Mineral Resources and Material Substitution (MISU) Academy Programme

Analysis of Impact Towards and Interaction with Economic Life

ACADEMY OF FINLAND

Contents

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Executive summary

This report provides an international expert evaluation of a 13 million euro research programme, the Academy of Finland's Academy Programme Mineral Resources and Material Substitution (MISU). The evaluation was initiated by the Academy of Finland. The expert evaluation group, referred to as 'panel' in this report, was asked to provide a critical final evaluation of the programme, focusing on the *impact towards and interaction with economic/business life.* Based on its findings on this area, the panel was expected to identify strengths and weaknesses of the programme and to provide any recommendations for use of the Academy of Finland.

Specifically, the panel was asked to rate the research projects of the programme individually against chosen evaluation questions, and form a programme-level synthesis of the programme's impacts and interaction based on the individual ratings. The panel was expected to choose independently the relevant evaluation questions.

The Academy of Finland provided the panel with a range of data sources, which included the programme memorandum, the final reports from 16 out of the 19 projects (calls 1–3) of the programme, and the impact stories from the 26 out of 42 subprojects of the programme. Here, a subproject refers to a part of a consortium project.

The evaluation covered the projects of the first three calls of the programme. The three projects from the fourth call were still ongoing in spring 2021, and they were not considered in the evaluation.

The panel worked during and between a series of online video meetings. In May 2021, members and the chair of the panel participated in and impact seminar organised by the MISU programme. The seminar included invited presentations from industry and MISU project leaders.

The MISU programme memorandum included the improvement of the international competitiveness of research and industry as one of the goals of the programme, and projects were observed to show activities towards this goal. The panel judged that the programme promoted interaction between universities and business life and created opportunities for knowledge transfer. Many projects organised seminars with invited participants from industry and received samples or data collected by companies.

Some projects provided evidence of deeper collaboration with industry, where company members had an active role in project planning, research and scientific publishing. The panel found two cases in which the research of the project was assessed to approach commercial applications, at an approximate technical readiness level of 5–6.

The panel also observed that about two-thirds of the projects had limited or no interaction with industry, and, similarly, about two-thirds of the projects had zero ratings in all impact-related questions. It is understandable that projects having their focus in fundamental research may have little interest to industry cooperation. In addition, the projects of the programme had been selected based on scientific excellence. However, in general, the projects of the MISU programme were inclined to applied research, and, therefore, the panel judged that despite strong industry ties shown by some projects, the programme was not able to take full advantage of all benefits offered by collaboration with industry.

The panel recommends that the Academy of Finland, in future calls in the mineral resources sector, strengthens the emphasis on industry collaboration, especially in applied or advanced TRL (Technology Readiness Level) research.

1. Introduction

During its council period 2010–2012, the Academy of Finland's Research Council for Natural Sciences and Engineering proposed to the Board of the Academy that minerals research be a part of the Arctic research programme. The Research Council for Natural Sciences and Engineering in 2013–2015 proposed a full "minerals and mining" research programme to be launched with a focus on critical minerals, and the Board of the Academy then decided to start the programme.

A programme workshop to discuss the more specific contents of the programme was organised in 2014. The steering group of the programme prepared a programme memorandum in 2014–2015 and named the programme the Mineral Resources and Material Substitution (MISU) programme. The programme memorandum is available at www.aka.fi/misu.

1.1. Scope and objectives of the programme

The programme was focused around three research themes: Primary mineral resources, Materials efficiency and recycling, and Material substitution.

The objectives of the programme were

- to strengthen multidisciplinary and interdisciplinary approaches and to move towards a more systemic orientation in the research
- to provide a broad and in-depth coverage of the occurrence, properties, processing, use and recycling of rare, especially metallic minerals as well as alternative materials used as substitutes for metallic minerals
- to create a knowledge base that will facilitate responsible mining and recycling operations that are aware of their impacts on the natural environment and the surrounding society.

The other objectives of the programme were

- to establish new multidisciplinary research groups and networks of national and international collaboration
- to increase the national and international mobility of researchers
- to improve the international competitiveness of research and industry
- to bring Finnish research to the international forefront in selected research areas
- to achieve broad societal impact for research into mineral resources and alternative materials.

The scope and objectives of the programme are described in more detail in the programme memorandum (www.aka.fi/misu).

1.2. Programme calls

In total, the programme launched four funding calls. The funding for the programme totalled 13 million euros. In total, 22 projects were funded (either individual or consortium projects). The funded projects are listed in Appendix A.

The first call on Primary Mineral Resources had the above-mentioned specific requirement for fostering “knowledge-based growth”. In total, six projects were funded in this call. The funding volume for this call was 4 million euros, and the funding period ran from 1 September 2014 to 31 August 2018.

The name of the second call was Mineral Resources and Material Substitution. Research projects from all aspects of the programme could be offered for this call. In total, eight projects were funded. The funding volume for this call was 6.5 million euros, and the funding period ran from 1 September 2015 to 31 August 2019.

The third call was the International Call for Joint Projects in Mineral Resources Research: Academy of Finland and NRF, South Africa, and Academy of Finland and CONICYT, Chile. In total, five projects were funded in this call: four Finnish-South African collaboration projects and one Finnish-Chilean collaboration project. The total funding in this call was 1.5 million euros, and the funding period ran from 1 March 2016 to 28 February 2019.

The fourth call was named MISU Academy Programme: Funding for International Projects. The call was aimed at providing funding for specific topic areas of the programme, chosen by the steering group, and for international collaboration in these chosen topic areas. In total, three projects were funded. The funding for this call amounted to 1.0 million euros, and the funding period ran from 1 October 2018 to 30 September 2021.

2. Evaluation

2.1. Premises of evaluation

The Nomination letter of the steering group of the programme stated that the decision on the final evaluation will be made by the steering group.

In 2019, the steering group decided that the final evaluation of the programme should be focused on *impact towards and interaction with economic/business life*. This choice was in part due to the fact that 30% of the funding was aimed at fostering knowledge-based growth This in turn was in part due to the fact that particularly minerals research as a field of research is close to the industry, and the role of the minerals industry in Finland is important. Furthermore, one of the objectives of the programme was to improve the international competitiveness of (Finnish) industry.

The Academy of Finland decided the evaluation process and collected material for the evaluation. The evaluation panel was recruited to carry out the evaluation in early 2021.

2.1.1. Panel members

The panel was assembled in 2021, and it included the following members: Professor (emeritus) Juha Karhu, University of Helsinki (Chair), Dr Roland Gauss, EIT Raw Materials, Professor Britt-Marie Steenari, Chalmers University of Technology, Dr Patrick Nadoll, EIT Raw Materials, and Dr Olli Salmi, EIT Raw Materials.

2.1.2. Terms of reference

The goals of the panel were to provide a programme-level synthesis of the impacts and interaction of the programme, identify strengths and weaknesses of the programme, and, based on its findings, provide any recommendations for use of the Academy of Finland.

The panel was given a time frame from March 2021 to June 2021 to perform the actual evaluation work. The final report was to be completed by autumn 2021.

The panel was asked to rate the research projects of the programme individually against the chosen evaluation questions, and form the programme-level synthesis of the impacts and interaction of the programme based on these individual ratings. It is noted that the panel was asked also to choose independently the evaluation questions that it considered relevant, based partly on the information contained in the materials available and partly on judging the importance of the questions. The list of evaluation questions is given in Appendix B.

2.1.3. Materials for the panel for evaluation

The key material delivered to the panel for the evaluation included:

- programme memorandum
- final reports from 16 out of 19 subprojects (calls 1–3) of the programme
- impacts stories from 26 out of 42 subprojects of the programme (see Appendix C)
- answers to six evaluation questions received from 17 out of 19 consortium projects.

Before performing the evaluation, the original evaluation criteria for selecting projects for funding were discussed with the panel. It was emphasised to the panel that the primary and most important criterion was scientific excellence, whereas the projects' potential for generating impact towards and interaction with economic life was of secondary importance and not a necessary requirement for funding.

2.2. Evaluation process

The panel worked during and between a series of online video meetings. In May 2021, some members and the chair of the panel participated in an impact seminar organised by the MISU programme. The seminar included invited presentations from industry and MISU project leaders.

To evaluate the impact and interaction of the projects with economic/business life, the panel prepared nine evaluation questions, six of which were separately forwarded to the eleven consortium project leaders and the eight PIs of the individual projects. The three remaining questions were assessed solely based on the project impact stories and final reports. The panel evaluated the answers from 0 to 3. For a score of 0, the panel did not find any evidence for activity around the question. A score of 1 indicates fair, score 2 good and score 3 excellent results in the question.

After considering different alternatives, the panel decided that the evaluation of the programme would be performed at consortium project level, including the consortium projects and the individual projects outside consortia. In total, 17 out of the 19 consortium projects and individual projects responded to the evaluation questionary sent by the panel. In the following, consortium projects and the individual projects outside consortia will be referred shortly as projects.

3. Specific findings

3.1. Interaction with economic/business life

Two different points of view were considered in evaluating interaction of the projects with economic and business life. Firstly, the panel assessed the extent of active industry participation in the project, covering planning, research and joint publishing of project findings. Secondly, the panel evaluated the active role taken by the projects in getting industry partners involved and in promoting knowledge transfer between the projects and industry.

The three evaluation questions in this group were assessed based on the responses received from the 17 project leaders.

3.1.1. Evaluation question 1: Active industry participation

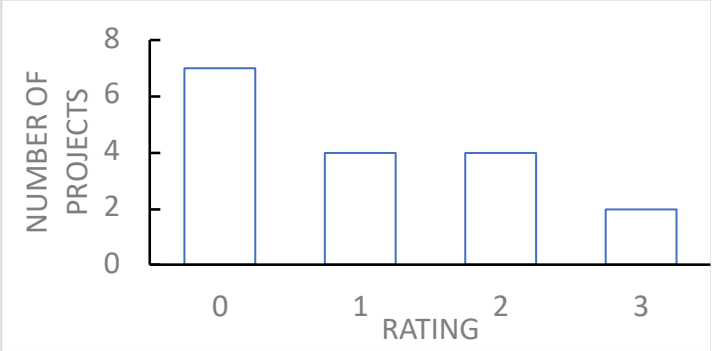

Figure 1. Activity of industry partners in the projects (0 = no evidence, 1 = fair, 2 = good, 3 = excellent).

It is notable that six projects (35%) included members from industry in project planning, meetings, research, and/or project reporting. The panel judged these projects to show industry-related activities at a good or excellent level (Fig. 1).

3.1.2. Evaluation question 2: Joint publications with industry

To further characterise scientific collaboration with industry, the panel collected information about publication activity jointly with co-authors from industry. Joint articles provide definitive evidence for active research collaboration and commitment of the industry partners to the project. The publication process is typically slow, and the statistics of the survey presented here do not necessarily provide the final situational picture.

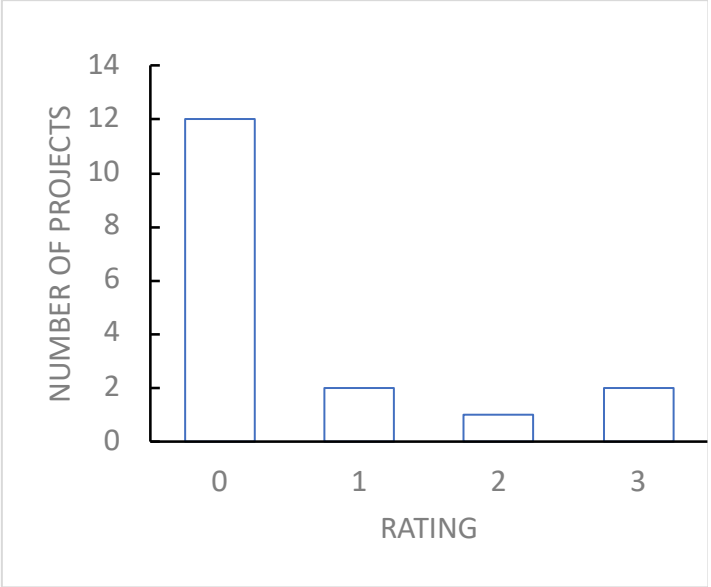

Figure 2. Activity of scientific publishing with industry partners included as co-authors (0 = no evidence, 1 = fair, 2 = good, 3 = excellent).

According to the judgement of the panel, joint publishing activity with industry was relatively rare. A large majority of the projects did not report any publications with company members, and five projects (29%) had submitted or published joint publications with industry (Fig. 2). Based on a large number of publications, two projects were assessed to show excellent level of activity in this area.

3.1.3. Evaluation question 3: Organisation of seminars and meetings with invited participation from industry

The panel also considered the role taken by the projects in creating and maintaining connections and enhancing collaboration with business life. Evidence for an active role in collaboration was provided, for instance, by the organisation of interactive seminars or informal meetings with industry partners. The panel judged six projects to have performed at a good level, but none of the projects had reached an excellent level (Fig. 3). Surprisingly, five projects reported no meetings, seminars or other activities targeted at business life.

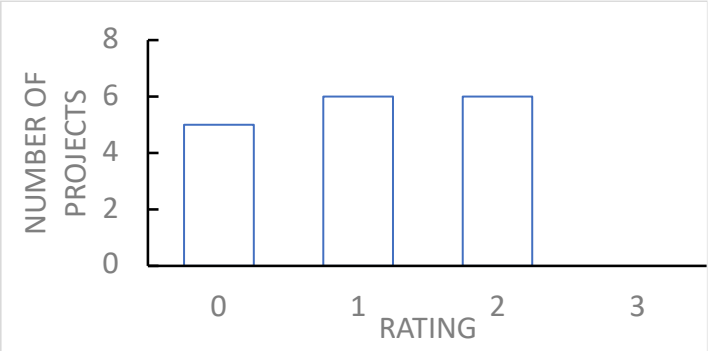

Figure 3. Activity of projects in creating interactive seminars or other events with invited participation from industry (0 = no evidence, 1 = fair, 2 = good, 3 = excellent).

3.1.4. Summary of interaction with industry

In summary, about one-third of the projects showed good or excellent performance in interaction with and involvement of business life in project activities. Also, in the open comments to the Academy, project researchers emphasised the possibility for collaboration with industry as a major advantage. About two-thirds of the projects had either no documented interaction or only limited interaction with industry.

3.2. Impact towards economic/business life

A successful project in mineral resources sector is expected to influence its environment in the form of growth in scientific understanding, as innovations affecting society and as knowledge transfer from universities to companies. In many cases, the knowledge transfer is indirect and not necessarily purposedly planned by the project, and the impact towards economic/business life may be delayed.

At a more general level, implementing science-industry collaborative projects not only increases the likelihood of research results being commercialised but it also can have a positive impact on how scientific knowledge is perceived in industry. This, in turn, leads to better anchored, science-based research in industry, and can increase much needed industry investments in R&D.

