, 1935). Unfortunately, while the cost of producing a ton of nitrate dropped dramatically, so did the demand.

Decline of the Natural Nitrate Industry

Many of the factors which precipitated the decline in the use of natural nitrates were in place by 1900. Although exports to the United States continued to increase, perhaps the largest potential market was closed to Chilean nitrates. American agriculture had become mechanized and it was impractical to use natural nitrate fertilizers with mechanized agriculture at the turn of the twentieth century.[6] The seed planting machinery of this period relied on the soil's friability, which was compromised by the addition of nitrates. Natural fertilizers were found to be most effective when used with traditional farming methods. However, traditional farmers rarely could afford the added cost of fertilizers, and as mechanized agriculture replaced traditional farming techniques, the demand for natural nitrates waned. Ultimately British nitrate companies in Chile found themselves with ever increasing quantities of unsold nitrates which would then be dumped on the market at a discount. These periods of oversupply resulted in the familiar boom and bust cycles, something which the natural nitrate industry suffered from throughout its early history (O'Brien, 1982).

While problems with mechanized agriculture were keeping potential markets closed, this was certainly not the death-knell for the Chilean nitrate industry. No single event was more influential in the decline in the natural nitrate industry than the introduction of artificial nitrates prior to the First World War (Reilly, 1951). During the lead-up to the war, Germany was the world's largest consumer of Chilean nitrate. However, once the war started most of Chile's exports went to the Allied war effort, leaving Germany without a source for one of the key ingredients in high explosives. It was during this period that Germany perfected the method of converting ammonia to nitric acid, a process that would have serious implications for the Chilean nitrate industry (Jones, 1920). Although the war created a temporary rise in demand, the armistice signaled an end to the Chilean monopoly. In 1939, after flying over the nitrate district, geographer John Rich (1941) noted that:

> "…the nitrate district was a sorry spectacle. Most of the plants were closed … and the nitrate towns were truly 'ghost' towns, rendered particularly unattractive by the barrenness of their surroundings."

The advent of artificial nitrates and continuing agricultural mechanization led to an increase in nitrate demand throughout the mid-twentieth century, but Chile's share of the nitrate market continued to fall. In 1952 there were 33 mining operations in Tarapacá employing 9,903 workers, yet by 1960 the number of mining operations had dropped to 12 and the number of employees to 2,650 (Mamalakis, 1980, Tables 10.1 and 10.2). This long period of decline resulted in a near wholesale abandonment of the industry in Tarapacá. Machinery that had value and was salvageable was dismantled and removed, but in most cases companies and investors simply walked away from their holdings. The intense dryness of the desert has preserved most of the physical remains of the nitrate industry, resulting in a landscape of abandonment unlike any other.

METHODOLOGY

Because of the intense dryness of the desert, any activity which has impacted the landscape remains preserved, as evidenced by the longevity of the ancient geoglyphs (Figure 2, foreground). Since nitrate mining in the region was a surface activity, its impacts on the landscape will be extremely long-lived. To gauge the extent of these impacts, field data were gathered over a two week period during August of 2007. The ruins of five *oficinas* were examined in detail in order to determine their overall layout and how each of the different processes used to produce nitrate were organized and linked together. Areas of the desert which had been mined were visited and their geographic coordinates were

recorded. The height of each tailings pile encountered while in the field[7] was estimated using a clinometer and the standard trigonometric equation for height estimation[8] and then averaged to produce an average pile height. The size of the tailings piles was used as a proxy measure of the total production of the nitrate plant, and by extension the size of the operation. Publically available high resolution aerial photographs of the Tarapacá Region were then photo-interpreted using the data collected in the field as a guide. The locations of all *oficinas*, abandoned towns, rail stations, rail lines, nitrate storage, and tailings piles were then digitized and given attributes for subsequent spatial analyses and mapping. Finally, areas that had been mined were digitized from the aerial photographs and used to make estimates as to the extent of surface disturbance.

