"Not seeing the forest for the trees" (or not seeing the geology for the glaciers): Revisiting the Pascua Lama mining project within a framework of environmental impact assessment, sustainability, and geoethical aspects

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Abstract

This paper presents a retrospective analysis that mainly addresses the interplay of the geological, environmental and sustainability dimensions of the Pascua Lama mining project, located in the high-altitude Andes of Chile and Argentina. Although the project was binational in scope, this analysis focuses on the Chilean context, examining both the environmental assessment processes associated with the technical studies submitted by the mining company and the subsequent inspection and sanctioning procedures undertaken by Chilean State agencies. This is done within the broader context of the relationship of Environmental Impact Assessment (EIA) processes to sustainable development of projects, as well as actions aligned with geoethical principles, in particular in relation to a recently proposed Chilean Code on such issues. Although the results of the referred EIAs of Pascua Lama were not necessarily incorrect, too much attention was paid on aspects that proved to be not as important when compared to others that could have indeed led to major environmental impacts. The misplaced priorities, a consequence of various factors that extended beyond strictly environmental issues, created a selective attention on a problem (impact on glaciers) which hindered an adequate estimation of the magnitude and

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importance of acid drainage generation and metal and metalloid release to the river system, which ultimately proved to be of high relevance in the halt and closure of the project. What happened raises important lessons in terms of the use of EIA as a tool to ensure the sustainable development of mining projects, and to achieve desired outcomes consistent with geoethical or other self-imposed or declared guidelines, especially those related to the proper use of geological information to prevent or minimize the occurrence of environmental impacts, allowing the sustainable development of mining projects.

Keywords: Pascua Lama; water quality; acid drainage; sustainable development; Chilean geoethic code

Cuando "los árboles no dejan ver el bosque" (o los glaciares no dejan ver la geología): Una mirada contemporánea al proyecto minero de Pascua Lama desde el punto de vista de la evaluación de impacto ambiental, la sostenibilidad, y los aspectos geoéticos. Este trabajo presenta un análisis retrospectivo que aborda principalmente la interacción entre las dimensiones geológica, ambiental y de sostenibilidad del proyecto minero Pascua Lama, ubicado en los Andes entre Chile y Argentina. Si bien el proyecto era de carácter binacional, este análisis se centra en el contexto chileno, examinando tanto los procesos de evaluación ambiental asociados a los estudios presentados por la compañía minera como los posteriores procedimientos de fiscalización y sanción llevados a cabo por organismos del Estado de Chile. Esto se presenta en el contexto más amplio de la relación entre los procesos de Evaluación de Impacto Ambiental (EIA) y el desarrollo sostenible de proyectos, así como de acciones alineadas con principios geoéticos, en particular algunos descritos en un recientemente propuesto Código Chileno sobre estas materias. Si bien los resultados de las EIA de Pascua Lama no fueron necesariamente incorrectos, se prestó excesiva atención a aspectos que demostraron no ser tan relevantes en comparación con otros que efectivamente podrían haber conducido a impactos ambientales significativos. Las prioridades mal establecidas, como consecuencia de diversos factores que iban más allá de las cuestiones estrictamente medioambientales, provocaron que se prestara una atención selectiva a un problema (afectación de

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glaciares), lo que dificultó realizar una estimación adecuada de la magnitud y la importancia de la generación de drenaje ácido y de la liberación de metales y metaloides al sistema fluvial, lo que finalmente demostró ser relevante en términos del cese y cierre del proyecto. Esto plantea importantes lecciones respecto del uso de las EIA como herramienta para asegurar el desarrollo sostenible de proyectos mineros y alcanzar resultados consistentes con lineamientos geoéticos u otros autoimpuestos o declarados, especialmente aquellos relacionados con el uso adecuado de la información geológica para prevenir o minimizar la ocurrencia de impactos ambientales, favoreciendo el desarrollo sostenible de este tipo de proyectos.

Palabras clave: Pascua Lama; calidad del agua; drenaje ácido; desarrollo sustentable; código de geoética en Chile

1.- Introduction

Mining constitutes a key activity in contemporary society, enabling the extraction of raw materials essential to a wide range of human endeavors, including infrastructure development, technological advancement, and the transition toward clean energy systems (Fuentes *et al*., 2024). However, owing to its inherently extractive character, it inevitably generates environmental impacts, which tend to be diverse and complex in nature (Dudka and Adriano, 1997). Minimizing such impacts represents a critical challenge for the mining industry. For such purpose, one of the main instruments available prior to the development of a mining project (and the actual occurrence of potential problems) is its environmental impact assessment (EIA; similar acronysm in Spanish for the same concept, i.e., Evaluación de Impacto Ambiental). Indeed, an effective EIA process should systematically and properly identify the potential

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environmental consequences of a project and support the adoption and implementation of measures aimed at avoiding, mitigating, or compensating for those impacts.

In Chile, mining has long constituted a core component of national economic development (Rodríguez-Luna *et al*., 2022). As of 2024, the country ranked first globally in the production of copper, rhenium, iodine, and natural nitrates, and second in molybdenum as well as lithium and boron compounds (SONAMI, 2025). This prominence is reflected in its substantial contribution to the national economy, with the mining sector accounting for approximately 10–14% of gross domestic product during the 2020–2024 period (Consejo Minero, 2025). Despite these economic benefits, recent years have witnessed increasing opposition to mining project development, or directly the surge and escalation of social and socio-environmental conflicts linked to mining activities (Bornschier and Vogt, 2024; Ho *et al*., 2023).

In this context, the Pascua Lama mining project case is of relevance, given its prominence and high level of public visibility both within Chile and internationally. The project has been widely recognized as one of the most significant environmental conflicts in Chile (Urkidi, 2008) and is documented in the Global Atlas of Environmental Justice (Temper *et al*., 2015). Given the foregoing, this work examines, with emphasis on the Chilean context, the EIA processes conducted for the Pascua Lama project contrasted with what ultimately happened during its construction. Although the results of the assessments were not necessarily incorrect, too much attention was paid on aspects that in our opinion were not true priorities compared to others that indeed resulted in major environmental disturbances, and for which the baseline information existed and that should have made it possible to adequately estimate their occurrence and potential severity. Thus, nearly two decades after the project's environmental approval, a retrospective analysis of this case helps identify key factors that can contribute to a better or more effective approach in similar situations in the future, i.e., evaluation of projects in related contexts and that may pose equivalent environmental risks, from the perspective of responsible geoscientific approach, including geoethics aspects.

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2.- Scope and organization of this work

This work is presented as a reflective essay, structured around four main parts. The first one provides a conceptual analysis of the EIA process and its role in promoting the sustainable development of projects, especially in the mining sector. It also includes an overview of the characteristics of the environmental assessment process in Chile, and ends with geoethics issues, in particular a rather recently proposed Code for Chile.

The second part identifies the geographical location, environmental setting, and the geopolitical context of the Pascua Lama project, and offers a general account of the project's environmental evaluation processes, as well as the subsequent regulatory oversight during the construction phase.

