Environmental & social maturity as a new concept for self-assessment of best practice in a mining context

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Abstract. Significant industrial and mining incidents have motivated widespread studies into the relationship between safety culture and the incidence of workplace accidents. Safety culture maturity has been used to develop a tool that enables organisations to self-assess their overall safety performance. In modern day mining operations, risks are also evaluated in terms of environmental and social (E&S) impacts, which is built into mine planning. In this work, we apply the principles of safety maturity to E&S factors to develop a novel approach to cultural maturity, allowing companies to self-scrutinize their operational practices from an E&S perspective. The culture models each comprise 5 levels that progressively increase in maturity, with the goal being to improve standards by implementing the criteria provided at each stage, based on factors such as community involvement, employment opportunities, energy use, etc. The case studies used to develop the model are located in Bosnia and Herzegovina where several mines recommenced operations recently following conflict in the region. This was chosen to consider the specific, complex challenges that are most influential in earning an SLO, and it is predicted that the outcome of a mining project is primarily influenced by the level of trust between the company and communities.

1 Introduction

Mining plays a major role in meeting the world's resource demands, with operations taking place across 6 continents, the largest of which being situated in countries such as China, Australia, South Africa, etc. Europe has a wealth of proven mineral potential (BRGM 2016), but very few of these prospects are feasible for large companies to exploit due to their small size & grade, close proximity to densely-populated settlements, and land use & tenement constraints. Obtaining social acceptance from the surrounding populations is difficult to achieve when they are led to believe that the risks associated with a mining operation outweigh the benefits, opting for the 'NIMBY' (Not in my back yard) attitude. Public perceptions of mining can also be adversely affected by past accidents that have resulted in loss of life and capital, which creates further difficulties in securing a social licence to operate from community stakeholders. So, establishing trust and rapport between companies and local populations, understanding their requirements and frequently communicating relevant updates are essential factors for maintaining strong relationships during long term mining operations.

Safety culture has been the common denominator in a number of major industrial and mining incidents, including notably the BP Texas City refinery explosion, claiming 15 lives and injuring a further 180. The official investigation report concluded that the incident "was caused by organisational and safety deficiencies at all levels of the BP corporation… the extent of the serious safety culture deficiencies was further revealed when the refinery experienced two additional serious incidents just a few months after the disaster…" (CSB 2007). So, ensuring that an effective safety management system is implemented with a high level culture underlying those measures can considerably reduce the chance of major accidents occurring, as well as mitigating risks to a level that is as low as reasonably practicable.

2 The development of safety culture maturity

Early studies into safety culture established that employees develop their own perceptions of occupational safety based on the working environment that is significantly influenced by factors such as the level of management commitment to safety (Zohar 1980). The International Nuclear Safety Advisory Group (1991) first addressed safety culture as a concept and subsequently produced guidance documentation on how organisations may self-assess and continuously improve their safety best practice from a cultural perspective. The report defines safety culture as "…that assembly of characteristics and attitudes in organisations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance" (International Atomic Energy Agency 1991).

Hudson et al. (2000) reviewed the link between intrinsic motivation and safety culture, and found that the effects of a highly motivated workforce are; (a) less requirement for sites to dedicate time to occupational safety as every employee understands the importance of personal safety, and (b) more time being allowed for performance optimisation, in turn generating further profit while maintaining high safety standards.

The UK Coal Safety Way model was tested at a number of deep, surface and underground coal mines in 2011, which provided some insight into the culture of the mines in question, and allowed the authors to develop action plans for future improvement (Foster and Hoult 2011; 2013). This study showed that when attempting to

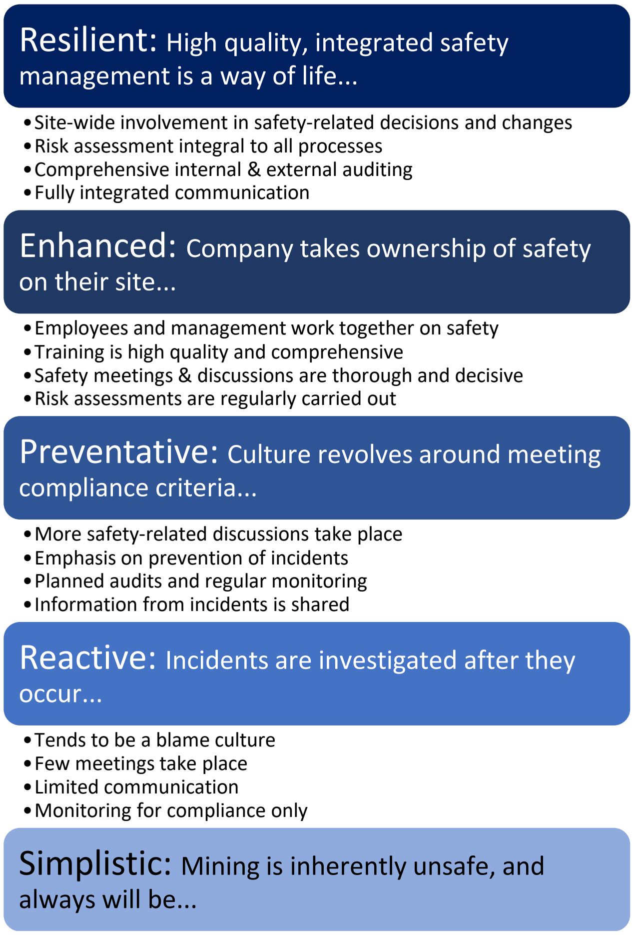

Figure 1. The safety culture maturity model applied to mining, comprising 5 stages of increasing maturity with associated criteria that should be met in order to make improvements in overall occupational safety culture. Edited from Anglo American Plc 2010; Foster and Hoult 2011; 2013; The University of Queensland 2008.

improve the safety culture of an organisation, there is no 'one size fits all' model; each site or organisation should be investigated on a case-by-case basis. It is also important to consider that not all organisations will have the resources to make large steps towards high maturity, so areas for improvement should always be prioritised (Foster and Hoult 2011; 2013).

In summary, occupational safety management is strongly influenced by the existing safety culture of the organisation, demonstrated by the prevailing attitudes and perceptions of the workforce, supervisory team and management towards safety issues (Glendon and Stanton 2000; Guldenmund 2000; International Atomic Energy Agency 1991). High levels of workplace culture can be defined by consistent enforcement and encouragement from managers towards employees regarding safety, freedom for employees to voice safety issues to management and supervisors, and regular meetings involving members from each hierarchical level ensuring fair representation and equal opportunity, (International Atomic Energy Agency 1991; Niskanen 1994; Simard and Marchand 1994; Zohar 1980). From the 1990's to present, the concept of safety culture maturity has been developed to suit various organisations and industries, moving from a model comprising 3 steps from dependent to interdependent, to 5 levels from pathological to generative (Anglo American Plc 2010; Fleming 2001; Fleming and Lardner 1999; Hudson 2003; 2007; Hudson et al. 2000; The University of Queensland 2008; see Fig. 1). Later studies have utilised the 5 stage maturity model to assess safety culture in mining (Bascompta et al. 2018; Foster and Hoult 2011; 2013; Stemn et al. 2019), coming to similar conclusions that management commitment to safety, effective site-wide communication, integrated safety management systems and safety focused meetings can all promote improvements in safety maturity. However, the principles of cultural maturity have not yet been applied to environmental and social aspects, so it is vital to first understand the main factors that define environmental and social sustainability, in order to establish appropriate requirements for each maturity level.

