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Chapter 9

Geophysical Expressions of Ore Systems—Our Current Understanding

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Abstract

Mineral exploration is the primary means to define new mineral resources. Following the end of World War II, there was a global economic boom which required the identification and mining of vast numbers of new deposits in order to provide the needed raw materials to sustain the demand. By and large, shallow easy-to-define orebodies were recognized first and developed. In the past 20 years, the discovery performance across virtually all mineral sectors has fallen, resulting in growing concern that if unchecked, there could be shortfalls in a number of commodities within the next 20 years. The collective sense is that there are more deposits to be found, but these are expected to be at greater depths than those that have been typical targets in the past.

To operate in this environment, new approaches for identifying deposits are required and the concept of a mineral systems approach, first suggested 20 years ago, has emerged as a powerful means going forward to build strategies and capabilities. In terms of geophysical exploration, the major change that will be required is a shift from a focus almost entirely on direct targeting with geophysical surveys of deposits, to a staged process where geophysical approaches are used initially to help define the pathways in the earth that carried the mineralizing solutions, which formed the target deposit. These pathways would provide a much larger target and if detected and mapped, should allow explorers to follow the pathway to the location of potential deposits.

This task is different from most geophysical studies, where the focus has typically been on improving the direct targeting capabilities and not the larger scale mapping problem that a mineral systems approach requires. A review of the current state-of-play for a number of major deposit styles shows how geophysical data are being used at present to explore for the larger scale mapping problem. The assessment overall is encouraging but major challenges remain outside of the technical issues of defining a mineral systems strategy that relate primarily to human resources and the commercial environment. With regard to the human resources issue, are there going to be a sufficient number of the right people to develop and implement the required programs? Universities play a critical role in producing new geoscientists but the industry then must take responsibility to train and mentor these people to become functioning professionals. In the commercial environment, at present there is little interest for long-term, strategic programs, either in terms of the needed fiscal support or commitment to undertake the implementation of outcomes. Although governments likely have a greater sense of urgency with regard to this problem, it may be difficult to unilaterally and successfully deal with this complex issue.

Introduction

The mineral exploration industry is undergoing a "reboot" after 10 years of rapidly increasing expenditures that peaked in 2012 at $29.5B US (Doggett, 2013; Schodde, 2013). All indicators for 2013 and early 2014 show that the past levels of expenditure by junior companies is no longer being supported by the investor community or major mining companies, their two primary sources of funding over the last 10 years. The past decade also marked large increases in profits for producing companies, primarily as a result of the enormous growth of the Asian economies, particularly China. In the past several years, however, an oversupply of many commodities has resulted in downward pressure on many commodity prices. In addition, development costs skyrocketed for a number of large projects, resulting in further losses, thereby accelerating the withdrawal of the majors from the junior sector for the foreseeable future. Whereas the exploration industry (comprised of both majors and juniors) enjoyed a veritable Golden Decade that began soon after the start of the new millennium, it has now come to an abrupt close with relatively few new major discoveries available to shepherd into production. This outcome has disappointed many stakeholders and investors, given the huge expenditure on exploration during the previous 10 years (over $80B US; Doggett, 2013) and has resulted in an across-the-board loss of confidence in the exploration business.

It is unclear when the exploration industry will "rehydrate" and become functional again. When this does happen, however, industry observers have suggested that more attention on greenfields exploration is required, because this is considered the best strategy for defining new high-value deposits (Hronsky, 2009; Sillitoe, 2010; Sykes and Trench, 2014). The major caveat is that much of what can currently be considered greenfields terrane lies below a surface that appears nonprospective due to either the nature and/or thickness of the cover material. Such covered areas present a major impediment to current state-of-the-art exploration targeting methods.

To address this challenge, there are a growing number of explorationists that are proposing a fundamentally different approach (Wyborn et al., 1994; Barnicoat, 2007; Australian Academy of Sciences, 2010; McCuaig et al., 2010; McCuaig and Hronsky, 2014). Rather than relying on traditional regional mapping to define areas for follow-up geochemistry and geophysics with the hope of developing attractive targets, the exploration community must learn to think about the mineral system as a whole. The major advantages of this approach

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are two-fold: first, the mineral system presents a relatively larger exploration target, and secondly, with a more complete knowledge of the entire mineral system, it should be possible to vector more effectively toward the economically significant parts of the system.

Geophysics has a major role in mapping mineral systems. However, the state of understanding of how mineral systems respond to the available geophysical techniques is still in its infancy. The present assessment is intended to (1) review the current understanding of the geophysical signatures of mineral systems, (2) show the effectiveness of these geophysical techniques in helping explorationists search for new deposits, and (3) identify future research and development needs before viable new approaches to exploration undercover can been achieved.

Setting the Stage

The quest and the problem

As more emphasis is placed on undercover exploration for mineral deposits, the direct detection of such deposits with standard geologic mapping, geochemistry, or geophysical approaches can no longer be expected. Ore deposits undercover are commonly below a column of earth that can differ significantly (e.g., physical and/or chemical properties) from the rock that hosts the deposit. This intervening material may attenuate the traditional geophysical responses produced from sensors at the surface or low-flying aircraft. Alternatively, some cover material may be relatively transparent to geophysical techniques and only the normal drop-off in response of geophysical signals with depth will be evident. An example is the use of electromagnetic (EM) techniques to explore for unconformity uranium deposits in the Athabasca Basin in Canada. In this example, the overlying Athabasca sandstone offers little interference and EM signals reflect the favorable graphitic horizons near the unconformity surface, which in some cases is well over 0.5 km below surface (Powell et al., 2007). In the same environment, the response of basement sources from potential field techniques is also only nominally affected, even with thick overlying sandstone, because there is typically a lack of significant susceptibility or density changes in the overlying sandstone. If density contrasts do exist, however, it could reflect the alteration halo in the sandstone possibly associated with a near-by deposit; this will be discussed in later sections (see below).

In other cases, however, the cover material will adversely affect the geophysical response, severely limiting both the depth of investigation as well as the overall sensitivity of the survey. Although there are methods for adapting various techniques to penetrate through interfering cover material, these approaches can degrade the survey results to the point that a technique will no longer be cost-effective. Some approaches that involve surveying at depth utilizing drill holes have proven effective in some situations (Dentith and Mudge, 2014).

Whereas pathways of mineral systems have been described recently in nonspecific spatial terms (Australian Academy of Sciences, 2010; McCuaig et al., 2010), specific geophysical analogues are required to quantify mineral system terminology for geologic, mineral system, and geophysical scales (Table 1). For example, the geologic term of "regional" is

TABLE 1. Terminology Used to Relate Geologic and Geophysical Scales to Mineral Systems

Geological scale	Mineral systems definition	Geophysical scale
Regional	Source and exit pathways	Footpath
District	Ore deposit environment	Footprint
Target/deposit	Target/deposit	Target/deposit

equivalent to "source and exit pathways" in mineral system-scale terminology, which in turn is equivalent to "footpath" when describing geophysical responses.

The main components of a mineral system and corresponding geophysical attributes are shown in Figure 1. Geophysical surveys have traditionally focused on recognizing the "footprint-scale" response of a deposit, hopefully providing sufficient information to allow a drill test of the feature. Examples of footprints include the alteration halo around a porphyry copper deposit that can be mapped with an induced polarization (IP) survey; the isolated strong EM target, which could represent a possible volcanic-hosted massive sulfide (VHMS) or magmatic nickel deposit; or a small discrete magnetic feature that could be a diamondiferous kimberlite. The term "footpath" is chosen as the geophysical proxy for the overall corridor along which mineralized fluids have passed, thereby creating an extensive disturbed zone with a size far greater than the resulting deposit. Such a footpath can be 10s of kilometers in length and will carry some residual signature of the major hydrothermal event(s) that produced the deposit(s). This assumes a footpath was created during the formation of the deposit. Whether the footpath and deposit have been preserved remains part of the investigations now underway to develop a greater understanding of the history of the formation of mineral systems and how they change with time.

Traditional approaches

Depending on the deposit style and terrane, exploration targeting has typically been a two-stage process. The first stage involves selecting an area to explore, which is commonly done through a mixture of prior knowledge of an area, followed by basic prospecting and follow-up geologic mapping. Regional geochemistry and geophysics may be applied at this stage as well. Historic evidence of mineralization in an area is often an important factor in drawing explorers back to an area, the assumption being that the best place to look is where something has been previously found. The second stage is to define targets for follow-up exploration based upon detailed geologic mapping, geochemical analyses, and possibly geophysical surveys.

In the early stages of area selection, the use of regional geophysical coverage can help to define the geologic framework and guide a prospectivity assessment of the terrane. Some explorers will actively seek out available data sets, whereas others do not see the value in having access to such data. In some jurisdictions, governments will attempt to facilitate the process and transform geophysical coverages into products which explorers can more readily use. However, neither industry nor government agencies have been able to define a "best practice" approach to using these data to aid in regional mapping. Typically, explorers who spend more time in areas

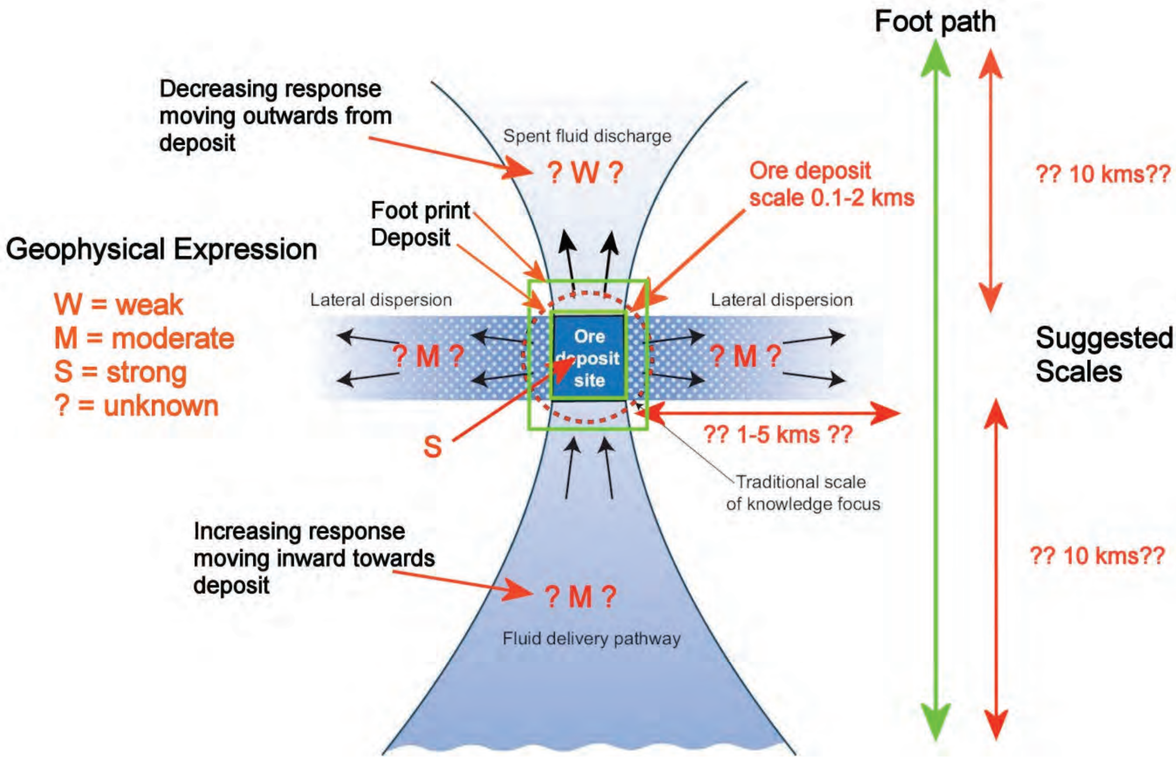

FIG. 1. Diagram of a mineral system with geophysical properties, modified from Australian Academy of Sciences (2010).

with extensive weathering and cover tend to rely more on regional geophysical surveys and those who focus exploration in outcropping areas consider regional surveys of less value. As the exploration focus moves into areas with an ever-increasing amount of cover material, these biases are important to recognize. Arguably, those who are already comfortable with using geophysical data to assist in building a subsurface geologic framework will have an advantage over those who don't.

The more popular role for geophysics has been in the second stage of exploration when targets are being generated. In some settings, geophysics has enjoyed an enviable reputation as being an "ore finder." The success in using EM techniques in massive sulfide exploration (Donohoo et al., 1970; Pemberton, 1989) is one well-documented example of this. In many cases however, geophysical surveys alone can't provide an unambiguous response to the sought-after target, and in such cases, mapping or geochemical surveys are used to help screen the "false positives." The first several decades, during which EM was successfully employed, drilling was a primary screening tool. This was possible because of the generally shallow depth of most EM targets. However, in the same terranes that yielded numerous deposits in the first wave of exploration, subsequent efforts (Witherly and Allard, 2010) proved to be largely unsuccessful, even with a new generation of exploration technology available. This is seen as a likely harbinger of the challenges explorers will face when having to carry out exploration in frontier areas with thick cover.

Going forward

The move to undercover exploration (Berryman, 2009) will require a change in the way geophysical methodologies are viewed in the exploration process. A full assessment of all geophysical data at the regional scale in three-dimensional (3-D; and with interpreted 4-D) will be required. Integration with all geologic information (especially any subsurface data) is critical to both constrain and explain the nature of the derived geophysical models. Recognizing a mineral system footpath is a desired outcome but considerably more work is required in order to understand how to define and recognize a footpath. Direct targeting will still be a required second phase in the process using 3-D geochemistry and direct detection geophysical techniques, but will much more likely be deployed along subsurface traverses accessed by next-generation drilling technology (Hillis et al., 2014).

At the present time, it is far from certain if mineral systems have larger signatures that can be defined remotely by geophysics. As is the case with much economic geology research, geophysical characterization has historically focused on direct detection of deposits and not the alteration envelope, or footprint, in which the deposit is contained. Chopping (2008) attempted to define the geophysical signature of the larger alteration footprint of several deposit types. Whereas the work was technically encouraging for the deposits studied, it is not clear how well these results can be extrapolated to other terranes. Although more work is required, the expectation is that some deposit types will have a mappable and recognizable extended signature, or footpath, proximal to the primary deposit that is both a vestige of the fluid-flow pathways and the tectonic events that led to the formation of the deposit. Other deposit styles are likely to be less distinctive. As noted earlier, the preservation of the mineral system from either erosion or retrograde alteration (either of which would in effect mask the pathfinder attributes of the footpath) is required to build a forensic case that a mineral system signature can lead to the discovery of a deposit.

False positives are a major problem that has challenged the users of geophysical techniques since the inception of modern geophysical practice. From the 1950s to the 1970s, the low cost of drilling shallow holes was likely the unglamorous, but critical factor, in the successful use of airborne EM to locate VHMS deposits in Canada. Targeting deposits under deeper cover will lead to more false positives due to the expected subtle nature of deposit and footpath responses and the depth of origin of the deposit and/or footprint. Therefore, reducing the cost of drilling during exploration is critical (Hillis et al., 2014).

A long-standing problem in the exploration industry is that, due to limited time and fiscal resources, field trials of new approaches are typically conducted over too few situations to properly understand the full range of responses likely to be encountered. Too often, an early sign of a diagnostic response is taken as a "global" positive and the expectation then is that the positive response will occur over similar targets in similar geologic environments. How unique the response is will only be realized through systematic assessment of the new approach that investigates the full range of responses in the "real world." Typically one company (often an early player) lacks the patience to undertake the full range of investigations required to master a new approach and it is left to more cautious companies who come in later and build on other's experience.

Although the topic of mineral systems has been discussed over the last two decades, efforts to incorporate the concepts during exploration under cover are new. However, major efforts to address the challenges of exploration undercover are now underway in Australia (Australian Academy of Science, 2010) and Canada (Galley et al., 2014), and therefore there will be a steady stream of information and ideas that can form a critical body of knowledge from which explorers can draw.

The Back Story

The curse of the silver bullet

Modern exploration geophysics has had to live with the curse of the "silver bullet" (effortless or "magical" solution) almost since its inception in the decade that followed World War II. The likely culprit for this attribution was the apparent magical way in which deposits could be mapped from the air, a capability never before dreamed of, even in science fiction. Some explorers consider geophysics to be a technology discipline that assists exploration. However, others accept that geophysics needs to play a bigger role if the industry as a whole is to regain its status as a preferred investment vehicle.

One senior member of industry stated the following: "We need a paradigm shift in exploration and exploration technology. Where is the equivalent of 3D geophysics that they've got in oil and gas? We haven't got that in our business. Why not? " (Pierre Lassonde, Chairman Franco-Nevada Corporation, 2013, oral commun.; from Keen, 2013).

Invoking the need for a "paradigm" shift in technology is one thing, but making such "tall leaps" is limited by physics as much as funding and ideas. Invoking the petroleum industry as a worthy role model is fine, but a lot of the important characteristics of petroleum deposits are easier to define with geophysics than can be achieved in most hard-rock settings. In part, this is because the energy industry has invested a huge amount of funds over many decades to develop both an acquisition technology infrastructure and the petrophysical understanding that far exceeds the commitment of the minerals industry. Whereas different in the past, mineral companies currently spend little on developing new exploration technologies, preferring to let the service sector take the lead in providing new technology to the marketplace.

After over 60 years of the development of geophysical methodology for minerals exploration, the invocation of silver bullet approaches should be abandoned. However, the desire at the societal level for "quick fixes" is strong and the exploration community is no exception. As exploration turns to deeper targets with greater attendant discovery and exportation risk, silver bullet enthusiasts will remain part of the environment.

The inventory

The geophysical technologies available in the future for the search undercover will largely be the same ones currently in the marketplace. Some changes may occur that relate to developments in drilling and the ongoing efforts to provide a suite of logging tools that operate downhole while drilling is ongoing. While these have some similarity to what the oil industry uses, it remains to be seen if an equivalent set of technologies can be developed and deployed in mineral exploration at a reasonable cost to the industry. Historically, downhole logging or acquisition of physical properties has generally not had much support within the exploration community. The exception is in brownfields applications where there are numerous wells and a close linkage can be forged between geophysical results and improvement in mining efficiency (reduced risk and improved profitability).

The field of ternary data processing is steadily advancing. Ternary refers to the value-added processing performed subsequent to the processing associated with the initial data acquisition, which is then followed by the reduction of the data into industry standard formats. These first two levels of processing are typically the domain of the equipment service providers and often involve the use of proprietary software that the service groups have developed to support their systems. The development of software to perform ternary processing, typically characterized as modeling and visualization, is divided between universities and software service companies. A major focus of these development efforts in the past 20 years has been to transform geophysical responses into quasigeologic sources (Oldenburg and Pratt, 2007).