The third part presents an analysis of the availability of geological and mineralogical information associated with the project at the time of its environmental assessments. Emphasis is placed on issues related to acid mine drainage generation, the historical context in which the assessment was conducted, and, in connection with this, the local and international significance attained by concerns regarding glacier impacts over acid drainage. It also presents a documentary analysis focusing on these two main elements, i.e., acid mine drainage (linked to geological conditions) and glaciers, across a range of technical, scientific, and outreach-oriented documents.

Finally, the fourth part proposes an integrated analysis of the information presented, extending the discussion of the Pascua Lama case to a broader audience, which takes significance in the context of environmental project assessment, sustainability, and professional practice from a geoethical and related corporate social responsibility perspective.

3. Analysis and discussion

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3.1. EIA of projects, sustainable development, and geoethic issues

3.1.1. *EIA as a tool for sustainable project development*

EIA was initially promoted by various environmental organizations during the 1970s, later promoted more formally by the European Union from 1985 onward, subsequently by the World Bank from 1989, and more recently by the Earth Summit held in Rio de Janeiro, Brazil, in 1992. Thus, EIA was progressively and firmly adopted by governments worldwide as a mechanism to promote sustainable development (Cashmore *et al*., 2007).

At present, EIA systems are estimated to be implemented in approximately 190 countries worldwide (Caro-González *et al*., 2023), and constitutes an important environmental management and regulatory tool, enabling the anticipation and evaluation of the impacts associated with a given project on its overall sustainability (Rodríguez-Luna *et al*., 2022). Also, the adoption of EIA procedures has been identified as a key element for achieving the United Nations Sustainable Development Goals (SDGs) (Kørnøv *et al*., 2020). Regarding the mining industry, and according to Fuentes *et al*. (2024), the 17 SDGs represent a suitable framework "to assess the compatibility in decision-making along its entire production chain". Similarly, the International Council on Mining and Metals (ICMM) asserts that the mining and metals industry has a pivotal role in advancing multiple SDGs (ICMM, 2026a), and also explicitly presents, on its corporate webpage, a set of principles or "good practice environmental, social, and governance requirements for company members". Some of these principles specifically relate to ethical business (Principle N° 1), decision making (Principle N° 2), risk management (Principle N° 4), and environmental performance (Principle N° 6), i.e., within the broader context of responsible mining (ICMM, 2026b).

3.1.2. *EIA system in Chile*

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A detailed description of the EIA system in Chile is beyond the scope of this work, as recent publications offer comprehensive and suitable references on this issue (e.g., Bergamini and Pérez, 2022; Rodríguez-Luna *et al*., 2022). Nevertheless, it is important to at least briefly review the EIA process for projects in the country, as well as the Chilean institutional framework in place at the time of the assessment and subsequent oversight (including enforcement and sanctions) of the Pascua Lama project.

The Environmental Impact Assessment System in Chile (i.e., Sistema de Evaluación de Impacto Ambiental in Spanish; acronym: SEIA) was established under Law 19,300 (1994), and its implementing regulation was enacted in 1997 (Brenning, 2008). The SEIA is conceived as an environmental management instrument designed to exercise preventive control over a range of project types and categories listed in Article 10 of the 19,300 Law, which must consequently undergo EIA (Herr, 2021). The process comprises two modalities: Environmental Impact Study (i.e., Estudio de Impacto Ambiental in Spanish; acronym: EIA, but from here onwards EstIA will be used to avoid confusion with Environmental Impact Assessment, EIA), and Environmental Impact Declaration (i.e., Declaración de Impacto Ambiental in Spanish; acronym: DIA). EstIAs are intended for projects that produce any effect specified in Article 11 of Law 19,300, such as significant impacts on human health, natural resources, or the resettlement of communities, among others. For all other projects, the assessment is conducted through a DIA.

At the time of the evaluation of the Pascua Lama Project, the management of the SEIA was the responsibility of the Chilean Environmental Commission (i.e., Comisión Nacional del Medio Ambiente in Spanish; acronym: CONAMA), while the assessment itself was conducted by various State agencies with environmental competence (i.e., Organismos de la Administración del Estado con Competencia Ambiental in Spanish; acronym: OAECAs). Upon completion of the evaluation process, a report was issued that could require clarifications or corrections from the project proponent, who then had the opportunity to submit an addendum. If, following this process, the project received a favorable evaluation

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from the Regional Environmental Commission (i.e., Comisión Regional del Medio Ambiente in Spanish; acronym: COREMA), it was granted environmental authorization in the form of an Environmental Qualification Resolution (i.e., Resolución de Calificación Ambiental in Spanish; acronym: RCA). This document establishes the conditions, requirements, or measures that the project proponent must comply with during the execution of the project or activity.

In 2010, with the enactment of Law 20,417, a series of modifications to the country's environmental institutional framework were implemented (Bergamini and Pérez, 2022). Of specific relevance to this contribution, CONAMA was dissolved, and the Environmental Assessment Service (i.e., Servicio de Evaluación Ambiental in Spanish; acronym: SEA) and the Environmental Superintendence (i.e., Supertintendencia del Medio Ambiente in Spanish; acronym: SMA) were established, while the participation of OAECAs in the assessment processes was maintained. The SEA became responsible for the administration of the SEIA, whereas the SMA assumed, among other functions, the organization, coordination, and execution of monitoring and enforcement processes related to RCAs. Subsequently, in 2010, with the enactment of Law 20,600, the Environmental Courts (i.e., Tribunales Ambientales in Spanish; acronym: TAs) were created. These TAs are responsible, among other functions, for attending claims regarding the illegality of administrative acts and regulations issued by the SMA, SEA, and other OAECAs, as well as claims seeking compensation for environmental damage.

3.1.3. *Geoethics and its relevance in the context of this paper*

Geoethics can be defined as "research and reflection on the values which underpin appropriate behaviours and practices, wherever human activities interact with the Earth system" (IAPG, 2026). More specifically, in the Chilean context, in April 2024 the Geoethics Group of the Geological Society of Chile, representing the Chilean section of the International Association for the Promotion of Geoethics (IAPG), proposed a Code of Geoethics associated with the various domains of practice within the geoscientific

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community in the country (Pinto *et al*., 2024). Although the Code itself does not constitute a legally binding instrument, it nevertheless represents a recent and innovative development within the field of geosciences in the country. This is significant insofar as its principles are conceived as desirable rules or standards that promote the adoption of specific values in the professional conduct of practitioners in the field, extending beyond the scope of actions regulated by Chilean law.

This Code contains several provisions (i.e., specific articles) that are directly relevant to the matter of interest examined in this work. By way of illustration, some of these provisions are presented below (the full text is available at the link provided in the references): Article 14, Commitment to sustainability; Article 20, Promotion and facilitation of spaces for dialogue, exchange, and collaborative work with public, private, and autonomous institutions, particularly those at national and municipal levels responsible for territorial planning and land-use management, efficient use of natural resources, dissemination of geosciences, and disaster risk management, among others; Article 37, Reduction of negative environmental impacts and promotion of adaptive measures throughout the lifecycle of projects in which one participates, including formulation, development, implementation, and closure; Article 40, Duty to report, to the appropriate authorities, critical assessments regarding potential negative environmental impacts arising from projects in which one is involved; and Article 41, Promotion of the study and understanding of anthropogenic impacts on the environment.

