Environmental Geochemistry of Abandoned Mines in the Puno Region of Peru – to Guide Strategic Planning for Regional Development and Legacy Site Management

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Research aims:
The aim of this research was to provide technical support to an ongoing targeted geochemical investigation at three abandoned mines in the Puno region of Peru. The purpose of the investigation program is to:

- characterise mine wastes at abandoned mines to evaluate the potential environmental harm in the context of regional geology
- inform management and rehabilitation of these sites as well as to provide baseline data for other mine sites

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IM4DC Action Research Report

www.im4dc.org
Summary of Action Research Activity

Environmental geochemistry of abandoned mines in the Puno region of Peru – to guide strategic planning for regional development and legacy site management

The existence of legacy mine sites in future potential mining regions in Peru is recognised by the Peruvian Energy and Mining Ministry as negatively influencing the community perception of mining and social license to mine. Abandoned mines in sensitive water catchments also pose potential risks to environmental values which need to be defined. The Geological Mining and Metallurgical Institute, INGEMMET, is a technical decentralised public agency of the Energy and Mining Ministry of Peru. The aim of this action research was to provide technical support to INGEMMET as they undertook a targeted geochemical investigation at three abandoned mines in the Puno region of Peru, a region which lies within the catchment of Lake Titicaca. The purpose of the INGEMMET investigation program is to characterise mine wastes at these abandoned mines to evaluate the potential environmental harm from these abandoned mines in the context of regional geology.

Through this project, researchers were able to provide guidance on the monitoring program as well as oversight for fieldwork. Researchers also supported INGEMMET with planning and presentation of a multi-departmental and stakeholder workshop on abandoned mines. They also provided guidance on data presentation, management and reporting. The research was focused on capacity building of INGEMMET technical personnel during one phase of monitoring within a multi-year program.
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June 2015

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Executive summary

The existence of legacy mine sites in future potential mining regions in Peru is recognised by the Peruvian Energy and Mining Ministry as an impediment to social license to mine and future access to land for mining. The Geological Mining and Metallurgical Institute, INGEMMET, is a technical decentralised public agency of the Energy and Mining Ministry of Peru. This agency developed a project for which assistance was sought through IM4DC.

The aim of this action research was to provide technical support to INGEMMET as they undertook a targeted geochemical investigation at three abandoned mines in the Puno region of Peru, a region which lies within the catchment of Lake Titicaca. The purpose of the INGEMMET investigation program is to characterise mine wastes at these abandoned mines to evaluate the potential environmental harm from these abandoned mines in the context of regional geology. This information will then be used to inform management and rehabilitation of these sites as well as to provide baseline data which may be of value to other mine sites in the same geologic region and similar climate.

Through this project, researchers were able to provide guidance on the monitoring program as well as oversight for fieldwork carried out during September 2014. Researchers also supported INGEMMET with planning and presentation of a multi-departmental and stakeholder workshop on abandoned mines. They also provided guidance on data presentation, management and reporting. The research was focussed on capacity building of INGEMMET technical personnel during one phase of monitoring within a multi-year program. The disciplines of personnel within the INGEMMET team included geology and environmental engineering.

This preliminary investigation of the three abandoned mines, identified the major geochemical hazards at the sites based on field observations and limited mineralogical, water quality and assay data. At Aladino, tailings and waste rocks contain residual sulfide and locally generate acid mine drainage despite the presence of potential alkalinity in the geology. At Palca, tailings play a significant role in the chemistry of mine drainage flowing downstream from the site. Tailings are highly oxidised and are particularly enriched in arsenic and lead. Stream sediments also show signs of heavy metal contamination related to the mine site. At Jornune, the mine workings are the major sources of contamination transport into the mine catchment. The streams in the catchment may also receive contaminants from the illegal mining.

Following the fieldwork a number of steps were outlined to guide the team in their future work on this project. A preliminary analysis of data has been carried out however, due to the long term nature of this project, further funding would be required for researchers to evaluate the data from this multi-year program. The report recommends research in related disciplines in order to add value to this research. Abandoned mines pose complex multi-disciplinary impacts and opportunities. This project forms a foundational basis for planning which is systematic and structured.

This project supports a) regional and local economic and social development objective of IM4DC as well as b) Minerals policy, regulation and agreements and c) Environmental management and regulation.
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Introduction

Since the Spanish colonial times, mining activities have impacted the environment, water resources and soil of Puno Region, Peru. Most of these activities have been abandoned with minimal or no environmental care, causing significant damage to the surrounding water resources. There are approximately 50 abandoned mines distributed in the entire region.

For this reason the Geological, Mining and Metallurgical Institute of Peru (INGEMMET) decided to start the geochemical characterisation of mine wastes in abandoned mines in Puno region. INGEMMET were also interested in establishing collaboration with Sustainable Minerals Institute (SMI), particularly with the professionals of the Centre of Mined Land Rehabilitation (CMLR), in order to improve this research project and elaborate a report that supports future programs of remediation in Puno region.

