The Extractive Industries and Society 8 (2021) 176–187

Contents lists available at ScienceDirect

The Extractive Industries and Society

journal homepage: www.elsevier.com/locate/exis

Review article

Mining region value and vulnerabilities: Evolutions over the mine life cycle

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ARTICLE INFO

Keywords:
Values
Vulnerabilities
Mining regions
Territorial trajectories
Multidisciplinary approach

ABSTRACT

This paper asserts that the value of a mining region does not only depend on the economic benefits from mining activity, but also on its geological, environmental, social and cultural values. Values and vulnerabilities evolve over the mine life cycle, forming specific territorial trajectories that depend on the initial conditions as well as on political, economic, and socio-cultural contexts. A simple graphical framework is proposed to represent and describe the changing values and vulnerabilities over the mine life cycle. This framework, which has been developed for industrial metal mines, is applicable whatever the spatial scale considered and emphasises the complexity of territorial trajectories in relation to local governance and policies. It allows for easy comparison of mining regions. Future work should focus on defining integrative indexes for the different types of territorial values and vulnerabilities.

1. Introduction

Production of raw materials has increased exponentially since the early 20th century. Demand up to 2050 is forecast to follow a similar trend (+3% to +6% per year depending on the metal; Christmann, 2018) due to world population growth, increase in urban populations and rapid expansion of the middle class. Primary production (mining) and discovery of new deposits will remain a necessity considering that secondary raw-metal production (recycling) and present-day reserves will not be sufficient to face the forthcoming demand (Christmann, 2018).

Mining activity (metal extraction and ore processing) strongly impacts the environment. We can see the evidence in landscape modifications; removal of topsoils (in open-pit mining); hydrological side-effects; air, water and soil contamination; dust emission, increased noise, and habitat degradation, etc. (Ripley et al., 1996; Dudka and Adriano, 1997; Younger et al., 2002). And when mining becomes the main economic activity of a region, it also has significant impact on social and cultural structures: it increases economic inequalities, results in land-use and resource conflicts, and modifies community identity in depth, etc. (Werner et al., 2019; Horowitz et al., 2018; Smart, 2020).

The socio-environmental impacts of mining cover a wide range of situations and depend mainly on territorial identity, local and national governance, and the type of mine and mining techniques. This article looks at industrial mining only (artisanal and small-scale mining will not be considered here). We can see three types of mining regions:

1) Regions with a long mining history and a strong mining identity, where mining has been taking place for more than a century (Ireland, Scandinavia, USA, Canada, Australia, Chile, etc.). In these regions, mining remains one of the main economic activities, and its social acceptance is rather significant (Devenin et al., 2019).
2) Former mining regions. These had mining activities in the 19th and early 20th centuries but no longer have active mines (e.g., most European countries). Mining identity in those regions has often been lost or relegated to cultural heritage (Hendrychová and Kabrna, 2016; Oakley, 2018). Most raw materials are imported, and the social acceptability of new potential mining projects is very low (NIMBY and BANANA syndromes).
3) Regions which previously had no mining activity but which have been affected by a relatively recent (i.e., in the last few decades) and rapid mining boom. This latter often generates socio-environmental conflicts (e.g., Latin America, Africa; Haslam and Tanimoune, 2016; Walter and Urkidi, 2017).

Literature on mining and its territorial impacts is often segmented by discipline. Metallogeny studies, for example, focus on the characterisation and formation of ore deposits in order to propose metallogenic models (Hedenquist et al., 2005) and to provide updated exploration guides for mining companies (e.g., Rossi et al., 2017). In contrast, environmental studies focus on understanding the processes involved in:

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https://doi.org/10.1016/j.exis.2020.07.010
Received 15 October 2019; Received in revised form 6 July 2020; Accepted 8 July 2020
Available online 31 July 2020

1) contamination of soil, water, sediment, fauna and plants by trace metals (Ripley et al., 1996; Dudka and Adriano, 1997; Younger et al., 2002);
2) the legacy of former mining activity on present-day ecosystems (Baron et al., 2006; Casiot et al., 2009; Camizuli et al., 2018); and
3) the effects of mining on health (Carvalho et al., 2017; Hadzi et al., 2019).

Such environmental degradation caused by mining activities can lead to conflicts on a local or national scale. In fact, in human geography, anthropology and sociology, mining activity is often analysed through the conflicts that arise during mine construction and operation (Martinez-Alier, 2001; Bebbington, 2012; Forget, 2015; Forget and Carrizo, 2016; Karakaya and Nur, 2018). Most of the literature claims affiliation with political ecology; it analyses the relations of power within regions and often denounces the hand of transnational firms and the weakness of state policies (Acosta, 2011; Svampa, 2011).

Meanwhile, territorial analysis emphasises the struggle for transversal resources, such as water and energy, between mining companies and local populations (Forget, 2015; Bos and Grieco, 2018) and investigates the role of governance and local vs national politics (Liping et al., 2015; Coumans, 2019; Haikola et al., 2020). Furthermore, the social sciences have documented the notion of "social licence to operate" (Moffat and Zhang, 2014; Zhang et al., 2015; Vanclay and Hanna, 2019), territorial identity changes and the construction of a mining identity (Harner, 2001; Ballesteros and Ramirez, 2007; Parmenter and Trigger, 2018) as well as inequalities and environmental justice (Rodríguez-Labajos and Özkaynak, 2018).

While scientific literature does cover many aspects of the impacts of mining on the local area, it most often covers particular case studies. It would benefit from the inclusion of economic, environmental, social and cultural aspects, with regard to local and national governance and to the ore deposit properties. Indeed, ore mineralogy, ore grade, rock and mineral textures, and deposit geometry determine the exploitation and ore-processing techniques, and these latter in turn determine the economic and environmental impacts. In contrast, local and national governance as well as the political context (democratic vs non-democratic) directly determine the social impacts.

Sustainable development of extractive industries should (i) contribute to health, wealth and well-being for all, (ii) maintain the quality of the environment and other resources, and (iii) rely on inclusive governance by all stakeholders (IRP, 2020). For these reasons, environmental, social and cultural values must be identified and taken into consideration together with economic value. To facilitate this process, this paper seeks to provide a framework for representing the trajectories of mining regions via the changes of territorial values and vulnerabilities related to mining. First, we will define territorial values and vulnerabilities, and then break them down into geological, economic, environmental, social and cultural components. We will then discuss how these values and vulnerabilities change over the mine life cycle. Finally, we will present and discuss several specific territorial trajectories.

2. Framework and methods

The framework we propose for representing territorial trajectories is based on data visualisation of changes in territorial values and vulnerabilities over the mine life cycle. Only industrial metal mines will be considered here.

In this paper, a broad definition of the concept of "value" has been adopted. Here, it is considered as a socio-cultural construction that means something important to a person or a social group (Stephenson, 2008; de la Torre, 2013). This concept is therefore not restricted to monetary value, but also includes direct-use values (economic provisioning of goods, etc.) and non-use values (e.g., habitat support and related ecological diversity preservation, heritage conservation, indirect cultural services such as locally perceived value, etc.).

In this paper, the territorial value has been broken down into **economic value** (financial gains), **environmental value** (environmental quality and the capacity to use or preserve it), **social value** (value given by the inhabitants, taking into account well-being and wealth) and **cultural value** (identity, revealed heritage or cultural potential). The ore-deposit mineralogy and geometry determine the extraction type (underground vs open-pit), the scale of the mining site and the ore-processing techniques, which directly impact economic and environmental values and indirectly impact social and cultural values. Therefore, the authors define **geological value** in relation with the ore deposit (geometry, ore grade, mineralogy, etc.).