From the foregoing, it is evident that environmental considerations, impact identification, and sustainability in general constitute important aspects of professional practice within a geoethical context. Also, and from an even more comprehensive perspective, sustainable development must be viewed not only as a techno-economic challenge but also as a socio-ethical goal (Panagiotis-Stavros *et al*., 2026); therefore, efforts to achieve it implicitly include elements of geoethics (Sánchez, 2025).

3.2. The Pascua Lama project and its EIA and sanctioning processes

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3.2.1. *Pascua Lama project*

Pascua Lama is a high-sulfidation Au–Ag–Cu epithermal deposit located along the NNE trending Miocene El Indio-Pascua belt, comprising alteration zones, prospects, and Au-Cu-(As) epithermal deposits. It had reserves (before mining) of more than 16 million ounces Au and 585 million ounces Ag. The host rock is a granite of Triassic age (Deyell *et al*., 2005). The project was planned to begin operations in 2008, with an anticipated lifespan of approximately 20–25 years (Kronenberg, 2013; de los Reyes, 2022). At the time, Pascua Lama was presented as the second largest gold mining project in South America (Brenning and Azócar, 2010; Haslam and Godfrid, 2020).

A distinctive feature of the project was its location in a high-altitude Andean environment (approximately 4,500 m above sea level), on the international border between Chile, which contained an estimated 75% of the ore body, and Argentina, with the remaining 25%. On the Chilean side, the Project is located in the Andean sector of the Huasco Valley, Huasco Province (Atacama Region), North-Central Chile (Fig. 1). Thus, Pascua Lama constituted the first mining project designed for simultaneous exploitation in both countries under the "Treaty on Mining Integration and Complementation" signed by Chile and Argentina in 1997 (Aguilar, 2013; Herr, 2021).

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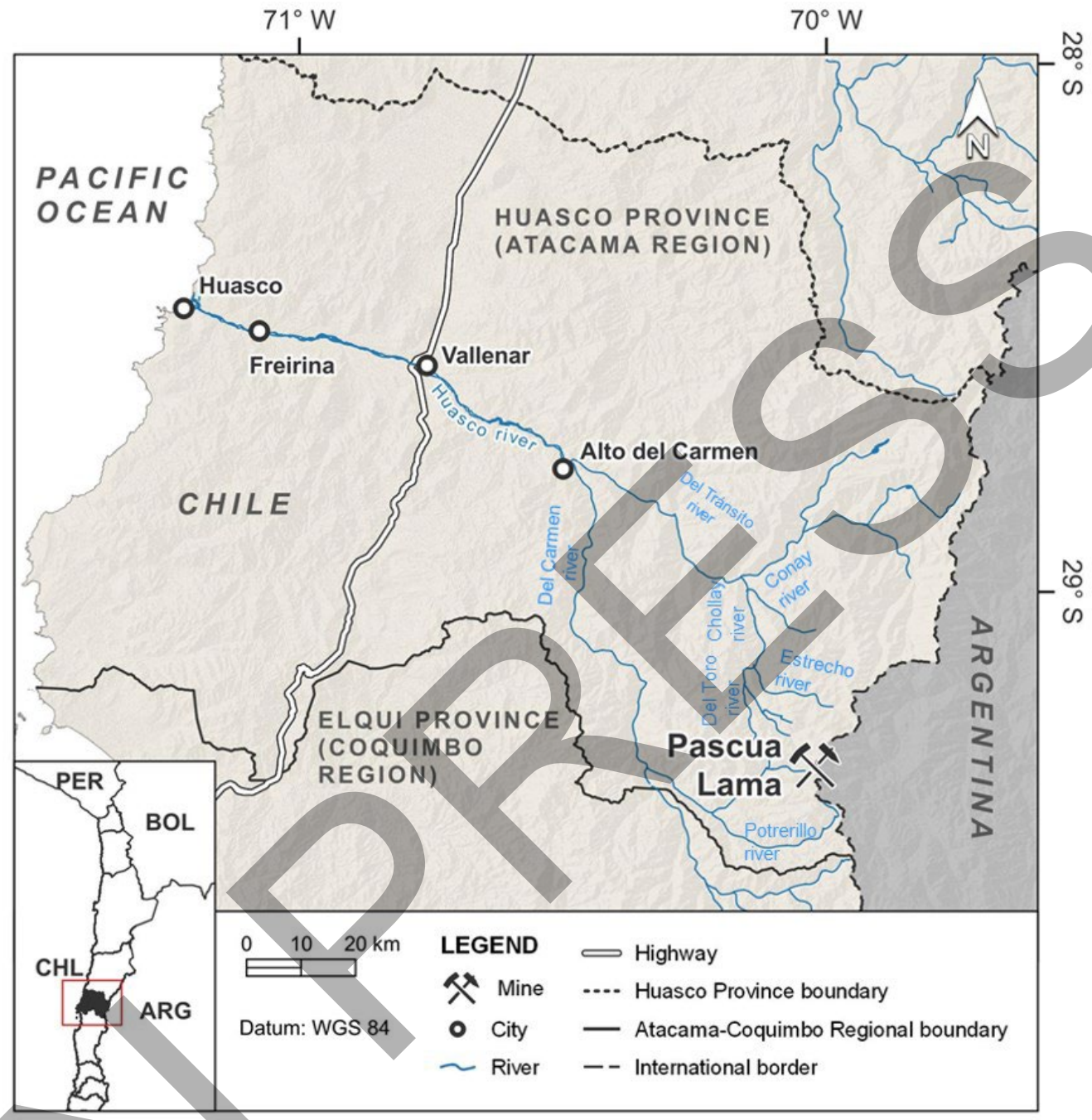


Fig. 1. Location of the Pascua Lama project.

3.2.2. *Chronology of the EIA processes of Pascua Lama*

Although Pascua Lama was presented as a binational project, Article 12 of the Treaty on Mining Integration and Complementation stipulated that the environmental impact assessment should be

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conducted separately, in accordance with the respective environmental legislation of each country (Herr, 2021).

In the Chilean side, the focus of this work, the project was initially submitted to the SEIA on August 2000 through an EstIA presented by Compañía Minera Nevada (i.e., Barrick), aimed at the production and commercialization of gold, silver, and copper. Following two rounds of review, evidenced by the submission of two addenda, the COREMA of the Atacama Region issued a favorable RCA of the Pascua Lama project through Resolution N° 39/2001 (Delzo and Rubina, 2024; Herr, 2021).

However, a period of low gold prices delayed the development of the project. This, together with other adjustments, such as modifications in design and operational measures aimed at increasing the rate of mining and mineral processing, led the company to submit a new EstIA. It was referred to as the "Pascua Lama Project Modifications," and essentially represented an expansion of the original project. This second EstIA was submitted to the SEIA in December 2004 (Aguilar, 2013; Haslam and Godfrid, 2023). The project underwent three rounds of review, documented through three addenda, between 2005 and 2006. Ultimately, the COREMA of the Atacama Region approved the project in February 2006, subject to the conditions and requirements specified in Resolution (RCA) N° 24/2006 (Brenning, 2008; Urkidi, 2008).