RESULTS: IMPACTS OF NITRATE MINING

To process the *caliche*, both foreign and domestic concerns built more than 100 *oficinas* in the Tarapacá Region over the course of the nitrate boom period. Although the majority of the *caliche* deposits in Tarapacá occur north of Pozo Almonte along the edge of the *pampa*, substantial deposits were found to the southwest along the edges of large, flat interior basins within the coastal mountain range. The desert has been most impacted by the nitrate industry between Pozo Almonte and Huara, where over 30,000 acres of desert have been disturbed (Figure 6). In total some 103,000 acres, or about 160 square miles, of desert has been mined in the region. Mining completely transforms the desert from flat and traversable to nearly impassible (Figure 7).

The processing facilities ranged from small operations on limited or isolated *caliche* deposits to huge plants with an associated company town that serviced entire regions (e.g. Humberstone). Of the 105 plants located by photo interpretation, six had tailings piles of less than 2 acres and tailing pile volumes of less than 150,000 cubic yards (Figure 8). When examining these sites on the aerial photographs it became obvious that they were very early manual operations, where the *caliche* was dug and transported by hand. Twenty-seven of the processing plants in Tarapacá had tailings piles of between 3 and 15 acres, and tailing volumes of between 200,000 and 1,000,000 cubic yards. These small facilities were located either in far northern *pampa* or within the coastal mountains. The size and, more importantly, the shape of the tailings piles point to early

Figure 6. A digital elevation model of the Tarapacá study area and the nitrate. Note that the caliche is found primarily on the western edge of the *pampa*.

Figure 7. A mined portion of the desert. Note that mining continued up the lower slopes of the hills.

Figure 8. The location of nitrate processing plants. The size of the symbols reflects the total volume of tailings produced at the plant.

mechanization in waste disposal. Whereas the smallest piles appear as simple mounds of waste, these piles are "fan" shaped and signal a more systematic and mechanized means of disposal.[9] Moderate size plants—those with tailings piles between 15 and 80 acres and volumes between 1 and 5 million cubic yards were found throughout the study area. While these piles are also fan shaped, their most distinguishing characteristic is that they have multiple layers of waste materials, indicating both an increase in the total volume of ore and the speed at which it was processed. The largest operations (those that generated over 5 million cubic yards of tailings) were found along the Salitrero Railroad south of Huara. Examination of these plants reveals that they tended to have multiple processing operations, resulting in multi-lobed tailings piles. The largest single operation in terms of output over the course of its lifetime was the processing plant at Oficina Victoria, which had a 160,000 metric ton capacity annually, and was the last *oficina* to operate in Tarapacá. The plant was built on the site of the old *oficinas* Brac and Franka, and operated from 1941 until 1979, producing nearly 30 million cubic yards of tailings covering over 450 acres (Figure 9). For the region as a whole, tailings piles cover an approximately 3,593 acres (5.6 square miles) and are estimated to contain nearly 232 million cubic yards of material.[10]

The amount of transportation infrastructure built and subsequently abandoned is fairly substantial, and is directly related to the difficulty of moving nitrate from the *pampa* to the ports. Although movement in the interior is fairly easy, hampered only by the severe dryness, movement between the interior and the coast blocked by a nearly vertical cliff face approximately 1,000 feet high. No major river reaches the coast in the region and so there is no convenient route to circumvent the cliffs. Only the Rio Loa reaches the coast but does so well south of the Tarapacá's major *caliche* deposits (Rudolph, 1927). The earliest rail lines in the region were constructed in 1870 with British capital by the Nitrate Railways Company to connect the mines to Iquique (Brown, 1958). As the nitrate industry expanded in the 1880s, rail lines connecting the mines to the ports at Pisagua, Junin, and Caleta Buena were built (Figure 10). The railroads actually reached the towns of Iquique and Pisagua, but this was only accomplished by building a series of switchbacks to bring the rail lines down the steep cliff face. In the case of Iquique a 180 degree turning-tunnel and two straight tunnels were constructed to accommodate the trains coming down the cliff. Rail service stopped on the cliffs overlooking Junin and Caleta Buena, and nitrate bound for these ports was taken down-slope on inclined planes. The rail line from Caleta Buena to the *pampa* was over 30 km in length to cover a straight-line distance of only 14 km with curve radii as little as 130 feet. Given the circuitousness of the routes through the coastal range, small but powerful articulated locomotives (e.g. Kitson-Meyer and Farlie) were employed to haul 125 ton loads of nitrate over the meter-gauge rail lines. During the course of

