Breakthrough technologies for mineral exploration

Kazuya Okada

Received: 6 September 2021 / Accepted: 22 March 2022 / Published online: 19 May 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
Breakthrough technologies for mineral exploration are discussed from two perspectives. The first perspective is intended to discuss the important factors required for exploration technologies, derived deductively from a review of the role and expectations of exploration in the mining industry and the current situation of the mining industry. The second perspective is intended to discuss the common characteristics of breakthrough technologies for mineral exploration derived inductively from a review of specific examples of technological breakthroughs that actually brought about innovation to exploration: e.g. induced polarization (IP); airborne electromagnetics (EM); airborne gravity gradiometry (AGG); spectroscopic methods; global navigation satellite system (GNSS); unmanned survey platform; and neural networks/deep learning. The specific issues to be solved as breakthroughs in exploration technology in the near future are summarized as follows:

(1) Significant improvement in economic efficiency, namely: labor-saving, automated or unmanned operation, e.g. unmanned aerial vehicle (UAV)-based exploration and automatic spectroscopic scanning of drill cores; higher accessing capability, e.g. improvement of various airborne exploration techniques including airborne EM, AGG, and especially airborne IP; higher work efficiency and productivity, e.g. automatic data processing by neural networks/deep learning; and lower cost to implement, e.g. less expensive platforms such as UAVs.

(2) To obtain information that is really needed for exploration, specifically: IP effect of sulfide minerals associated with mineralization, i.e. practical spectral IP (SIP); geophysical characterization of the deep underground, e.g. enhancement of superconducting quantum interference device (SQUID)-based time-domain electromagnetic (TDEM); and removal of effects of the surface layer, e.g. very conductive deeply-weathered overburden and younger volcanics rich in magnetic minerals.

(3) To obtain information that could not be obtained by the conventional methods, specifically: distribution of endmember minerals related to mineralization, i.e. hyperspectral mapping with high spatial resolution.

Keywords Airborne · Breakthrough technology · Deep learning · Electromagnetics (EM) · Gravity gradiometry · Induced polarization (IP) · Mineral exploration · Neural networks · Remote sensing · Spectral · Unmanned aerial vehicle (UAV)

Introduction
As the world’s demand for mineral resources is in the upward trend along with the population growth, advancement of urbanization and industrialization, the mining industry needs to discover more resources in the earth’s crust to meet the demand for metals and/or raw materials. On the other hand, the discovery rate of new ore deposits, especially from the greenfield exploration, has kept declining over the recent years under more challenging conditions and circumstances for mineral exploration: e.g. thick overburden; isolated district; ore grade decline; social and environmental issues and so on. For that reason, technological innovation in mineral exploration is expected more than before to secure the sustainability of non-renewable resources.

In this paper, breakthrough technologies for mineral exploration are discussed from the following two perspectives: (a) requirements and expectations for exploration...
technology in consideration of recent and expected future changes in the circumstances surrounding exploration, and (b) a review of examples of significant breakthrough technologies in the history of exploration technology development.

Requirements and expectations for exploration technologies are clarified based on the discussion about the role of exploration in the mining industry, the characteristics of exploration technologies compared with those of other technical fields, and the recent situation of the mining industry where exploration technologies are applied.

Breakthroughs in exploration technologies are clarified based on the discussion about the intrinsic value of exploration technologies and a review of specific examples of technological breakthroughs that actually brought about innovation to exploration: e.g. induced polarization (IP); airborne electromagnetics (EM); airborne gravity gradiometry (AGG); spectral remote sensing; global navigation satellite system (GNSS); unmanned survey platform; and neural networks/deep learning.

The first perspective (a) is intended to discuss the important factors required for exploration technologies, derived deductively from a review of the role and expectations of exploration in the mining industry and the current situation of the mining industry. The second perspective (b), on the other hand, is intended to discuss the common characteristics of breakthrough technologies for mineral exploration derived inductively from a review of those breakthrough technologies. It would be useful to consider those discussions of both directions comprehensively to discuss breakthrough technologies for mineral exploration. Summarizing the results of the reviews and discussions, future prospects for breakthrough technologies for mineral exploration are discussed.

Requirements and expectations for exploration technologies

Mining-specific risks and the role of exploration

Aside from the inherent risk of the mining industry—that the mineral resources, the source of the mining industry’s wealth, are finite, non-renewable, and may eventually be depleted—the main risks peculiar to the mining industry compared to other business sectors are as follows:

1. There is almost no choice in location nor other locational conditions of the business base because they are determined by the location of the ore deposit itself.
2. It is necessary to deal with nature, i.e., uncertainty; eventuality; and unpredictable change of natural conditions.
3. Success rate of mineral exploration is extremely low.
4. An initial investment that covers exploration and evaluation of mineral resources and development of a mine, does not yield profit directly.
5. Mining projects usually require a relatively long leadtime in comparison with other business sectors. This feature strengthens the impact of uncertainty.
6. Mineral resources are distributed unevenly in the world, so every country must rely on imports for some commodities to greater or less degree. This means that the mining industry is exposed to country risk.
7. There are geographical, religious, or cultural differences in state systems governing mining business.
8. Environmental impact of mining projects has the potential for a relatively large footprint.

Among those risks, the first two—inability to choose a location and uncertain natural phenomena—are the largest; and the other risks can be said to be caused by or associated with these two risks. It goes without saying that mine development cannot be achieved without successful exploration, moreover, the role that exploration should play does not end there. After the discovery of the ore deposit, exploration should help to reduce the risks at each subsequent stage of the mining cycle—from feasibility study, through development, production, closure, and rehabilitation. At the feasibility study stage, exploration should provide information for the criteria to evaluate whether or not the deposit can generate economic value; and from the mine development to mine operation stages, exploration should provide information about the amount and grade of ore to secure the development and operation of the mine as expected. It is also important to obtain additional ore volume in and around the deposit. The role of mineral exploration in the mining business is to be the gateway to the mining cycle and to reduce risk at each stage of the mining cycle.

Characteristics of exploration technologies

The first important point in considering exploration technologies is that exploration is generally an economic activity carried out by private companies. As mentioned in the previous section, the success rate of exploration is extremely low. Mineral exploration is a high-risk business that is commonly said to have three successes in a thousand tries. Moreover, mining exploration itself makes no profit. Therefore, the first hurdle for the personnel engaged in exploration business is to explain the potential of exploration projects to the risk-averse management and persuade them to approve an appropriate budget.

The series of processes in mineral exploration has many similarities to research activities such as in natural sciences in that they are planned and carried out based on various working hypotheses. However, mineral exploration is
decisively different from research activity in that it is an economic activity. The purpose of mineral exploration is to discover ore deposits, not to prove the correctness of the working hypothesis. Therefore, whether or not an ore deposit is discovered in a working hypothesis-based survey, there is a tendency not to fully verify the correctness or error of the relevant working hypothesis. Decision-making in mineral exploration is similar to investment decisions in general business; although it is based on scientific knowledge and experience, a leap of faith is often necessary. In a nutshell, mineral exploration is a prime example of “You never know unless you try.”

An important point to consider is the strict fact that ore deposits can never be found without drilling which is very expensive compared to other exploration methods. It is impossible to drill blindly and randomly, and it is also impractical to drill all over the target area in sufficient detail to remove all uncertainty in understanding the mineral deposit. Therefore, exploration engineers allocate as much budget as possible to drilling to make the exploration successful within the limited budget. Also, if possible, they select less expensive drilling methods and formulate a drilling program to drill as many holes as possible in a promising area.

Based on the above, in research on exploration technology, cost-effectiveness is more important than other technical fields, and economic rationality is strictly required. No matter how good the technology is, if its operating cost is high, it will not be put into practical use. In that sense, the mining industry is rather conservative in terms of technological development and the introduction of new technologies. Also, in research on exploration technology, innovation tends to be more important than invention. Technological innovation generally refers to the creation of better products or more effective processes that are accepted by the markets. Innovation differs from invention in that, while invention signifies the first creation of something new, innovation signifies a substantial positive development of something that already exists and inherently carries less risk.

Another important feature when considering exploration technology is that various advanced exploration technologies are often provided as a service by contractors who apply such technologies to mineral exploration for the clients. The results of exploration using those technologies are often highly confidential to the clients and are rarely fed back from the clients to the contractors. Therefore, the contractors—developers and/or practitioners of the advanced exploration technologies—have very few opportunities to learn from the implementation results of the said technologies.

Reflecting the above circumstances surrounding exploration technology, many successful exploration engineers, especially geologists, tend to be critical or skeptical of so-called high-tech exploration technologies, including geophysical methods. Such tendencies are symbolically summarized in the following words of David Lowell (2014):

High-tech devices and geophysical surveys are very rarely of value in mine discovery. There should be an almost metaphysical communication between the rocks and the successful explorationist in which the rocks talk to the explorationist. If he turns part of this job of geological mapping over to a high-tech gadget, he may look good to uniformed management, but he is less likely to find a mine (Lowell 2014).

The opinion of Lowell is of course backed by his wealth of experience, and also by objective statistical data. Sillitoe (1995) reviewed case histories of exploration and discovery for a representative selection of base-metal and precious-metal deposits including 38 gold, 14 copper, 1 silver, and 1 zinc deposit in the circum-Pacific region found in a quarter of a century from 1970 to 1995. Regarding the discovery methods, Sillitoe (1995) concluded that geological work had been the most successful discovery technique and geophysics had played a minor role in successful exploration, with only seven (13 %) of the deposits reviewed having a geophysical input to their discoveries.

However, circumstances surrounding exploration technology are changing over time. Sillitoe (2000) provided an update to his previous review (Sillitoe 1995) mentioned above, investigating case histories from 14 additional deposits discovered in the late 1990s, and concluded that the most outstanding change in the discovery process since 1993 was in the use of geophysics, which played a valuable role in 43 % of the reviewed case histories. Further ten years later, according to Sillitoe (2010), the contribution of geophysical exploration continues at the same level. The contribution of geophysical exploration is not necessarily because the subject was a “geologically blind” concealed deposit; nine of the 13 deposits in which geophysics assisted the discovery process are in fact exposed and not concealed. The geophysical methods deployed appear to have been well selected for the mineralization styles concerned and the results then effectively integrated into the accompanying geological and geochemical conceptual model (Sillitoe 2010).

**Current situation surrounding the mining industry**

As noted at the introduction of this paper, the current situation in the mining industry is that international demand for mineral resources is increasing, while exploration for mineral resources is becoming increasingly difficult. Under such circumstances, over the past 30 years, the discovery rate of ore deposits has continued declining (e.g. Sillitoe 1995, 2000, 2010; Blain 2000; Schodde 2011).

