Nano-particle products from new mineral resources in Europe

Final Report Summary - PROMINE (Nano-particle products from new mineral resources in Europe)

Executive Summary:

ProMine Executive Summary:

The FP7 ProMine project answered the call of the Commission to address the annual 11 billion euro imbalance of imported raw materials into the EU. ProMine was the first large integrating project focussed on raw materials to be financed by the Commission in more than 20 years. As such its success was crucial in underpinning the renewed interest shown by the Commission in European raw materials. ProMine, with 30 partners and a total budget of approximately 18 M euro looked at the whole value chain from raw materials derived at exploitation sites through conversion into nano materials and their application in innovative industrial products. Industrial participation was important both for the credibility of the project, as well as for testing and evaluating the nano-material based end products.

Guaranteeing the supply of European raw materials for industry is essential in any industrial process. The first two WPs of the project dealt with this. WP1 created the first pan-European Georesource database which includes not only primary raw materials, but also secondary raw materials of anthropogenic origin. In other words, waste which can be considered as a usable resource. WP1, at the request of the Commission, was able to deliver the first and only map of critical minerals in Europe, a map which has been widely used by Commission services, not only DG RTD but also DG Enterprise. WP2 took mineral resource evaluation to a new level by applying 4D modelling to four mineralised belts in Europe. A better understanding of the evolution through time (the 4th dimension) means mining industry is able to predict new ores with greater accuracy, and the results have already found practical application.
Developing new nano-materials up to pilot scale production, and their industrial application was the core task of WP3. Extremely pure nano-silica has been produced by the interaction of Greek mining waste (Magnesium Silicates) with industrial acids. Characterisation showed it has the same specifications as the most expensive nano-silica on the market, but in contrast to commercial silicas, produced at low temperature and pressure, and with minimal waste stream. It has been tested industrially as an additive in Dutch construction materials with great success. The same nano-silica has been tested in the Finnish paper industry, in one of the coating layers as well as in binders and adhesives. These industrial tests gave extremely positive results and commercialisation is now planned. Rhenium alloys made with nickel and cobalt have been developed from the waste stream of Polish copper mining. These nano-spheres are essential components in special materials used in jet engine turbines, high speed train shields, and space vehicles. Schwertmanite produced as a waste material from iron rich, acidic water at lignite mining sites in Germany was prepared as a powdered nano material and used successfully as a pigment in paints, and as an adsorbant to remove Arsenic and other contaminants from water.

WP4 developed several innovative technologies for preparing secondary mineral resources (eg. crushed rocks with a low metal content) for metal extraction and recovery, primarily by bioleaching technologies using specially developed strains of bacteria. Industrial partners are patenting results which have economic potential.

Environmental issues including LCA were the focus of WP5 which spotlighted the advantages of the new ProMine products over current market competitors, and which give an added value to the results of the project. Dissemination was a central theme from the first month of the project, since it was clear that in order to achieve success a range of stakeholders had to be informed of the results. A series of stakeholder workshops and mineral markets complemented press releases, folders and fact sheets, and the results of ProMine were even carried to Japan where a stand at the Green Expo was the only European contribution to this major Asian event.

The ProMine project achieved all the main goals and milestones it set out to achieve, and is now regarded by the Commission as an exemplary project giving real meaning to the raw materials initiative which will continue to be a focus of the new Horizon 2020 programme.

Project Context and Objectives:

Context and main objectives

The non-energy extractive industry (NEEI) of the EU-27 has a direct turnover of about €48 billion, and provides employment to about 280 000 people. Moreover, the downstream industries dependent on the NEEI provide a total value added of about 1300 billion and employment for about 30 million people.

NEEI is clearly a significant contributor to the economy of the EU. The use of primary raw materials in the products of other branches of EU industry means they have a central role in guaranteeing industrial and economic sustainability. Nevertheless current demand exceeds production, and so the EU is heavily dependent on mineral and metal imports leading to an annual trade deficit of about €11 billion in 2007. Metallic minerals accounted for 90% of this deficit (€10 billion), while there were also net trade deficits in construction minerals (€456 million) and industrial minerals (€798 million). Europe is totally dependent on imports for some high-tech metals e.g. cobalt, niobium, rhenium, rare earth elements, platinum and titanium. In the development of state-of-the-art technologies and advanced products, high-tech metals have a crucial significance. Also, the demand for critical raw materials could more than triple by 2030.

It is a matter of high importance to put a strong effort in the identification of all the possible resources to be used in the production chain, waste generated and stockpiled in EU as resource stock, establishing an overview of the existing and relevant material flow, and in that way improving competitiveness.

The ProMine project answered the call of the Commission to address the annual 11 billion euro imbalance of imported raw materials into the EU. ProMine was the first large integrating project focussed on raw materials to be financed by the Commission in more than 20 years. As such its success was crucial in underpinning the renewed interest shown by the Commission in European raw materials. ProMine, with 30 partners and a total budget of approximately 18 M euro looked at the whole value chain from raw materials derived at exploitation sites through conversion into nano materials and their application in innovative industrial products. Industrial participation was important both for the credibility of the project, as well as for testing and evaluating the nano-material based end products. The ProMine consortium contained 5 key extractive industry partners from the SMR platform, who together are responsible for 70% of base and precious metal production in the EU, so implementation of results from the ProMine project will translate into direct, and significant economic benefits.
To redress the deficit imbalance of imported raw materials, a number of measures needed to be implemented, including:

- Developing and bringing to market new, high value products based on (nano)scale raw materials (metals and minerals) delivered by the extractive industry.
- Developing better exploitation and production practices on sites using a holistic approach, which includes using all resources, and a more environmentally responsible management.
- Ensuring that all potential resources (known and predicted) within the EU are fully documented and this information is available to the extractive industry in a GIS-based system, and which is clearly linked to the needs of manufacturing industry.

The ProMine project addressed these measures by working on three main themes:

- **Downstream**: Following 5 potential, high value, new mineral-based products from extraction, fundamental research to bench scale, and from these, selected products to demonstration scale, including production, testing and evaluation of these materials, with economic evaluation, life cycle cost analysis, and environmental sustainability, and
- **Upstream**: Developing a GIS-based resource assessment and modelling system for the extractive industry, showing both known and predicted mineral occurrences across the EU, whereby not only metallic but also non-metallic minerals are considered.
- **Upstream**: Demonstrating the reliability of new technologies (including biotechnology) for an eco-efficient production of strategic metals, driven by the creation of added value on site and the identification of specific needs of potential end-users.

Central to these themes, and in accordance with the cradle to cradle approach, is the holistic concept that all solid and liquid materials at an exploitation site are potential useful resources, even those traditionally considered as waste, until no final use can be found. This means that the way a site is exploited becomes environmentally more sustainable, new uses and products can be found for minerals leading to increased profitability, and the dissolved metal emissions and final waste burden will be reduced.

The verifiable objectives of the project were:

- To develop a pan-European GIS-based database containing the known and predicted metalliferous and non-metalliferous resources which together define the strategic reserves of the EU. This includes improving the knowledge at all levels of the location, characteristics, primary and secondary minerals, of the known and potential mineral occurrences in the EU, quantifying their economic value as reserves (proven) or resources (inferred).
- First attempt to evaluate the potential of mining and metallurgical residues, in terms of recovery of valuable products.
- To calculate the volumes of potentially strategic metals (e.g. cobalt, niobium, vanadium antimony, platinum group elements and Rare earth elements (REE)) and minerals which are currently not extracted in Europe.
- To develop the following five new, high value, mineral-based (nano) products, from a range of starting materials in the extractive industry, including testing, demonstration, economic evaluation and LCA, while minimizing the footprint of mining and extraction.
- To develop modern eco-efficient mineral processing and metal recovery methods, including biohydrometallurgy to enlarge the number of profitable potential targets in Europe and to minimize footprint of mining activities.
- To establish a new, cross-platform information group between the ETP-SMR and other platforms with the central theme "what can we offer, what do you need”.
- To exploit and disseminate the project results to stakeholders and industry and public by organizing workshops, conferences, extensive training, and producing demonstration software, publications, CD’s and videos.

The ProMine project developed a more responsible approach to the development, exploitation and use of mineral resources (metallic and non-metallic) in the EU and beyond. The ProMine project aimed to develop new nano-products from raw materials, as well as new technologies of the extractive industries which will have a significant impact on the current deficit in imports. This was achieved by intensive research in mineral processing and production technologies followed from laboratory to demonstration scale. Resource assessment on both a pan European and regional scale will help define new sources of raw materials which can be used in future new products, and through ProMine a methodology for evaluation of raw material for new products.

The research activities of the project were divided into three clusters, with 7 Workpackages (WP) and a number of tasks in order to achieve the main aim of a realistic strategy for reducing the trade deficit, and environmental pressures from the mining and metallurgical industries. The project focused on 4 R&D WPs, supported by an assessment of sustainability and environmental impact, knowledge management, exploitation of IP results and project management. The three clusters were:
Cluster 1 Resource assessment: Compilation of all relevant data carried out in completed and ongoing EU networks, platforms and projects, developing links to ProMine and establishing cross ETP platform between the extractive industry and other ETPs; preparation and surveying test sites, and selection of sites for pilot tests.

Cluster 2 New Products and production methods: evaluation, testing and demonstrating innovative technological solutions, including biological and inorganic treatment of mining waste, in order to generate high value products.

Cluster 3 Sustainability assessment and exploitation: Impact and performance evaluation; integration of results from WPs 1-4 into exploitation plans for the different extractive industries.

In conformity with the objectives of the NMP call, the project targets the overall assessment and quantification of the ore resources in the EU, known and unknown. The project must deliver this information to the manufacturing industry in such a way that there will be an increased awareness of potential raw materials which can be delivered by the extractive industry. The first two clusters were linked in order to achieve this aim. The first cluster gathered a vast range of mineral and other data into an easily accessible GIS, which can model mineral resources in 2D. Detailed studies of 4 mineralised regions were carried out in 4D, leading to predictive modelling and resource assessment. Within each belt a region was chosen in order to cover the most pertinent deposit types. It covered several individual mines or deposits but not the entire belt, and lead to the definition of regions with large potential for further discoveries at depth.

Cluster 1 provided a cross-sector approach for solving resource issues and improving the resource independence and security for European companies both involved in the projects and others. Geological databases and 4D modelling put a strong tool in the hands of raw material suppliers and manufacturers of the final products. A major deliverable from the cluster was an interactive GIS-based database, which will give data on a wide range of mineral and ore occurrences, useful not only for the extractive industry, but also for the manufacturers. When a specific metal or mineral is required, the database can show the geographical location as well as known or predicted reserves. 4D modelling took the resource assessment to new levels of sophistication not seen before in the EU, providing a powerful tool for the extractive and manufacturing industries.

The second cluster developed highly innovative nano-products based on a range of minerals produced by the extractive industries. Each product development was monitored by relevant extractive and end-user industrial partners. The implementation of innovative metal extraction technology, particularly bioleaching, was also be an important topic, as well as the use of secondary minerals in new products. The main objectives for Cluster 2, the crucial technological cluster of the project, were to develop new products and technologies of significant innovativeness on the one hand and wide range of applicability on the other. Direct industrial needs and requirements were addressed. For a sustainable development of a certain product and a long-term production planning, a constant supply of the raw material is of critical importance. The raw materials used in the development of the ProMine project products are minerals or by-products and can also include waste generated during their treatment.

An assessment of the sustainability of the production of the new products, as well as knowledge management and exploitation form the third cluster. Environmental issues including LCA were the focus of this cluster which spotlighted the advantages of the new ProMine products over current market competitors, and which give an added value to the results of the project. Dissemination was a central theme from the first month of the project, since it was clear that in order to achieve success a range of stakeholders had to be informed of the results. A series of stakeholder workshops and mineral markets complemented press releases, folders and fact sheets.

Finally, all the milestones for the project were approved by the industrial partners.

Project Results:

Pan-European mineral resource databases and data interoperability

The purpose of Work Packages (WP) 1 and 2 was to deliver interactive GIS tools to define new reserves of strategic minerals in the EU, that the extractive industries can quantify and exploit in the future, and which will be the source of raw materials for the manufacturing industries. The objective of WP1 was to develop a Pan-EU GIS data management and visualization system for natural and man-made mineral endowment and the realization of a Pan-EU predictive resource assessment. In order to reach this objective, WP1 produced a pan-European database of primary mineral resources (including new strategic and 'green' commodities such as Ga, Ge, In, Li, Nb, Ti, Ta, PGE and REE), the ProMine Mineral Deposit (MD) database, and a pan-European database of secondary mineral resources (concentrations related to mining and downstream activities), the ProMine Anthropogenic Concentration (AC) database. These
Databases serve the development and feeding of a homogeneous multi-layer information system covering the whole European territory and including mineral deposit, anthropogenic concentration, geological, structural and geophysical layers.

