



# Use of discharged brine from reverse osmosis plant in heap leaching: Opportunity for caliche mining industry



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## ABSTRACT

Caliche is a highly water-soluble mineral that is exploited in northern Chile for its valuable content of iodine and nitrate, which are used in technological, medical, agriculture, dietary, and industrial applications. The processing of this mineral is through vat or heap leaching, where the species are dissolved using mainly fresh water and intermediate solutions. Since the deposits are located in zones with scarce water availability, one of the challenges for this industry is the search for new sustainable sources of water to face the process requirements. The use of groundwater sources by the mining industry has affected the domestic water supply for the nearest populations, increasing the need for new water alternatives as desalination of seawater by reverse osmosis (RO). A disadvantage of this method is the generation and discharge of highly concentrated brines to sea. In this work, the feasibility to use RO brine for caliche leaching was empirically proved through column-leaching experiments, which showed high recoveries of iodine and nitrate. Therefore, the use of RO brines may be an interesting option, on one side, for covering the increasing demand of processing water and, on the other side, to diminish the negative impact of brine disposal to the sea.

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## 1. Introduction

In desalination there are two basic technologies for salt removal of seawater, which are by thermal evaporation or by using membranes. The thermal evaporation has been used hundreds of years ago in Middle East (UAE, Jordan, Kuwait and Saudi Arabia), but only in the 1950s began the industrial processing of seawater by this method. Later, in the 60s less expensive techniques based on membrane separation emerged, such as reverse osmosis (RO) (Fritzmann et al., 2007; Greenlee et al., 2009). Due to the fact that RO consumes 60% less energy than evaporation; it is the technology most used in the new desalination plants. Its widespread implementation has also been driven by the improvement of membranes and energy recovery processes (Morillo et al., 2014).

In Chile, the desalination of seawater is a growing activity that is concentrated in the northern region, being mainly driven by the mining sector (Table 1). Since 2003, when the first desalination facility was installed up to now, many projects have appeared with different capacities. It is expected that in the next years, uptake of seawater for desalination will increase.

While the development of the RO technology has allowed the use of seawater for human and industrial consumption as a feasible

alternative, one of the negative consequences of its process is related to the effluents that are generated and how these are disposed. In the process of RO, brines are generated with high concentrations of dissolved solids that are commonly discarded to the sea due to its low cost. Current operations have yields close to 50% i.e. from 100 L of taken seawater; 50 L of desalinated water and 50 L of brine are produced. This type of discharges may have a negative environmental impact on the ecology of the outfall vicinity. There is evidence that, depending on habitat conditions and the hydrological characteristics where discharge occurs, exposure to these brines can cause osmotic stress to salinity-sensitive organisms, leading to increased turbidity, limiting photosynthesis and breaking existing trophic chains (Fritzmann et al., 2007; Roberts et al., 2010). One alternative to eliminate this problem is to find uses for the RO brines, like the leaching of copper oxides and caliche minerals.

Caliche is a mineral composed by a high proportion of water-soluble species at room temperature, such as nitrates (Nitratine, Humberstonite and Darapskite), sulphates (Glauberite, Polyhalite, Bloedite, Gypsum and Anhydrite) and chlorides (Halite) as shown in Table 3. Relatively high proportions of iodate (mainly Lautarite and Hectorfloresite) are contained in caliche ores compared with other minerals (Ericksen, 1983; Jackson and Ericksen, 1994). The importance of the exploitation of this resource is that it is the largest mineral natural source of iodine and nitrate (saltpetre) known (Ericksen, 1983). Iodine is primarily used in medical applications (contrast medium in X-rays) and as a

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**Table 1**  
Main projects of seawater desalination in Chile (Cochilco, 2013; Moreno et al., 2014; CSEA, 2014).

Project	Company	Capacity, L/s	Status
Human consumption			
La Chimba plant	Agua Antofagasta	600	In operation
Desaladora Sur plant	Agua Antofagasta	400	In study
Industrial consumption			
Doña Inés de Collahuasi SCM, III expansion	Anglo American plc Glencore Mitsui & Co, Ltd.	1000	In study
Coloso plant	BHP Billiton	525	In operation
Coloso expansion	BHP Billiton	N/A	Approved
Radomiro Tomic expansion	Codelco	1100	In study
Candelaria	Freeport McMoran Copper & Gold	300	Under construction
El Abra	Freeport McMoran Copper & Gold	1300	In study
Cerro Negro Norte	CAP	200	Under construction
El Morro	GoldCorp	740	Under construction
Mantoverde	Anglo American	120	Under construction

N/A: Not available.

nutritional supplement for animals and humans, as well as in the production of LCD screens, among other products (Polyak, 2014). On the other side, nitrates are employed in the manufacture of fertilizers for crops with special nutritional requirements and as industrial salts for thermal storage in solar plants (SQM, 2012).