Figure 1 shows historical trends of annual global exploration expenditure in billion US dollars (Metals Economics
Investment in mineral exploration showed a solid increase in the early 1990s, peaked in 1997, then declined and bottomed out in 2002, and after that, showed a rapid increase. Exploration investment halved from 2008 to 2009 due to the global financial crisis, but the upward trend recovered in 2010 and peaked in 2012. Since 2013, exploration investment has decreased along with lower metal prices. In those circumstances, there are some background factors that investors refrained from investing in junior exploration companies; mining companies refrained from exploration to improve their profitability.

The above changes in the total amount of exploration investment corresponded to the periodic fluctuations in metal prices; the fluctuations between the exploration investment and metal prices are harmonious although there is a slight time lag. However, in recent years, there have been qualitative changes in the substance of exploration investment. Exploration investment has shifted its focus from early-stage assets to late-stage assets, mine-site and brown-field, i.e. near mine. This trend became even more pronounced during the recession; junior companies allocate their scarce funds on proven assets rather than risky early-stage exploration, while major companies maximize the value of their existing mines. This is further supported by the reports from various organizations that there is no concern about the long-term supply of non-ferrous metal resources in general (e.g. The International Copper Association 2021).

In 2020, the world experienced unprecedented turmoil due to the pandemic of the novel coronavirus (COVID-19), however, expenditure on mine-site exploration fell by only 4% from the previous year, accounting for 41% of the world’s total exploration budget. Expenditure on mine-site exploration peaked for two consecutive years. Meanwhile, grassroots and late-stage exploration budgets have fallen 19% and 10% from 2019 respectively. Prospectors continue to avoid risk and prioritize more promising advanced projects and existing mines (S&P Global Market Intelligence 2021).

This tendency to move away from grassroots exploration further reduced the probability of discovering new deposits, which has been already declining. It is self-evident that a shortage of new deposits will result in a shortage of mineral resources in the future; from a long-term perspective, grassroots exploration needs to be leveraged. Some countries are actively tackling the problem of lack of grassroots exploration through incentive schemes, however, it will take some time before they produce the desired effect.

### Requirements and expectations for exploration technology

Considering the risks peculiar to the mining, the role of exploration and the characteristics of exploration technology, mentioned in the preceding paragraphs, improvement of cost-effectiveness and labor-saving are the most important requirements for exploration technology. Each company always focuses on improving cost-effectiveness. A typical example of a major technological development to improve cost-effectiveness is the rise of heliborne time-domain electromagnetic (TDEM) systems in the early 2000s described in the section entitled “Review of Examples of Breakthroughs in Exploration Technologies”. An example of labor-saving is the use of an unmanned platform such as an unmanned aerial vehicle (UAV) also known as a drone, described in the paragraph entitled “Unmanned survey platform”.

Given the current status of mineral exploration and the factors that make it difficult, the technical challenges that can and should be overcome include dealing with thick cover layers and remote areas with logistical difficulties.
Typical thick cover layers, obstacles to mineral exploration, include glacial deposits in the Canadian Shield and deeply weathered regolith bearing high electrical conductivity in Australia. In both countries, unique geophysical exploration techniques have been developed to explore under these thick cover layers. Representative examples of such geophysical techniques are the airborne electromagnetic methods in Canada, the time-domain electromagnetic methods and the airborne gravity gradiometry methods in Australia. For the exploration of deeper resistivity structures, the electromagnetic methods, in which the exploration depth is parametrically controlled by the transmission frequency and other factors, are more widely used than the conventional galvanic resistivity methods. In both ground and airborne electromagnetic methods, continuous efforts have been made to increase the exploration depth, such as larger dipole moments, greater transmission power, and higher sensitivity of detectors by utilizing high-temperature superconducting quantum interference devices (SQUIDs).

Remote exploration methods such as airborne geophysics and remote sensing are important for mineral exploration in remote areas with logistical difficulties. Also, in those explorations, it is very important not to damage human resources even if an accident occurs in an airborne vehicle—a platform on which a measuring instrument is mounted. For this purpose, it is effective to use unmanned artificial satellites and various UAVs. The use of the UAV, which was given as an example of labor-saving measures, is also important for this purpose.

In the current socio-economic turmoil described in the previous section, mining companies continue to avoid risk and avoid grassroots exploration in favor of more promising late-stage projects and exploration of existing mines. However, from a long-term perspective, we will have to look at grassroots exploration as well. It is important for grassroots exploration to develop a more conceptual exploration plan.

For practical application of the theory into mineral exploration, the traditional approach based on ore deposit models (e.g. Cox and Singer 1986) had some limitations, especially often excessive variations of models due to over-classification caused from different geological environments and favorable host rocks as well as source rocks in local scale. In other words, it was necessary to find analogues of some certain deposit models out of too many different deposit models, which can only be applied to similar geological environments, similar host rocks, and similar source rocks. That is not suitable for planning exploration in a new area where the geological environment is unknown in detail. This is because nowadays prospectors must face concealed deposits, requiring piled-up working hypotheses and their validation in the long and winding road to exploration success.

Under these circumstances, a more conceptual framework such as the mineral systems approach (Knox-Robinson and Wyborn 1997), which allows ideation and substantiation of the ore-deposition concept with different spatial scales and different types of ore deposits including unknown types, became more favorable, especially for a large-scale greenfield exploration. Knox-Robinson and Wyborn (1997) defined a “mineral system” as all geological factors that control the generation and preservation of mineral deposits, based on (a) sources of fluid and of metal, (b) transport, and (c) traps. To promote grassroots exploration over a wide area, the efforts of national; local governments; and public institutions (including exploration incentives and data preparation) are important. In that sense, the mineral systems approach is well suited for nationwide regional exploration conducted by governmental organizations.

### Breakthroughs in exploration technologies

#### What are breakthroughs in exploration technologies?

Table 1 shows the information provided by the various techniques used in mineral exploration. The higher the exploratory value of the information that can only be obtained by a certain exploration technology, the higher the intrinsic value of said technology will be. In addition, it can be assumed that the value of each exploration technique increases as targets become more difficult to detect. For example, drilling costs are extremely high in the case of exploration for petroleum, including natural gas reserves embedded in the deep underground. So, in order to select petroleum exploration drilling sites, it is necessary to obtain information on deep underground areas in advance. Therefore, it is almost mandatory in petroleum exploration to conduct a variety of geophysical surveys, including seismic surveys. On the

| Geology          | Lithology          | Mineralogy         | Topography / Structural geology / Stratigraphy |
|------------------|--------------------|--------------------|-----------------------------------------------|
| Chemical composition | Density        | Magnetic susceptibility | DC resistivity                                |
| Physical characteristics | Complex resistivity / Chargeability and Frequency-dependence | Dielectric permittivity | Reflectance / Emissivity                          |
|                   | Radiation / Radioactivity | Elastic wave velocity | Rock mechanics                               |

Table 1 Information provided from various exploration techniques
other hand, in the case of the exploration targeting mineral resources embedded generally shallower than petroleum reservoirs, geophysics is expected to grasp the location and scale of the deposit in addition to investigating the geological environment favorable for mineralization. The weight of these two objectives depends on the type of ore and of the ore deposit, however, with the exception of the cases of gold exploration, direct detection of ore deposits is more expected in general.

A breakthrough is born out in technological development when it is truly needed—unachievable without it. The most important technologies developed for mineral exploration would be the airborne electromagnetic (EM) method and the induced polarization (IP) method. Behind the development of these exploration methods, was the issue of national security of the United States due to the Cold War between the U.S. and the U.S.S.R. after World War II. The need to secure a stable source of strategic metal resources close to the U.S. both geographically and politically prompted the development of new methods for efficient mineral exploration. In the political and economic environment described above, the focus of mineral exploration was on deserts in the U.S. such as in Arizona and Nevada, and on the vast unexplored areas of neighboring Canada. In particular, when exploring cold districts in Canada, it was essential to introduce an exploration method using aircraft due to the size of the target area; difficult access; and harsh climatic conditions. The airborne EM method is described in more detail in the next section. The use of the IP method began in earnest in the late 1940s to early 1950s for the exploration of porphyry copper deposits in Arizona and Nevada. Prior to the introduction of the IP method, there was no effective geophysical exploration method for the discrimination of low-grade and large-scale disseminated copper deposits. The development of the IP method was revolutionary in the exploration of porphyry copper deposits.

In general, a technological breakthrough is a concept that contrasts with incremental innovation and refers to innovation that involves a leap from existing technology; mechanism; and paradigm. A breakthrough of exploration technologies, when claimed by the mining industry, seems to be more often a mere extension of existing technology; introduction of technology from other fields; or a combination of them at best, rather than innovation that involves a leap. However, this is not the right observation. Because breakthroughs in exploration technologies in the mining industry is a cumulative process as mentioned above, and each small step has a nature of breakthrough in itself. Thinking of this matter as a metaphor for climbing stairs makes it easier to understand. Climbing the stairs is certainly gradual, but it’s revolutionary enough that you can see a whole new world every time you go up one level. For example, the IP method was developed and put into practical use from the late 1940s to the early 1950s as mentioned above. Although IP is effective in the discrimination of metallic sulfides, IP also reacts strongly to polarizable substances such as graphite, so it often misleads exploration and is commonly considered misleading - “the IP red herring”. With the advent of the spectral IP method in the late 1970s, arose a possibility that meaningful IP anomalies for mineral exploration can be separated and extracted even in areas where other polarizable substances are distributed. The IP method is described in more detail in the next section.

**Review of examples of breakthroughs in exploration technologies**

This section provides a review of the history of the development of exploration technology and typical technological breakthroughs in the context of the previous discussion. Regarding the history of the development of exploration technology, the author provided a historical review of the development of exploration technology over the 30 years from the 1990s to the 2010s (Okada 2021). Citing results from this previous work as appropriate, specific examples of breakthrough technologies are described below.

**Induced polarization (IP)**

The principle of induced polarization (IP) phenomena associated with metal sulfide was observed by Schlumberger (1920) in the 1910s. Although Schlumberger suggested that the IP phenomena could be useful for distinguishing various rock types, he did not pursue the IP phenomena for mineral exploration. His main interest in the IP phenomena was directed to petroleum exploration. During the Great Depression that began in 1929, the mining and oil industries in the liberal economic zone such as the United States were hit hard and exploration became sluggish; he contracted with the U.S.S.R. to carry out an extensive logging program at the oil fields in the U.S.S.R. After that, laboratory experiments and research on the IP phenomena continued in the U.S.S.R., and the effectiveness of IP for mineral exploration was predicted. This scientific research was hindered by World War II, however, further theoretical and laboratory studies were conducted in the U.S.S.R. on the nature of IP responses from both metallic and non-metallic materials and led to the practical application of the IP phenomena to mineral exploration.