3 Environmental & social sustainability

The requirements of local communities affected by mining operations are a crucial consideration for companies assessing project feasibility. These "social stakeholders" have significant leverage in preventing projects from initiating, meaning a strong company-community relationship must be established before operations commence, thereby earning a social licence to operate (SLO). The expectations of the local community and stakeholders often exceeds the requirements set by law, meaning companies must go 'beyond compliance', because serious economic implications can be felt by those who do not meet the terms of the SLO (Gunningham et al. 2004). Horsely et al. (2015) stated 5 important sustainability cornerstones; financial, human, natural, social and physical. When mining operations commence in a populated region, these sources can be affected positively or negatively depending on the company's approach to sustainable practice. Kemp (2009) pointed out that mining companies are generally well resourced to meet community requirements, however progress in this respect is commonly hindered by corporate decision-making and governance that is positioned towards increasing production.

Hodge (2014) identified that the accelerating development of global communication channels are giving local communities a greater voice with regard to mining-related social issues. Walsh et al. (2017) found that public perceptions are negatively affected by a lack of consistent, two-way communication. The risk of difficulties arising during public consultation always exists, tends to vary with location, and can become a detriment to decision making if not carefully managed.

Therefore, establishing strong relationships early with communities, and demonstrating transparency in information disclosure throughout, can lead to greater trust between parties (Gunningham et al. 2004; Grubert 2018; Hodge 2014; O'Faircheallaigh 2010; Walsh et al. 2017).

The effective management and mitigation of E&S impacts in mining is primarily dictated by the existing attitudes towards the environment and communities by the operating company. So, those organisations that encourage sustainable working practices and open dialogue with local populations are demonstrating a high level of E&S maturity. By providing a novel tool that can assist other companies in understanding their own level of maturity, clear tasks and objectives can be set out that contribute to improving their E&S culture in existing and future mining operations.

4 E&S culture maturity model

Since safety culture has been shown to be an important leading indicator of H&S-related incidents, it would be reasonable to infer that the nature of environmental-related accidents and social-related conflicts can be

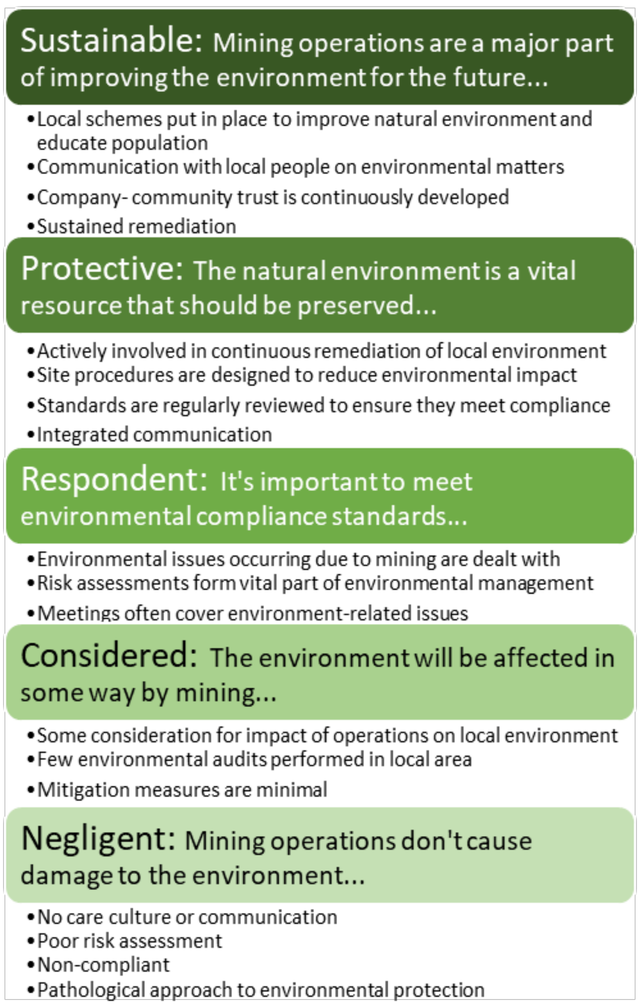

Figure 2. Environmental maturity model, with five stages which gradually improve in terms of environmental management, designed to inform best practice from a mining perspective.

Figure 3. Social maturity model, with five stages which represent systematic development in social management standards, advising companies on best practice.

influenced to an extent by a company's socio-environmental culture, defined as the prevailing attitudes and perceptions of management and employees towards occupational risks and hazards that have direct and indirect implications for local & regional communities, authorities and ecosystems.

'Negligent' companies lack effective communication regarding environmental matters, little to no compliance with environmental standards, and minimal emphasis on environmental protection. Moderate to high maturity organisations ('Considered' to 'Respondent') demonstrate more consideration for the potential environmental impact of operations, carry out systematic environmental risk assessments and monitoring activities and meetings more regularly discuss environmental concerns. Companies at the highest tiers of environmental culture, 'Protective' and 'Sustainable' respectively, consider environmental protection to be a high priority by implementing the majority of community requests, showing commitment to remediation throughout the mine life, and supporting outreach and education programmes for local people (Fig. 2).

The social culture maturity model is similar in structure (Fig. 3), but instead it considers the typical features of a company's social management system. 'Inattentive' and

'Inconsistent' companies demonstrate poor communication, a passive approach to dealing with local concerns and minimal compliance 'Planned' organisations will consider potential social impacts in more depth during feasibility studies, carry out internal management meetings dedicated to social issues and regularly collaborate with community representatives. 'Integrated' and 'Entrusted' companies go beyond compliance, offer employment to local people, helping to develop personal skills whilst boosting economic growth. The strong relationships sustained throughout the mine life ensure conflict risk is reduced, and that disagreements are resolved swiftly. The model is designed to inform companies of best practice when working with local populations, and how a collaborative management style can accelerate the process of earning an SLO.

Table 1. Main factors informing environmental & social maturity criteria, tailored to a mining context.

Environmental	Social
1a: Policy & regulations 1b: Environmental impact assessment 2a: Risk assessments 2b: Hazard monitoring 3a: Incident analysis & responsibility 3b: Emergency measures 4a: Energy use 5a: Mine waste management 5b: Air quality management 6a: Reclamation	1a: Policy & standards 2a: Corporate social responsibility 2b: Social impact assessment 3a: Community dialogue & decision-making 3b: Outreach programmes 4a: Local employment opportunities 4b: Local education prospects 5a: Infrastructural investment 6a: Conflict management

5 Conclusion

The principles of safety culture maturity have been useful for providing companies with guidance to improve their operating standards and practices. As mining often has positive and negative implications for environmental and social conditions, it is important to understand whether a company has the necessary level of maturity in order to make constructive changes. The optimal approach set out by the E&S culture maturity model is to operate in an environmentally sustainable way, where communities are entrusted with making decisions on issues that have effects on their quality of life. The journey towards high level maturity is guided by E&S management criteria (see Table 1), ensuring that each step up the maturity ladder is achievable regardless of company size or resources.

Acknowledgements

This paper was produced in partnership with the H2020 IMP@CT project, which has received funding from the EU Horizon 2020 research and innovation programme under grant no 730411.

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Re-thinking the concept of small-scale mining for a European social context

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Abstract. In an attempt to secure access to minerals, European strategy includes the development of new models to mine metal and mineral deposits, in particular by means of small-scale operations. However, the application of traditional thinking and definitions of small-scale mining to a European concept of small-scale mining operations are problematic. The majority of existing research around small-scale operations refers to artisanal mining (Hilson and McQuilken 2014; Lahiri-Dutt 2018; Milanez and de Oliveira 2013), which occurs mostly in developing countries. Meanwhile, the discourse around social sustainability of mining operations is largely oriented to large-scale mining. An analysis of published literature has been undertaken in order to define the limiting characteristics of the term "small-scale mining" to modes of mining other than artisanal. Subsequently, we consider these limits in the context of strategy concerning the extractive industries, in order to re-conceptualize small-scale mining. This will enhance the precision of European small-scale mining discourse and avoid any ambiguity of definitions. We develop the concept of modern non-artisanal small-scale mining, which utilises modern industrial best practice standards and technological innovation with associated smaller workforces.