3.2.3. *Project construction and regulatory sanctioning processes*

Although the project's second EstIA was approved in 2006, construction was initially delayed until 2009. While the plan aimed for the production of the first gold bar in 2013 (Urkidi and Walter, 2011), this goal was never achieved. Notably, the project encountered a series of challenges from its early stages due to complex environmental conditions related to the relief and climate of the Andean landscape, which required adaptations resulting in costs increments. In fact, of the initially estimated investment of US$950 million, by February 2007 it was reported that between US$2.3 and US$2.4 billion had already been

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invested (Urkidi, 2008), while subsequent estimates ranged from US$4.8 to US$8 billion (Haslam, 2018; Smith and McCormick, 2018; de los Reyes, 2022).

At the same time, the project began to generate significant and growing opposition in Chile, evidenced by the presentation of numerous complaints to Governmental Agencies. While providing a detailed account of the oversight processes related to these complaints is beyond the scope of this contribution (for comprehensive discussions, see Leblanc, 2020; Delzo and Rubina, 2024), it is instructive to highlight certain aspects, specifically after the SMA began operating. Specifically, in 2013, the company submitted a self-complaint report, which was rejected by the SMA arguing that "the facts described were not accurate, truthful, or verifiable" (SMA, 2013). However, this did trigger audits by the SMA, which filed more than 33 charges between 2013 and 2015 to the mining company for non-compliance with the RCA, with six of them for very serious violations (Herr, 2021). Moreover, in 2018, the SMA filed five closure charges related to RCA non-compliance and serious violations, of which the First TA (located in Antofagasta) ultimately upheld three of them, along with the application of a fine of more than CLP$7 billion (over US$10 million at the time). The three charges upheld referred to environmental violations regarding the monitoring of glaciers and glacierets; the monitoring and discharge of contact water into the Estrecho River; and the use of an unauthorized methodology for calculating water quality alert levels, which considered more permissive levels than those contemplated in the environmental assessment and the RCA granted (Primer Tribunal Ambiental, 2020). From the foregoing, it is noteworthy that two of the three charges for which the Court ordered the closure of the project were related to water quality, while only one explicitly concerned glaciers. The Presiding Judge of the TA at that time stated that "the contamination of the waters of the Estrecho River constitutes one of the environmental effects evaluated in greatest depth, given the magnitude of its impacts on human health" and that "it is the company itself that proposes to develop a mining project under adverse conditions; therefore, it should have taken into account the geographic and climatic conditions of the area

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and ensured the safety of workers when designing a monitoring plan, so that it could be effectively implemented" (Primer Tribunal Ambiental, 2020). Once again, concepts such as those mentioned by the court appear entirely logical and consistent with what would reasonably be expected in the context of a conduct aligned with the geoethical principles discussed above, as well as from the point of view of an effective (and realistic) environmental impact assessment.

Finally, in 2022, the Supreme Court, the highest judicial authority in the country, rejected appeals for cassation filed by an agricultural company against the ruling of the First TA, thereby confirming the legality of the permanent closure order of the Project and a series of fines imposed on the mining company by the SMA (Poder Judicial, 2022).

3.3. Availability and consideration of geological and environmental information, and the focus put on glaciers

3.3.1. *The significant (yet seemingly underutilized) geological and mineralogical information*.

Based on what has been presented above, a key question arises: to what extent the environmental impact assessment process for the project, in alignment with key aspects of geoethical practice or sustainable mining principles, could or should have reasonably anticipated the environmental problems that subsequently emerged? Of special interest is water quality, a factor that played a decisive role in the governmental sanctions imposed on the project (SMA, 2018) and in the subsequent judicial order for its closure (Primer Tribunal Ambiental, 2020).

Given the relevance of acid drainage (AD) for water quality issues in mining projects (Park et al., 2019), it deserves a special consideration, albeit briefly, within the context of the present work. Indeed, AD, and related metal leaching, is a natural phenomenon that can be exacerbated or triggered by anthropogenic activities (i.e., mining among others). The literature typically distinguishes between acid

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rock drainage (ARD) and acid mine drainage (AMD); ARD is considered a naturally occurring process, whereas AMD is generally associated with mining (and other) activities favoring the exposure of rock materials, which significantly accelerate the oxidation of sulfide minerals and their interaction with water, thereby amplifying the effects of ARD (Grande *et al*., 2005). Regardless of whether it is ARD or AMD, one specific consequence of the phenomenon, of great environmental importance, is the generation of significantly low pH (acidic) solutions accompanied by the increased solubility, and therefore an enhanced leaching and transport of metals and metalloids such as Fe, Pb, Zn, Cu, Cd, Cr, Co, Ni, Al, Sb, and As through water systems (Moncur, 2006; Tabelin *et al*., 2020).

The chemistry of this process is related to different factors, including those associated to the formation of the ore deposits. In this regard, epithermal gold deposits such as Pascua Lama involves two sequential processes that occur under highly acidic conditions. First, a hydrothermal process takes place, during which advanced argillic alteration occurs, which is followed by a supergene process involving the oxidation of the sulfide mineral phases that were previously formed. The chemical and mineralogical processes can be summarized as follows (e.g., Oyarzun *et al*., 2007a, 2010, 2011): strong hydrolysis during hydrothermal alteration leads to the destruction of rock-forming minerals such as feldspars (minerals typical of felsic and intermediate plutonic and volcanic rocks), and the subsequent formation of sericite (Eq. 1), kaolinite (hydrolysis of sericite) (Eq. 2), and eventually alunite (Eq. 3) if sulfuric acid is still available. The latter originates first in the high-sulfidation hydrothermal system itself and later in the oxidation of pyrite during supergene alteration.

(Eq. 1) $3KAlSi_3O_8 + 2H^+ \rightarrow KAl_3Si_3O_{10}(OH)_2 + 6SiO_2 + 2K^+$

(Eq. 2) $2KAl_3Si_3O_{10}(OH)_2 + 2H^+ + 3H_2O \rightarrow 3Al_2Si_2O_5(OH)_4 + 2K^+$

(Eq. 3) $KAl_3Si_3O_{10}(OH)_2 + 4H^+ + 2(SO_4)^{2-} \rightarrow KAl_3(SO_4)_2(OH)_6 + 3SiO_2$

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This matter is especially relevant in high-sulfidation gold epithermal deposits, such as Pascua Lama (Fig. 2), which are rich in pyrite (FeS_2) and other sulfide minerals, with pyrite being especially "favorable" to the generation of AD. This is the key issue here and the reason why strong AD is formed: once pyrite oxidation starts (Eq. 4) there are no buffering minerals such as feldspars remaining in the rock to neutralize the acid (H_2SO_4) because these have already been hydrolyzed (Oyarzun et al., 2007a). This process increases the mobility of copper from chalcopyrite (Eq. 5), as well as copper and arsenic from enargite (Eq. 6).