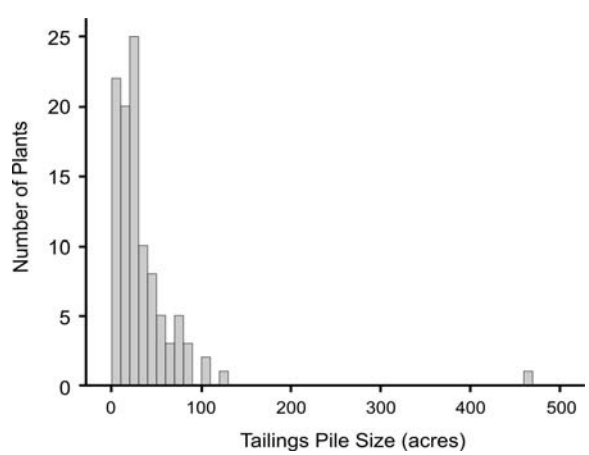

Figure 9. The number of nitrate plants by tailing pile size. Oficina Victoria falls on the far right of the graph.

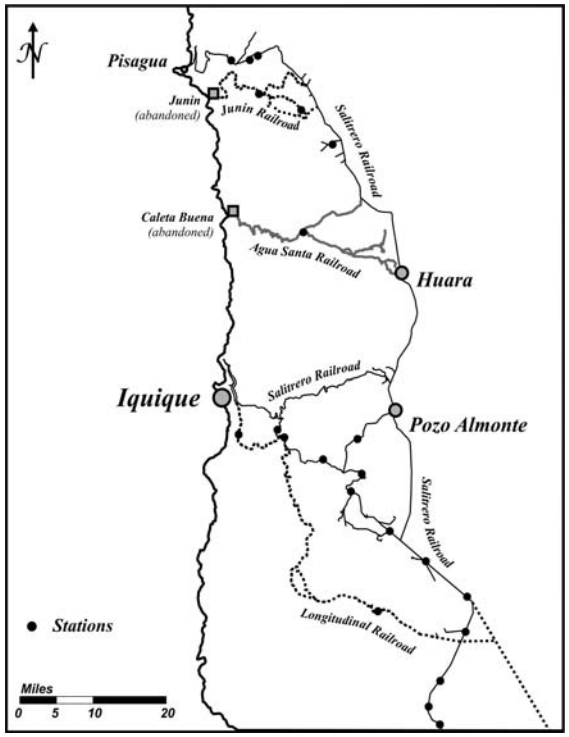

Figure 10. Nitrate era railroads and rail stations. All but the Longitudinal Railroad have been abandoned.

the nitrate boom era over 500 miles of primary rail (meter gauge) and thousands of miles of secondary and temporary lines were constructed. Some 25 stations and switching yards were built to accommodate the rail lines, several of which appear to have had shops to repair the rolling stock. With the exception of the Longitudinal rail line to Iquique, all of this transportation infrastructure—including the ports of Junin and Caleta Buena—was abandoned.

It is estimated that approximately 110 million cubic yards of *caliche* were abandoned in storage piles,[11] and many of these piles are currently being processed by the two modern nitrate plants operating in the region. Two of the *oficinas*, Santa Laura and Humberstone, are United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage historic sites[12] and have been preserved nearly intact (Figure 11). In the case of Humberstone much of the original mining town remains, but this town was likely atypical of mining towns of that era. Located directly on the rail line to Iquique, Humberstone boasted amenities such as a movie theatre, swimming pool, and tennis courts. The typical mining town offered little in the way of amenities, consisting of little more than the nitrate works, shops, and miners' quarters. Built primarily of adobe, the small towns supporting the nearby processing plants have suffered the ravages of time

Figure 11. The abandoned processing plant of Oficina Santa Laura. This site and the site at Humberstone are now UNESCO sites.

and neglect (Figure 12). Any remaining material that could be reused was stripped from these sites long ago by people living in the area.

