COMMISSION INTERNATIONALE

DES GRANDS BARRAGES

VINGT SIXIÈME CONGRES

DES GRANDS BARRAGES

VIENNA, JUILLET 2018

SMALL TAILINGS DEPOSITS IN CHILE: NATIONAL IMPACT OF PUBLICLY AVAILABLE DATA *

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1. INTRODUCTION

In Chile, massive mining wastes (waste-rock, low grade minerals, tailings, leaching gravels, and slags) are not considered to be hazardous solid waste [1], but are regulated by special laws, that differ from the disposal of all other hazardous waste. Of these residues, tailings are notable for their fine grain and water content,

* *Dépôts de Petits Résidus au Chili: Impact National des Données Publiques*

which enables chemical oxidative reactions that can dissolve toxics or generate acid that could reach natural waters of the surrounding ecosystem.

The national solution, to avoid harming the environment and people's health, has been the traditional containment of tailings in Tailings Deposits (TDs) that isolate the tailings from water and wind of the receiving ecosystem, at given specific legal margins given in a national regulation "DS 248 [2]: Regulation for the Approval of the Design, Construction, Operation and Closure of Tailings Deposits". Furthermore, all TDs that begun operations after 2012, must render a closure plan, to properly close and monitor the Post-Closure, according to Law 20,551: "Regulation of the Closure of Mining Works and Mining Facilities" [3].

The authority responsible for the correct application of these laws and regulations, in Chile, is the National Service of Geology and Mining (SERNAGEOMIN). Specifically, to verify the rightful application of the aforementioned DS 248, the Tailings Depository Department was created within SERNAGEOMIN (year 2014), as the technical entity that oversees the country's TDs. During these years, officials of this Department have travelled the national territory to verify and register, on the ground, the existence and the basic data of the TDs. Simultaneously, samples of the bucket; wall and downstream soil of the deposits have been taken for geochemical analysis. All this information, both Cadaster [4] and Geochemical Analysis [5], has been made available to the world on the Department's website [6].

In this work, we examine the recent and future impacts of the public availability of data pertaining to installations that have worried communities and the general public at large, including NGOs and academics, over the years. The major impacts should favor the adoption of public policies that help to restore the environment affected by TDs all over the country. Furthermore, it is expected that a deeper understanding of mining and its consequences might develop at all levels, fuelled by private and public sectors cooperation.

2. MAGNITUDE OF TAILINGS DEPOSITS IN CHILE

According to the data, of the 696 Tailings Deposits registered in Chile, 582 have volumes below 1 million cubic meters, which fall into the "small" class of ICOLD [7]. In terms of the number of deposits, it corresponds to 84% of the facilities, which is somewhat smaller, but within the order of magnitude of 90% of the total number of dams recorded by ICOLD for any given country or state.

In volumetric terms, however, the 696 total TDs, sum up to 15,500 million cubic meters, while the 582 smaller ones add up to only 63 million cubic meters; that is, in volumetric terms, the small TDs account for only 0.4%. Still, the risks associated with small TDs, in physical and chemical terms, might be very high, for a variety of reasons.

The classification criteria, for small TDs could differ from general dams classification, essentially because the rheology is sufficiently different as to imprint important differences in the distance and area affected by a break or collapse of dam structures. In Chile, the Department is studying a proposal to define 3 size classes, based on the risks involved, although there are still no accepted risk calculation methods. The 3 classes would have the limits of 1 and 10 million cubic meters; their total number and volume are shown in table 1.

Table 1
Dimension of Tailings Deposits in 3 classes

Volume (M=Million)	Number	Total Volume (m^3)
Less than 1 Mm^3	582	63,151,018
Between 1 and 10 Mm^3	62	198,262,774
Larger Than 10 Mm^3	101	15,467,858,262

The criterion will probably evolve in time to some other values, because the intermediate class is small in number, compared with the larger class. On the other hand, cluster analysis suggests that 5 classes should be defined; therefore, the matter of class sizes is an open question for TDs in Chile, mainly due to the presence of the very large and very small deposits, that covers 7 orders of magnitude, as can be seen in table 2.