The panel restricted its assessment to consider only the evidence for direct and immediate impact towards business life. These include knowledge transfer to industry by researcher recruitment, patent applications and the establishment of start-up companies. Finally, the panel evaluated the distance of the research from the point where it could find commercial applications, and the descriptions of the routes, how the research leads to applications in industry.

Evaluation questions 5 and 6 were assessed based on the 17 responses from the project leaders. Evaluation questions 4, 7 and 8 were evaluated based on the

information included in the final reports and impact stories. This assessment was also restricted to the 17 projects that had responded to the evaluation questionnaire.

3.2.1. Evaluation question 4: Knowledge transfer and mobility

Active industry connections enhance the possibilities of recruitment of university researchers to industry, which leads to knowledge transfer. This is fruitful for both parties. University researchers with a master's or doctoral degree find jobs outside academia, and industry gets experts with an up-to-date education.

Nine of the 17 projects (53%) reported that project researchers had transferred to industry. In the assessment of interaction with industry, most of these projects were judged by the panel to include at least fair industry participation.

3.2.2. Evaluation question 5: Start-ups

Establishment of a start-up company by project staff provides solid evidence for impact towards business life. Some projects are strongly inclined to fundamental research, and it is understandable that their activities do not generally lead to start-up companies. However, the panel acknowledges that the MISU programme included four projects that had proceeded to the stage of establishing a start-up company. The establishment itself was judged to mark the impact, without consideration of the subsequent success of the start-up company.

3.2.3. Evaluation question 6: Patent applications and patents

The panel also considered the number of patent applications (Fig. 4). Patent applications provide evidence of innovation leading to new solutions, possibly to new commercial applications. The panel noticed that most of the projects had not filed any patent applications. However, the MISU programme included a small group of four projects that had filed one or more patent applications.

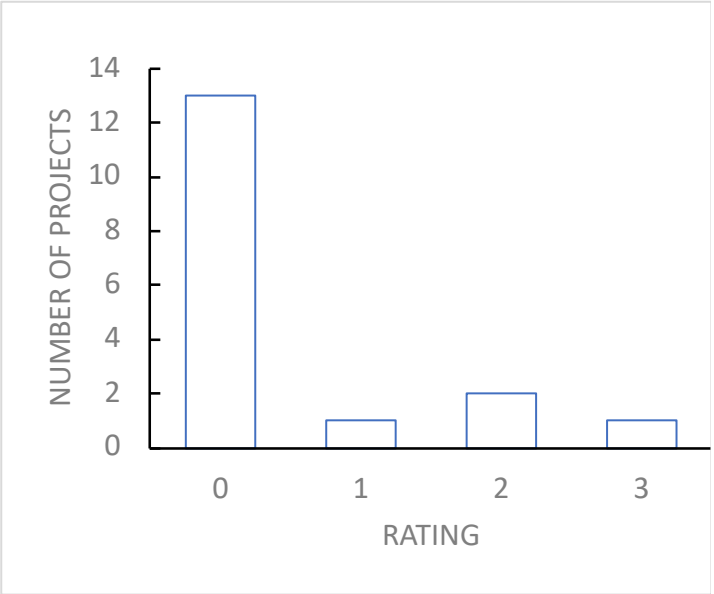

Figure 4. Activity of projects in making patent applications (0 = no evidence, 1 = fair, 2 = good, 3 = excellent).

3.2.4. Evaluation question 7: Prospects for commercial applications

In considering the possibilities for finding commercial applications, the panel judged that two projects had fair, and three projects had good or excellent possibilities (Fig. 5). The two projects with excellent possibilities for commercial applications were estimated to be on technology readiness levels 5 or 6.

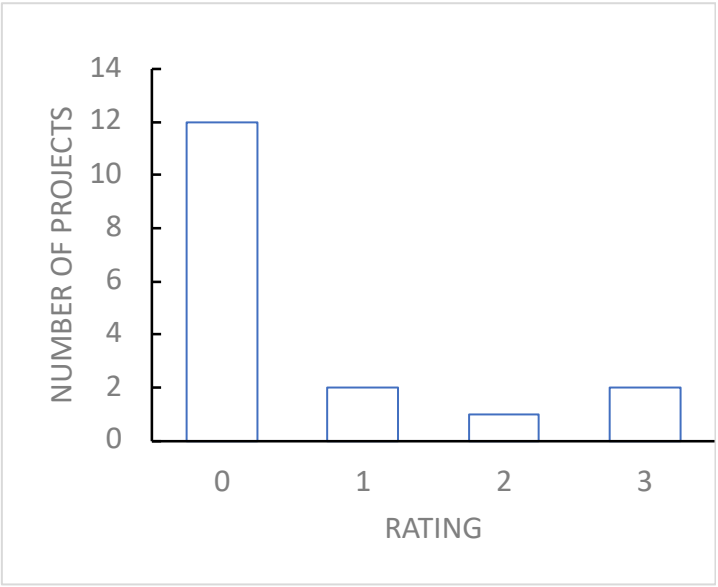

Figure 5. Closeness to finding commercial applications (0 = no evidence, 1 = fair, 2 = good, 3 = excellent).

3.2.5. Evaluation question 8: Description of routes to commercial applications

The panel assessed how well the projects had described routes to possible commercial applications. The panel judged that four projects expressed realistic considerations for commercial applications, and three of these were estimated to have good or excellent insights of the routes to commercial exploitation of project findings (Fig. 6).

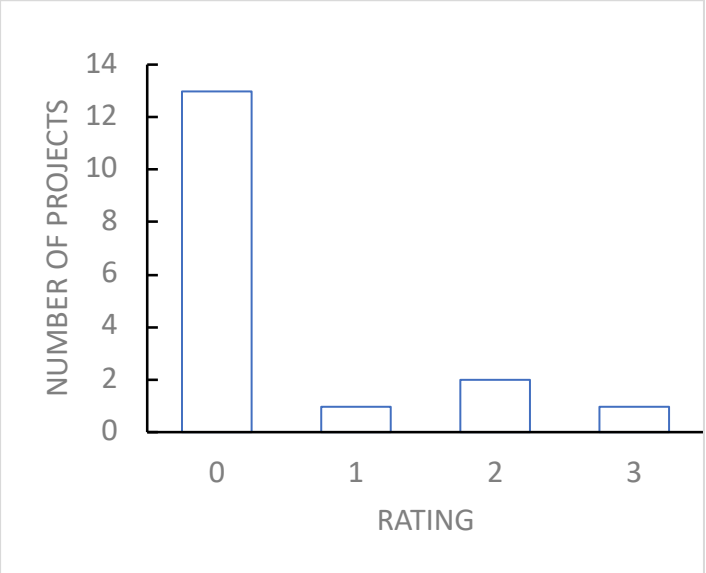

Figure 6. Level of description of routes leading to commercial applications (0 = no evidence, 1 = fair, 2 = good, 3 = excellent).

3.2.6. Summary of impact

In total, the panel was able to identify six high-impact projects (35%), which had positive ratings in one or more impact-related assessment questions 5, 6, 7 or 8. Correspondingly, 11 projects (65%) had zero ratings in all these questions.

An analysis of the share of the high-impact groups in the three calls reveals considerable variation between them. The first call of the MISU programme was targeted at primary mineral resources. Six projects were funded, and only one of these was included in the high-impact group.

In the second call, named Mineral Resources and Material Substitution, eight projects were funded and three of these were included in the high-impact group. The proportion of high-impact projects in this call was clearly higher than in the first call.

The third call was the International Call for Joint Projects in Mineral Resources Research with international funding partners from South Africa and Chile. In total, five projects were funded, and three of these were included in the assessment. Two out of the three projects belonged to the high-impact group. The number of

evaluated projects in the third call was small, but clearly the call attracted research groups with a large potential for industry cooperation and impact.

3.2.7. Evaluation question 9: Funding

Finally, as a separate question, the panel considered the success of the researchers of the MISU programme in attracting additional funding (Fig. 7). The assessement was made without consideration of the funding source or the research topic of the new project.

The period in question covers the beginning of the project between 1 March 2014 and 1 September 2016 to the time of the evaluation in spring 2021.

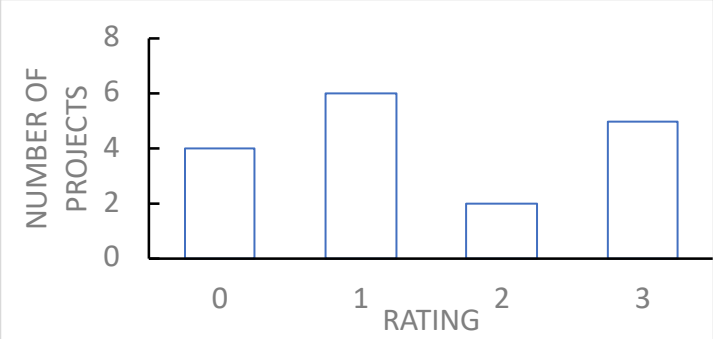

Figure 7. Volume of additional funding (0 = no evidence, 1 = fair, 2 = good, 3 = excellent).

The amount of new funding varied from nothing to several million Euros. The panel could not observe any dependence between the acquired external research funding and the activity in industry cooperation. In general, the research projects active in the field of mineral resources and material substitution seem to have been able to find new funding sources reasonably well, irrespective of the level of industry collaboration.

4. Discussion and recommendation

The panel discovered that the Academy's MISU Academy Programme promoted interaction between universities and business/economic life and created opportunities for knowledge transfer. About one-third of the participating projects were assessed to show interaction with and impact towards business life at a good or excellent level. Two-thirds of the projects had only limited or no interaction with industry, and a similar proportion of the projects showed no activities towards business life. This brings up the possibility that the programme did not take full advantage of all benefits offered by collaboration with industry.

The programme memorandum defined multi- and interdisciplinarity as important goals of the programme together with other objectives, such as increase in

mobility, improvement of international competitiveness, bringing Finnish research to the international forefront and achieving broad societal impact. One of the additional aims listed in the memorandum was “improving the international competitiveness of research and industry”. Although not written explicitly, this can be implied to include interaction with economic/business life as one of the programme goals.

The panel understands that the Academy of Finland is the main organisation funding basic research in Finland. Also, the projects of the MISU programme provide evidence of fundamental research as a significant and valuable sector of research. Considering this and the formulation of the objectives in the programme memorandum, the interaction with and impact towards business life may be considered to be at a good level.

However, bearing in mind the field of mineral resources and material substitution, the panel thinks that even larger benefits would have been realised if the programme had paid more attention to promoting interaction between university researchers and industry, specifically in projects operating in applied and/or advanced Technology Readiness Level research.

RECOMMENDATION OF THE PANEL:
The panel recommends that the Academy of Finland, in future calls in the mineral resources sector, strengthens the emphasis on industry collaboration, especially in applied or advanced Technology Readiness Level research.

Appendix A: List of MISU projects

Primary mineral resources – targeted call

Funding : €4 million. Funding period: 1 Sep 2014–31 Aug 2018

1. **Multiple lines of evidence in assessing ecotoxicological and human health risks of mine effluents and public perception**

   - Jussi Kukkonen, University of Jyväskylä
   - Timo Huttula, Finnish Environment Institute
   - Ilkka Miettinen, National Institute for Health and Welfare
   - Rauno Sairinen, University of Eastern Finland

2. **"Social license to operate": a real tool or rhetoric? Examining the mining industry in Finland, Australia, and Canada**

   - Rauno Sairinen, University of Eastern Finland
   - Tapio Litmanen, University of Jyväskylä

3. **Rapid analysis of minerals and rare earth elements by time-gated laser spectroscopy – LaseREE**

   - Saara Kaski, University of Jyväskylä
   - Mircea Guina, Tampere University of Technology
   - Heikki Häkkänen, University of Jyväskylä
   - Juha Kostamovaara, University of Jyväskylä

4. **Safe, sustainable and selective methods for dissolution and recovery of noble metals**

   - Timo Repo, University of Helsinki

5. **New Chelating Agents for Selective Extraction of Uranium (URAEXT)**

   - Heikki Tuononen, University of Jyväskylä

6. **Mineral Systems and Mineral Prospectivity of Finnish Lapland**

   - Ferenc Molnár, Geologial Survey of Finland
   - Eero Hanski, University of Oulu

Mineral resources and material substitution call 2014

Funding : €6.5 million. Funding period: 1 Sep 2015 – 31 Aug 2019

1. **New laser and spectral field methods for in situ mining and raw material investigations**

   - Jussi Leveinen, Aalto University
   - Juha Hyyppä, Finnish Geospatial Research Institute FGI
   - Saara Kaski, University of Jyväskylä
   - Juha Kostamovaara, University of Oulu

2. **Sustainable platinum group metal free catalyst materials**

   - Kari Laasonen, Aalto University
   - Tanja Kallio, Aalto University
   - Esko Kauppinen, Aalto University

3. **Novel synthesis methods for porous ceramics from mine tailings**

   - Jouko Niinimäki, University of Oulu
   - Päivi Kivikytö-Reponen, VTT Technical Research Centre of Finland Ltd
   - Erkki Levänen, Tampere University
   - Marja Liisa Räisänen, Geological Survey of Finland (GTK)

4. **High-performance geoscientific computing in multi-scale mineral potential studies**

   - Jan Westerholm, Åbo Akademi University
   - Eevaliisa Laine, Geological Survey of Finland (GTK)

5. **Advanced technologies for sustainable exploitation of uranium-bearing mineral resources**

   - Jouko Vepsäläinen, University of Eastern Finland
   - Aino-Maija Lakaniemi, Tampere University
   - Vesa-Pekka Lehto, University of Eastern Finland
   - Raisa Neitola, Geological Survey of Finland (GTK)

6. **Identification of potential flake-graphite ores in the Fennoscandian shield and utilization of graphene (FennoFlakes)**

   - Nils Olav Eklund, Åbo Akademi University

7. **Thermoelectric Materials based on Earth-Abundant Oxides (TEOX)**

   - Maarit Karppinen, Aalto University

8. **Development of novel electrodeionization system for recovery and recycling precious metals and rare earth elements from mining effluents**

    - Mika Sillanpää, Lappeenranta University of Technology

International call for joint projects in mineral resources research: Academy of Finland and NRF, South Africa, and Academy of Finland and CONICYT, Chile

Funding : €1.5 million. Funding period: 1 Mar 2016 – 28 Feb 2019

Academy of Finland and CONICYT, Chile

1. **Particulate matter in mines and mining environments**

    - Hilkka Timonen, Finnish Meteorological Institute
    - Jorma Keskinen, Tampere University

Academy of Finland and NRF (South Africa)

2. **Recovery of rare earth elements from phosphogypsum**

    - Tuomo Sainio, Lappeenranta University of Technology
    - Pertti Koukkari, VTT Technical Research Centre of Finland Ltd
    - Jason Yang, Geological Survey of Finland (GTK)

3. **On-line Risk Management in Deep Mines (ORMID)**

    - Mikael Rinne, Aalto University

4. **Towards sustainable mineral processing via plantwide eMPC**

    - Sirkka-Liisa Jämsä-Jounela, Aalto University

5. **Protocol development for evaluation of water-saving alternatives in minerals processing - “Bridging North to South”**

    - Pekka Taskinen, Aalto University

Please note that the projects below were not included in this evaluation.

