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Knowledge and technology transfer in and beyond mineral exploration

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Abstract

In natural sciences, mineral exploration has a high network centrality. For industries with high technological- and knowledge proximity, transfer effects are an important function for innovation. Despite the high level of proximity between mineral exploration and other natural sciences, scholars hardly examine transfers from and to mineral exploration. This paper analyzes obstacles and mechanisms of transfer effects in and from mineral exploration and finds answers on how to institutionalize knowledge and technology transfer (KTT). The study employs a qualitative research design. The underlying database consists of 16 expert interviews, from the fields of natural science. The results show that KTT between areas as diverse as mineral exploration, healthcare, and arts are possible. A lack of interdisciplinary exchange and rigid scientific structures is the main inhibitor of KTT. Before this study, evidence for KTT from and to smaller industries is mostly anecdotal. The study is among the few, which investigates KTT concerning functional transfer opportunities.

Keywords: Knowledge transfer, Technology transfer, Mineral exploration, Natural sciences

Introduction

Increasing technological complexity and rising development costs forge closer links between innovation activities across industries. According to Woerter (2012), industries with similar targets, challenges, and high technological proximity show strong potential for KTT (knowledge and technology transfer). The position of institutions in an industrial network further mediates KTT (Huggins et al., 2020). Huggins et al. (2020), proved that network centrality increases "relational involvement" and supports open innovation processes. Own-industry applications in mineral exploration such as the Full Tensor Magnetic Gradiometry (FTMG) are used in unexploded ordnance (UXO) (Stolz et al., 2015) as well as archaeology (Linzen et al., 2009). Likewise gas detection, agriculture or vegetation mapping applies thermal hyperspectral cameras (Holma et al., 2012). Machine learning, which originated from computer sciences is another technique applied in but not limited to mineral exploration (McCorduck, 1979). Despite the transfer of different applications and techniques from and to mineral exploration, little research has been published on this subject. Consequently, methodological and technical adaptation benefits or obstacles related to governance or policy discussions are poorly understood. Evidence from European-funded projects such as INFACT (innovative, non-invasive and fully acceptable exploration technologies) suggest that interdisciplinary work in mineral exploration is among the most important factors for technological growth (Kesselring et al., 2020). Throughout the project physics-centered applications were introduced into mineral exploration and exchange platforms for joint advancements in natural sciences were demonstrated to be viable (Nevalainen et al., 2020). Publicly funded project, that can support the freedom to explore novel angles to innovation are thus a well-cited KTT driver (Carayannis & Campbell, 2011, Davies et al., 2021). However, the linkages between technological functions, systems and resulting transfer directions are hardly analyzed (Ferraro & Iovanella, 2017). Similarly lacking is the mediator and moderator of such transfers across industries of different sizes. While, transfer directions from industries such as aerospace seem intuitive, knowledge about transfers from smaller industries is limited (Piller et al., 2021). Evidence suggests that applied technological innovation, associated with smaller industries may lead to higher market responsiveness and reduced innovation inertia (Eggers & Park, 2018). Transferring different technologies, applications, techniques, and knowledge from and to smaller industries, such as mineral exploration, may thus have a significant impact on innovation, economic growth, resource utilization, and sustainable development. However, much of the research up to now has been descriptive in nature. There is little published data on strategic attributes concerning upstream collaborations between small and large industries. In addition, reverse innovation of functionalities and applications to explore entrepreneurial opportunities are hardly analyzed. Research is needed to develop strategies and policies that promote more equitable and sustainable development outcomes by understanding the factors that contribute to successful KTT to and from smaller industries. Investigating KTT in and from mineral exploration is therefore the concern of the present study. This paper is a frontier with undertaking an analysis of KTT from and to mineral exploration. The analysis considers the technologies, methods, and systems applied in mineral exploration. It aims to obtain in-depth information about the existing mechanism, drivers, and obstacles of knowledge transfer between mineral exploration and industries that employ similar sensing data processing technologies and techniques. To this end, the research follows a qualitative approach employing semi-structured interviews. Compared to quantitative or conceptual work, this method leads to a comprehensive understanding of complex, new, and evolving phenomena (Guta, 2013).