Table 2
The 5 smallest and 5 largest Tailings Deposits registered in Chile

Registered owner Company	Deposit Name	Authorized Volume (m^3)
Soc. Guerrero Hermanos Cia. Ltda.	*Arcadio 1*	250
Rubilan Gonzalez	*Tranque 1-2*	360
Cia. Minera Purificacion	*Purificacion 1*	500
Cia. Minera Purificacion	*Purificacion 3*	600
Cia. Minera Kalleu	*Los Canelos 2*	750
Los Pelambres mining Co.	*El Mauro*	1,133,333,333
CODELCO	*Ovejería*	1,286,666,667
CODELCO	*Talabre*	1,451,000,000
CODELCO	*Caren*	2,192,000,000

Escondida mining Co.Ltd.	*Laguna Seca*	3,000,000,000

3. ACTIVITY STATUS OF TAILINGS DEPOSITS

As can be seen in the graph of Fig. 1, of these 582 small TDs, only 62 (11%) are active, while 379 (65%) are classified as "inactive" (deposits that reached the end of their useful life, without executing legal closure, but with a known responsible person) and 141 (24%) are classified as "abandoned" (they reached the end of their useful life, without executing legal closure and there is no legal responsible person identified). In other words, 89% of the small TDs are not receiving fresh tailings flow and are classified into 2 categories, depending on whether or not they have a known responsible person for them.

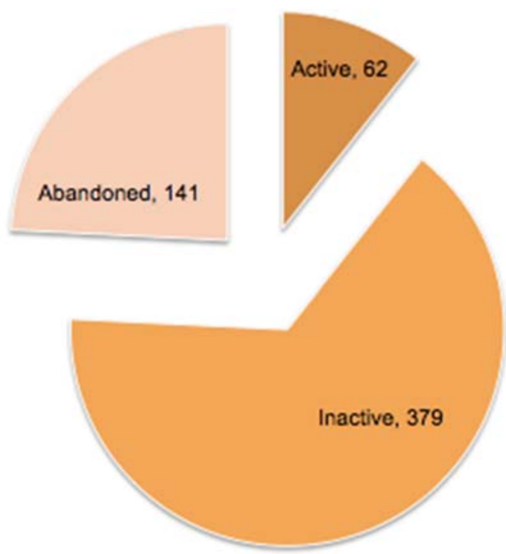

Fig. 1
Activity status of the 582 Tailings Deposits of volume less than 1 million cubic meters, registered in the cadaster in Chile.
Statut d'activité des 582 Résidus de gisements de volume inférieur à 1 million de mètres cubes, enregistré dans le cadastre au Chili

Only 89 of these deposits have a current closure plan and, moreover, many do not need to present a closure plan to operate, if their permits are prior to the effective date of the Mine Closure Act (year 2012). In addition, those mining operations that process less than 5,000 tons per month do not need to present closure plans, according to the same law; it is simple to calculate that these miners could operate for about 11 years and be in the category of small TDs. However, the legal standard of design, construction, operation and closure of tailings deposits do not distinguish -today- the scale of the operation.

There are also TDs within the urban territory of various cities in the country, since cities dedicated to mining have grown around this economic activity, at a time when there were no precise regulations on tailings. Recently, the Cadaster has made it possible for urban regulatory authorities to begin considering the area within the dangerous distance as a non-urban site.