The MD database stores all the information related to mineral deposits in Europe. Each deposit is described through about 40 fields, distributed into 8 categories. Most fields that contain text values (i.e. non-numerical) are lexicon guided, in order to improve efficiency of data querying. Lexicons are either a simple list of predefined values, or hierarchical (tree-like list with father/son relationships) allowing to store critical information according to its level of accuracy. The 8 categories and main fields they contain are the following: (1) General information, incl. status, owner, location; (2) Deposit information, incl. deposit type and morphology; (3) Information on mineralization and host rocks, incl. age of mineralization and host rock, mineralogy of the ore, gangue and hydrothermal alteration, host rock formation name and lithology; (4) Economic information, incl. the exploitation type, and per commodity and ore type, former production, reserves, and resources with associated grades; automatic calculation of the metal potential per commodity; (5) High-tech metals with per commodity the characterization of high-tech metals hosts (mineralogy, grade, abundance); link with the AC database; (6) Comments (free text); (7) Iconography, including photographs, sketch maps, cross-sections, etc. and (8) Bibliography, i.e. main geological and economic references related to the deposit.

The AC database stores all the information related to anthropogenic concentrations. Each site is described through about 35 fields distributed into 6 categories: (1) General information, incl. status, owner, location and the list of processing that have been implemented on the site. From this folder a link with the MD database can be created, allowing identifying which deposits fed the site. (2) Information on wastes and products incl. the type of storage, the type of waste, the mineralogy, estimation of volume/tonnage, the type of commodity available and the grade, with automatic calculation of potential resource, per commodity, at the site scale and the type of environmental impact; (3) The environmental aspects, with per environmental impact, the type of environmental pathways and receptors, the type of water treatment and the description of the type of restoration used. The three last categories – Comments, Iconography and Bibliography - are identical to those of the MD database.

The final version of the MD database, contains 12,979 records (mines, deposits, occurrences or showings) and covers 34 European countries. The total number of records of the AC database is 3,408. As an exhaustive inventory was far beyond the scope of the project, ProMine focused on major anthropogenic concentrations and on the most interesting in terms of volume/tonnage and content (i.e. possible presence of strategic metals).

The main objective of Work Package 1 was to help improving assessment of mineral resources in Europe. Elementary statistics calculated on both databases, such as the endowment (in other words the global mineral budget of a deposit, incl. past production, reserves (not incl. production) and resources (not incl. reserves) allow to get some insights on European metallogeny. European endowment was calculated per commodity for precious metals, base metals, iron and ferro-alloy metals, speciality and rare metals and also for the 14 critical mineral raw materials identified for EU by the European Commission, Enterprise and Industry Directorate General. The database content also allows statistics calculation on the main metallogenic types present in Europe and their contribution to EU mineral budget and more geological approaches such as the temporal distribution of commodities.

In order to display and to deliver data through the Internet, a web portal was developed. The ProMine portal architecture is based on OGC principles related to open architecture and interoperability:

- the data and the layers are described by their metadata (according to the ISO 19115 standard and to the INSPIRE rules) registered into a catalog connected to the ProMine portal;
- the data and the layers are delivered thanks to OGC services:
  - a WMS (Web Map Service) to deliver the layers,
  - a WFS (Web Feature Service) to deliver the data according to the standard data model EarthResourceML developed by the IUGS/CGI (International Union of Geological Sciences / Commission for Geoscience Information).
- a mapping between the data stored in the ProMine databases and standard data models like GeoSciML for geological information contained in MD & AC databases and EarthResourceML for mineral deposits and mines and mining wastes has been implemented to deliver the data according to these international standards.

The ProMine databases, presented herein, are a significative outcome from the EU co-funded ProMine project and a crucial step toward...
better assessment of primary and secondary resources in Europe that, in turn, will strengthen the extractive industry and help secure European supply in mineral resources, including critical and “green” commodities. The MD dataset particularly is a new homogeneous and thorough dataset, containing a considerable amount of information that allows, from now, mineral resources potential and predictive assessment studies that were not possible so far. The ProMine portal complies with the most recent directives in terms of data visualization and delivery and it establishes a core knowledge on which new EU-FP7 projects (e.g. EURARE, Minerals4EU) can lean to go farther.

Pan-European mineral resources potential and predictive mapping

The purpose of Work Packages (WP) 1 and 2 was to deliver interactive GIS tools to define new reserves of strategic minerals in the EU, that the extractive industries can quantify and exploit in the future, and which will be the source of raw materials for the manufacturing industries. To achieve this objective, ProMine WP1 partners have – amongst other tasks - developed a pan-European homogeneous database of known showings, occurrences and deposits that covers the whole European Union, the Mineral Deposit (MD) database. The next step was to valorize the knowledge contained within this database by using it to identify 1) the areas of high mineral resources potential, and 2) the areas where new mineral resources could be discovered. This was done with several types of data processing which produced sets of potential and predictive maps.

Maps of mineral resources potential

The goal of potential mapping is to identify areas of high mineral resources potential, based on the distribution and size of known mineralization. As the MD database contains a very large number of deposits of various characteristics (type, size, contained commodities, etc ...), a first work was to “group” deposits on the basis of their contained commodities and/or types. 16 deposits “families” or groups were thus identified and extracted from the MD database. From each of these 16 homogeneous populations of deposits (based on commodity association), a single map of mineral potential was calculated. The methodology was set to couple 1) a statistical study of the spatial distribution of deposits (kernel density in a first stage), 2) geological constrains, by selecting lithology polygons containing deposits of the selected population and 3) the introduction, as a weight, of the size (class of the main commodity) of the deposits. 16 potential maps were thus produced to get a representation of the mineral potential of the 16 selected metallogenic types. The interest of such a methodical approach is that it is reproducible, whatever the type and the density of deposits. These maps will be presented, with a special focus on selected. They show how the continental scale distribution of known mineralization described within the ProMine MD database is consistent with the regional geological and tectonic context. This point confirms the reliability of the database, and its scientific value for further studies.

Maps of mineral resources predictivity

The goal of predictive mapping was to identify areas where unknown mineral raw materials could favorably be discovered. Methodologies used for the calculation of mineral predictive maps vary depending on the fact that the studied commodity is a main element in the deposit or a by-product. Up to now, a very large majority of predictive studies dealt with a relatively low number of elements which are the main commodities in their deposits and/or which belong to the main paragenesis (for instance, copper or gold in porphyries). However, ProMine project bears a great attention to strategic and critical commodities – and especially to the 14 critical raw materials identified by the European Commission - which may or may not be the main commodity within a given deposit.

In practice, these strategic or critical commodities may either be 1) the main commodities with a proper mineral expression in mined ores (e.g. W, Sb, F, Sn ...) or 2) commodities which are by-products from mining (e.g. Ge, In, Ga, Ta ...). As a consequence, predictive method needed to be adapted to consider both possibilities. In the present work, we used, for the first case, a geographic prediction method (Weight of Evidence, or WofE) and, for the second case, a database querying method. The WofE method was applied to geographically predict favorable areas for tin, tungsten, antimony, fluorite, copper and a selection of lead-zinc carbonate-hosted deposits. The same data processing was used for all these commodities. WofE was performed within Arc SDM software, using lithostratigraphic code as evidential theme and commodity occurrences as data set. Other evidential themes or combinations of evidential themes have been tested, but yielded more debatable results.

The database querying method was applied to explore the relationships between descriptive fields of the database, and to predict among the 13,000 deposits those possibly containing cobalt, gallium, germanium, indium and tantalum. Based on their relationships with deposits containing the considered commodity, favorable deposits of the database were selected and ranked relatively to their
This work led to the production of 16 mineral potential maps and 11 mineral predictive maps (6 by geographic prediction, or WofE method and 5 by database querying method). All these maps cover the whole Europe and constitute the first pan-European mineral potential and predictive map coverage in Europe. They have been included in the ProMine web portal and can be freely accessed.

3D/4D modeling, principles

The 3- and 4-dimensional modeling work package (WP2) of Promine has for the first time in Europe addressed the issue of pan-European three and four dimensional geological models as a basis for mineral exploration and extraction under cover. The work package has been developed to address the geological modeling not only in deposit scale but also in semi-regional (near mine) and regional (mineral belts) scales. The models that have been established cover four major mineral belts in Europe: Skellefte-Vihanti-Pyhäsmälki in Fennoscandia, Forsudetic monocline in Poland-Germany, the Iberian pyrite belts and the Ozza Morena zone in Spain-Portugal and the Hellenic belt of northern Greece.

The work flow in the project have been as follows:

1) Establish a common database structure for 3D geological data
2) Build 3D models based on the database structure
3) From the 3D models combined with the understanding of the geological evolution (time) develop 4D models for the different belts
4) Based on the 3- and 4-dimensional models derive predictive models in 3-4D for the mineral belts.

The database structure for the 3D data was developed by TU BAF. This also constituted the first deliverable of the work package and the concept also led to a spin-off company now developed by former students from TU BAF. ProMine adopted the data model for a 3D Geoscience Information System GISTriX compiled previously by the Geoscience Mathematics and Informatics Group of TU BAF. GISTriX is a fully-edged information management system for 3D geoscience data and geo-models with spatial and non-spatial query functionality necessary to analyze and interpret 3D data and models. It has plug-in for the 3D modelling software "gOcad 2.0" which will be the primary modelling software of ProMine, and is able to combine logical operators with topological, geometrical and non-spatial queries. Its 3D GIS architecture combines modelling system with 3D GIS functions, data management using XML database server and spatial query computation supported by application server.

The three-dimensional modelling had the aim to build three-dimensional geological models of the crust down to mineable depth, typically upper 2 000 m, in the involved mineral belts in Europa. The modelling was carried out primarily in the gOcad software. Modelling was also done in the software i.e. GEMCOM Surpac. The concept of compiling the 3D models were different in the different mineral belts mainly due to different geology, different availability of geophysical data, different spatial resolution of data and different access to data. The basic principle for the modelling was to combine geological information from the surface, drill cores/holes, underground exposures with geophysical data, both airborne, ground and drill hole measurements. By using this data in an integrated manner surfaces (faults, geological boundaries, shear zones etc.) and volumes (rock units, alteration zones, mineralization etc.) could be constructed in three dimensions.

Normally all existing and acquired data was imported and visualized in the gOcad software package. To simplify modelling workflows the regional scale modelling volume was split up into several semi-regional scale sub-projects. For each sub-project available data was imported in form of maps and cross-sections into gOcad. In the models drill holes can be visualised as lines with attached lithological information. Structural measurements can be displayed with real 3D orientation. The regional models have been developed also by simplify the geological parameters to enhance the “readability” of the models. For some belts we also developed uncertainty models. As an example the final 3D-model of the Skellefte district uncertainty values from one to four for the relevant regions on the 3D-objects have been assigned and colour-coded. The assigned uncertainty values represent: 1) Observed in field, mine or drill-core; 2) Interpreted from geophysical data; 3) Interpreted from structural data or extrapolated from geophysical data, and 4) Inferred / unknown.

Subsequent 4D-modelling added the time aspect to the 3D-models and aimed at visualizing the geological history in the district and as a support for ore targeting. Four-dimensional modelling was carried out utilizing the MOVE software package in the Skellefte district. The 4D-model shows schematically the formation of listric and related transfer faults, the formation of volcanic and sedimentary rocks and VMS deposits during crustal extension. Furthermore, the subsequent deformation of rocks and transposition of ore bodies and the effect of different block-rotations, subsequent erosion and deformation between the neighbouring fault-bound compartments and the
tectonic transposition of the ore bodies were illustrated. A different approach, due to geological conditions, was used for the Forsudetic monocline. Here the 3D model was restored and decompacted using the surface Kine3d gOcad plug-in. Temperatures, pressures, hydro-fracturing probabilities, oil and gas maturation during the burying history had then been reconstituted using the PetroMode 1D software.

Three-dimensional predictivity maps were the final deliverable of the work package. We used some different principles for the predictive models. In the Skellefte district, in order to visualize the predictivity for VMS deposits, values from one to five were assigned on the relevant regions of the model, based on the correlation between distribution and shape of VMS deposits, and regional deformation patterns. Another interesting approach was used for the Kupferschiefer area and expansion to a pan-European potential map of reserves in copper and base metals associated to Kupferschiefer in Central Europe. This predictive model was built using geological, structural and geo-variable descriptive predictors. Several predictive methods were compared including the Support Vector Machine (SVM) and the Logistic Regression Method (LRM). The SVM gives the best results. It is a supervised learning algorithm developed in statistical learning theory for classification. It searches an optimal hyper-plane in the multivariable space for separating groups. It comprises an initial phase on training dataset (here deposit from non-deposit classes), followed by a predictive phase. The free R package e1071 were coupled to gOcad using a gOcad Python plug-in for this purpose.