Generally speaking, vulnerability can be defined as the inability of a system to withstand the disturbances of external stressors (Becerra, 2017; Mathis et al., 2016). In this paper, territorial vulnerability has been broken down into **geological vulnerability** (e.g., changes of the ore grades), **economic vulnerability** (global market volatility or destabilisation of the economic system), **environmental vulnerability** (contamination or ecosystem degradation), **social vulnerability** (potential harm to people) and **cultural vulnerability** (potential modification of the territorial identity).

Table 1 summarises the main quantitative and qualitative indicators used to estimate the territorial values and vulnerabilities, which are extremely dynamic concepts. Evolution of these indicators over the mine life cycle helps to evaluate the changing values and vulnerabilities of mining regions over time. The framework proposed in this paper is based on visualisation of these changes using graphs, where the vertical axis represents the values and vulnerabilities and the horizontal axis represents time (Figs. 2 to 11). Time thus integrates the mine life cycle, which has been broken down into the following stages (Fig. 1): (1) prior to mining, (2) exploration, (3) mine and processing plant construction, (4) mine operation and mineral processing, (5) mine closure, (6) post-mining management, (7) post-mining development. The territorial trajectory over the mine life cycle is constructed by compiling the trajectories of each stage (Figs. 12 and 13).

3. Evolution of values and vulnerabilities

The discussion below focuses chiefly on regions with no strong mining identity. However, when relevant, the specific case of regions with a long or strong mining identity is also presented.

3.1. Prior to a mining project

In the case of regions that have not previously experienced mining activity, their main economic activity is usually based on agriculture, livestock farming, or other ecosystem services. In regions with past mining activities, it may be based on industries (e.g., metallurgy, power plants, etc.). Economic and social values and vulnerabilities depend on the economic activity dynamics, the global market and local policies (Fig. 2).

At this stage, the geological value is considered to be null or stable in case of promotion of the local geology (landscape, former mining heritage, etc.), and cultural values are considered stable. Environmental value depends on the ecosystem services, and environmental vulnerability depends on the environment quality and local contamination due to the presence of ore. Cultural value depends on the territorial identity, and its vulnerability depends on policies.

3.2. Exploration phase

Exploration is carried out to identify and target ore deposits to develop mining projects. Early exploration, which involves mainly airborne and terrestrial geochemical and geophysical surveys, has no or limited incidence on the regions. If mining potential is identified from early exploration, advanced exploration follows to fully characterise the

Table 1
Parameters and indicators that contribute to the geological, economic, environmental, social and cultural values and vulnerabilities of mining regions.

	Quantitative indicators	Qualitative indicators
Geology		
Mineralogical assemblage	-	mineralogy
Ore grade	Grade (g/t)	-
Ore volume	Tonnage (tons)	-
Stability	Proportion of instable areas; instability degree	Past mass movements (e.g., collapses, landslides, etc.)
Ore continuity / discontinuity	Continuity degree (for vein deposits)	-
Homogeneity / dispersion	Dispersion degree	-
Economy		
Metal market & benefits	Benefits, global demand / offer (dollars)	-
Infrastructures	Length and proportion of asphalt roads (km) / railway; number of energy plants; distance to port (km)	Connectivity to other cities
Investment needed	Investment (dollars)	-
Other economic activities and land use	Number of activities; benefits (dollars), proportion in the economy; etc.	Types of activities and land use; localisation of other resources; hierarchisation of land use
Environment		
Natural geochemical background	Average trace metal content (mg/kg)	Spatial approach
Stock and quality of water / soils	Average trace metal content in surface waters / soils (mg/kg); surface and proportion of contaminated land (km^2); river discharge; proportion of soil / water resources for other uses than mining etc.	-
Contamination	Surface and proportion of contaminated land / waters; amount of dust emission; average trace metal content in dust (mg/kg)	-
Biodiversity	Number of species (fauna, flora); surface and proportion of the various ecosystems; etc.	Perception of "living" land, perception of changes
Ecosystemic services	Number and variety of ecosystemic services; benefits from each service (dollars); number and proportion of the population that benefit from these services; etc.	-
Perception of nature	-	Spiritual perception, recreation and healing activity
Society		
Inhabitants	Number of inhabitants, age distribution, proportion of men / women / children / elderly people	-
Employment	number and proportion of local employment at the mine; number of unemployed and unemployment rate; etc.	-
Conflicts	Number of conflicts; number and proportion of (local) people protesting; etc.	Types and spatial distribution of conflicts
Income	Average income and distribution of income	-
Criminal / illegal activities	Benefits from illegal activities	Structuration of society by criminal / illegal activities
Community health	Number and proportion of diseases amongst the population; number and proportion of diseases related to environmental degradation due to mining	Diseases typology
Indigenous communities	Proportion of indigenous community members	-
Culture and heritage		
Mining heritage	Number of mines transformed into heritage sites; number of visitors per year; benefits	How well known it is
Territorial identity	-	Presence / absence of indigenous communities; resonance of past mining identity; other territorial identities
Culture	-	Individual and/or collective identification; collective oral transmission; indigenous heritage; ethnological approach of spirituality

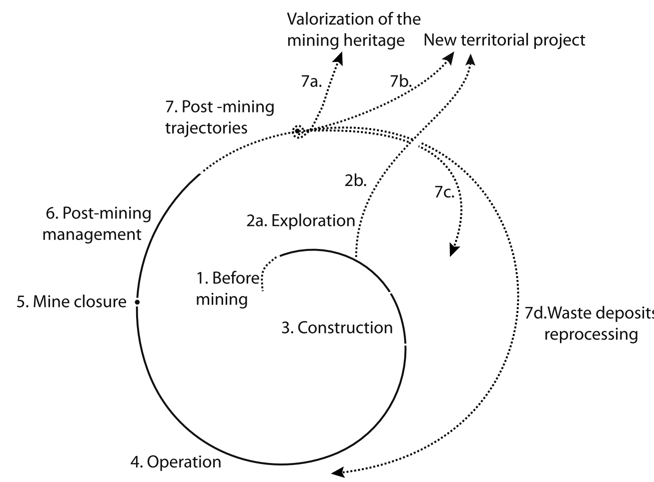

Fig. 1. The different stages of the mine life cycle. .

ore deposit (ore type, grade and tonnage, mineralogy, geometry, geological context, etc.) and to estimate the mineral resources and reserves. The geological value thus increases considerably at this stage, according to the mining potential. Advanced exploration involves drilling and trenching, which often require road opening. As a result, environmental value starts to decline and environmental vulnerability increases (Fig. 3).

Next, market speculation starts as the mining potential of the targeted ore occurrence is revealed by advanced exploration and the resources and reserves are estimated. As market speculation intensifies, both economic value and vulnerability increase. At this stage, mining is seen either as an opportunity, especially in fragile and peripheral regions (Forget, 2015; Forget and Carrizo, 2016, 2018), or as a threat when the prospect of mining makes the region susceptible to dispossession and jeopardises other economic activities such as subsistence farming (Harvey, 2005; Svampa, 2011). Economic vulnerability depends on trends in the global metal market, available infrastructure, the political context and social acceptability (Bebbington et al., 2008; Bridge, 2008; Forget and Carrizo, 2018). Use of the new infrastructure (power lines, roads) for the regions is one of the main challenges in negotiating a mining project with local authorities (Jackson, 2015; Loutit et al., 2016; Forget et Carrizo, 2018).