Important research on IP in North America started to develop a detector for mines-underwater explosive device—conducted by William Keck at the U.S. Naval Ordnance Laboratory (NOL) during World War II. The technology responsible for the mine detector—called “induced electrical potential (IEP) method”—could not be directly transferred to detect buried minerals, however, David Bleil, one of the key persons of IEP technology development at NOL, intensively
developed laboratory and field experiments to establish the technological basis of IP method (Bleil 1953).

For the practical application of IP, a series of contributions by Newmont Mining Corporation, starting in 1946, was significant. With Arthur Brant’s consulting, Newmont conducted field trials and research on the IP method at selected porphyry copper fields including San Manuel, Arizona, U.S. and Cuajone, Moquegua, Peru (Baldwin 1959a, b). By 1950 Newmont had established its IP procedures and equipment as a fully operational technology for mineral exploration (Wait 1959). This time may be regarded as the first breakthrough in the IP method.

IP method is an extension to a resistivity method that measures potential differences associated with artificially generated direct-currents passing through the ground. In a time-domain IP system, the decay voltage is measured as a function of time, while in the frequency-domain IP system, apparent resistivity (actually a complex impedance) is measured at two or more frequencies, generally below 10 Hz. Prior to the introduction of the IP method, there was no effective geophysical exploration method for the discrimination of low-grade and large-scale disseminated ore deposits. The development of the IP method was revolutionary in the exploration of porphyry copper deposits—the main source of copper in the world today.

The second breakthrough since the practical application of the IP method was the development of the spectral IP (SIP) method in the late 1970s (e.g. Zonge and Wynn 1975; Pelton et al. 1978). Although IP is effective in the discrimination of metallic sulfides, IP also reacts strongly to polarizable substances such as graphite, so it often misleads exploration. SIP provided a possibility that meaningful IP anomalies for mineral exploration can be separated and extracted even in areas where other polarizable substances are present.

For modeling the impedance of the ground by SIP, Cole–Cole model (Cole and Cole 1941) for complex resistivity is the most often used. The Cole–Cole model is written as:

\[ Z(\omega) = R_0 \left[ 1 - M \left( \frac{1}{1 + (\omega \tau)^c} \right) \right] \]  

where \( Z(\omega) \) is complex impedance (\( \omega \)); \( \omega \) is frequency; \( R_0 \) is a resistive component (\( \omega \)); \( M \) is chargeability; \( \tau \) is a time constant of the decay curve and \( c \) is a parameter controlling the frequency dependence.

To apply the SIP method successfully, it is necessary both to discriminate between different types of rocks and to remove the EM coupling effect. Among the parameters in Eq. 1, \( \tau \) and \( R_0 \) have a wide variation, while the others are restricted or have a narrow variation. The EM coupling effect shows different values of these parameters; \( \tau \) being very small and \( c \) large. These findings are used to distinguish between mineralization and the EM coupling effect. After removal of the EM coupling effect, phase spectra of complex impedance can be examined to locate meaningful IP anomalies for mineral exploration such as those caused by porphyry copper mineralization.

The development of IP equipment designed for SIP measurement also resulted in improved accuracy in normal IP measurement and expanded the field of IP application to exploration targeted at a variety of deposits other than porphyry copper. Figure 2 and 3 show the plan view of apparent DC resistivity and of apparent chargeability (in millivolts/volt at the time window of 690-1050 ms) respectively, measured around the Hishikari epithermal gold deposit, using dipole-dipole arrays with the current and the potential electrodes spacing \( a = 50 \) m, overlayed with a vein map of the Hishikari deposit and sampling point numbers corresponding to those in Fig. 5 (Sanematsu et al. 2005). Extremely low resistivity anomalies of less than 2 ohm metre are widely distributed over the entire deposit (Fig. 2). On the other hand, chargeability anomalies of more than 10 millivolts/volt, slightly higher than the surrounding area, are localized around the veins and are stronger in the Yamada Zone than in the Honko-Sanjin Zone (Fig. 3). It is noteworthy that even in such an extremely conductive area where it is very difficult to measure even the primary voltage, slight but important IP anomalies for exploration purposes can be detected as secondary voltages with an intensity of less than 1 % of the primary voltages.

Figure 4 shows schematic geologic sections of the Honko-Sanjin and Yamada zones. The Shimanto Super-group of Cretaceous age, the basement rocks of the southern half of Kyushu Island of Japan, are interbedded shales and sandstones. Quaternary volcanic rocks are Hishikari Lower Andesites, Kurozosan Dacites, Hishikari Middle Andesites, Shishimano Dacites, and Hishikari Upper Andesites. The Hishikari deposit is an epithermal, fissure filling, gold-silver bearing quartz-adularia vein system, occurring mainly in shale in Honko-Sanjin zone (Fig. 4(a)) and in andesites in Yamada zone (Fig. 4(b)). Figure 5 shows the diagram indicating the timing of mineralization in the Hishikari deposit (Sanematsu et al. 2005). Mineralization ages of the Honko-Sanjin zone range from 1.04 to 0.75 Ma, while the majority of results are concentrated in a range from 1.01 to 0.88 Ma. Those of the Yamada zone range from 1.21 to 0.64 Ma. These results indicate that fracturing and subsequent vein formation in the Yamada zone lasted for a longer time than in the Honko-Sanjin zone (Sanematsu et al. 2005). The mineralization of the Yamada zone over a longer time period is considered to be the cause of the stronger IP anomaly in the Yamada zone. From 1985 to 2020, Hishikari produced 248.2 tons of gold, the largest production in Japanese history, and has reserves of 158.5 tons of gold. The remarkable feature of the deposit is its extremely high concentration of gold. All
reserves were found in an area of 2.3 km by 1 km with thickness of 150 m, delineated roughly by low resistivity anomalies, and more precisely by high chargeability anomalies.

The next breakthrough for IP will be airborne IP. As mentioned before, almost all the conventional ground IP methods are galvanic methods, in which current electrodes and potential electrodes are inserted in the ground for the measurement of IP phenomena. In other words, conventional IP techniques cannot be transferred directly to airborne surveys. Employing galvanic sources, IP phenomena can be detected by grounded electrodes measuring the potential difference, or by magnetometers measuring the magnetic fields of the primary and secondary currents; i.e. magnetic induced polarization (MIP) method (Seigel 1974). As well as galvanic sources, IP phenomena have been detected using inductive sources such as negative transients in time-domain electromagnetic systems (e.g. Lee 1981; Weidelt 1982). Figure 6 shows a field example of negative transients in the TDEM survey in Western Australia (Okada 1998). Since negative values cannot be put on a logarithmic scale, negative values were plotted after inverting the sign in Fig. 6. Figure 7 shows an entire profile section of the same data; negative transients were observed at all the sites. It was confirmed that this phenomenon was due to the IP effect, by the additional vertical electrical sounding (VES) using Wenner array, IP survey using a dipole-dipole array, and diamond drillings. The source of the IP effect was considered to be a strongly weathered layer with high clay content.

IP phenomena are measurable with any combination of galvanic or inductive transmitters and galvanic or inductive receivers. However, to realize the airborne IP system, the transmitter can be either galvanic type or inductive type.
but at least the receiver must be inductive type. Considering the large area that airborne exploration should cover, it would be advantageous to use an inductive source rather than a galvanic source which must be fixed to the ground. The airborne electromagnetic (EM) system is a typical practical example of a combination of an inductive transmitter and an inductive receiver. Actually, the IP effects have been occasionally observed in airborne TDEM data (e.g. Smith and Klein 1996). Smith and Klein (1996) pointed out that IP effects can only be measured with standard airborne EM systems in very special circumstances: when the conductivity is less than 0.003 S/m and when the dispersion in the off-time bandwidth is very strong.

It is not easy to extract IP information from airborne EM data, however, various methods have been proposed and tried in practice (e.g. Kratzer and Macnae 2012, 2012; Hodges and Chen 2014; Kang et al. 2014; Macnae 2019); further development both of equipment and of analysis techniques is expected in the future.

In addition, the development of technology for measuring IP phenomena with inductive transmitters and receivers is beneficial for the IP measurement not only in the air but also in the water. Marine mineral resources, including polymetallic sulfides, cobalt-rich ferromanganese crusts, and manganese nodules, have been receiving a lot of attention (e.g. Hein et al. 2018). Nakayama et al. (2011) demonstrated that drill core samples of the sea-floor polymetallic sulfides deposit exhibit an IP signature, and developed a TDEM system operated with a remotely operated vehicle (ROV) in the sea to investigate resistivity and IP effect of the sea-floor
polymetallic sulfides deposit. Nakayama et al. (2019) presented the IP effect of the sea-floor polymetallic sulfides observed in the field measurements.

Airborne electromagnetics (EM)

As an aircraft-based geophysical exploration technology, the airborne magnetic method has been used since World War II for the purpose of detecting submarines, etc., and was used for mineral exploration soon thereafter. However, magnetic exploration is not a direct exploration of mineral deposits but rather an indirect exploration aimed at investigating geological structures surrounding mineral deposits; and in exploration targeting areas where a large amount of magnetic minerals are distributed and undergo significant metamorphism. Therefore, the airborne magnetic method is often not very effective in narrowing down the area for further detailed exploration.

The airborne electromagnetic (EM) method was developed and put into practical use from the late 1940s to the early 1950s due to the need to develop a more direct exploration method targeting mineral deposits. This time may be regarded as the first breakthrough in the airborne EM method.

Until the mid-1970s, the airborne EM method was mainly used for the exploration of base metal resources such as copper, lead, and zinc, and was particularly effective for the exploration of massive sulfide deposits. Kidd Creek is a representative early achievement. The target area was mainly Canada and the Scandinavian Peninsula and was also expanded to Australia and Brazil. However, the airborne EM devices at that time were designed to meet the

Fig. 4 Schematic northwest-trending cross section across the Honko-Sanjin and Yamada zones of Hishikari deposit (after Ibaraki and Suzuki 1990; Okada 1995)

Fig. 5 Diagram indicating the timing of mineralization in the Hishikari deposit (Sanematsu et al. 2005). Error bars of mineralization ages are shown as 2σ. Solid lines show the periods of volcanic activities and mineralization, and dashed lines show the age errors of the periods. The sample number is shown in parenthesis, followed by a sample name.
geological conditions of Canada and did not produce outstanding results in Australia and other countries of different geological conditions. For this reason, Australia conducted a national project to develop an airborne EM system suitable for its own geological environment.