4. ENVIRONMENTAL CONCERN

The Geochemical Registry consists of:

- ✓ 12 rock forming minerals, expressed as oxides: silicon (SiO_2), aluminum (Al_2O_3), titanium (TiO_2), iron (Fe_2O_3), calcium (CaO), magnesium (MgO), manganese (MnO), sodium (Na_2O), potassium (K_2O), phosphorus (P_2O_5), sulfur (SO_3) and compounds loss on ignition (such as carbonates, for example);
- ✓ 30 common trace elements (below 1%): copper (Cu), vanadium (V), chromium (Cr), cobalt (Co), nickel (Ni), zinc (Zn), rubidium (Rb), strontium (Sr), zirconium (Zr) niobium (Nb), barium (Ba), lead (Pb), cesium (Cs), hafnium (Hf), tantalum (Ta), arsenic (As), scandium (Sc), yttrium (Y)), molybdenum (Mo), antimony (Sb), tin (Sn), thorium (Th), silver (Ag), cadmium (Cd), bismuth (Bi), tungsten (W), uranium (U), gold (Au), and mercury (Hg); and
- ✓ 14 elementary rare earths: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu).

The effort of the Department will eventually influence the development of public policies that allow the improvement of the sites that house TDs, so that their eventual impact on the surrounding ecosystems is minimized, to protect the country's resources and the health of the population.

A first visible effect of the public dissemination of TDs data has been the decrease in the fears of indiscriminate contamination from the deposits, hypothetically tolerated by the authorities. Apparently, before knowing the specific values of the Geochemistry, toxics concentration in the tailings was expected to be much higher.

The measurement of downstream soil samples (simultaneous with the basin and the dam) has proven useful for studies where TDs were suspected (or accused) of contaminant failure during extreme climatic events. In a 2015 flood in the area of the Copiapo river basin, the study of data from the Geochemical Registry and the current sediments samples showed that the flood had actually improved the quality of the sediments in the area. According to the study [8], the old soils were the result of mining contributions during an extensive historical period. As these soils were replaced, due to washing effect, or to erosion and / or to change of the old soils by materials with a lower content of pollutants, contributed by the alluvium, the final soil samples had lower concentrations of metals. In addition, the geochemical comparison of soil samples against basin and dam samples, showed that, contrary to the common belief, the tailings deposits of the Copiapo basin did not contribute to the debris in the sediments observed after the flood.

On the contrary, in another extreme climate event occurred in 2016 at *Quebrada La Marquesa*, near the city of *La Serena*, the water undermined and dragged 3 or 4 dam walls toes, transporting them to the river. The Department took samples and, although they are still awaiting analysis, the sediments had the color and texture of common tailings.

In many cases, the availability of geochemical data of all TDs in Chile, has promoted a number of academic studies that, previously, had to work under diverse hypothesis regarding such compositions. Typically, it was assumed that a certain deposit was "representative" of all others in a region, while now, the diversity can be analyzed in quantitative terms. Clearly, however, more data is needed, as a simple sampling of the surface of a tailings basin is, again, not representative of the whole.

A general look at the data has shown, for example, that most of the tailing samples are constituted by rock forming minerals. Although much detailed mineralogical studies should be performed to be able to explain the rock substrate of a sample, it is commonly accepted that the oxides of these elements give a good approximation. Simple calculation shows that the average sum of rock forming materials adds up to 98.9%, while the sum of the average of trace elements accounts for 0.98% and rare earths for 0.009%. All of these measurements, then, explain 99.89 of the total mass, leaving 0.01% for the rest of the elements that were not measured. However, these values should be taken as general indications only, especially because the mineralogy of the materials are not known, therefore the direct addition of oxides concentrations could suffer from errors if a particular mineralogy is observed.

It appears that a minor percentage in mass would be responsible for all environmental toxicity concerns, where a low mass percentage (0.98%) could produce an important effect. This is not surprising, considering, for example, that copper mining exploits rocks where only 0.7% is copper. In tailings, traces of metals can be dissolved in a small flow of water, giving place to a high concentration. The most common concern, however, is the potential generation of acid; acid is commonly produced from sulfide oxidation and in these TDs, sulfur averages 0.75%, which is a rather high value, from the point of view of acid generation.