The aim of CMLR research input to the project was to support Sheyla Palomino and her colleagues at INGEMMET to build capacity in data gathering and interpretation of geochemical impacts from abandoned mines.

At a national level INGEMMET hope to develop a model at a regional scale which can be applied to other mining regions in Peru. The starting place is this project in Puno. This has never been undertaken before and represents a pilot research project with opportunities for subsequent research to build upon this knowledge and collaboration.

Three abandoned mines that were selected by their existing hazards and their significance for the communities and the water resources.

a. Aladino VI Mine (PAM 016)
b. Palca Mine (PAM 009)
c. Jornune Mine (PAM 013)

INGEMMET expect the completed project to generate interest from mining companies currently active in the Puno Region. They hope to generate enough interest to raise funds for the rehabilitation of these abandoned mines. INGEMMET are working toward an understanding of the geology and geochemistry of abandoned mines in the Puno region so that it will support improved mine waste characterisation and management to mitigate water pollution in the future, and identify suitable materials for rehabilitation. Acid and Metalliferous Drainage (AMD) due to the exposure of mine waste materials to oxidation and mobilisation by water is a key factor in the environmental and human health impacts of abandoned mines.

Cultural connections to mining in Peru

Peru has an important history in mining activities extending back to the Inca Period when mineral deposits were considered the most important “Apus” (Andean Mountain Gods). Some of these deposits were used as sources of minerals for their daily and ceremonial activities. Years later, during Spanish colonisation, the Andean ‘cosmovision’ (value system based on spiritual connection of humanity and nature) was used to locate gold and silver deposits. This was the beginning of mining activities in Peru.
Growing environmental awareness of mining impacts

Mining expanded in the absence of an environmental legal framework which resulted in the creation of negative environmental impacts and liabilities. This continued until 1993, when the Peruvian government became more aware of these impacts and began to develop environmental regulations. In 1995 a number of studies and environmental investigations identified the environmental impacts and liabilities caused by mining activities in Peru. Studies included a Project on Sustainable Development (1995-2000), Territorial Environment Assessment (TEA) and the inventory of inactive mines. The TEA involved 16 environmental investigations of hydrographic basins where mining activities were being undertaken. The Energy and Mine Ministry was the responsible agency for development of the inventory of the abandoned mines which also provides an important planning tool.

From 2001, there has been a greater focus on the elimination of environmental liabilities in order to reduce the negative impacts of the liabilities concerning to the public health, flora and fauna and economic activity. An inventory was developed which identified 610 environmental liabilities, 72% with mining tenure and associated responsibility. The cost of remediation was estimated between 200 -250 million US dollars.

This amount did not consider the environmental liabilities generated by national companies which was estimated at 300-400 thousand dollars (US) to remediate each site. This was considered an underestimate1. In order to prioritise risks, sites were evaluated for: risk of catastrophic failure, the size of the population, risks to infrastructure, level of pollution of the water, air, soil, flora and fauna as well as impacts upon the quality of life quality of the population ie. socio-environmental impacts. The initial prioritised basins were in Puno, Cajamarca, Ancash and Huancavelica.

In May 2006, Energy and Mines Ministry began the update of the inventory of environmental liabilities considering the study developed in 2001. In order to develop this work was established the “Guide of procedures for field work”. As a result of this inventory 850 environmental mining liabilities were identified.

During the data gathering process further information on tailings, waste rock dumps, leach pads, underground workings and open pits were identified and evaluated for the following risks: acidic drainage of contaminated water (AMD), risk of catastrophic failure, erosion and sediment pollution impacts. The location, size and catchment area impacted was also recorded.

Since 2012, the Energy and Mines Ministry through the Technical Director of Mining have been working through four stages:

- Stage 1: Update of environmental mining liabilities - Identification, characterisation and prioritisation of environmental mining liabilities
- Stage 2: Determination of ownership and responsibility for remediation.
- Stage 3: Further studies of environmental mining liabilities which are the responsibility of the Peruvian government.
- Stage 4: Remediation projects.

From this process 8,616 environmental mining liabilities were identified. Three abandoned mines were subsequently prioritised to receive funding so that site characterisation for remediation planning could proceed in the Puno region. They included Aladino VI, Palca, Jornune Abandoned Mines.

1 Office of the Ombudsman (2005)
Abandoned Mines inventory

Legislation was introduced in Peru addressing abandoned mines in 2005 (Law No 28271, Government of Peru) to require identification and characterisation of abandoned mines. It also requires resourcing and responsibilities to be defined. The inventory in 2006 identified 611 abandoned mines in Peru (Villanueva, 2014). More recently, a total of 8,616 sites were identified (Figure 1) (Peruvian Ministerial Resolution, N° 234-2014-MEM/DM; Lima, May 19, 2014).