Chile is the world leader producer of iodine and natural nitrates, since 63% of the iodine produced worldwide in 2012 came from the exploitation of caliche, followed by Japan and United States that exploit seaweeds and subterranean brines, respectively (Polyak, 2014). Moreover, 50% of natural nitrate based fertilizers that is marketed, has a Chilean origin, then follow Jordan and Israel (Moreno et al., 2014).

The deposits of caliche are distributed in northern Chile, for about 2100 km<sup>2</sup> under a sterile layer called Chuca (Erickson, 1983). After extraction of the ore by blasting or mechanical rupture, the caliche is leached in vats or heaps. For both cases, the dissolution of the species of interest from the solid matrix is carried out using water or intermediate solutions, because unlike most ores, the leaching of this mineral is governed by the solubility of the species (Valencia et al., 2008; Wheeler, 2010; Gálvez et al., 2012; Ross et al., 2013; Ordóñez et al., 2014a). For heap leaching, the ore is watered, usually by spraying, from the crown of the heap at low irrigation rates, between 1.5 and 6 L/h/m<sup>2</sup> (Wheeler, 2010). The leaching cycles last between 3 and 7 months, reaching a ratio leachant/caliche of about 1 m<sup>3</sup>/t (CSEA, 2014), afterwards the leachate is treated to obtain the products of interest.

The sustained growth of population and mining industry results in an increasing demand for water. In areas where this situation coexists with natural scarcity of water resources, such as northern Chile, the looking for new sources of water supply is becoming increasingly necessary (Cisternas and Gálvez, 2014). Since water is essential for mineral processing, several initiatives about the best use of water within the processes have been implemented (Donoso et al., 2013; Gálvez et al., 2014); however it is known that in the near-future, sustainability of the mining projects will depend in more significant changes of water usage (Cochilco, 2013). In this regard, several researchers and companies have studied and used seawater as process water, both directly and after salt removal treatments as desalination (Moreno et al., 2011; Philippe et al., 2011; Ordóñez et al., 2013; Torres et al., 2013; Cisternas and Moreno, 2014).

This work is based mainly in two aspects; on the one hand, the growing demand for alternative water sources for mining industry and on the other hand, the increasingly existence of brines that will be discarded to sea. The work aims to validate experimentally by pilot tests that brines

coming from reverse osmosis plants may be used in leaching of caliche mineral with similar performance than traditional leachants. In this context, the effluents produced in the desalination of seawater, instead to be disposed in the sea, should be pumped-up to the desert through distances of a few hundred kilometres and elevations of between 1000 and 2000 m.a.s.l. to be used in mining operations; e.g., leaching. The solution could be based on a configuration where seawater is transported to the desert and a fraction (or all) is desalinated and used in mining operations or as potable water and the brines (or no-desalinated water) used for leaching.

## 2. Experimental procedure

### 2.1. Column leaching experiments

Caliche used in the leaching experiments was obtained from natural deposits located in northern Chile. The material was size-screened between 1.3 and 3.8 cm, with an average particle diameter of 2.5 cm. The caliche was then loaded by batches in 5 Polyvinyl chloride columns of 0.2 m of diameter and 1.0 m of height. Table 2 details the chemical composition of soluble species of caliche ore.

Mineralogy of caliche was also examined by the semi-quantitative technique X-ray diffraction (XRD), being its main constituents: Quartz, Anhydrite, Glauberite, Halite and Nitratine, which represent about 75% of mass. The ore has a high fraction of soluble minerals, reaching 45% in mass (Table 3). Nitrate and chloride are present uniquely as Nitratine and Halite, respectively, both very soluble species. In opposition, sulphate is the anion mostly shared among mineral species with different solubilities, such as Anhydrite, Glauberite, and Loewite. Through XRD iodine is not perceptible, due to its small relative abundance in the solid ores. However, it is known that usually iodine minerals are Lautarite (Ca<sub>2</sub>(IO<sub>3</sub>)<sub>2</sub>), Bruggenite (Ca<sub>2</sub>(IO<sub>3</sub>)<sub>2</sub>·H<sub>2</sub>O) and Hectorfloresite (Na<sub>9</sub>(IO<sub>3</sub>)(SO<sub>4</sub>)<sub>4</sub>) (Jackson and Erickson, 1994).

The RO brines were obtained from a desalination plant located in Antofagasta (Chile) and untreated seawater, used for comparison purposes, was collected by a submarine outfall in Antofagasta. The leaching was carried out during 22 days using 3 different irrigation rates and 2 solution temperatures. The conditions used in these experiments are detailed in Table 4.

Insulating foam (Ethylene Vinyl Acetate) was used to isolate the walls of the column and the solution container in the test with high temperature. The water was maintained at the required temperature by heaters controlled by thermostat.

The irrigation of leachants to columns was done continuously through peristaltic pumps and the containers with the leaching solution were covered from light to avoid the growth of algae. The leachant compositions are listed in Table 5. The wetting of caliche was done at the nominal rate and once the leachate begun to drip from the column bottom, the leaching was considered started. No recirculation of the leachate was conducted.