1 Introduction

Over the last decade, the European Union has articulated that its stability and the competitiveness of its economy are dependent on the import of raw materials, in some cases from vulnerable supply chains. In 2008, the European Commission (EC) launched The Raw Materials Initiative, which set a framework for more reliable and secure access to raw materials. The EC identified mining scenarios that have the potential to contribute to raw materials production in Europe: mining operations at greater depths, mining of non-conventional surface deposits and mining of small deposits (Strategic Implementation Plan 2013). Further, in 2011, the EC issued a list of 14 Critical Raw Materials, which was extended to 20 CRMs in 2014 and 27 CRMs in 2017. Rare earth elements serve as an example of a CRM: The domestic reserves of rare earth mineral in Europe account for less than 1% of mining production, though the potential for REE production in Europe is high (Goodenough et al. 2016; Rollat et al. 2016).

The imperative to unlock small deposits in Europe has triggered activities towards understanding the geological, technological and economic step-changes that would be required. The IMP@CT project, funded by the EC Horizon 2020 programme, is developing a small-scale, compartmentalised whole systems mining approach for responsible extraction and processing of small deposits, including deposits of CRMs. The research is founded on the premise that a climate of increasing costs (including those relating to environment) from large deposits at decreasing grade may create a space in the market for small-deposit mining at high grades, with technological solutions that increase competitiveness.

This paper reviews the use of the concept "small-scale mining" in various contexts and discusses different connotations of the term.

2 "Small-scale mining" concept

For the last twenty years, discussions about "small-scale mining" have largely referred to artisanal mining activities. Terms have been used interchangeably, so that "small-scale mining" has effectively become a synonym for "artisanal small-scale mining" (ASM) (see e.g. Hilson 2006; Aryee et al. 2003).

Artisanal small-scale mining typically describes a poverty-driven activity, usually practiced in the poorest and most remote rural areas of a country by a largely itinerant and poorly educated populace with little other employment alternatives (World Bank 2013). ASM can include men and women working on an individual basis as well as those working in family groups, in partnerships, and enterprises involving hundreds or even thousands of miners (OECD 2016). 6 million people were directly engaged ASM in 1993, rising to 13 million in 1999, up to 30 million in 2014, and 40.5 million people were directly engaged in ASM in 2017 (IGF 2017). Since ASM is labour-intensive and the notion of "small-scale" relates to capital investment and the size of local enterprises, it may be expected that ASM production and revenue figures might be quite moderate and share an insignificant fraction of the global mining economy. The evidence is to the contrary and, in some cases, the cumulative amount of the mineral production by ASM can surpass that of large-scale operations. (Aubynn 2009; Zvarivadza and Tholana 2015). According to very rough estimates, the artisanal and small-scale mining produces around 15-20% of global minerals, including 80% of all sapphires, 20% of all gold, and 20% of diamonds (Buxton 2013, citing Estelle Levin 2012).

The relationship of ASM to large-scale mining (LSM) by major mining companies has often been conflictual where both types of miners compete for the same resource, occupy the same concession or perceive one other as a threat (World Bank Group 2009; IGF, 2017). The LSM and ASM are frequently used in comparative studies representing two major (and opposite) paradigms of mining operations (e.g. Aubynn 2009; Luning 2014). Mineral governance frameworks tend to favour foreign direct investment by multinational companies over ASM, such that there are significant power imbalances, clashes over claims and the classification of ASM mining as illegal or extralegal (Siegel and Veiga 2009; IGF 2017).

The existing mining paradigm has led to the situation where mining activities that happen to be “formal” but “not so big” as LSM attract rare attention. Their operations remain largely invisible, particularly in comparison to multinational corporations. This establishes limits on the application of the term “small-scale” to other contexts and identifies a need for new research to address the issues of modern (not artisanal), potentially low-impact and sustainable small-scale mining operations.

3 Defining non-artisanal small-scale mining

In order to develop a clearer understanding of how the scales of formal mining projects can more effectively co-exist, the fundamental issue around meanings and definitions needs to be clarified. Early studies into the structure of the global mining industry established a hierarchical system dominated by “major” companies, who have an established practice of steering sectoral trends, and “intermediate” and “junior” companies that have corresponding practices (see e.g. Thomson and MacDonald 2001; Dougherty 2011). Artisanal small-scale mining does not sit neatly within the hierarchical and regulated global mining system.

A traditional description of “intermediate” is used for those companies that operate one or more small mines (see e.g. Thomson and MacDonald 2001) but the status of an “intermediate” company remains unclear since no comprehensive research on the performance of “intermediate” mining activities has been published. Additional terms that have been used in the published literature are “mid-tier resources companies” (Lyons et al 2016) and “smaller mining companies” (Shankleman 2009). In 2001, the ITDG (Intermediate Technology Development Group) defined small-scale mining in terms of a given production ceiling and the level of sophistication by which minerals are exploited. In this way, “small-scale mining is any single unit mining operation having an annual production of unprocessed material of 50,000 tonnes, or less as measured at the entrance of the mine” (Aryee et al. 2003 citing ITDG (2001)).

The new term “small-scale mining” which has started to appear recently in think tank and policy discussions, particularly in Europe, is different from conventional understanding. The implication of these characteristics is that the mining operations are likely to have a short duration, perhaps between 2 and 10 years, which will reinforce the small-scale of socio-economic impacts. It also means that the local community will usually not suffer a big influence or disturbance from the mine culturally and socially, in terms of population structure etc. However, this potentially has both positive and negative implications. In small-scale mining that is legally and environmentally well-regulated, the scale of environmental impacts and risks should be smaller than in both large mines and ASM. This usually implies lower harm for neighbouring housing, other livelihoods and businesses in the area, although the risks are dependent on the mined metal and the use of chemicals. While small-scale mining would be appropriate for extraction from small mineral and ore deposits, there exists the potential that small-scale mining either by sophisticated and light technologies may be appropriate on large deposits for environmental and socio-economic reasons.

4 Questions of sustainability and social acceptance of non-artisanal small-scale mining

The concepts of social acceptance and social sustainability of mining operations have been increasingly used in the extractive sector to describe the complexity of mining-community relations and the commitment of mining companies to perform more sustainably. In this regard, it is essential to investigate how small-scale mining operations may be placed in wider sustainability discourses of the mining industry.

The discourses of large mining companies pre-empted considerable attention from economic/investment and academic sectors, which placed them under scrutiny. This is reflected not only in an increased number of case-studies about LSM, but also in the direction of the concepts about sustainable development of the mining industry. The idea of “sustainable mining” (Amezaga et al. 2010; Azapagic 2004), which has been widely adopted by academia over last decades, was initiated by major mining players in the late 1990s in response to global environmental movements against mining (Kapelus 2002; Franks 2014).

The geography of mining operations and shift of the production to developing countries have significantly influenced the agenda of sustainability performance of mining companies. Mining operations were widely seen as an engine for regional development and poverty reduction, which followed the global development discourse for the countries of the Global South. At the same time, strong sustainability research in the traditional mining countries of Australia and Canada have contributed other unique aspects to the global sustainability discussion. Since the preoccupations of large mining companies centred on large mines, with large workforces and large impacts, then the question arises as to whether concepts around sustainability and social acceptance can simply be scaled down for smaller forms of mining operations or whether concepts need to be re-evaluated.

5 Conclusion

The term “small-scale mining” has been widely used in the extractive industries; however, its meaning has become synonymous with practices that are globally recognized as “artisanal small-scale mining”. This paper attempts to shed light on how non-artisanal small-scale mining practices differ from conventional understanding. We will position the concept in relation to the current dual mining paradigm of large-scale and artisanal small-scale mining operation, describe its features and likely impacts, and delineate a reference frame for further discourses.

Acknowledgements

This paper was produced in partnership with the H2020 IMP@CT project, which has received funding from the EU Horizon 2020 research and innovation program.