Airborne EM systems are classified roughly into two types: frequency-domain electromagnetic (FDEM) and time-domain electromagnetic (TDEM) systems. Typical FDEM systems have three coplanar and two coaxial coils with frequencies ranging from 400 Hz to 200 kHz and are commonly used for accurate mapping of shallower targets. On the other hand, TDEM systems are mainly used for exploration aiming at highly conductive or deeply buried mineral targets. Intensive efforts were concentrated to increase transmitter dipole moment to achieve greater penetration depth throughout the 1990s. The transmitter dipole moment of GEOTEM in the early 1990s was $0.69 \times 10^6 \text{ Am}^2$ and then was increased to $1.1 \times 10^6 \text{ Am}^2$, giving the name MEGATEM in 1998 to a larger transmitter loop installed on a larger aircraft. The transmitter dipole moment of MEGATEM was upgraded twofold to $2.2 \times 10^6 \text{ Am}^2$ by reinforcement of the transmitter in early 2001 (Smith et al. 2003). By such enhancement of the transmitter signal, the penetration depth of the system was increased from 100 m to 250 m. Smith et al. (2003) presented a comparison of the detectability of various airborne TDEM systems including INPUT, GEOTEM, QUESTEM, SPECTREM, and MEGATEM, based on the case histories over a test area near Matagami including the Caber deposit (Gingerich and Allard 2001). Reford and Fyon (2000) presented a comparison of Dighem V, Geotem III (30 Hz and 90 Hz base frequency) and High-Sense and SPECTREM 2000, flown over the Reid-Mahaffy airborne geophysical test site, established by Ontario Geological Survey, Canada, as part of their Operation Treasure Hunt (OTH) program.

![Decay Line 5950E](image)

**Fig. 6** A field example of negative transients in TDEM survey (Okada 1998); the vertical axis shows TDEM response, the logarithm of dB/dt ($\mu\text{V/Am}^2$), and the horizontal one show time (ms). Negative values, observed in the late time windows, are plotted after inverting the sign.
The second breakthrough since the practical application of the airborne EM method was the advent of helicopter TDEM systems. In the 1990s or earlier, the platforms for TDEM systems were mainly fixed-wing aircrafts, while those for FDEM systems were mainly helicopters. Both systems existed alongside each other in their own separate niches. The fixed-wing systems were deployed to benefit from their larger footprint and greater penetration depth while the heliborne systems were deployed to benefit from their higher resolution and better maneuverability. Economic circumstances from the late-1990s to the early-2000s encouraged the development of heliborne TDEM systems, which were equipped with the merits of the heliborne FDEM systems and fixed-wing TDEM systems. In the early-2000s, a number of manufacturers almost simultaneously developed and released heliborne TDEM systems: AeroTEM developed by Aeroquest (Balch et al. 2003), VTEM developed by Geotech (Witherly et al. 2004), THEM developed by THEM Geophysics, SkyTEM developed by SkyTEM (Sørensen and Auken 2004) and Helitem (Konieczny et al. 2016) were improved steadily throughout the 2010s.

Witherly et al. (2004) added case histories from VTEM surveys flown over the Reid-Mahaffy airborne geophysical test site. Besides these systems, major mining companies developed their own in-house systems: HoisTEM developed by Normandy Exploration, NewTEM developed by Newmont Mining, and ExplorHEM developed by Anglo American. Fountain et al. (2005) summarized the advantages of the heliborne TDEM systems over the heliborne FDEM systems and over the fixed-wing systems:

- Greater effective depth of exploration compared with frequency-domain systems;
- Better economics on very small surveys or very isolated surveys;
- Better lateral resolution of shallow conductors; and
- Better terrain following in rough terrain.

Market share of the heliborne TDEM systems increased dramatically because of the advantages mentioned above. Various heliborne TDEM systems were manufactured by more than ten companies. The major existing systems such as VTEM, SkyTEM, AeroTEM, and Helitem (Konieczny et al. 2016) were improved steadily throughout the 2010s. Besides the realization of the airborne IP method by applying the airborne EM method, mentioned in the previous paragraph, the next breakthrough will be the development of less expensive means for the airborne EM method. As with other airborne geophysical methods, the use of UAV-based EM systems seems to be effective in the reduction of operation costs. Due to the limited payload of UAVs, it is difficult to mount conventional airborne EM equipment. One practical solution is to separate the transmitter by installing it on the ground and mount only the receiver on the aerial platform, e.g. D-GREAT (Jomori et al. 2020).

**Airborne gravity gradiometry (AGG)**

In the mid-1990s, along with the end of the Cold War, the Full Tensor Gradient (FTG) system technology was declassified and was allowed to be commercialized to maintain the technology for future use. The FTG system was originally developed by Bell Aerospace (now Lockheed Martin) for the U.S. Navy’s requirements to acquire detailed high-resolution gravity data onboard submarines to map underwater
Breakthrough technologies for mineral exploration

produces a large gravity anomaly of about 17 mGal (signatures vary widely, particularly in their magnetic and copper-gold (IOCG) mineralization. IOCG’s geophysical anomalies caused by mineral deposits from the air for the first time. Therefore, it was a breakthrough in that major mineral deposits are plotted well above the noise level of AGG systems. Therefore, it was a breakthrough in that the introduction of AGG provided a means to detect density anomalies caused by mineral deposits from the air for the first time.

The preferred target for AGG exploration is iron oxide copper-gold (IOCG) mineralization. IOCG’s geophysical signatures vary widely, particularly in their magnetic and gravity signatures. For example, the Olympic Dam deposit produces a large gravity anomaly of about 17 mGal (10^-3 m/s^2), but a magnetic anomaly of only 1,000 nT (Rutter and Esdale 1985; Esdale et al. 1987, 2003; Reeve 1990), while Ernest Henry deposit produces a gravity anomaly of about 2 mGal and a magnetic anomaly of 7,000 nT (Webb and Rowston 1995). Hence, a combination of airborne magnetics and gravity gradiometry is a good tactic for exploration targeting IOCG mineralization. Besides successful verification and validation works over already-known IOCG deposits, an important new discovery was made by a strategic alliance formed by Far West Mining and BHP Billiton in the Candela copper belt, Chile (Dransfield and Milkeriet 2007).

The second breakthrough since the practical application of AGG was the downsizing of the FALCON system. In 2005, the FALCON system was upgraded with digital electronics, and the resulting reduction in weight and size allowed the FALCON system to be installed and deployed in a medium-sized helicopter (Christensen and Hodges 2013). The deployment of a helicopter-borne FALCON system, named HeliFALCON, provided three advantages over a fixed-wing aircraft system: (a) improved horizontal data resolution achieved by slower ground speed, (b) smaller terrain clearance required, and (c) higher applicability to steep and rugged terrain (Christensen and Hodges 2013). These advantages are particularly advantageous for surveys in mountainous areas. Ishikawa et al. (2020) presented an application of multiple geophysical techniques for regional geothermal exploration in the Teshikaga area, Japan, based on the AGG data from HeliFalcon and on the airborne electromagnetic and magnetic data from Helitem. Ishikawa et al. demonstrated three-dimensional inversion of AGG data enabled a detailed interpretation of the deep subsurface structure related to geothermal resources such as an intrusion and a caldera, and that distribution of resistivity and magnetism in the relatively shallow subsurface revealed conductive anomaly overlapping low-magnetic anomaly suggesting hydrothermal alteration related to geothermal resources. There are many similarities between geothermal resources and hydrothermal deposits, and the above findings are also useful for the exploration of hydrothermal deposits.

The next breakthrough for AGG will be simultaneous operation with the airborne gravity system. Since the gravity gradiometry is a spatial differentiation of the gravitational field, it is effective for detecting relatively small-scale (i.e. short-period) gravity anomalies such as ones caused by mineral deposits, while, in principle, it is not suitable to capture changes in the long-period gravitational field. To make up for this shortcoming of AGG, Full-spectrum FALCON, combined use of AGG and airborne gravity, has been devised in practical application (Chen et al. 2017).

**Spectroscopic methods – Remote sensing**

When atoms and molecules that make up a substance have different energy levels, the transition between those energy levels results in the absorption or emission of electromagnetic waves with wavelengths that correspond to the difference in energy between those energy levels. The energy level responsible for the atomic spectrum represents the state of orbital electrons; the transition between electron levels induces absorption in the visible to ultraviolet region. Similarly, in a molecule, there are transitions between electron energy levels related to molecular orbitals, also there are spectra due to changes in the vibration of the molecule and in the rotation of the molecule. Transitions between vibrational levels in the same electronic state produce absorption in the near-to–mid-infrared region, and transitions between rotational levels cause spectra in the far-infrared to microwave region. Therefore, by observing the interaction between electromagnetic waves and substances, it is possible to obtain knowledge about the structures of the molecules and crystals, which make up the substances producing the spectrum.

The first attempt to identify rocks and minerals from their electromagnetic spectra was a pioneering proposal and research for its use in the discrimination of minerals on the lunar surface based on the mid-infrared spectra by Lyon (1962, 1964). Since then, interest in this field has increased.
in particular due to Hunt et al. (1970–1976), which details the reflectance of rocks and minerals in the visible to short-wavelength infrared regions (Hunt et al. 1970–1976). For the first time, this study revealed that various minerals have characteristic absorption in this wavelength range. Phyllosilicates bearing Al-OH and Mg-OH have narrow spectral absorption features within the 2.1–2.4 \( \mu \text{m} \) region. Clay minerals such as kaolinite; montmorillonite; muscovite; pyrophylite; illite and dickite are found in hydrothermally altered aureoles around ore bodies such as porphyry copper and epithermal gold deposits.

The first breakthrough in spectral remote sensing was the launch of Earth Resources Technology Satellite (ERTS-1) in 1972—renamed Landsat 1 in 1975—which carried the Return Beam Vidicon (RBV) and the Multispectral Scanner System (MSS). The MSS provided an important new tool for mineral exploration in the form of small-scale multispectral–visible and near-infrared (VNIR)–digital images, covering an area of 170 km by 185 km per scene under nearly constant lighting conditions. A notable early research result was the discrimination of alteration zones associated with epithermal gold deposits in Nevada (e.g. Goldfield) by digital processing of MSS data, enhancing spectral feature of iron oxides in gossan; i.e. intensely oxidized rocks in the upper and exposed part of an ore deposit (Rowan et al. 1974).

The second breakthrough was Thematic Mapper (TM) mounted on Landsat 4 launched in 1982, which provided improved spectral bands and spatial resolution, especially in the 2.08–2.35 \( \mu \text{m} \) region, so-called “clay band”, later added according to the strong recommendations from the Geosat Committee (Brant 1977), a nonprofit organization seeking to further the incorporation of pertinent, geologically related objectives into the ongoing governmental remote sensing programs. After Landsat 4, improvement of satellite-borne multispectral remote sensing was mainly driven by a series of Japanese national projects; i.e. Japanese Earth Resources Satellite (JERS-1) launched in 1992, operated in four spectral bands at VNIR, including off-nadir viewing of 15.3° forward in flight direction to acquire stereoscopic pairs, and four spectral bands at SWIR, providing three bands in “Clay band”; and then Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) launched in 1999, composed of three subsystems, one for each of the VNIR, SWIR and TIR regions. The VNIR subsystem operates in four spectral bands at the VNIR region, which consists of two telescopes; one nadir-looking with a three-spectral-band detector, and the other backward-looking with a single-band detector for stereo observations. The SWIR subsystem operates in six spectral bands at the SWIR region, designed to identify the representative alteration minerals. The TIR subsystem operates in five bands at the TIR region, which is nearly equivalent to NASA’s Thermal Infrared Multispectral Scanner (TIMS).