### 2.2. Sampling and chemical analysis

Liquid samples of leachates were taken every 12 h for the first 5 days of leaching, and then a daily sample was collected until the final of the experiments. Solid sampling was also done at the beginning for homogenized caliche and at the end for the residues of each column, when they were dismantled.

**Table 2**  
Water-soluble composition of caliche (g/100 g) used in leaching experiments.

Anions						Cations			
NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	IO <sub>3</sub> <sup>-</sup>	Cl <sup>-</sup>	ClO <sub>4</sub> <sup>-</sup>	BO <sub>3</sub> <sup>-</sup>	Na <sup>+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>	Ca <sup>2+</sup>
7.8	15.6	0.04	7.0	0.02	0.09	8.7	2.0	1.5	0.6

**Table 3**  
Mineral composition of caliche determined by XRD analysis.

Name	Formula	Concentration, g/100 g
Quartz	SiO <sub>2</sub>	37.3
Glauberite	Na <sub>2</sub> Ca(SO <sub>4</sub> ) <sub>2</sub>	12.4
Anhydrite	CaSO <sub>4</sub>	9.4
Halite	NaCl	8.2
Nitratine	NaNO <sub>3</sub>	8.1
Loewite	Na <sub>12</sub> Mg <sub>7</sub> (SO <sub>4</sub> ) <sub>13</sub> ·15H <sub>2</sub> O	6.8
Polyhalite	K <sub>2</sub> Ca <sub>2</sub> Mg(SO <sub>4</sub> ) <sub>4</sub> ·2H <sub>2</sub> O	4.9
Bloedite	Na <sub>2</sub> Mg(SO <sub>4</sub> ) <sub>2</sub> ·4H <sub>2</sub> O	4.0
Albite-Ca	(Na,Ca)Al(Si,Al) <sub>3</sub> O <sub>8</sub>	3.5
Andalusite	Al <sub>2</sub> (SiO <sub>4</sub> )O	1.7
Orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>	1.6
Montmorillonite-15A	Ca <sub>0.2</sub> (Al,Mg) <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> ·4H <sub>2</sub> O	0.8
Kieserite	MgSO <sub>4</sub> ·H <sub>2</sub> O	0.7
Sepiolite	Mg <sub>8</sub> (OH) <sub>4</sub> Si <sub>12</sub> O <sub>30</sub> ·12H <sub>2</sub> O	0.2
Chlorite-Fe	(Mg,Fe) <sub>6</sub> (Si,Al) <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>	0.2
Probertite	NaCaB <sub>5</sub> O <sub>7</sub> (OH) <sub>4</sub> ·3H <sub>2</sub> O	0.2

All the samples, including leaching agents, were chemically analysed for the ions: nitrate, iodate, chloride, sulphate, perchlorate, boron, sodium, potassium, magnesium and calcium. Nitrate was quantified by UV molecular absorption spectroscopy, iodate, chloride and boron by volumetry, and sulphate by gravimetry. Metallic ions were determined by atomic absorption spectroscopy and perchlorate by ion selective electrode. The density was measured by picnometry.

Additionally, the mineralogy of solids was studied using the D5000 diffractometre (Siemens) in order to observe the possible variation of the mineral species that may occur during the leaching. For the determination of water-soluble components of solids, the samples were mixed and stirred with distilled water in a ratio of 1:10 (kg:L) for 6 h. Later, the suspension was decanted and the liquid analysed.

### 3. Results and discussion

#### 3.1. Concentration profile

In order to evaluate the performance of the leaching process, the dissolution of the most important soluble ions was followed in terms of leachate volume. It is clearly observed that while some species rapidly disappeared during leaching such as nitrate, sodium, perchlorate and iodine, other ones decreased their concentrations much slower, such as sulphate, potassium, magnesium and boron (Fig. 1). In the right axis of these plots, arrows are drawn indicating the concentration in the RO brine of the respective ion. The dissolution behaviour was similar in all the experiments only with small variations provoked by the different operating conditions used, which are discussed subsequently.

The dissolution rate of the caliche species is mainly determined by the irrigation rate. Therefore when the concentrations were visualized against time (presented in the Supplementary data in Fig. 1A) the fastest responses were achieved by the most intensively watered experiments. On the other side, the recovery of the soluble species is mainly determined by the volume of leachant added.

The volume of leaching solution per mass of caliche used in industrial heap leaching is of about 1 m<sup>3</sup>/t; which corresponds to about 35.4 L of leachate in these experiments. However, in order to study the behaviour

**Table 4**  
Column leaching experiments.

Experiment name	Leaching agent	Irrigation rate, L/h/m <sup>2</sup>	Temperature, °C	Mass loaded, kg
SW6A	Seawater	6	19	35.8
BR6A	Brine	6	19	36.3
BR8A	Brine	8	19	35.3
BR4A	Brine	4	19	35.5
BR4T	Brine	4	35	35.1

of the minerals that show slow dissolution rate, such as sulphate, magnesium, and potassium more leachant was added.