Although there is no accurate tracking of improvements in technological capability and discovery outcomes, the overall trend of declining significant discoveries suggests that the advances in geophysical technology in general (defined here as acquisition, processing, and visualization) are not influencing the discovery performance in a measureable way. Examination of the discovery record by some authors over even longer periods of time suggests that the use of geophysical approaches has in general had little positive impact on the discovery record (Sillitoe, 1995). A cautious statement could be that geophysical technology has made a good contribution in the brownfields and production settings, but the record in the greenfields environment is less impressive.

The reasons for this are deemed complex but human factors relating to the implementation of technology are considered to have a much stronger control on the successful use of technology than is generally believed. In the oil and gas industry, there is an emerging awareness that the interpretation of geoscience data seriously lags technology associated with the acquisition of data (Eastwood, 2011; Heron, 2011) and this is having a measureable impact on the industry's discovery performance. The interpretation process has to deal with how well both individuals and groups interact with information and each other. With the major restructuring that has taken place in the minerals industry over the past two decades, the work environments of many people have become suboptimal to challenges faced with ever increasingly complex technology. The major issue is the decreasing amount of quality time (termed "soak time" by Heron, 2011) that the geoscientist has to think about complex data sets.

In the major mining firms, most groups are supporting fewer professional staff (including geophysicists), with far fewer technical and support staff than were commonly part of these groups 20 years ago. Time lines for projects are typically shorter, survey acquisition rates for many techniques are prodigious, and the professional staff is now required to spend time (as a priority) on issues such as contractor safety, as part of changes in corporate priorities across the mining industry. Such requirements have eroded the available time for carrying out geoscience work, resulting in an inevitable decline in achieved results. There is no simple answer because the minerals industry seems overwhelmed about how to deal with the human resources issues on virtually all fronts (Doggett, 2006, 2007).

Going forward, the expectation is that exploration technology will continue to advance, since this part of the business is largely driven by commercial competition among the service sector for market share. The human factors side of technology deployment appears to be the weak link but the industry is not well prepared to address this issue.

Current technologies

The current roster of geophysical techniques includes four major categories: potential fields, EM, electrical, and seismic. A good up-to-date review of these techniques is provided in Dentith and Mudge (2014). Table 2 summarizes these techniques and provides some guidance as to how these techniques can be employed. Airborne techniques are most effective for regional assessments (i.e., mapping). Ground and borehole techniques are more costly per unit area surveyed and tend to be limited to deposit-scale targeting investigations. The data acquired with airborne techniques such as EM and electrical methods can be depth limited due to the dynamic sampling (limited sample times) possible in an aircraft. Examples of using these various techniques are provided in the case studies that are examined in later sections of this paper.

The successful application of any technique relies on the presence of a contrast in the physical property to which the technique responds. Physical property measurements are commonly used to better understand the variations reflected in the geophysical data. Unfortunately, most physical property investigations are focused on either very anomalous samples associated with a mineral deposit (the economic part of the deposit or a closely associated gangue alteration) or on background rock samples that have not been affected by the mineralization process. Little effort has been made to define the petrophysical character of what would be termed the footprint (immediate environment) rocks, let alone the footpath.

In some cases, good access to a reasonable suite of rocks on which to perform physical property tests has been possible (Chopping, 2008). However, due to both economic reasons and a lack of understanding of a mineral system as a whole, most samples will be restricted to the rocks within deposits and footprint environment.

Building the petrophysical story of the whole mineral system will most likely involve a blending of actual measurements with laboratory studies and numerical modeling of rock properties. These collective inputs will then need to be assembled into a large numerical model of the earth, which can allow for the simulation of the entire mineral system. Initially this model will likely be a static "as is now" but it should be possible to build a dynamic model that allows for the entire life cycle of the mineral system to be modeled and better understood. This level of sophisticated 4-D modeling is becoming common place within the oil and gas industry (Fehler and Keliher, 2011; Li, 2013).

Human capacity

The challenges of finding mineral resources undercover are coming at a pivotal time in the exploration industry. The minerals industry, similar to the oil and gas industry, is experiencing a shift in demographics, which has been referred to as the "Great Crew Change" (Doggett, 2006, 2007). Essentially, this is the period between now and ~10 years from now when the Baby Boomers (those born shortly after World War II from

TABLE 2. Geophysical Technologies: Summary of Primary Geophysical Techniques and Their Applicability to Mapping Mineral Systems

Methodology	Technique	Airborne	Surface	Borehole	Marine
Potential fields	Magnetics	X	X	X	X
	Gravity	X (limited bandwidth)	X	X	X
EM	Active source	X (limited bandwidth)	X	X	Limited
	Passive	X (limited bandwidth)	X	?	Limited
Electrical	Resistivity	Ø	X	X	Limited
	Chargeability	X (limited bandwidth)	X	X	Limited
Seismic	Seismic	Ø	X	X	X

Notes: X = common practice, Ø = not applicable, ? = uncertain application about 1946–1964) who have built and driven the exploration industry for the last 50 years will no longer be active. This would not pose a problem if suitable experienced workers were currently being trained in the industry, but this is not the case. In addition, the number of new graduates entering the field is relatively few. More on-the-job education and mentoring of younger geoscientists are required.

Using the most recently available figures, in 2010 the western exploration industry spent roughly $US553 M on geophysical surveys, or just under 5% of the total estimated global exploration expenditure for that year (Doggett, 2013). In addition, there were an estimated 1,000 geophysical professionals (Fig. 2) to oversee this work (Witherly, 2012). The majority of these geophysicists were employed by data acquisition companies. The number of geophysicists who are actively engaged in general exploration through survey design, supervision, processing, and interpretation is less than about a third of the total employed geophysicists. Professional geophysicists are likely only involved in about one- to two-thirds of the assessments of geophysical surveys. The bulk of the current geophysical work is directed toward defining discrete deposit responses (targeting), and if exploration undercover increases significantly in the next 5 to 10 years (with increased emphasis on defining footprints and footpaths), the industry would be considerably stretched to cope with this change in emphasis, both in terms of technical and commercial focus.

The expectation is that the industry will have to turn to the universities to generate more of what would be described as multitalented geoscientists. These would be graduates with a fundamental understanding of both economic geology and the geophysical techniques needed to explore for deposits. While the oil and gas industry accepts the need to do a large amount of in-house training of young explorers, the mining industry is no longer capable of doing the level of required training on an in-house basis. Facilities and experienced professionals who can provide training within the exploration industry are very limited and by and large driven by Baby Boomers who are withdrawing from the active workforce.

Funding

Considerable work remains to develop a set of technologies and procedures (best practice) that will allow explorers to work cost effectively undercover. The funding source(s) for this work remains unclear. Junior companies (supported largely by speculative investors who take equity in companies) have contributed about 50% of the $US80 B spent on exploration in the past decade (Doggett, 2013). During the past decade, very little of this money was invested in supporting geoscience and now little of this is left to even support the companies themselves. Major companies (defined as those who pay for exploration from earned income) have reduced expenditures on exploration technology due to general fiscal constraints implemented in the last few years, but also due to the perception that in large part research projects have generally failed to capitalize on the outcomes of supported research and development efforts.

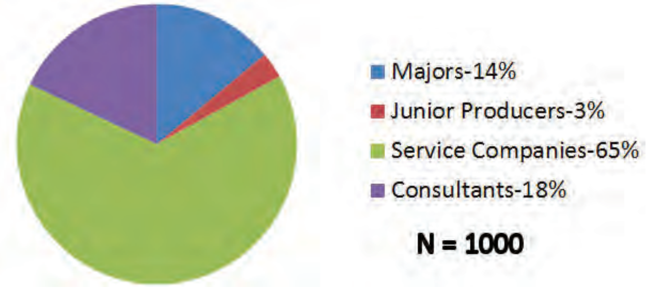

FIG. 2. Estimate of areas of employment for geophysicists in the minerals exploration industry (total population ~1,000) in 2012 (excludes China and Russia; from Witherly, 2012).

The paradox has been that while major companies have historically made significant investments in new geoscience knowledge and technologies, they have found it difficult to turn the new knowledge into effective workflows away from their actual production environments. Going forward, the concept that revenue-generating companies will fund exploration by external groups is not new. However, helping such groups by funding the development of new technologies is not a model that has been accepted in the past, but going forward it may have to be considered. If an industry leader such as Lassonde were to create a "technology challenge" to significantly improve a critical technology area, then possibly the calls for a silver bullet would fade and real progress could be made with regards to the challenges the industry faces.

Governments at different levels have made major investments in geoscience knowledge but have generally hesitated at direct investment in new technology, possibly believing that this would upset the level playing field they try to maintain between themselves and their user base. The expectation is that governments will continue to focus on primary geoscience data acquisition as this is close to supporting a level playing field with a broad range of players. What is expected to change, however, with the undercover story growing in importance, is that the style of geoscience infrastructure will be changing and more baseline, hard data in greenfields areas will be needed to lower the risk of exploration by the private sector. This would include more systematic seismic and magnetotelluric (MT) traverses, and drilling to well below likely target depths to define the overall search area for new deposits in 3-D. The combining of these data sets as well as processed potential field data to produce "work in progress" 3- and 4-D models of terranes will be in effect the next generation GIS package that explorers will expect and need to then define their programs. Groups such as the South Australian Geological Survey are undertaking some of these initiatives (Tyne, 2013), including the direct fiscal support of drilling by the exploration industry.

The service sector has always been cautious about injecting large amounts of funding into new technologies and much prefers to invest in incremental improvements to their existing capabilities because this is a low-risk method of providing a positive return in a suitable time frame. Service groups see little upside in taking a large amount of risk on either development or deployment of new technology unless there is some guarantee of fiscal security in the event of unexpected outcomes. However, the end-user community is typically loath to consider this level of support.

Overall, funding of new technologies and the time and cost of developing new processes using these technologies remains a major issue for the industry. The encouraging sign is that industry and governments seem to be aware of this issue.

Geophysical Signatures of Ore Systems

There have been a number of recent efforts at defining mineral systems for several major deposit styles. The examples provided below are from work on porphyry Cu-Au, Carlin-style Au, Athabasca Basin-style unconformity U, iron oxide-copper-gold (IOCG) (focusing on the Gawler craton of Australia), and VHMS deposits (focusing on the Abitibi of Canada). The examples highlight work in specific geographic areas, but the expectation and/or hope is that the lessons learned are fairly generic, and therefore, should be broadly considered in terranes similar to those described in the examples.

Porphyry copper deposits

Porphyry copper deposits have a well-understood genetic model and are among the most economically significant deposits. Typically they display robust subsurface signatures compared to most other deposit types, due primarily to their large size and wide distribution around the world (Seedorf et al., 2005). It is understood that their footprints are large, and by inference their footpaths are assumed to be as well, but far less study has been made of the footpaths of these systems. Given their size, direct detection to considerable depths is also more likely compared to deposits with smaller footprints and/or paths. The examples provided below show a mixture of direct detection and footprint and/or footpath recognition.

Bingham Canyon deposit: The Bingham Canyon deposit is located 26 km southwest of Salt Lake City, Utah. As of 2012, the reported resource was 835 million metric tons (Mt) at 0.48% Cu, 0.3 g/t Au, 2.10 g/t Ag, and 0.041% Mo (InfoMine, 2014). The oldest rocks are sandstones, quartzites, and limestones of late Paleozoic age (Fig. 3). The Oquirrh Mountains were formed between 60 and 135 m.y. ago. At about 30 to 40 m.y. ago, monzonite and quartz monzonite porphyry intrusions formed the Bingham complex, which was responsible for most of the copper-molybdenum mineralization (Kloppenburg et al. 2010).

Recently, regional aeromagnetic data have been used to better understand the geometry of the intrusive rocks associated with the Bingham Canyon deposit (Fig. 4A; Steinberger et al., 2013). Iterative 2.5-D modeling shows that a large

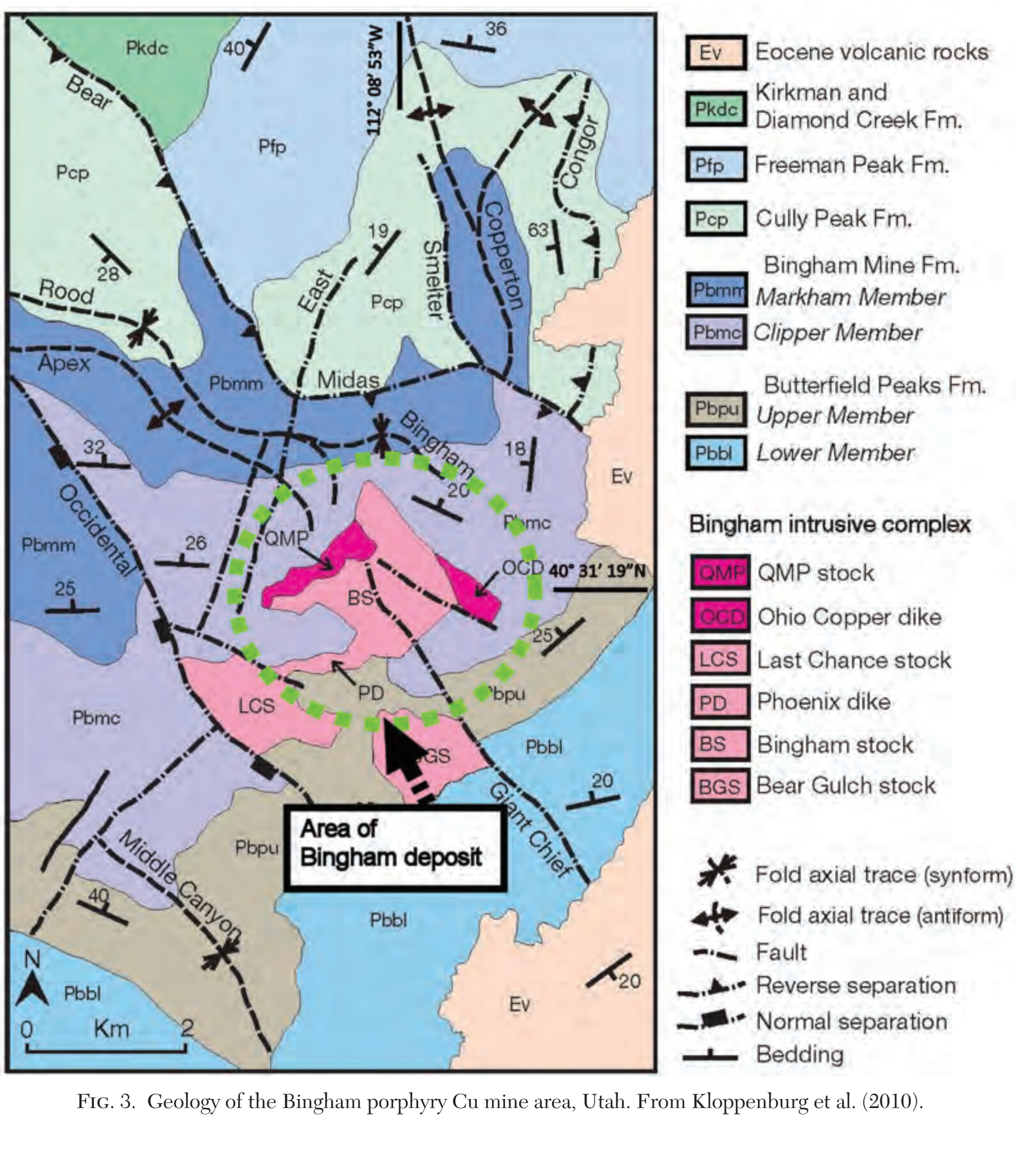

FIG. 3. Geology of the Bingham porphyry Cu mine area, Utah. From Kloppenburg et al. (2010).

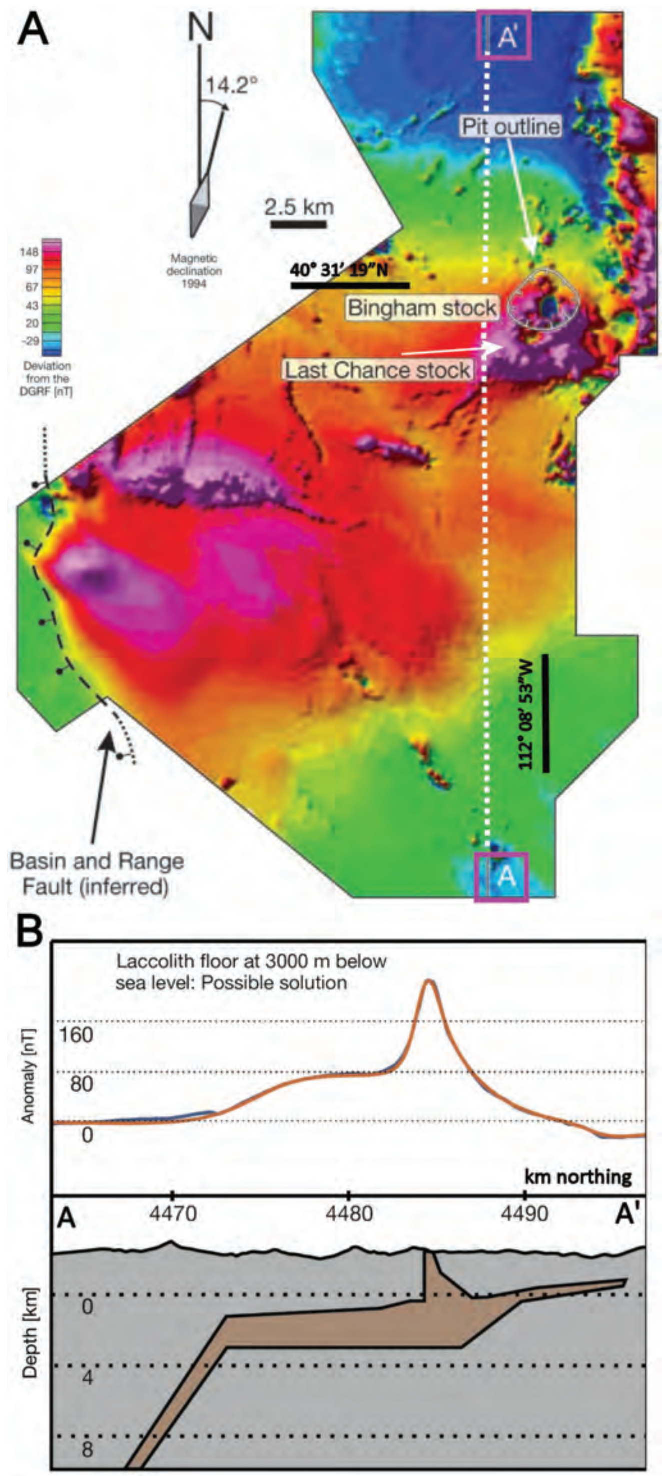

FIG. 4. A. Image of parts of the aeromagnetic anomaly (reduced to pole with definitive geomagnetic reference field (DGRF) subtracted) over the Oquirrh Mountains and adjacent basins (Kennecott data). Print image is slightly distorted in nonlinear fashion so that scale and northing are approximate only. The Bingham Canyon suite is composed of the Last Chance stock (south) and the partly mineralized Bingham stock (north, ~pit outline), in which hydrothermal destruction of igneous magnetite causes a small strongly negative anomaly centered on the quartz monzonite porphyry. Modified from Steinberger et al. (2013). B. Cross section A-A′ of the modeled laccolith body under the Bingham deposit, with view to west; blue line is observed data; brown line is calculated. From Steinberger et al. (2013).

laccolith-shaped intrusion with an average thickness of 2 to 3.5 km may occur beneath the floor of the current open pit (Fig. 4B; Steinberger et al., 2013). The modeling supports the presence of several protrusions that emanate from the laccolith with one corresponding to the stock which hosts the Bingham deposit. Steinberger et al. (2013) suggested that the modeling was successful because the intrusive rocks had a much higher susceptibility than the intruded sedimentary rocks, and the original volcanic edifice had eroded. Based on the amplitude of the observed response (~120 nT), it is suggested that the same body could be seen another 1 to 2 km below the surface assuming that the same low susceptibility host rocks were present.