Literature review, hypotheses, and research framework

Knowledge and technology transfer

Technology transfer and knowledge transfer are concepts often used as synonyms for spillover effects. Conversely, to spillovers, transfer mechanisms are not externalities, but refer to the intentional transfer of technology and knowledge “among research institutions, industry, and the public” with the objective to make scientific contributions (Audretsch et al., 2012). Existing systems are transferred into new areas to realize novel or optimized technologies and knowledge-based systems. Technology transfer and knowledge transfer are intertwined. To explain this interdependence (Gibson & Niwa, 1991) introduce the term knowledge-based technology transfer. The term highlights the interdependencies between effective knowledge transfers as means of technology transfer. However, controversial is the direction and shape of this interdependence. For some authors, knowledge management triggers effective transfer first (Gopalakrishnan & Santoro, 2004). Others suggest that effective transfer strategies should be tailored so that transfer can emerge from built technologies or functionalities and complement the results of knowledge accumulation (Gibson & Niwa, 1991). Transfer strategies can help to bridge the gap between academia and industry, and promote the commercialization of scientific research (Lucas & Taylor, 2021). However, many KTT initiatives fail to achieve their intended outcomes due to various factors, including misaligned incentives, lack of trust between stakeholders, and limited capacity for absorptive learning (Ranga & Temel, 2018; Hayter et al., 2020). To address these challenges, KTT strategies need to adopt a more strategic and systematic approach to technology transfer that considers the specific knowledge and capabilities of different stakeholders (Cameron et al., 2014, Glynn et al., 2018). Despite the relation between technology and knowledge management, previous research indicates that transfers can occur in own? and other?industry sectors whereby the receiving sector is the use-industry (Choe & Ji, 2019). While such definition arose from organizational (Jiao et al., 2018) and economic research (Grassi & Sauvagnat, 2019), such studies omit the challenges of dealing with the complexity of innovation in entrepreneurship. Thus, the present paper aims for a more precise distinction to realize in-depth analysis. Adopted from open innovation research (Karlsson & Sköld, 2013) the paper suggests that transfers can occur within an industry ("horizontal" transfer) and alongside supply chains ("vertical" transfer). While the research distinguishes between "horizontal" and "vertical" technology transfers, recent studies have shown that the outcomes of KTT are shaped by challenges such as organizational culture, absorptive capacity, and intellectual property rights (IPR) (Argote et al., 2022; Li et al., 2019; Favorskaya et al., 2017). Thus, a more nuanced approach is needed to understand the outcomes and challenges of technology transfer in different industries and contexts. Beyond these definitions, transfers are not limited to suppliers or customers in complementary sectors. Linkages also exist between parties on the same value chain level but from different industries (Barros et al., 2020). Introducing the term diagonal transfer, such linkages occur between two or more parties using a similar technology, system or method but for different purposes. For all transfer directions, various authors reported that realization of KTT can reduce innovation gaps (Heinzl et al., 2013), generate productivity gains (Siegel et al., 2003), and lead to cost reduction (Pinto et al., 2019). Enforcing mediators of transfer are regional proximity (Ng et al., 2020), social, and intersectoral visibility (Jiao et al., 2018), adaptation as well as integration capacity (Carayannis & Campbell, 2011), multidisciplinary cooperation (Piller et al., 2021), size and structure of the originating and receiving industry, as well as knowledge-, technological-, and industrial proximity (Shi et al., 2020). Conversely, market rivalry (Prud'homme et al., 2018), intellectual property rights (IPR) (Scherngell & Jansenberger 2006) and narrow funding programs (Chang, 2016) limit KTT. The effectiveness of KTT is however contingent upon a variety of contextual factors and potential drawbacks should also be considered, perspective that the current literature fails to cover fully. Concerning funding programs, most public grants, evaluate how well a project responds to a specific grant description. According to Chang (2016) criteria satisfaction rather than scope-oriented scoring, limits the innovative capacity, and close-off exploratory KTT. However, where non-rivalry and non-excludability do not hinder transfer, multidisciplinary cooperation encourages KTT (Piller et al., 2021). Various authors analyzed challenges and barriers to technology transfers (Corsi et al., 2021). Current research on the limitations of KTT predominantly focuses on high-level concepts that exhibit a substantial degree of generalization potential. Yet a closer examination of limitations can reveal an array of nuanced features that appear to be overlooked by current investigations.

Technological perspective of KTT in mineral exploration

Transfer in sensing devices used in modern mineral exploration, dating back to Aristotle who aimed to capture human motion via light reflection (Moore, 1979). Magnetic sensors have an even longer history, with 4000-year-old reports about magnetic load-stones for directional aid (Boll, 1989). More often than not today's versions of these devices were developed by industries with high research and development (RnD) funding (Okada, 2022). Unsurprisingly, the origins of many mineral exploration techniques and applications stem from defense and aerospace. For example one of the earliest forms of remote sensing was developed for camouflage detection late during World War 2 (Taylor & Mondey, 1972). The same applies to fluxgate magnetometer initially developed to decrease signatures of naval vessels and later adapted to mineral and petroleum exploration (Holmes, 2015). Today, the complexity of functions within a single device opens up the spectrum for transfer inspirations (Okada, 2022). Consequently, it is no longer sufficient to track progress in one industry but to open the search. Table 1 provides evidence for the requirement to open knowledge flows. Here the most recent applications in

Table 1 Cross-industry technology usage associated with mineral exploration

Technology	Usage scope	Source
Induced polarization	Environmental applications, temperature measurement, geochemistry, delineation of contaminant plumes	(Smith, 2016, Kwan and Müller, 2020, Auken et al., 2015, Mashhadi & Ramazi, 2018, Kaminski & Viezzoli, 2017)
Longwave infrared hyperspectral imaging	Agriculture, vegetation science, construction, security, medical	(Hecker et al., 2019, Nadal et al., 2017, Tratt et al., 2016, Weksler et al., 2016)
UAV magnetics	Defense, archaeology, engineering/construction	(Funaki et al., 2014, Jackisch et al., 2019, Macharet et al., 2016)
UAV hyperspectral imaging	Natural hazard, aerospace, defense, civil engineering, environmental sciences, archaeology, construction	(Adao et al., 2017, Banerjee et al., 2020, Dutta et al., 2019, Kirsch et al., 2018, West et al., 2018, Kurz & Buckley, 2016)
Light detection and ranging	Archaeology, cultural heritage documentation, forestry, construction, corridor mapping, hazard assessment, agriculture	(Chase et al., 2011, Favorskaya et al., 2017, McCoy et al., 2011, Mora et al., 2015, Thiel & Schmullius, 2017)
Ground-based hyperspectral imaging	Natural hazards, defense, civil engineering, construction, environmental, archaeology, industrial engineering, agriculture, medical, art, defense, mining	(Khan et al., 2018, Kirsch et al., 2019, Krupnik & Khan, 2019, Kurz et al., 2010, Stuart et al., 2019, Wendel & Underwood, 2017)
Magnetotellurics	Groundwater exploration, buried waste, archaeology, agriculture, geothermal	(Aivazpourporgou et al., 2015, Aizawa et al., 2009, Heinson et al., 2018, Wannamaker et al., 2019, Karshakov et al., 2020)
Ground-floor electromagnetics	Groundwater mapping, engineering, medical	(Bengert et al., 2020, Cameron et al., 2014, Rageh et al., 2020)