The third breakthrough was hyperspectral remote sensing deploying airborne sensors such as NASA/JPL Airborne Imaging Spectrometer (AIS), Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), GeoScan AMSS MKI, and GER Imaging Spectrometer. The discovery of buddingtonite by AIS at Cuprite, Nevada in 1984 (Goetz and Srivastava 1985) was especially worth mentioning.

Mapping alteration mineralogy and the chemical substitution in specific minerals can provide paths to potential economic mineralization. Cudahy et al. (2000a) differentiated endmembers of white mica using a shift of the absorption feature, reflecting chemical substitution in white micas, from HyMap airborne hyperspectral imager data over the hydrothermal system related to VMS mineralization in Panorama area, east Pilbara, Western Australia, which is important for mapping of the architecture of the hydrothermal system. In particular, Tschermak substitution in the white micas \([\text{Si} + (\text{Fe}^{2+}, \text{Mg}) \leftrightarrow \text{Al}]\), gauged using the wavelength of the 2.2\( \mu \text{m} \) absorption define the location of the known discharge zones in the volcanics, which are characterized by aluminium-poor micas at the base of the marker chert, including known mineralization and a new exploration target. The associated seawater recharge zones are characterized by aluminium-rich micas. This association indicates that fluid chemistry and not fluid temperature was the key factor in white mica chemical composition, at least for the upper parts of the volcanic pile. Seawater entering the volcanic pile along the zones of recharge was initially poor in dissolved metals and silicon.

The phenomena described above can be observed from the outer space. Figure 8 shows Hyperion spaceborne hyperspectral imager data acquired over the Panorama area. The image on the right of Fig. 8 represents the distribution of pixels showing absorption of white mica at wavelengths shorter than 2200 nm and pixels showing absorption of white mica at wavelengths longer than 2200 nm (red: longer wavelength white mica, blue: shorter wavelength white mica). Figure 9 shows comparison of the average apparent reflectance (Logarithmic Residual) of pixels showing absorption at wavelengths shorter than 2200 nm and pixels showing absorption at wavelengths longer than 2200 nm. Comparing the results of the reflectance measurements of the representative rock samples collected in the studied area (Fig. 10) with the results of the EPMA analysis of the white mica in those samples (Fig. 11), it was found that samples with a white mica + paragonite content of less than 40 % (Fig. 10(a)) showed absorption at wavelengths longer than 2200 nm, samples with a white mica + paragonite content of 40 % to 60 % (Fig. 10(b)) showed absorption near 2200 nm, and samples with a white mica + paragonite content of 60 % or more (Fig. 10(c)) showed absorption at wavelengths shorter than 2200 nm.
Cudahy et al. (2000b) illustrated that the compositions of Fe-Al chemistry of calcium-rich series of garnets over porphyry-skarn alteration systems in Yerington district, Nevada, USA, could be measured and mapped by the SEBASS system. Following instrument and atmospheric correction of the 124 SEBASS TIR spectral bands between 7.6–13.4 μm to apparent surface radiance, coherent mineral maps were generated including: quartz; grandite (andradite to grossular); clinopyroxene (diopside-hedenbergite); plagioclase feldspar (albite-oligoclase to oligoclase-andesine); carbonate (calcite and dolomite); epidote; muscovite; kaolinite and gypsum. Of these minerals, the grandite Fe-Al solid-solution chemistry was accurately measured with SEBASS and clearly delineated areas of calcium-exoskarn alteration and even sites of known copper mineralization.

Even if the spectral resolution is increased, if the spatial resolution is low, the change in the composition of the endmembers may be buried in the mixed pixel and cannot be detected. Since the required spectral resolution and spatial resolution differ depending on the type of the targeted ore deposit, it is important to balance the two resolutions according to the targets in the system design. Table 2 shows requirements for the specifications of next-generation satellite-borne sensors, based on the case histories deploying airborne hyperspectral sensors for mineral exploration, from a variety of hydrothermal deposits including: porphyry copper; IOCG; skarn; volcanogenic massive sulfide (VMS) and epithermal gold deposits (after Okada 2004). In Table 2, minerals marked with an asterisk (*) are exploration indicators in themselves. On the other hand, for minerals not marked with an asterisk, the composition of endmembers—i.e. changes in the chemical composition within the mineral which can only be captured by high-spectral resolution data as mentioned above—are pathfinders for exploration.

The next breakthrough will be the development of less expensive means for hyperspectral remote sensing. The amount of hyperspectral data becomes enormous because the spatial resolution in the image-domain is
two-dimensional, and when the spectral resolution in the spectral-domain is combined, the amount of data increases three-dimensionally as both spatial and spectral resolutions increase. One of the main reasons why HIRIS—the completed form of a series of hyperspectral sensor development of NASA—was canceled was its requirement to transfer huge amounts of data. Also, HISUI—a Japanese satellite-borne hyperspectral sensor installed on the International Space Station (ISS) in 2019—plans to transfer data offline in order to avoid this problem. Although airborne hyperspectral remote sensing is a proven technology, since remote sensing is a means of early-stage exploration, private demand for airborne hyperspectral remote sensing cannot be expected due to cost. As a solution, each mining company embraces an opportunity of cost-sharing and so on. In this respect, UAVs are an inexpensive alternative to satellite-based methods that do not require huge amounts of data transfer and are attractive platforms for mineral exploration. Recent developments in the UAV-based hyperspectral remote sensing are briefly described in the paragraph entitled “Unmanned survey platform”.

**Spectroscopic methods – Proximal sensing**

GER-IRIS, developed by Geophysical Environmental Research Corp. (GER) in 1978, was the first field spectrometer to measure visible to short-wavelength infrared region. Since then, a number of instruments have become commercially available, including PIMA, POSAM, and ASD. Basically, these field spectrometers can be categorized into those that have their own light source to illuminate the sample and those that use sunlight for illumination. Both types of instruments measure a portion of the 400-2500 nm wavelength band with a very high spectral resolution of 1-2 nm. This makes it possible to accurately determine not only mineral species but also variation in chemical composition within the molecular structure of mineral crystals.

Field spectrometers have made the task of ground-truth checking and verification of the results from the analysis of remotely sensed data much easier. The utilization of field spectrometers has been supported by the vast digital libraries of mineral spectra created and maintained by the USGS and other agencies (e.g. Salisbury et al. 1987b; a; 1993; Clark et al. 1993). Australian Mineral Industries Research Association (AMIRA) conducted P435 Project – Mineral Mapping with Field Spectrometry in 1994-1997, supported by 15 mining-exploration companies and two Australian Federal/State government geoscience agencies aiming at widening the range of applications of the field spectrometer (Huntington et al. 1999).

From the mid-2000s to the mid-2010s, spectroscopy for geological application added a new direction to the proximal targets such as drill cores, ores, mineral concentrates and mine-walls, mainly based on a series of research and development conducted by Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia, SpectraMap, Specim, CoreScan, and so on (e.g. Huntington et al. 2004; Cudahy et al. 2009; Hancock and Huntington 2010; Tappert et al. 2011; Quigley and Yildirim 2015). CSIRO’s HyLogging and HyChip, as well as other organizations’ attempts, were mainly a combination of handheld spectrometers covering 400-2500 nm wavelength region and moving tables. These handheld spectrometers measure the spectrum of an object as a point, rather than as an image. Drill cores or rock chip samples are placed on a moving table and the table is moved to achieve scanning.

CSIRO reconfigured the Operational Airborne Research Spectrometer (OARS) covering 500-2500 nm wavelength region (Hausknecht et al. 2001), and mounted it on a stable platform for semi-automated drill-core scanning system HyLogger-1. The OARS is a line profiler, i.e. a pointing device similar to a handheld spectrometer, and therefore, it requires a moving table to acquire spectral images. HyLogger-2, the second generation, deployed Fourier transform infrared (FTIR) system and HyLogger-3, the third generation, extended its spectral coverage to TIR (6000-14500 nm) region (Hancock et al. 2013).

Visible, SWIR and TIR spectroscopy of geological specimens such as drill-cores and rock-chips provided non-destructive recognition of a variety of minerals, improved productivity, and reduced costs compared to the conventional logging practices. This technological advancement may seem modest, however, it contributed greatly to improving cost-effectiveness and increasing the amount of information available for exploration. The most important contribution
of spectral proximal sensing is that it enables the systematic collection of consistent mineralogical information from the logging of drill cores, which is independent of operator bias. Although a significant level of skill and experience is required to perform consistent logging, the logging work is generally assigned to the most junior geologists. As a result, basic rock type recognition tends to be subjective, and especially when dealing with chips from reverse circulation (RC) drilling, there is an even greater lack of consistency in correctly identifying alteration minerals. The spectral proximal sensing has established itself as a routine method for core logging at the drilling site. As proof, nowadays, most of the major drilling service companies in the world offer drill core reflectance measurement as a routine service.

The information from the drill-cores accumulated in this way can be further enhanced by sharing it widely. One of the most notable results of these series of efforts is the AuScope National Virtual Core Library (NVCL) of Australia (Mauger et al. 2010). Processed spectral data, mineralogy, and high-resolution core images have been progressively uploaded to NVCL that is accessible worldwide to support research and mineral exploration.

Global navigation satellite system (GNSS)

Global navigation satellite system (GNSS) is a typical example of military technology that became open to the public and has been further applied to the general market and has brought a great impact on exploration technology. A satellite navigation system, beginning with Global Positioning System (GPS) and followed by GLONASS (Russia), GAGAN (India), BeiDou (China), and QZSS (Japan), consists of a network of satellites that transmit signals to receivers on the ground. These signals allow the determination of the location, speed, and direction of the receiver with high accuracy.

![Fig. 10 Reflectance spectra of selected rock samples collected in the studied area](image1)

![Fig. 11 Ternary diagram of the results of EPMA analysis of white mica in the rock samples shown in Fig. 10](image2)
The System (GPS), developed by the United States, is based on the simultaneous ranging of at least four members of a constellation of GPS satellites to give a precise position of a ground-based and/or aircraft-based receiver, became essential for navigation. Its release for non-military use in 1994 can be regarded as the first breakthrough in GNSS.