Regarding the ion outlet concentrations for a ratio leachant/caliche of 1 m<sup>3</sup>/t (about 35.4 L in the plots in Fig. 1), it is found that they are close to the concentration of the ion in the leaching solution for the highly soluble species. For nitrate, iodate and perchlorate it is very small, while for chloride and sodium the concentration is close to that found in the leaching solutions. On the other side, for the ions with a moderate dissolution rate such as sulphate, magnesium, and potassium, the concentrations are significantly higher than in the leachant for an added solution volume of 35.4 L. However the differences of concentration for these ions became very small at the final of the leaching (80 L of leachant).

Excepting nitrate and perchlorate, the maximal concentration for all other ions is not found at the beginning of leaching; the concentration peak is reached after a while, this could be due to the fact that the dissolution is not only occurring in the surface of the particles, but that this takes place in a layer of a certain thickness. Initially only the material very close to the surface is dissolving, with time the thickness of the layer, in which the dissolution is occurring, increases and higher concentrations may be obtained. This is determined by the dissolution rate, the solubility of the ions and the advance rate of the wetting front into the particle. The dissolution rate of nitrate and perchlorate is very high; therefore the dissolution is always occurring in a thin layer.

In all experiments, the maximum outlet concentration from the columns is lower than the solubility of the corresponding ion; this could be due to the fact that the leaching agent has not enough time to reach its saturation. In the case of nitrate and perchlorate, highly soluble species, the outlet column concentration diminishes rapidly from its maximum outlet concentration, which takes place at the start of leaching. However, this initial solution is not saturated, since the residence time of the leaching solution in the column is too short; a longer residence time is required in order to reach saturation.

Increase of sulphate concentration at the beginning is accentuated, reaching double the concentration of initial output. In a minor extent, chloride levels also increased at the same time. According to Ordóñez et al. (2013), the dissolution of caliche supposes an interaction of ions that result in the precipitation of sulphate species. Dissolution of magnesium, potassium and calcium is closely related with the removal of sulphate due to the fact that they are forming soluble species with this anion.

The calcium dissolution at the column bottom, in general, was steadily increasing during almost all the experiment, apparently the dissolution of calcium is controlled by calcium sulphate, when sulphate is released from the column and its concentration decreases, the concentration of calcium may be increased. The decrease that occurs at very short time may be due to the initial increase of sulphate concentration, which controls the calcium dissolution.

#### 3.2. Residues

Chemical composition of the residues was determined in order to establish the mass balance for each species, while mineral composition of the residues was determined for studying the variation of the mineralogy during the leaching. To compare the composition of the residues with that of the caliche, the concentration is expressed with respect to the initial mass of the caliche and is listed in Table 6. The analysis of the caliche loaded to the columns is also added for comparison purposes. Nitrate concentration in the residue is negligible, it decreases in more than three orders of magnitude, for the other ions the concentration decreases in one order of magnitude. The amount of a given species in the caliche and its solubility determine the residual composition of that ion.