mineral exploration and their application in other industries are illustrated. Apart from natural science, transfers from structural sciences exist. Only within the last 15 years, has machine learning entered the mineral exploration industry (Barnett & Williams, 2006). An industry, which unlike industries such as mechanical engineering does not suffer from data availability (Yousefi et al., 2019). Challenging to the transfer of machine learning, is however that mineral exploration deals with causation rather than correlation. Causal thinking in modeling limit the accuracy of associative algorithms (McCuaig & Hronsky, 2017). The existing accounts fail to resolve the contradiction transferability of algorithms and practical pathways to realize transfers. Besides data processing as well as applications and techniques, the role of platforms is crucial. Driven by the need for efficient and effective scanning aerial advances are a subject of interest. Unmanned Aerial Vehicle (UAVs) is among the best-published transfers (Kim et al., 2016). Benefits of UAVs include the possibility to access remote locations and decrease the distance between target and sensor (Donohue, 2014). Despite the evidence described, the research on diffusion patterns of UAVs is mostly limited to the literature on warfare. Thus, commercial and scientific diffusion patterns associated with UAVs are hardly understood.

Research narrative

The evidence reviewed suggests a pertinent role for economics and management in KTT literature. In addition, authors have demonstrated the application of a single technique in the varying field. Two aspects stand out here. First, theoretical evidence for KTT is mostly output oriented. The specific types that underpin outcomes and challenges of KTT in different industry sizes and contexts are not fully understood. Much uncertainty still exists about the relationship between intra- and inter-organizational drivers of KTT. Understanding the link between KTT and industrial and organizational context may support market responsiveness and the reduction of innovation inertia (Eggers & Park, 2018). To understand the dynamic nature of KTT associated with mineral exploration and the cross-level perceptual implementation of technologies, a descriptive analysis of the established facts is required. The second aspect comes from the technical perspective. While there are examples of joint usage of similar techniques (Okada, 2022), research has not caught up on the topic, still focusing on domain-specific research. For example, previous research findings in long-wave infrared hyperspectral imaging focus on one application field (e.g., mineral exploration) only. From the increasing complexity of functions within a single device, tracking progress in one industry only, disregards the expanding potential for transfer possibilities (see Table 1) (Okada, 2022). To conclude this section the existing literature has limited clarity about KTT in different industries and the associated challenges, such as the types of KTT that underpin different industries, the organizational drivers of KTT, and the exploitation of technical linkages. To address paucity in literature, the study investigates KTT in mineral exploration, including its types, drivers, challenges, mechanisms, and endurance of linkages. The research aims to provide an in-depth understanding of arguments that rely on expert knowledge. Mineral exploration was chosen as a suitable case study due to its complex technical processes and knowledge-intensive activities, which require collaboration and knowledge transfer between various stakeholders. As the mineral exploration industry faces increasing challenges related to KTT due to the high complexity and diversity of knowledge required for exploration activities this study can contribute to increasing KTT research in mineral exploration and industries facing similar problems. In demonstrating transfer opportunity, innovation mechanisms may be expanded. In this context, the present study attempts to investigate the types, drivers, challenges, mechanisms, and endurance of linkages of knowledge transfer and technology (KTT) in small and complex industries, and to provide insights into how this understanding can inform strategies for promoting sustainable and effective exploration practices. Thus, answering the following three research questions: (1) What are the types of KTT that underpin small industries, and what are the intra- and inter-organizational drivers of KTT in associated industries? (2) What challenges are associated with KTT from and to small industries, and what mechanisms can increase KTT and support the endurance of linkages? (3) How can a better understanding of KTT to and from small industries inform future strategies for promoting sustainable and effective KTT practices? In the context of KTT in mineral exploration, the present study explores: (1) the recognized types of KTT, (2) the driver of KTT, (3) the challenges associated with KTT, and (4) the mechanisms that might increase KTT as well as support the endurance of relational transfer.

Methodological approach

Study design

The study aims to identify transfer directions and obstacles as well as mechanisms within disciplines associated with the mineral exploration industry. Since a systematic analysis of KTT lacks in-depth information, a qualitative study design was identified as a suitable research approach. Identification of factors is limited to the type of KTT, existing mechanisms, and obstacles.