The results from the three- and four-dimensional modelling in Promine are very promising. We have shown that it is possible to build robust three-dimensional models of major mineral belts and by using different approaches it is also possible to carry out four-dimensional modelling to help exploration industry with better targeting. The three-dimensional predictive models for the mineral belts clearly show the potential of undiscovered resources in the various parts of Europe. Thus, the Promine project, with respect to the aims of WP2 to improve the knowledge base and resource base for majors as well as minor commodities, has fulfilled its goals. The results from the modelling in the Promine project is a proof of concept, and serves as a baseline study for future, more full scale, pan-European projects that could be developed, for instance, in the EIP on Raw Materials.

Geological multi-scale modeling of the Skellefteå and Vihanti-Pyhäsalmi districts

A multidisciplinary three dimensional modeling project was conducted on the Pyhäsalmi - Mullikkoräme mine camp located within the much larger Proterozoic Vihanti-Pyhäsalmi mineral district of Central Finland. The aim of this research was to predict and assess the exploration potential of Zn-Cu VMS type of mineralization in deep zones around the existing base metal mines and deposits. The Pyhäsalmi-Vihanti district has an active underground Zn-Cu mine that operates up to a depth of 1450m below surface (Pyhäsalmi mine), and several other minor deposits and base metal occurrences. Mullikkoräme is a small VMS deposit that was mined up to a depth of 600m located 8km from the Pyhäsalmi mine. The study focused on the development and test of new exploration tools and methods for detecting and predicting concealed massive sulphide ore bodies at depths greater than 600m and up to 3000 m below surface. The initial work consisted of identifying petrophysical and chemical attributes of the ore host rocks in order to characterize and make 3D models of the ore horizons. Such models were extended into new and deeper areas by interpreting data obtained from deep penetrating geophysical methods.

Lithogeochemical studies were very successful at defining the key criteria to characterize the ore horizons, and structural data obtained from oriented core measurements was an effective tool for the initial 3D delineation of such horizons. The lateral and deep extensions of the ore horizons were identified by the interpretation of data sourced from deep penetrating geophysical surveys (reflection seismics and magnetotellurics) and exploration drilling. A new mineralized horizon was found. Two small pilot studies were conducted as Master's projects on the Pyhäsalmi-Mullikkoräme area, the first study tested the lithogeochemical techniques in the Pyhäsalmi deposit and a second study covered the 3D modeling of the Mullikkoräme area. In addition, a PhD project focused on the use of reflection seismic data for VMS exploration. These studies were directly coordinated and supervised by Pyhäsalmi geoscientists, and the results contributed to better understand the area.

The semi-regional 3D model of the Vihanti area shows uplifted granulites and pyroxene granites in the east, migmatized mica gneisses in the north, gently folded intermeditated to mafic volcanic rocks in the central area, voluminous intrusive rocks in the south and west and the lowermost unit, which has been modeled as granulitic paragneisses. From the seismic sections it is evident that the latest SE-NW faulting has moved the blocks in vertical directions affecting the ore continuation. In addition, based on the seismic surveys there seems to be an older fault between Vihanti and Kuuhkamo deposits dipping to the southeast.

The Skellefte district in northern Sweden is a Palaeoproterozoic mining district with at least 85 known volcanogenic massive sulphide (VMS) deposits and several orogenic gold mineralizations, spread over an area of approximately 30 by 120 km. There is a large
potential for future discoveries as indicated by the recent results of mineral exploration by Boliden Mineral and by prospectivity analysis. In the course of the ProMine project detailed regional and semi-regional scale field mapping and associated structural analysis were carried out. The theory of basin inversion during crustal shortening was tested and validated by 2D-forward modelling with MOVE by Midland Valley Exploration Ltd. Combined with sedimentary facies analysis and structural analysis with geochronological studies a conceptual model for basin inversion in the central Skellefte district was developed. For the deposit scale model abundant near-mine drill core data, level plans and cross-sections were available from Boliden Mines. In addition to geological investigations, existing geophysical data were incorporated into the model, including 142 km of seismic reflection lines along six profiles and 120 broadband MT sites along six profiles and a 3D grid. Geophysical semi-regional scale modelling in the central Skellefte district utilized electrical, potential field and petrophysical data.

The goal of the ProMine project within the Skellefte district has been to develop the currently increased understanding of the crustal structure into regional and semi-regional-scale 3D models. Including the VMS-deposits in the regional 3D-models will enable a correlation between the occurrence of the deposits and the major geological features, in particular the shear zones and faults. Furthermore, constraining the shape and orientation of each individual deposit allows correlation of the style and intensity of regional scale deformation structures with the shape of the ore lenses. These correlations are positive throughout the district and are therefore used in prospectivity mapping and exploration.

Subsequent 4D-modelling added the time aspect to the 3D-models and aimed at visualizing the geological history in the district and as a support for ore targeting. Four-dimensional modelling was carried out utilizing the MOVE software package. The 4D-model shows schematically the formation of listric and related transfer faults, the formation of volcanic and sedimentary rocks and VMS deposits during crustal extension (Skyttä 2012). Furthermore, the subsequent deformation of rocks and transposition of ore bodies and the effect of different block-rotations, subsequent erosion and deformation between the neighboring fault-bound compartments and the tectonic transposition of the ore bodies were illustrated.

A pan-European Potential Map of Reserves in Copper and Base Metals associated to Kupferschiefer in Central Europe

Advanced modeling technology including 3&4D are now helpful in exploring old matured mining fields. The pan European potential map of reserves in copper and base metals associated to Kupferschiefer at the Zechstein basis in Central Europe is an illustrative example which has been studied during the ProMine European project.

A regional scale 4D reconstitution of the North German-Polish Depression was undertaken to better understand the formation, burial, deformation and natural hydro-fracturing history of the intra-basin sediment-hosted ore deposits in the Kupferschiefer, at Lubin in South West Poland. More than 270 wells coming from the mining exploitation of the Kupferschiefer, cross sections from seismic exploration and geological maps were used to build a 3D model of the present mining. This 3D model of the Lubin Kupferschiefer, was then restored and decompacted using the surface Kine3d Gocad plug-in. Temperatures, pressures, hydro-fracturing probabilities, oil and gas maturation during the burying history had then been reconstituted using the PetroMode 1D software. Conditions for hydraulic fracturing were identified at the base of the Zechstein formation, and during the inversion phase at the Late Cretaceous-Early Paleocene time. This Late Cretaceous up-lifting yields the conditions for hydrothermal recirculation of mineralizing brines explaining the location of Cu (Cu-Ag) sulfides ores in the area. The Zechstein evaporite series seems to have played an important role as an impermeable cover confining the hydrothermal fluids in the lower Zechstein series. The 4D restoring-decompacting modeling allows reconstituting the burial, deformation and natural hydro-fracturing history of intra-basin sediment-hosted ore deposits. In the Lubin region, the obtained results show a good agreement between the spatial hydro-fracturing index and the emplacement of the Cu (Cu-Ag) sulfides exploited today.

Based on the results obtained on the Polish area, a pan-European potential map of reserves in copper and base metals associated to Kupferschiefer in Central Europe was built using geological, structural and geo-variable descriptive predictors. Several predictive methods were compared including the Support Vector Machine (SVM) and the Logistic Regression Method (LRM). The SVM gives the best results. It is a supervised learning algorithm developed in statistical learning theory for classification. It searches an optimal hyper-plane in the multivariable space for separating groups. It comprises an initial phase on training dataset (here deposit from non-deposit classes), followed by a predictive phase. The free R package e1071 were coupled to oGocad using a gOcad Python plug-in for this purpose. The training dataset comprises the location of the known and not known deposits together with the predictive geo-variables available at the base of the Zechstein such as the Zechstein and Rotliegend thickness, the pre-Cenozoic faults, the Rote Fäule and high Pb and Zn concentrations, the Moho depth, etc. The training areas were selected in the Polish Lubin region.
Two types of predictions are distinguished: areas where the surface density content of Cu is greater than 10kg/m² and areas where the surface density content of Cu is comprised between 2 and 10kg/m². Most of the known mining areas are predicted by the SVM, referred to on the map by numbers. Some of them, not known before the study, were rediscovered by the SVM method such as in the area of the Graben of Schneverdingen, where old drilling works indicated locally copper. This gives confidence in the reliability of the method. Other big areas, especially in Germany and in the West of Poland are pointed out as potential rich copper zones (> 10kg/m²), while several large areas appear to have potential but with lower copper content (< 10kg/m²).

This study shows that huge potentials in copper still exist in Central Europe in the Kupferschiefer formation. The richer part (> 10kg/m²) is equivalent in size of twice the tonnage of El-Teniente (Chile), one of the biggest porphyry copper deposits in the world; while the less rich part is equivalent to five El-Teniente deposits. Given the total annual production of copper, silver and rhenium, it is possible to estimate the ratios Ag/Cu (resp. Re/Cu), and therefore the quantity produced per each ton of copper metal extracted. All the pointed potential areas are not equivalent in terms of availability as their depths vary largely from 1,500 to 3,000m. At such depths classical mining techniques are not feasible at present for technical and economic reasons. However, new advanced technologies can be envisaged to recover the metal from the surface using in-situ bioleaching, a technological challenge for Europe to restart mining industry.

3D, 4D and predictivity modelling in Ossa-Morena Zone and Iberian Pyrite Belt

Ossa-Morena Zone (OMZ)

Two local models have been built: Aguablanca mine as representative of Ni-Cu-PGE orebody and Cala mine depicting a Fe-Cu mineralization. A semi-regional model of ca. 400 km² comprising Cala area illustrates the surrounding geology of both mines. As previous information needed for the modeling process we improved available geological cartography, and structural knowledge, collected 421 rock samples of geochemical and petrophysical analysis, reviewed airborne high resolution radiometric and magnetic previous data and carried out a gravimetric field survey. Those field works were especially intensive on Santa Olalla Plutonic Complex which is related to the two aforementioned ore bodies.

Mine available information (drill holes, detailed cross sections and horizontal slices) were used to build the Aguablanca mine ore body provided by Lundin Mining. Up to 17 cross sections were used to construct the Cala semi-regional model taking into account the new geological collected data. Gravimetric and magnetic interpretation helped to calibrate 9 out of the 17 cross sections, that establish the framework of the gOcad 3D model. They were translated to 3D pdf format in order to load them into the 3D database. 4D shows the intrusion sequence of the different plutonic bodies. Another video shows a wide regional common history with the IPB.

Regarding predictivity mineral resources (i.e. Fe) and processes of mineralization: the common assumption that deposits are related to major intrusions or shear zones is today under debate. One of the outputs of the project after a detailed rock geochemical analysis of different mineralizations shows significant differences of composition (i.e. U contents). That drives us to establish a generic searching rule: prospectivity areas are those close to igneous intrusions, or skarn zones affected by contact metamorphism, and displaying positive gravity and magnetic anomalies, in conjunction with U signatures. Unfortunately, the intensity of anomalies is not a reliable indicator of the amount of reserves of unexplored ore bodies. Mine areas produce the following reserve numbers: 26.1 Mt (proved) and 90Mt (estimation) of Fe-Cu for Cala mine and 15,2Mt of Ni-Cu-PGE for Aguablanca mine. The major predictivity output comes from the radiometric, gravimetric and magnetic surveying and petrophysical characterization of rocks. A possible future research mining area is located in at east of the Santa Olalla Plutonic Massif depicting strong anomalies in the maps of the different described parameters. According to the collected data, another one arises at the north of Teuler Pluton.

Iberian Pyrite Belt (IPB)

Rio Tinto belongs to the north style of mineralization. A result of the Promine Project, a 3D model of the Rio Tinto mine district was build. It covers 88 km². Previous data of the 3D model includes a new geological map of the Rio Tinto area (latest dates from the twenties of the last century), 175 rock samples, reviewed radiometric and magnetic previous data. A new gravimetric field campaign fulfills previous ones. Old exploration wells were reviewed provided by EMED Tartessus. Detailed work was made on the Rio Tinto anticline where the historic ore bodies are hosted.

A local 3D model of the ore bodies is build upon a filtering (300) of about 7000 historical documents. Semi-regional 3D model is based on 44 geological cross-sections with a geophysical control on 10. Both models were translated to 3D pdf format in order to load them
into the 3D database. Two 4D models were made. One makes a restoration of the Rio Tinto area using GoCad software and a general one previously cited.

Predictivity can be guessed taking into account the two styles of mineralization. Estimated tonnage is ca. 1937Mt. Assuming that the two metalotecs are well explored, it is unlikely to discover new ones above 800m in depth from the known ones or 200m away through other directions. Thus, the amount of undiscovered massive sulphides is ca. 1.7 Gt in the southern part and 2.1 Gt in the northern part. These estimations include both massive sulphides and stockwork zones.