When exploration reveals significant mining potential, thereby leading to a feasibility study, the prospect of mine operation becomes

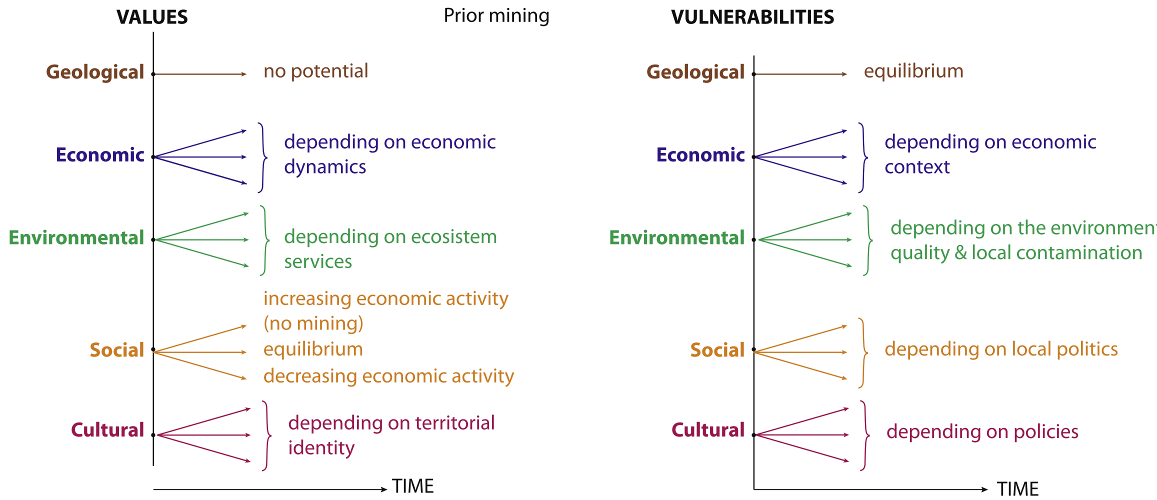

Fig. 2. Territorial values and vulnerabilities prior to a mining project. .

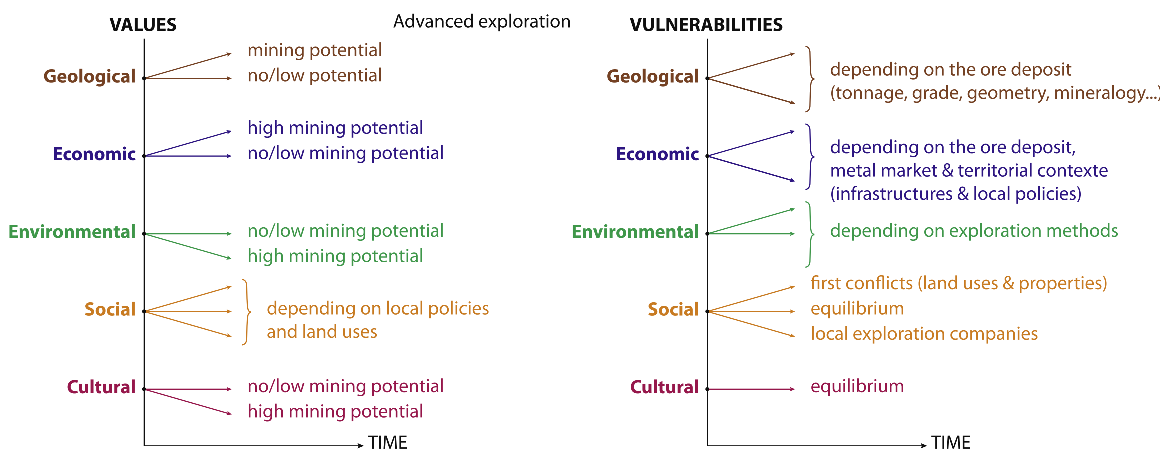

Fig. 3. Territorial values and vulnerabilities during advanced exploration. .

public. When allowed by the country's political regime (in a democratic system), mobilisation may start in defence of the region against non-native interests and in order to avoid future conflicts of a social, resource (water and energy) and land-use nature. In response to that mobilisation or according to obligation for public consultation, public meetings and negotiations usually take place between the region's inhabitants and the representants of the exploiting firm (which is usually national or transnational).

3.3. Feasibility and construction phase

About 1 discovery out of 200 goes beyond the exploration stage to feasibility studies. amongst them, about 50% end up in mine development (IRP, 2020). Economic value drops during the feasibility studies

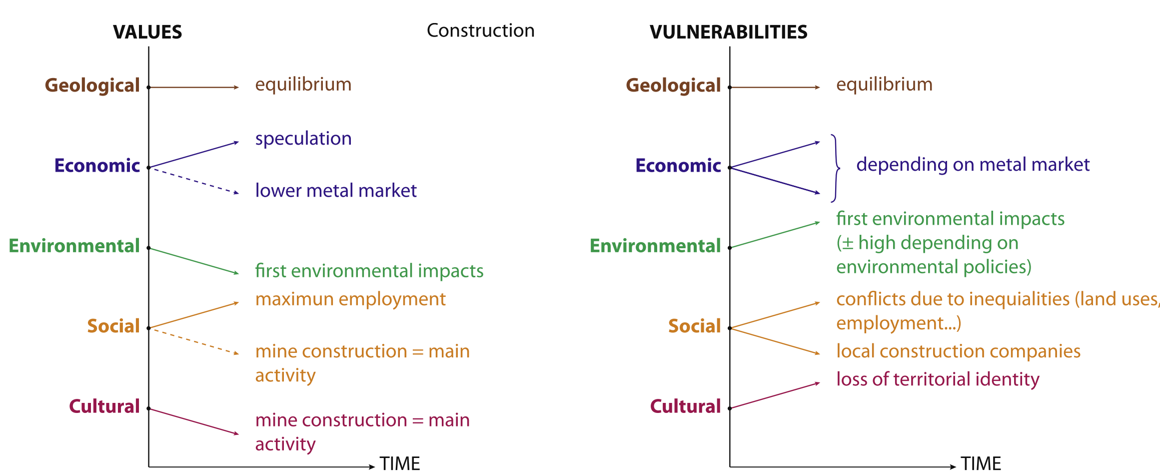

Fig. 4. Territorial values and vulnerabilities during mine construction.

(capital is needed for future mine development but there are no cash inputs yet), before rising again during mine construction (Fig. 4). At this stage, the ore deposit is now well known, so geological value and vulnerability are unchanged.

Employment is highest during mine construction: specialised workers come from outside the region, but local subcontractors are involved in roads and masonry work, plumbing, and logistics on-site (laundry, catering, etc.). The temporary job creation and the prospect of obtaining future jobs at the mine may decrease social vulnerability. In regions without a mining history, mine construction rapidly becomes the main activity: by impacting traditional land use, it contributes to the breakdown of the local community, leading to social conflicts and increased social vulnerability. Furthermore, slowdown in the mine's activity has significant impact on the local society, which is organised around services to the mine, and on the pace of successive labour migrations.

In most projects, cultural value rapidly decreases as the mining culture quickly takes precedence over local traditions, resulting in frequent loss of territorial identity. Mine construction leads to the first significant environmental impacts: the building of infrastructure, levelling works and transport of material significantly increase noise and dust emissions and damage the land. Consequently, environmental vulnerability rises significantly, and environmental value starts to decline. However, these impacts may be limited, as they depend on the environmental constraints determined by local policies.

3.4. Operation phase

As in the case of exploration, economic value during the mine operation is closely related to geological value and to trends in the metal market (Fig. 5). The volatility of metal prices on global markets may weaken the region. At this stage, geological value is highest but may evolve according to unforeseen events and to ongoing exploration. For example, if the ore grade turns out to be higher than had been expected during exploration, geological and economic values will both increase. However, geological and economic values can drop if the reverse occurs, or if the mining methods become unsuitable in the event of unexpected changes in the mineralogy or structural geology.