SUMMARY

The impacts that nitrate mining in the region have had on the landscape are large in scale and scope, as well as long term. A conservative estimate is that about 5-7% of the *pampa* within the study area has been directly impacted by nitrate mining. In Tarapacá over 103,000 acres of desert have been mined, nearly 174 million cubic yards of waste material has been generated, and hundreds of miles of rail line and over 100 processing plants have been abandoned. This has had a profound effect on the

Figure 12. The empty streets of Oficina Humberstone. Unlike most of the other oficinas, the company town here is well preserved.

desert environment, but also represents an important cultural resource. Although a substantial body of literature exists concerning the development of the Chilean nitrate industry (e.g. Centner, 1942; O'Brien, 1979; Mayo, 1981), very little is known about the abandonment of that same industry. Specifically, when *oficinas* began to close a greater proportion of the burden for maintaining the infrastructure necessary to export nitrate was shouldered by fewer and fewer nitrate operations. Over the course of the nitrate era foreign and domestic investment led to over-capitalization of the mining operations. This level of investment was tenable only as long as prices remained high, but the volatility of the nitrate industry ultimately made its collapse in Chile a foregone conclusion. Only recently has the industry been able to begin some measure of recovery, and that has been at a much reduced scale. The same story can be told for any number of locations that have economies of dependence, where there is too heavy a reliance on primary exports. What makes the Chilean case so interesting is scale of abandonment, and how clearly the story of over-specialization and over-capitalization can be read on the landscape.

ENDNOTES

[1] Literally broken or ragged ones. This derogatory term was often applied to anyone who was impoverished, and was commonly used in reference to the nitrate workers.

[2] Apparently the decline in *guano* exports was not solely a result of direct competition from *salitre*, but also from declining quality and unscrupulous dealers who over-priced inferior grades of *guano* (See Greenhill and Miller, 1973).

[3] See O'Brien, 1982 Table 2 for a production comparison between Chilean and European nitrate works. The unstable nature of Chile's nitrate operations in Peru during the early 1870s was due in large measure to declining prices for copper and silver, which caused foreign banks to limit credit (O'Brien, 1979).

[4] A Chilean quintal is approximately 101 pounds.

[5] Dollar amounts were calculated based on an exchange rate of $4.87 per £1 in 1889. See Lawrence H. Officer and Samuel H. Williamson, *Measures of Worth 2007.* Available at: http://www.measuringworth.com

[6] See *Scientific American* 1889, 61:407p for a complete explanation on the difficulties of using nitrate fertilizers with mechanized agriculture.

[7] Although many tailing piles were encountered, only 12 could be used to determine average pile height, the others being too distant to get an accurate clinometer reading.

[8] Piling height was estimated using the equation: *pile height = tangent(angle) x distance + observer height.*

[9] For more specifics concerning the information that can be gleaned from mining waste piles, see Paul J. White. 2003. Heads, Tails, and Decision in-between: The Archaeology of Mining Wastes. *IA, The Journal of the Society of Industrial Archaeology* 29(2):47-66.

[10] This is based on an average tailings pile height of 40 feet, which was derived from field and photogrammetric measurements. However, some tailings piles are much higher than 40 feet, such as the tailings pile at Humberstone which is well over twice that height, so these are considered conservative estimates.

[11] This is based on an average ore storage pile height of 30 feet, which was derived from field and photogrammetric measurements.

[12] These sites were placed on the UNESCO World Heritage list in 2005. See http://whc.unesco.org/en/list/1178 for documents pertaining to their listing.

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