MISU Academy Programme: funding for international projects

Funding: €1 million, funding period: 1 Oct 2018 – 30 Sep 2021

1. **Steps towards the use of mine tailings in geopolymer materias: reactivity, CO2 sequestration and heavy metal stabilization**
    - Mirja Illikainen, University of Oulu
2. **Towards Sustainable Gold Recovery from Tailings (GoldTail)**
    - Mari Lundström, Aalto University
3. **Geophysical and Geochemical Methods for Stope Design (GAGS)**
    - Mikael Rinne, Aalto University

Appendix B: Evaluation questions

Evaluation questions for the project principal investigators and for panel evaluation

1: Active industry participation:
How many industry representatives have there been involved in the project/project's steering group or performing part of the project's research? What has been their role in the project? Please, give a number and otherwise answer very briefly (on behalf of the whole consortium).

2: Joint publications with industry:
How many joint publications with companies has the project generated? Please, provide details (title, authors, journal). Please, provide the overall number for the whole consortium.

3: Organization of seminars and meetings:
Apart from the MISU programme activities, has the project (or sub-project) reportedly organized interactive happenings/seminars/meetings etc. with company representatives invited/present? Yes/no. If many, please provide a number (or how many per year approximately). Please, provide the data for the whole consortium.

4: Knowledge transfer and mobility:
Has any researcher in the research group moved to industry/company or vice versa? Please, provide a list.

5: Start-ups:
Has any of the project's personnel established a start-up company (essentially based or to the relevant parts based on the findings/ideas evolved in the project)? Yes/no. If yes, provide the name(s) of the start-up(s) (on behalf of the whole consortium).

6: Patents applications and patents:
How many patent applications or accepted patents has the project generated (EU/US)? Please, provide just a number (on behalf of the whole consortium).

7: Prospects for commercial applications:
How far is the research from the point when it could find commercial applications? In time? In steps to be taken and in further research to be made? TRL level?

8: Description of routes to commercial applications:
Has the project been able to describe the routes how the research leads ultimately for use in economic life? How credible is it?

9: Funding:
How much has the project generated additional research funding (EU, Academy of Finland …)? Please, provide list of projects (for the whole consortium), type of project and total funding (if possible). Have the project's results or ideas evolved in the project led to submission of funding application to Business Finland, EIT Raw Materials or concrete actions with companies? Describe with few sentences!

Appendix C: Impact Stories

Mineral Resources and Material Substitution (MISU) Academy Programme

Impact Stories

ACADEMY OF FINLAND

Contents

1. Multiple lines of evidence in assessing ecotoxicological and human health risks of mine effluents and public perception (MineView)

Finnish Institute for Health and Welfare (THL)

New knowledge generated in the project

The project enabled usage of next generation sequencing (NGS) techniques to explore microbial communities in mining affected watersheds. As an outcome, vast amount of comprehensive data on total and active microbial communities in lake water and sediments were received as well as novel understanding on the ecosystem level effects. The main outcomes can be concluded:

1) The water and sediment microbiome in water bodies receiving mining industry effluents was successfully characterized.

2) The information gained by multiple methods for a summarized assessment was finally integrated using the weight-of-evidence-approach, and the specifications on which of the levels of the ecosystem the effects are most severe were evaluated.

In the concurrent ERDF-funded project called Mine Water Excellence Network, an online, openly available tool called Mine Water Risk Assessment model (KAVERI model) – http://fi.opasnet.org/fi/Kaivosvesien_riskit_(KAVERI-malli) was developed for the purpose of risk assessment of mine waters. The model provides information to anyone interested in exploring the data behind the safety recommendations related to mine waters and contamination levels. The model even enables the users themselves to make their own risk calculations based on the available data. The development of the Mine Water Risk Assessment Model benefitted from the research simultaneously carried out in the MineView project and vice versa.

Exploitation of the project results by industry or economic life

The MineView project of the MISU programme and the concurrent ERDF-funded Mine Water Excellence Network complemented each other very advantageously in terms of the research themes, acquired data, developed tools and research and stakeholder networks. One practical result from the project concerns the novel risk assessment tool for mine waters in the Internet: 'Kaivosvesien riskinarviointimalli' http://fi.opasnet.org/fi/Kaivosvesien_riskit_(KAVERI-malli). The Mine Water Risk Assessment model (KAVERI model) is open, free and directly applicable for risk assessment of mine waters e.g. by consultants, companies of the field; basically by anyone harboring the necessary expertise. KAVERI model can also be utilized in promoting the knowledge of environmental effects of mine effluents and thereby it can be helpful e.g. in the issues of social license of mining industry.

The water and sediment microbiome results as well as the results of the integrated environmental assessment of the MineView project provide important novel information of the effects of mining effluents on the ecosystems of the receiving water bodies, which may be valuable e.g. when designing new (mining) industry, its placement and processes (like those related e.g. to mine/waste water treatment).

Researcher careers

The MineView project provided a good forum for contacts among scientists and representatives of the mine industry. The contacting activity could take place during the project meetings and specific seminars (see above).

Impact of the project in relation with the goals of the MISU programme

The MISU programme aimed "*to create a knowledge base to facilitate responsible mining and recycling operations that are aware of their impacts on the natural environment and the surrounding society*" .

MineView project addressed the impacts of mining activities on the surrounding aquatic ecosystems. Given the intense pressure on a national scale to increase the usability of mineral resources and mining activities to boost national economy and competitiviness, the project focused on the assessment of both ecological and human health effects and social implications as risk perception by the local people due to contamination of surface water and fish.

Interaction with industry/economic life

Main interaction event concerned the final seminar of the MineView project that was held at the University of Jyväskylä on 31.5.2018, with approximately 85 participants. Seminar participants were from research institutes, ELY-centers, mining and consulting business, and local ownership partners of the water area.

Besides the MineView seminar THL has presented the most significant results in many seminars and conferences: Kaivosten ympäristönsuojelupäivät Oulu 11-12.10.2017, FEM conference 31.10.-2.11.2017 Levi, Mine Water Excellence Network project seminar Kuopio 4.12.2017 and in international mine industry project meeting at GTK, Kuopio 10.4.2018. THL collaborated in exchange of knowledge with Sulfator Ltd and Terrafame Ltd during the project.

2. "Social license to operate": a real tool or rhetoric? Examining the mining industry in Finland, Australia, and Canada

Principal investigator: **Tapio Litmanen**, University of Jyväskylä

New knowledge generated in the project

Research on the social licence to operate (SLO) has traditionally focused on local communities directly affected by mining operations. There has been a lack of

systematic research exploring attitudes to mining among the public at large. Based on a national survey (N=1,091) of Finns' attitudes towards mining conducted in 2016, we tested a theoretical model using path analysis to examine the factors affecting the social licence to operate (SLO) of mining in Finland. The results show that among the Finnish public the factors having the greatest influence on the mining SLO (directly or indirectly) are balance of benefits over impacts, governance capacity, procedural fairness, distributive fairness, resource nationalism and trust in the mining industry. Our findings support the crucial role of trust for SLO, but additionally highlight the importance of balance over benefits. The results suggest that building trust and SLO requires more than just the actions of either the industry or governments alone – a social licence requires joint efforts.

When considering the importance of mining, the data shows that mining is generally considered as central to Finland. The respondents from mining regions (North Karelia, Kainuu, Northern Ostrobothnia and Lapland) tended to consider mining as more important to Finland than the respondents from the metropolitan region of Uusimaa. However, the results showed that mining was seen in all three geographical regions (1. metropolitan region of Uusimaa, 2. mining regions, 3. other Finnish regions) as the least important industry to the future of the Finnish economy when compared with other key industries.

Overall, when considering the general acceptance of mining, the results indicated a somewhat positive response. The general acceptance of mining was not weak nor very strong. The average scores were highly consistent across metropolitan region, mining regions and other regions.

In addition to the general acceptance of mining, we were also interested in examining more precisely the acceptance of mining for particular extractives both at the level of Finland in general and at the level of the respondent's home municipality. At the level of Finland in general, the acceptance levels especially for the mining of base metals, precious metals and industrial minerals were quite high. The most accepted were the mining of base metals, precious metals and industrial minerals and the least accepted was the mining of uranium. The acceptance of mining for base metals and industrial minerals was significantly higher in the mining regions than in the metropolitan region of Uusimaa. Interestingly the results showed that the acceptance levels of all the extractives of interest were generally lower when the perspective was shifted from the level of Finland to the level of one's own home municipality.

Exploitation of the project results by industry or economic life

The results of the project have been exploited by the industry or economic life through different channels. The findings reached Finnish mining industry through interest organization FinnMin (Finnish Mining Association). Generally, the understanding of public attitudes towards mining sector, mining activities and different minerals was at rather low level. The findings enabled industry, business life, public sector and civil society actors to revise their understanding of public attitudes and as a consequence of that possibly to reformulate their strategies. For instance, renewal of mining legislation is ongoing process. Thus, different

stakeholders have updated knowledge on social acceptance of mining as well as knowledge how citizens of different regions perceive challenges and problems of sustainable mining.

Development work during the MISU programme lead to cross fertilization of the concept of SLO to energy sector. SLO approach was developed further in cooperation with senior researcher Matti Kojo's (Univ. of Tampere) in a project "Acquiring Social License for Disposal: trust and acceptance" (SOLID) and "Governing Safety in Finnish and Swedish Nuclear Waste Regimes" (SAFER), which were funded by Finnish Research Programme on Nuclear Waste Management (KYT). The outcome is a research article "The roles of the state and social licence to operate? Lessons from nuclear waste management in Finland, France, and Sweden" (Energy Research & Social Science: DOI: 10.1016/j.erss.2019.101353).

Researcher careers

A researcher mainly in charge of everyday running of the project at the University of Jyväskylä was Tuija Jartti. Afterwards she was recruited to another project called "Collaborative remedies for fragmented societies – facilitating the collaborative turn in environmental decision-making – CORE". The project is part of the Strategic Research Council programme "Changing society and active citizenship". Currently she is on maternal leave. Her doctoral thesis manuscript on the acceptance of uranium mining will be ready by the end of the year 2020.

Dissemination of findings were actively promoted through different channels. For instance cooperation with Finnish mining industry was managed through interest organization FinnMin (Finnish Mining Association). FinnMin informed its members (50 members; including mining operators, contractors, suppliers of machinery and equipment, service providers and exploration companies). Another example of active information dispersal is joint press conference and briefing together with FinnMin, Finnish Nature Conservation Association, Ministry of Trade and Industry, Geological Survey of Finland, University of Eastern Finland and Academy Programme Mineral Resources and Material Substitution (MISU, 2014–2021). Another example of dissemination efforts are presentations in different events such as the Kokkola Material Week 27.10.–1.11.2018, which is a joint platform for representatives and stakeholders of chemical industry, bioeconomy sector and mineral economy sector.

Impact of the project in line with the goals of the programme

Among others the aims of MISU programme were to 1) establish new multidisciplinary research groups and networks of national and international collaboration, 2) increase the national and international mobility of researchers, 3) improve the international competitiveness of research and industry, 4) bring Finnish research to the international forefront in selected research areas, 5) achieve broad societal impact for research into mineral resources and alternative materials and 6) move towards a more systemic orientation in the research fields concerned, 7) create a knowledge base that will facilitate responsible mining and recycling operations that are aware of their impacts on the natural environment and the surrounding society.

The research project contributed to these aims for instance by participating on a network called “Partnering for global impact: National citizen attitudes to mining research program” (2012-2018). Network was led by Australia’s national research agency CSIRO (the Commonwealth Scientific and Industrial Research Organisation). The research network conducted national studies in Australia, Chile, China and a pilot in Zambia. This multi-country research program is also being extended through the Global Citizen Voices in Mining partnership with ICMM (International Council on Mining and Metals) and IIED (International Institute for Environment and Development). As part of this multidisciplinary collaboration Tuija Jartti made a research visit at CSIRO in Brisbane, Australia 10.8.-3.9.2017. She also networked with researchers especially at the Mineral resources –unit at CSIRO. During her stay she also visited Sustainable Minerals Institute (SMI) at the University of Queensland and met researchers there. One can say that successful participation on the work of network and groundbreaking publications together with CSIRO improved the international competitiveness of research and industry and brought Finnish research to the international forefront in this selected research area. The joint efforts of this network have had broad societal impact for research into mineral resources and has certainly meant a move towards a more systemic orientation in this research field. The overall achievement of the network has been in creating a knowledge base that has facilitated responsible mining operations that are aware of their impacts on the natural environment and the surrounding society.

Interaction with industry/economic life

See answers to questions 2, 3 and 4.

3. Rapid analysis of minerals and rare earth elements by time-gated laser spectroscopy – LaseREE

Principal investigator: **Saara Kaski**, University of Jyväskylä

In LaseREE, the consortium aimed at establishing an approach based on laser spectroscopy, with potential for real-time analysis of rare earth elements (REEs) in rocks. University of Jyväskylä (JYU) constructed a robust signal processing method on both LIBS and Raman data, based on multivariate analysis, to reveal the mineral distributions of REE-bearing rocks efficiently. Experiments on REE-selective LIF spectroscopy were started. The knowledge of REE-bearing minerals and their structure and the texture (e.g. the size, location, and association of the mineral grains) in rocks may in the future applications enhance the quality of concentrates, save energy and reduce waste materials. The new scientific findings were disseminated on the respective research fields, not only to the scientific community but also to the end-users and great public. The members of the project team at Jyväskylä made site-visits to *e.g.* Outotec and Keliber facilities, University of Vienna and participated FEM, Finnish Geokemian päivät, Finnmateria, Finnish National Colloquium of Geosciences, two international geo-excursions organized by Masaryk University, Czech Republic. In addition, the project findings were

presented to all visitors during several Researcher's Night –occasion. Future experts (4 B.Sc., upcoming Ph.D.) were educated.