(Eq. 4) $4FeS_2 + 10H_2O + 15O_2 \rightarrow 4FeOOH + 16H^+ + 8(SO_4)^{2-}$

(Eq. 5) $CuFeS_2 + O_2 + 2H_2SO_4 \rightarrow CuSO_4 + FeSO_4 + 2H_2O + 2S$

(Eq. 6) $Cu_3AsS_4 + 2.75O_2 + 3H_2SO_4 \rightarrow 3CuSO_4 + 4S + H_3AsO_4 + 1.5H_2O$

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Fig. 2. Landscape view (looking NE) of the Pascua Lama high-altitude gold epithermal deposit area, with significant advanced argillic alteration (light colors; kaolinite and alunite type minerals) and evidence of strong pyrite oxidation (yellow and reddish-ochre colors; jarosite and goethite type minerals). The mere presence of these colors (compare with the surrounding dark rock outcrops) should be a cause for major concern, because they reveal a very high intensity of hydrolysis, metal leaching, and oxidation in the area. Image from Thomsen (2017), with permission.

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The release of arsenic from enargite is particularly worrying as this metalloid can move in the river waters under a wide range of pH and Eh, as either oxyanions of arsenite (As^{3+}) or arsenate (As^{5+}) (e.g., Smedley and Kinniburgh, 2002; Oyarzun *et al*., 2004). In fact, enargite is the main arsenic-bearing

mineral at Pascua Lama, and, together with pyrite, carries the gold and silver mineralization in the area (Chouinard, 2003). As shown by equations (4) and (6) we see that pyrite leads to formation of strong acid solutions and enargite leads to the release of As^{5+}. Inorganic arsenic is extremely toxic, i.e. a confirmed carcinogen and one of the most significant chemical contaminant in drinking water worldwide. Thus, the release of arsenic into the local rivers could lead to a catastrophic scenario regarding both human health and ecological issues (Tabelin *et al*., 2020).

That said, Volume 100 (Issue 3) of *Economic Geology* from 2005 featured the Pascua Lama deposit on its cover (Fig. 3). The referred image, based on an article by Chouinard *et al*. (2005) included in that issue, already underscored two key aspects. First, it highlighted the extensive spatial distribution of argillic and advanced argillic hydrothermal alteration zones within the project area. With this information alone, it was possible, actually straightforward, to infer the significant AD generation problem that could be expected in the area. In fact, the article itself reaffirms the "high-sulfidation hydrothermal system" characteristic of the deposit. On the other hand, the cover image shows the highly dense network of fractures and faults associated with the mineralized area, which provides enhanced structural permeability to the rock massif (Oyarzun *et al*., 2007a) as preferential pathways for the movement of water (or acidic solutions with metals and metalloids).

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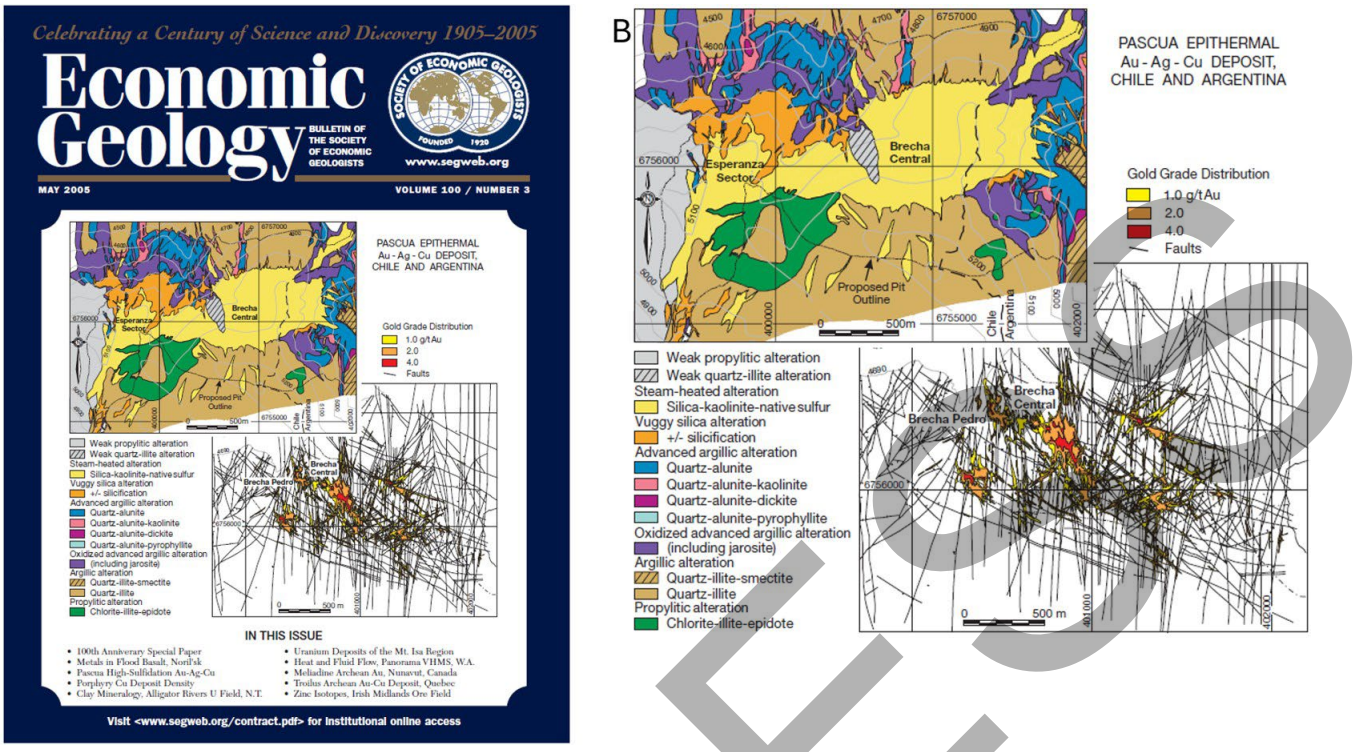


Fig. 3. A. Cover image of Economic Geology, Volume 100, Issue 3 (https://pubs.geoscienceworld.org/economicgeology/ issue/100/3). **B.** Detailed view of the Pascua Lama hydrothermal alteration zone and dense fault network (Chouinard *et al*., 2005). With permission from the Society of Economic Geology.