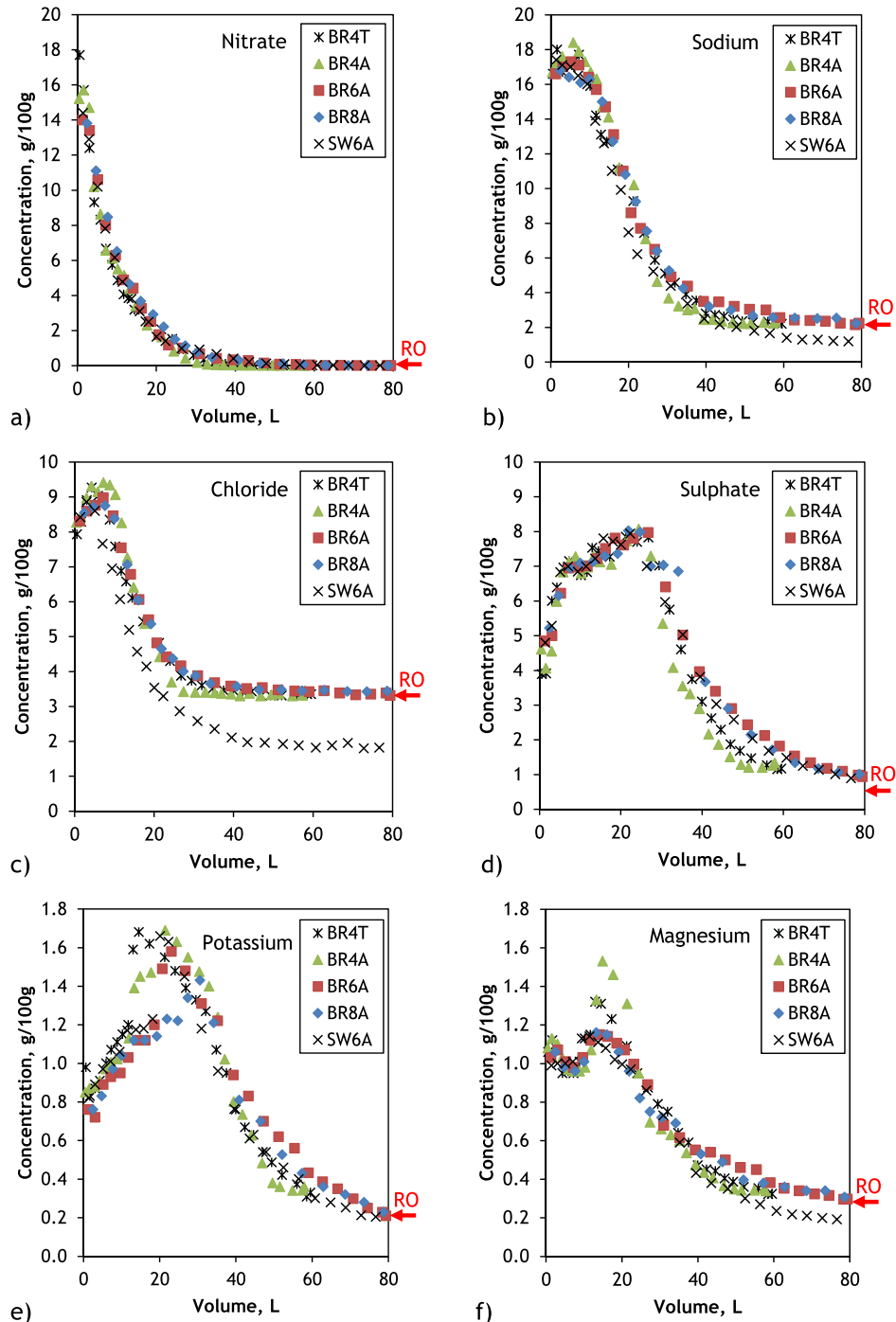
The calcium composition in the residues is close to the initial value; only a small fraction of calcium is dissolved during the experiments. The dissolution of boron was slow and about 20% of it was found in the

**Table 5**  
Chemical composition of leaching agents (kg/m<sup>3</sup>) used in column experiments.

Leaching agent	Density, kg/m <sup>3</sup>	Anions						Cations			
		NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	IO <sub>3</sub> <sup>-</sup>	Cl <sup>-</sup>	ClO <sub>4</sub> <sup>-</sup>	BO <sub>3</sub> <sup>3-</sup>	Na <sup>+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>	Ca <sup>2+</sup>
Seawater	1020	0.34	2.75	0.003	18.36	0.003	0.008	11.12	0.56	1.44	0.52
Brine	1040	0.43	5.35	0.005	35.98	0.005	0.034	25.15	2.45	2.85	0.86

residues. Therefore, for calcium and boron the residual fraction of these species is rather large. Chloride, iodide, magnesium, and sodium showed intermediate concentration variations in the residues.

According to the XRDs of residues, no considerable differences resulted among the 5 treatments and changes in the mineral composition occurred consistently throughout leaching (Fig. 2). Initially, the caliche



**Fig. 1.** Dissolution of the most important soluble constituents of caliche during different leaching experiments. a) Nitrate, b) sodium, c) chloride, d) sulphate, e) potassium, f) magnesium, g) iodate, h) calcium, i) perchlorate and j) borate. The arrows at the right of each plot indicate the concentration of the species in the RO brine.