MT data were also used to understand the Bingham Canyon porphyry copper system at depth (Hinks, 2013). A large conductivity zone located downdip of the surface expression of the Bingham stock was observed at roughly 2.5-km depth. Drilling of this feature confirmed the mineralized quartz monzonite porphyry at this depth. The exact cause of the strong resistivity low (<100 ohm-m) is still unclear. A smaller, relatively shallow conductive feature was imaged to the east of the Bingham open pit. The feature was named the Lark and drilling indicated this feature was caused by the presence of volcanic rocks and a diatreme. Below the Lark, a new unknown zone of copper mineralization was encountered (Hinks, 2013).

Pebble deposit: The Pebble deposit (Kelley et al., 2013) is located ~320 km southwest of Anchorage and 27 km northwest of the village of Iliamna in Alaska, USA. It is one of the largest undeveloped porphyry Cu-Au-Mo deposits in the world, with measured and indicated resources estimated to be 5,942 Mt at 0.42% Cu, 0.35 g/t Au, and 250 ppm Mo (Lang et al., 2013). The oldest rocks in the district are the Jurassic-Cretaceous Kahiltna flysch. These rocks were intruded between 99 and 96 Ma by coeval granodiorite and diorite sills, followed shortly thereafter by alkalic monzonite intrusions and related breccias. Subalkalic hornblende granodiorite porphyry plutons of the Kaskanak batholith were emplaced at ~90 Ma. Similar, smaller granodiorite plutons were emplaced around the margins of the batholith and are related to Cu-Au-Mo mineralization (Lang et al., 2013). The deposit has been described as two zones (Pebble West and Pebble East) that are part of the same hydrothermal system. However, Pebble West is shallow (50 m below surface) and relatively lower grade than Pebble East, which is at least 300 to 600 m below surface (Kelley et al., 2013).

The cover at Pebble East consists of volcanic and sedimentary rocks of late Cretaceous to Tertiary age, whereas Pebble West is overlain only by glacial sediments (Lang et al. 2013). Several ground and airborne geophysical methods including magnetics, IP resistivity, and EM (MT, Spectrem, and ZTEM) have been used to characterize the deposit and explore for additional resources in the district (Bedrosian et al., 2009; Pare and Legault, 2010, Anderson et al., 2013; Shah et al., 2013).

Regional and detailed aeromagnetic data over the Pebble deposit and surrounding terrane have been used to better understand the geology (Anderson et al., 2013). These data show that the Pebble deposit is not in itself particularly magnetic (Fig. 5). The total magnetic intensity reduced to pole

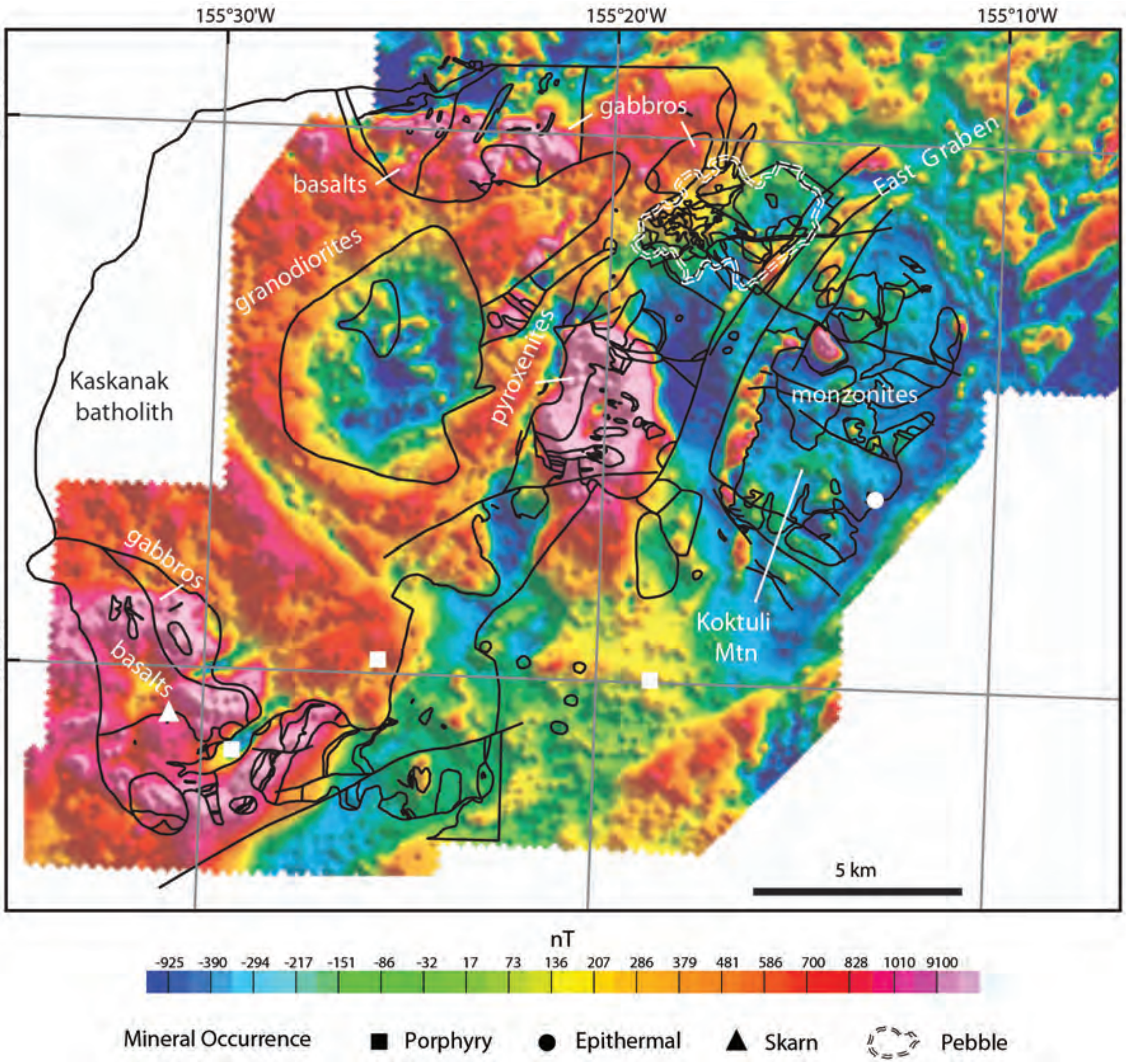

FIG. 5. TMI-RTP aeromagnetic map of the Pebble district from Anderson et al. (2013), superimposed on structures and contacts (black lines) from Lang et al. (2013).

(TMI-RTP) method used in Figure 5 removes the dipolar effects of variable magnetic inclination; there is a close spatial association between the deposit and associated magnetic intrusive rocks. At the regional scale, there is a string of magnetic highs representing intrusive centers with potential for hosting mineral systems similar to the Pebble deposit (Fig. 6; Anderson et al. 2013). The corridor of highs is defined as a footpath or favorable corridor with discrete footprints representing the (magnetic) intrusive centers (Fig. 6). These anomalies were further investigated using 3-D magnetic inversions (Anderson et al., 2013). The results showed that the causative geology consists of highly magnetic material that continues to depths of greater than 8 km.

IP resistivity surveys conducted over the Pebble deposit extend a considerable distance to the north and southwest of the deposit. The IP chargeability (Fig. 7; Rebagliati and Payne, 2006) shows a major zone of elevated response almost 9 km in strike and 4 km wide, within which the Pebble deposit is situated. Given the size and intensity of the footprint (interpreted to represent the overall extent of the alteration system associated with Pebble), it is suggested that a similar system buried at a depth of between 1 to 1.5 km below the surface would still be detectable. The chargeability response shows a high to the north, west, and south of the Pebble West zone (Fig. 7). It is assumed that initially the feature may have wrapped entirely around Pebble West but the eastern margin has been downdropped and is now covered with Tertiary rocks. Several of the other chargeability highs are spatially associated with porphyry mineralization to the southwest of Pebble.

A series of MT traverses were carried out around the Pebble deposit (Shah et al., 2013) and these results were used to build a 3-D conductivity model of the deposit area. An image of the subsurface conductivity at –600-m depth shows two major low resistivity zones (Fig. 8A)—one to the northeast of the Pebble deposit and a smaller zone along the southern edge of the deposit and extending to the south. Pebble West appears as a resistivity high and this is thought to be caused by the presence of relatively unaltered intrusive rocks in the core of Pebble West. The northeast conductive zone appears to be

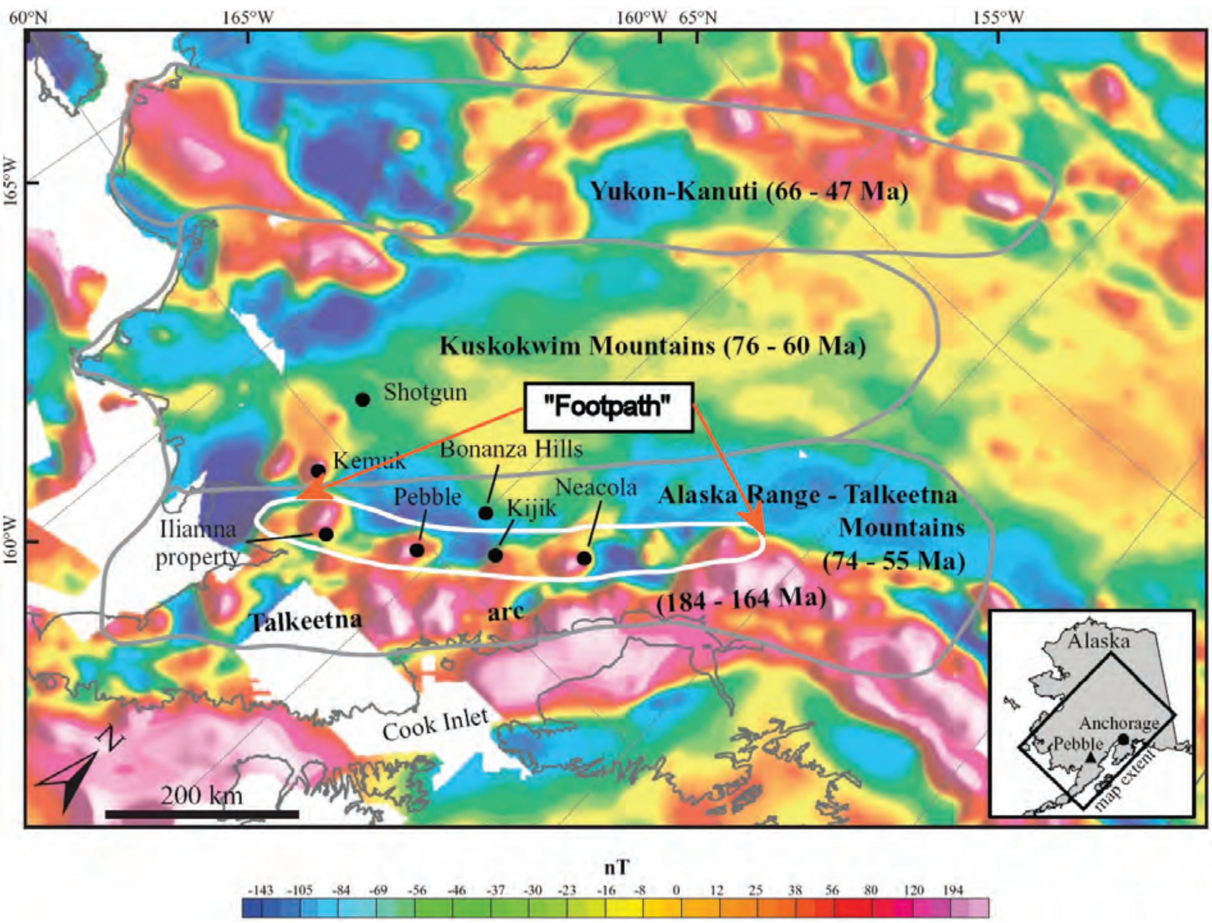

Fig. 6. Aeromagnetic map of southern Alaska. Trends outlined by white line are upward-continued magnetic anomalies with similar signature to the Pebble deposit and defined as "footpath;" modified from Anderson et al. (2013).

possibly related to conductive lithologies or a laterally extensive alteration zone (Shah et al., 2013). The southern central resistivity low appears to be more likely related to a fault zone that trends north-south. Given the position and orientation of this feature, it could be a reflection of the structure along which Pebble East was downdropped with respect to Pebble West.

An airborne variant of the MT technique called ZTEM (Lo and Zang, 2008) was flown twice over the Pebble deposit; the first survey was an orientation program in 2009 that covered the immediate area of Pebble West and East (Paré and Legault, 2010) and the second was a production survey over the district in 2011 (Holtham and Oldenburg, 2012). The ZTEM results showed considerable character in the conductivity structure in the upper ~1.5 km. An image of the 180-m depth slice below ground surface (Fig. 9A; Holtham and Oldenburg, 2012) shows a conductive ring around a resistive core that correlates with the pattern observed in the MT resistivity results (Fig. 8A). The ZTEM appears to have more resolution than that shown by the MT data but this can be attributed to two factors: the MT depth slice (–600 m) is much deeper, which results in an image of less resolution; and the ZTEM data were acquired at a much greater spatial resolution than that of the MT survey. When these factors are considered, the results are similar. Figure 8 illustrates the comparison in cross section between the MT (Fig. 8B, line 1) and ZTEM (line 2) results. In addition to ZTEM, Spectrem, which is the proprietary Anglo American Exploration time domain airborne EM system, was flown over the Pebble property (Paré and Legault, 2010; Paré et al., 2012). A conductivity depth slice for the entire survey at a depth of 150 m (Fig. 9B) is comparable with the ZTEM depth slice (Fig. 9A). Depth imaging along individual lines within the Spectrum conductivity data (Paré et al. 2012) shows more shallow detail than the equivalent ZTEM result; this is expected due to the lower effective frequency range of ZTEM compared with Spectrem.

Although the ZTEM technique has been shown to be capable of penetrating to ~2 km (Witherly, 2013a), this depth of investigation is achievable only in areas where there is no substantial conductive cover present. When conductive cover is present, the ZTEM's depth of investigation is typically a few 100 m, typical of most active source EM systems (Sattel and Witherly, 2012). The ground based MT technique would be required to penetrate such conductive cover; this is achieved by recording the MT signals to much lower frequencies than is possible with the ZTEM system, which is limited to ~30 Hz as the lowest recovered frequency.

Kemess: The Kemess North porphyry Cu-Au deposit is located ~430 km northwest of Prince George in British Columbia, Canada. The resource contains 300 Mt at 0.16% Cu and

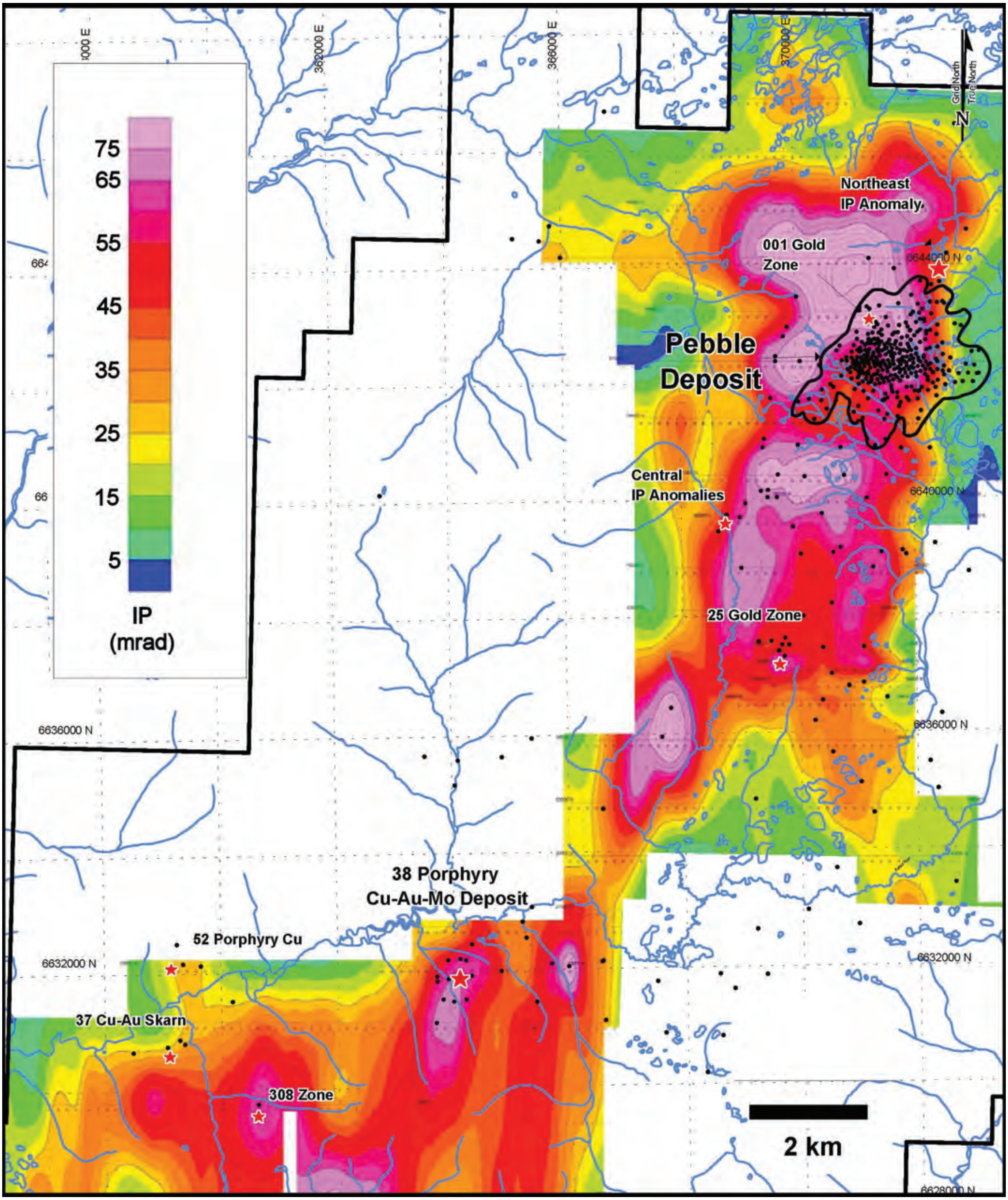

FIG. 7. IP chargeability over the Pebble property, from Rebagliati and Payne (2006).