Sub-projects:"Rapid analysis of minerals and rare earth elements by time-gated laser spectroscopy –LaseREE", and "New laser and spectral field methods for in situ mining and raw material investigations"

Principal Investigator: Prof. **Juha Kostamovaara**, University of Oulu

Key results:

A technological platform for the fast analysis of the rare earth element (REE) and mineral composition in REE-bearing rocks and ore was developed together with our research partners. Our part of the work was to develop time-gated CMOS single photon avalanche diode (SPAD) line detector technologies for the fluorescence-free Raman spectroscopy to be used in these analyses. The sub-ns pulse mode laser illumination and time gating of the SPAD detectors results in substantial reduction of the fluorescence background in the measured Raman spectrum allowing the improvement of the signal-to-noise ratio and thus the measurement sensitivity. A measurement setup was constructed for this purpose. It consists of a 532 nm pulsed laser developed by our research partner (Tampere University of Technology), optics, a spectrograph and a custom-designed CMOS detector array with 16x256 SPAD elements and 256 time-to-digital converters. The developed detector allows to simultaneously measure 256 different spectral points in the Raman spectrum. This setup was used to measure successfully the Raman spectra of the REE samples together with our research partner so that results could also be compared to those achieved with other spectroscopic techniques (by the group working at the University of Jyväskylä).

One part of the study was to configure the developed set-up to a measurement mode which allowed the Raman spectrum recording to samples at a distance of ~1m and also to record the sample distance simultaneously with cm precision. This approach and result paves the way for the on-line and off-lab Raman characterization.

From the detector development point-of-view, the custom designed time-gated 16x256 CMOS SPAD array was characterized with regard to its timing in-homogeneities. The accurate characterization and the subsequent software-based compensation enabled to further improve the signal-to-noise ratio in the Raman measurement allowing the characterization of otherwise unresolved samples. These developments have paved the way for new SPAD/TDC array designs with improved performance and with considerably more spectral points.

The key results of these projects are documented in 9 journal and 8 conference papers produced as a result of these activities.

The above developments were based on the original time-gated Raman measurement technologies developed by the University of Oulu and VTT in earlier

projects. These technologies are currently commercialized by Timegate Instruments Ltd., which start-up company also followed the current activity and was partly involved with the Raman spectrometer set-up development. The co-operation continues in new commercialization projects funded by Business Finland and Timegate Instruments Ltd. In here, the main goal is in the detector development with emphasis on higher spectral resolution and lower detector noise. The development of the time-gated Raman technology in general is continued in a two new Academy projects supervised by Associate professor Ilkka Nissinen. Ilkka Nissinen was a senior researcher in the current project and got an associate professorship in 2019. In the new research activities the main goal is in addition to the detector development in new applications in pharmaceutical industry in collaboration with the Professor Marjo Yliperttula's group (Helsinki University) and in green economy (e.g. in water protection and recycling).

The cooperation with the project partners and the industry has been very vivid during the course of the project.

4. Safe, sustainable and selective methods for dissolution and recovery of noble metals

Principal investigator: Prof. **Timo Repo**, University of Helsinki

The MISU project entitled “Safe, sustainable and selective methods for dissolution and recovery of noble metals” was clearly targeted for basic research and was based on an exciting observation – dissolution of gold in organic solvents. Generally, we studied a set of dissolution methods with high academic impact and industrially potential applications towards recycling. Dissolution of noble metals is a very hot topic and is in the core of circular economy of valuable metals. Still today, selective dissolution of noble metals remains challenging under mild conditions. With the recent surge of interest in circular economy inventions, our project targeted to develop efficient yet sustainable methods for selective dissolution and recovery of noble metals. To reach this goal, the following aspects were considered: 1) development and selection of *S*-donor containing ligands for different noble metals, 2) mechanistic studies of dissolution, 3) recovery of metals from the reaction solutions, and 4) applicability of the new methods on electronic waste. The key result of this project was a quantitative and selective dissolution of gold in a short time period and under mild conditions. This was the fundamental finding of the project as the method competes with other similar systems and serves as a base for other methods. We have now been able to broaden the limits of our standard dissolution method and improve the cost-effectiveness of it. This means, that it has evolved to a setting, which is extremely appealing for recycling industries. In specific terms, the project generated new molecular level knowledge on the properties of group 11 metals with organic thiol ligands and revealed trends in the oxidation tendency of gold in the presence of these thiols. In the big picture, the project has brought thorough understanding and knowledge on the challenges of circular economy of metals on the aspect of chemistry.

Although the work was set as pure basic research, it has a great industrial relevance. Therefore, excellent opportunities for exploiting the research results related to dissolution of noble metals with industrial partners, especially with recycling industry, are apparent. As a proof-of-concept, we were able to quantitatively dissolve gold from printed circuit boards. However, in the field of metal recycling and recovery, there is still a lot of room for industrial applications as well as basic research. The impact our research has on recycling industries can be significant as it offers a simple and fast alternative to the known cyanide leaching of gold. The results of this project form an excellent starting point for future findings, as it has already revealed a new innovative dissolution approach.

The project employed many researchers during the program 2014–2018. A long-term employee, post-doctoral researcher Minna Räisänen worked on the project most of the time (during years 2014–2017), and after, she transferred to an expert position in Academy of Finland. Doctoral student Eeva Heliövaara worked in the project during years 2016–2018 and continued with the topic after the project ended. She is currently working on an improved dissolution method for gold, that originated from the MISU research project, and she will finalize her doctoral studies within a year. As the project is strongly influenced by circular economy of valuable metals, the line between research mind-set and business-oriented thinking has narrowed and inspired project researchers to lean also towards the business side of new dissolution innovations.

The MISU project has many links with economic life, and collaborations/connections were built by events such as innovation competitions and high-impact publications, which all together increased the visibility of our research (interview and press-releases). The information flow is still ongoing and the results from the project continues to influence outside the academia. This was a fundamental research project, but we have recently been contacted by a company willing to licentiate and develop our dissolution methods.

The aim of MISU program was to create a knowledge base that would facilitate responsible mining and recycling operations that are aware of their impacts on the natural environment and the surrounding society. The fundamental purpose of the MISU project was to develop a selective recovery method especially for gold from secondary resources, such as waste electronics. With our research group's approach, it is possible to lower the environmental burden associated with metal leaching drastically, when comparing to e.g. cyanide leaching of gold. In addition, a circular economy project has given our group the possibility to network and sell innovations and ideas to several companies and other non-business organizations.

5. New Chelating Agents for Selective Extraction of Uranium

Principal investigator: **Heikki M. Tuononen**, University of Jyväskylä

New knowledge generated in the project

This research project aimed to find new chelating ligands for the selective extraction of metals, particularly uranium (as the uranyl dication), from different (aqueous) solutions. The research was carried out at the University of Jyväskylä and it involved mostly computational methods. Ligand systems that were deemed to be most promising based on computational work were also manufactured synthetically and their efficiency tested in a laboratory setting.

Our results showed that:

a. It is extremely difficult to build conventional hydroxyl-based ligands that would interact strongly not only with the uranium atom but also with the two oxo groups of the uranyl ion. This possibility has been speculated in the literature (see, for example, J. Am. Chem. Soc. 1992, 114, 8138) and our work clearly demonstrates that the approach does not function well in practice.

b. Strongly donating equatorial ligands significantly increase the basicity of the two oxo groups of the uranyl ion. Strongly Lewis acidic axial ligands can then bind to the oxo groups, which could increase the selectivity of uranyl capturing agents. The efficacy of such approach should be tested in practice with a carefully designed multifunctional ligand system.

c. Bis(phosphonomethyl) dodecylamine -based ligands can be used to manufacture 3D-printed metal extraction filters for the extraction of different metals from (synthetic) mining raffinates. Manufactured 3D-printed filters had high selectivity towards three important metals: iron, uranium and scandium.

Exploitation of results by industry or economic life

The research project succeeded in building a new 3D-printed filter system for the extraction of important metals, mostly uranium, scandium and iron, from (synthetic) mining raffinates. Filters that would be nearly 100% selective to uranium (uranyl) could not, however, be realized.

Researcher careers

Researchers working in the project have since found positions at the Academia (University of Oulu, University of Eastern Finland and University of Jyväskylä) and in industry (3M, FinnVector and Dinex Group). One of the researchers working in the project has started a business related to 3D printed scavenger technologies (WeeeFINer™).

Impact generated in line with the goals of the programme

The project generated impact that is well in line with the programme goal of "Materials efficiency and recycling", that is, the separation and recycling of different metals. The project also established a new network of international collaboration, increased the international mobility of researchers,and helped to bring Finnish research to the international forefront in selected research areas.

Interaction with industry/economic life

Direct interaction with industry/economic life was virtually non-existent during the project, but researchers working in the project have since found jobs in industry related to materials science and/or started their own business related to extraction of metals and other substances from multicomponent mixtures.

6. Mineral Systems and Mineral Prospectivity of Finnish Lapland

Not available.

7. New laser and spectral field methods for in situ mining and raw material investigations

Principal investigator: Professor **Jussi Leveinen**, Aalto University

The purpose of Aalto was to develop further the use of laser spectral methods in characterization of rocks, their mineralogical properties and ore grade for mining, engineering and environmental analysis and decision making. The motive was the need for fast and remote characterization of rocks in underground tunnels that had become evident in educational visits (during mining geological courses in Pyhäsalmi and Kittilä mines) and during the previous Tekes-financed (Business Finland) Ladimo-projects where a new methods for fast and accurate point cloud measurements had been developed.

The objectives included to test how well the Raman and LIBS measurements can be used in conjunction with spatial point cloud data to distinguish rocks and minerals and to classify rocks based of their ore grade and mining technical properties.

We started first Raman-methodology, which produces information about the mineralogy and carried out reference measurements with our own rock specimens that included a significant number of ore specimens from different types of metal and industrial mineral mines in Finland. These tests enabled us to distinguish Raman responsive minerals of economic interest and find potential application areas for the technologies. Next we contacted companies that process such minerals. An industrial mineral producer Nordkalk and rock aggregate

company Seesula, which provided us samples from their Ihalainen wollastonite mine and a rock quarry in Vantaa, respectively. Samples of Yara Siilinjärvi and Li-ore samples from Keliber were also obtained. This project enabled us to compare results that were obtained by using a small size beam-size in Jyväskylä University and high density measurements to our own data sets that were obtained using so large diameter laser beam that the probability to get responses of more than one mineral are high. Since strong lasers with such beam size must be used in practice in any remote measurements, capability to quantitative mineral detection based on the mixed spectral responses will be a key issue if Raman technology is going to be used to detect or monitor mineralogy in mining applications. By using EDS-SEM analyses as a reference, we have at least comparable if not better analytical results than those obtained through use of small beam and high point density measurements, published recently (Laakso & al. 2020). The Yara Siilinjärvi and the Keliber-samples contain significant number of minerals or trace elements effecting the Raman responses and for which EDS-SEM analyses are not a reliable reference. We have not been able cover cost of the analyses in external laboratories yet. This has postponed the publication of the results.

The early attempts pointed us also that Raman responses of metal sulfide and oxide ore minerals are typically very weak and comprise relatively broad and partly overlapping spectral peaks. For metal ore mining focus was changed on LIBS-technology. The Kittilä Mine/Agnico Eagel provided us a particularly challenging mine were due to variable stability of rock. In this underground mine, rock tunnel faces must be mapped from a safe working distance. In addition, the ore mineralogy containing graphite and refractory gold disseminated into arsenopyrite and pyrite caused that the mine is developing a new geometallurgical approach for the mining and processing of the ore.

We also exchanged experiences and information on laser measurements with LaserSec Systems and its founder Dr. Scott Buchter who has participated to the research as an advisor of the PhD-thesis of Lasse Kangas. The lessons learned from this collaboration was that by choosing appropriate wave length of laser and sufficiently short duration of the laser pulse, one can minimize the fluorescence effects that can hamper both to Raman and LIBS measurements. That means that much more affordable sensor techniques than time gated special cameras can be applied to record the laser spectral responses.

These experiences build us confidence that laser-spectral methods can be used to develop new commercially viable devices that can serve mining and mineral processing and even more widely, to provide information for production of cementitious materials and in construction industry. More importantly, we were able to also provide a convincing research plan for a stand-alone remote LIBS-scanner proof-of-concept device in the Challenge Finland technology competition by Business Finland (as a part of a consortium led by National Land Survey, and VTT as a partner). This device has now been tested in real tunnel conditions in Kittilä mine. Our PhD-student Lasse Kangas has also made a concept for a large area open source LIBS-based core scanner device that can be used to rapidly analyze a whole drill core box at a time. The proof of concept of this device is currently developed further in another project (Lasolibs Tutli) financed by

Business Finland. We have made two innovation disclosures for which the patenting process has been started. The steering group of this project includes representatives from GTK, Terrafame, Finnish Minerals Group, and Rio Tinto. It will be very likely that the commercialization of these innovations will continue after establishment of a new start-up or by some other forms such as by licensing agreements with Aalto University Foundation.

The interaction produced by the LaserInsitu-project with different players of mining sector has been vivid. It has led already to significant continuation projects and acquisition of external funding for Engineering geological research in Aalto University. There is now two full-time PhD-students and seven MSc-thesis in mining engineering, geoengineering, automation technology and in economics has been prepared as a part of the LaserInsitu-project and its follow-up and parallel projects. Besides the companies listed above, we have been able to build networks to small companies working in mineral sector (Stenmann minerals, Geopool, ELTR oy). We have also been in touch with the large mining technology companies but this far they have not showed interest to collaborate with us. These contacts have been useful anyways to delineated market niches for the applications that we have developed.

The activity to acquire the external funding was partly driven by the cuts made to the original LaserInSitu-budget. It took one and a half years before were able to fill the financial gap and purchase and pulsed laser source that would have been needed right from the beginning. Before that we managed by borrowing lasers sources, testing with recycled optical parts from old microscopes, cameras and slide-projectors. The lack of good optics and laser also postponed us to prepare high quality data and publications during the first year of the project. However, we also learned to design optical systems. We have also made innovation disclosures that are evaluated by Aalto Innovation Services as potentially patentable. The terms of set by the financing of these parallel projects has addressed preparation of commercialization instead of publication of research results. As soon as the decisions concerning the patents will be made, we can proceed with the manuscripts and publishing the data collected.

In short, LaserInsitu-project and in general the development of new laser-optical spectral techniques have enabled us to initiate a new multidisciplinary research area that will make a significant impact to raw-material sector in Finland. The LIBS-technologies that we have developed are particularly suitable to for Li-ores and also for battery metals in sulfide ores. Moreover, the laser-spectral technologies have even bigger potential in recycling and construction material sector.

Sub-project: Principal Investigator **Saara Kaski**, University of Jyväskylä

During the sub-project of consortium LaserInSitu, University of Jyväskylä (JYU) extended the LIBS detection to NIR spectral range, which has potential for remote applications. The feasibility of the setup was proven in the identification and classification of several sulfide-bearing minerals. The correlation between the Raman spectroscopy and scanning electron microscopy (SEM) quantitative

analysis was demonstrated at joint research of JYU and Aalto, in the enhanced quantitative analysis of wollastonite and calcite minerals. The combination of LIBS and Raman was used in the analysis of fluorite mineral. University of Oulu and Jyväskylä have also studied relations of rare earth element contents Raman spectral characteristics. The new scientific findings were disseminated efficiently via oral or poster presentations at scientific conferences. In addition, the topic was presented to all visitors during several Researcher's Night –occasion. Future experts in the field of spectroscopy were educated (1 M.Sc. at JYU).

