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Review

Lithium brine production, reserves, resources and exploration in Chile: An updated review

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ABSTRACT

The discovery of lithium in the Salar de Atacama of Northern Chile during a survey in 1969, initiated the identification of one of the worlds major continental regions of lithium brines. Today the Central Andes provides a significant part of the world's Li production.

Chile became a major producer due to the large size of the Salar de Atacama and the high quality of the lithium brines which resulted in Chile producing 23% of world lithium in 2019.

Several studies are reviewed in order to better understand Chile's remarkable current and future situation regarding lithium brine production, reserves, resources and exploration.

1. Introduction

Lithium has been listed as one of the critical or near-critical elements in several recent studies based mostly on its prominence in green technologies (Bradley et al, 2017).

The principal producer of lithium from brine is Chile. In 2019, produced 18,000 tons of lithium metal, some 23% of the world's total of 77,000 tons of lithium (t Li). Chile's total cumulative production during the last 35 years was 246,956 t Li.

The first published mention of lithium brines in Chile came in 1969 when an extensive survey was made of the Salar de Atacama (Moraga et al, 1974). Initial production from this deposit, began in 1984 from what is presently the world's richest commercial lithium brine deposit.

Lithium rich brines are predictable over a large area of Northern Chile from which some 59 occurrences have been reported so far (Cabello, 2017).

Here, we are counting only 23 deposits that include exploration or evaluation efforts. Of these 23 cases, only two; the Salar de Atacama and the Salar de Maricunga are the subject of evaluation work with enough detail to be able to define lithium reserves.

Reports, evaluations and exploration surveys on 23 salars completed during the last decade provide an updated view on the current situation of lithium production, reserves, resources and exploration in Chile.

2. Location, geographical and geological setting

Northern Chile is characterized by a succession of north–south-trending ranges and basins occupied by numerous saline lakes and salt crusts, collectively called salars (Chong, 1984; Risacher et al., 2003; Vila, 1990). These salars constitute one of the world's most important evaporite complexes that contain significant portions of the recognized resources of lithium (Ericksen and Salas, 1989; Cabello, 2010). At least 59 salars (about 5211 square km in surface), saline lakes and lagoons (some 222 square km), ranging in area from a few square km to about 3,000 square km are found in individual closed basins (endorheic basins) within a 53,000 square km of basins area with internal drainage (Fig. 1). This prospective belt runs N-S along Arica y Parinacota, Tarapacá, Antofagasta and Atacama Regions (between 18° to 27° south latitude) in Northern Chile (Cabello, 2017). It occupies the eastern side of the country, limited to the east by the Bolivian and Argentinean borders. The width varies from 50 to 250 km (120 km estimated average) and a length of about 1,000 km, resulting in an area of about 120,000 square km.

From a geomorphologic point of view, this region is characterized by a large number of endorheic basins, many of them with a marked tectonic control. These basin systems are important local base levels for the drainages of the Pacific divide.

An arid climate persisted in this region during most of the Miocene and Quaternary. The basins in which the salars and saline lakes are found were formed by faulting and by volcanic eruptions controlled by a combination of geological, morphological, hydrological, and climatic factors (Munk et al, 2016). The volcanic rocks are the major sources of the saline materials in the salars. Most of the salars formed by desiccation of saline lakes during the Holocene and by subsequent deposition of saline materials from evaporation of spring waters, ground water and annual or intermittent flood water.

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3. Production

With the world's principal reserves and lowest cost of production, it's not surprising that Chile is a worldwide frontrunner in the lithium market (INN, 2018). The Salar de Atacama, in Northern Chile is the largest producing brine deposit in the world. It has the highest known concentration of lithium, averaging 0.14% (or 1400 ppm) lithium equivalent to around 1,680 mg/l due to it 1.2 g/cc density, and is the world's largest producer of lithium carbonate. In 2019 from operations by Sociedad Química y Minera (SQM) and Albemarle, respectively, it produced 18,000 tons of lithium metal, some 23% of the world's total of 77,000 tons of lithium, excluding U.S. production (USGS, 2020).