Unlocking the exploration potential of northern Greece

The Hellenic-Balkan metallogenic belt was formed along the southern margin of the Eurasian plate during Mesozoic-Cenozoic time. Modern structural data indicate that the Rhodope and Serbo-Macedonian zones are products of Alpine convergence between Africa and Europe during Cretaceous to Tertiary time, which led to the formation of a metamorphic core complex and silicic to intermediate magmatism. Greece’s geology favors a potent and dynamic occurrence of mineral resources. Among the Non-Energy Metallic Minerals commodities, base and precious metals, in particular zinc, lead, copper, gold, and silver are becoming an increasingly important and rapidly growing target of the mining industry. In NE Greece, where most of the potential resources and feasible deposits are hosted, gold-polymetallic mineralizations occur in a wide range of genetic types. The mineralization potential is consisted of magmatic porphyry copper type deposits, hypothermal/mesothermal manto-type polymetallic sulphides and epithermal gold systems.

Through 3D/4D model applications, new metallogenic interpretations and exploration perspectives were achieved in relation to geologic and structural settings, stratigraphic and tectonic evolution, ore bodies form and extension imposed alteration zones, ore grades distribution and genetic links between the spatially related porphyry and manto-type systems, based on airborne geophysics, along with further interpretations for crossborder regional exploration and prospecting potential.

The 3D/4D models showed they can be very useful tools for improving the knowledge of ore deposition and be able conducting successful mineral exploration in order to outline new potential areas. The 4D models were incorporated into local exploration as they proved to be significant in identifying new potential mineralization targets.

Predictive studies were carried out at:

- Deposit scale (outlining areas with considerable potential of extending ore bodies including exploration drill holes)
- Local scale (the knowledge derived from the deposit and local scale 3D models contributes to defining new exploration potential targets)
- Semi-regional scale (predictive maps were approached using the knowledge obtained through 3D modelling at deposit, local and semi-regional scales and areas with common characteristics were selected as new exploration targets), and,
- Regional scale (using metallogenic data and related mineral districts based on ProMine databases, a prospective province for potential epithermal gold, porphyry copper-gold and replacement polymetallic deposits was identified).

Using existing and new geo-data on Greek mineral wealth, a multi-layer Geographic Information System was created. The system includes databases on mineral deposits and anthropogenic concentrations (mining and metallurgical residues, by-products etc) along with relevant geological, structural, geochemical, geophysical layers and other information from a diverse range of sources. Based on the databases information the following maps and products were created and delivered:

- Greek Minerals database
- Deposit types of Metallic Minerals map of Greece
- Metallogenetic districts map based on ProMine classification
- “Hot” Metallic commodities map of Greece
- Greek Anthropogenic Concentrations database
- Mining waste deposits map of Greece upon Promine classification
- Map of high potential areas for Au, Cu, Pb-Zn-Ag, REE and Ni discoveries

New rhenium-based products for demanding applications
Rhenium is one of the rarest elements in nature, its content in the Earth's crust is estimated at the level of 10-7%. It is mainly extracted from copper-molybdenite ores which are excavated for their copper content. A large part of primary rhenium is recovered from dusts and gases generated in molybdenite roasting plants. World rhenium resources are said to be at the level of 11-17 thousand tons and its production in 2012 was about 60 tons. In its solid state rhenium is a ductile material, presenting high hardness, high melting point (3,180 °C) and density (21.0 g/cm³). Because of its specific properties rhenium is applied in: production of heat-resisting alloys – used in heating components of electronic equipment and in production of superalloys – of high mechanical and thermal strength, applied in manufacture of rocket engine nozzles and rotating components in aircraft engines as well as in energy equipment.

Installations for the recovery of rhenium in the form of ammonium perrhenate(VII) from two acid waste water streams with an annual capacity of about 8 ton, have been operating in Poland since 2007. The majority of this product is processed by KGHM Ecoren S.A. sole European rhenium producer from its own resources, into pellets of metallic rhenium and sold to the manufacturers of superalloys. The main reason behind starting research work by IMN and KGHM Ecoren S.A in the Prominie project was to broaden the assortment of rhenium-based components produced in Poland.

The requirements for the new product were defined and specified by the industrial partner, i.e. KGHM Ecoren with an objective to make new product attractive for end-users and Ecoren customers. The specification was also used in verification of the project results.

The most valuable rhenium containing sources were identified in the Polish copper industry. Rhenium content in the Polish copper concentrates is at the level from 5 to 15 ppm. The concentrates are processed by KGHM Polska Miedz S.A. in three copper smelters, i.e.: Glogow I smelter, Glogow II smelter and Legnica smelter.

In the technological development of innovative products several methods were tested, such as solvent extraction and ion-exchange methods.

In the result of the studies technologies for production of two types of materials were developed:

- spherical metallic rhenium powder
- rhenium-based alloys with addition of about 14% of Co and Ni

When compared to the powder of irregular shape the spherical powders are characterized by higher density, better liquidity and higher chemical purity which is important when making coating on surface of other materials.

The spherical powder was produced by powder metallurgy methods with application of the following processes: reduction, sieving, plasma sparying. Ammonium perhhenate NH4ReO4 was used as the raw material. After reduction metallic rhenium powder in a “frayed” form of grains was produced, which was then sieved into fraction below 100 μm and plasma spraying was applied. In plasma spraying the irregular grains were introduced into plasma arch of temperature of several thousand degrees centigrade where they melted down and took sperical form in the result of surface tension.In the result high purity and density (over 20.1 g/cm³) metallic rhenium of spherical grains was produced.

Within the scope of the project also complex technologies for production of Re-Ni, Re-Co alloy powders in a form of pellets were developed. The products have lower melting point, which can result in lower smelting temperature and, consequently, reduction of rhenium loss. Another important advantage of that solution is a possibility to abandon application of nickel in a carbonyl form, which is very harmful for human health and natural environment and constitutes the main compound in which nickel is introduced into the superalloy. Ammonium perchhenate was used for production of high purity perchhenic acid of Re concentration 300 900 g/dm³ with application of strongly acidic cation-exchange resin. Sorption of nickel/cobalt from acidic sulfate or nitrate solutions and then elution with aqueous perchhenic acid solution resulted in production of Ni/Co perrhenates, which were then concentrated and dried to produce the anhydrous nickel perchhenate which contains up to 66,6%Re and 10,5%Ni, and the cobalt perchhenate which contains up to 66,6%Re and 10,5%Co, and up to 100 ppm of non-metallic impurities in each product. The developed technologies represent the most modern generation methods as all the solid and liquid waste is utilized, while the produced components are of high purity, produced at very high, over 95% efficiency and without any loss of valuable metals, such as rhenium, nickel and cobalt.

The nickel perchhenate and cobalt perchhenate powders were then reduced in hydrogen atmosphere of tubular furnace and the produced powder was comminuted and subjected to cold pressing operation into a form of pellets. The compacts were then sintered in hydrogen atmosphere to produce Re-based alloy materials with 14 % content of nickel and cobalt, respectively. Both produced materials showed
neither defects nor cracking.

The developed technologies were tested in pilot installations of capacities about 1 kg of ReNi/ReCo in a form of pellets and about 1.2 kg of ReNi/ReCo in a form of powder (without consolidation and sintering) per week, and about 100 g of spherical rhenium powder per week. KGHM Ecoren's specialists confirmed very good parameters of spherical rhenium in comparison with metallic rhenium produced by Ecoren commercially.

Ecoren contacted its customers, such as Rolls Royce, GE Aviation, Cannon Muskegon, Starck, Heraeus, Pratt& Whitney, Johnson Matthey, Siemens, Polish Aeronautical Technology Platform for testing of the products in their final applications.

Nanosilica for use in construction materials

In the earlier phases of ProMine, the S&T focussed on the production of a high purity nano-silica based on the dissolution of olivine, a magnesium silicate industrial mineral, in acids. Two years of experimental laboratory work was needed to optimise the process and conditions of the chemical reaction process, and was carried out by TU/e and SELOR. From initial small scale experiments the process was scaled up to a larger reactor system. These bench scale tests not only gave the first proof of concept, they produced small (200 gram) samples which could be used for characterisation by SELOR, and initial testing in cement pastes as a precursor to testing in construction materials.

While this work was going on in the Netherlands, Grecian Magnesite, supported by IGME-GR was looking at ways to optimise the production of a high quality olivine concentrate from the olivine bearing rocks of Gerakini in Northern Greece. Lab scale tests were used to develop a flow sheet for the crushing and grinding of the raw material, followed by mineral separation using an optimised mixture of techniques. This enabled Grecian Magnesite to produce a concentrate of 800kg of olivine which could be used in pilot scale testing.

Although not a deliverable in the project, SELOR established a pilot unit capable of producing batches of 100kg of nanosilica in the Netherlands, which produced the first batches of ultra pure nanosilica. This was a major achievement in the project, and TU/e provided essential support in this activity. The material was fully characterised and shown to be of the same quality as the most expensive nanosilica on the market, but with a production price estimate, based on data from the pilot, far lower than commercial competitors.

Extensive modelling of mortars and concrete mixes was performed at TU/e, in order to understand the behaviour of nanosilica in construction materials. This involved making different test samples, which were then subjected to a range of standard tests for construction materials which could show that materials meeting the technical requirements in buildings could be produced. The activities performed include: a) study of the dispersibility behavior of OnS particles in water (viscosity of the dispersion and selection of stabilization agents), b) study of the effects of admixtures on cement/nano-silica pastes applying rheometric tests to assess changes in the viscosity caused by the volumetric substitution of cement. These rheological tests were complemented with isothermal calorimetric measurements and standards mortar compressive strength test, c) tests on mortar level were carried out using standard sand, cement and different commercial nano-silica to study the effect on the behavior in fresh state (slump changes) and to determine the pozzolanic effect of OnS on the compressive and tensile splitting strength, d) test to determine the water demand and the workability on mortar scale of the OnS were performed (water layer thickness validation), e) experiments were performed to determine the maximum amount of OnS to be used as cement replacement in normal (vibrated) and self-compacting concrete (SCC). Finally, based on the SCC laboratory test results the potential reduction in the CO2 footprint of concrete was estimated.

The first small blocks of nanosilica cement were exhibited at the 2012 Green Expo in Tokyo, on the ProMine stand, and received a lot of interest from viewers.

A major deliverable of the ProMine project was to demonstrate the production of nanosilica from local mined and quarried materials at a model site of the project. This site is the Stratoni mine owned by Hellas Gold in Northern Greece. The aim was to use acid produced by the mining process with the olivine concentrated from rocks processed by Grecian Magnesite at Gerakini. In December 2012 staff from SELOR and TU/e made a field visit to Stratoni to train the local staff and help them to start up the pilot which they had constructed. This transfer of knowledge was successful, and now the Hellas Gold pilot is operating under their own control, and producing nanosilica.

Nanosilica samples (50kg) were provided from the SELOR pilot and also from the Hellas Gold pilot for end user testing. This was done by partner Kijlstra Beton, based in the Netherlands. The results were presented in the final ProMine meeting in Levi, in April 2013.
The work on the optimisation of nanosilica in construction materials is still incomplete. A number of technical issues have been identified by TU/e which shows there is a need for additional research, which is being undertaken by TU/e and SELOR.

One issue is the agglomeration of the nanoparticles, a naturally occurring process during the reaction. In order to maintain the required grain size, the process must be adjusted to deliver the silica in an optimal way. This research is ongoing by SELOR. The other issue is the dispersion of nanosilica in the mortar and cement mixture, since a homogeneous distribution is essential for the performance of the finished product. The work to achieve this is now being carried on by TU/e. No other partners are involved in these two lines of research which will go on past the end of ProMine.

Summarising, the following steps in the production of olivine silica will be:

1. Formulate stable of colloidal suspensions of olivine nano-silica for its application in concrete.
2. Study the effect of the packing optimization in the fresh and hardened properties of mortar with different nano-silica additions. (Olivine silica vs. Commercial).
3. Modify the concrete mix design model/optimization algorithm taking into account a water film, esp. relevant for nano particle additions.
4. Wet packing tests using rheometric techniques will be performed.
5. Design and testing at mortar and concrete level different recipes (VC and SCC) incorporating nano-silica produced by olivine dissolution in acid (laboratory and pilot scale).

Nanosilica for abrasive papers

In this work we have shown that a low-cost silica pigment produced from silicate mining industry sidestreams can be used as a coating pigment for inkjet paper and for production of abrasives. Silica pigment was produced from olivine (Mg,Fe)2SiO4 concentrate with an acidic dissolution method by Selor eeig. Silica pigment particle, coating color and paper coating properties were studied in a laboratory scale and in pilot coating trials at VTT. In the production of abrasives two different cases were selected, studied and evaluated on the modified KWH-Mirka pilot and production equipment.

Silica pigment particle and paper coating properties

The produced silica pigment was compared to a commercial colloidal nanosilica (Bindzil 50/80, Eka Chemicals AB), a fumed nanosilica (Aerosil MOX 170, Evonik Industries AG) and a precipitated silica pigment (Sipernat 310, Evonik Industries AG). Produced silica pigment is, according to X-Ray diffraction, infrared (IR) and Thermogravimetric analysis (TGA), in the form of amorphous hydrated silica, with the chemical composition SiO2*nH2O. The silica pigment produced at Selor had particle size of 250 nm, which is comparable to the commercial fumed and colloidal nanosilica pigments. All silica pigments slurries are anionic.