Sub-project: Principal Investigator **Juha Kostamovaara**, University of Oulu

See Section 3 for results of the project.

8. Sustainable platinum group metal free catalyst materials

Principal Investigator: Prof. **Kari Laasonen**, Aalto University

In this project we developed molecular modelling of electrochemical reactions. We can now model significantly more complex problems than in the beginning of this project. I see that the modelling will be develop rapidly also in future. The applications of modelling have increased significantly. We have been invited to several large EU projects to model various electrochemical reactions.

The molecular modelling has become an important part in modern materials development since that new materials are very complex and understanding reactions on them using only experimental methods is very difficult and slow. Molecular modelling provides information of the reaction details and suggest improved catalyst. We have recently done some extensive materials screening projects.

The molecular modelling based materials screening has also raised interest in industry. One example is Business Finland Funding for using molecular modelling to help companies to develop their products. To my knowledge, this is the first case in Finland and such projects are not common in Europe either. One of the companies is Canatu, which is actively developing carbon nanotube based materials that are an important role our MISU project.

Info (in Finnish): https://www.sttinfo.fi/tiedote/atomitason-ymmarrys-materiaalista-auttaa-uusien-tuotteiden-kehittamisessa?publisherId=37936456&releaseId=69879662

On European level, the European Materials Modeling Council is actively promoting the materials modelling as a tool in industrial development.

"It has been demonstrated in many individual cases that materials modelling is a key enabler of R&D efficiency and innovation. Companies reported that

computational modelling benefits include reduced R&D time and cost, more efficient and targeted experimentation, more strategic approach to R&D, a route to performance optimisation, wider patent protection, improved supply chain control, enhanced decision making and early understanding of application performance aiding faster and more assured market introduction." - The European Materials Modeling Council.

The economic impact of materials modelling, Goldbeck Consulting, 2016.

To summarize, the role of molecular modelling is increasing both in basic research and in industrial materials development. This increase has to be based on solid research and I see that our sub-project has increased the knowledge of molecular modelling in Finland.

Sub-project: Principal Investigator Prof. **Tanja Kallio**, Aalto University

New knowledge generated in the project

We developed new approach for synthetizing critical raw material free and lean electrocatalyst for hydrogen economy. Our investigations focused in activity and durability of these materials in acidic media, met in polymer electrolyte based hydrogen conversion technology. By combining experimental and theoretical approaches, we were able to elucidate the reason for the activity of these materials, which is needed for development of materials for other electrochemical reactions and other media. We investigated also integration of these electrocatalyst in laboratory scale devices and their aging mechanisms.

Exploitation of the results by the industry or economic life

The platinum lean electrocatalysts developed in this project were tested in a laboratory-scale water electrolysis cell by our industrial collaborator an Horizon 2020 EU project CREATE. One-year testing show better durability compared to commercial reference material. In principle, this material could be adopted in commercial use.

Researcher careers

- Mr. Olli Sorsa has submitted his doctoral thesis for the pre-examination process in April 2020 and is beginning to look for a job in industry.
- Dr. Fatemeh Davodi defended her thesis in October 2019 and is currently on maternal leave.
- Ms. Taina Rauhala is writing her doctoral thesis and it is expected to be ready for the pre-examination procedure in August 2020.
- Mr. Jussi Nieminen, M.Sc., is working in industry (Thermo Fisher Scientific)

We have been actively in contact with two European companies, Ocsial and ITM Power. The former is synthetizing the nanocarbon materials used for catalyst synthesis and the latter carried out the electrolysis tests.

Impact of the project in line with the goals of the programme

We contributed to replacing of critical raw material containing components in energy conversion applications. We also developed commercially viable approach for notable reduction critical raw materials used in these technologies and thus increased critical raw material utilization efficiency.

Interaction with industry/economic life

We have been actively in contact with two European companies, Ocsial and ITM Power. The former is synthetizing the nanocarbon materials used for catalyst synthesis and the latter carried out the electrolysis tests. Furthermore, we discussed with a Finnish company Canatu about new potential applications for nanocarbon materials fabricated by them.

Sub-project: Principal Investigator Prof. **Esko I. Kauppinen**, Aalto University

The new, economical floating catalyst chemical vapor deposition (FC-CVD) synthesis method using ethanol as the carbon source, ferrocene vapor as the iron nanoparticle catalyst precursor and economically feasible carrier gas i.e. nitrogen with around 10 % of hydrogen was developed as the main topic of the PhD thesis of Er-Xiong Ding. In a separate project funded by Canatu company we collaborated to develop economical, industrial scale manufacturing technologies of SWCNT based transparent conductors.

The new 1-D van der Waals heterostructure was invented in collaboration with the University of Tokyo, AIS Japan, MIT and Peking university and published in Science journal.

SWCNT thin films were used to replace the traditional rigid indium tin oxide (ITO) as well as metal based conductors in polymer and perovskite solar cells.

9. Novel synthesis methods for porous ceramics from mine tailings CeraTAIL

Sub-project: Principal Investigator **Päivi Kivikytö-Reponen**, VTT Technical Research Centre of Finland

New knowledge generated in the project

Research conducted at VTT Technical Research Centre of Finland (VTT) in CeraTAIL sub-project, generated a new scientific knowledge about valorisation of mine tailings as raw materials for added value ceramic materials. Research work concentred on solutions with added functionality such as ceramics materials for thermal- and electrical insulation. New knowledge about the novel ceramic materials microstructural phase structures and the effect of mine tailings chemical and mineralogical composition on formed microstructural phases and the achieved macro-level material properties as comparison to primary raw material

based counterparts were created during the CeraTAIL project. Altogether four peer-reviewed publications [1] [2] [3] [4] were published about these new findings combining mineralogical understanding to material synthesis design and materials science.

The Finnish mine tailings for investigation were selected concentrating on mineralogical compositions that hold potential to be utilized as raw materials for ceramic compounds with excellent high temperature properties. Quartz and alkali feldspar rich mine tailings, including molybdenum ore mine tailings, gold ore mine tailings and quartz ore mine tailings and magnesite rich talc ore mine tailings were investigated during the project, and several novel experimental materials synthesis were performed. Additionally, it was of interest whether it is possible to tailor the chemical composition, by mixing mine tailings with different secondary raw material streams. Two material compositions with excellent high temperature properties, mullite ($3Al_2O_3 \cdot 2SiO_2$), and magnesium aluminate spinel ($MgAl_2O_4$) were targeted in synthesis experiments. One of the key finding of the research was that quartz and feldspar rich mine tailings can be used as a raw material in an alumina-silicate based ceramic manufacturing. Reaction sintering of selected composition resulted formation of acicular mullite structure surrounded by amorphous glass phase. Mullite structure formation enables ceramics structures to withstand high temperature (>1450°C). Another novel key finding of the research was that $MgAl_2O_4$ spinel based powders can be synthesized by reaction sintering using magnesite rich mine tailings combined to aluminium anodizing process waste. Coating deposition resulted formation of ceramic coatings containing amorphous areas between the crystalline $MgAl_2O_4$ clusters. These glass-phase bonded ceramic coatings showed the electrical insulation capability at the same level but considerably lower wear rate than for primary raw material based magnesium aluminate coatings. These novel results are important for society indicating by secondary raw materials can be reached equal or better material quality compared to primary raw materials use.

Exploitation of the results by industry or economic life

Peer-reviewed publications about these new findings are publicly available for industry and economic life. These results have been found interesting by energy intensive industry, specifically by several Finnish companies. Therefore, as a continuation of CeraTAIL, VTT has prepared a Business Finland Co-Innovation MineralLoop project proposal around a wider utilization of mineral side streams together with Finnish companies. The project brings together data about industrial side-streams and provides information on their properties and valorisation in industrial solutions. The project provides added value through the

[1] Karhu, Marjaana; Lagerbom, Juha; Kivikytö-Reponen, Päivi; Ismailov, Arnold; Levänen, Erkki. Reaction Heat Utilization in Aluminosilicate-Based Ceramics Synthesis and Sintering. Journal of Ceramic Science and Technology 08 (01) (2017) 101-112.

[2] Karhu, Marjaana; Lagerbom, Juha; Solismaa, Soili; Honkanen, Mari; Ismailov, Arnold; Räisänen, Marja-Liisa; Huttunen-Saarivirta, Elina; Levänen, Erkki; Kivikytö-Reponen, Päivi. Mining tailings as raw materials for reaction-sintered aluminosilicate ceramics: Effect of mineralogical composition on microstructure and properties. Ceramics International 45 (2019) 4840–4848.

[3] Karhu, Marjaana; Lagerbom, Juha; Solismaa, Soili; Huttunen-Saarivirta, Elina. Magnesite-rich mining tailings as a raw material for refractory ceramics – microstructural and thermal analysis. Proceedings of the Estonian Academy of Sciences 68 (2) (2019) 145–149.

[4] Karhu, Marjaana; Lagerbom, Juha; Honkanen, Mari; Huttunen-Saarivirta, Elina; Kiilakoski, Jarkko; Vuoristo, Petri; Solismaa, Soili; Kivikytö-Reponen, Päivi. Mining tailings as a raw material for glass-bonded thermally sprayed ceramic coatings: microstructure and properties. Journal of the European Ceramic Society (2020), DOI: 10.1016/j.jeurceramsoc.2020.04.038

complementary role of companies, optimization of material flows and common research questions. The project would lay foundations for the commercialization of new 'design out waste' circular economy processes and products, and bring competitive advantage through capability of provision of comprehensive solutions, and international business networks. The project proposal involves 11 companies, 1 municipal council and 3 research Institutes with a total volume of 3.1 M€.

Researcher careers

CeraTAIL was successful in supporting research careers of the people involved: M.Sc. (Tech) Marjaana Karhu is finishing her PhD studies and her thesis has been sent to pre-examination at the end of May 2020. Additionally, a new team "Industrial Circular Economy" was initiated at VTT at the beginning of 2020 and PI, D.Sc. (Tech) Päivi Kivikytö-Reponen, was selected as team leader for this new team concentrating on Circular Industries and circular design strategies including "design out of waste". CeraTAIL is a central reference for this research topic.

There has been active communication to Finnish industry (MineralLoop project proposal) as well as communication in social media (LinkedIn, Twitter, blog).

Impact of the project in line with the goals of the programme

CeraTAIL improved scientific understanding of the potential end uses of mine tailings in Finland and around the globe. These findings and off-shoots will have long-term impacts in terms of lowering the environmental impact of mining industry, simultaneously improving the availability of raw materials as well as the lowering the CO2 footprint of the society by providing alternative, low-CO2, options to current materials as well as offering large scale carbon-capture potential. The project has provided knowledge in a raising and innovative field of tailings valorisation that has export potential toward mining intensive countries.

Interaction with industry/economic life

CeraTAIL started a new research topic at VTT: the added value material development based on secondary raw materials valorisation. The sustainable future and circular economy is supported by side stream, waste and tailings valorisation as a valuable raw material. The continuation projects to solve these challenges are applied. Additionally, a new collaboration was started between VTT and KU Leuven relating to new processing routes for the mineral side streams and the innovative, high-value applications that continues in the form of project proposal and planned research visit for M.Sc. (Tech) Marjaana Karhu.

Sub-project: Professor **Erkki Levänen**, Tampere University, M.Sc. **Arnold Ismailov**, Tampere University

New knowledge generated in the project

The aims on TAU/MSEE side were concentrated on studying tailings as potential raw materials for acid-based cementitious processing, neatly complementing the

alkaline processing routes of University of Oulu and exothermic studies at VTT. Thus, the key results were on the topic of phosphate reactivity of selected mixed-mineralogy tailings. Firstly, it was established, that while most tailings were not reactive (soluble in acids), some specific tailing fractions had several competing reactive components, forming a hierarchy of reactivity that needs to be taken into account when considering them for phosphate mixtures. Namely, in case of wollastonite-rich tailings, carbonate minerals present in the fraction were found to have a deleterious effect on the reactivity of the targeted wollastonite. Secondly, a talc mine-derived magnesite rich tailing was successfully used as the source of reactive oxide (MgO) in a phosphate cement formulation. This part of the study produced quick-setting and mouldable phosphate formulation that, when set, could be tested by 4-point bending and was found to have strength values in the appropriate range for a cementitious material. Magnesia reactivity was achieved with relatively low calcination temperatures and no additional grinding, demonstrating a low-energy route for utilizing these or similar tailings in a value-added way with a modest need for pre-treatment.

Results exploited by the industry or economic life

These results add to the knowledge base of the mining operations, on the one hand showing the obstacles that prevent direct utilization (Nordkalk Wollastonite) and on the other hand, offering a new addition to the list of ways to waste valorization (Elementis (ex Mondo minerals) Magnesite). In general, the results from this project can help guide process planning and development in the mining operations and companies in question.

Researcher careers

There is a Business Finland application under process around the MISU related topic, and in that consortium there are many companies involved. Also some direct company collaboration in form of M.Sc. works has started and expertise of MISU researchers are used as co-supervision. There are also new openings for carbon capture and mineralization processes which will be started by foundation funding, but also companies are charted for exploitation.

Impact of the project in line with the goals of the programme

One major aim of the programme was to strengthen multidisciplinary and interdisciplinary approaches and communication. The CeraTAIL consortium fulfilled this goal very well by showing strong collaboration between all members throughout the duration of the project and by forming collaborative network that stayed in place after the project ended. The TAU/MSEE unit has continued a fruitful publication-oriented collaboration with the new partners at University of Oulu Fibre and Particle Engineering unit as well as the new partners at GTK Kuopio. One Dr. thesis from VTT supervised by TAU is under pre-examination. The necessity for this kind of collaboration and discussions was apparent right from the beginning of the project, where establishing interdisciplinary language and vocabulary was required for fluent communication between different disciplines.

Interaction with industry/economic life

The interactions with industrial partners occurred on many levels, from frequent e-mail exchanges regarding samples and publications, to company visits. The most frequent communication with mining companies was by proxy (GTK) to acquire or replenish sample stock of tailings.

There is also a lot of discussions, short preliminary experiments and also thesis works with companies related to secondary raw materials. Unfortunately pandemic has practically stopped some activities.

Sub-project: Principal Investigator **Päivö Kinnunen**, University of Oulu

New knowledge generated in the project

Mine tailings are inorganic industrial side streams that are produced increasing amounts in the mining sector, and discarded in tailings ponds. As such, they constitute an environmental liability, but also an unutilized material resource in the circular economy. The goal of the Ceratail project was the utilization of mine tailings in ceramic materials using three different low-energy routes; geopolymerization, phosphate bonding and reaction sintering. Key results of the project were published in international scientific journals, and included development of successful pre-treatment methods that enabled the use of tailings in geopolymerization and in phosphate bonded binders, as well as surprising findings about high reactivity of studied impure kaolinite minerals when utilized in porous geopolymer ceramics. The project established the vast utilization potential of mine tailings in circular economy process industry.