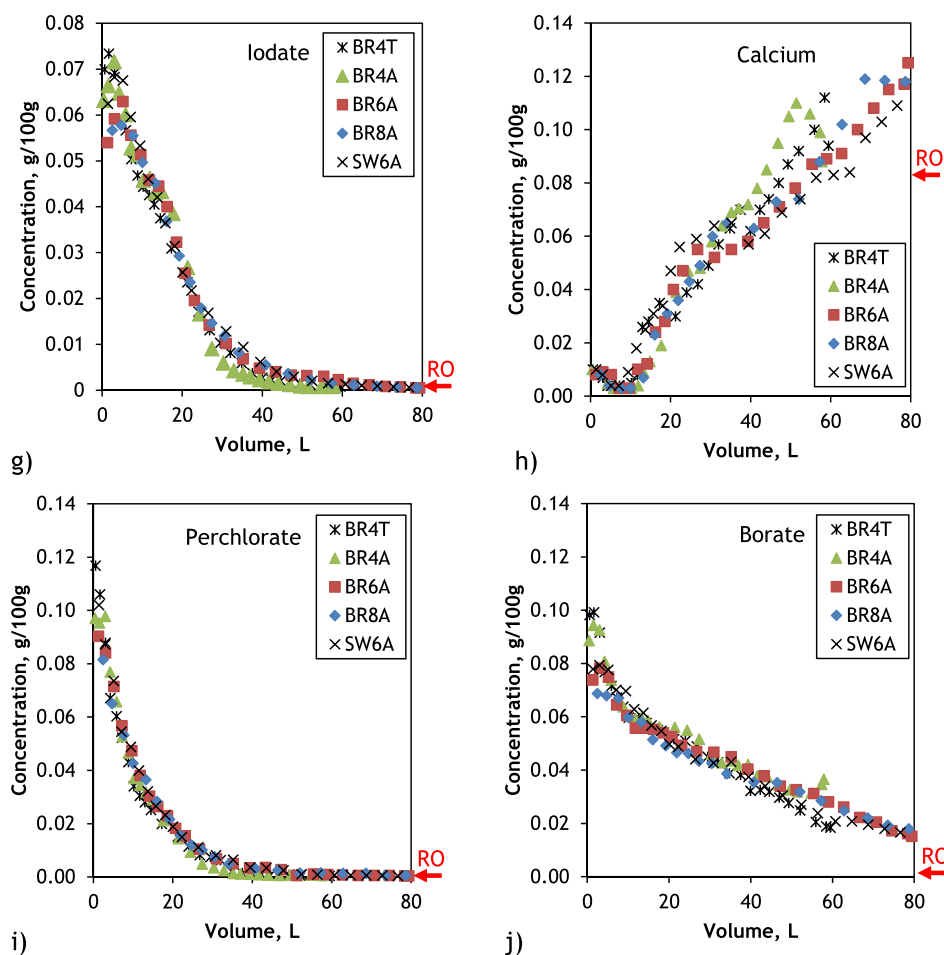


Fig. 1 (continued).

had 9% of the insoluble species Anhydrite, but the residues showed a decrease of this species; increasing the composition of Gypsum (the hydrate form of Anhydrite) in the residues. The fraction of calcium sulphate reached to almost 20% in the residues. In all the columns, a small amount of soluble minerals is found in the residues; between 2 and 9%, mainly as Halite and Polyhalite species. Detailed mineral composition of residues is shown in Table 1A of the Supplementary data.

### 3.3. Recovery

This work considered the use of alternative leaching solutions that could be used in the caliche mining industry as leachants. The utilization of discarded brines from reverse osmosis plants for leaching may be a possible alternative, which has not been evaluated. In order to demonstrate the feasibility to use RO brines for caliche leaching and to evaluate

the effect of leachant agent on the leaching, the recovery of the ions was studied.

No substantial differences in the recoveries were found between leaching using seawater and using RO brine; especially for nitrate and iodine, where even the recovery curves are overlapped and reaching almost the maximal values (Fig. 3). These results strongly support that it is technically feasible to employ RO brines for caliche leaching. As could be expected from the dissolution curves, the extraction of calcium is very small compared with the other species and for this reason calcium was not presented in the recovery plots.

The high recoveries obtained from the experiments for the most soluble species at a leachant/caliche ratio of 1.0 m<sup>3</sup>/t are due to the use of small particles; the mean particle diameter used in these experiments was 0.025 m, while in industrial operations ROM material is used. Caliche leaching of coarse particles was studied by Ordóñez et al. (2014b), they found that the recovery is significantly decreased when

**Table 6**  
Water-soluble composition of residues (g/100 g of initial caliche) obtained from the leaching experiments.

Experiment	Anions						Cations			
	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	IO <sub>3</sub> <sup>-</sup>	Cl <sup>-</sup>	ClO <sub>4</sub> <sup>-</sup>	BO <sub>3</sub> <sup>3-</sup>	Na <sup>+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>	Ca <sup>2+</sup>
SW6A	0.001	2.80	0.002	0.45	0.002	0.02	0.25	0.45	0.20	0.46
BR6A	0.001	1.79	0.002	0.75	0.002	0.02	0.40	0.18	0.09	0.47
BR8A	0.001	1.46	0.002	0.57	0.002	0.01	0.29	0.05	0.04	0.52
BR4A	0.002	1.55	0.002	0.59	0.002	0.03	0.31	0.12	0.07	0.44
BR4T	0.001	2.00	0.002	0.62	0.002	0.02	0.37	0.28	0.12	0.45
Caliche	7.80	15.60	0.04	7.00	0.02	0.09	8.70	2.00	1.50	0.60