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Gold mine tailings as future resources: long-term storage and behavior of As and Sb phases

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Abstract. Gold mine tailings contain sub-economic quantities of gold and therefore represent potential future resources if the gold price increases. Tailings should be managed to minimize the environmental impact and ensure they can be successfully reprocessed in the future. Elevated dissolved As, and in some cases Sb, can be a significant potential discharge issue at tailings storage facilities.

Mineralogical and geochemical characterization was undertaken on modern and historic mine wastes to evaluate their long-term behaviour. On a time-scale of years to decades, water-saturated sulfide-rich concentrate tailings were largely unoxidised and successfully reprocessed. Over longer timescales, unmanaged historic sulfide-rich concentrates show varying degrees of alteration, from minimally altered to fully oxidized. Tailings that have undergone roasting/pressure-oxidation processing now consist mainly of relatively stable iron oxides, iron arsenates, iron antimonates, and iron oxyhydroxides. Armoring of Au-bearing primary sulfides, and formation of stable secondary phases, can limit dissolved As and Sb concentrations in waters.

1 Introduction

Orogenic gold mining involves the excavation, crushing, concentration, and treatment of ore. This process generates significant quantities of mine wastes which typically have little economic value but must be contained to prevent environmental issues. Elevated dissolved arsenic, and in some cases antimony, is one of the most significant potential discharge issues at tailings storage facilities.

It is not possible to extract all gold from ore during the mining process due to recovery inefficiencies and dilution from wall rock, and some gold remains in mine wastes. Tailings therefore represent potential future resources from which the residual gold may be extracted as processing techniques improve. The re-mining of existing tailings is both economically advantageous and reduces waste burdens (e.g. Breytenbach 2016).

The long-term storage and re-mining of existing tailings presents different challenges to standard hard-rock (orogenic) mining. Tailings have undergone a range of ore processing techniques that have altered their physical, geochemical, and mineralogical properties and present their own environmental risks. For example, gold-bearing arsenopyrite (FeAsS) is commonly concentrated during processing, and tailings can be therefore be enriched in arsenopyrite and other sulfides. Sulfide concentrates may also be oxidized to liberate encapsulated gold, producing oxide minerals such as arsenolite or claudetite (As_2O_3; Fig 1a), and oxidized Fe^{III}-bearing minerals including scorodite ($FeAsO_4 \cdot 2H_2O$; Fig 1a) and tripuhyite ($FeSbO_4$; Fig 1b).

Historic and modern mine wastes in New Zealand provide useful insights into the mineralogical and geochemical properties of mine processing wastes and the long-term stability of such materials.

2 Methods

Samples were collected at the active Macraes gold mine in Otago, southern New Zealand, and at the (now inactive) Globe Progress mine, and at a historic gold mine processing site, both on the West Coast, southern New Zealand. At Macraes mine, water quality monitoring is carried out for processing and environmental purposes and the data were made available for this study. Mineralogical studies were carried out on sulfide concentrate tailings and 'scales' collected from the pressure-oxidation autoclave. At the historic site, mineralogical and geochemical characterisation was undertaken and water samples were collected and analysed at Hill Laboratories, Hamilton, New Zealand.

Mineral identification was conducted on a PANalytical X'Pert PRO MPD PW3040/60 X-ray diffractometer (XRD) with a CuK$_\alpha$ source (*λ=1.5406Å*). Scanning electron microscopy (SEM) imaging and analysis was undertaken on a Zeiss Sigma FEG scanning electron microscope with an Oxford Instruments XMax 20 Si drift energy dispersion X-ray detector (EDX).

3 Macraes gold mine

The Macraes orogenic gold mine has been in operation since 1990. The gold is typically disseminated, occurring in pyrite (FeS_2) and arsenopyrite. Between 1990 and 1993, a sulfide concentrate was produced via flotation of crushed ore, and this concentrate was fed directly to the cyanide system to extract the gold, after which the residues were stored in the concentrate tailings impoundment. From 1993, these sulfide-rich residues were combined with silicate tailings and discharged into a larger tailings dam: the Mixed Tailings Facility (MTF). In 1999, a pressure-oxidation autoclave was constructed to oxidize the sulfide-rich concentrate before the cyanidation step. The pre-1993 tailings, stored in the sulfide concentrates impoundment, were excavated and successfully reprocessed using the autoclave. From 2007, ore concentrate from OceanaGold's Globe Progress mine was transported and processed at Macraes treatment plant. In addition to pyrite and arsenopyrite, the Globe Progress ore also contains stibnite (Sb_2S_3; 4 vol%; Milham and Craw 2009).

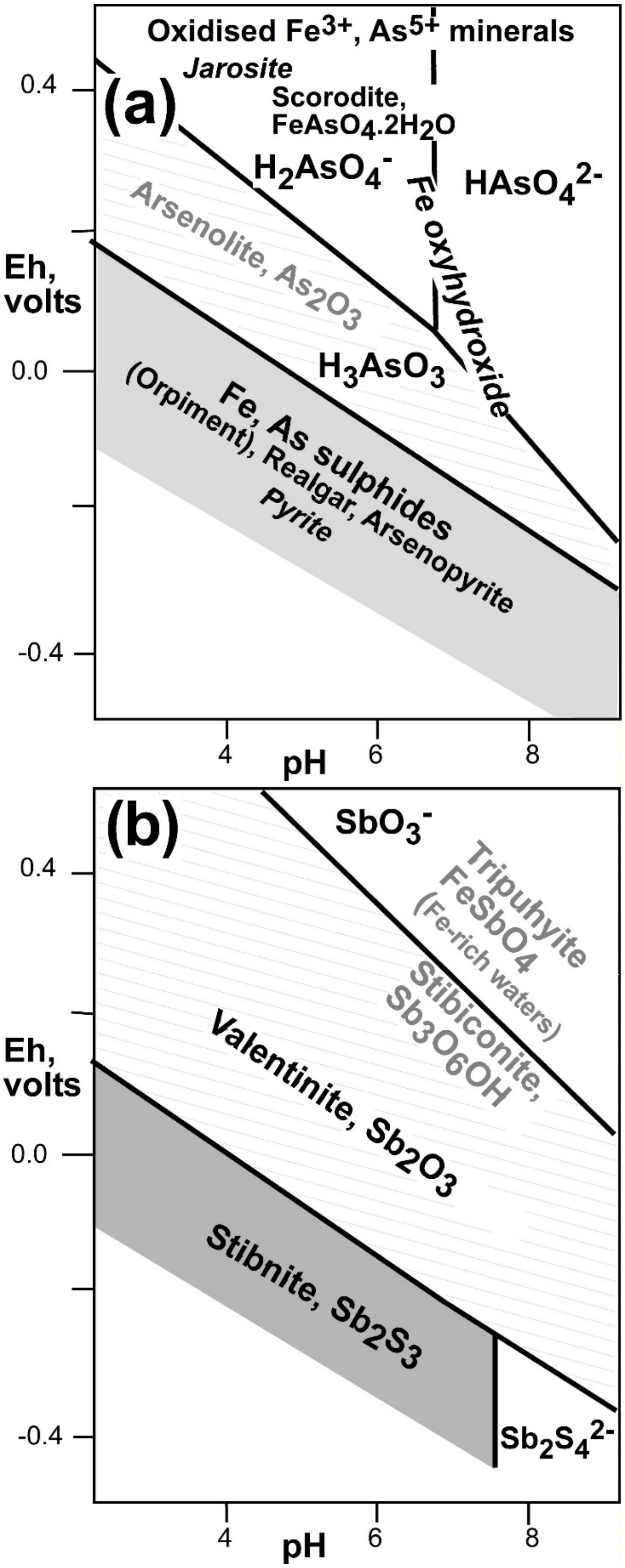

Figure 1. Mineral stability diagrams showing the geochemical relationships of As and Sb minerals in the surficial environment. Summary Eh-pH diagrams for oxidation of (a) pyrite and arsenopyrite, and (b) stibnite (compiled from Geochemists Workbench and Vink 1996).