Exploitation of results by the industry or economic life

CERATAIL improved scientific understanding of the potential end uses of mine tailings in Finland and around the globe. These findings and off-shoots will have long-term impacts in terms of lowering the environmental impact of mining industry, simultaneously improving the availability of raw materials as well as the lowering the CO2 footprint of the society by providing alternative, low-CO2, options to current materials as well as offering large scale carbon-capture potential.

Researcher careers

Researchers have continued from PhD students to postdoctoral fellows, or continued as doctoral students so far. Information has lead to multiple new research projects, with higher TRLs (technology readiness levels), a progression which usually leads to new projects or services in the marketplace in some of the technologies developed.

Impact of the project in line with the goals of the programme

CERATAIL increased the visibility of the mine tailings issue, and created deeper understanding about the potential end-uses of the mine tailings. Also helping the

society perceive mine tailings as a potential raw material instead of merely waste to be minimized.

Interaction with industry/economic life

GTK was interacting with several mining companies during the CeraTail project. All the mining companies contacted, regarded the project as beneficial and gave permission for sampling. Usually there was a meeting arranged in the context of sampling, where different possibilities to cooperate were discussed. Companies that gave samples and cooperated with CeraTail project were: Sibelco Nordic Oy, Endomines Oy, Nordkalk Oy, Aquaminerals Oy, LKAB minerals Oy, Yara Suomi Oy, Keliber Oy, Mondo Minerals, Tulikivi Oyj.

10. High-performance geoscientific computing in multi-scale mineral potential studies (Gecco)

Principal Investigator: **Jan Westerholm**, Åbo Akademi University

New knowledge generated in the project

The methods developed in the project contribute to a better assessment of the sizes and locations of economically interesting ore bodies by speeding up the process of forming a model and analyzing the gravitational and magnetic response of the models. A computer program called Geccogram was developed which enables the user to interactively change ore models and measure the changes to gravitational and magnetic responses.

Exploitation of results by the industry or economic life

We have seen the need for a more efficient modelling process for geologists. Geological modelling programs use traditional computer aided design methods to build geological models. Modern computer graphics methods could be introduced to facilitate easier model input, and the computational part of Geccogram could be used to calculate forward gravitation and magnetism.

Researcher careers

The researchers have gained knowledge and experience in the use of GPUs for calculation intensive applications. Several of them are now in industry utilizing e.g. artificial intelligence in industrial applications. The information flow to industry has been in the programming and utilization of GPUs.

Impact of the project in line with the goals of the programme

We have no way of calculating the extent of ore distributions based on electromagnetic and gravitational measurements. Instead, reasonable and feasible models are made and compared against measurements. Our projects has made the task of modelling faster and more interactive, giving the modeler room for experimentation and what-if analyses of the ore models.

Interaction with industry/economic life

The project used data from the proposed extension of the Pyhäjärvi mine to Mullikkoräme.

We participated in the British-Finnish Natural Resources Initiative 26 March 2018, and 2nd British - Finnish Natural Resources Initiative 2019, February 11-12th 2019, brain storming events organized by the British Embassy in Finland to explore, develop and initiate cross-border natural resource-based research, teaching and commercial services opportunities between the UK and Finland.

Sub-project: Principal Investigator **Eevaliisa Laine**, Geological Survey of Finland (GTK)

The goal of the GECCO project was to design, implement and run high-performance geoscientific computing in multi-scale mineral gravitational and magnetic potential studies on a selection of test sites in Pyhäjärvi and Mullikkoräme geological areas in central Finland. The mining site of Skorovass in Norway was added during the project as part of the cooperation with the Norwegian Geological Survey in Trondheim. The new results of the project are:

1. During the project Mullikkoräme, Pyhäsalmi and Outokumpu 3D geological models in different scales were built for testing various geophysical and statistical methods.

2. As one of the main results of the project, the Geccogram program was developed and used to model the test sites. Geccogram is a high performance parallel multicore program that uses all 40 cores on a node on the Puhti supercomputer and the nodes of the local computer cluster FGCI at Åbo Akademi University.

3. In addition, a Julia script was needed to aid the building of input files and analyzing the resulting calculated responses using Geccogram. This script will be demonstrated by a publication describing the use of Geccogram in detail with Mullikkoräme 3D models.

4. Mullikkoräme lithogeochemical data were used for petrologic norm calculation, k-means clustering, and multilayer perceptron (MLP) neural networks for analysis of alteration pseudo-mineralogy and artificial rock types compared to human observations, petrologic igneous rock classification major-element based system, and alterations indices, focusing on prediction of zinc and nickel concentrations. Enrichment of zinc and nickel was analyzed quantitatively, and derived rock labels were also classified into non-altered and ore-favoring altered ones.

5. Moreover, Julia 3D electromagnetic (EM) modelling programs of the jInv (JuliaInv) package were tested to frequency domain EM modelling at Outokumpu and Mullikkoräme test sites. The aim has been to use the existing EM measurements of these areas to verify the interpreted 3D models with that complementary information.

6. Important seismic signatures of massive sulfide ore bodies were studied using Pyhäsalmi mining site as an example.

Geccogram and Julia scripts give the possibility easily to test different alternative 3D geological models to look for potential ore deposits, estimate the possibility to extract thermal energy or evaluate possible structural risks for spreading of contaminated groundwater or the effects of rising sea level in the coastal areas. In general, the tools developed in the project can be applied in many different scientific applications.

All the GECCO project researchers continue their work at GTK. In addition to GECCO domestic and international collaboration GECCO tools will be also applied for other targets in the Outokumpu area befiting the ore exploration in the area. We may be able to GECCO tools also for geothermal energy studies and urban geology and, so, to build a beneficial collaboration with consulting companies within these fields.

11. Advanced technologies for sustainable exploitation of uranium-bearing mineral resources

Consortium Principal Investigator Professor **Jouko Vepsäläinen**, University of Eastern Finland (UEF)

This project aims to develop and demonstrate new techniques for the effective recovery of uranium from process and mine waters, even at very low concentrations. These techniques involve utilization of various bisphosphonate adsorbents, hybrid materials based on nanoporous silicon carbide frameworks and BPs, and biological/bioelectrochemical uranium reduction.

New knowledge generated in the project

In the SEXUM project were demonstrated in the co-operation with GTK and TAU the effectiveness of recent advances in the chemical and biological technologies to recover REE and remove uranium from various process and mine waters, acid mine drainage (AMD) waters and mine tailings. Our sample in this project arrived mainly from GTK, Huelva and TAU. GTK samples were from polymetallic deposits containing uranium and they were pretreated at MinTec GTK. Huelva samples were from four different AMD positions (Th2, TT4, POD2 and BR).

New knowledge generated in the project can be summarized as follows:

- fast, effective and accurate method to measure uranium concentrations on ppb level based on TXRF instrument was developed
- our main adsorbent material was on that time recently developed and patented N10O material being prepared from natural fatty acid and phosphorus derivatives
- adsorption/desorption properties of ca. 60 metals into solid N10O were tested including pH behavior from 0 to 12 pH
- several selective adsorption/desorption relationships with temperature (Pb), pH (Sc and Ir) and contact time (U) were observed

- high amounts of iron (>1000 ppm) or aluminum decrease dramatically selectivity of N10O
- in the laboratory scale N10O removed uranium effectively from typical mine waters up to 99.9% regardless of the concentration
- related to pilot experiments (ca. 1 m^3/h) in a Finnish cold mine afforded ca. 90% removal of U when the contact time of N10O with water was ca. 10 seconds.
- also several natural based adsorbents were tested e.g. hydroxyapatite and chitosan, but peat was clearly the best, since 92.4 – 99.9 % of uranium was removed depending on pH and type of peat (top of peat layer and step by step layers down to 2 m deep layers)
- related to REE a selective method to enrich scandium and collect simultaneously Fe, Al and Ti was develop and used in RaSPi project (scandium deposit in Rautalampi, EAKR funding)
- based partially on modofied N10O adsorbend four EU proposals were made: REMAIX, ADREC, REGALISCAN, ADMERE

Exploitation of results by the industry or economic life

Partially based on MISU results company BioSO4 Oy (https://bioso4.com/) was established. BioSO4 has two employees and it concentrates on zero waste water purification systems based on natural recyclable polymers. Also, prof. Lehto has established company 3AWater (https://www.3awater.com/) based on the results originated mainly from patented MISU results by prof. Vepsäläinen and prof. Lehto groups.

Researcher careers

One of the researchers got Erkko grant for three years and the other one is working in a EAKR project (Kuopio Water Cluster) related to developing novel water purification methods in co-operation with GTK, THL, Savonia, LuKe and Ruokavirasto.

As described above two companies have been established based on the information flow from university to industry.

Impact of the project in line with the goals of the programme

Novel method to enrich scandium and simultaneous collection of Fe, Al and Ti was developed and tested in Rautalampi scandium deposit (10 kg scale).

New multidisciplinary research groups and networks of national and international collaboration were fulfilled based on our four EU proposals with ca. 15 participants.

Interaction with industry/economic life

During the project we contacted most of the mining sites in Finland and visited couple of times in Huelva AMD area. Several research groups in Finland are

interested in our elemental analysis possibilities from lithium to uranium down to ppt level. Especially, recently purchased MP AES instrument for lithium, Be, Na and Mg analysis has gained a lot of interest, e.g. from Oulu Mining School. Moreover, we have developed nuclear magnetic resonance (NMR) based methods to identify and check purity of organic chemicals used in enrichment processes also including the residues and decomposition product in environmental waters. Several mining companies already use this service.

Sub-project: Principal investigator Asst. Prof. **Aino-Maija Lakaniemi**, Tampere University

New knowledge generated in the project

It was demonstrated that waste digested activated sludge (WDAS), which is a side product of anaerobic digestion of the excess microbial sludge generated at municipal wastewater treatment plants, can be used in removal and recovery of uranium(VI). By using a synthetic uranium-containing wastewater, a proof-of-concept on the use of fed-batch stirred tank reactor with WDAS to recover and concentrate U(VI) by means of adsorption/desorption was demonstrated. After this, the adsorption/desorption process with WDAS was further optimized for uranium removal from real acidic mining water containing range of metals (e.g. Fe, Ni, Co, Cu, V, and Zn) in addition to U. It was shown that U, Cu and Th can be selectively recovered from acidic mining waters using WDAS as adsorbent and two step 1 M Na_2CO_3 desorption.

The rate and efficiency of uranium bioreduction from U(VI) to insoluble U(IV) by enrichment cultures originating from an anaerobic municipal digester and from a sulfate reducing bioreactor were compared at three different pH values (5, 6, and 7). Uranium was removed with both cultures at all studied pH values, while the reduction efficiency was lowest at pH 5. Bioelectrochemical uranium recovery was studied in h-type bioelectrochemical systems, but the microbial activity in the process could not be verified.

The project has resulted in the following three peer-reviewed scientific publications:

- Jain R, Peräniemi S, Jordan N, Vogel M, Weiss S, Foerstendorf H, Lakaniemi A-M. 2018. Removal and recovery of uranium(VI) by waste digested activated sludge in fed-batch stirred tank reactor. Water Research 142: 167-175. https://doi.org/10.1016/j.watres.2018.05.042
- Lakaniemi A-M, Grant D, Kaksonen AH. 2019. Engineering and kinetic aspects of bacterial uranium reduction for the remediation of uranium contaminated environments. Journal of Hazardous Materials 371: 198-212. https://doi.org/10.1016/j.jhazmat.2019.02.074
- Kaksonen AH, Lakaniemi A-M, Tuovinen OH. 2020. Acid and ferric sulfate bioleaching of uranium ores: A review. Journal of Cleaner Production 264: Article 121586. https://doi.org/10.1016/j.jclepro.2020.121586

Two more publications are currently under preparation. In addition, the results of the project have been presented in several international scientific conferences including 13th International Mine Water Association Congress in 2017, Sustainable Minerals '18 and Goldschmidt 2019.

Exploitation of results by the industry or economic life

The adsorption/desorption process developed and demonstrated in this project could be exploited in treatment of acidic mining process or waste waters. This would also provide possibility of utilization for waste digested activate sludge, which is produced in large quantities in municipal wastewater treatment plants. Due to low technology readiness level of the process, the application has not been discussed with industry.

Researcher careers

A doctoral student, who worked in the project, has since worked as a Postdoctoral Researcher in the Autonomous University of Barcelona, Spain and is now working as a Research Fellow in University of Surrey, UK. A postdoctoral researcher, who worked in the project, later obtained an individual Marie Sklodowska-Curie fellowship to work as a Postdoctoral Researcher at the Helmholtz-Zentrum Dresden-Rossendorf, Germany, and is now an Assistant Professor at IIT Delhi, India. A project researcher, who worked in the project, continues at Tampere University in other ongoing projects with funding outside from the MISU programme.

Impact of the project in line with the goals of the programme

New knowledge on biological metal removal and recovery processes from mine waters was developed by utilizing advanced analytical tools and combining knowhow from microbiology, bioprocess engineering, and speciation modeling. The project enabled establishing new national and international collaboration networks and promoted research mobility especially via a 10-month research visit to the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia.

Interaction with industry/economic life

Industry representatives were met in international conferences, during annual seminars organized by MISU programme, and during the workshop

Sub-project: Principal Investigator Prof. **Vesa-Pekka Lehto**, UEF

New knowledge generated in the project

During the project, a hybrid adsorbent material was developed consisting of mesoporous silicon core stabilized with a carbide layer and modified with a metal chelator, bisphosphonate. Due to porosity, the adsorbent is permeable and can be used in flow through setups to collect the dissolved metals from aqueous solution streams even in ppb levels. The material is extremely stable, and it can be regenerated with strong acids, i.e., the adsorption/desorption cycles can be made

for tens of times without loosing the adsorption capacity. The adsorbent was further developed to adsorb specific metals (like U and Sc) for the enrichment purposes, which demanded also controlling the pre-precipitation process of excess metals (like Mn and Fe) in the solution to prevent the saturation of the adsorbent. At the later part of the project, we developed the technique to produce mesoporous silicon and silicon carbide from barley husk (purifying first the amorphous silica structures, phytoliths, and reducing them) instead of producing the mesoporous material from silicon wafers through electrochemical etching to support the sustainability and cascading principle in producing this high-tech material.