In pilot coating trials coating colors were prepared of produced silica pigment in batches of about 20 kg per each trial point. The produced silica pigment was combined at different proportions with commercial precipitated silica pigment. Polyvinyl alcohol (PVOH) 25 or 35 parts was added as a binder and 0.1 parts of antifoaming agent was added to reduce air content. The developed silica pigment coating formulations seem to work well and were stable. Surface strength requirement for abrasive application was achieved using higher 35 parts amount of fully hydrolysed PVOH. Base paper was an abrasive base paper of 120 g/m2 from Mirka. Coating trials were conducted at the Sutco line of VTT, and coating color was applied with kiss coater. Machine speed was 6 m/min. Drying was performed with five air dryers and one IR dryer. Target coat weight was chosen between 2 gm-2 to 8 gm-2. The length of the coated web varied between 250 and 330 meters.

Standard properties of laboratory coated samples show that produced silica has brightness on same level with commercial silica pigments. The coatings of produced nanosilica and commercially precipitated silica have high liquid absorption ability, which is shown as faster inkjet ink absorption speed compared to colloidal silica or fumed silica coatings. In the laboratory coatings pigment surfaces had some stripes, which are probably because of pigment agglomerates in coating color. Agglomeration of silica should be diminished to improve the coating quality if rod coating application is used.

The inkjet printing tests performed at VTT by HP Deskjet 2050 show that the inkjet properties of Mirka's technical base paper are improved by using the nano-silica coating. The silica containing coatings produced higher print densities than the base paper. The
silica coatings have reduced print-through, indicating that the colorant remains in the silica coating layers. It is concluded that produced silica pigment has potential as a matt coating pigment in inkjet papers. Further development work is proposed to diminish the pigment flocculation tendency of the silica pigment in coating color.

Production of abrasives

The silica coated paper supplied by VTT was cut into suitable width to be run in an inkjet printing line for pilot production of finessing abrasives for the automotive industry. The line consists of three Xaar print head stations (two front side and one on the backside of the web) in combination with two front side Fusion microwave assisted H+ UV lamps plus one backside UV-LED curing device. As to be expected from the VTT laboratory results, the inkjet properties of the paper had been significantly improved and the print pattern of the product was clear, homogeneous and undisturbed. In the backside pattern printing using a black UV-curing ink, line speeds of up to 30 m/min could be achieved and cured using the in-line UV-LED device. In the inkjet manufacturing tests, the best results could be obtained with the 4 g/m² silica coat weight paper. In this case, a good balance between even penetration and good pick-up properties of the inkjet applied make-coating could be achieved.

Today, inkjet printed finessing discs for the automotive industry are normally produced on a print quality polyester film. In this project, we have shown that high surface area silica coated paper can be used to make similar type of products. Evaluation of this type of products is normally complicated by the fact that the parameters of the abrasive need to be optimized towards the properties of the paint (hardness, degree of curing, surface properties etc.) that it is used on. However, the general trends are already clear. Inkjet finessing discs on silica coated technical papers could become a valuable addition to our range of finessing abrasives.

In addition to inkjet production, the silica coated paper was run in a conventional Mayerbar/roller paper coating process for abrasive papers. The first barrier coating layer was a SBR latex, followed by a conventional size and make coating as customary within the industry. The production tests verified the earlier results from the laboratory. The make coating level could be reduced with approximately 20-25 wt-% and the size coating level with 5-10 wt-%. The homogeneous absorption of make-coating into the silica coating layer gave a more open strewing that resulted in a more aggressive product. The open strewing could be achieved while still maintaining good grit adhesion.

The silica coated paper supplied by VTT was also processed to a structured coated abrasive product in a screen-print production line. Initial results with structured screen printed products are encouraging. The method seems especially promising for printing structures using slurries of UV curing adhesives and abrasive minerals. The high-surface area silica layer acts as a buffer taking up some of the ink and anchoring the structure firmly to the support while exposing more of the abrasive mineral for improved cutting action.

Adhesive filler in coated abrasives

The Selor silica was also evaluated as a filler in urea-formaldehyde and phenol-formaldehyde adhesives used for production of coated abrasives. Due to the limited amount of silica available, the abrasives were produced on a laboratory pilot. The target for the work was to see if we could achieve improved hardness of the make coating in combination with improved processing and better anti-clogging properties.

Produced silica could not reach as high hardness values as a commercial reference silica material. The most likely explanation for this difference is that the Selor silica has a native unfunctionalized surface which may not interact with the phenolic resin in an optimal way. Good processability and rheology could be achieved for the Selor silica filled phenolic resin by using dispersing aids in combination with high-shear ultrasound mixing. The improved surface properties of the coating could also clearly be seen in the final abrasive products. Results obtained with produced silica as a filler are very positive especially when considering that new products were made using approximately 20 wt-% less organic resin adhesives when compared against the reference.

Schwertmannite - transformation of an iron-rich residue from lignite mining into valuable products

Background and foreground

Mine water often contains high concentrations of metals and toxic elements and therefore has to be treated before its discharge into the rivers. In the Nochten open cast lignite mine (Germany) about 115 Mio m³ mine water per year are pumped from the subsurface. To
reduce the high iron content, the mine water is treated using lime milk for the neutralization and the precipitation of ferric hydroxide. This technology is (usually) the usual state of the art treatment and the precipitated ferric hydroxide sludge (a waste material) has to be deposited or disposed. G.E.O.S. has developed an innovative treatment, where the mine water is aerated and naturally occurring acidophilic iron oxidizing bacteria oxidize the ferrous iron in the mine water to ferric iron. Within this process an iron and sulphate containing mineral called schwertmannite is precipitated. Schwertmannite is an iron hydroxy sulfate and exhibits a molar ratio of Fe: SO4_2- of 8.00: 1 or 4.57: 1, respectively. The mineral schwertmannite produced in the pilot plant by treating the Nochten mine water is nearly free of impurities and has got a high specific surface.

The application of the new technology would be cheaper and more energy efficient than the conventional lime milk treatment due to saving of lime. The raw material schwertmannite is not stable under environmental conditions and thus cannot be deposited. This lead to the search for alternative utilization and recycling options for the material in project ProMine.

Utilization of schwertmannite – developed products

Due to the high iron content in the mineral (about 50%) the idea came to process the raw material to iron oxide pigments. In laboratory scale experiments the processing steps were tested and optimized to produce a low quality yellow iron oxide pigment and a high quality red iron oxide pigment (Nochten Red).

The quality of both pigments was tested in various applications e. g. for colour and coatings by the project partner WOLA in ceramics and in the brick industry. The high sulfate content in the yellow pigment extremely limited its application opportunities. Thus the further progress in the product development focused on the red iron oxide pigment. According to the laboratory results a technical scale production process was carried out by the help of the subcontractor IBUTEC and a pilot amount of 120 kg pigment Nochten Red was produced.

The project partner WOLA GmbH used the red iron oxide pigment for the development of corrosion resistant coatings. Subsequent tests showed that the developed coatings based on these pigments meet the specific standards in accordance with the legal requirements. But a market analysis and the assessment of the economic efficiency of a technical scale production showed that the economic and market entry barriers are currently too high to commercialize the iron oxide pigments.

Nevertheless, to demonstrate the successful development at large scale the mine operator Vattenfall Europe Mining AG agreed to apply the corrosion resistant coatings containing Nochten Red on a coal wagon used for the daily transport of coal to the power plant. Thus the coatings are tested for several years now under real weather and operating conditions.

Alternative research in a national R&D-project resulted in the development of a sorption material from schwertmannite. The high sorption capacity of schwertmannite for oxo anions (e. g. AsO_4^{3-}, Sb(OH)_{6}^3-) can be advantageous for the separation of toxic and valuable metals from mine water. Although the laboratory research results showed that the developed adsorbents were highly competitive with other granulated adsorbents only at pilot scale production the quality of the developed products can be proved at technical scale. This issue was of great interest for various mining companies and ProMine project partners, because it represents a new possibility to transform a secondary material of the mining industry and use it in passive, energy and cost efficient water treatment systems for the removal of toxic contaminants from mine water.

With the approval of the management committee in ProMine it was decided to change the objective for the pilot scale production described in the DoW from pigment to adsorbent production from schwertmannite. The pilot scale pigment production was not realized due to the increased costs for the plant components in contrast to the low estimated prospects of success to realize a later industrial production.

A new associated industrial partner, the UBIG GmbH, was found to realize the pilot scale production of schwertmannite adsorbents. The pilot plant for the adsorbent production was installed, with a potential processing quantity of 0.5 t schwertmannite per day. The technical process was optimized and a high quality adsorbent with sorption capacities and kinetics higher than similar commercial products were obtained.

Ecoefficient Mineral Processing Methods

Overview
The main tasks of Promine WP4 were to study innovative technologies, new integrated flowsheets and new equipment for mineral processing and extractive metallurgy (Pyrometallurgy and Hydrometallurgy). The general objective was to demonstrate that these new technologies/processes will enable the exploitation of more diversified and complex existing European resources. The development of new process options in the mineral processing value chain will also raise the revenues of the current exploitations and significantly improve the eco-efficiency of extractive methods in general. An improved recovery of the metals will reduce the metal grades in the wastes, minimizing the environmental impact of the final discharges and increasing the opportunity of transforming the wastes into new products. Particular attention was placed on secondary resources (mining and metallurgical wastes) in most of the work carried out in Promine WP4.

Two scientific approaches were followed. The first one was an applied R&D approach, targeting

(i) either mineral resources (wastes) that could be exploited if an efficient/innovative integrated process was developed;
(ii) or a new type of equipment that could be integrated in a process flowsheet making it technically feasible and economically profitable.

The work carried out included various “mineral processing process unit” and can be presented as PROMINE exploitable results.

The second approach was more academic. Some key scientific bottlenecks of the Mineral Processing value chain were specifically addressed:

- On pretreatment steps - Comminution and embrittlement technologies
- On concentration steps - new flotation devices for fine particle flotation
- On leaching steps - development of potential innovations in bioprocesses.

WP4 Exploitable Results

1. Improved (bio)processing methods for complex ore (KGHM Cuprum - BRGM - IMN – Warwick)

A potential global ProMine flow sheet was designed for the treatment of the Lubin concentrate. A preliminary economic evaluation of the whole processing route was carried out. A LCA-inspired analysis of copper concentrates bioleaching technology was also carried out on this case study. This work shows the potential advantages and drawbacks that would be related to the implementation of an innovative bioprocessing method in an industrial environment already in place.

2. Transformation of environmentally hazardous waste slags into mineral resources (IMN – Ecoren)

Within the scope of Promine project also basic engineering for the target pyrometallurgical treatment of the slags with process flow diagrams, list of main equipment and tentative plant layout were prepared together with estimation of the capital and operating costs, evaluation of process economics and comparison versus existing conventional technologies. The analyses confirmed applicability and potential of the technology for economic transformation of environmentally hazardous waste slags into mineral resources.

3. New Bioreactor for Bioleaching application (BRGM, MRM, AL & Boliden)

In this study, the work was focused on wastes generated by processing of sulfidic ores which constitute a great part of the mining activities in Europe. The new bioreactor concept is under evaluation for patenting. If successful, this new type of bioreactor will offer an alternative to the classical Heap or Tank leaching technologies.

4. Novel bio-mineralization techniques for the selective recovery of metals from acidic mine waters: Pyhäsalmi and Maurliden cases (Boliden Pyhäsalmi ; GEOS ; Bangor)

The main drivers of the technology, which is generic in application, are both economic and environmental. In contrast to most current practices, the process generates products (zinc and copper sulfides) that have known commercial value and a third (schwertmannite) that has considerable (though currently non-marketed) value as a pigment and adsorbent of environmental pollutants.
1. Energy savings in comminution – Innovative routes for mineral ores embrittlement (BRGM)

A specific research action aiming at evaluating the capabilities of two ores embrittlement technics to reduce the energy consumption during comminution was carried out. Weakening was performed through µwaves heat treatment and electro-hydraulic fragmentation (SelFrag technology). In conclusion, microwaves embrittlement appeared more or less efficient, depending on the material to be treated. Electro-hydraulic fragmentation looks promising as it brought gains both in energy consumption reduction and in sulphides liberation allowing further optimisation of the whole beneficiation process.

2. New flotation devices for fine particle flotation (University of Lorraine)

The work was focused on the demonstration of the possibilities of new flotation devices for fine particle flotation. The experimental set-up included a system of pulp preparation, a bubble-sparger, two reactors and a separation cell. The set-up has a two different separation cells and was mounted in two test configurations: circulation and flow modes.