Significance of the Puno Region

The Peruvian government has an agreement with Bolivia, ‘The Binational Autonomous Authority of Lake Titicaca’ (ALT), which aims to protect the environmental values of Lake Titicaca. The combined factors of this important catchment area; for its natural values, as a water resource, its cultural significance as well as the demand for access to land for exploration and mining within the Puno Region contributed to the Peruvian government identifying this region as a priority area for the study of abandoned mines (Figure 2).
The Puno region sub-catchments are significant to Lake Titicaca. There are zones of diminishing humidity from north to south, going from humid around Lake Titicaca, to semi-arid in the south of the catchment in Bolivia. The climate within the Puno Region is that of a high mountain region with a tropical hydrological regime of great inter-annual irregularity. Lake Titicaca exercises a moderating influence on temperatures and rainfall in the vicinity of the lake. Precipitation varies between 200 and 1,400 mm, with maximum value of 800 to 1,400 mm at the centre of the lake (ALT). There are great seasonal variations, as the area usually has wet summers and dry winters, with a rainy period from December through March and a dry period from May through August. The air temperature varies within the system depending on latitude, longitude, altitude and proximity to the lake, with minimums of -10 to -7°C and maximums of 19 to 23°C. Humidity is low throughout the system, with an average of 54 percent and variations depending on latitude and season.

Figure 2 The Puno region of Peru in the context of Lake Titicaca

Figure 3 shows the location of abandoned mines within two sub-catchments of the Puno region. From these abandoned mines three were selected for this pilot study by INGEMMET.
**Figure 3** Three abandoned mines studied, one in Illpa basin and the others in Coata Basin

**Objectives**

Broadly the objectives of this project are to;

- Geochemically characterise mining environmental liabilities in the Titicaca watershed by taking samples of surface water and mining waste, to delineate areas impacted by abandoned mines including the distribution of heavy metals in the environment.
- Quantify impacts from legacy mining features and provide data for development of management and remediation plans in order to reduce impacts. Use the data to adjust the risk prioritisation of mines (previously developed by the Ministry of Energy and Mines).
- Map the vulnerability of the environment to potential sources of contamination, and
- Contribute to thematic knowledge (geological, geomorphology, geodynamics and geochemistry) for environmental management in the region Puno generally.
The objectives of the INGEMMET project are to provide advice to the government on:

1. environmental impact assessments, characterisation and relevant findings,
2. geochemical characterisation of solid mine wastes from abandoned mines
3. characterisation of water quality in the surrounding rivers and associated discharges,
4. construction of a vulnerability map of abandoned mines in the Puno region as a guide for remediation planning,
5. modelling the geochemistry of the impacted environments,
6. development of a methodology for assessing the risk of pollution, and
7. collaboration on the publication of results

CMLR provided research guidance prior to, during and after the September 2014 fieldwork phase. CMLR also contributed to program planning for an abandoned mines workshop which was hosted by INGEMMET following the fieldwork. Researchers from CMLR also presented during this forum along with representatives from key agencies from the Peruvian government as well as industry stakeholders.

**Research approach**

The aim of this preliminary geochemical investigation was to better understand potential sources of acid and metalliferous drainage within the catchments of the three abandoned mines. A few snapshot solid phase and water samples were collected during the field trip in September 2014. This required a number of pre-fieldwork skype meetings to help INGEMMET plan the sampling program. The project involved the following components whilst in Peru:

- Meetings with INGEMMET officials and the team for this project
- Fieldwork in Puno Region
- An Abandoned Mine workshop which included other agencies and stakeholders

**Meetings at INGEMMET**

CMLR met with officials at INGEMMET prior to fieldwork in the Puno Region to discuss the project and collaboration between the two organisations (Figure 4). A memorandum of Understanding is being discussed between the two organisations.

![Figure 4 INGEMMET and CMLR met in the office of INGEMMET in Lima Peru.](image-url)
Fieldwork in Puno Region

Abandoned mine characterisation fieldwork was carried out from September 6-11. The team flew from Lima to Juliaca and were based at Puno, where they acclimatised prior to fieldwork at higher elevation. The first site was Aladino VI mine near the township of Mañazo. The second day of fieldwork was spent travelling to, and sampling wastes and water at Palca Mine. Jornune was the third minesite studied.

In summary pre-fieldwork preparation involved:

- literature review and synthesis of information on geology and sub-catchments
- preliminary interpretation and field trip planning
- preparation of base maps and sampling program
- field plan logistics, route plan and coordination,
- gathering laboratory sampling supplies and field equipment
- gaining approval for access to land in consultation with local authorities

Whilst in the field the following was undertaken:

- meeting with local officials to confirm permission (due to the local opposition to mining activities)(Figures 5 and 6) and safe access to land where abandoned mines were located, as well as engaging with landholders (Figure 7), where present, to explain the research being undertaken
- water sampling of upstream water quality as well as downstream - influenced by the abandoned mine(s). Samples were filtered in the field using 0.45 μm filters.
- sampling of solid materials – waste rock, tailings, sediments from within stream beds. Sediment samples were collected from fine and active streambed sediments using a plastic trowel in an area with a radius of five meters, and were mixed as a composite sample.
- testing physico-chemical parameters at specific sampling locations, with hand held monitoring equipment (pH, EC etc)
- all data points were accurately located using GPS in order to update spatial databases and maps
- samples were packaged for transport to the laboratory with instructions on specific analyses at the end of the fieldwork
- discussion of procedures was held to review the fieldwork methodologies and continue to improve these in the next round of sampling