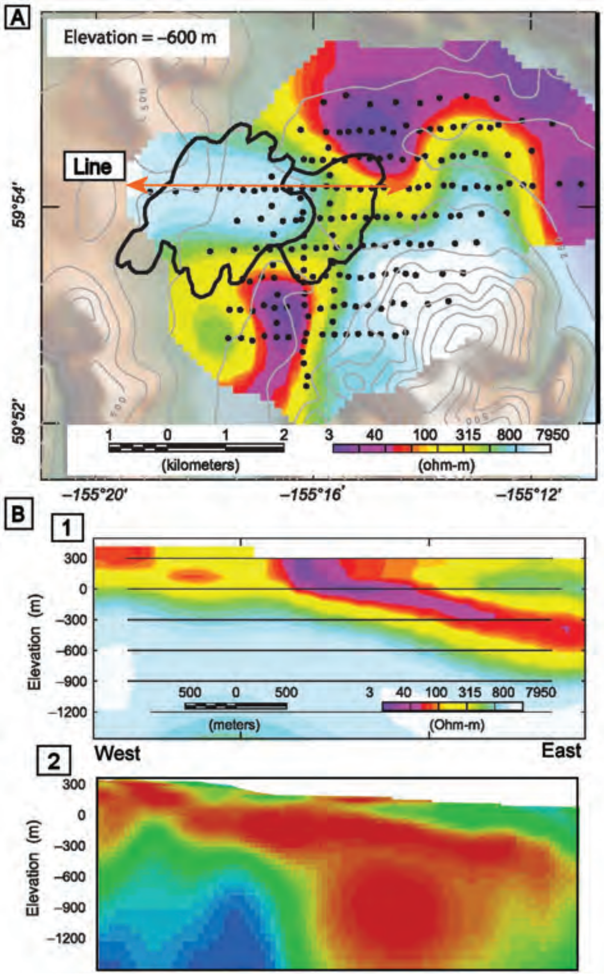

FIG. 8. A. Magnetotelluric (MT) resistivity (–600 m) depth over the Pebble deposit (from Shah et al., 2013). B. Resistivity depth slice sections over Pebble West and East: section 1 from Shah et al. (2013); section 2 from Condor Consulting Inc. (2010).

0.30 g/t Au. The deposit is situated in the Toodoggone district, along the eastern margin of the Stikinia terrane (McKinley, 2006). The Kemess North area is underlain by Upper Triassic (Takla Group) andesite/basaltic volcanic rocks and to a lesser extent Lower Jurassic (Toodoggone Formation) dacitic fragmental volcanics. Lower Jurassic stocks, dikes, and sills of quartz monzonite and/or quartz diorite composition intruded the Takla succession. Mineralization is genetically related to the ca. 202 Ma moderately SE-plunging Black Lake intrusion (locally termed the Kemess North diorite) and is also partially hosted by proximal Takla Group basalts (McKinley, 2006). The deposit area is transected by steeply dipping N- to NW-trending normal faults. Kemess South is a smaller deposit ~8 km to the southwest of Kemess North but has a higher gold grade and was mined in recent years.

The grade of the primary Kemess North deposit was too low to support a mining operation, but the area was still deemed prospective; however, given the structure in the area, other potential mineralized zones were presumed to be present at greater depths than Kemess North. IP resistivity surveying was regarded as the best exploration technique and a Titan survey was utilized to investigate the area northeast of Kemess North (Gharibi, 2013); the survey lines carried out are shown in Figure 10A, along with a basic outline of the major geologic units, superimposed on a TMI image. About 1.5 km northeast of Kemess North on survey line “TA,” a deep but strong chargeability zone was defined at a depth of ~700 m (Fig. 10B). Although the survey was a technical success, drilling showed the new target was low grade and hence subeconomic at this time. With the amplitude and size of the chargeability response noted from the new target, it is estimated that the feature could have been defined at a depth of up to 1 km in a similar geologic setting (Gharibi, 2013).

Resolution: The deeply buried Resolution porphyry Cu-Mo deposit is located in the Superior mining district approximately 100 km southeast of Phoenix, Arizona. The resource contains 1,624 Mt at 1.47% Cu and 0.037% Mo (Wikipedia, 2014). The deposit is hosted by a sequence of Cretaceous volcaniclastic and siliciclastic sedimentary rocks (Manske and Paul, 2002) that disconformably overlie older siliceous and calcareous sedimentary rocks and diabase (Fig. 11A). The sedimentary rock package is intruded by an E-NE–striking swarm of Late Cretaceous quartz porphyry dikes that are truncated by a basal Tertiary unconformity (Fig. 11A). The Mesozoic section is buried by 600 to 1,200 m of unmineralized overburden composed of the Oligocene-Miocene Whitetail Conglomerate and the Miocene Apache Leap dacite tuff (Manske and Paul, 2002).

An MT traverse was carried out over the deposit (McMonnies and Gerrie, 2007). The data have been modeled by what are termed unconstrained and constrained approaches (Fig. 11B, C). The unconstrained result is strictly a mathematical best fit to the data without any reference to apriori information, such as depths to various geologic units based on drilling. The geologically constrained inversion incorporates a priori information, but the degree to which the inversion is required to “honor” the constraint can vary depending in part on the confidence placed on the constraining information. Both models show a shallow resistive zone that correlates with the Apache tuff. Below that, a strong conductor is evident near the base of the Tertiary sedimentary rocks and correlates with the Whitetail Conglomerate (Fig. 11B, C). A pipe-like conductor that extends from the base of the flat-lying conductor to depth aligns closely with the porphyry stock and mineralized zone. The vertical conductive feature that appears correlative with the deposit lies at a depth of ~700 m below surface and the conductive unit above is 200 to 300 m thick based on the MT results. The unconstrained model shows a much wider vertical body compared to the constrained model. The cause for the vertical conductor is not known but it may be a clay alteration zone lying above the deposit (McMonnies and Gerrie, 2007). The Mesozoic sedimentary and intrusive rocks that host the deposit are moderately resistive.

Cadia: The Cadia district is located in central-western New South Wales, Australia. The district has produced over 44 Moz Au and 7.5 Mt Cu (Wood, 2012). Almost two decades of exploration in the district have shown that there are a number of porphyry systems at a wide range of depths, from outcropping to >500-m depth (Fig. 12). The mineralized stocks are associated with the Cadia Intrusive Complex that is Late Ordovician to Early Silurian and extends over an area of at

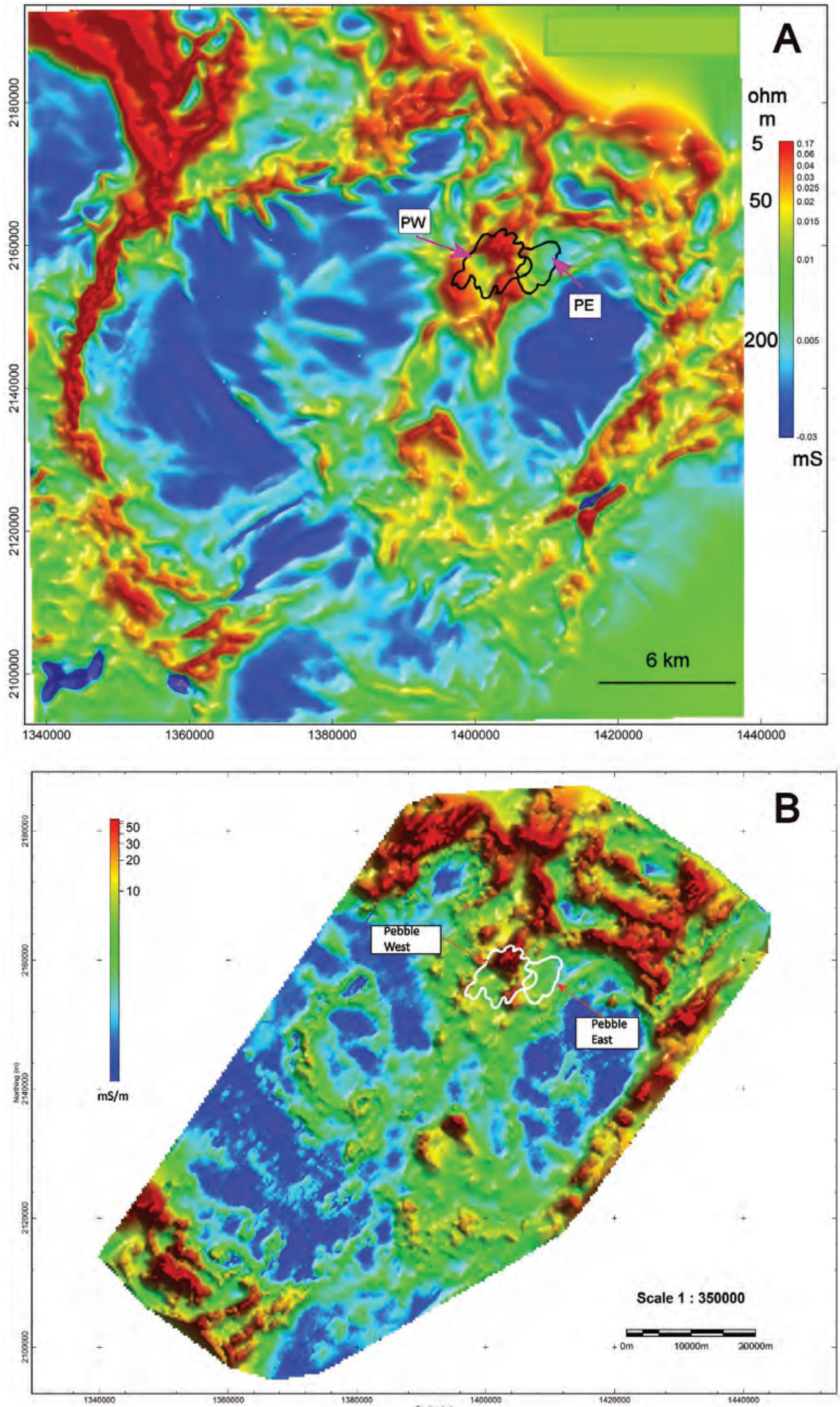

FIG. 9. A. Airborne electromagnetic ZTEM conductivity (–180 m) depth slice over the Pebble deposit area. From Holtham and Oldenburg (2012). B. Spectrem conductivity at –150 m below ground surface in the Pebble deposit area. From Paré and Legault (2010).

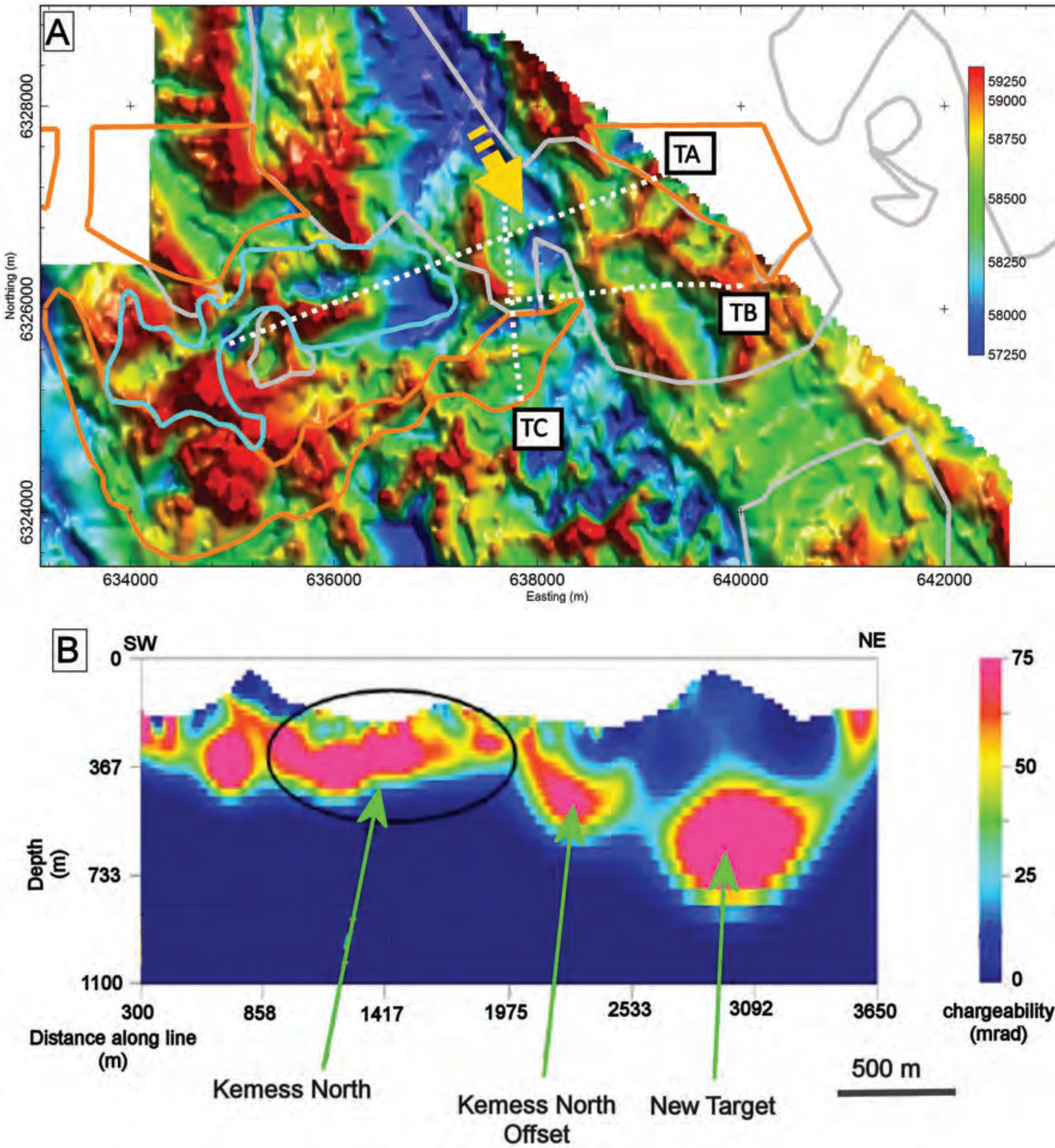

FIG. 10. A. Total magnetic intensity (TMI) map of the Kemess North porphyry Cu-Au deposit, British Columbia, Canada. Orange lines outline the Black Lake intrusion; blue lines are gossan that lies on top of the Kemess deposit; brown lines are dacite tuff. All other areas are underlain by basalt flows. Lines TA, TB, and TC refer to lines obtained during a Titan survey (line TA is shown in (B)). Geology modified from McKinley (2006); TMI from Shives et al. (2004). B. Preliminary Titan chargeability section, Kemess line TA; from Gharibi (2013).

least 6 × 2 km within the Ordovician Molong volcanic belt of the Paleozoic Lachlan fold belt (Holiday and Cooke, 2007). The Molong volcanic belt comprises limestone and a suite of intermediate to basic volcanic and volcaniclastic rocks and comagmatic intrusions. Mineralization styles include sheeted quartz veins, stockwork quartz veins, disseminated, and skarn deposits.

Aeromagnetic data show that a prominent magnetic anomaly occurs over the district (Fig. 13; Holliday and Cooke, 2007). These data directed the early-stage exploration drilling at shallow depths. However, interpretation of the data was complicated by the presence of multiple strong magnetic sources at both shallow and greater depths. The nearsurface sources include magnetic stocks, magnetic alteration of volcanic rocks, and skarn. There is an intense zone of magnetite destruction at depth associated with the Ridgeway deposit but the overlying magnetic features obscured this feature (Holiday and Cooke, 2007).