The project has resulted in the following peer-reviewed scientific publications:

1. Riikonen, J., Rantanen, J., Thapa, R., Le, N., Rigolet, S., Turhanen, P., Bodiford, N., Kalluri, J., Ikonen, T., Nissinen, T., Lebeau, B., Vepsäläinen, J., Coffer, J. & Lehto, V-P., Rapid synthesis of nanostructured porous silicon carbide from biogenic silica. ChemSusChem., Submitted, under evaluation (2020).
2. Thapa, R., Nissinen, T., Turhanen, P., Määttä, J., Vepsäläinen, J., Lehto, V-P. & Riikonen, J., Bisphosphonate modified mesoporous silicon for scandium adsorption. Micropor. Mesopor. Mat., 296:109980, DOI:10.1016/j.micromeso.2019.109980 (2020).
3. Kalidas, N., Riikonen, J., Xu, W., Lahtinen, K., Kallio, T. & Lehto, V-P., Cascading use of barley husk ash to produce silicon for composite anodes of Li-ion batteries. Mat. Chem. Phys., 245:122736; DOI:10.1016/j.matchemphys.2020.122736 (2020).
4. Riikonen, J, Nissinen, T., Alanne, A., Thapa, R., Fioux, P., Bonne, M., Rigolet, S., Morlet-Savary, F., Aussenac, F., Marichal, C., Lalevée, J., Vepsäläinen, J., Lebeau, B., & Lehto, V-P., Stable surface functionalization of mesoporous silicon for metal adsorption. Inorg. Chem. Front. 7:631-641, DOI:10.1039/c9qi01140d (2020).
5. Rantanen, J., Majda, D., Riikonen, J. & Lehto, V-P., The atomic local ordering of SBA-15 studied with pair distribution function analysis, and its relationship to porous structure and thermal stability. Acta Mater. 175:341-347 (2019).
6. Nissinen, T., Tiihonen, T., Riikonen, J., Lehto, V-P., & Savolahti P., Portable assessment kit and method for measuring metal content of aqueous solution, Pat. Pend. FI20195649 (2019).
7. Riikonen, J., Lehto, V-P., Vepsäläinen, J. & Nissinen T., A material, a system and a method for collecting metals from an aqueous solution. Pat. Pend. PCT/FI2018/050950 (2018).

Four more publications are currently under preparation and as the outcome of the project four PhD thesis will be finalized within two years.

Exploitation of results by the industry or economic life

Based on the material developed in the project and the support from Business Finland (TUTL funding), a startup company 3AWater (https://www.3awater.com/) was established. The company is commercializing the technology that enables multimetal analysis of natural waters on-site and real-time. The technology

developed to produce biogenic mesoporous silicon was utilized also in producing silicon to be used as the anode material in Li-ion batteries.

Researcher careers

In 2019, the postdoc researcher, who graduated at the end of 2016 transferred to the startup company (3AWater) and is working there as CEO. Altogether there were four PhD students (two of them being required from abroad) working for the project and they all are expected to graduate within 2 years. The high turnover of the researchers was because of their personal grants. All of them were however working on the topic of the project all the time.

Impact of the project in line with the goals of the programme

The project generated know-how that leads to the commercialization of the disruptive technology for multimetal analysis of natural water in real-time and on-site. The technology has raised wide interest leading also to European-wide networks and joint project application. In the respect of social acceptance, reliable and fast monitoring methods are essential as well as the dissemination of advances in processing and monitoring technology.

Interaction with industry/economic life

The startup company 3AWater was established based on material development made in the project. Before establishing the company, support from Business Finland was received in the form of a TUTL project. We (UEF is the coordinator) have submitted a project application together with several European companies and research institutes to EIT Raw Material. At the moment we are planning a joint project with several national companies through CLIC Innovation.

Sub-project: Principal Investigator Dr. **Raisa Neitola**, Geological Survey of Finland (GTK)

New knowledge generated in the project

In the SEXUM project were demonstrated the effectiveness of recent advances in the chemical and biological technologies as well as various mineral processing methods to remove and recover metals from various materials, including crushed ore, process and mine waters and mine tailings. Polymetallic deposits containing uranium were selected for case studies, as uranium is commonly present as a potential co-product in magmatic ore systems containing REE and sedimentary ore systems containing the critical metals Co and Ni.

The new knowledge generated in the project can be summarized as follows:

- Extensive process mineralogical data of the U-bearing ore samples, and detailed information about the minerals that contained valuable elements (Au, REE, etc.), uranium, and thorium
- Knowhow and expertise of mineral processing and leaching methods for separation of valuable and harmful minerals in the case U-bearing ore

samples and REE and Nb minerals as well as deportment of U during various mineral processing stages

- Increased understanding of the effect of operating parameters on high-gradient magnetic separation of a REE ore, and optimization of these parameters
- This study demonstrated that a low-cost, non-modified organic materials can be implemented as a potential adsorbents to improve the quality of discharged mine process waters
- The examined adsorbents exhibited a strong affinity for uranium ions present in the tailings water of a complex chemical composition under various process conditions
- The findings indicated that the chitosan was capable of recovering uranium ions from mine effluents and could be regenerated and reused in the treatment process
- The project developed expertise in characterizing the environmental properties of uranium-bearing extractive waste using mineralogical, geochemical and radiological methods

The project has resulted in the following scientific publications:

- "Effective separation of uranium from mine process effluents using chitosan as a recyclable natural polymer" by M. Szlachta, R. Neitola, S. Peräniemi, J. Vepsäläinen Paper submitted to Separation and Purification Technology journal (IF=5.107)
- "Treatment of mine effluents and recovery of selected metals using reusable biopolymer" by M. Szlachta, R. Neitola, S. Peräniemi, J. Vepsäläinen IWA World Water Congress and Exhibition, May 9-14, 2021, Copenhagen, Denmark. Abstract submitted and accepted for the presentation at the conference
- "NORM related mineral developments in Finland" E. Pohjolainen, H. Tuovinen, P. Sorjonen-Ward, R. Neitola IAEA Naturally Occuring Radioctive Material (NORM VIII) Proccedings of an intervational Symposium 2016.

The results of the project have been presented in several international scientific conferences including 2nd European Rare Earth Resources Conference in Santorini 2017, International Atomic Energy Agency URAM 2018 in Vienna and Garry Davidson Symposium 2018, in University of Tasmania. More publications are currently under preparation.

Exploitation of results by the industry or economic life

The outcome of the SEXUM project has been to advance awareness and assist in developing more comprehensive and systematic workflows from mineral exploration and ore deposit characterization through to beneficiation and environmental assessments. The results could be exploited in connection with new projects or for the needs of the mining industry directly as customer work when researching similar materials and waste fractions to develop and improve processes and products. Additionally, GTK will have the know-how to characterize

the environmental properties of waste fractions arising from the enrichment of uranium-containing materials. The results of the SEXUM project were already utilized in studying the feasibility of sulfuric acid leaching to reduce the U contents and a the effects of process variables on gold leaching of the tailings commissioned by mining companies.

Collaboration has also been enhanced with external partners through the associated exploration companies who have sponsored post-graduate research with universities outside the SEXUM consortium (Oulu University). Additionally, ongoing engagement with the Center of Excellence in Ore Deposit Studies (CODES) at the University of Tasmania and further synergy has been obtained through participation in EIT Raw Materials KAVA projects (inSPECTor and RAMSES-4-CE, led by Helmholtz Institute Freiberg) that overlap within the area of analytical techniques for critical raw materials.

A further potential application of the SEXUM research also relates to the efficiency of uranium sequestration in that the major global source for phosphate for fertilizer comprises sedimentary deposits in which uranium is typically present, in concentrations that are occasionally favourable for uranium recovery. Otherwise, the toxicity of uranium, as well as other trace elements is a matter that needs to be addressed and, providing upscaling of the SEXUM technologies are economic, this presents a significant future opportunity.

Researcher careers

One researcher, who worked in the project, is now working at a company that acts in the field of water treatment products and also as a distributor supplying to global mining reagent producers.

Impact of the project in line with the goals of the programme

There are advantages in the techniques developed and applied in the SEXUM project in terms of ability for high-percentage recovery from solution, even at very low concentrations, and also in re-use of chemical reagents, which is of importance both economically and environmentally. Economic and environmental considerations, together with public approval ultimately dictate whether mineral resources are mined and utilized so the project outcomes are seen as facilitating both sequestration and safe storage of undesirable metals or recovery for commodity markets.

Interaction with industry/economic life

The two deposits examined were undertaken with permission of the exploration companies and this involved regular informing and discussions of relevant project results. Industry representatives were met in international conferences, during annual seminars organized by MISU programme, and during the workshops organized within the project.

12. Identification of potential flake-graphite ores in the Fennoscandian shield and utilization of graphene (FennoFlakes)

Principal Investigator: Professor **Olav Eklund**, Åbo Akademi University

The aim with the project was to find areas in Finland suitable for graphite ores, purify and exfoliate domestic graphite and graphene and create technical solutions for domestic graphene. The project was divided into four work packages intimately connected to each other.

WP 1. Identification of flake graphite ores

The geological surveys to find potential graphite ores was an intimate cooperation with the company Fennoscandian Resources (part of the Beowulf group in UK). In all, 10 areas in Finland and Sweden were investigated. In all, these regional investigations resulted in 11 M.Sci. thesis, 4 B.Sci. Thesis, two peer review papers and several conference abstracts. Methods used were compilation of old data, field mapping, SLINGRAM electromagnetic survey, sampling and drilling campaings. The most important outcome for this WP were:

- High-quality graphite appear in areas with the highest metamorphic degree, upper amphibolite to granulite facies rocks.
- High-quality graphite migrate to fold hinge areas in high-grade rocks.
- The most suitable areas for further investigations were found in South Savonia.

Beowulf Mining played a central role to finance the drilling campaigns (through Fennoscandian Resources) and the results were continuously reported to the stakeholders of Beowulf Mining. Fennoscandian Resources have continued surveys in the critical areas.

WP 2. Fragmentation and flotation

The aim with WP 2 was that the graphite flakes should not be damaged in the fragmentation process. The project used SelFrag electric fragmentation (at the Geological Survey of Finland) and ZRI-treatment (together with Haarla company) before flotation to avoid damaging the graphite flakes. However, these methods did not fill the espected results. There were too many contaminating minerals adjusted to the graphite, which is why we continued to fragmentate and flotate the graphite ore mechanically and by conventional flotation methods. After flotation, the graphite content was enriched to about 88%. After chemical digestion, we managed to enrich the ore to 99,3 %.

WP 3. Solution processing to graphene

We developed a process based on shear stress induced into graphite powder and a surfactant solution with rotor-stator mixers. The concentration of the graphene

dispersions was detected with UV-visible spectroscopy and a yield of 1.15 % was obtained being higher than usually obtained by similar methods.

WP 4. Proof-of-concept applications

We have prepared nanocomposite films consisting of few-layer graphene and nanocellulose by using a standard airbrush to spray-coat glass substrates. This simple and cheap method produces 200 nm thick composite films with the electrical conductivity in the upper semiconductor regime (ca. 30 S cm-1). Flexible substrates can also be coated with these thin films. In future, we aim to use the spray-coated composite films in electrochemical sensor and energy storage applications.

Summary and further plans

The project was able to receive results from all work packages. All results will be presented in detail in international publications. Fennoscandian Resources continues their surveys in critical areas with the goal to find an area for a graphite mine in the future.

There is an interest to use domestic graphite and graphene among research groups working with these materials in Finland. Due to a maternity leave the reports from the technical applications are somewhat delayed, but will be published in the close future.

After this project, we know there are suitable areas for graphite exploration in Finland. This graphite is of high quality and can be exfoliated to graphene.

We already started a small scale project focusing on the global graphite value chain (with the laboratory of Industrial Management at ÅAU). We hope that this new project can establish a sustainable and efficient value chain for such production as well as an enabling business ecosystem that will engage all the crucial actors. We will contact Academy of Finland when we have results from the small scale project and are ready to investigate value chains for all critical battery minerals.

13. Thermoelectric Materials based on Earth-Abundant Oxides

Not available.

14. Development of novel electrodeionization system for recovery and recycling precious metals and rare earth elements from mining effluents

Not available.

15. Particulate matter in mines and mining environments PARMAT

Funding call: Joint projects (MISU): Academy of Finland and CONICYT

Principal Investigator: Doc. **Hilkka Timonen**, Finnish Meteorological Institute

New knowledge generated in the project

This project has created improved understanding on sources of particles in an underground mine. Measurements conducted in mine indicated that main sources of pollutants in mine are traffic, blastings and mining activities for submicron particles. Coarse, supermicron particles, were mainly originating from mining activities. This information can be used to reduce the health effects, adjust the ventilation in mine to improve air quality and to create cost savings via ventilation optimization. Furthermore, a prototype sensor with both optical and electrical detectors that is able to detect particles over large size range was built and tested in laboratory and mine condition in Finland and Chile. Several problems were identified in tests and based on these several improved versions of sensor were created during the project.

Exploitation of results by the industry or economic life

This project provided new information about health, air quality and environmental impacts of mining. This data can be used in future studies and modeling to estimate the impacts of mining to nearby nature and people. Furthermore, the results can be utilized to improve air quality in mines and optimize ventilation, thus providing more healthy and sustainable working environment for workers. Due to their ability to provide better spatial coverage, developed sensor type measurement methods could be an important tool in future in identification of environmental or health risks of mining activities. In short term, the further development of low-cost sensor towards more commercial version is planned. Furthermore, three new projects have started last year. EU2020 project TUBE focuses on health effects of nanoparticles and Business Finland project BC Footprint focuses on Black carbon emission. UIA-HOPE; healthy outdoor premises for everybody project aims to improve urban air quality measurements using air quality sensors. All these new projects are benefitting from the work and collaboration network built and knowledge gained in the PARMAT project. The Chilean partner will utilize the sensors developed in the

PARMAT project in the new projects. A MOU was signed between FMI and CMMCh to continue and increase collaboration with CMMCh.

Researcher careers

Altogether 11 researchers from Finnish Meteorological Institute and Tampere University worked in this project. Four of these researchers are currently employed by industry and one researcher has moved to another university. This project, done in close collaboration of different national research institutes, international partners and industrial partners, has increased collaboration between partners and enabled fast transfer of research results to the industry. Close collaboration with Kemi mine has continued even after the project and we have presented results to Kemi mine and discussed possible future collaboration.

Impact of the project in line with the goals of the programme

This project has studied the air quality impact of mining, developed new measurement method suitable for air quality measurements in mines and improved both multidisciplinary and international collaboration. The air quality of mines is poorly known, thus information provided by this project is very important in order to decrease the adverse health consequences of poor air quality in mines and to improve the competitiveness of mining industry. By improving the air quality, and thus decreasing the impacts of mining activities to health and environment, the sustainability of mining can be increased. Collaboration with Chilean partner has been also tightened the collaboration between institutes and has generated several new projects between Finnish and Chilean partners.