On return from fieldwork;

- the INGEMMET team followed up on laboratory analyses and processed the laboratory data, developed graphs and other plots to support interpretation
- data recorded in Excel spreadsheets
- maps were reviewed and updated with new data
- compilation of data for technical papers, reports and conference presentations.
Figure 5 Sign in Mañazo local government office ‘we will decide – If you don’t have social license you cannot mine on our land’

Figure 6 Meeting with the Mayor of Mañazo not far from Aladino VI
Figure 7 Engaging with a landowner living near Aladino VI abandoned mine

Figure 8 Water quality monitoring upstream of the Aladino VI abandoned mine
Abandoned mine workshop “challenges and opportunities”

An abandoned mine forum was held on 12 September 2014 at INGEMMET. The workshop brought together government agencies who were stakeholders in the abandoned mine environmental geochemistry project (Figure 9). Appendix A includes a list of participants. CMLR presented at this forum to share leading practice knowledge of AMD and abandoned mine management. Themes addressed water management aspects, funding for abandoned mine rehabilitation, prioritisation and risk assessment. Also explained was the national legislation for abandoned mines in Peru. The forum included leaders from small mining, other agencies, academics actively involved in related areas of research and provided a boost to the profile of this team within INGEMMET (Figures 10, 11 and 12).

Figure 9 shows the program for this forum.
Figure 10 CMLR and INGEMMET team at the abandoned mine workshop

Figure 11 Some of the participants at the INGEMMET Abandoned mine forum
Copies of the presentations were given to all participants before they left at the end of the day (Figure 12).

A summary of knowledge gaps was prepared at the end of the forum with a discussion of how issues would be addressed and who would accept responsibility for those tasks.

Recommendations included the following, (translated by S Palomino, INGEMMET):

- Establish links and synergy with common objectives among institutions.
- Establishment a multi-sectoral commission on issues as environmental management and management of environmental mining liabilities.
- Creation of virtual platforms in order to maintain the communication between government institutions.
- Creation of virtual platforms to communicate to the community with information that contains simple language.
- Promote, between the higher authorities of Peruvian national institutions the establishment of strong ties, and request to research institutions (eg universities and other organisations) their participation.
- Improvement of legislation to address loopholes, especially for small mining projects and related issues.
- Provide technical support for development of management tools and environmental management.
- Enrich and update the databases of institutions with competence in these matters (INGEMMET, MINAM – Ministry of Environment, MINAM – Energy and Mines Ministry, ANA – National Authority of Water).
• Promote exchange of information during and after studies.

**In the short term:**

- Maintain the communication and exchange of information between the institutions with the projects, which are being developed in Puno region.
- Enrichment, update and incorporation of information in virtual Peruvian platform (INGEMMET-Geocatmin, MEM, MINAM, ANA, MINING ASSETS).
- Register a permanent record of participants from each institution for consultation and exchange of information.
- Participation of universities in Geo-environmental research studies through thesis, internship, conventions, etc.
- Call and participating in meetings as the activities of joint projects, considering the registration of participants generated. Being the closest:
  - Meeting between INGEMMET and representatives of ‘Activos Mineros’ (Remediation company).
  - Meeting between representatives INGEMMET and MINAM.

**In the long term:**

Provide support to the following institutions according to their competencies and responsibilities with all the information collected and generated (water, soil, sediment, rock and mining liabilities) in the Geo-Environmental studies:

- National Authority of water (ANA): Water quality information for the re categorisation of rivers.
- Ministry of Environment (MINAM): Geo-environmental information of the study (water, soil, sediment) for review and adaptation of the standards to the Peruvian reality
- Recommendations and results of geo-environmental studies that will be useful for environmental strategies and guidelines developed by the MINAM.
- Activos Mineros Company: Geochemical characterization information of mining environmental liabilities as support for remediation projects.
- Information for environmental baseline studies and land managed by the regional, local and district government.

Development of future geo-environmental studies based on needs of government agencies and critical areas for social and environmental aspects.

Organisation of courses related to geochemistry and environmental legislation to the institutions involved in the management of environmental liabilities, with the support of Australian specialists.
Aladino VI Mine

The Aladino VI Mine is located close to a rural dwelling with grazing activities. The runoff from this mine flows toward an ephemeral creek system which flows toward the town of Mañazo. The abandoned mine is unfenced so there is uninhibited access to waste materials by humans and other animals.