Two lines of IP data acquired over the property (Fig. 13) are shown in Figure 14; one line is a calibration line over the shallow Cadia East deposit (L1; Fig. 14A). When a similar response was obtained on L2 (prior to the discovery of Ridgeway), it was interpreted as a possible similar style of mineralization. This proved not to be the case, but rather it was

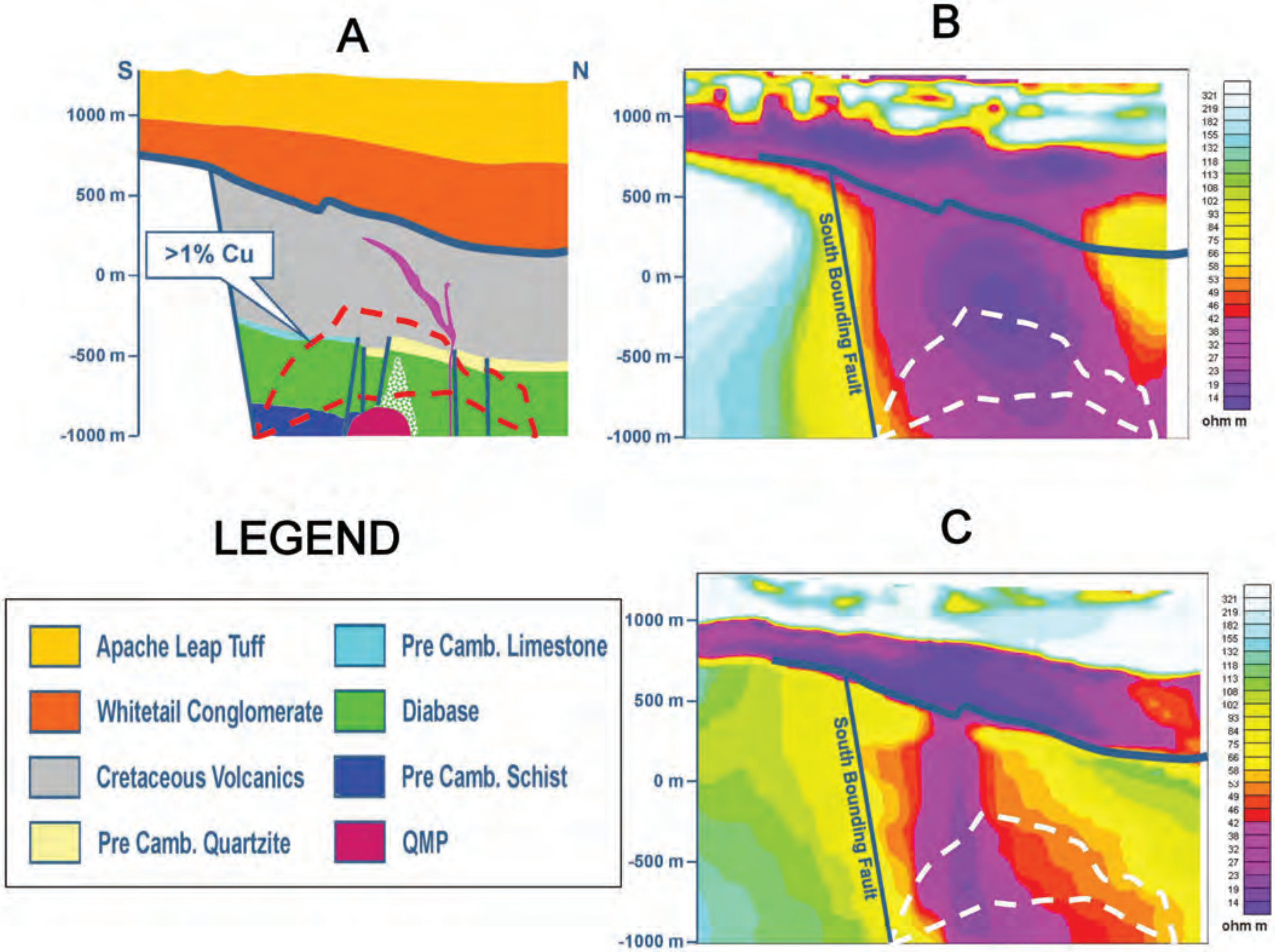

FIG. 11. Resolution Cu-Mo deposit, Arizona. A. Geologic section. B. Unconstrained MT inversion section. C. Constrained MT inversion section. Modified from McMonnies and Gerrie (2007).

later assessed that the response reflected a distal pyrite halo surrounding what later became known as the deep Ridgeway deposit. In fact, it was learned that the alteration proximal to the deposit was different than that observed at Cadia East and so although direct detection of the Ridgeway deposit was not achieved with the IP survey, the sulfide mapping assisted in understanding the alteration patterns, which in turn, resulted in the discovery of Ridgeway (Holliday and Cooke, 2007).

Escondida: The Escondida deposit and satellite systems in northern Chile have a measured resource of 4,069 Mt at 0.72% Cu (Basto, 2012), making it one of the largest copper deposits in the world. Escondida is a porphyry-style deposit that is associated with the emplacement of late Eocene-Oligocene quartz monzonite to granodiorite stocks that intrude Paleocene andesite rocks (Garza et al., 2001).

A regional TMI aeromagnetic image over Escondida is shown in Figure 15A (from Behn et al., 2001). Two large batholithic-type sources are located north and south of Escondida and its companion deposit Zaldivar. Escondida, Zaldivar, and the Chimborazo deposits are located within a ~17-km NW-SE–trending zone of discrete and semidiscrete highs and lows. A TMI-RTP image of the aeromagnetic data is shown in Figure 15B (Witherly, 2013b). There is a large zone of magnetic highs that trends ~N 65° E and encompasses Escondida North (E) and the Pampa Escondida (PE) deposit that lies between Escondida and Escondida North/Zaldivar (ENZ). Escondida itself appears to lie within a relative low with the pit outline bounded by higher magnetic response to the northwest and west (Fig. 15B). This suggests that a major magnetic source (possibly a deep-seated intrusion) is associated with the porphyry cluster; local variability in magnetic response is likely due to differences in the composition and alteration history of the different intrusive events (Garza et al. 2001).

Two IP resistivity surveys were conducted at Escondida; a single line (IP line 1) through the known deposit (Zonge Engineering and Research Organization, 1982) and a reconnaissance induced polarization (RIP) survey (Kennecott Chile S.A., 1985), which covered a larger area around Escondida and to the northeast. The dominate feature on IP line 1 is the very low resistivity source centered over the deposit (Fig. 16A). While the observed response shows a dipping source (Fig. 16C), 2-D modeling suggests that a more flat-lying body is the causative source (Fig. 16A). This conforms closely to

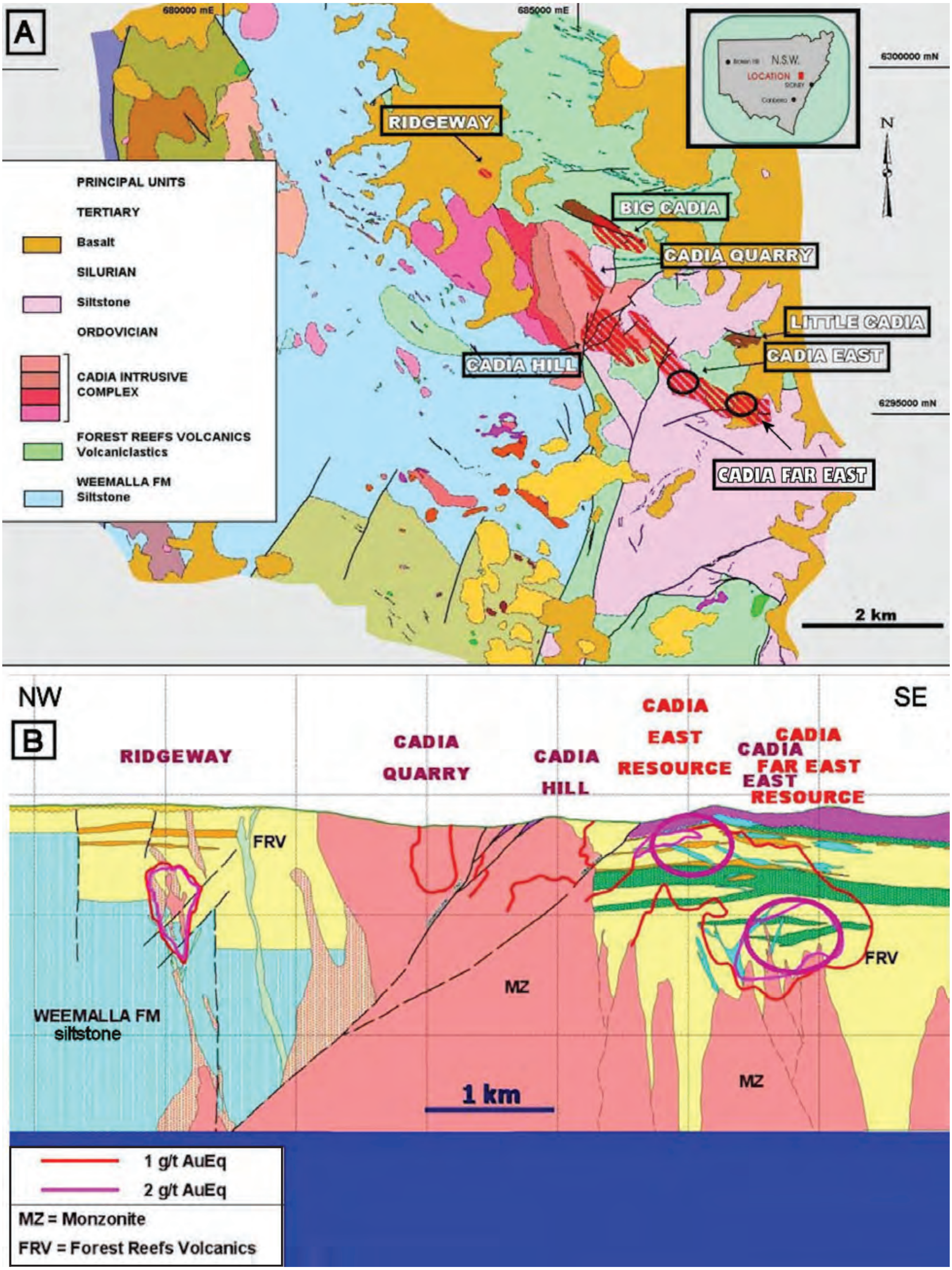

FIG. 12. A. Geology of the Cadia area. B. Long section from northwest to southeast of the Cadia district. Several porphyry deposits are known, from those cropping out at surface to >500-m depth. From http://www.datametallogenica.com/pages/minidisc/html/cadia_files/cadiadistrict-mapsect/page.html.

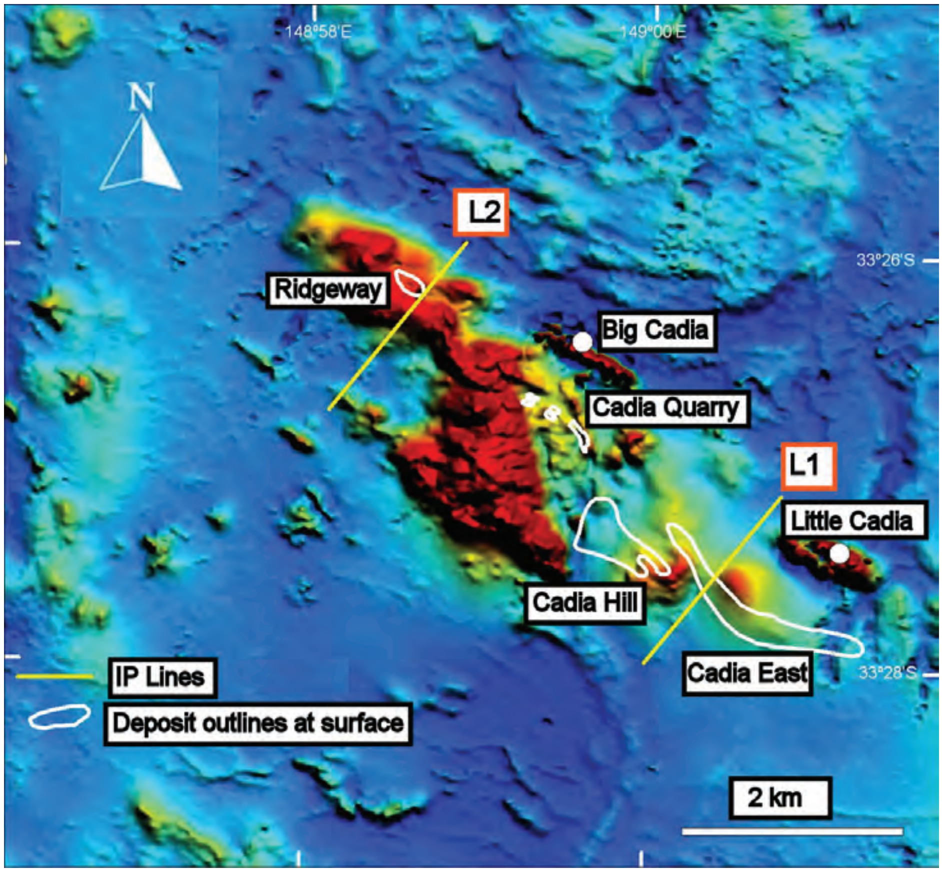

FIG. 13. TMI-RTP of the Cadia district. The locations of two IP lines (L1 and L2), illustrated in Figure 14, are shown. Modified from Holliday and Cooke (2007).

the shape and depth (~200 m below surface) of the supergene blanket over the intrusive system (Garza et al., 2001). The chargeability results show some shallow anomalies that appear to be related to the conductivity source (Fig. 16D). The RIP resistivity survey (Fig. 17A) shows a strong feature that is <10 ohm-m about 2 km in strike length located along the southern edge of the pit. The 20 ohm-m contour extends both northwest into the pit and southeast into areas of unknown geology. The chargeability (Fig. 17B) shows a central high of >30 m centered over the southwest part of the pit. This zone appears to trend north-northeast, on-strike with Escondida North. The chargeability feature associated with Escondida is not considered particularly diagnostic, possibly due to the difficulties acquiring good-quality data to the depth where fresh sulfides would be present (~250–300 m). The strong resistivity low is thought to be at least in part associated with the supergene blanket. The reason for the displacement of the conductivity response to the southeast of the deposit center is unclear. Subsequent ground EM over Escondida North mapped the secondary blanket associated with this deposit with a high degree of spatial definition (R. Nickson, per. commun., 1996).

Carlin-type deposits

Geophysics has not historically proved to be a major component in the exploration for Carlin-type deposits. Wright and Lide (1999) provided a good review of how a variety of techniques can be applied at the targeting scale for deposits in northern Nevada. However, even the most prolific terranes become exhausted of near-surface and easy to discover deposits and explorers will be required to develop new strategies to explore at greater depths. Given the difficulty in defining a unique set of targeting attributes for this type of deposit, greater attention is being paid to mapping the lithologies and structures that are deemed permissive for hosting mineralization. A good review of these approaches can be found in Townsend et al. (2011). High-resolution seismic reflection appears to be a promising geophysical method (Fig. 18). These data map stratigraphic layers at depth and they have the inherit advantages of acoustic imaging methods in that they maintain resolution to great depths, unlike potential field, EM induction, or DC resistivity approaches, which all lose resolution when the sensor is farther from the source or target.

Another major challenge in the search for Carlin deposits in Nevada, which affects other areas as well, is the presence of near-surface heterogeneity. In Nevada, the younger Basin and Range tectonics have resulted in major changes to the upper several kilometers and these can have a strong influence on the observed geophysical responses. Also, one of the critical aspects of the emplacement of Carlin deposits is the presence of long-lasting structures, which by their nature are favorable conduits for intrusive events, structural movement,

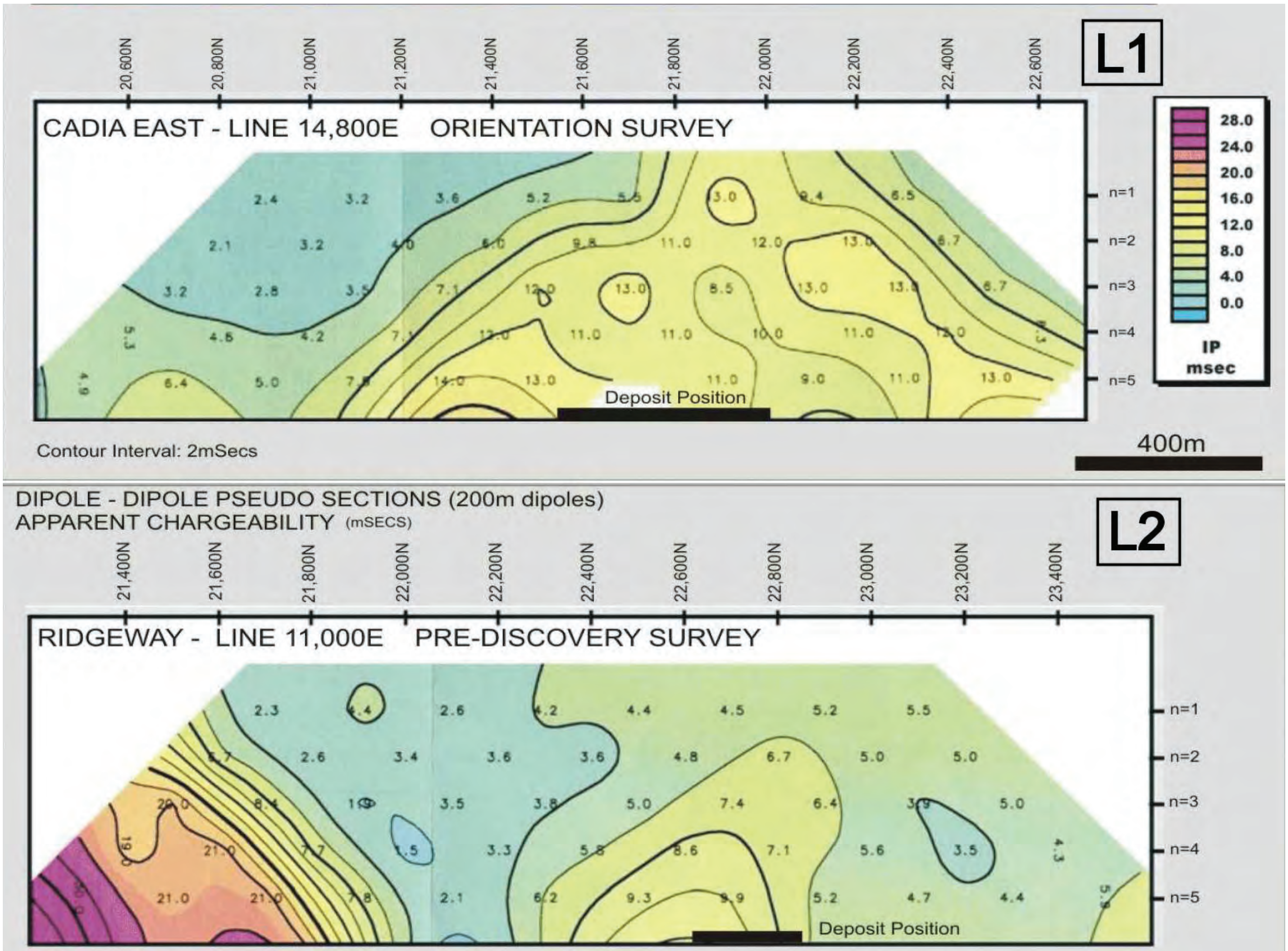

Fig. 14. IP chargeability lines through the L1 Cadia East deposit and L2 Ridgeway deposit (see Fig. 13). Modified from Holliday and Cooke (2007).

or hydrothermal fluid flow over time (Grauch et al., 1995; Ponce and Glen, 2002). This implies that the typical deposit setting has been subject to many events that commonly have very similar geophysical expressions as the actual event that produced the ore system.