One year after the aforementioned inclusion of the Pascua Lama paper on the cover of Economic Geology, Fields (2006) emphasized the significance of hard-rock mining impacts, such as those associated with the Pascua Lama project, on water quality, specifically acid drainage. Two snippets from the referred document are noteworthy in the context of the current work. The first one refers to a declaration from Barrick's then Senior Vice President of Corporate Communications, who stated "the Pascua Lama project has included in its design significant facilities to minimize the possibility of surface and subterranean water coming in contact with waste rock as well as a comprehensive system of passive and active barriers to collect, store, treat, and reuse any water that does come in contact with the waste rock. This will ensure the quality of the water downstream of the project. The mine will also include

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state-of-the-art facilities for controlling acid mine drainage". The second snippet of interest shows the following: "But according to a U.S. government mining expert who is familiar with the Pascua Lama site and who asked not to be identified, the altitude and terrain of the site present unique challenges. In more hospitable locales, even the most up-to-date acid mine drainage prevention technologies, tailings holdings facilities, and cyanide handling schemes have failed (…). For the Pascua Lama operation, the source says, the company would need "great engineering" to prevent the environmental damage that hard-rock mines often inflict". Thus, it becomes evident that the inherent complexities associated both with the characteristics of the Pascua Lama deposit and with the physical environment of the project site, complexities that were relatively easy or reasonable to foresee, were not adequately internalized by the Company, at least in its public discourse. Likewise, it is apparent that this situation nevertheless clearly emerged ca. 15 years later in the ruling of the First TA as observed from the above referred statement from its Presiding Judge. Finally, it is important to emphasize that, at the time of the Pascua Lama EIA, there was already substantial knowledge regarding the prevailing conditions of naturally occurring AD, later exacerbated by mining activities, and their documented impacts on water quality in the nearby El Indio area (Oyarzun *et al*., 2006, 2007a, b). This deposit, which was mined until 2002, is located just 60 km south of Pascua Lama, in the neighboring Coquimbo Region, in the same mineralization and epithermal deposit belt and, therefore, with lithological and environmental conditions very similar to those of Pascua Lama.

In summary, the information presented supports that, by 2005–2006, when the second EstIA was assessed and finally approved, the geological, lithological, structural, and hydrogeological conditions of the project area were clearly leading to an acid drainage generation problem. The environmental implications derived from these descriptions were both explicit and well substantiated by the available, public information. So why did the issue not raise the alarms it should have, or why did significant

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problems associated with water quality ultimately occur anyway? In the following section, we seek to address this issue.

3.3.2. *Glaciers and acid drainage: An "uneven competition" in the context of the EIAs of Pascua Lama*

A final aspect of interest of the current section is to examine the relative importance given to the geological/mineralogical information, and its implications for AD, in comparison with other impacts, in specific those related to glacier and ice sheets. This analysis is framed within a broader context that extends beyond purely technical considerations, incorporating elements of the social, political, and environmental context in which the EIAs were conducted.

Regarding the initial EIA for the Pascua Lama project, it is noteworthy that, prior to submission of the first EstIA to the SEIA, the project proponent conducted an early public participation process to receive community feedback. These observations were incorporated into the EstIA and were later confirmed through the formal public participation process managed by the CONAMA in the Atacama Region. Furthermore, during the formal participation phase, a total of 53 submissions containing community comments were received. An analysis of these submissions identified three observations related to glaciers and three concerning water pollution (Delzo and Rubina, 2024). Overall, however, the community did not raise significant concerns regarding the deterioration of water resources resulting from acid drainage. Moreover, the first RCA did not impose substantial restrictions on the project with respect to its potential impacts on glaciers. This fact subsequently contributed to the emergence and intensification of complaints and concerns expressed by local communities and non-governmental organizations whatsoever (Haslam and Godfrid, 2020). Indeed, between the first and second EstIAs, Pascua Lama faced increasing opposition, driven primarily by concerns regarding its potential hydrological impacts and, in connection with these, its relationships with local communities, including indigenous groups. These issues rapidly escalated to acquire both national and international prominence

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(Haslam and Godfrid, 2023). It was in that period that glacier-related concerns gained increasing relevance in the public discourse (Haslam and Godfrid, 2020). Thus, the evaluation of the second EstIA was conducted within a context that differed markedly from that of the initial one (Haslam and Godfrid, 2020; Herr 2021). The conflict was "nationalized" and activists in the Huasco Valley connected to a broad range of allies elsewhere, especially in Santiago (Chile's Capital).

In the second EstIA, the Proponent explicitly identified, for the first time, potential impacts on three glacier bodies (Herr, 2021). Community concerns raised during the public participation process primarily focused on potential water contamination, impacts on glaciers, and the allocation and use of water rights within the valley (Delzo and Rubina, 2024). In response to escalating concerns over water resources, the RCA granted in 2006 imposed a requirement that the company refrain from removing, relocating, or otherwise physically intervening the glaciers (Aguilar, 2013).

It was during and following the second environmental assessment process that opposition to the project intensified and it acquired international visibility. Glaciers emerged as a central symbol in environmental campaigns and became the focal point of public and scholarly debate about the project (Haslam and Godfrid, 2023). Li (2016) documents that project opponents contended that the glaciers located within the mining area functioned as critical water reservoirs, playing a key role in regulating the local hydrological cycle. This argument, more than any other, proved particularly effective in mobilizing the attention of environmental activists both in Chile and abroad. Also, Urkidi (2010) notes that "The international relevance given to glaciers due to climatic change can be understood as a post-materialist conservationist value introduced by supralocal actors". Kronenberg (2013) advances a similar argument, observing that glaciers had come to be portrayed in public discourse as "endangered species," serving as an iconic representation of the consequences of climate change. The author further emphasizes that, by that time (i.e., late 2000s), climate change had attained a substantially higher level of public awareness. Thus, although glacier damage was only one of several issues driving local protests, it readily attracted

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international attention due to their symbolic significance. According to White-Nockleby and Odell (2025), Pascua Lama represents the first extensively documented instance of what they called as “cryoactivism”. Also, they note that several authors demonstrate how glaciers' growing relevance in climate and mining conflicts was to some extent a product of intentional strategies to mobilize multilevel support against two related environmental threats, with both global and local dimensions: climate change and the expansion of mining in glaciated regions.

Needless to say, the Pascua Lama glaciers also received special attention from Barrick. For instance, a 2011 presentation by the then Vice President of Permitting and Approvals (Riehm, 2011) identified, on its slide 7, the key issues related to the approval process, describing them as follows: “water, water, and water: glaciers; others: water, air quality, local procurement and hiring, community development, flora and fauna, water!”. This was followed immediately (i.e., slides 8–10) by a further discussion of glaciers and ice masses. Although the presentation subsequently addressed water-quality issues related to ARD (e.g., slides 13 and 15), the above can be interpreted, in our view, as an example of the importance given by the Company to issues related to water availability (quantity), specially those directly concerning to glaciers, to some extent at the expense of the issue of acid drainage, at least in the public discourse.

With respect to the EIA processes, it would be inaccurate to suggest that it explicitly or excessively prioritized glacier-related issues over acid mine drainage, or that the latter was entirely disregarded (Delzo and Rubina, 2024). Indeed, acid drainage was among the aspects examined in the project’s initial EIA submitted in 2000, and it was also addressed during the second assessment process. Nevertheless, a review of the RCA for the second EstIA shows a predominance in the mention of glacier-related impacts compared to acid drainage ones. Specifically, the term “glacier” appears approximately 220 times, whereas the term “acid” is mentioned only about 140 times across the 170 pages of the document (SEA, n.d).

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In summary, it becomes apparent, at least preliminarily, that the attention devoted to glaciers in the public discourse, both spontaneously and intentionally by different stakeholders (and under different motivations), was quite substantial, especially when compared with the attention given to the other key issue addressed in this contribution, namely acid drainage (and related water quality impairment).