Data collection

In-depth semi-structured interviews were chosen as the primary source of data sampling. Semi-structured interviews are a qualitative research design that allows for a predetermined set of open-ended questions or topics, and follow-up questions and probes to explore participants' responses in greater depth (Kallio et al., 2016). Semi-structured interviews provide a structured framework to guide the conversation, while allowing for a more nuanced understanding of participants' experiences and perspectives (Gioia et al., 2013). The method was adopted as it is (1) suitable for research embedded in novel, complex contexts; (2) provides well-founded information; (3) fits with the exploratory nature of this study (Kallio et al., 2016). The study is exploratory and aims to identify novel patterns in existing processes. Case studies are one approach to generating distinctive insights from complex scientific settings. Compared to empirical studies, case studies retain comprehensive characteristics of real tasks (Yin, 2018). Structured, semi-structured or unstructured interviews can be used to generate case study data (Yin, 2018). The data sample consists of 16 experts from academia and practice. Experts are respondents in middle to top management positions. An expert is an individual who has experience in an interdisciplinary exchange between their industry and mineral exploration. The experts come from different technology branches and industrial fields. All experts are credited with mineral exploration. Seven experts stem from academia (R), and nine are from industry. For participants from industry practice, a further distinction is applied. Industry experts, divide into consulting (C) and general industry (I). A consultant is understood as an expert providing independent evaluations, advice, and solutions in a specific field. Consultants interviewed either work as freelancers or a part of impartial consultancy cooperation. The diversity of the interviewees minimizes potential sample bias. The inclusion of scientific as well as practical experts increases the comprehensiveness of the data. Table 2 provides information on the sample. Notation No. indicates the number of participants with the illustrated characteristics. As the sample is male-dominated, there is a potential for bias. The male-dominated sample means that generalizability is limited and it is impossible to investigate the significant relationships in gender-biased answers. Interviews were held between June and August 2020. The interviews lasted between 26 to 49 min and were conducted in English. For confidentiality reasons, the interview data were anonymized. The questions are informed by literature but follow the principle of openness and flexibility (Kallio et al., 2016). To detect errors in content, comprehensibility, and plausibility, two pre-tests were conducted. After the pre-tests, minor edits were made. In line with Kallio et al. (2016), the questionnaire consisted of three parts. To verify the expertise of the interviewee, part one contained general and personal questions. Part two dealt with questions about the feasibility of different kinds of transfer, existing mechanisms, drivers, and obstacles of KTT. Participants were asked to refer to their experience rather than quote acquired knowledge. Part three asked which mechanisms could be valuable to increase and institutionalize KTT. The interviews were audio-recorded and later transcribed. For triangulation, secondary data were collected from company websites, as well as annual and project reports. With triangulation, the statements of individuals can be verified, and the validity of the study increases (Yin, 2018). The content analysis was aligned to Gioia et al. (2013) and Mayring (2004). A combination of data and concept-driven coding was applied to structure the data. The combination allowed a structured, yet open data analysis and enabled the inclusion of new and unexpected information. The concept-driven coding was applied, to link the data to the research question and generate top codes

Table 2 Data sample

No.	Field	Technology	Industrial fields	Type	Code
2	Engineering	Gradiometers; Magnetometers	Geophysical exploration	Research	R
1	Engineering	Magnetics; EM	Geophysical exploration	Research	R
1	Exploration	EM	Archaeology; Civil engineering; Mineral exploration	Research	R
1	Exploration	Ground penetrating radar, magnetics, gravity, EM	Hydrology; environmental Geophysics; Mineral exploration	Consulting	C
2	Exploration	Geophysics (all)	Mineral exploration; Archaeology, environmental Geophysics	Consulting	C
2	Exploration	Magnetics	Archaeology; Mineral exploration	Research	R
3	Exploration	Geophysics	Mining; Mineral exploration	Industry	I
3	Exploration	Remote sensing	Agriculture; Mineral exploration	Industry	I
1	Exploration	Remote sensing	Hydrology; Mineral exploration	Research	R

(TC). Data-driven coding was employed to identify sub-codes (SC). The structuring was reviewed by the research team. Some SC were synthesized based on team consensus. Quotes illustrated in this paper shall accurately describe each SC. TC and SC are illustrated and discussed in the Analysis and Results section.

Analysis and results

Types of KTT

Figure 1 shows that the techniques, equipment, application, data sets, and knowledge used in mineral exploration possess high transfer potential. The phenomenon was measured by asking experts whether own-industry applications have multiple usages in other industries. 94 percent of respondents proposed at least one commercial application outside their industry. The potential diffusion of techniques and methods is consistent across the five transfer classes (techniques, equipment, application, data sets, and knowledge). The five classes are assigned to three transfer categories. Namely, data acquisition, data analysis, learning, and training. Techniques for data acquisition had the most use-industry applications. Identified techniques analyze surfaces with reflecting potential and subsurface structures. Data processing uses applications, such as filters or machine learning. The figure displays the fields where quality enhancements or casualty detection, benefit from the knowledge obtained in mineral exploration. Adaptation requirements for the applications vary across fields. Machine learning applications showed the highest adaptation requirements. Tactical knowledge such as mindset, social, and