Athabasca Basin unconformity associated uranium deposits

The Athabasca Basin (Saskatchewan, Canada) is host to approximately 33% of the world's current production of uranium and contains the known highest grade uranium deposits (Delaney, 2013). In the Athabasca Basin, the deposits are generally located at or slightly above or below the unconformity between the late Paleo- to Mesoproterozoic conglomeratic Athabasca sandstone and the Archean basement (Fig. 19). In general, metal-rich fluids are focused along basement structures and precipitate uranium-rich minerals when such fluids mix with circulating meteoric water. In almost all cases, the uranium mineralization is associated with conductive graphitic or pelitic horizons (Jefferson et al., 2007). Airborne and ground EM techniques have been a critical tool in the detection and mapping of the graphitic horizons.

Much of the exploration activity in the past decade has been driven by improvements to airborne EM technology in an effort to explore for basement conductors under greater thickness of sandstone. The MegaTEM airborne EM technology developed in the late 1990s (Smith et al., 2003) was successfully applied to exploration in the Athabasca Basin in the early 2000s. In the mid-2000s, popularity increased for the new VTEM helicopter time domain EM system with an improved signal/noise and spatial resolution compared to MegaTEM (Witherly and Irvine, 2006). The ZTEM system that was introduced in 2008 (Legault et al., 2009) is thought to have the capability to map basement conductors to a depth of 1 km or more. An example of the ZTEM and the MegaTEM response over a conductive zone at 825-m depth is shown in Figure 20. Evident from this example is the fact that the signal/noise of the basement conductive features for the ZTEM is much higher than that obtained with the older MegaTEM system. Thus, the ZTEM method results in better detection of marginal features and some features not previously identifiable can possibly be identified. As a consequence, explorers would have more confidence when drill targeting features at depth.

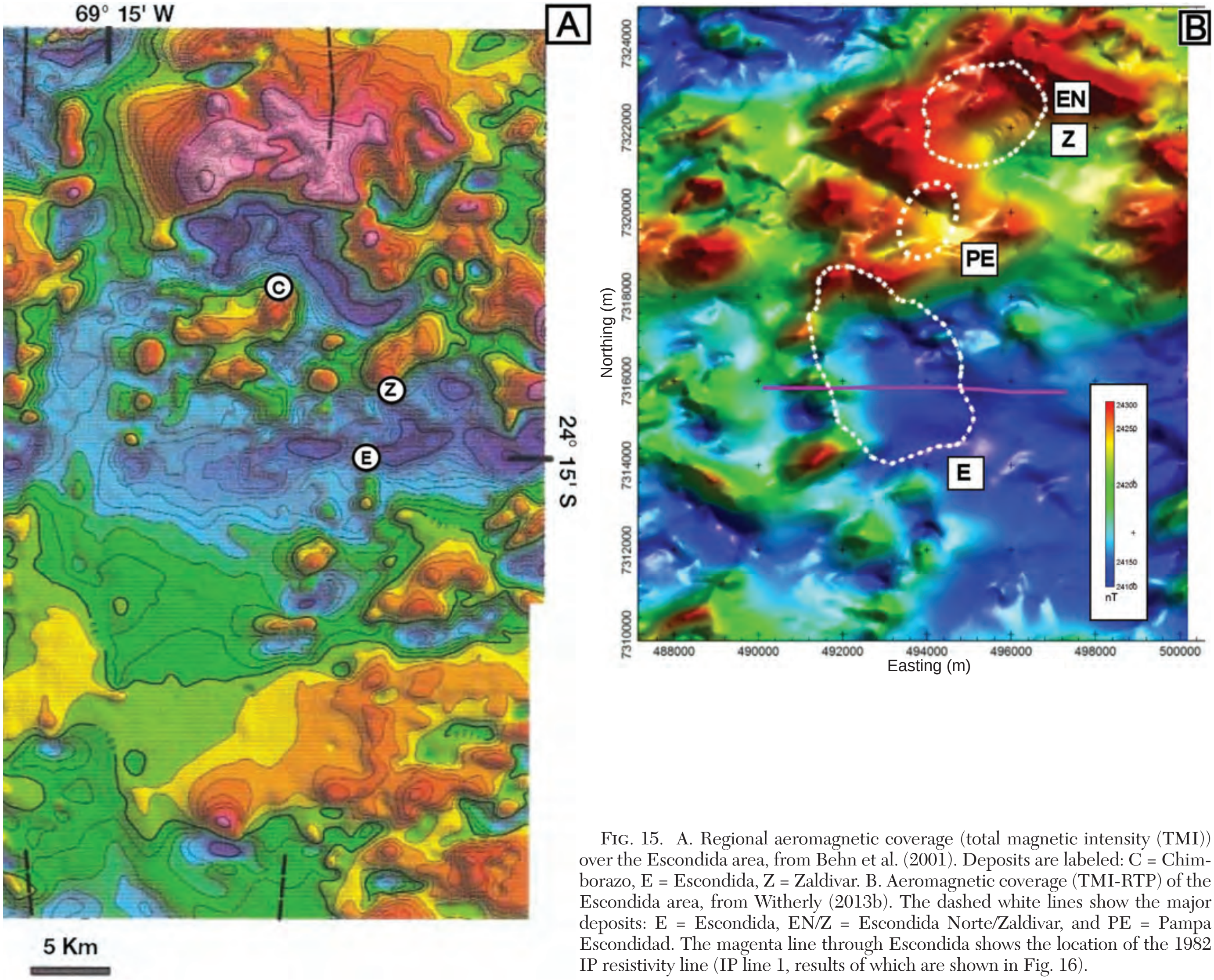

Fig. 15. A. Regional aeromagnetic coverage (total magnetic intensity (TMI)) over the Escondida area, from Behn et al. (2001). Deposits are labeled: C = Chimborazo, E = Escondida, Z = Zaldivar. B. Aeromagnetic coverage (TMI-RTP) of the Escondida area, from Witherly (2013b). The dashed white lines show the major deposits: E = Escondida, EN/Z = Escondida Norte/Zaldivar, and PE = Pampa Escondidad. The magenta line through Escondida shows the location of the 1982 IP resistivity line (IP line 1, results of which are shown in Fig. 16).

As explorers have found, mapping conductors alone do not constitute a definitive target because the actual zones of economic mineralization are commonly <100 m in strike and 10s of meters in thickness within the conductive zones. Defining conductors could be considered mapping the mineral system footpath, but additional predrilling geologic information is required to enhance the likelihood of targeting the most permissive location, or footprint, along the defined footpath. The challenge in part is that at increasing depths, the resolution of geophysically derived images drops off such that targeting becomes problematic and at some stage, cheaper drilling is required to off-set the inherit loss of clarity in the geophysical results.

The Deep Exploration Technology Cooperative Research Centre (DETCRC) program in Australia is developing a method of cost-effective drilling at increasing depths, with a major effort to modify tube drilling technology from the oil and gas industry to the hard-rock environment (Hillis et al., 2014). The Athabasca Basin would likely be an excellent environment to apply this new style of drilling technology, with small, high value targets at considerable depths but with enough character to define a prospective corridor that can be delineated with geophysics.

A systematic approach to mapping structure and lithology using aeromagnetic data can produce results that are quite valuable for reducing the exploration risk (Isles and Rankin, 2013). An example of applying such a methodology is from the southeast corner of the Athabasca Basin (Fig. 21). The multigeneration assessment (Fig. 21A) by Annesley et al. (2010) of this very prospective part of the Basin (I. Annesley, pers. commun., 2014) was considered to be "best in show" when presented. Regional geophysics played a role in this interpretation, but much of the structural character is captured as very linear features, whereas the gneissic basement rocks are expected to be more curvilinear. An image generated only with aeromagnetic data (Fig. 21B) but using a variety of derived products from the TMI data, along with a systematic interpretive methodology, produced a basement character expected from the known geology (Condor Consulting, Inc., 2013).

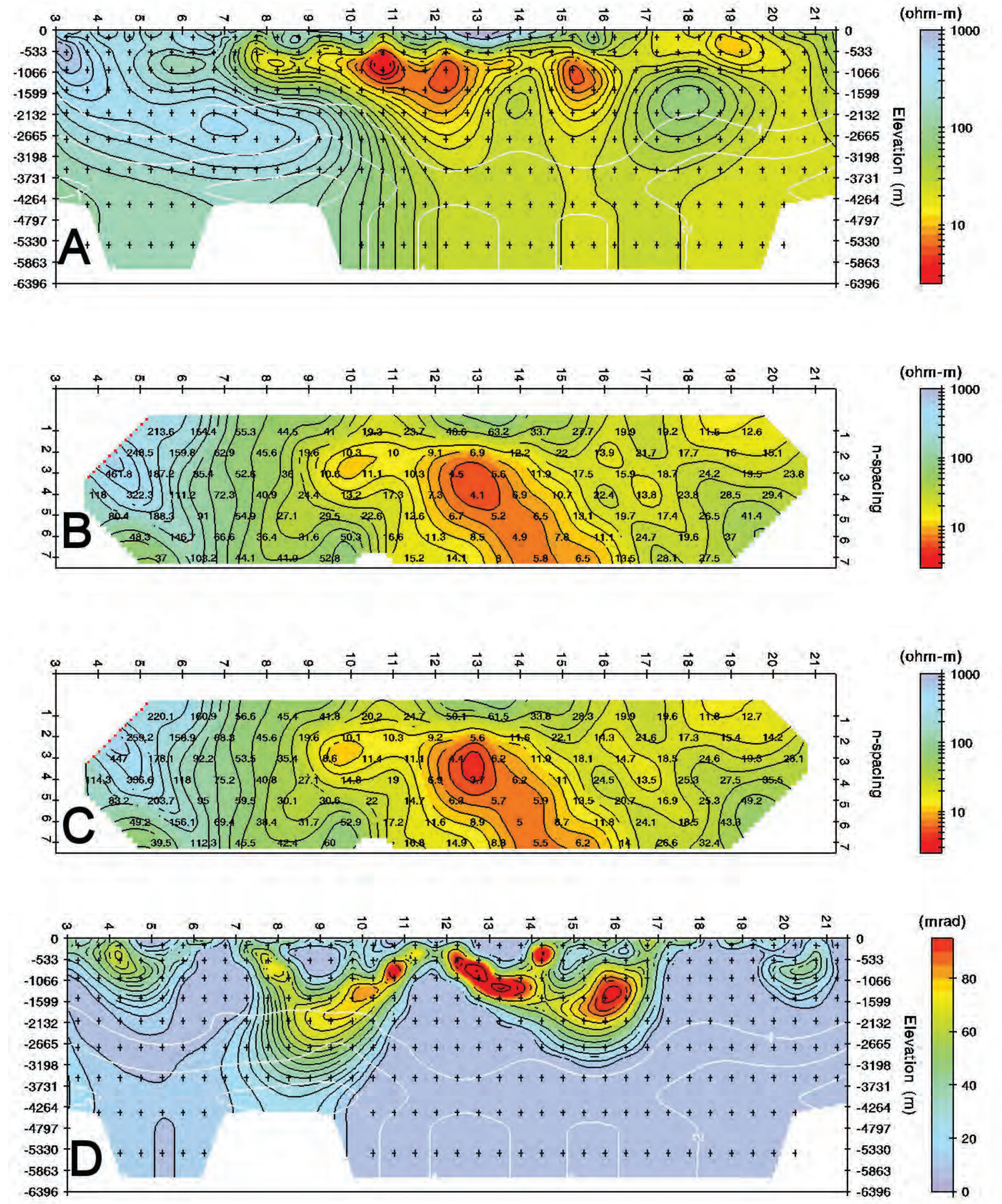

FIG. 16. A. Resistivity inversion model. B. Calculated data. C. Observed resistivity results. D. Modeled chargeability results. E. Calculated chargeability results. F. Observed chargeability results of the Escondida IP line 1. From Zonge Engineering and Research Organization (1982), and Witherly (2013b).

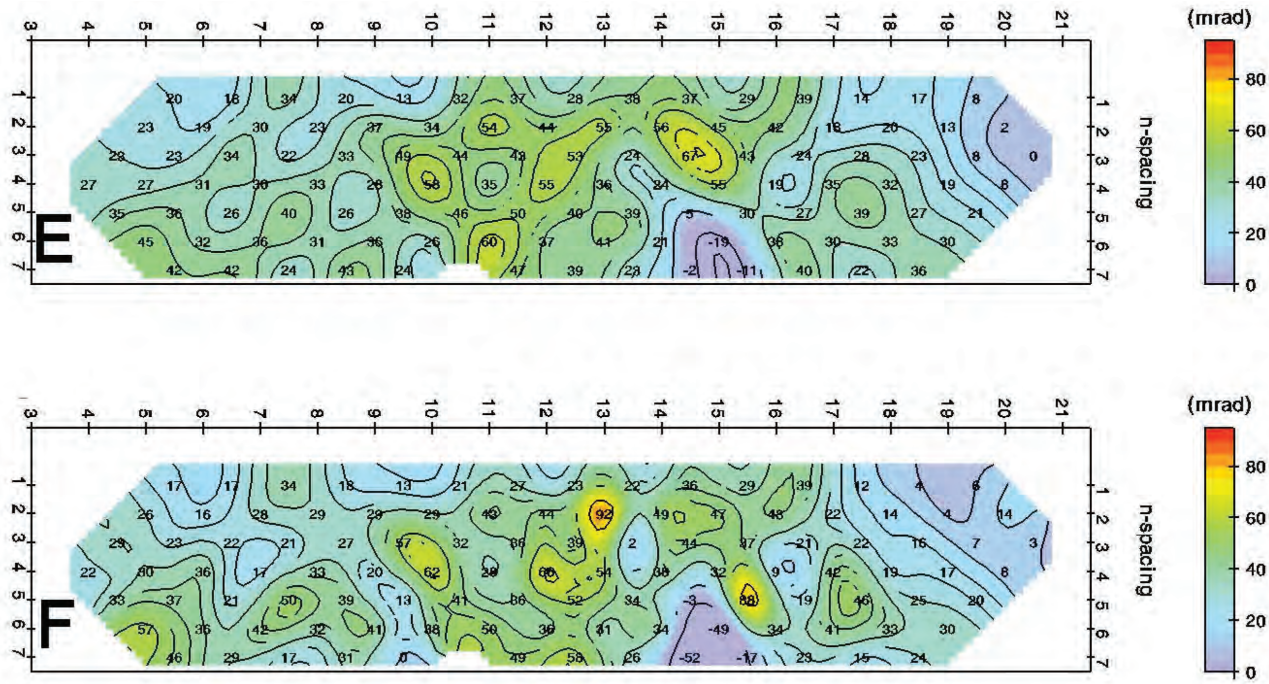

FIG. 16. *(Cont.)*

Another geophysical parameter that may be of value in mapping the alteration zones associated with Athabasca-style mineralized systems is density. Depending on the style of alteration, a density low (loss of silica) or density high (enhanced silicification) can occur (Jefferson et al., 2007). Given that these alteration zones can be much larger than the deposits themselves and extend upward for 100s of meters from the unconformity surface, these represent a footprint response that could assist in targeting. The result of 2.5-D modeling of a line of Falcon airborne gravity data from the north central Athabasca Basin is shown in Figure 22 (Witherly and Diorio, 2012). There are two zones of enhanced density in the sandstone. Although there is inherit ambiguity in these types of inversions, this was the preferred model based on the understood geologic constraints. Based on the traditional deposit model, conductive zones in the basement with a nearby density feature would likely motivate explorers to test such features. However, without such a footpath along the unconformity surface, the density anomalies alone are not sufficiently compelling to warrant drill testing.

Iron oxide-copper-gold (IOCG) deposits

Iron oxide-copper-gold (IOCG) deposits occur in a number of locations around the world. The example used here focuses on the Gawler craton, a world class IOCG province in South Australia that hosts the Olympic Dam deposit, plus several other smaller but still significant deposits (Fig. 23). Olympic Dam was discovered in 1976 while drilling gravity and magnetic anomalies (Esdale et al., 2003). Since then, this terrane has been subject to a large exploration effort involving both commercial and government groups. A major challenge in this setting is the thick cover of younger rocks overlying the ore-hosting stratigraphy. The geophysical methods that have been applied to this problem include magnetics, gravity, IP resistivity, seismic, and MT.

At the deposit scale, IOCG systems can show distinctive magnetic and gravity signatures (Fig. 24; Esdale et al., 2003; Vella and Cadwood, 2006; Vella and Emerson, 2009; Funk, 2013a, b). However, there is an abundance of "false positives" (similar-looking magnetic and gravity features not associated with economic mineralization, which adds considerably to the overall exploration risk). Efforts to define favorable alteration signatures, as well as to quantify and rank potential field responses have been undertaken (Hanneson, 2003; Skirrow, 2006a, b). What is observed is that the zones of better mineralization are often not the ones which show the strongest geophysical response (Funk, 2013a, b).

As noted earlier, an additional complication is that much of the prospective geology is covered by postmineralization sedimentary rocks that vary in thickness from a few 10s of meters to almost 500 m. These sedimentary rocks are often moderately conductive; this can inhibit the usefulness of electrical and EM techniques used primarily to screen the potential field anomalies prior to drilling. As the cover rock becomes thicker, detection and vectoring of drill holes into basement targets becomes increasingly problematic.