As previously mentioned, average values are not strictly meaningful. To analyze TDs in geochemical terms, a case-by-case analysis is required. The most commonly feared contaminant in Chile is arsenic, because its natural presence in water in the north of the country has prevented the installation of cities or camps. Some other towns have survived with bottled water for the visitors, while the native residents have ingested arsenic for many years, with the known consequences to their health.

In general terms, it was surprising to many that arsenic was in traces in the most feared large TDs that are currently in operation. High values of arsenic were expected because the arsenopyrites have increased their concentration in the ore, as deeper mineral deposits are exploited in recent (last 30) years. This scarce presence of arsenic in TDs shows that the floated fraction takes most of this element to the concentrate, leaving a smaller fraction in the tailings. As a matter of fact, arsenic is abundant (15 to 20 g/L) in the rejection line of the acid plants used to clean smelter gases and in anode sludge in electrolytic copper refineries. Chilean commercial electrolytic copper is known to have excessive arsenic contamination.

Arsenic can be very abundant (concentration within the same order of magnitude as copper) or very low (undetectable) in old, small TDs. There are 162 small TDs that have arsenic above detection limit (10 g/t) and, as shown in the graph of Fig. 2, they range up to almost 40.000 g/t. Many other species can be simply plotted from the public data, making public participation more informed and more technically based. We have known of a number of studies and university projects that changed from eminently qualitative or local results, to more specific quantitative and countrywide results. In the case of arsenic, a university project set out to establish the bases for the design of a methodology to assess the health risk of people due to exposure to arsenical residues in Chile depends heavily on these public results (Professor C. Parodi, UTEM, personal communication). Another half a dozen theses or research projects are devoted to studies of separation technologies in tailings materials (see below, in economic value in TDs).

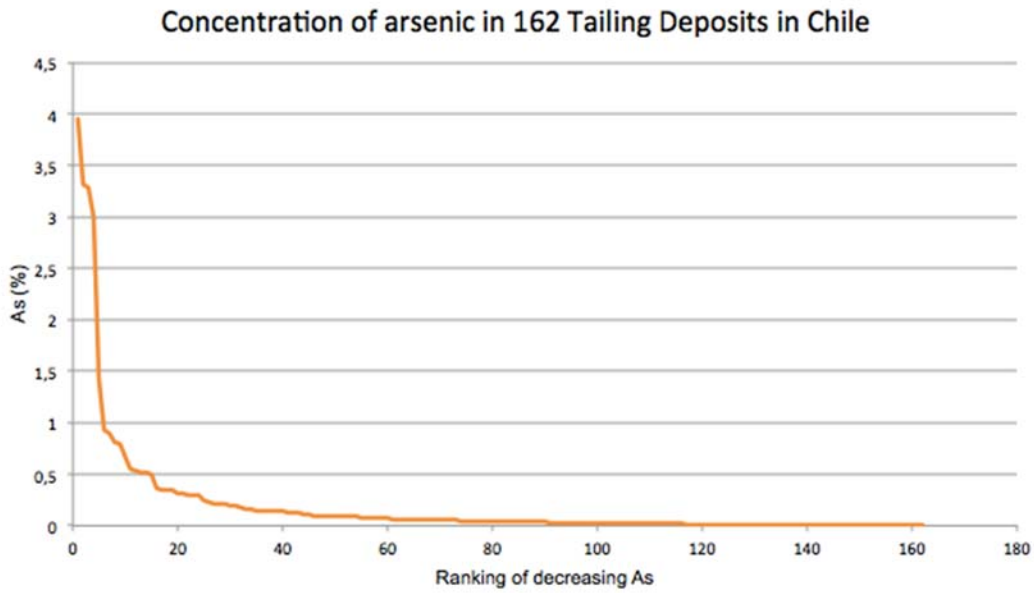

Fig. 2
Arsenic % concentration in the 162, out of 582 deposits smaller than 1 million cubic meter, ordered by decreasing ranking of arsenic content.
Concentration en arsenic% dans les 162 dépôts sur 582 inférieurs à 1 million de mètre cube, classés par ordre décroissant de teneur en arsenic.