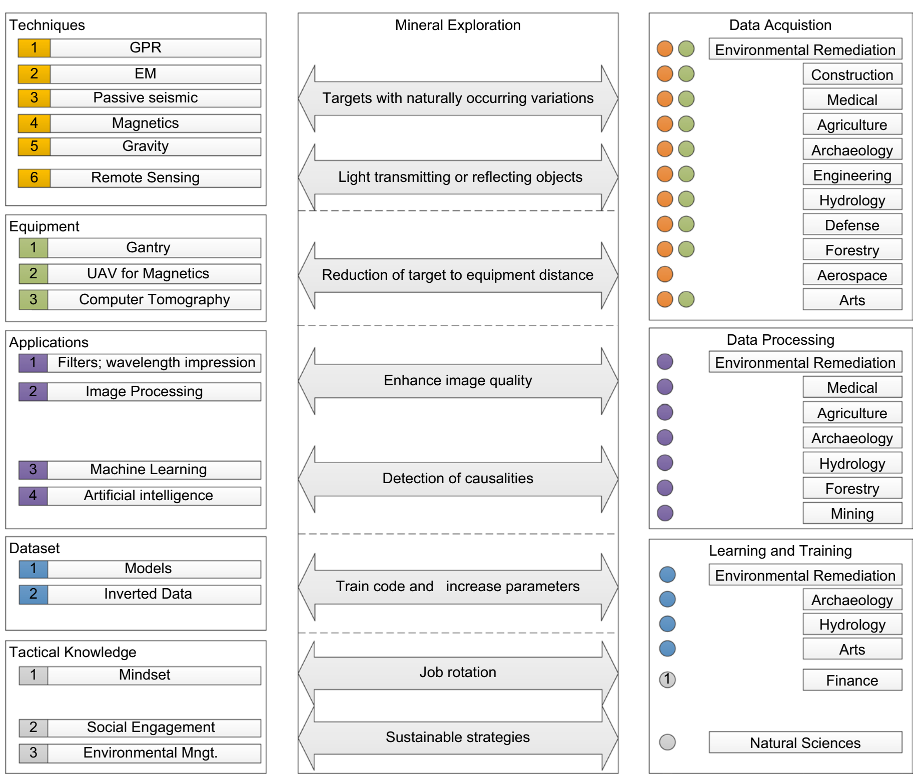

Fig. 1 Types and nature of transfer to and from mineral exploration. The figure illustrates KTT types and directions in mineral exploration

environmental protection strategies can be transferred across industries. Mindset refers to a cognitive procedure required when performing geosciences and may expand career chances outside the use industry. A mindset transfer is possible where similar behavior can guide the pursuit of different research objects. Experts explained that transfer from geoscience into finance is practiced. This is the case, as both industries require decision-making with incomplete information. As a result, geoscientists may migrate into finance and vice versa.

Drivers of KTT

To assess own- and other-industry drivers associated with mineral exploration, respondents should report circumstances that support the diffusion of knowledge and technologies. The results were analyzed and coded. Table 3 illustrates the identified TC, and SC and gives an exemplary statement for each SC. Identified drivers of KTT are consistent across the five transfer categories. Economic: Economic drivers are the second-highest-ranked TC. The recognized direction of this driver is a technology push ("First

Table 3 Drivers of KTT deducted TC: (a) economic-, (b) personal-, (c) structural-, and (d) spatial drivers as well as (e) data accessibility

TC	SC	FQ	Exemplary statement
a	Market opportunities	5	"Diversification by companies with industrial applications and the reduction of risks is of true value." (I)
	Competition	3	"Transfer result from competition between companies with comparable systems or technologies. In both cases, if the end-user can make use of this scenario, it adds value." (I)
	Expected cost savings	3	"Use of new technology if recognition in a specific field and low costs of technology can compensate for missing proof of concept." (R) "With innovative technologies more applications mean more body of evidence, economies of scale that decrease costs." (C)
b	Mindset	10	"We are opening our minds and starting looking at other disciplines." (I) "First the transfer of questions happens; second the transfer of knowledge. " (R)
	Network	7	"You have to know a lot of people across different industries and know their language; You understand these different institutions, not just from an abstract perspective." (I) "Personal scientific and Interdisciplinary networks." (R)
	Evolution	5	"What we do today is the basis for the future." (I) "The technological environment is accelerating at a rate that we may not even realize." (R)
c	Interdisciplinary education	5	"Experience, understanding of literature and demands across fields are required." (R) "It's challenging to get everything together. Your knowledge needs to be deep and wide. You need to speak the language of others. You don't need to be an expert everywhere." (I)
	Industry/ research dialogue	5	"Technology transfers happen through technology application and feedback." (R) "Discussion of problems between scientists and industry and possible collaboration." (C)
d	Regional proximity	3	"Exchange in close proximity is more fluid." (I) "It is beneficial to be next to each other and to know each other's technologies, requirements and capabilities." (I)
e	Open access	3	"The code and data sets are published for free to make transfers possible." (R) "Proprietary technology really is losing out from collectively developed open-source technology. You do not have to deal with the licensing issues. It runs everywhere. It runs on different platforms." (I)
	Ease of data sharing/www	6	"Putting work completely online, e.g., on GitHub." (R) "Worldwide people work with open-source software, improve things gradually and build huge libraries.' (I)

we develop a technology, then we explore relevant applications across industries" (I)). Moreover, three participants see the reduction of development costs as a driver for KTT. Competition later surfaced as an obstacle to KTT as well. Personal: Personal drivers are the most recognized TC. Respondents argue that mindset precedes knowledge sharing within and across industries. The network is the second-highest ranked personal driver. The size, scientific direction, and type of the network mediate the exchange. Concerning the direction, a respondent from consulting argued, that "research might be more likely to spread its knowledge between peers with close linkages to their expertise. Industry is trimmed to look across boundaries; this might lead to more diverse input" (C). Owing to the type, a participant advocated, that "informal exchange is more likely to spread into unexpected territories which formal exchange is reluctant to immerse in." (R). Structural: Interdisciplinary education, industry, and research dialogue support KTT. Spatial: Least recognized are spatial factors. Per the categorization, regional proximity includes relational proximity (e.g., network), institutional proximity (e.g., neighborhood) as well as technological proximity (e.g., similar techniques or applications).

Data accessibility: The majority of the experts named data accessibility as a driver of knowledge transfer. Here open access is recognized as a prerequisite for knowledge transfer. The ease of data sharing was mentioned six times.