In the course of characterizing the geophysical response of the basement in the vicinity of Olympic Dam, regional seismic reflection (Lyons and Goleby, 2005) and MT (Heinson et al., 2006) transects were carried out (Hayward and Skirrow, 2010). The location of the transect is shown in Figure 23, which extends northeast-southwest across Olympic Dam. The results are shown in Figure 25; the MT shows a deep conductive root zone beneath Olympic Dam that is also characterized by an extensive zone of what is described as bland or textureless seismic response. This is thought to possibly be the remnants of the altered conduit through which the fluids that formed Olympic Dam had passed. If this is correct, this would represent the largest mineral system footpath yet

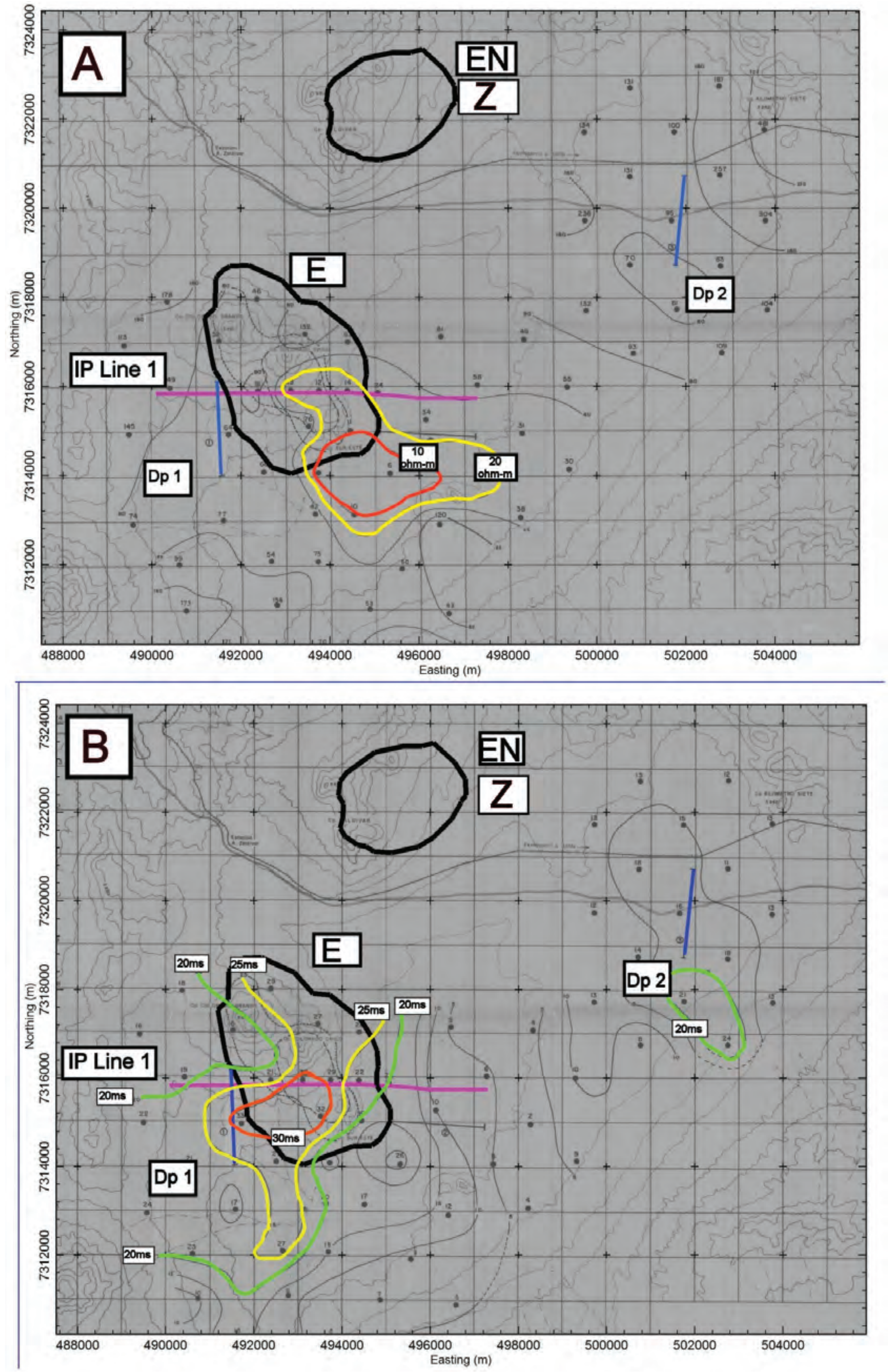

FIG. 17. A. Observed RIP resistivity plan. B. Observed chargeability plan over Escondida. Data displayed on topographic base. E = Escondida, EN = Escondida North; blue lines show current dipoles; black dots are observed stations; ohm-m = contours of resistivity, ms = contours of chargeability. From Kennecott Chile S.A. (1985) and Witherly (2013b).

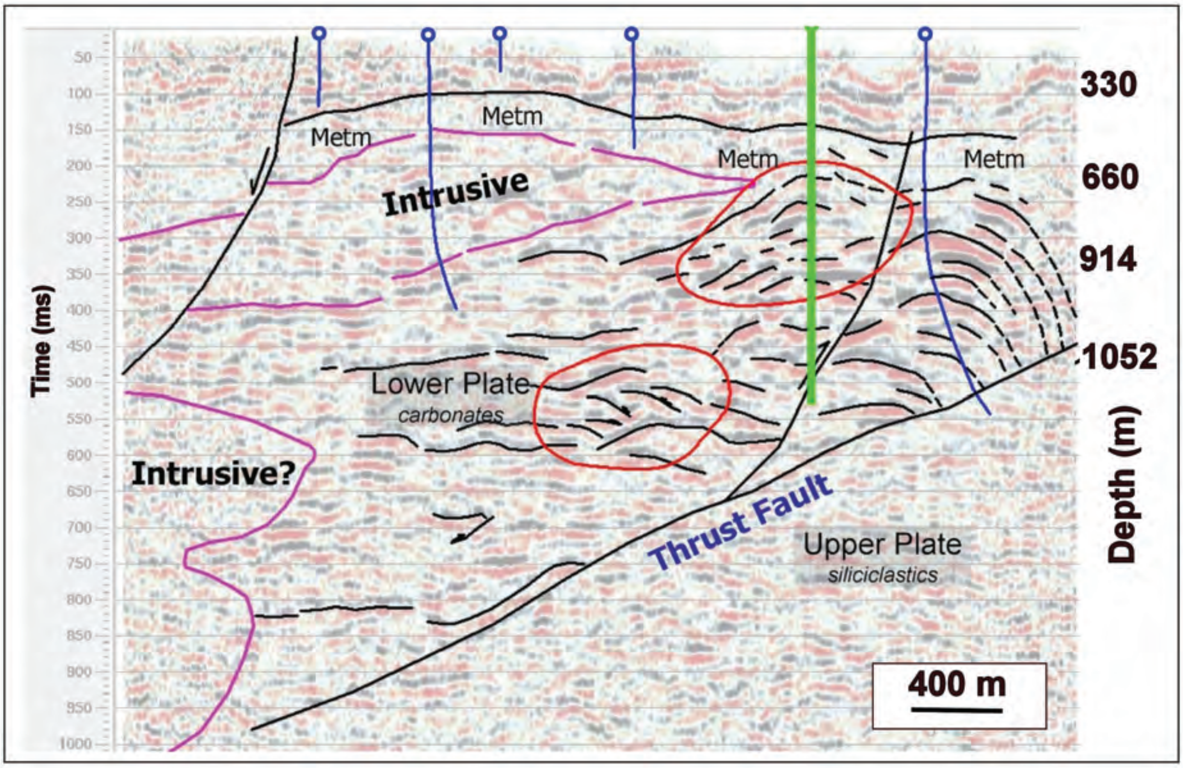

FIG. 18. Processed seismic reflection section from the Carlin Trend, Nevada. Blue drill holes used to constrain inversion; red circles show target areas with interpreted stacked thrusts; proposed drill hole shown in green. From Townsend et al. (2010).

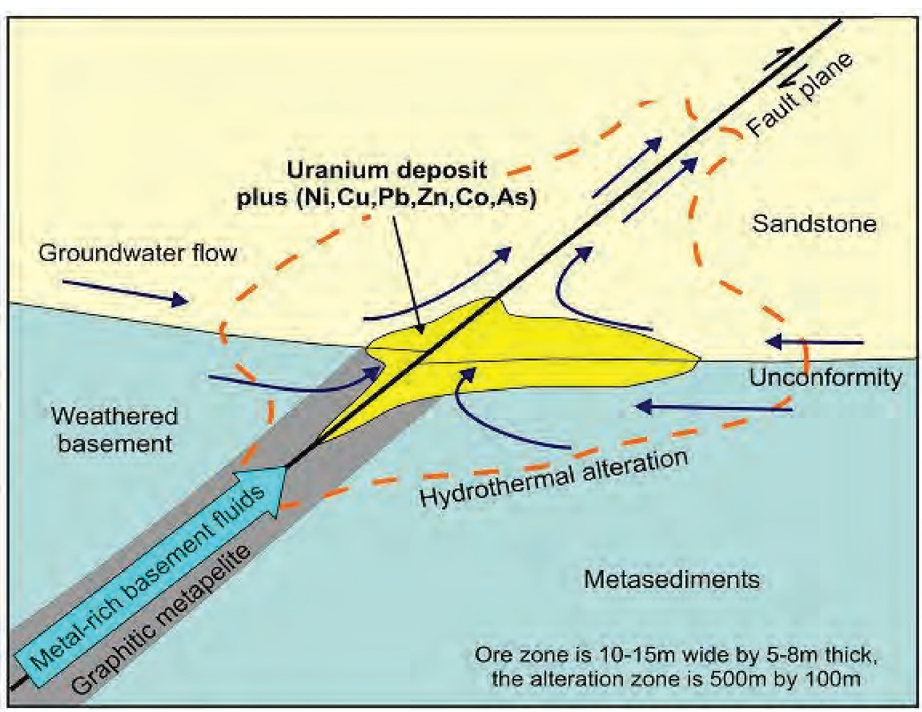

FIG. 19. Unconformity uranium model. Modified from Jefferson et al. (2007).

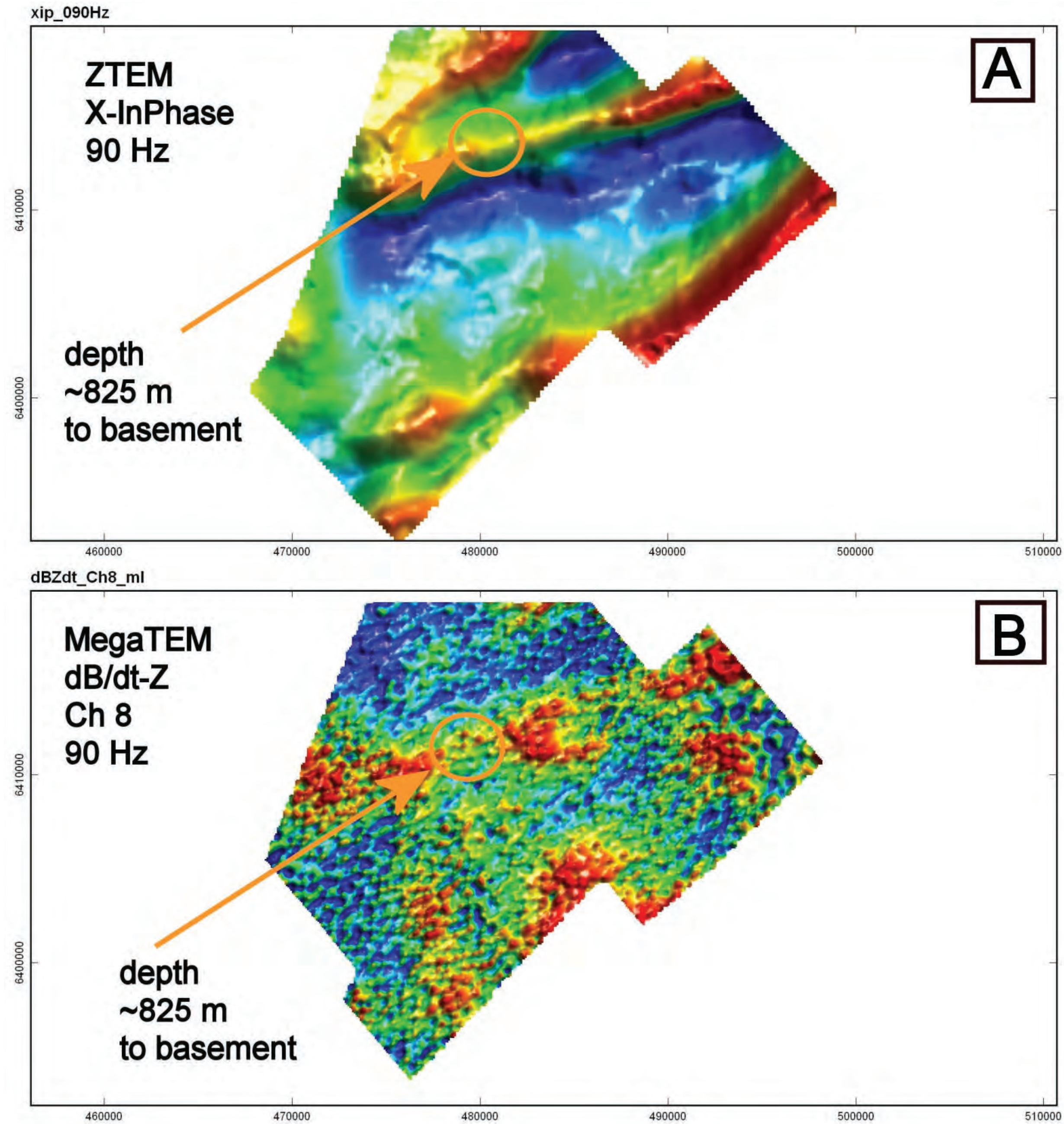

FIG. 20. Comparison of (A). ZTEM, and (B). MegaTEM over a deep conductor in the Athabasca Basin. Data courtesy of CanAlaska Uranium Ltd.

defined. However, additional tests with MT designed to identify root zones for a number of known IOCG systems elsewhere in the Gawler craton produced what was described as "mixed results" (M. Hayward, per. commun., 2014).

Volcanic-hosted massive sulfide (VHMS) deposits

The Abitibi greenstone belt is located in the Canadian provinces of Ontario and Quebec. The greenstone belt is a subprovince of the Superior Archean craton and has been a world-class resource of base metals and gold, with 67 significant (>0.2Mt) volcanic-hosted massive sulfide (VHMS) deposits. Many of the major base metals deposits (i.e., Matagami Lake, Kidd Creek) were discovered using airborne EM (Pemberton, 1989). Noranda Mining was a major player in the Abitibi, and in the mid-1990s became concerned that few new resources had been found to replenish the existing deposits. In the late 1990s, Noranda Mining undertook a major effort to define new resources that were assumed to have been missed using earlier technology (Witherly and Allard, 2010).

The Noranda Mining (succeeded later by Falconbridge Ltd. and the Xstrata Zinc Ltd.) exploration program started with a systemic evaluation of essentially all commercially available airborne EM technology, using a challenging VHMS deposit

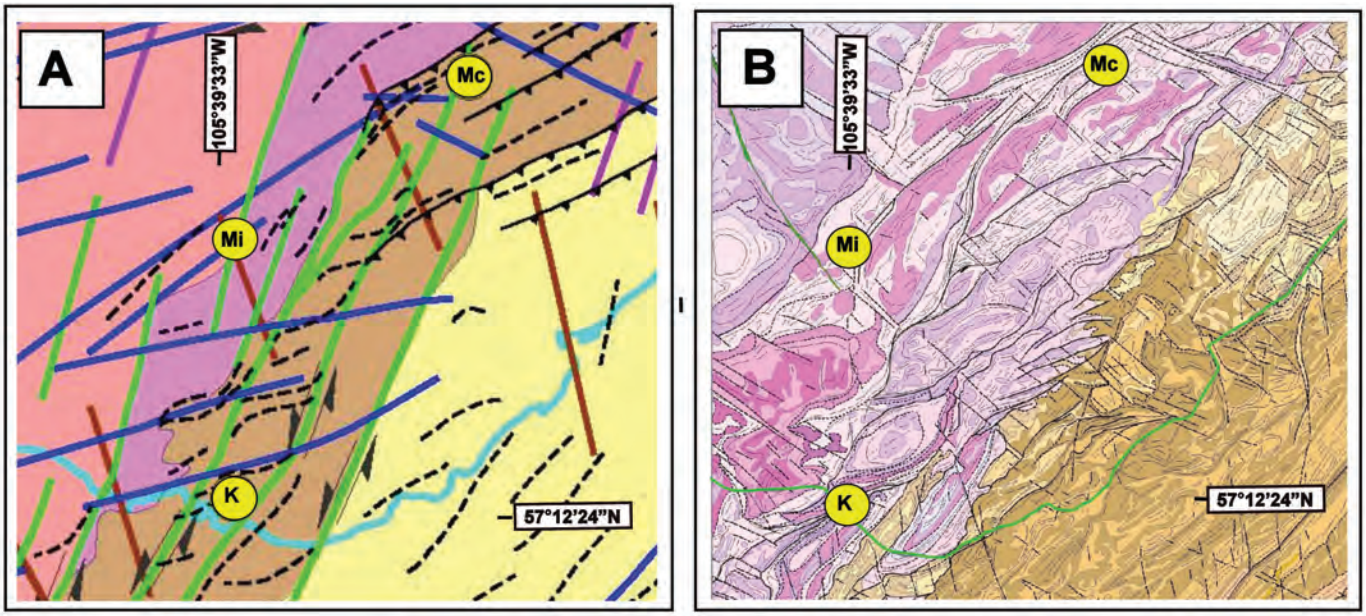

FIG. 21. A. Geologic map of the Athabasca Basin from Annesley et al. (2010). B. Geology map derived from aeromagnetic data. From Condor Consulting, Inc. (2013).

in Matagami camp called Caber (Gingerich and Allard, 2001). The MegaTEM system was selected and as a result of the first production survey over the historic Matagami camp, a previously unknown deposit called Perseverance was located. Although Perseverance was not very deep, it was still considered an "early win" and strongly reinforced the belief that the overall premise and design of the program was correct. In the following six years, extensive airborne surveys were conducted over the Abitibi belt, followed up with ground geophysics, geochemistry, and drilling. A flow chart that integrated geology, geophysics, and geochemistry was used to prioritize EM anomalies as drill targets (Fig. 26; Martin et al., 2007). Starting with 40,000 anomalies, 350 targets were selected and 268 were drill tested.

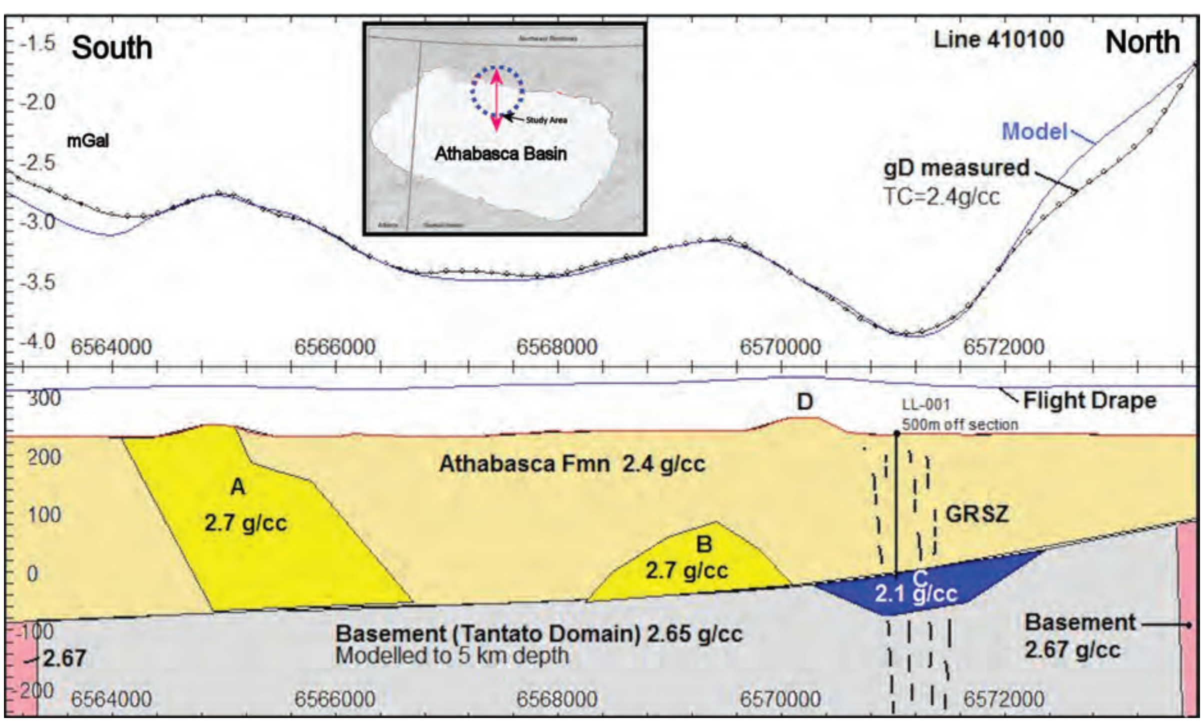

FIG. 22. 2.5-D model of Falcon gravity data from the Helmer property in the Athabasca Basin. From Witherly and Diorio (2012).