Chile owes its low production costs to the geological nature of the deposit and an ideal climate. Cochilco (2013) reported a production cost for lithium carbonate ton of US$ 2,000–2,300 but in the 2017 this figures were estimated in US$ 2,600 to 3,100. The Salar de Atacama lacustrine brines and playa evaporites contain the lithium dissolved in solution, derived from dissolution of surrounding rocks in drainage basins. (Gruber and Medina, 2010). Lithium is extracted from brine deposits with high lithium concentrations and high evaporation rates in a hyper-arid continental basin (Munk et al, 2018). The Salar de Atacama hosts approximately 60% of the world's lithium reserve base, and is the largest and highest-grade lithium-from-brine producer in the world (USGS, 2020). The proprietor of the claims in the Salar de Atacama nucleus is the state owned Corporación de Fomento de la Producción (CORFO). SQM and Albemarle have a rental agreement to extract and produce lithium from the brines stored in the Salar de Atacama reservoir. SQM rents an area about 1,400 square km with permission to extract brines from an area of 820 square km with two operations in the nucleus. It currently produces lithium from its southwestern operation. Albemarle rents an area of 137 square km and one operation in the southeast, part of which is devoted to lithium extraction. A buffer zone of around 100 square km separates the two companies' leased claims.

Brines containing high concentrations of lithium are pumped from saltwater aquifers using extraction wells. From the wellhead, the brine is diverted to an evaporation pond system.

Fig 1. Andean and Pre-Andean Salars in Northern Chile.

Using solar evaporation, the lithium salts are concentrated in the brine and then sent to the next pond in the system. This step is continued multiple times, until the lithium concentration reaches a level (6% solid wt in the solution) high enough for conversion to lithium carbonate or lithium hydroxide.

The altitude and inherently arid conditions of the region contribute to an evaporation process that is completely powered by the sun. The entire concentration process can take 12–18 months.

During evaporation, other minerals, which typically contain sodium, potassium and magnesium, precipitate from the brine, leaving higher concentrations of lithium chloride (LiCl). The resulting concentrated LiCl brine from the last pond in the system is then transported to chemical processing plants near Antofagasta city (Salar del Carmen and La Negra Plants) where it is converted to lithium carbonate, lithium hydroxide or lithium chloride.

The deposit also contains large amounts of other useful elements, including sodium, potassium, magnesium and boron, which offset some of the costs of pumping and processing brines. Potash, which is any of several soluble potassium salts, is the main product, and lithium is a byproduct.

Regarding the lithium operations (Table 1), the data available indicate that the total cumulative production from 1984 to 2019 (35 years) in the Salar de Atacama is 1,149,000 t lithium carbonate, 61,400 t lithium hydroxide and 43,000 t lithium chloride, all corresponding to some 247,000 t of lithium metal.

New agreements between Corfo (Corporación de Fomento de Chile, owner of the mining claims) with SQM & Albemarle indicate that future lithium production from the Salar de Atacama could, at some stage, reach 48,800 t per year.

Table 1
Lithium Brines Production Chile 1984–2019 (Salar de Atacama).