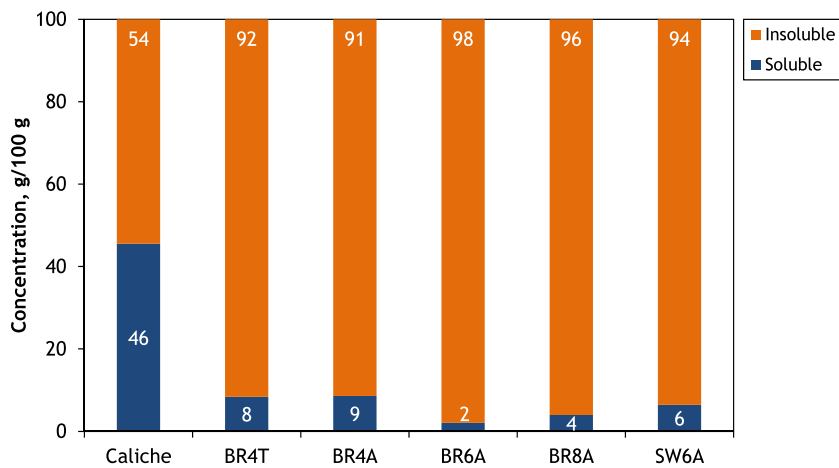


Fig. 2. Decreasing of soluble fraction in caliche after leaching for each experiment.

large particles are used. A model for caliche leaching (Gálvez et al., 2012), which considers the particle size was applied to these results with an acceptable agreement.

Higher irrigation rates imply shorter residence times in the column, therefore, the contact between the leachant and the caliche is less. The most intensively watered column (BR8A – 8 L/h/m<sup>2</sup>) shows recoveries, which are lower than those obtained in the other experiments with lower irrigation rate for the same volume of leachant added.

Regarding iodine recovery, it is possible to observe that the experiments with high irrigation rates (6 and 8 L/h/m<sup>2</sup>) show low recoveries (89 to 91%). On the other hand, the experiments with low irrigation rate show higher recoveries (93 to 95%). The recovery using seawater (89%) is some lower than that using brines (91%). This small difference may be explained by a high variability in the iodine grades within the caliche ore (Ross et al., 2013).

In terms of the elapsed time, the recovery of the highly soluble species reached high values faster in the experiments with the larger irrigation rates. This is not directly observed in the figures since the results are expressed in function of the leachant/caliche ratio. The industry usually handles values close to 1.0 m<sup>3</sup>/t, for this reason, the recovery curves were presented up to this ratio.

According to the effect of temperature on recovery, the use of warmer leachant (35 °C) does not significantly affect the leaching of the soluble fraction, since after making contact with the bed, its temperature rapidly decreases to near room temperature. In this experiment the temperature has relevance only at the upper part of the column, where a higher temperature of the leachant favours the dissolution kinetic of soluble species that are present there. Comparing the first points of the columns BR4T (35 °C) and BR4A (19 °C), the first column showed slightly greater values, which confirm the effect of temperature in the upper part of bed. Later, the recoveries were similar when the dissolution occurs at the middle and the lower part of the column. To analyse the effect of temperature, it would be necessary to heat and insulate the bed in order to maintain a constant temperature in it. However, this is not a practical industrial alternative.

During leaching, the bed heights were measured; at the beginning all the beds had the same initial height and the used loading procedure was similar of all columns. The heights diminished importantly in all the experiments, between 13 and 17%, due to the dissolution of the high soluble fraction that caliche ore contains. This diminution of heights is relatively close to actual industrial operations (Private communication). The variation of the height may be influenced by several factors such as different compaction levels and the wall effects, which may be important due to the small column diameter used in the experiments. For this reason the height decreasing during the leaching may be found in a wide interval; however the trends should not change drastically.

It is important to indicate that the use of RO brines for caliche leaching does not imply the replacement of pipelines and other equipment in the mine site, because in the operation more concentrated solutions are usually managed. If brines are transported instead of seawater from the coastline to the mine site, no changes are needed since the corrosion of brines and seawater is similar (Cáceres et al., 2007).

The recovery results show that it is feasible to leach caliche using RO brine, however to evaluate the use of this solution in actual operations economic and technical issues should be considered.

#### 4. Conclusions

Column leaching experiments of caliche ore using RO brine and seawater as leaching agents were performed, analysing the changes of concentration and recovery of the ions of interest like iodine and nitrate. High recoveries were obtained in these experiments using brines obtained from the discharge of reverse osmosis plants, which are similar to those obtained using seawater in this and in earlier works (Ordóñez et al., 2013). This demonstrates that it is technically feasible to leach caliche with these brines with similar dissolution kinetics and recovery levels. The experiments showed that for the used irrigation rates, between 4 and 8 L/h/m<sup>2</sup>, no significant differences of recoveries were obtained.

In northern Chile, some companies are using seawater to leach caliche and the cost associated with this operation includes the caption of seawater, removal of organic matter and other impurities, in addition to the transport cost to the mining site that is very important, since the operations are located a few hundred kilometres from the coastline and nearby elevations around 1500 m (Moreno et al., 2014). On the other hand, there are towns that are using seawater after desalination by reverse osmosis; where brines are generated in amount similar to the desalinated water and they are disposed into the sea far away from the coastline in order to avoid the negative impact on the environment; this disposal implies an additional cost. The use of RO brines in the leaching may be feasible from an economical viewpoint since although the transport costs are slightly higher compared with the leaching using seawater, based on a marginal increasing of the density and viscosity, they are compensated by the saving in the intake and pre-treatment of seawater. Moreover, the production of domestic water through seawater desalination would not require the brine disposal, suppressing by this way the negative impacts on the environment.