The geology of Aladino VI mine area is dominated by limestone or calcareous sedimentary and intermediate porphyry rocks. Therefore, the waste rocks are either calcite dominated (R2) or silica dominated (R4). Some rocks are extremely mineralised. For example, R3 contains galena (18%), sphalerite (26%), pyrite (6%), chalcopyrite (3%), and Jacobsite (2%) (a manganese iron oxide mineral with the general formula MnFe₂O₄). The waste rock dumps are located to the west of the site where old mine workings have cut into an area which seems to be at the contact of carbonate rocks and volcanic or intrusive intermediate rocks. Figure 13 shows the geology of the sub-catchment for the Aladino VI mine.

Figure 13 Geology of Aladino VI abandoned mine sub-catchment

The research team provided guidance on water quality measurement during the sampling program (Figure 8).
The geology of Aladino mine area is dominated by limestone or calcareous sedimentary and intermediate porphyry rocks. Therefore, the waste rocks are either calcite dominated (R2) or silica dominated (R4). Some rocks are extremely mineralised. For example, R3 contains galena (18%), sphalerite (26%), pyrite (6%), chalcopyrite (3%), and Jacobsite (2%) (a manganese iron oxide mineral with the general formula MnFe₂O₄). The waste rock dumps are located to the west of the site where old mine workings have cut into an area which seems to be at the contact of carbonate rocks and volcanic or intrusive intermediate rocks. The mineralogy of waste rocks is shown in Figure 14 and Figure 15.

![Figure 14 Mineralogy of waste rocks at Aladino mine](image)
Figure 15 Mineralogy of a typical waste rock collected at Aladino VI mine, including XRD results (pie chart), and a photomicrograph; galena (gn), gray copper (CGRs), pyrite (py), sphalerite (ef), chalcopyrite (cp). The original calcareous rock is strongly silicified and contains fractures filled in with calcite.

Figure 16 Acid mine drainage pool near waste rocks at Aladino VI mine

Contaminated water ponds onsite (Figure 16) likely to contribute to the ‘first flush’ runoff during rainfall events.

The tailings cover a wide area to the east of the site, between the remnants of old mineral processing structures and a stream which flows in a north-westerly direction (Figures 17 and 18). The tailings are partly eroded and incised, and show signs on highly oxidised on the surface. The mineralogy of tailings may include residual pyrite and other sulphides (RV-2) (Figure 19), or may show more advanced stages of oxidation with the dominance of iron oxide (RV-1). One samples (RV-3) collected at the lower section of tailings profile contained rare minerals including Zabuyelite, which is the natural mineral form of lithium carbonate, with a formula Li$_2$CO$_3$, villamaninite [(Cu,Ni,Co,Fe)S$_2$], and Uvarovite [Ca$_3$Cr$_2$(SiO$_4$)$_3$]. The tailings contain elevated concentrations of zinc, bismuth, cadmium, copper, manganese, lead, and antimony (Figure 20 and Table 1).
Figures 17 & 18 Tailings disposal area and erosion gullies

Figure 19 Sampling locations in tailings profile
Figure 20 Mineralogy of tailings samples (RV1-3) from Aladino mine
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The stream water sample (0174-154-034) collected about 0.5 kilometre downstream from the tailings location showed similar chemistry compared to those above and outside the mine influence with the pH in the range of 7.00 to 8.48, which is in the near-neutral/low metal classification (Figure 21 and Figure 22). The conductivity of the sample collected above the mine is 473 μS/cm, in contrast to those for other samples in the range of 1000 to 1413 μS/cm. The sulfate concentration in the downstream sample is 484 mg/L compared to 88 mg/L upstream from the site. A few pH measurements at drainage channels at the base of old mine workings also showed near-neutral to alkaline property which indicates to the buffering capacity of carbonate rocks.
Figure 21 Sample sites at Aladino VI
The collected stream sediment samples showed higher concentrations of arsenic, copper, lead, and zinc near the site and at a downstream location not far from the tailings disposal area (Figure 23).
Palca mine

Mining at Palca ceased around 1956. It was a former copper lead and zinc mine. This is the highest elevation site included in the fieldwork at around 5000m ASL. **Figure 24** shows the Palca mine sub-catchment geology and drainage.

![Figure 24 Palca abandoned mine sub-catchment geology and sample sites](image)

Snowpatches were evident on the mountain above the minesite. This is the most remote site included in the study. **Figure 25** shows the grazing land uses downstream of the mine (tailings visible in the background) where llamas and Alpacas were seen drinking AMD-impacted site drainage. The remoteness and high elevation of this site poses numerous challenges which would need to be addressed as part of any implementation plan for long term management of these sites.
The geology of Palca is dominated by felsic to intermediate volcanic rocks. The mineralogy of the rocks (e.g. 0176-155-RX2) reflects the local lithology with dominance of quartz, plagioclase, some mafic minerals (pyroxene?), and with some pyrite. A sample from dumps of crushed rocks (0176-155-RM01) that could be mill rejects contained similar mineralogy with the addition of secondary minerals (e.g. jarosite). There are several waste rock dumps at various elevations at places where old mine workings have cut into the mountain (Figures 26, 27 and 28).
Figure 26  Mine waste dumps at Palca