Mining involves extraction of ore minerals from deep in the earth, where metal-bearing minerals are rather stable, and their accumulation at the surface in waste deposits (tailings and slags). These waste deposits generally contain rather high amounts of trace metals (As, Cd, Sb, Pb, Cu, Zn, etc.) which can easily be leached out by weathering and infiltration of water, causing acid mine drainage. This results in the transfer of trace metals into the environment (soils, stream and lake sediments, vegetation, biota, etc.) and contamination at various scales at the mine site or in river catchments, downstream to estuaries (Ripley et al., 1996; Dudka and Adriano, 1997; Younger et al., 2002).

Dust and noise emissions due to intense transport (of ore, metal and workers) are still present at this stage. Furthermore, metal processing usually requires the use of chemicals (e.g. cyanide for gold extraction) which may be released into the environment in the event of accidents or bad management, thus putting local people at risk (Bose-O'Reilly et al., 2008;Harmanescu et al., 2011). Therefore, during the mine operation, environmental vulnerability is highest and environmental value is lowest. However, depending on local policies, the environmental impacts may be restricted: suitable management of tailings and waste deposits may reduce the development of acid mine drainage and thus limit contamination.

Mine operation requires qualified workers. In regions without previous mining, most qualified workers usually come from other regions, whereas the local people live from economically insecure services to the mine. Upgrading of work qualifications usually tends to decrease social value during the mine operation (Russell, 1995). Indeed, as mining employees often enjoy relatively good income compared to people working in other activities, inequalities and social vulnerability increase. Public policies regarding employment of local people may help mitigate these inequalities. In regions with previous mining activity, qualified workers can be hired locally, thus increasing social value and decreasing social vulnerability.

In whatever region, mining plays a significant role in structuring the local society. Informal and sometimes illegal activities such as prostitution may occur (Laite, 2009). As mining requires transversal resources (water, energy and land), the operation stage is characterised by the rise of socio-environmental conflicts. Indeed, in regions without previous mining activities, destabilisation of traditional land use and of local arts and crafts may increase cultural vulnerability due to a loss of territorial identity and the weakening of heritage values. In regions with a strong mining identity, cultural and social values are closely related to mining.

3.5. Mine closure and post-mining management

Mine closure generally induces strong territorial destabilisation (Fig. 6; Baiton and Holcombe, 2018). Drop in interest in the ore body results in a rapid decline in the geological and economic values that were very closely correlated with those results during the mine operation. Consequently, economic vulnerability rises significantly as the benefits come to an end and cash is needed for mine closure and post-mining management. Without any new territorial project, economic value is thus lower than before mining, due to the socio-environmental impacts mining has generated. At this stage, the cultural value of the mining site may have been identified if a mining

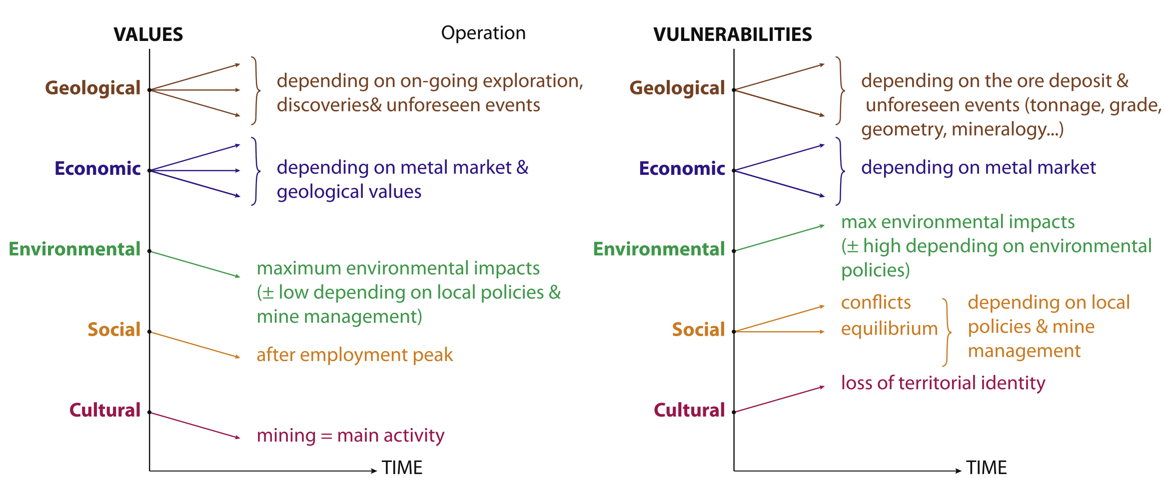

Fig. 5. Territorial values and vulnerabilities during mine operation.

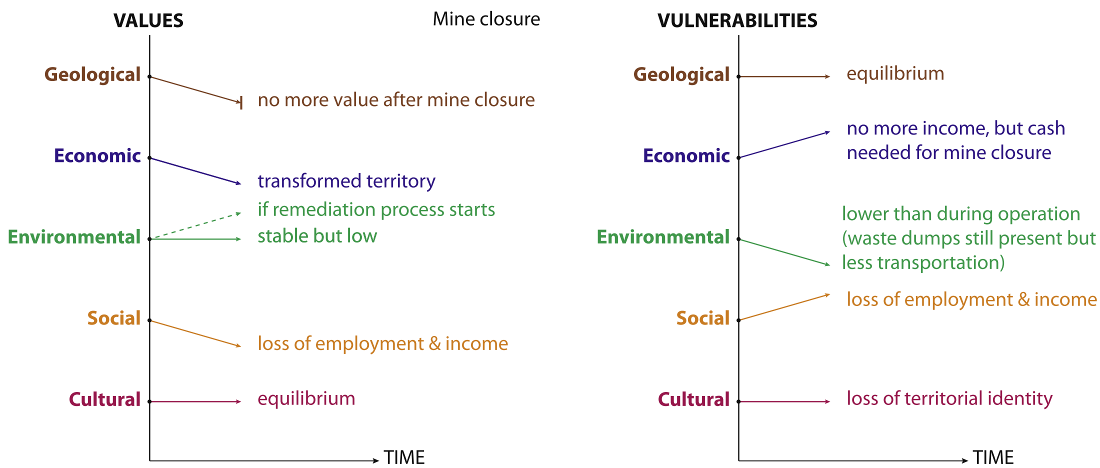

Fig. 6. Territorial values and vulnerabilities during mine closure.

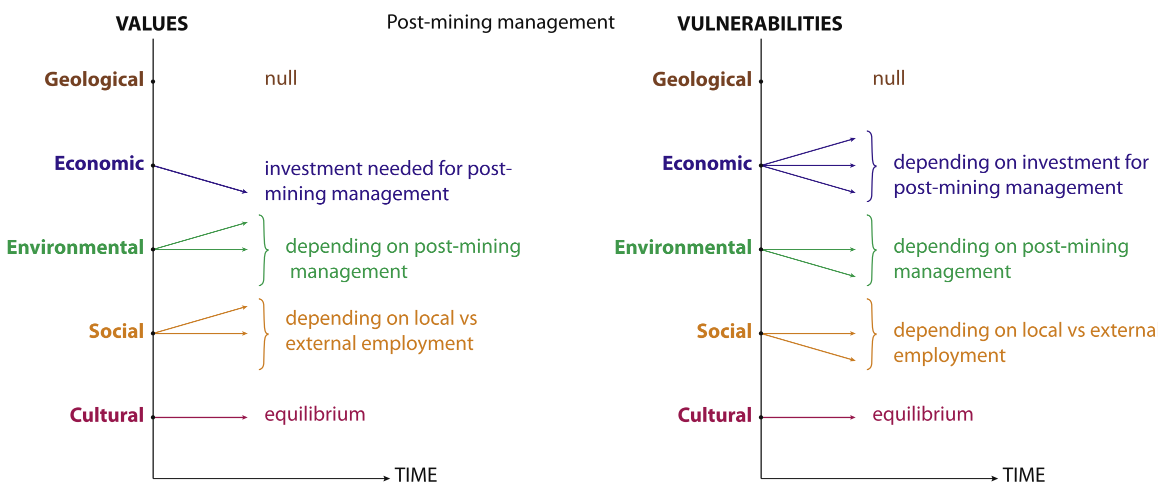

Fig. 7. Territorial values and vulnerabilities during post-mining management.

identity has been built, but development of cultural value must wait for development of a new territorial project.