3.3.3. *Documentary analysis*

Through a Scopus search (https://www.scopus.com/pages/home#basic), as summarized in Table 1, considering various terms appearing in the title, abstract, and keywords of published articles, it is possible to observe that indeed the majority of the international scientific literature also addressed the Pascua Lama case primarily from a glaciological perspective or with glaciers as a key aspect of the analysis. Moreover, closely related to this focus, issues concerning social, political, human rights, and environmental justice dimensions also received a significant scholarly attention (e.g., Urkidi and Walter, 2011; Aguilar, 2013; Kronenberg, 2013; Haslam, 2018; Barandarián *et al*., 2025). Nevertheless, relatively little of the existing literature examined Pascua Lama from a technical environmental perspective, particularly in relation to a major factor that ultimately contributed to the closure of the project, i.e., acid drainage (and water quality related issues).

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Table 1. Scopus query. Number and type of documents identified for different search terms, 1960 to present (results as of December 2025)

Terms considered for title, abstract, and keywords	Articles	Book chapters	Reviews	Total
Pascua Lama	32	4	2	38
Pascua Lama and Environmental impact	9	1		10
Pascua Lama and Glacier	13	1		14
Pascua Lama and Indigenous	1			1
Pascua Lama and Water quality	1			1
Pascua Lama and Hydrothermal alteration	4		1	5
Pascua Lama and Acid drainage	1			1

Complementarily, a bibliographic search using the Harvard University Library's HOLLIS database (https://hollis.harvard.edu) was performed to extend the scope of this analysis beyond technical publications (papers and book chapters), thus including sources such as newsletter and magazine articles, among other categories. This approach captures the media attention and gray literature (i.e., research produced by organizations outside of the traditional commercial or academic publishing) related to the project, considering various components and search criteria (Table 2). As the temporal range (indicated in the table) was automatically restricted by the search engine according to the concept being searched, two analyses were developed: from 1991 and from 2001 (to 2025), when possible.

Based on the results, several key observations can be put forward. First, the environmental implications (i.e., impacts) of the Pascua Lama project have indeed received substantial attention worldwide. Second, it is evident that the Pascua Lama Project received considerably greater attention from 2001 onward, compared with the preceding years. This is reflected in the substantial similarity

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between the number of mentions identified for the 2001–2025 period and those identified for the extended 1991–2025 period (in cases where both analyses could be conducted). Third, there is a clear predominance of bibliographic resources related to glaciers and social aspects (e.g., indigenous communities), to the detriment of aspects more directly related to water quality, particularly concepts such as “hydrothermal alteration” and “acid drainage”. This evidences that discussions of environmental impact and water quality in the reviewed literature were primarily linked to glaciers rather than to the geological and mineralogical setting of Pascua Lama. In summary, analyses of both the Scopus and Harvard databases confirm a pronounced imbalance in the attention received, with substantially greater emphasis placed on glacier-related issues than on the potential generation of acid mine drainage.

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Table 2. Harvard query. Number of resource types associated with the Pascua Lama Project. The searches were conducted using the terms "Pascua Lama," "Pascua Lama" AND glacier, or "Pascua Lama" AND "water quality" (and so forth), considering the elements listed in the table headings.

	Pascua Lama	Pascua Lama and Environmental impact	Pascua Lama and Glacier	Pascua Lama and Indigenous	Pascua Lama and Water quality	Pascua Lama and Hydrothermal alteration	Pascua Lama and Acid drainage
Search period	1991-2025 (2001-2025)	1991-2025 (2001-2025)	1991-2025 (2001-2025)	1991-2025 (2001-2025)	2001-2025	2001-2025	2001-2025
Newspaper articles	6,282 (6,241)	430 (429)	369 (357)	359 (356)	57	5	5
Web resources	2,230 (2,230)	3 (3)	10 (10)	9	2	0	0
Articles	1,166 (1,157)	300 (300)	165 (161)	211	103	7	7
Reports	805 (796)	295 (293)	77 (76)	139	20	0	0
Newsletter articles	640 (639)	188 (188)	21 (21)	44	3	0	0
Transcripts	313 (313)	53 (53)	16 (16)	16	8	0	0
Magazine articles	133 (130)	26 (26)	37 (37)	28	4	0	0
Book chapters	123 (123)	53 (53)	45 (43)	81	22	2	2
Dissertations	34 (34)	6 (6)	6 (5)	8	1	0	0
Review articles	17 (17)	10 (10)	7 (7)	9	5	0	0
Books	16 (16)	2 (2)	0	4	0	0	0
Reference entries	13 (12)	2 (2)	3 (3)	1	1	0	0
Reviews	12 (12)	8 (8)	5 (5)	3	0	0	0
Total	11,784 (11,720)	1,376 (1,373)	761 (741)	912 (909)	226	14	14

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3.4. Final insights

It would be unfair to ignore that the Pascua Lama case had significant positive externalities in terms of raising awareness of the importance of glaciers from the perspective of water resource availability, both

in Chile and elsewhere. However, it does not necessarily appear to be a successful case in terms of the EIA process, and its contribution to the sustainable development of projects, specially within a geoethic perspective context.

Glaciers, encompassing "white," "rocky," and other cryospheric forms, certainly play an important hydrological role in regions such as the arid and semi-arid Andes (Brenning, 2008; Brenning and Azócar, 2010; Kronenberg, 2013). Within this context, the considerable national and international attention devoted to the Pascua Lama 'glacier case' stimulated numerous studies, fostered in-depth discussion on the topic, and prompted notable attempts of formal legal protection both in Chile and Argentina (Barandiarán *et al*., 2025). Likewise, the project did in fact generate impacts on the glaciers, as evidenced by the inspection and sanction initially imposed by the SMA and subsequently upheld by the courts (First Environmental Court and Supreme Court), as well as by studies conducted on the matter (e.g., Hess *et al.*, 2020). However, the Pascua Lama case underscored a pronounced and somewhat biased focus on glaciers, accompanied by a relative minor consideration of acid drainage issues that ultimately proved to be equally or far more significant in terms of impact. The key question here is: what would have happened during the EIA of Pascua Lama if glaciers had not been present? Given that the mining project was authorized after the first EIA, it seems that it would have gone ahead without major delays and, therefore, the potential risks related to acid drainage and the leaching of metals and metalloids would have continued. Needless to say, most likely this potentially grave problem would not have received the attention it deserved. With the benefit of hindsight, it is evident that the Pascua Lama case provides important lessons for future environmental assessments of similar projects and characteristics. Indeed, despite the existence of relevant knowledge, different participants involved in the EIA process and the subsequent project implementation were unable to adequately identify, and especially to appropriately weigh, the full range and magnitude of environmental problems that could arise.