3.1 Concentrate tailings impoundment (1990-1993)

Water monitoring data collected at the sulfide concentrate tailings impoundment from ca. 1990-2003, provides insights into the geochemical and mineralogical processes occurring during long-term storage (Craw et al. 2017).

Dissolved As levels in surface water were generally high (10’s-100’s of mg/L). Water pH was initially high (pH 10-11) as it was sourced from the alkaline cyanidation system (Craw et al. 2017). As the impoundment became inactive, downward percolating waters interacted with both tailings and the waste rock dam, and became mildly acidic (~ pH 6). During the monitoring period, the tailings remained saturated with only minor oxidation of sulfides in the top metre causing minor acidification and Fe-arsenate precipitation. Calcite, derived from the waste rock, reacted with the acid, producing high levels of dissolved sulfate (3000-6000 mg/L; Craw 2003). Dissolved sulfate concentrations subsequently dropped due to gypsum precipitation within the dam structure. Precipitation of iron oxyhydroxides adsorbed dissolved As. At the toe of the dam, As levels are generally below 1 mg/L and dissolved sulfate is ~2000 mg/L (Craw 2003).

Excavation and handling of the concentrates during re-processing resulted in minor oxidation of sulfides (Craw et al. 2017). As with the minor surface oxidation, calcite rapidly neutralized the acidified tailings waters and iron oxyhydroxides formed (Fig 1a).

3.2 Pressure-oxidation autoclave (1999)

In the pressure-oxidation autoclave, the sulfide-rich concentrate is oxidized at 225 °C and >3,000 kPa (residence time ca. 1 hr). Oxidation of pyrite results in a slurry pH of <2 (Craw 2006). Iron and arsenic are rapidly oxidized as they pass through the autoclave and Fe^{III} and As^{V} are the dominant species in the discharge waters. The oxidized slurry then undergoes cyanidation treatment to extract the gold.

During the autoclave process, mineral deposits (‘scales’) precipitate on the walls and agitators. These scales are composed of mm-cm thick layers with variable grain size and mineralogy that reflect chemical changes in the passing slurry. The scales provide insights into the geochemistry of the process waters. As the scales are ultimately deposited in the MTF, the mineralogy of this material is relevant to the long-term environmental management of the MTF.

In the first half of the autoclave, Ca sulfate, alunite ($KAl_3[SO4]_2[OH]_6$), and ferrous sulfates dominate, and the principal As minerals are As^{III} oxides (arsenolite or claudetite; Fig. 1a, 2a). Antimony occurs in this section of the autoclave as a As-bearing iron antimonate (possibly tripuhyite; inferred from SEM-EDS analysis), closely associated with fine-grained hematite and ferrous sulfate (Fig. 1b, 2b). As oxidation progresses in the downstream half of the autoclave, ferric sulfates and jarosite precipitate (Fig. 1a; 2a). At the discharge point, jarosite, Ca sulfate, and ferric arsenate dominate (Craw 2006).

The jarosite is fine-grained (typically 1–10 µm) and contains little or no detectable As in solid solution (<0.2 wt% As; Kerr et al. 2015). Most arsenic is present as ferric arsenate (Fig 2a), which is intimately intergrown with the jarosite and Ca sulfate.

Water in the MTF has a pH of ~6 and high dissolved sulfate (Craw 2003). Under these conditions, jarosite dissolves relatively slowly and particles will survive for hundreds of years (Zahrai et al. 2013). Although the absence of solid solution As in the jarosite means no As will be directly mobilized, jarosite dissolution will further expose the intimately intergrown ferric arsenate to the tailings waters. At pH 6, the ferric arsenate dissolves at a faster rate than jarosite but also yields As-bearing ferric oxide/hydroxide precipitates (Roddick-Lanzilotta et al. 2002).

Dissolved Sb is not elevated in the Macraes waters despite the processing of Globe Progress ore (Weightman et al. 2018), indicating that the autoclave process assists in the removal of Sb through the formation of insoluble phases such as the As-bearing tripuhyite.

4 Historic tailings

As the tailings from the pressure-oxidation system are remixed and diluted approximately ten-fold with the silicate-rich flotation tailings, it is difficult to evaluate their long-term stability once in the MTF. As a proxy, we have examined historic tailings (ca. 90 years old) at an abandoned processing site. The historic processing of ore was similar to modern-day processing, albeit less technologically advanced, and involved sulfide mineral separation, oxidative roasting through the use of a furnace, and cyanidation.

Ferric iron oxides (e.g. hematite) and arsenolite were the principal waste products of the roaster furnace, and the hematite forms distinctly red tailings of which small quantities persist on site today. The hematite grains are porous and contain up to 4 wt% As and appear to have undergone only minor alteration. Similar results were observed at a nearby site with large volumes of hematite and low dissolved As levels (<0.01 mg/L; MacLachlan & Craw, 2017) indicating that hematite may be providing effective long-term As sequestration. Arsenolite is highly soluble and in most parts of the site has now been replaced by scorodite and ferric oxyhydroxide phases (Fig. 1a, Fig. 3a-d).

Unroasted sulfide concentrates remain on site and consist of quartz-bearing sand, rich in arsenian pyrite and arsenopyrite (Fig. 3). Arsenic content ranges from ~1400 mg/kg to 21 wt%. There are apparently steep redox gradients within the residues on the cm scale between largely original sulfides and fully oxidized residues that contain no sulfides and consist of almost pure Fe oxyhydroxide (Fig. 1a, Fig. 3b). Scorodite is an intermediate phase, which contributes to cementation and armoring of the sulfides. Arsenic in the Fe oxyhydroxides is 5-20 wt%, showing that at least some of the mobilized As has been adsorbed.

Fragments of timber framing are now intermixed with the sulfide concentrates and have developed authigenic As sulfide (predominantly realgar, Fig. 1a, 3b,c). This organic debris has acted as a reductant within the predominantly oxidizing environment, causing dissolved sulfate to be reduced. This reducing microenvironment, which is sequestering As, is likely to persist until all wooden material has decomposed, after which the realgar will oxidize.