Figure 27  Representative mineralogy of rocks at Palca
The tailings disposal area covers a wide flat area to the west of the site. Tailings are coarse-grained hence deeply aerated and oxidised. Nevertheless, still contain considerable amount of pyrite (11% in the case of 0176-155-RV01). Tailings samples showed elevated concentrations of arsenic and lead. Arsenic concentrations were particularly higher in the more oxidised sample (RV01) which also contained more amorphous iron oxide (Figure 29, 30, 31 and 32, and Table 2).
Figures 29 and 30 Tailings at Palca showing signs of advance oxidation
Figure 31 Mineralogy of oxidised tailings at Palca

Figure 32 Sampling tailings and mine waste at Palca
The main sources of acid and metalliferous drainage at Palca are the underground workings, the tailings, and waste rock dumps. There is also a small glacial lake which has been modified with a dam wall which perhaps was used as the water source for the operation (Figure 33). A small wetland area near the tailings and waste rocks is covered with moss-like plants and grasses and attracts migratory birds, despite the presence of contaminated mine water.

**Table 2 Geochemical composition of solid samples collected at Palca mine site**

<table>
<thead>
<tr>
<th></th>
<th>0176-155-RV01 (tailings)</th>
<th>0176-155-RV02 (tailings)</th>
<th>0176-155-RM01 (mine waste)</th>
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*Figure 33 Modified glacial lake-dam at Palca mine site*
The mine drainage adjacent and downstream from the tailings disposal area (0176-155-76) was particularly acidic and contained higher concentration of metals (Figure 34) with a conductivity above 5000 mS/cm. Sulfate concentration at this point was 3607 mg/L. Stream sediment sample collected downstream from this point showed elevated concentrations of arsenic and lead which reflects the geochemistry of tailings (0176-155-SED01).

![Figure 34 Mine water chemistry at Palca](image)

Groundwater flowing from the underground mine workings (Figure 35) was sampled during fieldwork. The wetland feature below the mine is shown in Figure 36 and 37. Parts of the wetland are more affected by AMD than others.
Figure 35 Entrance to underground mine workings
Figures 36 and 37 Wetland area at Palca mine
Jornune Mine

The Jornune Mine is located in a narrow and steep catchment in a broad valley where grazing is carried out. On the opposite side of the valley evidence of small scale, illegal, mining was apparent. Figure 38 shows the geology of the Jornune mine sub-catchment with Figure 39 providing an aerial image of the mine and its surrounds (including illegal mining areas).

![Geology of the Jornune abandoned mine sub-catchment](image)

**Figure 38: Geology of the Jornune abandoned mine sub-catchment**
The geology of Jornune mine site is dominated by intermediate volcanic (andesite) or intrusive (diorite) rocks. The mineralogy of rocks may consist mainly of plagioclase, and some pyrite may also be present (e.g. RX-1 Figures 40, 44 and 45). The mine workings are along a valley which is filled in and obstructed by dumps of weathered coarse mine residues (Figures 42 and 43). The mine residues which seem to be a mix of crushed rocks and tailings, ranging in size from gravel to sand and silt, also contain pyrite, but are highly weathered and enriched in secondary minerals (e.g RM-01 and RM-02, Figures 46 and 47).
At the bottom of the valley, there is a pool of water which collects seepages from mine workings. At the seepage point, white coloured aluminium floc and red iron floc are precipitated (Figure 44). A precipitate sample from this point contained a large amorphous fraction and some hematite and goethite. Aluminium floc is usually undetectable by XRD. Table 3 summarises the waste geochemistry.

![Figure 40 Mineralogy of a typical rock sample from Jornune mine site](image-url)
Figures 41, 42 Mine residue (top and middle) and Figure 43 mine drainage precipitates (bottom) at Jornune
Figure 44 Mineralogy of mine residues at Jornune mine
Table 3 Geochemical composition of solid samples from the Jornune mine area

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Figure 45 Mineralogy of mine drainage precipitate at Jornune
The high concentrations of arsenic in sediments samples (Table 3) may indicate the influence from informal mining to the south of the catchment. Tributaries of the alluvium laden steam in the middle of the catchment are from the mines at both side of the catchment.

The three water samples collected at the seepage point, and downstream from the mine site were classified as near-neutral low metal. The conductivities were above 1000 mS/cm and sulfate values were above 400 mg/L. Figure 46 shows the chemical composition of water samples.

![Chemical composition of water samples from Jornune mine](image)

Figure 46 Chemical composition of water samples from Jornune mine
Conclusions

This preliminary investigation of the three abandoned mines, identified the major geochemical hazards at the sites based on field observations and limited mineralogical, water quality and assay data.

At Aladino, tailings and waste rocks contain residual sulfide and locally generate acid mine drainage despite the presence of potential alkalinity in the geology. Tailings are particularly enriched in heavy metals which are readily mobilised through physical and chemical weathering processes. The tailings mineralogy is enriched in secondary minerals which may act both as the sink and source of heavy metals. Downstream from the tailings disposal area, stream sediments are enriched in lead, arsenic, and copper.