Dismantlement of the mining infrastructure starts at mine closure. Transition from mining to post-mining activities then requires management of the socio-environmental impacts. Lima et al. (2016) distinguish four post-mining management strategies Figure 7: (i) remediation, to decontaminate the site by removing trace metal contaminants or preventing their transfer to the ecosystem; (ii) restoration, to recover the ecosystem and its functions; (iii) reclamation, to recover the original ecosystem services and biogeochemical functions; and (iv) rehabilitation, which prioritises the ecosystem services to be reclaimed or the building of new infrastructures for new economic activities.

These strategies help enhance environmental value, which was lowest at mine closure. However, if there is no post-mining strategy, environmental value remains low and stable, and environmental vulnerability remains high.

At mine closure, social value drops significantly, and vulnerability is high due to the loss of employment and income. Employment of local people for post-mining management may aid in hindering the drop in social value and in tempering its vulnerability. On the contrary, employment of outside people will generally lead to social contestation. Local or national policies can provide constraints for post-mining management. If these constraints are low or lacking, the mining sites might well be abandoned, in which case social and environmental values are kept very low. The more constraining the policies are, the higher the environmental and social values become and the lower the socio-environmental vulnerabilities become. Post-mining management helps curb economic vulnerability, by allowing the territorial stakeholders to plan future post-mining trajectories.

3.6. *Post-mining trajectories*

Four main territorial trajectories have been identified following completion of the mine life cycle: a new mining project, reprocessing of mine wastes, promotion of the mining heritage, or any other economic activity (Fig. 1; e.g., Kivinen, 2017).

3.6.1. *New mining project*

Depending on the metal market and on geological value, an ore body that had not been mined before may become of economic interest. New exploration may also take place for the metals that were formerly mined, or for other metals with a higher mining potential. A new mining project may thus arise. In the case of new exploration (Fig. 8A), the evolutions of geological, economic and environmental values and vulnerabilities are similar to those of the previous mine life cycle.

If infrastructure is still present, the construction stage may be limited or unneeded. If the exploration companies hire local employees, social value will increase and vulnerability will decrease. Depending on local policies and mine management (i.e., employment of mainly local people), social value will remain stable or increases during the mine operation, and social vulnerability will either be stable or decrease (Fig. 8B). Indeed, mining usually leads to low social vulnerability in former

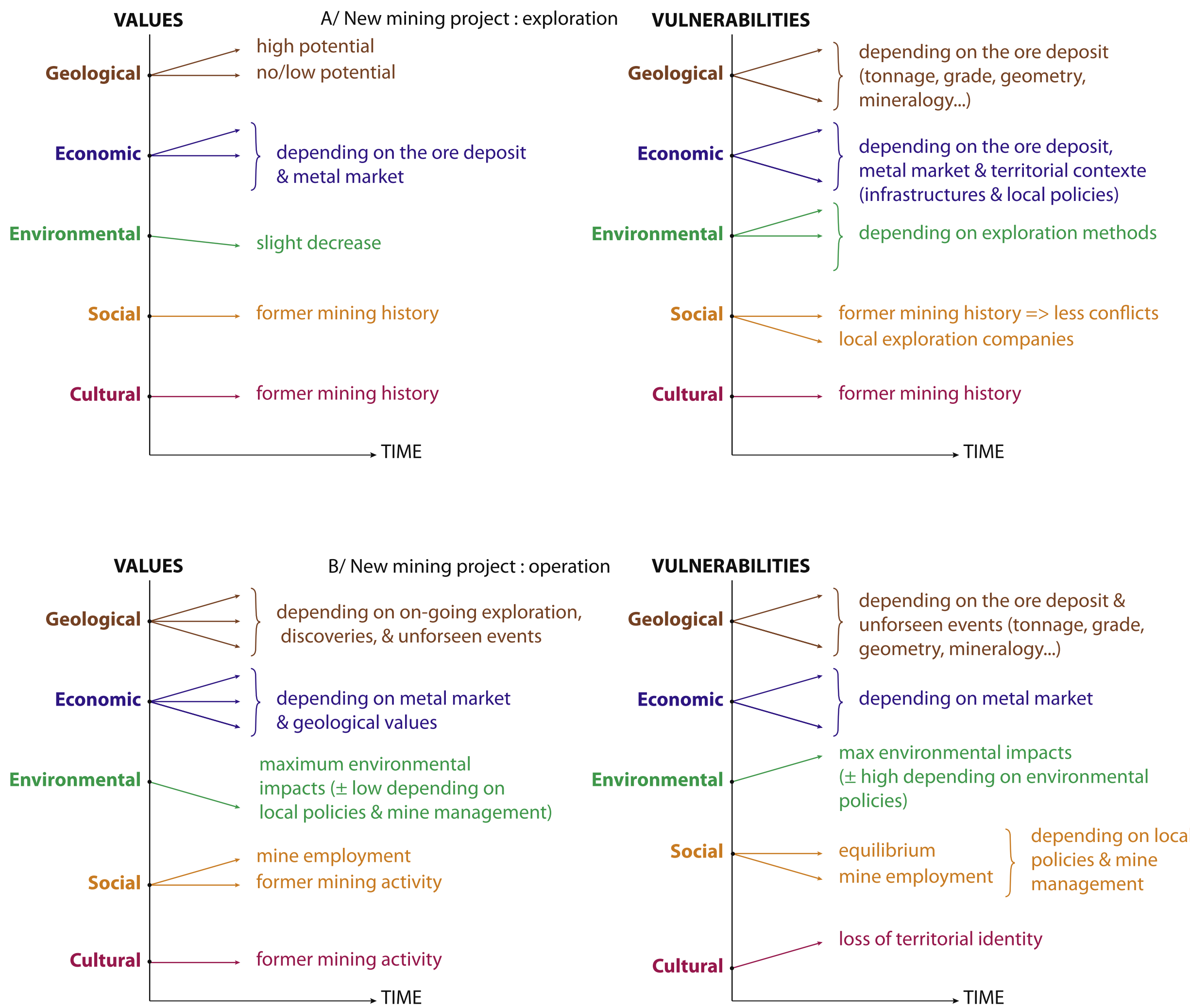

Fig. 8. Territorial values and vulnerabilities for a new mining project. A) exploration stage; B) operation stage.