Major benefits received from GNSS are highly accurate position and time-mark. In common among all the airborne methods, higher accuracy of position provided by GNSS brought about a more dense and a more regular flight-line pattern with a relatively smaller terrain clearance.

For airborne geophysics, the resolution of adjacent sources as separate geological bodies increased as the ground clearance of the sensor was reduced due to GNSS. Additionally, GNSS provided a very precise time base which is convenient to synchronize magnetometers. In the airborne magnetics application, removal of the effect of temporal variations in the Earth’s magnetic field from the airborne observations was achieved by utilization of a base-station magnetometer on the ground to subtract its time-synchronized observations from the airborne observations.

As with airborne geophysics, GNSS brought about an increased density of observation sites in ground geophysics. GNSS receivers can achieve accuracy of ±20 m horizontal position in real-time in standalone mode and improved accuracy of ±5 m by post-processing in the so-called differential mode. GNSS also provides a precise time base which is essential for Magnetotelluric (MT) to perform post-processing of the time-series recordings with those from a remote reference site. The precise time base provided by GNSS is also convenient to synchronize transmitters and receivers, needed by certain ground-geophysical methods such as TDEM, SIP, Controlled Source Audio MagnetoTelluric (CSAMT), and so on.

The second breakthrough since the full constellation and opening to the public of the GPS was the development and operation of similar global satellite navigation systems by countries other than the United States. GLONASS, a Russian satellite navigation system, began its launch in 1982 and completed full constellation in 1995. It provides an alternative to GPS with global coverage and of comparable precision. As of March 2020, GPS, GLONASS, China’s BeiDou Navigation Satellite System (BDS), and the European Union’s Galileo system formed a global navigation satellite system (GNSS). In addition to GNSS, Regional Navigation Satellite System (RNSS) such as Japan’s Quasi-Zenith Satellite System (QZSS) and Indian Regional Navigation Satellite System (IRNSS) provide complementary navigation services to improve positioning accuracy. In mountainous areas, the coverage of radio waves transmitted from satellites may not be discontinuous or patchy. However, by using more satellite positioning systems, it becomes possible to receive radio waves from a sufficient number of satellites and to obtain one’s position. Once all these global and regional systems become fully operational, users will have access to positioning, navigation, and timing signals from more than one hundred satellites.

**Unmanned survey platform**

Unmanned aerial vehicles (UAVs), also known as drones, for airborne geophysical surveys such as aeromagnetics,
remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs) for marine surveys have been widely used in mineral exploration.

The attempt to demonstrate the UAV concept was made during World War II. UAV control technology was evolved to be more precise, not only as a destructive weapon but also for intelligence applications. The use of aerial intelligence collection platforms carried significant risks and repercussions, including detection of such an intelligence activity and even pilot and/or platform loss, e.g. U-2 incident in 1960. U.S. Central Intelligence Agency (CIA) tested the UAV concept codenamed “Aquiline” in the 1960s. While it did not become operational, the concept proved invaluable as a forerunner to contemporary intelligence UAVs and development efforts continued. Drawing upon developments supported by the military/intelligence and advances in software and navigation technology, commercial UAVs began to spread in the early 2000s. This time may be regarded as the first breakthrough in the UAV technology for mineral exploration.

The most common instruments on UAVs are magnetometers. Many of the early research work demonstrated that UAV-based magnetic systems could collect high-quality data (e.g. Anderson and Pita 2005; Partner 2006; Barnard 2008). The UAV platforms deployed in these studies were fixed-wing systems.

The second breakthrough since the practical application of UAV-based mineral exploration was the spread of rotary-wing UAVs. The world’s first rotary-wing UAV with multiple rotors on the market was the Gyrosaucer E-170, a radio-controlled hobby helicopter released by KEYENCE, Japan, in 1989. Rotary-wing UAVs with multiple rotors have a relatively simple mechanism but have good maneuverability and are now widely used in academia, industry, and recreation. At present, there are many companies offering UAV magnetometer surveys. Most UAV platforms to date have been of the rotary-wing type. The current use of a rotary-wing UAV. In general, the scale of the survey is a determining factor in choosing between fixed-wing and rotary-wing UAVs. Rotary-wing UAVs are an adaptable and cost-effective solution for mapping sites of up to 1 km². Fixed-wing UAVs are more suitable for larger areas. Malehmir et al. (2017) presented a case study of rotary-wing UAV-based magnetic surveys for mineral exploration targeting iron-oxide mineralization in central Sweden. Coupled with the development of related laws and regulations, the UAV magnetic survey is rapidly expanding its market for mineral exploration and effectively replacing ground magnetic surveys.

Although much research has been done on UAV-based electromagnetic (EM) methods, UAV-based EM systems available on the market are still limited. Mobile Geophysical Technologies (MGT) in Germany offers a VLF system suspended from a rotary-wing UAV, using a local VLF transmitter (Mobile Geophysical Technologies 2021). As mentioned in the paragraph entitled “Airborne electromagnetics (EM)”, due to the limited payload of UAVs, it is difficult to mount conventional airborne EM equipment and one practical solution is to separate the transmitter by installing it on the ground and mount only the receiver on the aerial platform, e.g. D-GREAT EM (Jomori et al. 2020).

UAV-based spectral remote sensing is carried out with various multispectral cameras and hyperspectral sensors, even so, many of these sensors have an observation wavelength limited to the VNIR region, which is insufficient for mineral exploration. However, small-sized hyperspectral sensors for observing the SWIR region have also been developed (e.g. Headwall 2021), and are expected to contribute to the spread of UAV-based spectral remote sensing in the near future. On the other hand, if the targets of the mineral exploration are limited to transition metals, the VNIR system can also be an effective exploration tool. Representative elements that show spectral characteristics in the VNIR region are transition metals such as iron and copper, but in addition, rare earth elements (REEs) also show distinctive spectral characteristics in the VNIR region (e.g. Clark et al. 1993). Figure 12 shows reflectance spectra of REE-bearing minerals selected from USGS digital spectral library (Clark et al. 1993). The spectral features observed in the VNIR region are undetectable at the spectral resolution of conventional satellite sensors, but can be identified by hyperspectral sensors. Booyse et al. (2020) presented case histories on the detection of REEs with UAV-based hyperspectral remote sensing, using Neodymium as a key pathfinder element for REEs as a whole.

For the exploration targeting marine mineral resources, including polymetallic sulfides, cobalt-rich ferromanganese crusts, and manganese nodules, ROVs and AUVs are commonly used for underwater work. Various types of geophysical surveys have successfully deployed ROVs and AUVs; e.g. a sea-floor EM survey for polymetallic sulfides deposits (Kowalczyk 2008), a TDEM, Spontaneous potentials (SP), and Magneto-Impedance (MI) magnetometer system suspended from an ROV (Nakayama and Saito 2011), and a sea-floor DC resistivity EM survey (Goto et al. 2013). Japan Agency for Marine-Earth Science and Technology (JAMSTEC) succeeded in the undersea structural survey for the first time in 2018 by operating multiple AUVs (Japan Agency for Marine-Earth Science and Technology 2018). In this survey, an AUV equipped with a current source preceded and another AUV equipped with a receiver followed along the survey line.
Unmanned survey platforms are an evolving technology area. Although it is unclear what the next technological breakthrough for mineral exploration will be, advanced maneuvering control technology and the technology to operate multiple unmanned platforms simultaneously will be the keys to increasing the use of automation to reduce the cost of labor-intensive exploration.

Neural networks/Deep learning

Neural networks/deep learning, which are prosperous today, are a prime example of the fruits of many years of tireless research. The history of neural networks dates back to the 1950s. It is said that the first boom of neural networks was in 1958 when Rosenblatt (1957) invented a neural network called a simple perceptron. A simple perceptron is a model that classifies input data into two classes as a linear discrimination problem. This model consists of two layers, an input layer and an output layer. The mechanism is that the neural network learns the boundary between the two classes. However, it turned out that simple perceptrons had the drawback of being able to solve only linearly separable problems, and then the first boom came to an end.

The second breakthrough was the backpropagation method invented by Rumelhart et al. (1986), solving the shortcomings of the simple perceptron by forming a neural network with a three-layer structure, with a new layer between the input layer and the output layer, so-called multilayer perceptron. The error backpropagation method corrects the weight of the previous layer so that the error between the correct answer and the output value approaches the correct answer. However, it turned out that the multi-layer perceptron model also had problems such as overfitting/overtraining—phenomena that the error between the training data and the output cannot be reduced well and it gets stuck in the local minima—and gradient disappearance—a problem that the error gradient shifts toward the end of the S-shaped sigmoid function, and the error does not decrease. Eventually, the second boom of the neural networks also came to an end.

The third breakthrough lay in overcoming the defects of the neural network developed in the second breakthrough. In 2006, Geoffrey Hinton proposed autoencoder (Hinton and Salakhutdinov 2006) and deep belief network (Hinton et al. 2006) as a means to solve the problems of overfitting/overtraining and gradient disappearance. These techniques have made it possible to continue the learning process even if there are three or more layers—two or more intermediate layers. In 2012, AlexNet, a convolutional neural network (CNN) architecture, designed by Hinton’s group (Krizhevsky et al. 2012), won the annual ImageNet Large-Scale

Table 3 Comparison of a rotary-wing and fixed-wing UAV

|              | Pros                        | Cons                          |
|--------------|-----------------------------|-------------------------------|
| Fixed-Wing   | Long flight duration        | Take-off and landing needs a lot of space |
|              | Large area coverage        | No VTOL/hovering              |
|              | Fast flight speed          | Harder to operate—more training needed |
|              | Stability in high winds    | Low maneuverability           |
|              | Ability to recover from power loss | Expensive                   |
| Rotary-wing  | High maneuverability       | Short flight duration         |
|              | Easy of use                | Small payload                 |
|              | VTOL and hover flight      |                               |
|              | Automatic pilot            |                               |
|              | Versatility, interchangeable payload |                    |
|              | Can operate in a confined area |                             |
|              | Portability                |                               |

Fig. 12 Reflectance spectra of REE-bearing minerals selected from USGS digital spectral library (Clark et al. 1993)
Visual Recognition Challenge (ILSVRC) by a large margin over second place and past winners. AlexNet uses deep learning parameter optimization methods that are still used today, such as an activation function called ReLU instead of the sigmoid function as a measure against gradient disappearance, and Dropout to avoid local optimization and overfitting. Neural networks have been reactivated and continue to their prosperity today.