5. ECONOMIC VALUE IN TAILINGS DEPOSITS

There are still no public policies that require the remediation or the reduction of the risks of sites allocating old, abandoned TDs. One possibility that has been examined nationally is to use the dangerous distance or the affected area, to regulate state investment in remediation, but advances are slow and irregular.

There are, on the other hand, State programs to stimulate the economic recovery of the metallic value eventually contained in the deposits [9], as a way to favor their processing, implying their removal from urban places, and re-deposited in sites and conditions that meet the modern requirements of the current laws and regulations.

Within the smaller TDs, there are 109 (17%) deposits whose copper content is greater than 0.3%, a value considered as an economic cut-off limit for said metal. There are, of course, many other metals and -depending on their market value- they could be economically recovered. Currently, poly-metallic exploitation strategies are being sought to improve the technical-economic feasibility of TDs re-mining. The scale of the operation plays a critical role, since the cut-off law assumes a reservoir dimension that is not met in the case of especially small TDs. The size of the TDs that have copper over 0.3% are represented by the blue line, read on the left axis, of the graph in Fig. 3.

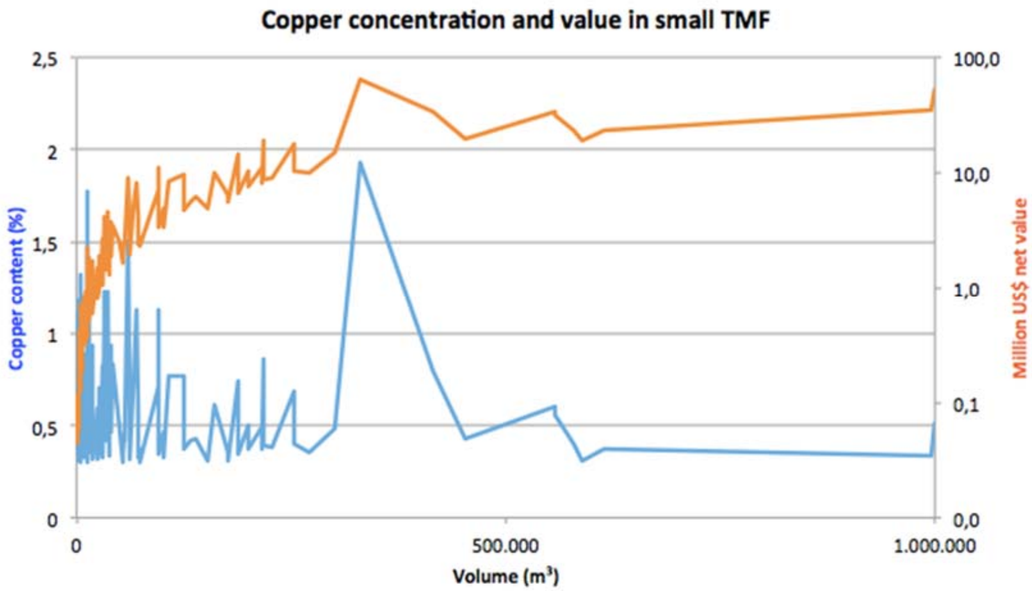

Fig. 3

Copper above 0.3% concentration (blue) and their economic value (red, note the logarithmic scale).

Cuivre supérieur à 0,3% de concentration (bleu) et leur valeur économique (rouge, noter l'échelle logarithmique)

Most of the high concentrations of copper, above 1% for example, occur in small deposits, although the highest concentration (1.9%) corresponds to a TD of 330 thousand tons (*El Gringo Deposit*, of CODELCO Chile), which would be immediately exploitable, according to the usual economic criteria prevalent in the country.