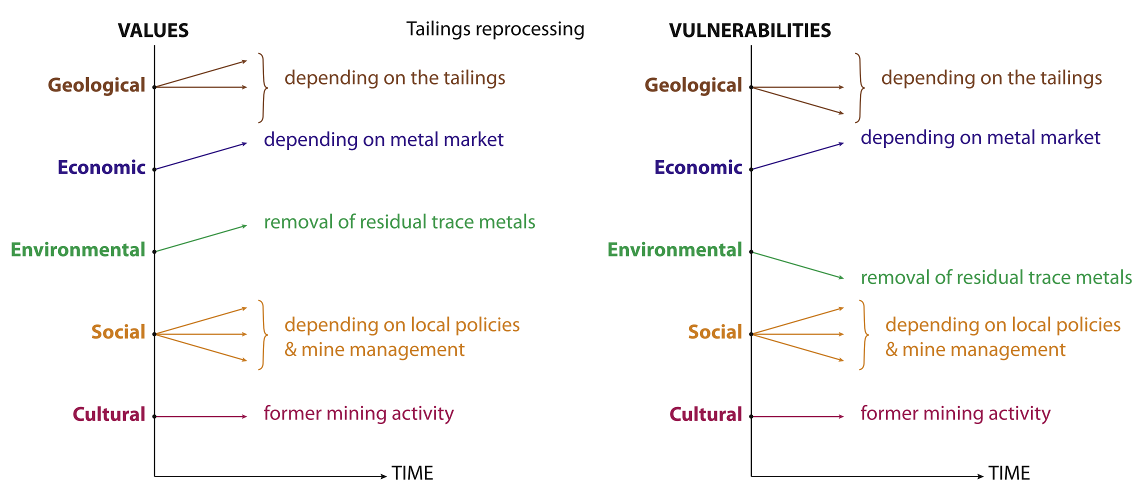

Fig. 9. Territorial values and vulnerabilities during reprocessing of waste deposits.

mining regions because the social pattern already matches the needs. Therefore, a new mining project reinforces the mining territorial profile. Cultural values and vulnerabilities are either unchanged or increase due to reinforcement of the mining identity.

3.6.2. Reprocessing of waste deposits

Mine wastes usually contain significant amounts of metals, especially in tailings Figure 9. Reprocessing of waste deposits leads to the production of secondary ore that had not been recovered during previous processing, or to the production of metals that had been considered as by-products during the former mining operation (Edraki et al., 2014 and

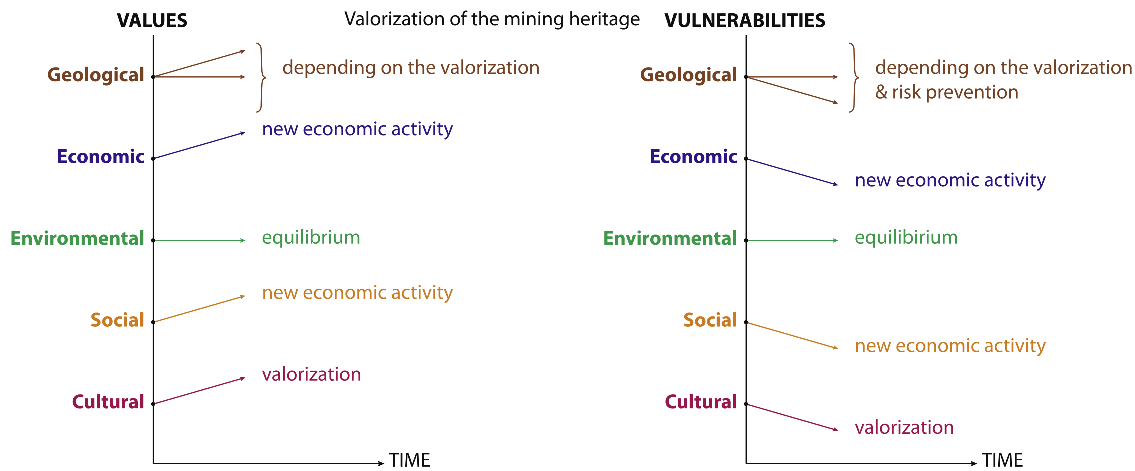

Fig. 10. Territorial values and vulnerabilities during the promotion of mining heritage.

references therein; Longhi et al., 2016). Reprocessing of mine wastes leads to increased geological value, but geological vulnerability remains stable. Removal of mine waste deposits for reprocessing usually involves removal of residual trace metals. As it contributes to decontamination, it induces a slight increase in environmental value and a significant drop in environmental vulnerability.

Reprocessing tailings is a way to extend the life of the mining site by maintaining an economic activity; in this case, economic and social vulnerability can be expected to decrease as economic and social value increase. However, depending on local governance, social value and vulnerability may differ considerably amongst mining regions. Very few studies have investigated the social effects of waste reprocessing, but high economic and social value can be expected, as it maintains employment for the local population.

3.6.3. Promotion of mining heritage

After mine closure, most traces of the mining activity slowly disappear: gallery entrances are sealed, waste deposits are most of the time covered with vegetation, and mine infrastructure is largely dismantled. However, some tangible and intangible remains are left behind, and these can be promoted as mining heritage in such forms as thematic trails, museums and underground tours (Conlin and Jollife, 2011; Bergstrom, 2017; Oakley, 2018). Development of mining heritage leads to increased geological, economic, social and cultural values. Geological vulnerability remains stable or decreases if securing of the mine site occurs. As promotion of mining heritage implies a new economic activity (most of the time tourism), cultural, economic, and social vulnerabilities decrease in the event that the activity becomes profitable and mining becomes part of the territorial identity. In this case, environmental value and vulnerability are unchanged Figure 10.

3.6.4. Other economic activity

Besides promotion of mining heritage, any other activity not directly related to mining can be developed. Former mining sites are often used for recreational or cultural activities: open-pits are most often transformed into lakes to practice deep-diving or nautical activities; hiking, biking or motorbiking trails are opened; golf courses are developed on tailings; and the mine buildings may be transformed into holiday villages or museums, etc. (Kivinen, 2017). In addition, open pits can take advantage of the opportunities provided by the characteristics of the mining site and become privileged grounds for the installation of photovoltaic solar plants, whereas underground galleries and former buildings may be well-suited for the development of mushroom plantations (Deshaies, 2016; Kivinen, 2017).

As mining is usually the first step towards industry, the infrastructure and skills that have been developed for mining may be used for other industrial activities, such as metallurgy, energy power or other industrial activity (e.g., Pessina, this volume).

4. Territorial trajectories of some case studies

Figs. 2 to 11 highlight shifts in the territorial values at each stage of the mine life cycle. These shifts depend on governance and territorial development strategies, suggesting that the territorial trajectories are nonlinear and that bifurcations are possible at each stage. The framework discussed above was applied to Murdochville (Canada) and Chuquicamata (Chile) to display two different trajectories of mining regions facing different issues. Murdochville, a boom town developed for mining in a remote area in the mid-20th century, is a good example for discussing the full mine life cycle and post-mining strategies. In contrast, Chuquicamata is a long-standing anthropised region with several centuries of past mining activities, with new mining projects and diverse economic activities. As not all the indicators listed in Table 1 are available, the trajectories focus on a selection of quantitative and qualitative indicators (Figs. 12 and 13). A strong anti-correlation between value and vulnerability trajectories has been highlighted from Figs. 2 to 11. Therefore, their representation evolves in opposite directions in the following examples.

4.1. The boom town of murdochville (Quebec, canada)

Murdochville (Quebec, Canada) is a boom town that developed in the 20th century following the discovery of copper in 1909 in a river. Starting in the 1920s, prospection led to the discovery of the ore body (a skarn and porphyry-copper deposit; Allcock, 1982) and estimation of copper reserves of 19.6 Mt in 1940. Mining operations and ore processing started in 1953 after settlement in that remote part of central Gaspésie (40 km to the closest village of Anse-Pleureuse, and 90 km to the closest town of Gaspé). Because of the lack of data about First Nation settlement and land use in the Murdochville area, it is assumed that geological, economic, social and cultural values and vulnerabilities were null prior to mining and that they all increased during exploration and operation because of the economic and job prospects.