At Palca, tailings play a significant role in the chemistry of mine drainage flowing downstream from the site. Tailings are highly oxidised and are particularly enriched in arsenic and lead. Stream sediments also show signs of heavy metal contamination related to the mine site.

At Jornune, the crumbly weathered mine waste in the valley of the mine as well as the seepages from the mine workings are the major sources of contamination transport into the mine catchment. The streams in the catchment may also receive contaminants from the illegal mining.

In the absence of hydrological data it is not possible to estimate the loads of contaminants leaving those sites or predict any changes to water quality. However, the steady infiltration of precipitation and replenishing groundwater, particularly abundance of snow melt at Palca, indicate that the sites will continue to discharge contaminated mine water all year round.

Recommendations

This project was multi-facetted involving several preliminary skype meetings and the following components whilst in Peru;

- Meetings with INGEMMET officials and the project team;
- Fieldwork in Puno Region; and
- An Abandoned Mine workshop which included other agencies and stakeholders.

This is a project being undertaken by INGEMMET over several years during which time a significant volume of data are being gathered. Fieldwork recommendations were made during in-country meetings. Some of these are already being implemented. In summary;

**Systems, procedures and knowledge management**

1. Quality assurance methods need to be embedded in data management processes to ensure that labelling of results is aligned with sample labelling.
2. Similarly, the accurate location of sample sites must be verified through the development and maintenance of a high quality spatial data systems and checked when maps are produced showing sample locations,
3. Roles and responsibilities as the project evolves, should be documented and kept current so that within the team the work is shared and appropriate skills and expertise are assigned to the task,
4. Further develop the risk assessment and management method for fieldwork to ensure the ongoing safety and health of technical personnel working in remote areas

5. Like any data and knowledge gathering project, the information needs to remain accessible to other personnel within INGEMMET, any future geochemical characterisation personnel who follow on from the current team into the future in the event that there are any personnel changes.

6. All sample preparation and handling procedures must be documented, as well as community engagement methods by finalizing the guidelines which are in progress by INGEMMET;
   - Water quality monitoring sampling (first draft completed)
   - Sediments monitoring sampling (first draft completed)
   - Community communication procedures
   - Geo-environmental study methodology and procedures.

Additional technical studies which may be required to help interpret the data

1. Gathering accurate climate data for each site is an integral component of understanding the impacts of abandoned mines in their sub-catchments and overall region. Where no climate stations exist, collaborate with climatology expertise to interpolate climate data to provide as accurate estimates as possible of climate parameters which influence abandoned site hydrology.

2. Environmental values need to be determined and then appropriate water quality objectives determined (see example from ANZECC, 2000, Figure 47). Peru has its own water quality guidelines and this may simply require collaboration with another agency (ANA).
3. Additional studies may be needed to understand how the local surface and groundwater systems interact with mine wastes to influence contaminant loads. Through such analysis a means of prioritising mine wastes for rehabilitation and other management actions can be undertaken. Within each individual site, it should be possible to identify which features are generating the most pollution (e.g., individual areas of tailings, waste rock, and so on).

4. In specific instances where human and animal health (for human consumption) issues are of potential concern, an understanding of bioavailability and bioaccessibility of contaminants is likely to be required to evaluate options for management or remediation.

5. Collaboration with other agencies is likely if the findings from this study are to be used to evaluate risks and inform the prioritisation of funding and resourcing efforts.
6. Water engineering design may also be needed to evaluate options for diversion of clean water around AMD generating mines, as well as redirection/containment and/or treatment of polluted waters. It was noted that channelized irrigation flow was common in this landscape to direct water to where it was needed for stock watering and irrigation of crops. In some instances this already was being used to mitigate the reliance upon potentially contaminated waters. Further studies of the sub-catchments and local drainage is needed in conjunction with geochemistry to develop appropriate strategies.

7. In some instances, as an interim measure, fencing would be useful to keep grazing animals from drinking contaminated water and grazing on areas potentially influenced by AMD.

8. Biodiversity studies are recommended to complement the baseline geochemistry. In some areas downstream and adjacent to mine-impacted areas there could be significant biodiversity values which should be protected as part of any rehabilitation planning. Eg the wetlands near the Palca mine.

Recommendations based on a preliminary review of the geochemistry data

It is recommended that conceptual models be developed that would describe the sources, pathways and fate of contaminants in the catchments for each abandoned mine. Such models can be used as a basis to plan for further monitoring. They can be also used to assess the cumulative impact of the abandoned mines. Conceptual models are also important to help identify the higher risk aspects of the abandoned mine and where to focus attention (whether that be further monitoring, management, or later remediation).

It is important to establish the geogenic sources as well as mining related sources of contaminants in the catchment of abandoned mines. However, catchment scale geochemical balance will require reliable hydrological data including water balance models.

- Instalment of stream flow gauging stations would assist interpretation of data,
- Collection of local meteorological data is essential,
- Continuous monitoring of flow, conductivity and pH at key locations, for example at the exit of the mine portal at Palca will be necessary,
- An understanding of local and regional groundwater is essential for any catchment scale water and chemical balance as well as rehabilitation of those sites.