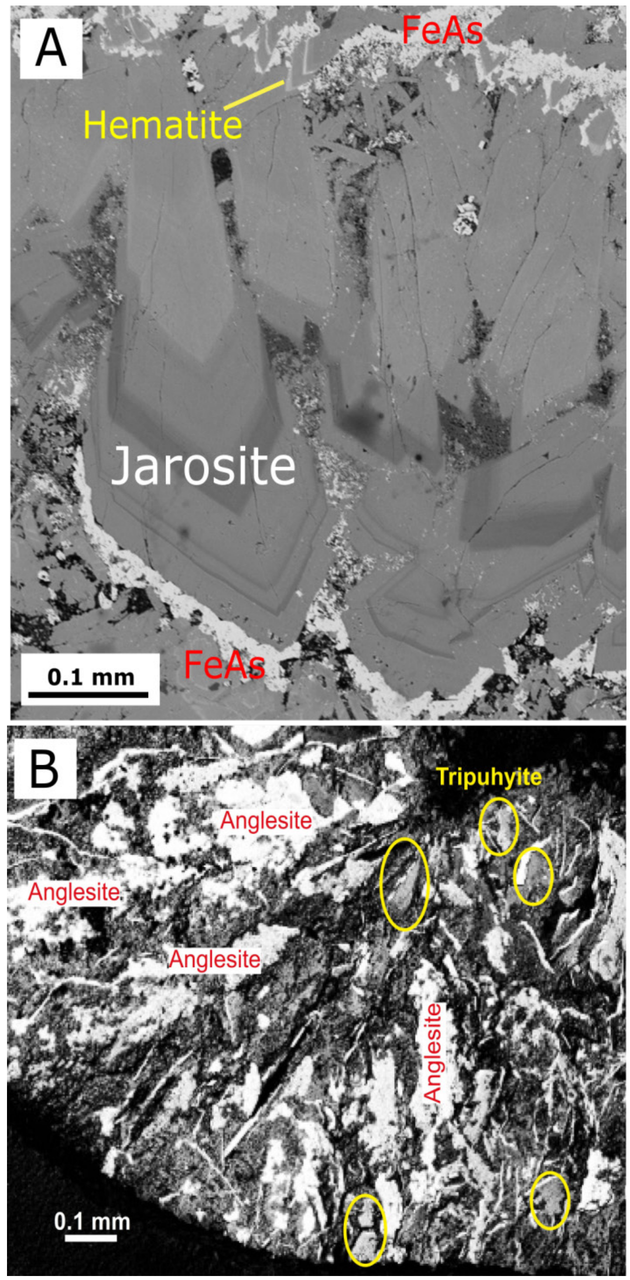

Figure 2. (a) Backscatter electron image of jarosite crystals in Macraes mine autoclave scale. Jarosite is shades of **grey** (**darker** higher Al content), **white** ferric arsenate (FeAs) or hematite, and **black** mounting medium (modified from Kerr et al. 2015). (b) Backscatter electron image of Sb-bearing minerals in autoclave scale. The coarse, very bright grains are predominantly anglesite ($PbSO_4$; lead derived from autoclave mortar), surrounded by a micron scale matrix of iron-antimony-arsenic-bearing oxide precipitate, with some larger grains of an As-bearing tripuhyite-like mineral. Black zone is ferrous sulfate.

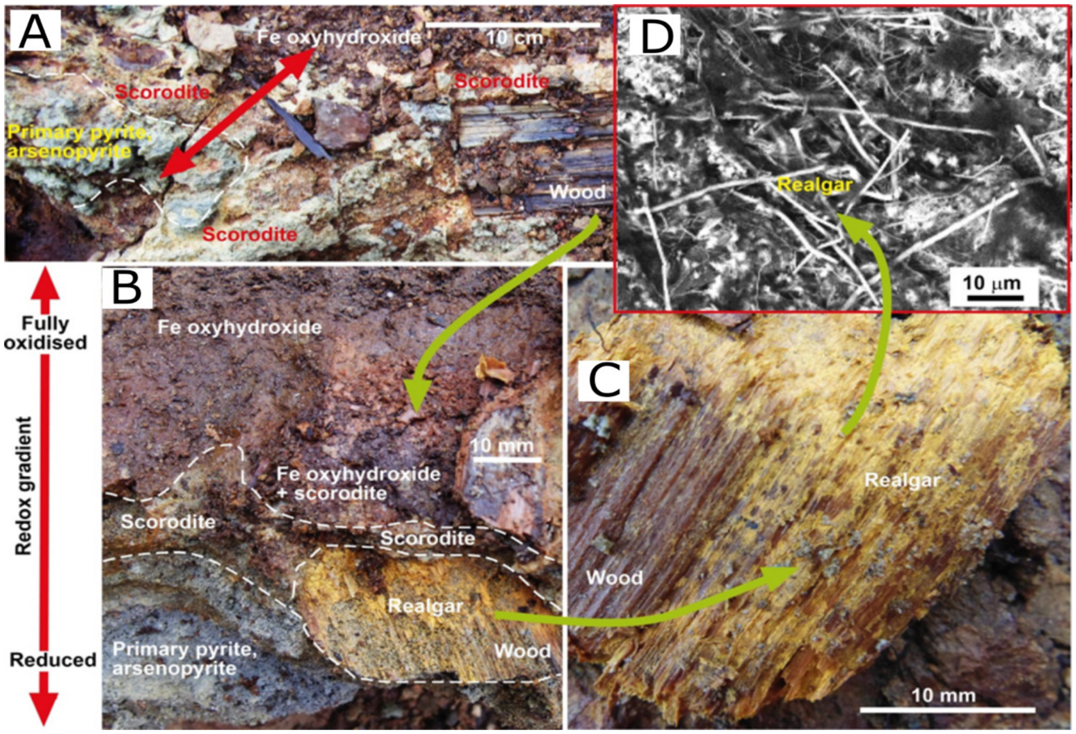

Figure 3. Weathered sulfide concentrate at an historic ore processing site. Primary arsenopyrite has weathered to Fe oxyhydroxide and scorodite (modified from Kerr and Craw 2018). Green arrows indicate progressively closer views of minerals; red arrows indicate redox gradients. (a) General view of tailings. (b) Close view of redox gradient showing primary arsenopyrite with oxidized scorodite and Fe oxyhydroxide. Low-temperature realgar has formed on fragments of wood. (c) Close-up photo of low temperature realgar. (d) SEM electron backscatter image of low temperature realgar.

5 Conclusions

- Mine tailings represent important future Au resources and to ensure their long-term stability, should be managed to minimize oxidation and secondary alteration.
- 13 year old tailings at a New Zealand mine, which had undergone only minimal surface oxidation, were successfully reprocessed.
- Dissolved As and Sb are low in the tailings dam, due to the formation of moderately stable phases in the autoclave (jarosite and tripuhyite) and formation of iron oxyhydroxides in the dam.
- Over longer timescales, unmanaged historic mine wastes show varying degrees of alteration, from minimally altered to fully oxidized.
- Armoring of primary sulfides, and formation of stable secondary phases, can limit dissolved As and Sb concentrations in waters at historic sites.

Acknowledgements

This research was funded by a New Zealand Ministry for Business, Innovation and Employment (MBIE) grant via CRL Energy Ltd. Additional funding was provided by Otago University. Logistical support was provided by OceanaGold Ltd and the Department of Conservation.

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Characterization of serpentinites in Tolima and Antioquia (Colombia): analyzing their CO_2 sequestering potential through carbonation processes.

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Abstract. The increasing trend of atmospheric carbon dioxide (CO_2) is a critical problem all around the world. In order to decrease CO_2 high concentrations, scientists are trying to generate mechanisms that can sequester this atmospheric gas. A viable alternative is to inject atmospheric CO_2 along with water in serpentinite-hosted aquifers where carbonation reactions will help sequestering the gas. With this in mind, is important to identify possible serpentinite reservoirs around the world that could potentially be used as CO_2 sequestration sites. In this work, we made a complete characterization of different serpentinites in two localities of Colombia, including their formation conditions and mineralogy. This allows us to identify critical areas in which CO_2 sequestering could be applied in the future.

We determined that the serpentines of Tolima have higher iron content (Baumite) and higher proportion of antigorite in relation to the polymorphs lizardite and chrysotile. In Antioquia, the serpentines are more magnesic with predominance of clinocrhysotile over the other phases. In this way, it is proposed that Antioquia is a better locality for CO_2 sequestration.

1 Introduction

Serpentinites are rocks composed mainly by serpentine-group minerals formed by the alteration of ultramafic rocks, a process known as serpentinization. This process can occur in different geological settings including mid ocean ridges, subduction zones and mantle wedges (Deschamps et al. 2013). The process modifies the physical and chemical properties of the rocks, and this is commonly identified by reduction of seismic velocities and the increasing of peridotites´ magnetic susceptibility. During the serpentinization process, density changes are dramatic due to the increasing content of water (13-15%) (Iyer 2007).

The most abundant serpentinite-group minerals are lizardite, chrysotile and antigorite with an idealized chemical formula $Mg_{2.813}Si_2O_5(OH)_{3.647}$ (Moody 1976). They are all trioctahedral phyllosilicates with different crystallographic structure and contrasting habit: lizardite appears like planar layers, crhysotile forms scrolled layers which tend to form cylindrical forms and antigorite possesses a modulated structure with periodical inversions of the tetrahedral-octahedral layers (O´Hanley 1996; Iyer 2007). These three minerals appear associated, in serpentinites. The maximum stable temperatures of serpentines are between 450-500°C and pressures from 3 to 3.5 kbar. Antigorite is the high-temperature stable polymorph (Prichard 1979).