The mine rapidly developed and employed about 1000 workers by the end of the 1950s. Ten years later, the city of Murdochville had nearly 5000 inhabitants, and 2000 people worked for the *Gaspé Copper Mines*, which was renamed *Mines de Cuivre Gaspé*. The reserves were estimated at 67 Mt of ore containing 1.3% Cu. The rapid territorial development contributed to the development of a strong mining identity. In 1982, as the copper market dropped and its reserves declined, open-pit and then underground mine production came to an end. Half of the employees were made redundant. The following year, no more ore from

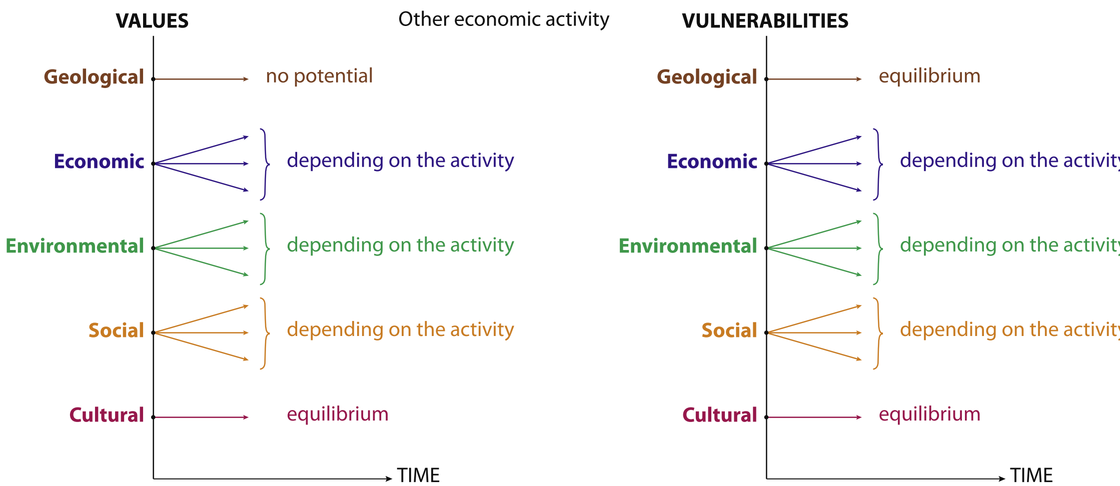

Fig. 11. Values and vulnerabilities related to other economic activities.

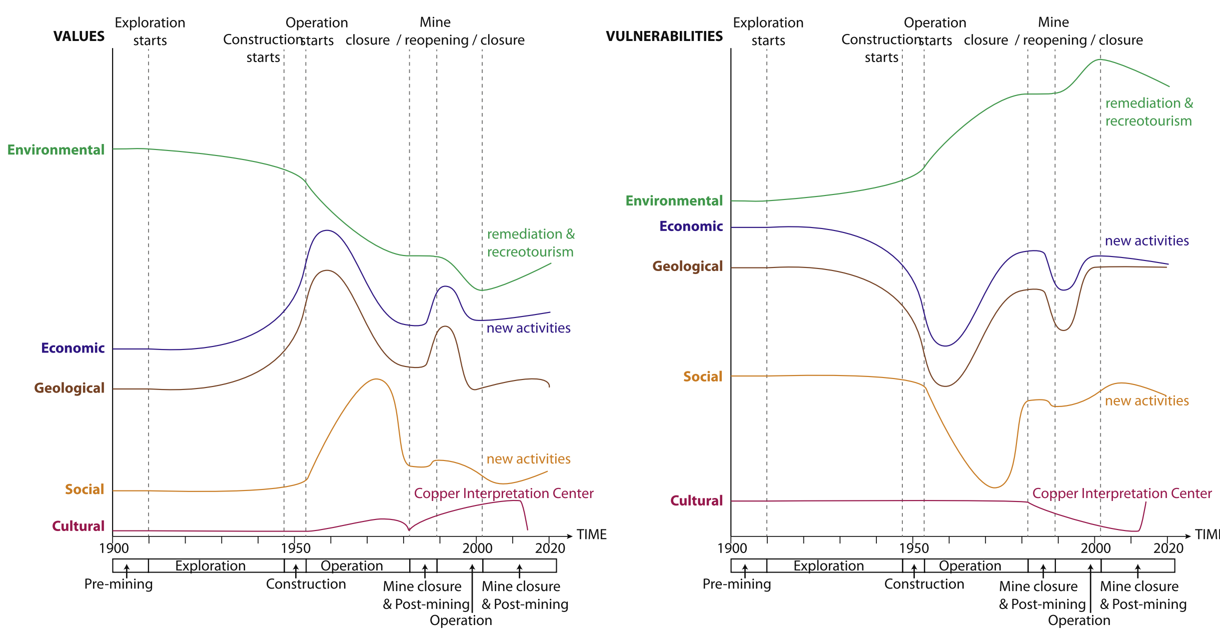

Fig. 12. Territorial trajectory of Murdochville (Quebec, Canada), evidenced through the evolution of territorial values and vulnerabilities.

Murdochville was being processed in the smelter and the mine closed; as a result, geological, economic and social values dropped. In 1989, due to market changes, the mine reopened with 500 employees, but it closed down ten years later, in 1999, as the reserves ran out: 300 people became unemployed at that time. The smelter was definitively stopped in 2002: 300 more people became unemployed. Meanwhile, environmental value had significantly decreased over time. Environmental studies clearly show that the mining operation and ore processing contributed to soil and vegetation contamination (Aznar et al., 2007, 2008a, b).

Without any prospects of further re-opening, 70% of the local residents voted the closure of the town of Murdochville; their demands for compensation were refused by the Quebec Government. As the town had developed exclusively for mining, mine closure affected all economic activities: debt and unemployment both exploded, and the real estate market dropped drastically, etc. People who could afford it moved out of Murdochville, lowering social value significantly. The town, which had almost 5000 inhabitants in the 1970s, had only 1600 in 1991 after mine reopening, less than 1000 in 2002, 651 in 2016 and 635 in 2019. In 1989, the Copper Interpretative Centre opened and helped increase cultural value; it proposed an interactive exhibition and underground guided tours in the mine until 2017, when it closed following a fatal accident. In 2003, the creation of a call centre for the Quebec Automobile Insurance Society, employing 60 workers, helped maintain an economic activity. In 2005, some Murdochville inhabitants found work in a wind blade factory that was built in Gaspé, 90 km away.

Today, the Murdochville economy relies essentially on the call centre, on recreational outdoor activities (off-piste skiing, hiking, fishing, etc.) and on renewable energies. Murdochville proposes business opportunities for companies for which energy costs are strategic, by allowing them to use the low-geothermal potential of the flooded mine galleries to produce energy for free (Raymond and Therrien, 2008). Therefore, after mine closure, while economic and social values dropped drastically, decline has to some extent been limited by the development of new activities. Past mining has transformed the representation and therefore the perceived value of the region by the local population, increasing its resilience.