Barriers to KTT

To assess own- and use-industry barriers associated with mineral exploration, respondents were asked to report on obstacles to the diffusion of knowledge and technologies. The results were analyzed and coded. Table 4 illustrates the identified TC, and SC and gives exemplary statement for each SC. Internal barriers: Barriers within the community, received the highest recognition. IPR is recognized most. Two discrete characteristics of IPR emerge from the study. Especially within regional clusters, experts from research argued that competition hinders the exchange. The obstacle wears off with diagonally and horizontally linked industries. Competition also surfaced as a driver of KTT. Additionally, industry-indoctrinated IPR decreases the researchers' ability to share their work. Hence, knowledge transfer is limited to the point when patents are filed. Owing to cultural barriers, the interviewees suggested that a lack of recognition of associated disciplines and perceived superiority of one discipline over another limits transfer. One consulting expert argued that the objectives of different disciplines differ. This is not limited to either academia or industry but bound to the disciplines. For example, both engineers from industry and academia focus on commercialization. Contrary experts with a sociology background rather aim for knowledge gain. Such differences result in contrasting goal-pursuing strategies. The interviews showed that goal conflicts between natural and social sciences arise from the granularity in their perspective. Three interviewees named the selection of the disciplines and team members as a barrier to knowledge transfer. External barriers: Insufficient time for transfer projects was mentioned four times. One research participant argued that "low funding rates contradict the high complexity of interdisciplinary projects" (R). One-fourth of the participants said that governance is a barrier to KTT. Despite recent efforts to promote cross-industry exchange the design of grants remains very bureaucratic. Personal barriers: Personal barriers

Table 4 Barriers to KTT deducted TC: (a) internal barriers, (b) external barriers, (c) personal barriers, (d) technical barriers

TC	SC	FQ	Exemplary statements
a	Agent selection	3	"Actors must be able to transport their messages" (I) "project groups need to fit and be inclusive." (R)
	Lack of open exchange	2	"Need for a platform to exchange ideas between different parties with categorized codes and datasets" (R)
	Time for transfer	2	"Most of the time you don't have that time to find patterns in a dataset." (R)
	Terminology	3	"Different terminology for the same facts and figures." (R)
	Academic operations	5	"Multidisciplinary journals are scarce. (R). "Measures to analyze multidisciplinary innovation are scarce." (I)
	Cultural barriers	6	"Engineers and Researcher have different goals, agendas and understanding of added value." (R) "Cultural barriers are especially true for theoretical or practical projects." (I)
	IPR and rivalry	11	"Competition and conflict of interests, especially when people work in close proximity or in the same sector." (R)
b	Insufficient funding	4	"Funding for such projects is limited, in both big and especially small industries'(C)
	Governance	4	"Governmental or institutional rules, often forbid or hinder exchange." (R) "Cooperation gets bureaucratic, fast."(I)
c	Interdisciplinary understanding	10	"Without knowledge about the other discipline, it takes a long time to find out the patterns in a dataset." (R) "There are hardly any people that know enough about [different] industries to see to see correlations" (R)
	Path dependency	3	"Established strategies for publishing, promotion, advancements or recognition are dominantly taken." (R)
d	Notations	1	"We require common wording." (R) "Models for hyperspectral data can be used for other high dimensional data, this requires common notations." (R)
	No standards	2	"Codes and campaign processes evolved over time. Standardization is scarce, thus limiting exchange." (R)
	Abundance of data	4	"We have too many different datasets which we could try to cross correlate [...]" (R)
	Procedural constraints	3	"Differences in time, size, scale and processing, limit the ability for causation. E.g. forestry scans entire forests over years while we need daily agricultural data." (I)
	Dissimilar development progress	2	"At the system level, different maturity levels in industries challenge the compatibility" (I) "Progress in software and hardware happens at different speed." (R)
	Standardized data formats	2	"[Non-]standardized codes and datasets within a community [impede knowledge transfer]" (R)

account for 14 mentions. Identified SCs are a lack of interdisciplinary understanding (FQ1) and path dependency (FQ3). According to the participants, few experts have a sound understanding of more than one discipline. The lack of interdisciplinary expertise challenges the identification of correlations between different disciplines. The adversity deviating from success-proven strategies is another barrier. One scholar said that "research funds leave little room to look outside the box."(R). Technical barriers: Technical barriers received the second-highest recognition. Six SC were identified in this category. Listed by their FQ (low to high), these SC are: data modeling notations, non-standardized procedures, dissimilar development progress, standardized data formats, the abundance of data, and procedural constraints. (Data modeling-) Notations received the least attention. One research participant argued that "models for hyperspectral data can be used for other high dimensional data, but this requires common notations." (R). When stating that dissimilar development progress is a barrier, one industry participant argued with Wirth's law. The expert stated that "software is getting slower more rapidly than hardware is becoming faster" (I). Also on the hardware side, there are dissimilarities between "progress in data processing (power) is comparably slower than sensor technology improvement" (R). Participants recognized a lack of standardized procedures. Non-standardized data formats, limit transfer and effective data management. Concerning technical barriers, procedural constraints are highly recognized. Experts argue that the scope and timing between research targets differ significantly. The "differences between sectors concerning time, size, and scale of campaigns limit our ability for causation." (I). The abundance of data accounts for the highest FQ. Participants argued that the sheer amount of available data sets makes the identification of relevant, reliable, and accurate data "incredibly hard" (C).

Mechanisms to support KTT

To identify mechanisms that might increase KTT and support the endurance of linkages the interviewees were asked what mechanisms can support KTT in the future. The results were analyzed and coded. Table 5 illustrates the identified TC as well as SC and gives exemplary statements for each SC. Education and training: Multidisciplinary-mentorship (FQ3) and workshops (FQ2) may help to encourage interdisciplinary exchange.