On the right-hand axis, the gross value of the total copper contained in each deposit was plotted in red, (in logarithmic scale) and calculated by Eq. [1].

$$C(MUS\$) = \left\{ \frac{Cu\left({}^{g\,Cu}\!\big/_{tailings\,ton} \right)}{10^6 \left({}^{g\,Cu}\!\big/_{ton\,Cu} \right)} \right\} V\left(m^3\right) d\left(\frac{ton}{m^3}\right) \left\{ \frac{6{,}831\left({}^{US\$}\!\big/_{ton\,Cu} \right)}{10^6 \left({}^{US\$}\!\big/_{MUS\$} \right)} \right\} \qquad [1]$$

where C is the gross value of fine metallic copper in the TD; Cu is the concentration of copper in the TD; V is the volume of the deposit; *d* the conventional average density of tailings (1.5 t / m^3); the current fine copper ton value is US $6,831 [10], and there are two conversion factors of 10^6.

Although the value associated with these deposits in the current discussion is strictly economic, there are other obvious sources of value that have not yet entered the public discussion. The most crucial aspects, especially from the point of view of the public policies that should arise, are related to the use of soils, the protection of the environment and the people’s health. The value should be multidimensional, considering the metal value but also the costs that the TDs have for society at large. The most evident cost elements that can be identified are:

- Economic value, associated with carrier species that, in spite of the small mass, allow an economic recovery that, simultaneously, reduces the chemical threats of the tailings of the case (removal of Chalcopyrite recovers copper and reduces acid generation potential, for example).
- Soil and urban value, associated with the value of the land once the tailings deposits are removed; this is especially true for cities that have TDs within the urban radius. Similarly, tailings beaches remediation would improve the value of such sites for tourism and second residence urban development.
- Scenic or touristic value associated with the disturbance produced by TDs that have not been properly closed.
- Value of risk reduction to: property, welfare, health and people's rights, by withdrawing deposits or mitigating them through exploitation.

Chile has important experience in tailings processing. The greater part, however, consists in recovering copper and molybdenum (Valle Central Mining Co. [11], for example), without funding the costs of Tailings Deposits or Closure Plans, since they send their final tailings to the "*Tranque Carén*", a Depository in force and in operation of the “Division *El Teniente*” of CODELCO Chile. The cost reduction is such that tailings with as low as 0,17% copper can be processed. The investigation of new processes, on the other hand, focuses on other metallic values and on economic projects that can finance the closure plans of the new TDs.

6. CONCLUSION

The availability of the National Cadaster of Tailings Deposits and the geochemical data of its composition have positively impacted the country, contrary to prior belief (fears of public accusations). The public data has allowed the design of ways to increase the social and economic value of these sites, whether due to monetary, environmental, urban, tourist, human or other forms.

The design of social and economic base solutions should be able to form the bases for the appropriate design of public policies that allow to significantly reduce the risks that can be detected at present.

It is to be hoped that international researchers will use these data and further help Chile to advance in the correct treatment of Tailings Deposits according to current best practices and sustainable principles.

This is an on-going subject, that can be reported only as an invitation to use the data to compare to other Tailings Deposits in the world, so that the final sum of world knowledge could solve the current impact they have, which is a current and urgent concern, not only in physical terms, but also in chemical terms for the next few centuries, if not longer.

ACKNOWLEDGEMENTS

It is not hard to imagine the personal effort it took for the Department´s officers and truck drivers, to run up and down the country, to verify the existence and follow hints of even the slightest possibility of a deposit to exist, somewhere in the fields. Many thanks go to them; this work and many more to come are a fruit of their many weeks, days and hours out of the office and home.

The Laboratory of the SERNAGEOMIN processed these samples with care and compromise, using frontier techniques and devoting many hours to this geochemistry analysis effort. Thanks are due to their staff and director.