Rehabilitation of the mine sites will require estimates of the volumes and tonnages of the mining and mineral processing waste. Reprocessing of some tailings and mine waste may be viable but it requires detailed metallurgical examination and resource evaluation.

A source, pathways, and fate model can be used to predict potential impacts on the receiving environments. Residual contaminants which may have been accumulated over time in the streambed. Metals are either accumulated as surface adsorption on fine sediments, or may have been transported downstream as particulate matter and trapped in the sediments. There may be local reducing environments due to the presence of organic matter that would change the redox conditions and precipitate metals.

The bioavailability of dissolved metals, and metalloids in the aquatic environments downstream from the mine sites should be investigated for assessing and predicting potential eco-toxicological impacts.

Once the two year monitoring program has been completed it may be possible to develop a prioritisation framework which supports the site selection and monitoring requirements for other abandoned mines.
Acknowledgements

The authors would like to acknowledge the INGEMMET project team;

Ms Sheyla Bethsy Palomino - B. (Hons) Sanitary (Environmental) Engineering, National University of Engineering (UNI-2010), Peru. Her thesis was: Risk Assessment of groundwater pollution using vulnerability and danger maps. Case: Aguascocha Aquifer. Her current position is a geo-environmental researcher in INGEMMET in the projects:

- Geochemistry characterization of waste mine of abandoned mines in Puno Region,
- Risk assessment pollution of groundwater in Aquifer located in mineralized places - this project include the use of GIS reference in the construction of vulnerability map (DRASTIC method) and the dangerous map (COST ACTION 620 method).
- Participation in multisectorial dialogue tables to solve conflicts between mining companies and communities by water and groundwater pollution issues through developing technical studies. Areas of Expertise: Hydrogeology, environmental, drinking water and wastewater systems.

Dr Mirian Irene Mamani Huisa - PhD (Dr. rer. nat.) Geologist engineer at Göttingen University-Germany (GZG-2006), her dissertation thesis was: Variations in Magma composition in Time and Space along the Central Andes (13°S - 28°S). She is Post-Doctoral Researcher at Geoscience Center Göttingen since 2007, in Geochemistry, Petrology, and thermos-chronology signals in Neogene Sediments of the Western Andean Escarpment in order to perform the geochemistry of the sediments and palaeorivers reconstructions during the Andean Evolution. She is professor in the National University of engineering and University of San Marcos in the master programs. Her actual position is geoscientist advisor in INGEMMET and as referee in scientist magazines. Areas of Expertise: Geochemistry, Petrology, Volcanology, Mineral deposits and Sedimentology.

Magdie Ochoa Zubiate, Geologist Engineer from the National University of Cajamarca. She works in the geological risk program and Geo-Environmental projects at INGEMMET.

Shianny Vasquez Cardeña, Geologist Engineer from the National University of Saint Anthony the Abbot in Cuzco. She works in the National Program of Hydrogeology and Geo-Environmental projects at INGEMMET.

Franz Garcia Huazo, Bachelor in Environmental Engineering from the National Agrarian University-La Molina, Lima. He works in the Geo-Environmental projects at INGEMMET.
(L to R) Corinne Unger, Sheyla Palomino, Shianny Vasquez, Magdie Ochoa and Mansour Edraki at Jornune abandoned mine, Puno Region, Peru.
Authors

Dr Mansour Edraki - Following extensive overseas work experience with the mining industry in the areas of ore deposit geochemistry and mineralogy, and with a M.Sc. in earth science, Mansour completed his PhD at the University of New England (Armidale) in 1999. The primary focus of his PhD research was on isotope and trace element geochemistry. He then joined CMLR to participate in interdisciplinary research projects related to mine site rehabilitation. Mansour’s research interests are in innovative approaches to the understanding and monitoring of geochemical processes applicable to mining environmental management and mine closure, with a focus on mine water hydro-geochemistry.

Ms Corinne Unger - completed her Bachelor of Science Degree majoring in geomorphology and climatology with a Diploma of Education at Macquarie University, NSW. Later she completed a Post Graduate Diploma in Geoscience in Applied Geomorphology. Corinne worked in Soil Conservation then in the mining industry in areas of mine rehabilitation, planning and research in the Northern Territory then environmental regulation and abandoned mine site management for the Queensland government. She has also worked on rehabilitation of abandoned mines in several states of Australia. Corinne was awarded a James Love Churchill Fellowship in 2009 to study Abandoned Mine Rehabilitation and Post-Mining Land Use in Austria, Germany, England and Canada. Corinne is a self-employed environmental consultant specialising in mine rehabilitation and closure planning whilst undertaking research part-time at the CMLR for the last 4 years. Corinne is currently Chair of the Community and Environment Society Committee of AusIMM.

References


## Appendix A – Participants at abandoned mines workshop

List of Participants at the INGEMMET-hosted Abandoned Mines Workshop

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