Year	Li carbonate (t)	Li hydroxide (t)	Li chloride (t)	Eq. Lithium (t)
1984	2,110	0	0	397
1985	4,508	0	0	847
1986	4,458	0	0	838
1987	6,139	0	0	1,.154
1988	7,332	0	0	1,378
1989	7,508	0	0	1,411
1990	9,082	0	0	1,707
1991	8,575	0	0	1,612
1992	10,823	0	0	2,036
1993	10,369	0	0	1,949
1994	10,439	0	0	1,962
1995	12,943	0	0	2,433
1996	14,180	0	0	2,666
1997	24,246	0	0	4,558
1998	28,337	0	807	5,458
1999	30,231	0	161	5,709
2000	35,869	0	0	6,743
2001	31,320	0	0	5,888
2002	35,242	0	0	6,625
2003	41,667	0	0	7,833
2004	43,971	0	494	8,346
2005	43,091	504	681	7,134
2006	46,241	3,794	1,166	8,883
2007	51,292	4,160	4,185	10,324
2008	48,469	4,050	4,362	9,823
2009	25,154	2,987	2,397	5,610
2010	44,025	5,101	3,725	9,724
2011	59,933	5,800	3,864	12,853
2012	62,002	5,447	4,145	13,229
2013	52,358	4,197	4,091	11,201
2014	55,074	4,194	2,985	11,531
2015	50,418	3,888	2,069	10,456
2016	70,831	5,576	1,,775	14,525
2017	73,563	5,279	2,535	15,113
2018	87,029	6,468	3,826	17,000
2019	n.a	n.a	n.a	18,000
	1,148,829	61,446	43,268	246,956

Source: Sernageomin (2018), Cochilco (2018), and USGS (2020).

4. Reserves

As expected, during the last 10 years, important progress has been made on lithium rich brine deposit evaluation (Houston et al., 2011; Hains, 2012; Kunasz, 2013; Evans, 2014). Brines are distinctive amongst mineral deposits as the valuable elements are enclosed in a mobile environment, and both brine composition and grade change with time, before and during extraction. In the case of Chile, the Salar de Atacama, a mature halite salar in production since 1984, and the recently evaluated Salar de Maricunga, are the only deposits including reserves calculated according current mining industry protocols.

The SQM operation released a public presentation (Fock, 2019) which describe reserve calculations from their mining claims (819 square km). In it, a professional team from SQM calculate the volume of the brine host aquifer, halite body porosity, density and lithium concentration. Additionally, a 3D geological model was generated, supported by RC and DDH drilling with QAQC protocols. This estimation method by SQM yielded a reserve of some 9,200,000 t of lithium that can be considered NI 43–101 compliant (SQM, 2020).

Another recent article (Osses, 2018), reported 1,290,000 t of lithium reserves included in the Albemarle 167 square km mining claims but without references to a related company technical report. By reviewing the size of the mining claim as well as a comparison with the SQM reserve estimation, this number could be reasonably assumed to be valid.

The second most important lithium brine deposit in Chile, the Salar de Maricunga, was recently the subject of a feasibility study (Worley Parsons, 2019) for a lithium carbonate project, which reported 389,000 lithium t reserves.

When considering the information related to the two operations in the Salar de Atacama plus a recent evaluation at the Salar de Maricunga, a total estimated reserve of 10,879,000 t lithium is obtained (Table 2). This figure corresponds to some 64% of world reserves (17,000,000 t Li) using the most recently published statistics (USGS, 2020).

5. Resources

Since the lithium discovery in the Salar de Atacama in 1969, some studies in several salars materialized (Gajardo and Carrasco, 2010; Troncoso et al., 2013; Carrasco et al., 2018) in addition to evaluations from some mining companies. This resulted in technical information from 22 salar deposits.

A group with 9 deposits corresponds to those that include individual tonnage calculations with reported average lithium concentrations. They are (Table 3): Surire, Atacama, Punta Negra, Aguilar, La Isla, Las Parinas, Pedernales, Laguna Brava and Laguna Verde. This group covers 2003 square km total area with an estimated 3,335,10 t lithium from a 561 ppm Li average concentration.

The lithium tonnage figures (Table 3) are not NI 43–101 compliant, but could be used as a fair preliminary indication of economic potential as well as a reference for future exploration and evaluation activities.

6. Exploration

Brines are unique amid mineral deposits because the valuable elements are enclosed in a mobile environment, and both brine composition and concentration have a temporal component (Hains, 2012). These aspects present distinctive problems in exploration and sampling of lithium brine deposits.