The application of neural networks to mineral exploration also has a long history. The spatial association between the known occurrences and the predictive data sets is used to determine weights, and the weights are then applied to predict areas with similar characteristics to the known occurrences. Such an approach is well suited for brownfield exploration because it requires a large number of training sets, attained by extensive exploration, to recognize characteristics of mineral occurrences exactly (e.g. Bonham-Carter et al. 1988; Agterberg et al. 1993). Also, such an approach is well suited for supervised learning with neural networks, learning a function that maps an input to an output based on example input-output pairs. More complex spatial patterns of geochemical data can be accommodated by treating variables as rationalized variables using the methods of geostatistics, particularly, various forms of kriging (e.g. Goovaerts 1999). The prosperity today of neural networks is due largely to enormous datasets, so-called “big data”, and is intended to scale up to provide a superset, integrating the datasets into one large hierarchical structure. This makes big data well-suited for regional exploration.

In the field of neural networks/deep learning, research and development is being actively pursued, and various ideas are being tested. As an application to exploration technology, it is expected to contribute to the inversion of geophysical data. Inversion analysis of geophysical data is a typical underdetermination problem, i.e. the solution is not uniquely determined. Derivation of IP parameters by TDEM, including potential application to the airborne IP method, is also a very difficult problem because the solution is not uniquely determined by resistivity and depth, and still more difficult by the addition of unknown IP parameters. Hence, usually in the inversion of geophysical data, it is necessary to use various foresight information and/or assume a smooth underground structure. If nonlinear optimization by neural networks/deep learning can be applied to the inversion of geophysical data, a new breakthrough may occur.

Discussion and conclusion

Based on the comprehensive analysis combining (a) findings deductively derived from consideration of exploration technologies and the important factors necessary for breakthroughs, and (b) findings about the characteristics that breakthrough technologies should have, inductively derived from a review of technologies that actually brought innovation to exploration, specific issues to be solved as breakthroughs in exploration technologies in the near future are summarized in the following:

(1) Improvement in economic efficiency, namely:

- Labor-saving or unmanned operation, e.g. UAV-based exploration and automatic spectroscopic scanning of drill cores;
- Improved access (no need to cut down vegetation or build access roads), e.g. improvement of various airborne exploration techniques including airborne EM, AGG, and especially airborne IP;
- Increased work efficiency and productivity, e.g. automatic data processing by neural networks/deep learning; and
- Lower cost to implement, e.g. less expensive platforms such as UAVs.

(2) To obtain information that is really needed for exploration, specifically:

- IP effect of sulfide minerals associated with mineralization, i.e. practical SIP;
- Geophysical characterization of the deep underground, e.g. enhancement of SQUID-based TDEM; and
- Removal of effects of the surface layer, e.g. very conductive deeply-weathered overburden and younger volcanics rich in magnetic minerals.

(3) To obtain information that cannot be obtained by the conventional methods, specifically:

- Distribution of endmember minerals related to mineralization, i.e. hyperspectral mapping with high spatial resolution.

Needless to say, the above technologies are not omnipotent “magic wands” that can be used alone but should be used judiciously and selectively depending on the case, and in some instances should be used in combination with conventional methods. Above all, conceptual integration should be achieved by modifying the interpretation of the geophysical data and deposit model so as to maintain consistency between the assumed deposit model and the geological and geochemical knowledge obtained on the ground. In any case, these techniques provide exploration insights that must be accompanied by detailed ground follow-up and may help discover deposits through steady verification work and drilling.
From a long-term perspective, following only the economic rationality will not secure enough resources for the exploration activities and development of exploration technology. Considering the circumstances discussed, leaving the development of exploration technology solely to private companies seems inappropriate. The support of public institutions in the development of exploration technology is also important. Schimpf and Sturm (2016) reported the operational analysis of research and innovation in the mining sector targeting five reference countries: Australia; Canada; Japan; South Africa; and the United States, comparing their innovation systems; main role players; institutions and policies that drive research and innovation in the mining sector. Among the targeted countries, mining plays the biggest role in countries rich in mineral endowments, such as Australia, South Africa and Canada whereas it plays a minor role in the U.S. and only a marginal role in Japan (Table 4). On Research and Development (R&D) across the full mining spectrum, Japan spends the most, followed by the U.S., Australia, Canada and South Africa (Table 4). However, despite the overall high research intensity in Japan, only a minor part of R&D expenditure is allocated to the mining sector. Regarding the overall business expenditure in R&D, companies in the mining sector in Australia are those who spent most (Table 4). In other countries as well, in addition to the competitiveness of their own secondary and tertiary industries, the allocation of investment in R&D of the mining industry, which supports all industry sectors, should be reconsidered for the sustainable development of the world economy.

Some countries are promoting the exploration of seafloor mineral resources and asteroid resources. For instance, Japan Oil, Gas and Metals National Corporation (JOGMEC) conducted and succeeded in the world’s first pilot test of excavating and ore lifting for seafloor polymetallic sulfides under the sea near Okinawa Prefecture in 2017 (Yamaji et al. 2019). Hayabusa, an experiment research spacecraft on new engineering technologies for sampling extraterrestrial planetary materials, developed and launched in 2003 by Japan Aerospace Exploration Agency (JAXA), collected samples from a small near-Earth asteroid named 25143 Itokawa, and returned to Earth in 2010 (e.g. Yoshikawa et al. 2015). The development of seafloor mineral resources is still a long way off, and the asteroid resources will be targeted in the distant future. However, just as spectral remote sensing technology was born from the purpose of mineralogical investigation of the lunar surface, the knowledge gained from the exploration of seafloor mineral resources and asteroid resources may be of great help to an exploration of mineral resources on the ground.

As we have seen, many of the major exploration technologies in use today are derived from military technology. In addition, if we look back at human history, the struggle for resources has been the cause of various conflicts and wars. It is also true that each country has allocated a considerable amount of wealth to military purposes according to its own interests. However, it would be far more important and healthy for the sustainable prosperity of humankind to switch public funds to R&D for peaceful purposes, such as mining, which enhances national security.

Ultimately, the mining is all about finding and excavating mineral resources. The ore will run out at some point in the future, hence mines have a limited lifetime. In this respect, mining is similar to living organisms. Exploration activities can be considered as the blood that revitalizes and keeps alive the body referred to as the “mining industry”. Now that the long-term supply of mineral resources is uncertain, exploration engineers and researchers should combine their experience, knowledge, and wisdom to bring about breakthroughs in mineral exploration technology in order to revitalize exploration and lead it to success in order to secure mineral resources for the future.

Table 4: Contribution of mining to the countries’ GDP—Contribution to GDP, gross expenditure on R&D standardized by GDP—Research Intensity, and business expenditure on R&D (BERD) in mining and quarrying related to overall BERD in the countries—Mining BERD / Overall BERD (after Schimpf and Sturm 2016)

| Country      | Contribution to GDP (Rank/5) | Research Intensity (Rank/5) | Mining BERD / Overall BERD (Rank/4) |
|--------------|------------------------------|----------------------------|-------------------------------------|
| Australia    | 8.5 % (1)                    | 2.11 %*** (3)              | 22.4 %* (1)                         |
| Canada       | 4.0 % (3)                    | 1.61 %** (4)               | 6.4 %*** (2)                        |
| Japan        | <0.1 % (5)                   | 3.58 % ** (1)              | <0.1 %*** (4)                       |
| South Africa | 4.9 % (2)                    | 0.73 %* (5)                | n.a.                               |
| United States| 1.4 % (4)                    | 2.74 %*** (2)              | 0.9 %** (3)                         |

*2012; **2014; ***2013
*2011; **2012; ***2013
Funding No funding was received for conducting this study.

Declarations

Conflicts of interest Financial interests: The author is paid by Ocean High Technology Institute, Inc. Non-financial interests: The author is an unpaid member of the following academic societies: The Society of Exploration Geophysicists (SEG); European Association of Geoscientists and Engineers (EAGE); The Society of Exploration Geophysicists of Japan (SEGJ); The Remote Sensing Society of Japan (RSSJ); The Mining and Materials Processing Institute of Japan (MMIJ)