Interaction with industry/economic life

The main contact in Industry was the Kemi mine. The measurement campaigns conducted in this project were planned and implemented in collaboration with Kemi mine. After the campaign, results have been presented to them and discussed. Further collaboration has been planned. The results of this project have been actively communicated via presentations (e.g. Kaivosten ympäristöpäivät 2017, 2018, Nordic Society for Aerosol Research conference Helsinki 2018 and International aerosol conference St. Louis 2018, MISU seminars 2017 2018, Finnish embassy in Chile) to industrial partners, authorities and scientific actors in the field. For general public, the main results of this project were published as Science News at FMI internet-pages (https://www.ilmatieteenlaitos.fi/tutkimustoiminta).

16. Recovery of Rare Earth Elements from Phosphogypsum/REE–PG

Principal investigator: **Tuomo Sainio**, LUT University

Scope and key results

Millions of tons of rare earth elements (REE) are locked in phosphogypsum (PG) that is formed in phosphate fertilizer production. The objective of REE-PG project

was to develop new technology for recovering REEs from PG and solutions that have been in contact with PG. LUT worked together with VTT and GTK from Finland and Mintek from South Africa.

More specifically, LUT focused on intensification of acid leaching of REEs using polymeric separation materials ("resin-in-leach", RIL). The phenomena in the RIL process were studied with commercial resins and novel resins. In contrast with previous literature, where conventional resins are recommended, chelating resins were found superior. They offered significantly higher REE purity over calcium (20%) than conventional resins (3%). Moreover, it was found that REE purity increases with loading when a chelating resin is reused in cross-current mode. The leaching yield remained much higher than with conventional resins.

Application of the results

RIL is a known technology and applied in production scale in, for example, gold and nickel industry. In large scale REE recovery application, post-treatment of the wet residual PG would be a major concern if concentrated acid is used. The results obtained make resin-in-leach with chelating resins an attractive process option because leaching can be made at very mild conditions (1 g/L sulfuric acid). The research is currently continued in a project funded by Suomen Luonnonvarain Tutkimussäätiö.

In principle, the RIL approach could be applied to other waste materials available in large quantities. After REE-PG project, preliminary tests were made with industrial fly ashes but selectivity was not satisfactory.

Researcher careers

Most of the researchers who participated in REE-PG project have advanced in their careers in the same research institute. One researcher moved from Finland to Belgium and works in an R&D manager position in the industry.

Impact and interaction with the industry

Even though REE-PG was an academic project, its relevance for minerals processing industry was secured by staying in contact with certain companies. Phosphogypsum raw material was obtained as a donation from Yara's site in Siilinjärvi and used in all research work in REE-PG. The company also shared information and views on apatite processing globally during the project.

The scientific results pertaining to the resin-in-leach recovery and purification of REE from phosphogypsum have been disseminated to the industry to encourage them to utilize phosphogypsum waste as a secondary source for rare earth elements. After the project was completed, a series of meetings and teleconferences was organized to present the results for several companies including

- a major phosphate fertilizer producer and the owner of a large phosphogypsum reserve that has operations in Finland
- a producer of REE oxides based in Norway

- an OEM company based in Finland and interested in commercialization of RIL technology
- a company that currently produces REEs in Estonia using liquid-liquid extraction
- a German company currently producing REE based end-products.

Sub-project: Principal investigator Prof. **Pertti Koukkari**, VTT

Research results

The hypothesis in the research was the earlier suggestions that the rare earth metals (REM), typically present in moderate amounts in the phosphogypsum waste of fertiliser production, could be enriched by subjecting the aqueous phosphogypsum leachate to treatment with sulphate-reducing bacteria (SRB) in analogy with the well-known SRB treatment of heavy metals in acid mine drainage. The study focused on cultivation of microbial strains from environmental samples and studies on their activity in phosphogypsum leachates. The experiments performed however showed that little or no enrichment of REM could be found in chemostats operating at near neutral conditions. Continued research with strains enduring more acidic conditions, however, led to more promising results concerning the efficient treatment of acidic sulfate-containing effluents where dissolved rare earth cations were obtained by utilizing sulfate-reducing bacteria. A thorough investigation on interactions between different microbial groups will further be conducted, which can offer new information on bioreactor performance in more extreme conditions.

Thus far, the sub-project has published four referee articles, three conference papers and one general publication.

Practical applications

The apatite minerals, industrially utilized for manufacturing phosphate fertilizers represent a potential secondary source of REM. In the current fertilizer manufacturing process even 80% of the these will end up in the phosphogypsum side product, which then holds 0.15–0.5 % of rare earths. The process generated in this project could provide a basis for a passive phosphogypsum effluent treatment system for related industrial sites, such as the fertilizer plants.

Researcher positions

The funding was but for a limited part time research at VTT and did not lead to changes in researcher positions.

Impacts and interactions

Throughout the project, extensive co-operation between the partners was practised, resulting in a one-month visit from VTT to Mintek in South Africa, as well as several co-publications between VTT and Geological Survey of Finland (GTK), combining mineralogical analysis with development of process concepts. The

project elucidated the possibilities to combine chemical and biological phenomena both in the treatment of harmful effluents and in the recovery of valuable elements. In addition, one article and one conference paper was published jointly with the Rare Earth research group of Ural Federal University, led by professor V. Rychkov, thus giving insight in the academic practices of recovering rare earths from secondary sources by using both chemical techniques and bio-hydrometallurgy.

The project outcome has been disseminated at several different national/international seminars and conferences with participants from both academic and industrial fields. The results of the project were also presented to the industrial partner who provided the materials and future research possibilities have been discussed.

The general paper published in Materia 2 /2017, titled 'Waste heaps may be set to reveal their content of critical metals', authored by professors Pertti Koukkari (VTT) and Mari Lundström (Aalto University) was given the Petter Forsström Best Paper award by the Finnish Association of Mining and Metallurgical Engineers.

Publications

Referee articles:

- Marja Salo, Oleg Knauf, Jarno Mäkinen, Xiaosheng Yang, Pertti Koukkari. Integrated acid leaching and biological sulfate reduction of phosphogypsum for REE recovery, 2020, Minerals Engineering Vol. 155 (published online).
- Marja Salo, Jarno Mäkinen, Jason Yang, Matti Kurhila, Pertti Koukkari. Continuous biological sulfate reduction from phosphogypsum waste leachate, 2018, Hydrometallurgy, Vol. 180, pp. 1–6.
- Mäkinen, J., Bomberg, M., Salo, M., Arnold, M. , Koukkari, P: Rare Earth Elements Recovery and Sulphate Removal from Phosphogypsum Waste Waters with Sulphate Reducing Bacteria, Solid State Phenomena, Vol. 262, pp. 573-576, 2017
- Rychkov, V., Koukkari, P., Kirillov, E., Kirillov, S.:Best Practices of Russia and Finland in Extracting REE from Fertilizer Waste, KnE Materials Science; Technogen-2017 pp. 168-173, DOI: 10.18502/kms.v2i2.965

Conference presentations and papers:

- Marja Salo, Johanna Björkmalm, Erika Lönntoft, Karin Willquist, Jason Yang, Oleg Knauf, Pertti Koukkari, Jarno Mäkinen. Towards comprehensive sulfur and metal management: combining biological sulfate removal and metal recovery, 2019, International Biohydrometallurgy Symposium, Fukuoka, Japan. (Oral presentation)
- M. Mashkovtsev, M. Botalov, D. Smyshlyaev, R. Pajarre, P.Kangas, V. Rychkov, P. Koukkari, Pilot-scale recovery of rare earths and scandium

from phosphogypsum and uranium leachates, ES Web of Conferences conf /2016 3 30 010288 MEC2016, 10 pp DOI:10.1051/e3sconf/20160801026

- J. Mäkinen, M. Bomberg, M. Salo, M. Arnold, P. Koukkari. "Rare Earth Elements Recovery and Sulphate Removal from Phosphogypsum Waste Waters with Sulphate Reducing Bacteria", 22. International Biohydrometallurgy Symposium, 24 - 27 September 2017, TU Bergakademie Freiberg, Sachsen Germany

General publications:

- Pertti Koukkari, Mari Lundström, Antti Porvali, Sergei Kirillov: Waste heaps may be set to reveal their content of critical metals, Materia 2 / 2017 61-65.

Sub-project: Principal Investigator **Jason Yang**, Geological Survey of Finland (GTK)

Summary

In the MISU project REE-PG, GTK had mainly carried out research on the characterization of phosphogypsum samples. Over ten research scientists and assistants were involved in the project. Funded by the project three research papers had been completed and published in peer reviewed journals.

Mainly two studies were conducted:

1. Rare earth occurrences including the REE-bearing phases and their distributions, measured by rare earth oxides (REOs), in the streams of processing a phosphate ore were determined by using MLA, the mineral liberation analysis and EPMA, the electron probe microanalysis. The percentages of the total REOs (TREO) contents from the ore end up in the products of beneficiation tailings, phosphogypsum (PG) and phosphoric acid, respectively, were determined. Apatite, allanite, monazite and pyrochlore are identified as REE-bearing minerals in the beneficiation process.
2. Collaborated with VTT the modal mineralogy determination in the biological sulfate reduction treatment of phosphogypsum leachate was conducted.

Impacts

Through the project some impacts have been displayed:

1) It positively had affected our research practice and promoted our service in the field of processing mine tailings for recovering valuables metals;

2) It had promoted our collaboration with the Finnish partners, LUT and VTT, and the partner of South Africa, in the field of research.

17. On-line Risk Management in Deep Mines (ORMID)

Principal investigator: Prof. **Mikael Rinne**, Aalto University

The main goal of the research project was to find out if deep mines could use real-time monitoring of stresses to avoid collapses. The project cooperated with two mines, Garson Mine in Canada and Kemi Mine, in Finland. The research was conducted in parallel with Queen's University in Canada.

New knowledge generated and key results

1) The research resulted in a method to back-calculate stress changes from observed rock movements. Using the results, mines can track stress evolution as the mining progresses and avoid unexpected ground movement such as collapses.

1) The results address the methodology to carry out a detailed geotechnical risk assessment in underground mines using a Bayesian network and on-line data from a site. In this method multiple probability distributions of failure to forecast the geotechnical risk is proposed.

2) During the project, it was demonstrated that an integrated circuit or a microcomputer can be used to read and transmit data from sensors to provide initial data for a real-time risk management system. As a result, preparation of commercialization of the research results project was launched (REMOS - Real-time monitoring of stress). Field measurements conducted in Kemi Mine showed that the system could reliably transmit data from 500 m depth to the surface for integrated computing of the stress state.

3) Understanding of how the fracture zone develops around excavations was increased by conducting in-site measurement in Garson Mine using ground-penetrating radar and numerical modelling. The likely location of stress-induced fractures was predicted using a fracture propagation code FRACOD2D. Unfortunately, a large collapse in the test mine prevented further research of the site to confirm the modelling results.

Applications based on the research made for the ORMID project

The research conducted in the ORMID / MISU initiated a new Academy of Finland project, named “Geophysical and Geochemical Methods for Stope Design (GAGS)”. We aim to develop scientifically based solutions for fast and reliable predictions of geotechnical conditions so that safe and profitable operations can be maintained in the future. The GAGS focus on utilization of geophysical and geochemical methods to characterize rock properties for stope design and geometallurgical analyses. The ORMID project also initiated the (REMOS - Real-time monitoring of stress) project, which aims to commercialize the research results of it. REMOS is a device that integrates measurements from extensometers, cable bolts, or rock bolts. It calculates and displays in real-time the stress state changes of the rock mass and enables the extraction of the ore with instant warnings for unexpected

ground behaviour. Partners in the REMOS project are Aalto University, Outokumpu, Afry (former Pöyry), FinMeas, and Suomen TPP. Business Finland is involved by funding the main part of the project.

Positions of the researchers after the project

Two doctoral theses dealing with the ORMID research questions were produced during the project. The title of Ritesh Mishra's doctoral thesis is "Geotechnical classification and Bayesian network for real-time risk assessment in mining". After the dissertation, D. Sc. Mishra continued his work at First Quantum, a big international mining company. His current position is Optimisation Manager on a mine site in Zambia. The second doctoral thesis by Lauri Uotinen deals with "Prediction of stress-driven rock mass damage in spent nuclear fuel repositories in hard crystalline rock and in deep underground mines". D.Sc. Uotinen currently holds the position of a Staff Scientist at Aalto University. In addition, the doctoral studies by Mateusz Janiszewski also contributed to ORMIDs research. All three doctors are currently involved with the afore-described REMOS project.

Impact generated in line with the goals of MISU programme

The aim of the Mineral Resources and Material Substitution (MISU) programme is to strengthen multidisciplinary and interdisciplinary approaches and to move towards a more systemic orientation in the research fields concerned. This is made by creating models for a new generation of sustainable extractive industry that takes seriously its environmental responsibilities. Another central issue is the profitability of mining operations across their life cycle. Measurable results of the ORMID project are not easy to express. It is however clear, that better understanding of rock stresses yields to safer and more resource-efficient mining in terms of better ore recovery and less ore dilution.

One of the aims of MISU is to establish good interactions with research funding agencies like Business Finland (former Tekes). The REMOS project is a so-called Tutli project, which aims to initiate business from research ideas and results.

MISU also aims to selectively establish cooperation with research funding agencies in other countries that are committed to supporting leading-edge scientific research in the field. South Africa, Canada, Australia, Sweden, and Chile, among others, are identified as interesting target countries. It was unfortunate that the cooperation with South Africa (CSIR Natural Resources & Environment Unit) never materialized. However, Canada is one of the leading nations in mining and Queen's University with prof. Steve McKinnon, one of the leading universities in this field. The co-operation with Queen’s University was successful and it will continue in the future.

MISU program aims to generate new multidisciplinary research knowledge. Multidisciplinary research has been recognized in the ORMID project by utilizing geophysics and rock mechanics with mining engineering. GAGS project, which is partly an extension of the ORMID, aims to improve the interphase and interaction between rock mechanics, geophysics and geochemistry to mining and geometallurgical challenges.

Interaction with industry/economic life

Online monitoring of the rock mechanics conditions in deep mines is a challenging task, but an essential part to improve safety and profitability of mining. The result of the ORMID project has initiated cooperation with companies involved with geotechnical monitoring, like Finmeas and Geovisor. Suomen TPP is a company specialized in rock reinforcement. In the REMOS project, we jointly aim to develop a smart bolt that will monitor online the changes in the stress field. AFRY (former Pöyry) is a big Finnish consulting company that is interested in applying the created knowledge to plan safer and more resource-effective mine lay-outs. Cooperation with KEMI mine continues under the same theme as was investigated in the ORMID project.

18. Towards sustainable mineral processing via plantwide eMPC

Not available.

19. Protocol development for evaluation of water-saving alternatives in minerals processing - “Bridging North to South”

Not available.