3. Development of potential new bioprocess innovations (University of Warwick)

The development of potential new bioprocess innovations comprised:

(i) evaluation of anaerobic bioprocessing for ore heap leaching improvement [by removal of ore surface-passivating iron precipitation and by removal of flow-restricting iron precipitation in ore columns/heaps];
(ii) evaluation of bioprocessing of Lubin copper/silver concentrate at high temperature.

Fundamental support work for assessment/monitoring of bioleaching processes comprised:

(iii) evaluation of rapid, high-throughput monitoring of specific organisms through electrical impedance/fluorescence analysis of particle suspensions;
(iv) evaluation of a species-specific fluorescently-tagged antibody microscopy protocol;
(v) functional genomic analyses (proteomics) with biomining organisms, aimed at discovery of relevant targets (genes or proteins) for process monitoring.

New flotation devices for fine particle flotation

This work of University of Lorraine was focused on the demonstration of the possibilities of new flotation devices for fine particle flotation. Multi-zone flotation cell of reactor separator type (RS) is a cell of intensive flotation, which provides optimal hydrodynamic conditions for all flotation sub processes. The new multiple-zone flotation cell differs from other intensive flotation units of reactor-separator system with number of zones considered and mode of their connection. Particle attachment activation by nanobubbles, creation of conditions for coalescent flotation, selection of spatially separated zones according to optimal hydrodynamic conditions of flotation sub-processes are proposed as main principles to design a multi-zone flotation cell. In addition to the high specific capacity and low energy consumption, RS demonstrates a high flotation rate and increased selectivity in stable range of hydrodynamic effects. Hydrodynamic effects can be achieved by external energy action like ultrasonic impact or by internal energy action made by geometric changes along flow, like turbulence promoters.

Two kinds of materials were tested: Pyrite containing tailings from Aitik deposit (Sweden) ; Fine fractions of a feldspar ore, which are considered as tailings in conventional method.

The new multizone flotation cell developed by University of Lorraine in comparison with conventional mechanical cells shows at lab and pilot scales:

- Very high feed flowrate
- High specific surface area flux (bubble mineral load)
• A high pyrite grade without significant recovery loss. The leaching of pure pyrite concentrate from tailings of Aitik deposit can lead to higher cobalt recovery in comparison with direct leaching of tailings with 50-52 % of pyrite.
• New flotation cell allow to recover the valuable product from some waste stream as was demonstrated at pilot scale for HF-free feldspar/quartz separation.

Development of potential new bioprocess innovations

(i) Anaerobic metabolism in ore heap leaching improvement

The anaerobic potential of bacteria and archaea over a wide temperature range (30 – 75 °C) was assessed to select the most useful strains. Initial evaluations involved shaken flask tests. A potential benefit was demonstrated with thermophilic archaea at a temperature 70 °C which could be appropriate for hot ore heaps. Ore fragments were then incubated with constant aeration or with alternating aerated and anoxic phases. Oxidized iron precipitates accumulated on ore surfaces during aerated phases and were removed during anoxic phases when the organisms used the precipitated ferric iron as an electron acceptor for the anaerobic oxidation of sulfur compounds from the ore. The medium was removed and replaced with new medium at each gas phase switch to simulate the flow through an ore heap. Much greater iron removal from the ore environment occurred when anoxic phases were present. Target (valuable) metal leaching ceased during anoxic phases but occurred at faster rates when aeration was restored, increasing the final yields by between 5 and 10% for zinc, nickel and copper. Further tests (at 30 and at 47 °C) were completed to simulate heap leaching. Effects of anoxic phases were most notable with moderate thermophiles at 47°C.

(ii) Evaluation of bioprocessing of Lubin copper/silver concentrate at high temperature

Bioprocessing of the Lubin concentrate has been successfully demonstrated at pilot scale at low temperature. However, there is doubt concerning the economic and practical feasibility of such a process because of slow leaching times. High temperature bioleaching has been considered in conjunction with hydrometallurgical steps with the following results. Bioleaching of copper at 77°C was rapid and efficient, but there was some apparent toxicity-induced instability of some cultures. Copper leaching (chemical) was efficient and rapid with ferric sulphate (at 70°C but not at 30°C), but silver remained in the residue. Silver extraction was rapid and efficient with ferric chloride leaching at 70°C (chemical), but copper leaching was less efficient than with ferric sulfate. Chemical leaching would require regeneration of ferric iron (the inhibitory chloride concentration would prevent a microbial option for this if ferric chloride was used).

Silver extraction from bioleached residues was unexpectedly found to depend greatly on the temperature of the bioleaching and the solvents used for extraction. Optimization of high temperature bioleaching could be considered. There would be a silver-enriched residue (~ 50-60% of mineral feed by weight) but this would not be amenable to standard acid/brine silver extraction, in contrast to low-bioleach-temperature residues. Thiosulfate was the most effective solvent with 78°C residues, but further work is required (linked to analysis of the silver mineralogy) to see if the efficiency could be increased. Sulfur was absent from the 78°C bioleached residue but abundant in the ferric sulfate-leached one.

Improved (bio) processing methods for complex ore, Lubin black shale case study

The subject of this study was copper concentrate (containing 14,6% of Cu and 0,087% of Ag) produced at Lubin concentrator by KGHM Polska Miedź S.A. (Poland). The concentrate is produced from three lithological types of ores, including black shales. The main copper-bearing minerals are: chalcocite, bornite, chalcopyrite and covellite. In the last few years, an increase of organic carbon and As contents as well as a decrease of Cu content in ore were observed at Lubin mine, resulting in a decrease of the concentrate quality. It determined a need to look for new methods of the concentrate treatment.

Bioleaching efficiency was previously demonstrated in the frame of Bioshale FP6 European project. However, some improvements were still needed to be achieved in order to meet process economic viability. In bio-hydrometallurgy, the most important investments costs generally come from bioleaching and electrowinning unit operations. When focusing on bioleaching itself, capital costs largely depend on global tank volume and agitators. In the frame of Promine FP7 European project, our study aims at improving the profitability of the bioleaching of the copper concentrate in stirred tank reactors taking into account the results of the pre-feasibility study performed in BioShale project. The following objectives were identified:
• increasing revenues by improving chalcopyrite dissolution and thus bioleaching operation efficiency;
• reducing capital costs by reducing global bioleaching tank volume, which means decreasing residence time in the bioleaching unit
and increasing the feed solids content from 15% to 25%;
- reducing capital and operating costs by introducing direct electrowinning instead of the classical association solvent extraction/electrowinning.

The bioleaching performances at 25% solid rate were similar to those obtained in Bioshale with 15% solid rate in the same operating conditions. In the literature, there is a controversy on the feasibility of working at such high solids content. In Promine bioleaching experiments no mixing or microbial issues were encountered. Bioshale-BRGM consortium showed a rare copper tolerance: copper content increased up to more than 40 g/L without any negative effect on the bacterial community. Combining high solid content and reduced residence time, “Promine bioleaching process” would need 2.3 less tank volume than “Bioshale bioleaching process”, which means a significant reduction of investment costs.

Electrowinning tests performed using solution coming from bioleaching tests show that copper removal can be achieved by direct electrowinning without any solvent extraction step. Preliminary removal of Fe(III) from the bioleaching solution significantly increases current efficiency of electrowinning operations. The iron excess can be successfully removed by precipitation in jarosite form. That method provides possibilities to precipitate Fe(III) in a form of residue of good filtration properties at low copper loss in the residue. An improvement of the structure of copper cathodes can be achieved by decreasing chloride ions content in the bioleaching solution from the level of about 0.5 g.dm-3 to 0.01 g.dm-3. Chlorine content reduction should be done in a separate process of concentrate washing before its bioleaching.

Experimental results were used to design a global treatment process scheme.

Transformation of environmentally hazardous waste slags into mineral resources

Smelting operations in non-ferrous metals metallurgy usually produce slags, which can't be directly utilized. Sometimes they are stored as environmentally hazardous wastes. The main goal of the research carried out was to establish technologies transforming these wastes to products – construction aggregates, with the recovery of the contained metal value.

Three types of slags from different metallurgical operations were treated:
1. Lead-bearing material from copper metallurgy smelting in a short rotary furnace of HM Glogow,
2. Copper dross from lead refining smelting in a short rotary furnace of zinc smelter HC Miasteczko Ślaskie,

The main objectives of experiments were:
- Extraction of metal value, mainly copper, zinc and lead
- Correction of mineralogical composition of the slags by melting in appropriate oxides (SiO2, CaO, FeO).

The tests were performed in IMN experimental installations, i.e.:
- Electric furnace
- TSL reactor (Top Submerged Lancing)

Both reactors met the established aims enabling recovery of valuable metals in usable products, such as: crude lead, copper and iron, copper matte, Zn-Pb dust and transformation of not-reduced remains into mineral resource – silica slag of low heavy metals content. Electric furnace provides possibilities for recovery of Pb and Fe in a form of metals and for retaining of sulphur in solid products. TSL reactor brings lower Zn content in silica slag, possibilities for production of metallic copper and transfer of majority of sulphur to gases – which requires their desulphurization. Transformation of slags into construction materials after metals recovery needs correction of their composition by introduction of sand, limestone to melt in oxides (SiO2, CaO) and to transfer the material into silica form of iron-calcium silicate. For this purpose the slags were heated up to the temperature of 1329-1462oC in electric furnace and 1222-1255oC in TSL reactor and tapped to a steel mould of capacity 200 kg of slag.

Samples of slags were delivered to accredited laboratory for testing of the material applicability for aggregates production. Eight specific properties were verified: grain density, absorbability, abrasion resistance, resistance to crumbling, freeze resistance, freeze
resistance in NaCl, dangerous substances release (leachability), natural radioactivity. Test showed that all three slags fulfill requirements of respective standards.

Within the scope of Promine project also basic engineering for the target pyrometallurgical treatment of the slags with process flow diagrams, list of main equipment and tentative plant layout were prepared together with estimation of the capital and operating costs, evaluation of process economics and comparison versus existing conventional technologies. The analyses confirmed applicability and potential of the technology for economical transformation of environmentally hazardous waste slags into mineral resources.

New Bioreactor for Bioleaching application Aitik case study

Bioleaching appears more and more industrially proven as a portfolio of flexible techniques to provide an efficient way of recovering base metals. Bioleaching is envisaged for processing low grade ores, particularly when they contain deleterious elements that result in heavy penalties in pyrometallurgical treatment, as well as for processing mining wastes containing valuable metals.

In this study, we focused on wastes generated by processing of sulfidic ores which constitute a major part of the mining activities in Europe. These wastes (tailings) which often contain secondary valuable metals pose a threat to the environment since they are sources of acid mine drainages that contain elevated fractions (or quantities) of potentially toxic metals. There are nowadays two types of bioleaching processes: suspension bioleaching in stirred tank reactors (STR) which is dedicated to high-grade ores, and heap leaching which is dedicated to low-grade primary ores. Neither of those technologies can be applied for the re-processing of tailings, which requires the development of a new type of bioleaching reactor as an alternative to existing technologies. The bioreactor to be developed is expected to have the following characteristics:

- Low CAPEX; Easy maintenance; Continuous service; Flexible operation; Highly profitable.

In ProMine, preliminary research was carried out by BRGM, MRM and AL to develop this new type of bioreactor called “LDBO2”. This concept is mainly related to a new type of agitation-aeration system.

The purpose of the work done in ProMine was to test this new agitation/aeration device for bioleaching applications. Experimental tests were conducted to test:

- the impact on the bioleaching efficiency
- the ability of the system to ensure the agitation of the bioleaching pulp

The wastes chosen for this study come from a European copper mine (Aïtik, Sweden) whose mineral of economic interest in the ore body is chalcopyrite (CuFeS2). Copper contained in the chalcopyrite is recovered by smelting whereas pyrite is discharged in tailings where the material used in this study was sampled. It is mainly composed of pyrite (60%) and contains cobalt (0.06 %) and gold (0.95 g/t). Experiments were performed in 2L stirred reactors and in pilot tanks (20L and 2m3). Bioleaching tests were undertaken using the "BRGM-KCC" bacterial consortia (Leptospirillum, Acidithiobacillus and Sulfobacillus)

No deleterious impact on bacteria was noted and high dissolved metal rates were obtained (cobalt dissolution rate higher than 90%). The agitation device was tested for several solid loads (from 20% to 30% m/m of tailings material in the pulp); despite the high density of the pulp (due to the pyrite content), no mixing problem nor wearing issues were encountered.

Experimental results were used to design a global treatment process scheme. Major equipment items were sized based on mass balance and design specifications. From this process flowsheet, a preliminary economic evaluation was performed comparing LDBO2 to classical bioleaching in stirred tank reactor (STR). The evaluation confirms the decrease of the capital costs and demonstrates the good profitability of such an industrial project.