References

Agterberg F, Bonham-Carter G, Cheng Q, Wright D (1993) Weights of evidence modeling and weighted logistic regression for mineral potential mapping. Computers in Geology 25:13–32
Anderson D, Pita A (2005) Geophysical surveying with GeoRanger UAV. In: AIAA Journal, American Institute of Aeronautics and Astronautics, p 6952, https://doi.org/10.2514/6.2005-6952
Balch S, Boyko W, Paterson N (2003) The AeroTEM airborne electromagnetic system. The Leading Edge 22(6):562–566
Baldwin RW (1959a) A decade of development on overvoltage surveying. Mining Engineering 214:307–314
Baldwin RW (1959b) Overvoltage field results. In: Wait JR (ed) Overvoltage (Research and Geophysical Applications, International Series of Monographs on Earth Sciences, Pergamon, chap 9, pp 115–124, https://doi.org/10.1016/B978-0-08-099272-0.50014-5
Barnard JA (2008) The use of unmanned aircraft in oil, gas and mineral E+P activities. SEG Technical Program Expanded Abstracts 2008:1132–1136. https://doi.org/10.1190/1.3059122
Blain C (2000) Fifty-year trends in minerals discovery-commodity and ore-type targets. Exploration and Mining Geology 9(1):1–11
Blei DF (1953) Induced polarization: A method of geophysical prospecting. Geophysics 18(3):636–661
Bonham-Carter G, Agterberg F, Wright D (1988) Integration of geological datasets for gold exploration in Nova Scotia. Photogrammetric Engineering and Remote Sensing 54(11):1585–1592
Booysen R, Jackisch R, Lorenz S, Zimmermann R, Kirsch M, Nex PAM, Glöguen R (2020) Detection of REEs with lightweight UAV-based hyperspectral imaging. Scientific Reports 10(1):17450. https://doi.org/10.1038/s41598-020-74422-0
Brant AA (1977) The geosat committee, Inc. Geophysics 42(4):887–889
Bruten AM (2000) Improving the accuracy and resolution of SINS/DGPS airborne gravimetry. PhD thesis, University of Calgary
Chen T, van Galder C, Dransfield M (2017) Full spectrum Falcon: Measuring broadband airborne gravity. In: SEG Technical Program Expanded Abstracts 2017, Society of Exploration Geophysicists, pp 1823–1828
Christensen AN, Hodges G (2013) HeliFALCON airborne gravity gradiometer data acquisition in rugged terrain. In: Proceedings of the 11th SEGJ International Symposium, The Society of Exploration Geophysicists of Japan, Yokohama, Japan, pp 140–145
Clark RN, Swayze GA, Gallagher AJ, King TVV, Calvin WM (1993) The U. S. geological survey, digital spectral library: version 1: 0.2 to 3.0 microns. Tech. rep., U. S. Geological Survey, USGS Open File Report 93-592
Cole KS, Cole RH (1941) Dispersion and absorption in dielectrics I. alternating current characteristics. The Journal of chemical physics 9(4):341–351
Cox DP, Singer D (eds) (1986) Mineral deposit models, vol 1693. US Government Printing Office Bulletin, USGS Bulletin, p 1693
Cudahy T, Okada K, Brauhart C (2000a) Targeting VMS-style Zn mineralisation at Panorama, Australia, using airborne hyperspectral VNIR-SWIR HyMap data. In: ERIM Proceedings of the 14th international conference on applied geologic remote sensing, pp 395–402
Cudahy T, Okada K, Yamato Y, Huntington J, Hackwell J (2000b) Mapping skarn alteration mineralogy at Yerington, Nevada, using airborne hyperspectral TIR SEBASS imaging data. In: ERIM Proceedings of the 14th International Conference on Applied Geologic Remote Sensing, pp 70–79
Cudahy T, Hewson R, Caccetta M, Roache A, Whitbourn L, Connor P, Coward D, Mason P, Yang K, Huntington J, Quigley M (2009) Drill core logging of plagioclase feldspar composition and other minerals associated with archean gold mineralization at kambalda, western australia, using a bidirectional thermal infrared reflectance system. Economic Geology 16:223–235
Dransfield M, Milkereit B (2007) Airborne gravity gradiometry in the search for mineral deposits. In: Milkereit B (ed) Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, pp 341–354
Esdale D, Pridmore D, Coggon J, Muir P, Williams P, Fritz F (1987) Olympic Dam deposit? geophysical case history. Exploration Geophysics 18(2):47–49
Esdale D, Pridmore DF, Coggon J, Muir P, Williams P, Fritz F (2003) The Olympic Dam copper-uranium-gold-silver-rare earth element deposit, south australia: A geophysical case history. In: Dentith M (ed) Geophysical Signatures of South Australian Mineral Deposits. The University of Western Australia, ASEG and PIRSA, pp 147–168
Fountain D, Smith R, Payne T, Limieux J (2005) A helicopter time-domain EM system applied to mineral exploration: System and data. First Break 23(11)
Gingerich J, Allard M (2001) Geophysical techniques for VMS exploration in Matagami camp. In: PDAC Annual Meeting
Goetz AF, Srivastava V (1985) Mineralogical mapping in the Cuprite mining district, Nevada. In: Proceedings of the Airborne Imaging Spectrometer Data Analysis Workshop, Jet Propulsion Laboratory, JPL-PUB-85-41
Gooi F, Faye M, Koyama T, Sato T, Nakamura Y, Suzuki K, Sawamura T, Iijima C (2017) Remote detection of high geothermal gradient areas in the Iheya north area, off Okinawa, Japan. In: Proceedings of the 11th SEGJ International Symposium, Yokohama, Japan, 18-21 November 2013, The Society of Exploration Geophysicists of Japan, pp 298–301
Hancock E, Huntington JF (2010) The gsaw nvc1 hylogger: rapid mineralogical analysis for characterizing mineral and petroleum core. Tech. rep., Geological Survey of Western Australia, rRECORD 2010/17
Hancock E, Green A, Huntington J, Schodlok M, Whitbourn L (2013) Hylogger-3: Implications of adding thermal-infrared sensing. Tech. rep., Geological Survey of Western Australia, record 2013/3
Hausknecht P, Whitbourn L, Connor P, Flack J, Wells G, Mason P, Huntington JF, Hewson R, Batty S (2001) Oars - a new system for mapping surface mineralogy simultaneously with airborne geophysics. Exploration Geophysics 32(2):102–106
Headwall (2021) Hyperspectral sensors. https://www.headwallphotonics.com/hyperspectral-sensors, (Accessed on 21/07/2021)
Hein J, Mizell K, Gartman A (2018) Global deep-ocean mineral resources and the future of seabed mining. In: Proceedings of
Nakayama K, Shingyouji T, Motoori M, Yasui M, Kobayashi Y, Yamazaki A, Saito A (2011) Marine time-domain electromagnetic technologies for the ocean bottom mineral resources. In: Proceedings of the 10th SEGJ International Symposium, The Society of Exploration Geophysicists of Japan, pp 1–4

Nakayama K, Morooori M, Saito A (2019) Application of time-domain electromagnetic survey for seafloor polymetallic sulphides in the Okinawa trough. In: 25th European Meeting of Environmental and Engineering Geophysics, European Association of Geoscientists & Engineers, pp 1–5

Okada K (1995) Geophysical exploration for epithermal gold deposits: Case studies from the Hishikari gold mine, Kagoshima, Japan. Exploration Geophysics 26:78–83

Okada K (1998) In-loop/coincident-loop method. In: Handbook of Geophysical Exploration, vol 3, The Society of Exploration Geophysicists of Japan, chap 4.3.1, pp 340–346, in Japanese

Okada K (2004) Strategic significance of advanced mineral and lithological mapping based on hyperspectral remote sensing for mineral exploration; perspective of next generation satellite-borne sensors as successors to ASTER. In: Proceedings of the 12th Australasian Remote Sensing and Photogrammetry Conference, The Remote Sensing and Photogrammetry Commission of the Spatial Sciences Institute, Fremantle, Western Australia

Okada K (2021) A historical overview of the past three decades of mineral exploration technology. Natural Resources Research 30(4):2839–2860. https://doi.org/10.1007/s11053-020-09721-4

Partner R (2006) GeoRanger aeromagnetic UAV: Development to commercial survey. Preview 125:28–29

Pelton WH, Ward SH, Hallof PG, Sill WR, Nelson PH (1978) Mineral discrimination and removal of indigenous coupling with multifequency IP. Geophysics 43(3):588–609. https://doi.org/10.1190/1.1440839

Quigley MA, Yildirim G Baris (2015) Mineral identification and domain characterisation using two automated hyperspectral core logging systems, Los Bronces Cu-Mo porphyry deposit. In: 13th Australasian Remote Sensing and Photogrammetry Conference, Perth, Western Australia

Rutter H, Esdale D (1985) The geophysics of the olympic dam discovery. Exploration Geophysics 16(3):273–276

Salisbury JW, Walter LS, D’Aria D (1987a) Mid-infrared (2.5 to 13.5 μm ) spectra of igneous rocks. Tech. rep., U. S. Geological Survey, uSGS Open File Report 88-686

Salisbury JW, Walter LS, Verge N (1987b) Mid-Infrared (2.1-25μm) Spectra of Minerals. Tech. rep., U. S. Geological Survey, uSGS Open File Report 87-263

Salisbury JW, Walter LS, Verge N, D’Aria DM (1993) Infrared (2.1-25μm) Spectra of Minerals. The Johns Hopkins University Press Sanematsu K, Duncan R, Imai A, Watanabe K (2005) Geochronological constraints using 40ar/39ar dating on the mineralization of the Hishikari epithermal gold deposit, Japan. Resource Geology 55(3):249–266

Schimpf S, Sturm F (2016) Fostering international raw materials cooperation: Analysis of research and innovation. International Raw Materials Observatory

Schlumberger C (1920) Etude sur la prospection électrique du sous-sol, Gauthier-Villar et Cie, chap VIII, pp 70–72

Schodde R (2011) Recent trends in gold discovery. In: NewGenGold Conference, Perth, Western Australia, vol 2

Seigel HO (1974) The magnetic induced polarization (MIP) method. Geophysics 39(3):321–339. https://doi.org/10.1190/1.1440431

Sillitoe RH (1995) Exploration and discovery of base-and precious-metal deposits in the circum-Pacific region during the last 25 years. Society of Resource Geology, Special Issue No, p 19

Sillitoe RH (2000) Exploration and discovery of base-and precious-metal deposits in the circum-pacific region-a late 1990s update. Society of Resource Geology, Special Issue No, p 21

Sillitoe RH (2010) Exploration and discovery of base-and precious-metal deposits in the circum-pacific region-a 2010 perspective. Society of Resource Geology, Special Issue No, p 22

Smith R, Fountain D, Allard M (2003) The MEGATEM fixed-wing transient EM system applied to mineral exploration: a discovery case history. First Break 21(7)

Smith RS, Klein J (1996) A special circumstance of airborne induced-polarization measurements. Geophysics 61(1):66–73

Smith RS, Hodges G, Lemieux J (2009) Case histories illustrating the characteristics of the HeligEOTEM system. Exploration Geophysics 40(3):246–256

SNL Metals & Mining (2016) World exploration trends 2016. Tech. rep., SNL Metals & Mining, a Special Report from SNL Metals & Mining for the PDAC International Convention

Sørensen KL, Auken E (2004) SkyTEM - a new high-resolution helicopter transient electromagnetic system. Exploration Geophysics 35(3):191–199

S&P Global market intelligence (2021) World exploration trends 2021. Tech. rep., S&P Global Market Intelligence, PDAC Special Edition

Tappert M, Rivard B, Giles D, Tappert R, Mauger A (2011) Automated drill core logging using visible and near-infrared reflectance spectroscopy: a case study from the olympic dam icog deposit, south Australia. Economic Geology 106(2):289–296

The International Copper Association (2021) Copper demand and long-term availability. https://copperalliance.org/sustainable-copper/about-copper/cu-demand-long-term-availability/

Van Kann F (2004) Requirements and general principles of airborne gravity gradiometers for mineral exploration. In: Lane RJL (ed) Abstracts from the ASEG-PESA, Airborne Gravity 2004 Workshop, pp 1–6

Wait JR (ed) (1959) Overvoltage research and geophysical applications, International Series of Monographs on Earth Sciences, vol 4, Pergamon

Webb M, Rowston P (1995) The geophysics of the Ernest Henry Cu-Au deposit (N.W.) Qld. Exploration Geophysics 26(2–3):51–59. https://doi.org/10.1017/EG995051

Weidelt P (1982) Response characteristics of coincident loop transient electromagnetic systems. Geophysics 47(9):1325–1330. https://doi.org/10.1190/1.1441393

Witherly K, Irvine R, Godbout M (2004a) Reid Mahaffy test site, International Edition

Witherly K, Irvine R (2004) Morrison E (2004b) The Geotech VTEM helicopter transient electromagnetic system. Exploration Geophysics 35(3):191–199

Yamaji N, Okamoto N, Shikawa S, Kawano S, Sakurai H (2019) Achievement for pilot test of excavating and ore lifting conducted...
for seafloor polymetallic sulphides - world’s first success in continuous ore lifting test for seafloor polymetallic sulphides. Journal of MMIJ 135(6):42–51

Yoshikawa M, Kawaguchi J, Fujiwara A, Tsuchiyama A (2015) Hayabusa sample return mission. In: Michel P, DeMeo FE, Bottke WF (eds) Asteroids IV (Space Science Series). University of Arizona Press Tucson, Arizona, pp 397–418

Zonge KL, Wynn JC (1975) Recent advances and applications in complex resistivity measurements. Geophysics 40(5):851–864. https://doi.org/10.1190/1.1440572

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.