Asbestiform types of serpentinites were commonly used for their thermal and electrical properties. However, these minerals have been directly linked to diseases like mesothelioma and pneumoconiosis (Guillot and Hattori 2013).

Due to the climate change, the mineral carbonation through CO_2 sequestration has been one of the most important topics of investigation in the last decades. Many researchers integrated mineral carbonation processes in mining activities using ultramafic rocks and serpentinites in order to achieve the CO_2 sequestration obtaining at the same time financial benefits (Li et al. 2018). Power et al. (2013) *in-situ* industrial carbonation method in serpentinite-hosted aquifers is based on a chemical reaction that occurs naturally in subsurface conditions inducing a carbonation process by the injection of CO_2 directly to the rocks and precipitating magnesite. An experiment developed by Cipolli et al. (2003) showed that 33 g of CO_2 could be captured per kilogram of H_2O per year using serpentinites. In order to do this process more efficient, several conditions like reactive surface area, temperature, pH, solute transport, partial pressure of CO_2 and atmospheric conditions need to be considered (Bea et al. 2012).

The economic benefit is one of the most important factors in mining activities. Hitch and Dipple (2012) evaluated this through financial modeling and sensitivity analysis showing that the integration of industrial-scale mineral carbonation within mining operations is viable from a financial perspective.

2 Geological framework

The Colombian Andes are in a compressive tectonic regime with the collision of the South American, Nazca and Caribbean plates. Two main basement domains in the Colombian Andes can be differentiated: one with continental affinity (Eastern Cordillera and part of the Central Cordillera) and other with oceanic affinity (Western Cordillera and the west part of the Central Cordillera).

The serpentinites studied in this work were collected in the Central Cordillera (Antioquia and Tolima). This mountain range is mainly composed by metamorphic and igneous rocks from Cambric to Cretaceous ages which are limited at west for the Otú-Pericos Fault and at east for the Romeral Fault System.

The serpentinites of Antioquia were collected from: 1) Diorita de Pueblito (Grosse, 1926), an amphibolite diorite composed by amphibole gabbros and peridotites formed by magmatic differentiation; Rodríguez and Vinasco

(2010) reported an U/Pb in zircon age for this unit of 233±14 M.a. 2) Gabro de Heliconia or Gabros de Romeral (Mejía, 1894; Montoya and Pelaez, 1993), a gabbroic unit that surround the Diorita de Pueblito and located within the Romeral Fault System. This unit has a faulted contact with Diorita de Pueblito and Ultramafitas de Angelópolis (Tabares and Arredondo, 2006). A 126 Ma K/Ar in hornblende age was reported by Restrepo and Toussaint (1976). 3) Ultramafita de Angelópolis (González, 2001), a ultramaphic unit with peridotites, serpentinized dunites with ophiolitic affinity, gabbros and basaltic lavas.

Tolimas´s serpentinites are part of the Cajamarca Complex (Maya and González, 1995; Cajamarca Group of Nelson, 1957), a Paleozoic low-grade metamorphic package with green schist, quartz-sericitic schists, phyllites, quarzites and marbles; this unit is bounded at the west by the Armenia Fan deposits and at the east by the Ibagué Batholith. The Cajamarca Complex is truncated at the west by the San Jerónimo Fault. The radiometric ages of the Cajamarca Complex can be classified in three groups: 345-240 Ma, 130-105 Ma and 75-55 Ma. The oldest ages correspond to Acadian Orogeny metamorphism; the others are related to subsequent metamorphic overprints (Rodriguez et al. 2005).

Methodology

We made a compilation of reported localities of serpentinites in Colombia (Fig.1). Rock samples were collected from two potential places and then characterized petrographically and metallographically, using polished thin sections, to identify the principal mineral assemblages, alterations and textures.

Samples chips were powdered in order to use X-Ray Diffraction with a Bruker D2 phaser diffractometer and the software DIFFRAC.EVA in order to identify the polymorphs of serpentine-group. The powder was also analyzed to obtain SEM-images using a Tescan Vega 3 to identify the morphology of polymorphs. Raman spectroscopy was used to established punctual mineral compositions with the Nicolet Almega dispersive XR equipment with a laser of 532 nm and 35 mW.

Additionally, the electron microprobe JEOL JXA-8230 was employed to semiquantitative and quantitative analysis and compositional maps with EDS and WDS spectrometers. Quantitative analysis were used to calculate stoichiometric formulas of spinel, magnetite, serpentine, olivine and pyroxene in order to identify the proportion of magnesium in the minerals that could potentially generate carbonation reactions to sequester atmospheric CO_2, commonly represented by the reaction of olivine or serpentine with CO_2 to produce magnesite + quartz ± H_2O (Power et al. 2013).

Finally, the samples were analyzed using the ICP-AES technique to obtain trace elemental compositions. The Bruker D2 phaser diffractometer, Tescan Vega 3, and the JEOL JXA-8230 instruments are hosted at the Universidad Nacional de Colombia.

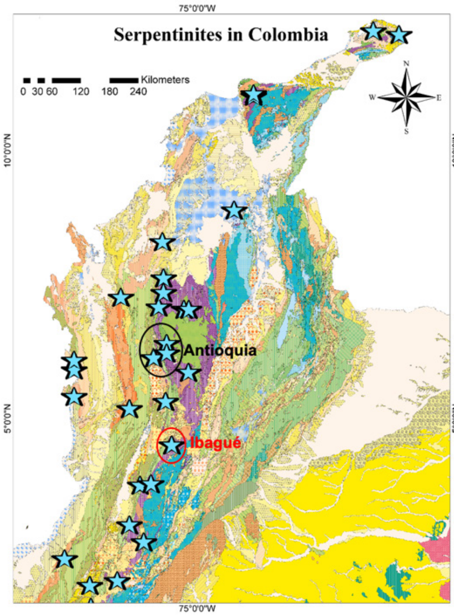

Figure 1. Localization of serpentinites outcrops in Colombia. The locations where the study was done, are marked in the map.

Results

4.1 Antioquia

Antioquia´s rocks were collected in an abandoned magnesite mine. Magnesite was not found in the ultramafic serpentinized rocks, because it was segregated in veins that were mined. The serpentinite tailings present intense fracturing (Fig. 2) which increases the reactive surface making those rocks a good prospect for applying the CO_2 sequestration through in-situ carbonation process (Power et al. 2013).

Figure 2. Outcrop of Antioquia's serpentinites in an abandoned magnesite mine. The rock is intensively fracture producing veins and veinlets that are filled with fibrous serpentine.

The studied samples present different grade of serpentinization that is evident in the proportion of pyroxene, olivine and amphibole relicts. Mesh texture and bastites were identified. Additionally, these lithologies have veins and veinlets of the fibrous polymorph chrysotile. Magnetite appears disseminated and in veinlets along with chrysotile, due to the segregation of this mineral during the serpentinization process (Fig. 3) (Huang et al. 2016).

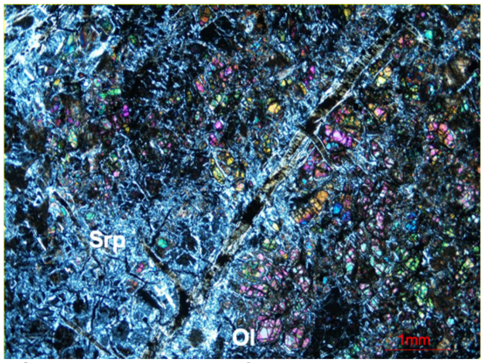

Figure 3. Cross polarized image of Antioquia's serpentinites. Olivine relicts can be observed placed in the center of mesh cells. A chrysotile veinlet crosses the section in NE-SW orientation.