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SUMMARY

The Chilean National Service of Geology and Mining authorities published a complete cadaster of the 696 Tailings Deposits visited by officials, in the country. Of these 696 Deposits, the large majority, 582 of them, fall in the small category proposed by ICOLD, i.e. they have a volume lower than 1 million cubic meters. Furthermore, samples were taken from the basin, dam wall and downstream soil, at each visited Deposit, to analyze the geochemistry of them; the whole data was made public on December 2016, and it is currently actualized as new data arrives from the laboratory. The data consists of 12 rock-forming minerals, expressed as oxides of the elements; 30 common trace elements (metals below 1%); and 14 Rare Earths elements. The data was seen to explain some 99.9% of the samples, leaving 0.1%

to be explained by not measured elements. The publication of the data prompted positive results in several senses: public fears were better focused; studies and projects became more quantitatively based; many actors conceived proposals for environmental mitigation; and proposals to use tailings as mineral resources acquired a better technical and economic feasibility base. Public policies to treat environmental passives posed by Tailings Deposits are yet to be proposed, but the availability of data has helped to estimate the costs of such treatments. The value associated with the treatment of tailings has many edges: actual economic value of the species therein contained; land use, considering that many deposits are within the urban area of towns in the North of Chile; increased value of the environment, once contaminants and acid generating materials are removed or neutralized by proper technologies; increased value of sites as touristic resources, for those tailing that perturbate the otherwise attractive environment; and increased value of human life, once unharmed by wind suspended materials from the tailings. It is expected that Chile will develop public policies and public-private collaboration to develop ways to completely solve the public concern about mining tailings. Hopefully, as this is an international concern in many mining countries, the public data could be the basis of an intense international collaboration in the very same sense of care for the planet and the people.

RÉSUMÉ

Le Service national géologique du Chili et les autorités minières ont publié un cadastre complet des 696 dépôts de résidus miniers visités par le Service. Sur ces 696 dépôts, la grande majorité, 582 d'entre eux, appartiennent à la petite catégorie proposée par la CIGB, c'est-à-dire qu'ils ont un volume inférieur à 1 million de mètres cubes. De plus, des échantillons ont été prélevés dans le bassin, le mur du barrage et le sol en aval, à chaque dépôt visité, afin d'en analyser la géochimie; L'ensemble des données a été rendu public en décembre 2016 et il est actuellement actualisé à mesure que de nouvelles données arrivent du laboratoire. Les données se composent de 12 minéraux formant des roches, exprimés en oxydes des éléments; 30 oligo-éléments communs (métaux inférieurs à 1%); et 14 éléments des terres rares. Les données ont été vues pour expliquer environ 99,9% des échantillons, laissant 0,1% à expliquer par des éléments non mesurés. La publication des données a donné des résultats positifs à plusieurs égards: les craintes du public étaient mieux ciblées; les études et les projets sont devenus plus quantitatifs; de nombreux acteurs ont conçu des propositions d'atténuation environnementale; et les propositions d'utilisation des résidus comme ressources minérales ont acquis une meilleure base de faisabilité technique et économique. Les politiques publiques visant à traiter les passifs environnementaux posés par les

dépôts de résidus n'ont pas encore été proposées, mais la disponibilité des données a aidé à estimer les coûts de tels traitements. La valeur associée au traitement des résidus a de nombreux avantages: la valeur économique réelle des espèces qui y sont contenues; l'utilisation des terres, étant donné que de nombreux dépôts se trouvent dans la zone urbaine des villes du nord du Chili; la valeur accrue de l'environnement, une fois que les contaminants et les matériaux générant de l'acide sont éliminés ou neutralisés par des technologies appropriées; la valeur accrue des sites en tant que ressources touristiques, pour ceux qui perturbent l'environnement autrement attrayant; et une valeur accrue de la vie humaine, une fois indemnes de matériaux suspendus par le vent provenant des résidus. On s'attend à ce que le Chili développe des politiques publiques et une collaboration public-privé pour développer des moyens de résoudre complètement les préoccupations du public concernant les résidus miniers. Espérons que, comme il s'agit d'une préoccupation internationale dans de nombreux pays miniers, les données publiques pourraient être la base d'une collaboration internationale intense dans le même sens de la protection de la planète et du peuple.