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Two additional aspects merit consideration in light of the Pascua Lama case (and therefore, the geoethical-, EIA-, and sustainable development-aspects involved). First, Li (2016) argues that the proper use of scientific and technical information should constitute a core component of corporate social responsibility (CSR) strategies and environmental management plans. Similarly, that CSR initiatives should, in general, be guided (or at least informed) by the expertise and input of engineers, scientists, and mining professionals. From this perspective, the technical analysis of the environmental impacts potentially arising from the project was insufficiently and improperly conducted in the case of Pascua Lama. In this regard, and with respect to issues addressed at the outset of this paper, specifically sustainable development and geoethics, it would be unwarranted to expect the Pascua Lama's EstIAs prepared by the mining company, their evaluation by the OAECAs, or the actions of other instances (e.g., non-governmental organizations) to have adhered to or followed the principles of the recently proposed Geoethics Code in Chile. Although this Code represents a valuable framework for future projects and is therefore addressed here, extending a critique of the Pascua Lama case on the basis of a subsequently proposed code would be anachronistic. However, from the perspective of the mining company, the guidelines declared at the time by the ICMM could, at least in principle, be considered as part of the analysis. In this regard, it may be of perhaps secondary significance, but nevertheless noteworthy, that Barrick withdrew from the ICMM in the early 2000s amid concerns regarding the pace and scope of initiatives aimed at improving the mining sector's performance, before subsequently rejoining the organization later in that decade in response to evolving global CSR standards (Dashwood, 2012), and has remained a member since. This "pause" (regarding participation at ICMM) roughly coincided with the period during which the company submitted its second EIA.

More recently, a March 2025 report in the Chilean newspaper La Tercera cites statements by the Executive Director of Government Relations at Barrick Gold South America, who acknowledged that "the worst mistake Barrick made was to be arrogant, overbearing, and not listen to the communities in

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the region" (Nogales, 2025). Relations with local communities were indeed contentious. However, what is especially striking is the lack of public recognition of the substantive environmental issues, specifically, impacts on water quality associated with acid drainage, and also the fate of glaciers, which ultimately determined the closure of the project on the Chilean side. In other words, the inadequate technical assessment of environmental problems, which should have been realistically identified by the Company and appropriately considered and weighted during the EIA process, represents a key structural deficiency. Publicly, at least, this shortcoming does not appear to have been fully acknowledged by the project proponent yet.

The second aspect concerns the application of the "Precautionary Principle," which can be understood as the protection of the environment through precautionary measures, even in the absence of conclusive evidence of harm or risk associated with an activity. As highlighted by Wang (2026), this is also an important ethical principle for dealing with uncertain issues and, despite of that, for addressing and resolving risks. Accordingly, it should serve as a guiding principle, or at least a critical consideration, within EIA processes, particularly for projects of clear complexity (Jalava *et al*., 2013), as was the case of Pascua Lama. In this context, Aguilar (2013) asserts that "the Chilean State failed to respect the precautionary principle when analyzing the environmental impact of the project." While we agree with this observation, we contend that the disproportionate emphasis on glaciers was ultimately misplaced: the precautionary principle should have been applied more explicitly with respect to the potential generation of acid drainage and metal and metalloid dispersal. We believe that the issue of misplaced priorities may have arisen from a form of tunnel vision (e.g., Posavac *et al*., 2010; Savasta-Kennedy, 2014), which creates a selective attention on a single problem (i.e., a few, and rather small glaciers in the Pascua Lama case) that can eventually result in partial solutions to complex problems, which usually leads to unintended side effects. In other words, the mere availability of scientific knowledge is

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insufficient, as its appropriate application is also essential: to know the answer helps to solve a problem, assuming you know there is a problem.

While all this may appear to be self-evident, the Pascua Lama case demonstrates that such application does not necessarily occur within EIA processes, whether due to the approach and priorities of the study proponents or the influence of political, social, and/or economic factors external to the technical assessment itself. In this context, a proper (and actual) adoption of geoethic principles such as those addressed by the proposed Chilean Code represents a significant window of opportunity for actual and practical improvement.

4. Concluding remarks

The case of the Pascua Lama project constitutes a paradigmatic example of how environmental impact assessment (EIA) processes can fail, not because of insufficient scientific knowledge or information, but due to the selective prioritization of environmental risks within a complex socio-political and environmental context. In a sense, what occurred reflects a convergence of shortcomings across several actors: the company, which failed to internalize foreseeable scientific and technical risks of the proposed project; the regulators, who approved a project proposed to be developed under complex conditions, especially given the direct empirical precedent provided by the nearby El Indio mine; and environmental activism, which turned glaciers into a global symbol and, consciously or unconsciously, contributed to shifting the focus of the debate toward these issues rather than toward others that ultimately proved to be equally or even more important in terms of environmental impacts and, consequently, the closure of the project.

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Nearly two decades later, it is evident that the environmental impacts that ultimately led to the project's closure were scientifically foreseeable and reasonably well constrained during the assessment stage, yet not adequately addressed. Pascua Lama is a classic high-sulfidation epithermal deposit characterized by advanced argillic alteration, abundant pyrite and enargite, and a near absence of acid-neutralizing minerals due to hydrothermal alteration. Such geological setting is known to be highly prone to acid mine drainage. Importantly, nearby mining districts within the same metallogenic belt (El Indio), had already provided empirical evidence of acid drainage affecting water quality. Therefore, the information necessary to anticipate the likelihood and severity of these impacts was already available during the EIA process. Despite this, the assessment failed to translate scientific evidence into preventive or precautionary measures proportional to the risks involved. This outcome departs from what would be expected under geoethical principles such as those currently promoted in Chile, specifically regarding the responsible and proper use of geological information to prevent environmental impact.

Another relevant aspect is that both the EIA and the broader public and academic debate surrounding Pascua Lama became increasingly dominated by concerns over glaciers. Although glaciers are undoubtedly important within arid Andean hydrological systems, the disproportionate emphasis placed on glacier-related impacts contrasted sharply with the comparatively lower attention given to the geochemical risks associated with acid drainage. This imbalance evidences a form of tunnel vision that weakened the EIA's capacity to properly anticipate environmental impacts and support sustainable decision-making. The regulatory history of the project clearly reflects this issue: sanctions imposed by the Chilean Environmental Superintendence (subsequently upheld by Environmental Courts and the Supreme Court) ultimately centered on effects on water quality as major impacts, in addition to that on glaciers.

The implications for sustainable mining development are substantial. In projects involving high-sulfidation deposits, acid drainage and the mobilization of toxic elements such as arsenic should be

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treated as first-order environmental risks because of their persistence, difficulty of mitigation, and long-term consequences for ecosystems and human health. Accordingly, the precautionary principle should be applied rigorously to such risks, rather than disproportionately focusing on impacts that are more visible or symbolically prominent but potentially less consequential environmentally.

This case also demonstrates that the mere availability of scientific knowledge does not guarantee environmentally sound outcomes. The effectiveness of an EIA will be enhanced when relevant information is properly recognized, weighted, and incorporated into enforceable design, monitoring, and management measures, an approach to be expected in a context of geoethical principles consideration, allowing scientifically grounded and socially responsible decision-making. A credible commitment to sustainability requires not only responsiveness to social concerns, but also a transparent and technically rigorous acknowledgment of a project's most significant environmental risks. Underestimating or misprioritizing these risks undermines public trust, intensifies conflict, and increases the likelihood of regulatory failure. Only through balanced and evidence-based prioritization of risks, EIAs can effectively fulfill their role in anticipating impacts, guiding decision-making, and preventing irreversible environmental damage.

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