Novel bio-mineralization techniques for the selective recovery of metals from acidic mine waters: Pyhäsalmi and Maurliden cases

Within the frame of ProMine and elsewhere, a novel bioreactor systems was developed that facilitate the selective recovery of various transition metals (e.g. copper, zinc and iron) as defined minerals that can be recovered and recycled. These have been tested at the laboratory scale using synthetic acidic, metal-rich waters from mines (Pyhäsalmi and Maurliden) owned by two partner companies. The systems utilize bacteria that initiate the formation of metal-containing minerals in low pH liquors. Based on their solubility products,
iron is removed by bacterial oxidation and formation of an oxy-hydroxide mineral (schwertmannite) while copper and zinc are removed as sulfide minerals using bacteria that generate H2S under anaerobic conditions.

(i) The iron oxidation/precipitation module has two components, and operates at ambient temperature: an iron oxidation bioreactor where ferrous iron is oxidized to ferric (90-99%, dependent on flow rates) and a schwertmannite precipitation vessel where sodium hydroxide solution is added to the stirred oxidized ARD to increase its pH to ~3.5. At this pH, co-precipitation of other metals (as hydroxides) is avoided. The schwertmannite so-formed agglomerates, and settles within the vessel when stirring is switched off, a process that can be accelerated by adding a suitable flocculating agent, such as FLOCCIN 1105.

(ii) Low pH sulfidogenic bioreactors (2.3 L working volume), inoculated with a consortium of acidophilic, sulfate-reducing bacteria, were established and used to sufficient generate hydrogen sulfide both to precipitate target metals within the reactor and excess which was removed and used to precipitate other metals (of lower solubility products) off-line. Key to this were the amounts of glycerol (the energy source for the bacteria) added to the mine water and the pH at which the bioreactors were maintained, which was generally between pH 2.5 and 4.0.

In the case of Pyhäsalmi, it was shown that 99.9% of the soluble iron in the mine water could be readily removed in situ using the iron oxidation/precipitation module. This would obviate the problem with ferric precipitates causing problems with the pump network. Alternative solutions to the problem (e.g. minimizing iron hydrolysis within the mine by acidification of the water and removal at the mine surface) have also been proposed to the mine company.

For Mauriliden mine water, the composite treatment protocol was demonstrated to be effective at the laboratory scale. In this, a small amount of the schwertmannite produced in the iron oxidation/precipitation reactor is used to remove arsenic as the first stage of the mine water treatment. Copper and zinc are removed (as sulfides) from the iron- and arsenic-free water: copper off-line, and zinc within the bioreactor vessel itself. Aluminium and manganese can also be removed as different mineral phases, though this was not demonstrated in the current project.

The main drivers of the technology being developed, which is generic in application, are both economic and environmental. In contrast to most current practices, the process generates products (zinc and copper sulfides) that have known commercial value and a third (schwertmannite) that has considerable (though currently non-marketed) value as a pigment and adsorbent of environmental pollutants. Other “added values” of this new biotechnology comes from the far smaller environmental hazards of the products generated. For mining to become a more sustainable and environmentally benign industry in the 21st century, it is important that wastes are minimized and, where feasible, considered as resources.

A way of assessing the influence of ProMine developments on the sustainable development of the European mining industry

The objective of Work Package 5 (WP5) has been to analyse the effect of the products, production methods, and improved mineral resource management developed in ProMine on the sustainability of the mineral-based industry in Europe. In order to be able to perform the analysis, one Model Site was selected for each of the five products initially planned to be developed in ProMine. For each of the model sites, a model site manager was appointed. The products with their associated model sites and model site managers were originally:

- Metallised fibres for abrasive products – Pyhäsalmi mine, Pyhäsalmi Mine Oy, Finland
- Nano-silica for high-strength concrete, Stratoni mine, Hellas Gold SA, Greece
- Nano-silica for ink-jet printing paper coating, Gerakini magnesite mine, Grecian Magnesite SA, Greece
- Schwertmannite for pigment production – Nochten lignite mine, GEOS Ingenieurgesellschaft mbH and Vattenfall Europe Mining AG, Germany
- Spherical rhenium particles and rhenium alloys for jet engine turbines – the Głogów copper smelter and refinery and KGHM Technology Park Legnica, KGHM Ecoren S.A. Poland

During the course of the project it became obvious that the development of metallised fibres could not successfully be completed within the scope of ProMine. Also, the original plan to react olivine with carbon dioxide to produce nano-silica for ink-jet printing paper proved unsuccessful. As a consequence, Pyhäsalmi was evaluated as a model site for a process for clean-up of mine water using bio-oxidation of iron to schwertmannite, while Gerakini became model site for the beneficiation of dunite to an olivine-rich fraction that could be used as raw material in the process for producing nano-silica for high-strength concrete at Stratoni.
The general procedure for the analysis is to conduct an assessment of the current (baseline) sustainability situation at the Model Sites and to investigate the impact of implementation of the products, eco-efficient production methods and improved mineral databases, developed within ProMine on the Model Site would have on the sustainability situation. This impact will then be projected to a European scale, in order to assess the impact on the sustainability situation for the European mineral industry.

The concept for sustainable development used in ProMine is that given by the so called Brundtland Commission: “a development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. This concept recognized the need for economic development and social stability, as well as the need for conscious resource management and environmental stewardship to achieve human and ecological welfare.

In order to be able to measure changes in sustainable development, a set of sustainability performance indicators were defined at the onset of the project. After a review of alternative indicator sets, it was decided to use a subset of the indicators published in guidance document G3 of the Global Reporting Initiative, GRI. Information from the model sites related to these indicators was published in a report in November 2010.

At the onset of the project it was anticipated that the improved information on ore deposits and anthropogenic resources coming out of the exploration cluster of work packages could improve the resource exploitation efficiency. This was investigated in separate task within WP5. Information on the composition of tailings and waste rock deposits at operating and abandoned mines was collected and the potential for exploitation was analysed. Conclusions were drawn about the potential impact of the resources on the three dimensions of sustainable development (environmental, economic and social) in a report that was published in November 2011.

The impact on the sustainable development at the model sites from the products and production methods developed in ProMine was addressed in a Life Cycle Assessment, LCA. This assessment resulted in SWOT analyses (Strengths, Weaknesses, Opportunities and Threats). A report was issued in December 2012.

The results of the LCA were combined with information on production costs and expected market prices in an overall assessment of the potential impact of the ProMine developments on the sustainable development at the model sites. A report was issued in April 2013 for review by the model site managers and the product developers.

The final stage of the WP5 effort has been to scale the model site impacts to a European scale in an attempt to forecast what the impact would be on the sustainable development of the European mining industry. This task also includes describing a possible method to monitor the sustainable development after the finalisation of ProMine.

Sustainability gains from the ProMine developments

Objectives and outline

The objective of Work Package 5 (WP5) was to analyze the effect of the products, production methods, and improved mineral resource management developed in ProMine on the sustainability of the mineral-based industry in Europe. In order to be able to perform the analysis, one Model Site was selected for each of the five products initially planned to be developed in ProMine.

The sustainability assessment is done by comparing the environmental situation at selected model sites before and after implementing the production of the new products and the ecoefficient metal production methods and by applying Life Cycle Assessment (LCA) and cost analysis techniques. The results are used as a basis for describing the effect on the model sites and for an extrapolation to a European scale to enable conclusions to be drawn about the overall effect of the products on the sustainability of the European mineral industry. In addition, methods are suggested for monitoring the long-term sustainability situation including economic and social development.

LCA

Detailed life-cycle assessments were performed for the new products to support the product and process development and including the changes at the model sites. The novel products and related production processes in ProMine utilize waste streams originating from mining activities as raw materials. The allocation principles for the environmental burden between multiple products (by-products) were identified as important factors in the assessment.
The assessment included a SWOT-analysis– highlighting Strengths, Weaknesses, Opportunities and Threats for each of the products developed.

Conclusions show that the new technologies have many benefits, for example, they reduce the amount of waste and the amount of harmful substances in the waste, while at the same time the technologies produce valuable products from waste materials. For the future, alternatives for virgin raw materials and ways how to improve the energy efficiency should be considered. Inclusion of ecodesign with special consideration for the environmental impacts of the product during its whole lifecycle to product development is the preferable way towards more environmentally sustainable global production and consumption.

Sustainability gains at the Model sites

Stratoni mine

Changes at the mine site include reopening of the tailings facility at the nearby Olympia mine, reprocessing of the tailings to produce a pyrite concentrate with gold as the value bearing mineral, building a new roaster at Stratoni with a connected sulphuric acid plant. The sulphuric acid will be used for nano-silica production using olivine from the Gerakini site.

Compared to the initial plans the introduction of a new water treatment facility at the Stratoni site has resulted in significant improvements in drainage water quality. Hence, the AMD cannot anymore be used for nano-silica production. Building of a new roaster with capturing of the off-gas in a sulphuric acid production plant will supply an acid suitable for nano-silica production. The acid is reacted with olivine that comes from the Gerakini site.

The roaster will use concentrates extracted from the old tailings at the adjacent Olympias site. Changes in Olympias need to be considered in the sustainability assessment, including tailings that will be removed which will free land previously occupied by tailings deposits. The depleted tailings are suitable for backfilling of the mine or may be used as raw material for the cement industry. The operation will include rehabilitation of the area leading to improvement of the landscape. Local employment will increase due to the new operation.

The market and price for this nano-silica production was investigated in WP3, and the results indicated that the initial production and market introduction should aim at the high quality – medium to high-price segment for special applications.

In conclusion this is definitely a green result from industrial developments driven by the desire to extract gold from old tailings, combined with the new production of nano-silica using sulphuric acid (produced in order to clean the off-gas from the new roaster) and reacting it with olivine (which is produced from dunite, a waste product of the Gerakini mine).

Gerakini

The new production at the Gerakini site includes a beneficiation of dunite waste rock to produce an olivine-rich dunite fraction (>70 % olivine) which can be used as a raw material for nano-silica production. The olivine produced at Gerakini may have different possible applications when processed to nano-silica, including abrasive paper application, ink-jet printing paper coating, and concrete additive application.

Based on the quality criteria set up for the nano-silica process, improvements in the beneficiation process at Gerakini have increased the quality of the olivine (i.e. by increasing the olivine concentration and reducing the iron content) which meets the quality criteria and is suitable for nano-silica production.

The indicated production costs for olivine at Gerakini is 69 €/t. A comparable product on market would cost about 103 €/t. Extrapolation to possible product price for large scale operation indicate a price at 80 €/t.

The green message for the Gerakini is that waste is turned into a profitable product with a significant added value that may find a large volume market.

Nuchten
At the Nochten site a new process for treatment of the drainage water from the lignite mine area based on a microbial process has been implemented. The new process and product development include precipitation of a high-quality schwertmannite that can be used for production of pigments and adsorbents. No relevant comparison of the before and after situation at the Nochten site has been possible to make since the water treatment facility is only a very minor part of the gigantic operation. Instead a comparison has been made with the conventional chemical water treatment process used at the site.

The green message is that valuable products, including pigments and water cleaning adsorbents can be produced from waste water, while at the same time reducing the demand for disposal of sludge and reducing the demand for added chemicals in the water treatment process.

Głogów & Legnica

At the Głogów smelters rhenium is extracted from the weak sulphuric acid coming from the off-gas cleaning system of the sulphuric acid plant associated with the smelters. The first step of the production involves precipitation of ammonium perrenenate (APR). In a newly developed process the APR is further refined to perrhenic acid and its salts with nickel, cobalt and iron, which in turn are reduced to spherical Re powder and to Ni-Re and Co-Re alloy powders at the Legnica site. In the final preparation the powders are sintered to granulate.

The extraction of rhenium is a very small part in a large copper smelter complex. Therefore, a direct comparison of the before and after situation at the Głogów site is not meaningful.

Although driven by the need of supply of rhenium for the air-space industry the impact on the environment and the sustainability situation is also of importance. The only source of rhenium is in fact originally a waste stream that has previously been diverted into the waste water treatment plant at the smelter site. The new process scheme has not only allowed the extraction of high-value, high-technological rhenium products, but also a significant recovery of lead sulphate. This has also improved the quality of the waste water.

This shows that there is definitely a green effect of the introduction of the new rhenium extraction processes at the Głogów and the Legnica sites.

Pyhäsalmi

At the Pyhäsalmi mine site, the current chemical drainage water treatment processes will be replaced by a biological treatment process involving precipitation of schwertmannite. In a second step, valuable metals may be extracted from the drainage water. This means that the quality of the drainage water will be improved, thus lowering the environmental impact on the recipients, while at the same time the extracted metals may contribute to reduce the overall treatment costs. The schwertmannite precipitation process is in the Pyhäsalmi case motivated by environmental reasons and not by the production of schwertmannite in itself.

The green message is that by applying tailored microbial processes the need for adding chemicals in the drainage water treatment may be reduced, the quality of the drainage water may be improved and the overall costs for water treatment may be reduced.