Lithium-rich brines are found across the Central Andes region. However, these brine deposits, referred to as “salars,” vary substantially in terms of lithium concentrations and are exposed to different weather conditions (i.e., evaporation rates, precipitation rates, wind patterns and ambient temperatures), all of which influence the ability to economically recover lithium from each salar. All these aspects are important to evaluate during the exploration stages but most important are: use of

Table 2
Lithium Brine Reserves.

Salar	Type	Altitude m	Basin km^2	Area km^2	Explot. Area km^2	Average Li Concentration ppm	Reserves Li t	References
Atacama (Nucleus)	Pre-Andean	2,300	18,100	986	167	1,500	1,290,000	Osses (2018)
Atacama (Nucleus)	Pre-Andean	2,300	18,100	986	819	1,500	9,200,000	Fock (2019); SQM (2020)
Maricunga	Pre-Andean	3,760	3,045	145	25	1,117	389,000	WorleyParsons (2019)
Total			21,145	1,131	1,011		10,879,000	

Table 3
Lithium Brine Resources.

Salar	Type	Altitude m	Basin km^2	Area km^2	Explot. Area km^2	Average Li Concentration	Resources Li t	References
Surire	Andean	4,260	574	144	**n.a**	400	180,000	Prokurika (2018)
Atacama	Pre-Andean	2,300	18,100	986	652	1,500	2,170,000	Osses (2018)
Punta Negra	Pre-Andean	2,945	4.263	250	n.a	280	220,000	Prokurika (2018)
Aguilar	Andean	3,320	589	71	n.a	337	70,000	Prokurika (2018)
La Isla	Andean	3,950	858	152	n.a	1,080	270,000	Prokurika (2018)
Las Parinas	Andean	3,987	676	40	n.a	477	50,000	Prokurika (2018)
Pedernales	Pre-Andean	3,370	3,620	335	n.a	423	375,000	Prokurika (2018)
Laguna Brava	Andean	4,250	504	10	n.a	310	3	Hiner (2010a)
Laguna Verde	Andean	4,350	1,075	15	n.a	247	97	Hiner (2010b)
Total			30,259	2,003		561	3,335,100	

geological models (Bradley et al., 2013; Munk et al., 2016) and then consider in good detail salars extension, nucleus size, halite crust and brine characteristics.

As previously stated, lithium rich brines are known across a large area, with some 59 occurrences reported so far (Cabello, 2017). Here, we are including only 23 salars (Fig. 1), for which different quality information from exploration or evaluation efforts is available. From these 23 cases, only the Salar de Atacama and the Salar de Maricunga include evaluation work acceptable in defining lithium reserves.

And from the already mentioned 23 salars group, 13 salars (Table 4), were subject to partial and preliminary sampling. This resulted in a total area of 579 square km with 290 ppm Li average concentration.

In the future an exploration effort can be anticipated, focused on the areas of highest prospectivity already tested, including some 36 priority areas to check if we add to the 13 salars already partially tested, other basins not sampled yet.

Studies must be carried out to define the exact location and thickness of brine deposits within the basins. Shallow pits, geochemistry and surface distribution will help define the targets for further exploration. This initial phase involves brine sample collection and chemical assays. Geophysical techniques can define the size and extent of brine pools inside the basins and also assist in delineating depth to basement rock as well as fresh water transition zones with the brine deposit. Saline deposits will be more conductive than enclosing materials and should be readily apparent by the use of a properly designed electromagnetic survey. The use of a TEM (Transient Electromagnetic) survey is suggested to define the brines.