Table 5 Mechanisms to support and optimize KTT deducted TC: (a) education and training, (b) open access, (c) standards, (d) easing of interdisciplinary exchange

TC	SC	FQ	Exemplary statement
a	Multidisciplinary mentors	3	"Every junior geoscientist with one or two mentors from completely different places." (I) "Experts familiar with both literature help with instrumentation and algorithms." (R)
b	Open access	3	"Basic codes need to be published and shared with the community as baselines for new approaches and improvements. (R) "The data need to be opened that people can work on it and provide new insights." (R)
c	Institutional support	2	"Institutes that look at the economic, the physical, the chemical, the biological, the cultural aspects are multipliers." (I)
	Structured keywords	2	"Allowing the publications to have more keywords than other papers. There is this tremendous amount of material being published. [.] which would allow people from outside of your discipline to get a sense of not only which field your publication is in, but also which techniques, including mathematical techniques, are being used in this discipline that can be applied in another discipline." (R)
	Common standards	3	"There are different rules in each country. All countries should accept the minimum level of exchange knowledge especially in the targets concerning life of people (e.g., economy, health, education, traveling, free-opinion)." (R)
d	Multidisciplinary platforms	4	"Sharing knowledge through a public platform where users can learn, replicate, and contribute to. A real interactive place you can spend time and navigate, contribute, ask questions, and download the data." (I)
	Promotion	2	"Publicity. Knowledge increases motivation."(R)
	Software	1	"A machine learning script that would be able to get keywords out of thousands of different abstracts from different scientific databases. The script strolls through thousands of different abstracts and highlights a couple dozen, which may potentially be interesting in your interdisciplinary research that could potentially work." (R)

Associated programs shall connect people across sectors and fields. Interdisciplinary mentors shall reiterate the common call for cooperation and secure protected time for exchange. Open access to data: Open accessibility contributes to better and more efficient transfer. Open access to scientific work and project data (including processed data, raw data) is a desired support mechanism. Standards: Interviewees suggested institutional support (FQ1), structured keywords (FQ2), and common standards (FQ3). Interviewees argued that both private and public broad-scale funding should be increased. To increase the willingness to engage in multidisciplinary projects, one participant suggested appropriate assessment strategies for interdisciplinary outcomes. For example, the interviewee suggested that interdisciplinary distance might be used as a proxy to discount risk and increase the chances of funding. Only researchers demanded common standards. The interviewees argue that increasing complexity requires robust yet adaptable standards to make data models and knowledge usable. Easing of interdisciplinary exchange: Concerns regarding interdisciplinary exchange were recognized most. Interdisciplinary exchange requires multidisciplinary platforms (FQ4), Promotion (FQ2), and Software (FQ1). Interviewees advocated automated mechanisms to identify and match patterns across literature, patents, and social media. "The process must be seamless in order to counteract the time and funding limitations posed to interdisciplinary work." (I). Additionally, public dissemination of benefits and dynamics of KTT must be encouraged. The most frequently recognized mechanism is the development of interactive exchange platforms. Scientists and industry representatives require a space to interact, share knowledge and contribute to information, data, and knowledge exchange.