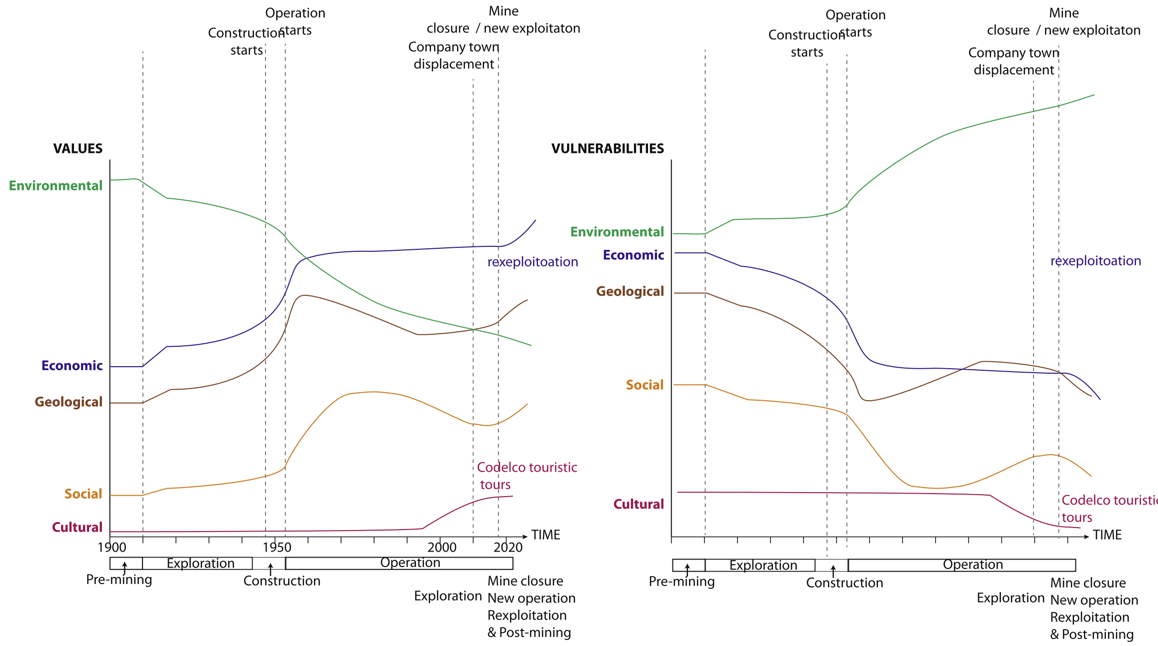

Fig. 13. Territorial trajectory of Chuquicamata (Antofagasta, Chile), evidenced through the evolution of territorial values and vulnerabilities.

4.2. The example of chuquicamata (Chile), an active copper mine

The mine life cycle of Chuquicamata (Chile) has not yet come to an end: its open pit is still being mined, and a new underground project is about to start up activity for the next forty years. Fig. 13 represents only the most significant mine development via open-pit exploitation. Situated in a desert environment, this region is traditionally the land of indigenous communities who used to live from livestock and oasis agriculture. In 1899, the discovery of "Copper Man", a mummy dated at about 550 A.D., provided evidence that copper has been mined there for centuries (Fuller, 2004). The extraction of ore went on during the Inca invasion and after the arrival of the Spaniards. By 1910, the exploitation and extraction of the mine was in the hands of foreign capital, and the copper mining industry had become the most important economic activity in the country.

Flotation and smelting facilities were set up in the 1950s and expanded ten years later. They produced 500,000 tons of copper per year in the late 1970s. In 1957 the Exotica deposit was discovered beneath tailings, leading the Anaconda copper company to build an oxide plant, concentrator, smelter, refinery and a town next to the mine, and an additional power plant in Tocopilla. In 1971, the mine was nationalised, and operations were then taken over by the Chilean state enterprise CODELCO. Since the 1990s, Chuquicamata has been the largest open pit in the world.

The Chuquicamata mine has played a key role in the territorial development of the region (Garces Feliu et al., 2010). Its geological, economic and social value started to rise quickly during exploration because of the high mining potential that was identified, speculation and the increasing number of workers needed. Indeed, the successive companies decided to build a company town equipped with modern conveniences for the well-being of the workers. It hosted an ultra- modern hospital, a cinema and a football stadium.

But when it appeared that the ore extended under the city, the company decided to move the town to Calama City, located 50 km further south. The workers were then deprived of basic services (housing and health care) that had been historically provided by the mining company, and they now lived under harsher conditions, in a city known for its delinquency, with the result that social vulnerability increased. Meanwhile, the unemployment rate, which varies mainly according to copper prices, tended to increase. There began to be conflicts, in which working conditions were denounced, giving rise to a hunger strike in 1985 and 1986. Additionally, the ore grade dropped, leading to a decrease in geological value. At the same time, environmental value has fallen, mainly because of high dust emission and freshwater capture in a desert environment.

The Chuquicamata project is still continuing: the creation of a new underground mine and tailing reprocessing have postponed mine closure. This has had a positive effect on economic and social values and reduced their vulnerabilities. At the same time, the cultural heritage of the mine is being developed: CODELCO organises touristic tours of the open pit and the former city, which has been slowly buried beneath tailings. These tours attract mainly Chilean tourists.

5. From framework to decision-making

This paper proposes a framework to represent and understand changes in values and vulnerabilities of a mining region over the mine life cycle. It emphasises the influence of the local political, geological, cultural and economic contexts on the territorial trajectories. Application of this framework to different mining regions highlights the impact of governance and identity on these trajectories, and it allows comparison of the evolution of the different values and vulnerability. Even though the framework has been discussed for industrial metal mines, it could be adapted to other extractive activities (e.g., industrial minerals, iron, etc.), to other regions by adding adapting the mine life cycle (single mine, several mines at the same time, successive mine cycles, etc.), and at various spatial scales (local, national or global scale).

In most mining regions, economic value takes precedence over the other values. However, this is not necessarily always the case, as political choices and regulation can help maintain high levels of social, cultural and environmental values for sustainable mining (IRP, 2020). Obtaining and maintaining a social licence to operate requires fair distribution of the mining benefits combined with fair procedures in the interactions between the mining industry and society, which can be achieved only with strong governance that involves the local population in decision-making (Zhang et al., 2015; Corrigan, 2019). Long-term territorial sustainability must rely on economic diversification and coexistence with other economic activities that will continue long after mine closure (Bergstrom, 2019). For activities such as agriculture, forestry, hunting, fishing, recreation and tourism to thrive after mine closure, a high level of environmental value must be maintained by limiting the environmental impacts of the mining activity (Daily, 1997; Costanza et al., 1998). Our simple way of visualising the changing values and vulnerabilities of mining regions over time proposed here may be useful for understanding and explaining the economic, social, cultural and environmental issues to stakeholders, and for planning future territorial trajectories.

However, for decision-making, the framework should evolve towards modelling (Lechner et al., 2017). Even though most indicators listed in Table 1 to determine geological, economic, environmental, social and cultural values and vulnerabilities are quantitative indicators, they do not have the same units, and some indicators are only qualitative. Some questions arise for future research work: How to quantify the qualitative indicators? How to weight the different indicators? How to merge all the indicators into a unique index for each value and vulnerability component? Which algorithm to use? And for which stakeholders? The methodology developed to determine the social risk index (Bergeron et al., 2015; Yates et al., 2016) could be an inspiring reference to define geological, economic, environmental, social and cultural indexes for mining projects.

6. Concluding remarks

In this paper we have asserted that the value of mining regions depends not only on economic value, but also on their environmental, social, cultural and geological values. For this reason, an integrative approach is necessary to understand the territorial trajectory of a given mining region. We have proposed a simple graphical framework to visualise the changes in geological, economic, environmental, social and cultural values and vulnerabilities over the mine life cycle, in relation with local governance and political choices. Application of this integrative representation to multiple regions with various mining histories would improve knowledge on the role mining activity has in territorial development, and on the governance required for sustainable development of mining regions. Further research work is needed to determine how to upgrade from this proposed framework to modelling of territorial trajectories.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.exis.2020.07.010.

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