Other configurations are also possible; e.g., combine the need of desalinated seawater in a mine with the use of the brines in other mine. The economic feasibility of this or other configurations should be carefully studied considering all the aspects of the process.

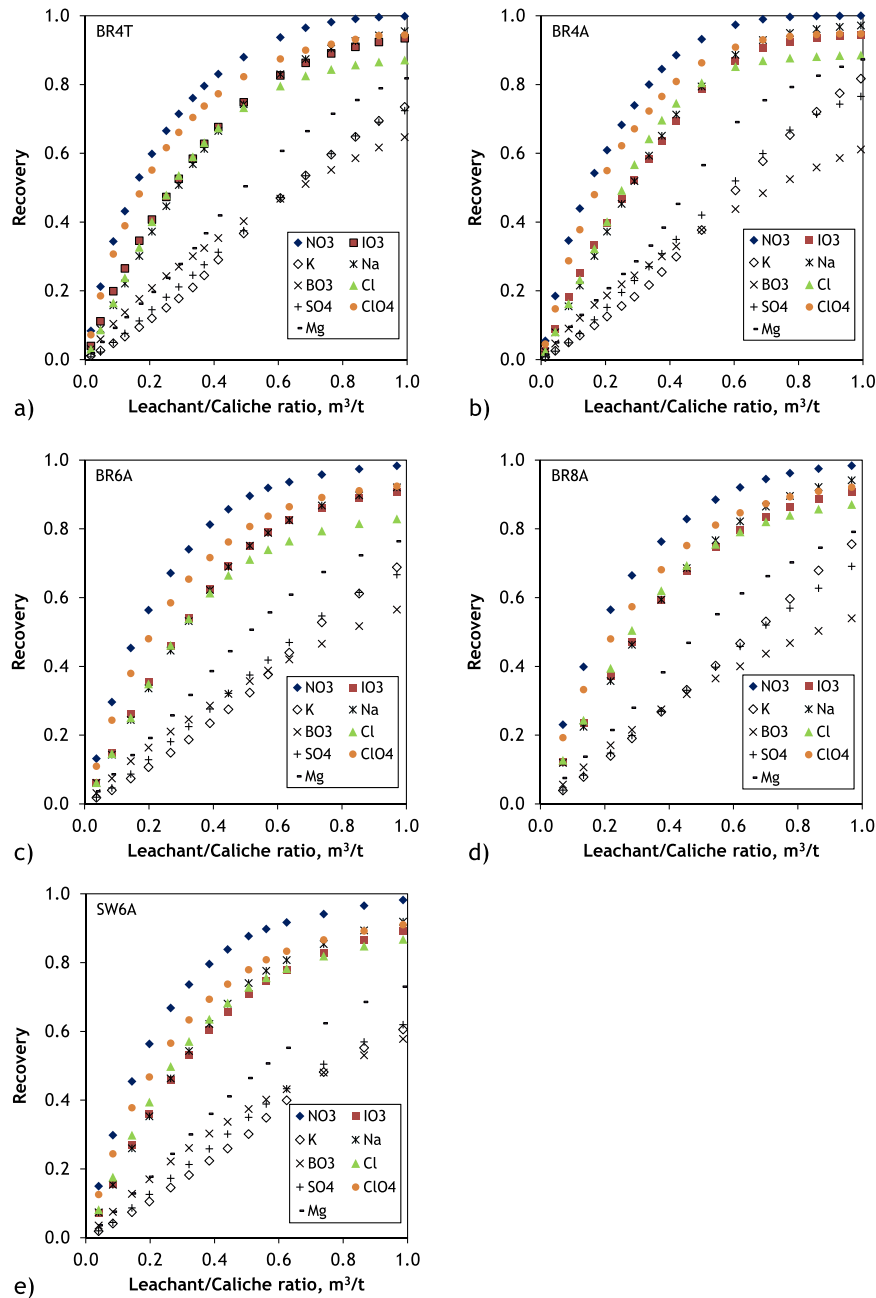


Fig. 3. Recovery curves of different species in the column experiments. a) BR4T, b) BR4A, c) BR6A, d) BR8A and e) SW6A.

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**Appendix A. Supplementary data**

The following information is provided as supplementary data:

- Plots of concentration against time.
- Experimental data of the main soluble ions for the BR6A experiment. Showing time, volume, concentration of ions and density of solution

for the leachate samples.

- Table of detailed mineralogical analysis of the residues.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.hydromet.2015.04.008>.

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