Discussion

First, this study explores the mechanisms, linkages, and challenges of knowledge and technology transfers in and from mineral exploration from an intra- and inter-organizational. Second, it analyzes drivers and challenges considered antecedents of KTT depending on the industry size. It thus contributes to the understanding of relevant opportunities, originating and migrating into mineral exploration. Third, the study analyzes challenges to the realization of KTT, aiming to inform future strategies for promoting sustainable and effective KTT practices. The total FQ of recognized challenges is a barrier in itself. The high number of challenges prevents taking advantage of identified opportunities. Proponents in research and consulting argued that challenges could be turned into opportunities, but optimism is not shared by practitioners. Fourth, it identified angles to encourage KTT. Having restated the four core findings, the following interprets the results regarding strategic opportunities and structural recommendations. Findings for the transferal of applications and techniques comply with the theoretical literature illustrated in Table 1. Unsurprisingly, "techniques" accounted for the highest mentions of transfer potentials. Most recognized recipients or distributors of technology transfer are environmental remediation and agricultural investigations. The proximity of the research objects of both industries may serve as a possible explanation. Across industries, magnetics and hyperspectral imaging show the broadest range of applications. A possible explanation is that hyperspectral imaging registers full spectra for every scanned pixel, allowing it to retrieve composite and wide-ranging information (Vitale et al., 2020). Remote sensing from satellites as well as industries with research objects as small as a leaf can therefore apply this technique. The role of magnetics may be explained by the fact that magnetics are among the oldest techniques for subsurface investigations (Boll, 1989). Hence, diffusion mechanisms may have started earlier, leading to wider adoption. While agriculture and forestry show the highest target similarity (e.g., leaf chlorophyll), the time-horizon and scope of the procedures differ significantly. A possible explanation for agriculture being more represented in the comments is that agriculture and mineral exploration share similar time-horizon and scope. One interesting finding is the transferal of mindset. Finding evidence for transferring mental procedures may be interpreted as a facilitator of innovation. An implication is that transfer potential increases, where the transfer is towards industries with common narratives. According to these data, we can infer that the common use of technology, the specific nature of the target and the technological proximity of the use and recipient sectors determine the diffusion of technological transfer. Therefore, the characteristics of technology and knowledge appear to be key criteria in analyzing the best team and alliance constellations. As shown, KTT helps to maintain and expand competitive edge (Nicodemus & Egwakhe, 2019). This study corroborates the earlier findings. The study reveals a stronger positive relationship for individual drivers than structural drivers. Mindset and network are the most frequently named drivers. The capacity to absorb knowledge builds on personal means and the capability to use inclusive notations to diffuse knowledge. This complies with open innovation literature in the entrepreneurial sector (Shi et al., 2020). Public, research and industrial pathways, as well as non-institutional drivers of KTT, are less recognized. There is a window of opportunity to promote interdisciplinary project funds. Compared to existing research (Liao et al., 2017; Nicodemus & Egwakhe, 2019), the market opportunities of KTT are underrepresented. Unsurprisingly, IPR is the largest obstacle to KTT. This corresponds with previous findings, which illustrate that stronger IPR protection impacts the ability to explore and exploit innovation (Gopalakrishnan & Santoro, 2004). The outlined differences in knowledge sharing are striking. The results indicate that companies with similar sizes are more likely to exchange knowledge. A decreased attitude towards sharing with smaller companies seem to exist. While this is not new within industries at the same value level, it is new to diagonal and vertical transfers. Overall, the study detects evidence for community-based barriers. Within the category, cultural barriers play a particular role in exchanging knowledge. Bottom-up or individually driven approaches of knowledge and technology transfer dominate. Bottom-up strategies sparked increasing research in innovation management. The wisdom of the crowd is a frequent analysis topic. Top-down, meaning structural challenges concerning interdisciplinary research infrastructure (e.g., recognized conferences or journals) and support (e.g., project funds) are equally limiting. This is surprising as multidisciplinary work sees increasing popularity. The majority of interdisciplinary work is horizontally linked. An example for this would be the INFACT project for innovative non-invasive but fully acceptable exploration technologies where social- and natural science work in tandem to support sustainable development in mineral exploration (Kesselring et al., 2020). Cultural as well as structural challenges seem to be dependent upon each other. Thus, tackling cultural barriers may increase demand for exchange infrastructure. Improved infrastructure may attract more mixed-scientific work and increase KTT. Finally, the paper identified mechanisms to support KTT in the future. Digital, as well as physical matchmakers, are of high importance. Physical matchmaking shall link people, organizations, and resources with diverse sets of knowledge and expand the competencies across industries. This argumentation is supported by research, which suggests that educational and programmatic support have to go hand in hand (Carayannis & Campbell, 2011). Here, mentorship may see faster realization potential than educational adaptations. In addition, one-on-one training may reduce structural barriers associated with the size and branches of different industries. This is the case as perceived industrial identification is minimized. Software-based matchmaking should provide digital environments with open infrastructures. A high ease of exchange in interactive virtual communities is vital to software-based matchmaking. Digital platforms orchestrate ecosystems that are widely accessible and connect sectors. Virtual connections reduce search times for information and provide the opportunity to use the wisdom of the crowd to solve innovation problems. From a theoretical point of view, the analysis of the first research question, has extended our knowledge of types and drivers associated with intra- and inter-organizational drivers of KTT in mineral exploration. Before this study limited in-depth analysis of barriers and drivers associated with knowledge and technology transfer into and from mineral exploration existed. Providing an answer to the second research question. This paper is the first to identify implicit dynamics of transfer effects supported by quantitative frequencies. Illustrating the perceived relevance of bottom-up versus top-down approaches, hence community versus structural drivers of transfer have so far received little attention in research. The paper extends the research in this regard. The present study extends the related discussion to linkages as essential components of value-added transfer support. To develop a full picture of top-down versus bottom-up efficacy, additional studies will be needed that analyze transfer strategies more deeply. With focusing on mineral exploration and associated industries, the results are generalizable. The generalizability of these results is subject to certain limitations. For instance, the male-dominated sample may lead to a biased output. To increase the generalizability, future research should focus on balancing the sample. The findings of this study have a number of important implications for future practice. By answering research question three and thus examining the mechanisms underlying the technology transfer the study found that diversely educated scientists drive KTT into and from mineral exploration. Practitioners could thus benefit from cross-disciplinary team compositions. Common transfer pathways are driven by technology pushes attempting to interest the market in new products based on the invention of new solutions. Therefore, technology pushes may not always be the most effective way to transfer knowledge or technology to the market. Instead, practitioners should focus on market needs and work collaboratively with smaller firms to identify areas of need and opportunities for technological innovation. Customer-centricity research backs this statement (Hashim et al., 2022). Providing evidence for the applicability of such inventions is frequently omitted by insufficient funding of transfer activities. Future strategies for promoting sustainable and effective KTT practices must therefore focus on the provision of resources to explore and exploit linkages. A comparison of the findings with domestic studies confirms that research objectives and call for projects are too industry specific. Therefore, a definite need for vertical and diagonal cooperation support exists. To support the endurance of linkage recognition the institutionalization of exchange platforms to harness innovation, and accelerating the overall innovation adaptation and its evolution is needed. Thus, this contribution stimulates the discussion on improving the innovation landscape and accelerating technological development by avoiding parallel actions.

Conclusion

This study sought to investigate the scope and nature of KTT in highly central industries. Interdisciplinary, cultural and transfer infrastructure emerged as the most important determinants for transfer in and from mineral exploration. This study has raised important questions about the nature of connectedness in natural sciences. The findings of this research suggest that connectedness and cooperation nourish exchange and encourage technological innovation. The results of this research support the idea that more work is needed to spread the benefits of transfer. For public innovation programs, this may imply a change from expertise-oriented funding to allocating RnD funds dependent on transfer potential. For mineral exploration, this may mean investigating the multidisciplinary expertise of applicants and comprehensively investigating technological and social platform components for joint technological development.

Abbreviations

FQ Frequency
IPR Intellectual property rights
KTT Knowledge and technology transfer
RnD Research and development
SC Sub-code
TC Top code

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Author contributions

MKe conducted interviews, analyzed and interpreted data and was a major contributor in writing the manuscript. MKi provided conceptual guidance, background theory on technologies and was a major contributor to the conception of the interpretation. RG contributed significantly to the acquisition and of interviewees and provided substantial guidance and background theory on technical aspects. FW provided substantial guidance and background theory to EU Research. The author(s) read and approved the final manuscript.

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Availability of data and materials

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Declarations

Competing interests

The authors declare no conflict of interest. The funding entity had no role in the design of the study, in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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