The X-Ray Diffraction evidenced the presence of the following mineral phases: clinochrysotile $Mg_3Si_2O_5(OH)_4$, chamosite $(FeAlMg)_6(SiAl)_4O_{10}OH$, magnetite $FeOFe_2O_3$, marcasite FeS_2, brucite $MgOH_2O$, antigorite 6M $Mg_3Si_2O_5(OH)_4$, lizardite-1T $Mg_3Si_2O_5(OH)_4$ and spinel $Ga_2Cd_{0.75}Cu_{0.25}O_4$.

Raman spectroscopy allow us to confirm the presence of chrysotile and lizardite, mainly within the veinlets, and the forsteritic component of olivines. SEM images also confirm the presence of the chrysotile polymorph as an important constituent of the rock (Fig. 4). If carbonation processes are planned to be implemented in this location, further considerations have to be taken in order to control the impact of chrysotile due to their associated health risks (Fubini and Fenoglio 2007).

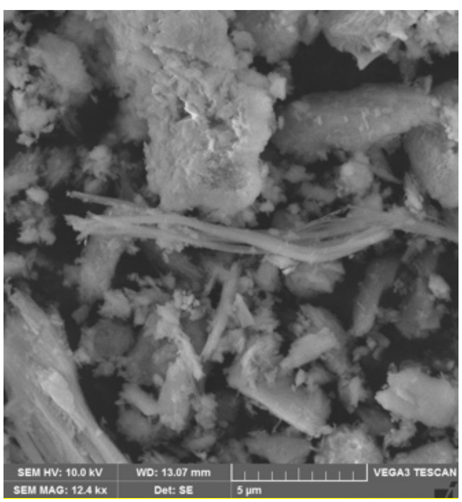

Figure 4. SEM image of the Antioquia's serpentinites showing the typical tubular morphologies of chrysotile.

Serpentine average calculated formula is: $(Mg_{2.77}Fe_{0.07}Al_{0.03})(Si_{2.05}O_5)(OH)_4$. Likewise, whole rock geochemistry shows an average of 35.45 wt% of magnesium in the serpentinized ultramafic rocks, which represent high magnesium concentrations that can be used to apply in-situ carbonation method (Table. 1).

Table 1. Percentages **(**wt%) of major elements obtained by whole rock geochemistry throw ICP-AES in samples from Antioquia.

Sample / Wt%	6	7	8	8A	12	13
SiO_2	40.9	41.6	40	38.3	41.5	41
Al_2O_3	1.63	1.9	0.77	3.62	1.22	2.82
Fe_2O_3	7.86	8.02	6.58	7.96	8.19	8.1
CaO	1.41	2.35	0.17	1.08	0.49	3.01
MgO	36.3	36.8	36.9	34.1	35.5	33.1
Na_2O	0.06	0.14	<0.01	<0.01	0.02	0.05
K_2O	0.01	0.02	0.01	0.01	0.02	0.02
Cr_2O_3	0.4	0.35	0.4	0.31	0.38	0.38
TiO_2	0.03	0.07	<0.01	0.07	0.04	0.05
MnO	0.12	0.12	0.13	0.09	0.12	0.13
P_2O_5	<0.01	0.01	<0.01	0.01	<0.01	0.01
SrO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
BaO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

4.2 Tolima

These rocks have a higher degree of serpentinization in comparison to the Antioquia's samples. No relicts of the ultramafic protolith were observed, and magnesite appears as anhedral crystals of approximately 550 microns in diameter. Serpentines are disposed in interpenetrating textures that indicates higher T-P condition than Antioquia's samples (Fig. 5). Magnesite appears as a product of the serpentinization process and may be explained by equations 1 and 2 of Johannes (1969):

$$2Mg_2SiO_4+2H_2O+CO_2 \leftrightarrow Mg_3(Si_2O_5)(OH)_4+MgCO_3 \quad (1)$$

$$Mg(OH)_2+CO_2 \leftrightarrow MgCO_3+H_2O \quad (2)$$

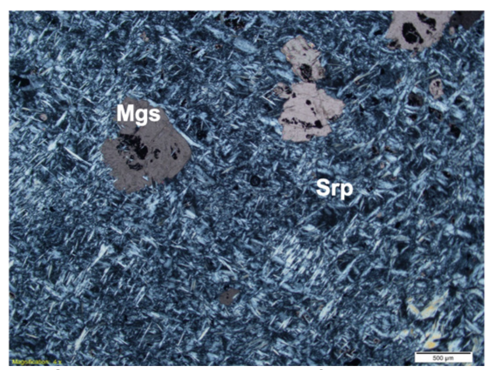

Figure 5. Cross polarized image of Tolima's serpentinites. Interpenetrating texture of serpentines is shown. Magnesite appears as anhedral crystals.

X-Ray Diffraction revels the presence of antigorite 6M $Mg_3Si_2O_5(OH)_4$, eastonite K-Mg-Fe-Al-Si-O-H_2O, baumite-1T $(MgMnFeZn)_3(SiAl)_2O_5(OH)_4$, magnesite $Mg(CO)_3$, spinel $Mg(Al_{0.91}Fe_{0.09})O_4$ and chamosite $Fe_3Si_2O_5(OH)_4$.

Additionally, Raman spectroscopy and SEM images confirm the presence of antigorite as the main polymorph of serpentine-group (Fig. 6). This is a positive point compared to Antioquia's rocks because no health problems related to asbestos need to be considered.

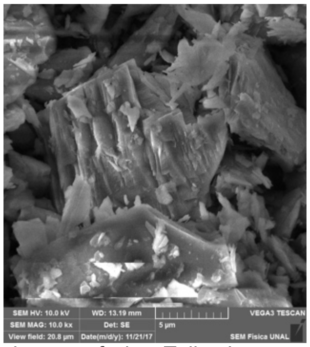

Figure 6. SEM image of the Tolima's serpentinites showing antigorite morphologies.

However, microprobe analyses show that the content of iron is higher in Tolima's serpentinites $(Mg_{2.63}Fe_{0.23}Al_{0.04}Cr_{0.01})(Si_{2.04}O_5)(OH)_4$ and the proportion of magnesium is lower than in Antioquia´s serpentinites. This characteristic may reduce the utility of this lithologies in the sequestration process as magnesium is one of the principal reactants needed to complete the carbonation reaction.

Conclusions

The magnesium rich serpentine polymorph that predominate in Antioquia is clinochrysotile while in Tolima is antigorite. The presence of antigorite in Tolima's rocks, along with its interpenetrated texture and the absence of relicts of the ultramafic protholith, indicates that these rocks experienced higher T-P conditions during their serpentinization process than Antioquia's rocks.

Although samples from Antioquia were collected in an abandoned mine of magnesite, this mineral was not found in the studied rocks, because it was segregated in veins that were mined. In contrast, magnesite was found as anhedral crystals in Tolima's samples. This difference could be related to the T-P conditions, pH and presence of CO_2 rich fluids that allowed the formation of magnesite in the latest location.

Tolima's serpentinites presented three times higher iron content than Antioquia's rocks. The lower magnesium proportion of Tolima's serpentines in comparison to Antioquia's serpentines make the last a more suitable prospect to apply the CO_2 sequestration method throw *in-situ* carbonation. However, the presence of chrysotile needs to be considered because of its potential health risks.

Localities sharing the characteristics reported in this investigation should be consider for applying potential CO_2 sequestration through *in-situ* carbonation process. The green characteristic of the technique could provide economic and environmental benefits in current and abandoned mines.

Acknowledgements

The authors thank the different laboratories of the Universidad Nacional de Colombia where most analysis were performed. We also thank Gloria Inés Rodriguez, Jimmy Fernández Lamus, Germán Bonilla Osorio, Ana Elena Concha Perdomo, Luis Demetrio López Carreño, Jesús Alberto Ágreda Bastidas and the geologist Carolina Jimenez Triana for their help with the data acquisition process and with discussions about geology and mineralogy of serpentinites.

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