Scaling and monitoring

The current impact of the products and production methods studied and developed in ProMine to the sustainability of the European minerals industry is relatively small. This arises from the fact that the produced amounts are small, and the processes are in operation in only a few sites. However, over time it is projected that the ProMine products and production methods will assist Europe to make a leap forward towards a more sustainable mining industry by:

- Enhanced production of metals and mineral products from secondary resources.
- Increased self-sufficiency on raw materials.
- New possibilities for waste water treatment with reduced costs.
- Increased ability to utilize complex and/or low-grade ores and waste materials.
- Application of the proposed methodology for monitoring of the sustainability.
The analysis has demonstrated that the implementation of the products developed will potentially have a positive effect on the model sites in terms of increased revenues, improved possibilities for employment and a positive development of the dialogue with the local community. The magnitudes of these effects vary between the model sites depending on the local premises.

Potential Impact:

The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

ProMine offered a unique opportunity to bring together the worlds of science, industry, economics and creativity, working towards the common goal of developing cutting edge new technologies and products.

The successful development of new high-value (nano-) metal and mineral products from mining waste, new avant garde biotechnologies in processing ore and mining waste, new methods and tools for mineral resource assessment and exploration enabled ProMine to play a major role in driving the mining industry forward, looking for options to green current practices and supporting the development towards an industry branch that is more environmentally friendly, socially inclusive, yet still economically competitive.

Improving Industrial Links

Improving industrial links has been given a very important role in the project. The partners from industry in the ProMine consortium are responsible for more than 70% of the metal production in the EU, so implementation of results from the project has a clear multiplier effect across the entire European mining and manufacturing industry.

The new technologies and products which have been developed are leading to new business ventures and boost growth in both the mining and manufacturing industry in Europe, contributing to a competitive position in the global market. Continuous consultation and transparent knowledge flows between the relevant partners have proved to be of the utmost importance to ensure that products and processes are accepted and owned by the mining and other industries involved.

The ProMine Deliverable D6.7 Improving Industrial Links highlights the improved links that have been forged with industry as a result of the research and technological development tasks carried out within ProMine and demonstrates how the project’s significant results have been achieved in particular through the successful interaction with the industrial partners in the ProMine consortium. The active engagement with industry has lifted the outcomes of the project from science-based to industrial-scale outcomes.

Recommendations for the Mining Industry

ProMine’s results and findings have also been taken up in the Deliverable D6.6 Recommendations which consists of two parts. The first part brings the ProMine Message for the European Industry with four keywords: Sustainable, Responsible, Competitive, and Acceptable.

The second part covers the extended recommendations which provide relevant reference materials, including worldwide examples of good practices and good governance, and also draws on stakeholder feedback that was collected throughout the project. The systematic collection of stakeholder feedback covered three distinct topics: a) contributions from ProMine partners to the proposal for a Raw Materials Innovation Partnership (RMIP), b) feedback collected from stakeholders on the occasion of the ProMine Stakeholder Workshops, and c) Write-ups on Conferences where ProMine has been represented.

Visibility of ProMine

A continuously updated ProMine website, press releases, TV clips, articles in the media etc., have all contributed to bring about an excellent visibility of the project across Europe and beyond.

ProMine’s objectives and achievements have been presented at 80 conferences reaching an aggregate audience of over 20,000 participants worldwide.

A further, brief write-up is provided on the ProMine Stakeholder Workshops, the ProMine Stories and the ProMine Factsheets, which all contributed to give ProMine an excellent visibility.
ProMine Stakeholder Workshops

Three successive series of stakeholder events were organized. The first series of stakeholder events were organized around the theme “What are your needs, what can we offer?”. These ProMine Information Days had the purpose of introducing ProMine to stakeholders and bringing together potential industrial end-users, decision-makers and representatives of various public interest groups already from an early stage of the project. During these events, stakeholder and potential end-user requirements and expectations were identified. The gathered information and knowledge was collected in a dedicated database.

The second series, the Model Site Workshops, had the aim to generate a discussion on the marketability of the new products that are being researched in ProMine and their potential applications in industry. These events provided valuable feedback on how to capture and integrate the potential end-users’ viewpoints in support of the Go/No Go decision making process for the new products and processes. In parallel, with the objective to re-affirm the link between the new products and their raw materials, the mining industry was tasked to validate the pan-European GIS and the 3D & 4D models that were developed specifically for the mineral belts researched in ProMine.

The third and final series of stakeholder events, the Mineral Marketplaces, were aimed at disseminating the results of the ProMine project by presenting these to a wider audience in innovative ways. The first Mineral Marketplace was organised in Wrocław, Poland on 25 April 2012 where presenters were literally placed under the spotlight and were encouraged to tell their story in a compelling way to fellow partners and other stakeholders from industry, research and policy backgrounds visiting the market, as well as to the camera, providing input to the ProMine Stories. The second edition of the Mineral Marketplace has been organized in conjunction with the ProMine Final Conference in Levi, Finland on 24 and 25 April 2013.

The final series of events also targeted the commercial exploitation of the ProMine results, by exploring commercial markets and marketing the products, processes and methodologies at an international trade fair. The new ProMine products were actively promoted to visitors at the Green Innovation Expo in Tokyo, Japan which was held from 14 to 16 November 2012, creating new business contacts with people from different industries and research institutions all around the world.

ProMine Stories

The ProMine Stories are a collection of video clips that present the breakthroughs and effective solutions achieved in ProMine.

The clips were uploaded on the dedicated YouTube channel www.youtube.com/ProMineStory and are accessible also via the ProMine homepage http://gtk.promine.fi. Three of these clips draw on footage taken by a Polish film crew on the occasion of the ProMine Mineral Marketplace which was held in Wroclaw, Poland in April 2012. Further video clips were added, including demonstrations on the use of the ProMine Portal, 3D & 4D modeling and more.

The Mineral Marketplace in Poland was also covered by a film crew from Euronews and broadcast as part of the Futuris programme in English, French, German, Italian, Portuguese, Spanish and Russian.

ProMine Factsheets

In addition to a suite of 3-gate promotional leaflets in different languages, the portfolio of ProMine promotional material also includes a folder with a collection of Factsheets. The first set of Factsheets introduces the respective model sites in ProMine, while a second set is dedicated to the results achieved: the ‘Factsheets illustrating the ProMine tools in decision-making’ focus on respectively the ‘Main Mineral Deposits of Europe’ and the ‘Critical Raw Materials in Europe’. The ‘Factsheet presenting new nano-particle products made out of mining waste streams’ draws on inputs provided by the partners responsible for the development of the products and the sustainability assessment carried out by KEMAKTA. The series is complemented with the ‘Factsheet presenting IRMCo’s communication toolbox for knowledge management throughout the ProMine project’.

Educational support

The ProMine Deliverable D6.5 Training Materials provides a self-tutorial in 3D & 4D modeling addressed to geo-practitioners and geoscientists. The international workshop entitled "Mineral resources potential maps: A tool for discovering future deposits" from 12 to
Sustainability Assessment

In order to be able to perform the analysis of the impact of the products and processes developed in ProMine on the sustainable development of the European mining industry, one Model Site was selected for each of the five products initially planned to be developed in ProMine. In order to be able to measure changes in sustainable development, a set of sustainability performance indicators were defined at the onset of the project. After a review of alternative indicator sets, it was decided to use a subset of the indicators published in guidance document G3 of the Global Reporting Initiative, GRI.

The Sustainability Performance Assessment started with an assessment of the baseline situation at the Model Sites with respect to the selected indicators. After this the impact of implementation of the products, eco-efficient production methods and improved mineral databases, developed within ProMine on the Model Site would have on the sustainability situation in general and in terms of the selected indicators. This impact was then projected to a European scale, in order to assess the impact on the sustainability situation for the European mineral industry.

At the onset of the project it was anticipated that the improved information on ore deposits and anthropogenic resources coming out of the exploration cluster of work packages could improve the resource exploitation efficiency. This was investigated in a separate task within WP5. Information on the composition of tailings and waste rock deposits at operating and abandoned mines was collected and the potential for exploitation was analysed and conclusions were drawn about the potential impact of the resources on the three dimensions of sustainable development, i.e. environmental, economic and social.

The impact on the sustainable development at the model sites from the products and production methods developed in ProMine was addressed in a Life Cycle Assessment, LCA. This assessment resulted in e.g. SWOT analyses (Strengths, Weaknesses, Opportunities and Threats).

The results of the LCA were combined with information on production costs and expected market prices in an overall assessment of the potential impact of the ProMine developments on the sustainable development at the model sites.

The final stage of the WP5 effort has been to scale the model site impacts to a European scale in an attempt to forecast what the impact would be on the sustainable development of the European mining industry. This task also includes describing a possible method to monitor the sustainable development after the finalisation of ProMine.

The impact of the products and production methods studied and developed in ProMine to the sustainability of the European minerals industry is relatively small. This arises from the fact that the produced amounts are small, and the processes are in operation in only a few sites. However, over time it is projected that the ProMine products and production methods will assist Europe to make a leap forward towards a more sustainable mining industry by:

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- Application of the proposed methodology for monitoring of the sustainability.

The analysis has demonstrated that the implementation of the products developed will potentially have a positive effect on the model sites in terms of increased revenues, improved possibilities for employment and a positive development of the dialogue with the local community. The magnitudes of these effects vary between the model sites depending on the local premises.

Exploitation of Results

As an industry-driven project, the ProMine project was designed from the outset on the basis of a set of clearly defined exploitable results. Reaching the end of the project's 4-year life-cycle, it can be confirmed that these exploitable results have been reached, and are
ready to be launched on the market as soon as the project ends in April 2013.

The range of ProMine products selected for development was based on the market needs. The mining industry partners in the project produce about 70% of the European base and precious metals and have played a key role in defining the needs and requirements of the market, and these have been used to further refine the scope and objectives of this project. The active participation of industrial end-users and the exchange of knowledge targets the strengthening of the technological position of the sector in the international market, and guarantees that the implementation of the project results will translate into direct and significant economic benefits.

A list of 16 exploitable results, which may have commercial or industrial application, has been identified.

IPRs and related issues have been considered during the preparation phase of the ProMine proposal and a plan for the use and dissemination of the Foreground has been prepared. Foreground capable of commercial or industrial applications has to be protected by the owners of the foreground taking into account confidentiality and the interests of the partners in the consortium.

The knowledge resulting from the project has been secured by filing of patent applications every time when felt necessary. Altogether 7 patents and one process/method knowhow have been applied for or have been filed. These are: the production methods for the rhenium alloys, method for production of schwertmannite adsorbents, method for production of nano-silica for special products and the method for transformation of environmentally hazardous slags into mineral resources.

The studies conducted on new rhenium-based products and new technologies leading to the generation of those materials were developed by IMN and KGHM Ecoren, which resulted in the preparation of 5 patents. The market analysis for further exploitation of the results performed indicate that the developed products have potential and can be placed in the rhenium market within the aerospace and gas turbines industries.

Methods for producing nano-silica from mining waste have been developed by SELOR and TU/e. ProMine nano-silica which can be used e.g. for paper coatings and for lean construction materials, has much improved properties compared to the currently available commercial nano-silica. The production method also reduces the CO2 footprint.

Biological methods to clean mine waters have been tested by University of Bangor, Wales and VTT, Finland. It is obvious that a great part of Cu, Zn and Fe can be technically precipitated from tailing waters and if methods prove to be sufficiently selective, also produce saleable metal compounds. These technical constructions have still to be developed further and their economical aspects solved.

As another example of an exploitable result, methods for mine site exploration have been tested. The methods involved are: lithogeochemistry, high resolution seismics, deep EM methods and structural analyses. All results have been compiled in the 3D modelling program, goCad to construct 3D and 4D models of the mine site geology. These predictive models form the base for future exploration around the mine sites. The results of this exploration can be a new ore body and extended mine life. These methods and modelling tools can be used also in exploration on already closed mine sites.

ProMine’s results have also made significant contributions at the policy & decision-making levels. The first map of the 14 Critical Raw Materials in Europe, delivered in September 2010, was used by EC Vice-President A. Tajani in an article, by DG Enterprise in the frame of EU’s Raw Material Initiative, and for the preparation of a Euromines – DG Trade meeting. The circulation of this document triggered a request by the Hague Centre for Strategic Studies (HCSS), The Netherlands, for a dedicated version to complement Europe’s Strategic Energy Technology Plan that comprises an inventory of the metal requirements for six high priority energy technologies (e.g. wind, solar, nuclear etc.) in order to assess whether metal supply may constitute a risk. The ProMine Critical Raw Materials map was used also in support of the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: “Tackling the challenges in commodity Markets and on Raw Materials”. Brussels, 2.2.2011 COM(2011)25 final.

List of Websites:

http://promine.gtk.fi

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Related documents

- [final1-promine-consortium.pdf](https://cordis.europa.eu/project/id/228559/reporting/en)

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