A study of available literature indicates that lithium bearing brines may be located just below the salt crust of the salar, as in the Salar de Atacama, Chile, or contained within aquifers that may form part of the

Table 4
Lithium Brines Potential Resources

Salar	Type	Altitude m	Basin km^2	Area km^2	Explot. Area km^2	Average Li Concentration ppm	References
Tara	Pre-Andean	4,400	2,035	48	n.a	600	Troncoso et al. (2013); Carrasco et al. (2018)
Aguas Calientes 1	Andean	4,280	221	6	n.a	290	Troncoso et al. (2013); Carrasco et al. (2018)
Pujsa	Andean	4,500	634	18	n.a	620	Troncoso et al. (2013); Carrasco et al. (2018)
Loyoques/Quisquiro	Andean	4,150	676	80	n.a	640	Troncoso et al. (2013); Carrasco et al. (2018)
Aguas Calientes 2	Andean	4,200	1,168	134	n.a	45	Troncoso et al. (2013); Carrasco et al. (2018)
Laco	Andean	4,250	306	16	n.a	32	Troncoso et al. (2013); Carrasco et al. (2018)
Talar (Aguas Calientes 3)	Andean	3,950	476	46	n.a	17	Troncoso et al. (2013); Carrasco et al. (2018)
Aguas Calientes 4	Andean	3,665	656	20	n.a	205	Troncoso et al. (2013); Carrasco et al. (2018)
Pajonales	Andean	3,537	1,964	104	n.a	350	Troncoso et al. (2013); Carrasco et al. (2018)
Gorbea	Andean	3,950	324	27	n.a	500	Troncoso et al. (2013); Carrasco et al. (2018)
Agua Amarga	Andean	3,558	863	23	n.a	60	Troncoso et al. (2013); Carrasco et al. (2018)
Grande	Andean	3,950	867	29	n.a	123	Troncoso et al. (2013); Carrasco et al. (2018)
Piedra Parada	Pre-Andean	4,150	388	28	n.a	288	Troncoso et al. (2013); Carrasco et al. (2018)
Total or Average			10,578	579		290	

basin fill, as at Clayton Valley, Nevada, USA. Lithium is not as a rule extracted from surface brines as these usually comprise dilute solutions and serve only as an indicator of the presence of lithium.

When possible, samples of brines should be obtained from surface brines in lagoons and from springs draining into the salars. Samples should also be collected under the salt crust, accessed both by shovel or auger as required.

7. Concluding remarks

Lithium occurs in economic concentrations in several salars of the Central Andes region in Northern Chile, which has developed into one of the most important productive centers of the world thanks to the development in the Salar de Atacama of the world's richest commercial brine deposit.

In 2019, Chile produced 18,000 tons of lithium metal, some 23% of the world's total of 77,000 tons of lithium. New investment agreements suggest that future lithium production from the Salar de Atacama could reach 48,800 t per year at some stage in the future.

Information related to the two operations in the Salar de Atacama plus a recent evaluation at the Salar de Maricunga, allow an estimated reserve of 10,879,000 t lithium. This amount corresponds to roughly 64% of world reserves (17,000,000 t Li) using the most recently available data.

Based on evaluations of varying quality for 23 salars, many of them at a very preliminary level, a lithium brine resource estimation (non-compliant with mining industry protocols) is presented. The number obtained for the group of 9 deposits corresponds to those that include individual tonnage calculations with reported average lithium concentration. This group represents an estimated 3,335,100 t lithium from a 561 ppm Li average concentration.

The accumulation of reserves and resources recognized so far, means the existence of plus 14,314,000 tons of lithium in the country.

As reported, lithium rich brines are known across a large area with some 59 occurrences reported so far. From that group, only 23 include exploration or evaluation effort including 13 salars for which partial sampling is available. This resulted in a 579 square km total area representing a 290 ppm Li average concentration deserving additional studies to clarify the meaning of their lithium anomalous content.

An important exploration effort is justified to obtain a clear picture of economic lithium brines present in this prospective region hopefully including 36 areas not tested yet.

The lithium brines reserves, resources and exploration potential identified and reported in this review warrant the future presence of Chile as a worldwide key player in the lithium industry.

Declaration of Competing Interest

The author declare that have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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