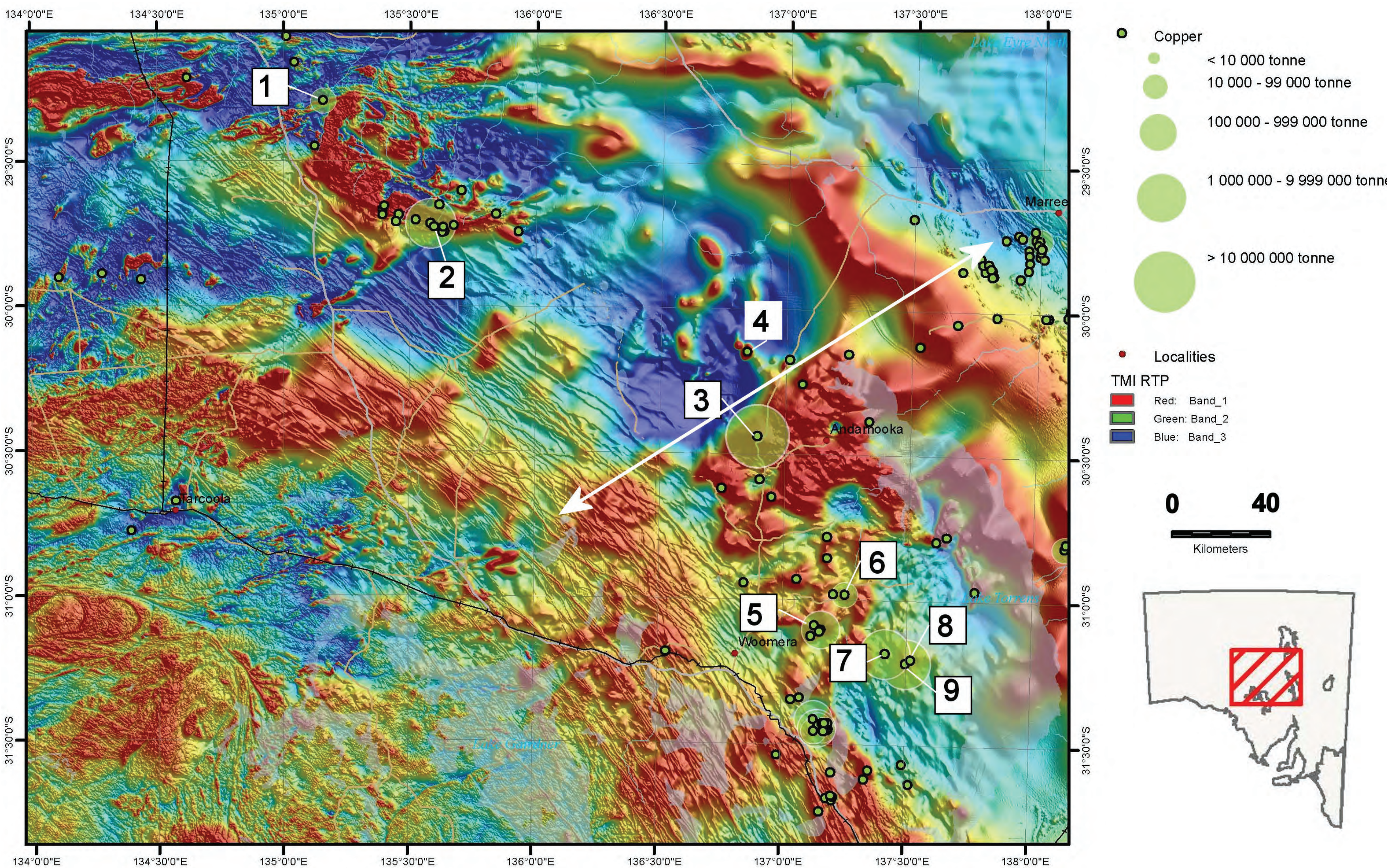

FIG. 23. Aeromagnetic (TMI-RTP) image of the Gawler craton, South Australia, with major IOCG Cu occurrences. 1 = Cairn Hill, 2 = Prominent Hill, 3 = Olympic Dam, 4 = Titan, 5 = Emmie, 6 = Oak Dam East, 7 = Khamsin, 8 = Fremantle Doctor, 9 = Carrapateena. White line with double arrow shows approximate location of seismic-MT section (Fig. 25). From South Australian Resources Information Geoserver (SARIG).

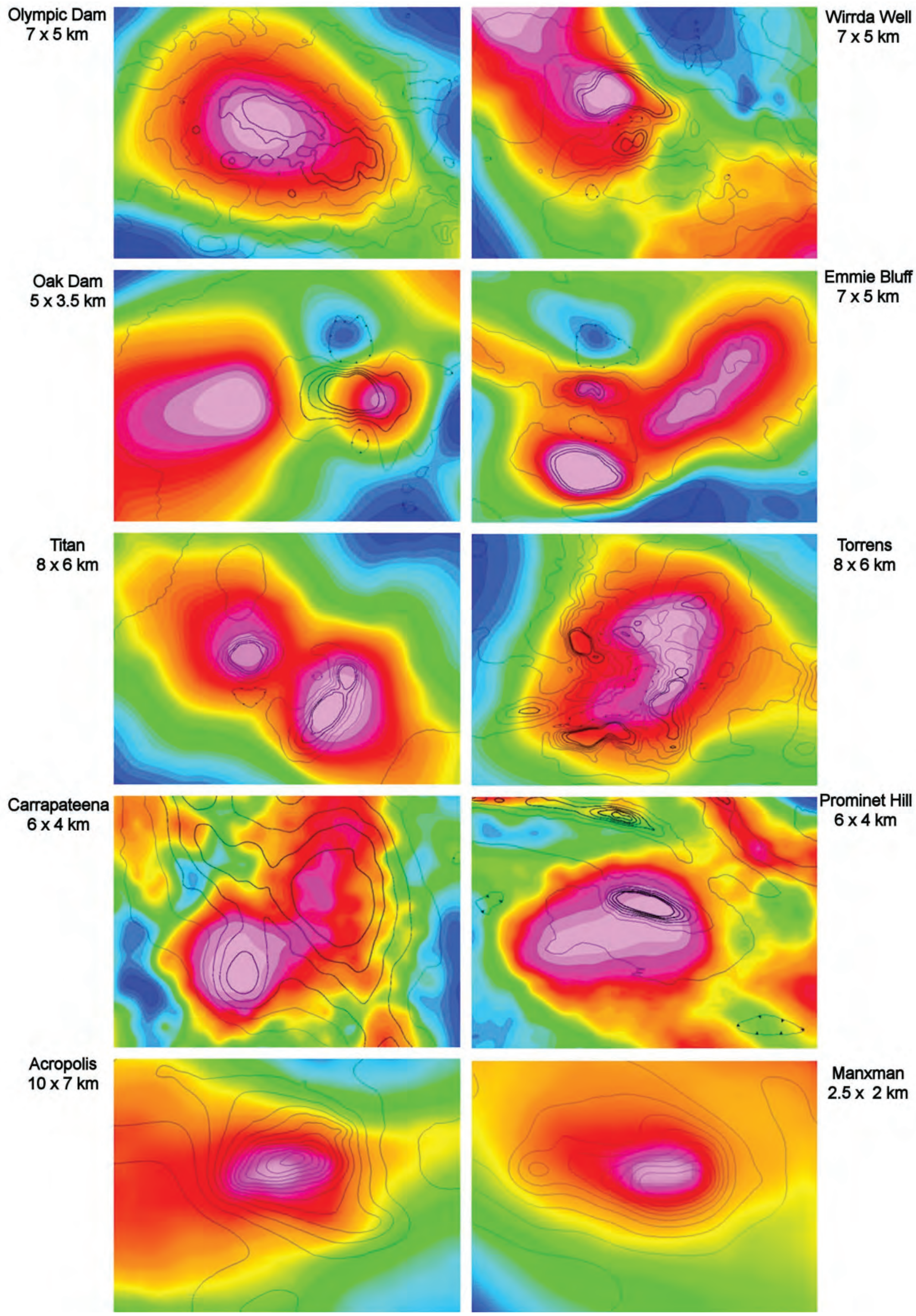

FIG. 24. Gravity and magnetic responses for ten deposits in the Gawler craton. Residual gravity grids are shown in color with TMI-1st vertical derivative as black contours. From Funk (2013a). For location of deposits, see Figure 23.

Despite the discovery of Perseverance early in the program, the project failed to result in the discovery of significant new mineral deposits. It is possible that although the geophysical approaches worked as planned, the mineral system associated with the sought-after VHMS deposits was not well enough understood. This resulted in an approach that had an overreliance on targeting footprints, albeit at a greater depth than had been previously explored.

Magnetic and gravimetric data have been helpful in understanding the Matagami area (Cheng et al., 2009). Continuing to use these techniques in similar geologic environments would be advantageous. When combined with other deep

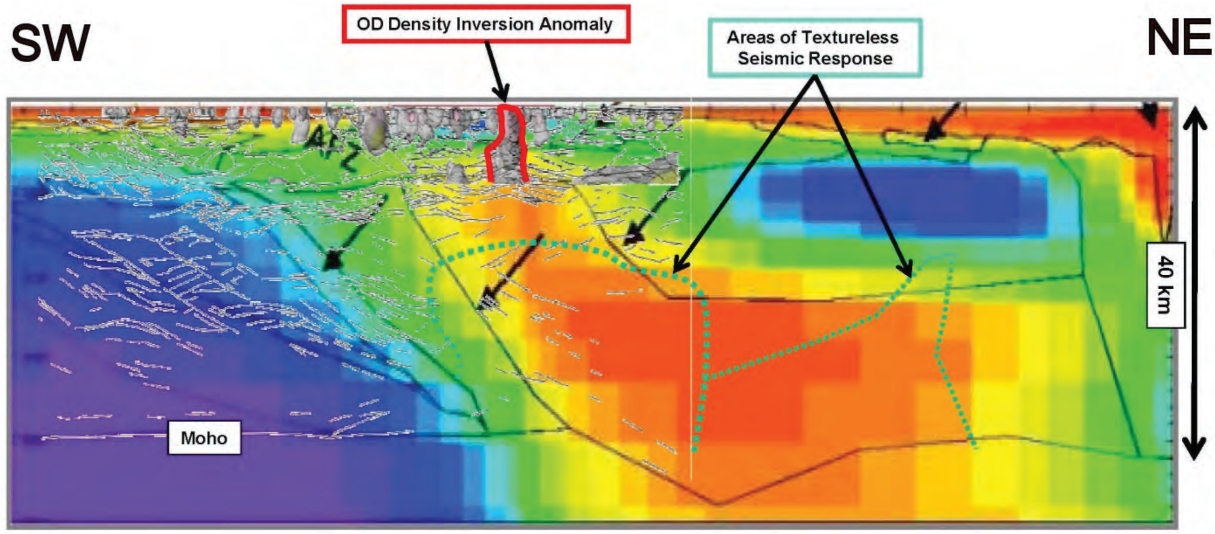

FIG. 25. Seismic (gray lines) and MT data (color contours) over the Olympic Dam deposit. Seismic reflection from Lyons and Goleby (2005) and MT from Heinson et al. (2006).

penetrating geophysics such as seismic and MT, it is expected that locating the potential footpaths associated with VHMS deposits may be easier. A 3-D model of the geology of the Noranda camp is shown in Figure 27 with conductivity values assigned to the rock units to simulate the response of a ZTEM survey (Fig. 28). This style of geomodel will become commonplace when studying footpaths and footprints of mineral systems. Within such a model, different techniques can be assessed to determine the optimum strategy to explore the setting. In addition, subtle but large-scale footpath signatures can be added to help assess the effectiveness of different exploration methodologies.

Conclusions

A review of the literature and examination of case studies have shown that a number of important mineral deposit styles or mineral systems have geophysical signatures that are much larger than the direct deposit responses. However, the sampling is not extensive and most of the observations lack a well-defined petrophysical basis for explaining the observed geophysical character, whether local (footprints) or more distal (footpaths). This means that conclusions drawn from this limited population of examples could be seriously skewed and more research into this field of study is required. A critical caveat is that these extended responses are strongly dependent on the lack of interfering affects from the surrounding geology.

Aeromagnetic and gravity data are considered key data sets to use for modeling and examination in order to provide evidence of the extended halos associated with mineral systems. More expensive ground-based MT, deep penetrating IP resistivity, and seismic surveys can add considerable value

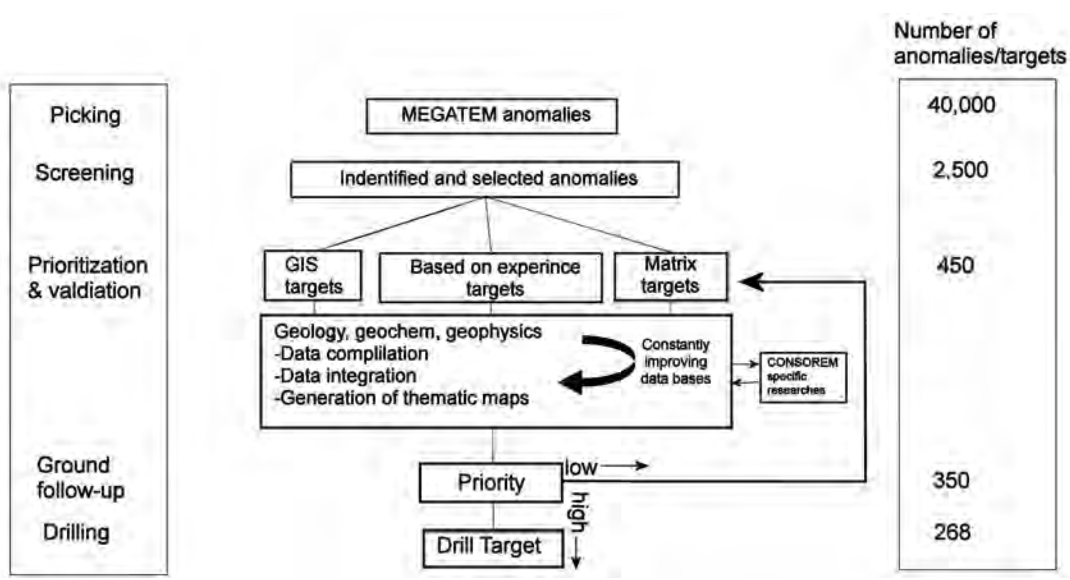

FIG. 26. Xstrata Zinc Ltd. Abitibi project exploration decision tree. From Witherly and Allard (2010).

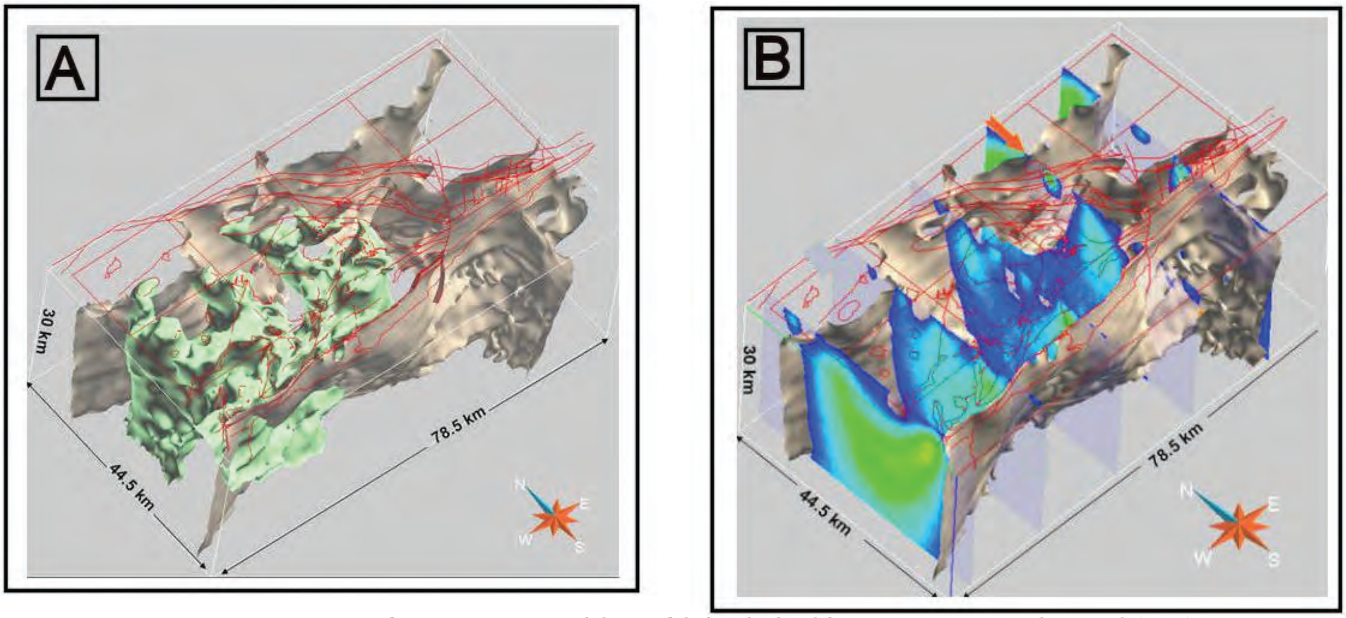

FIG. 27. A. 3-D gravity, and B. Magnetic susceptibility models for Abitibi Blake River group. From Cheng et al. (2009).

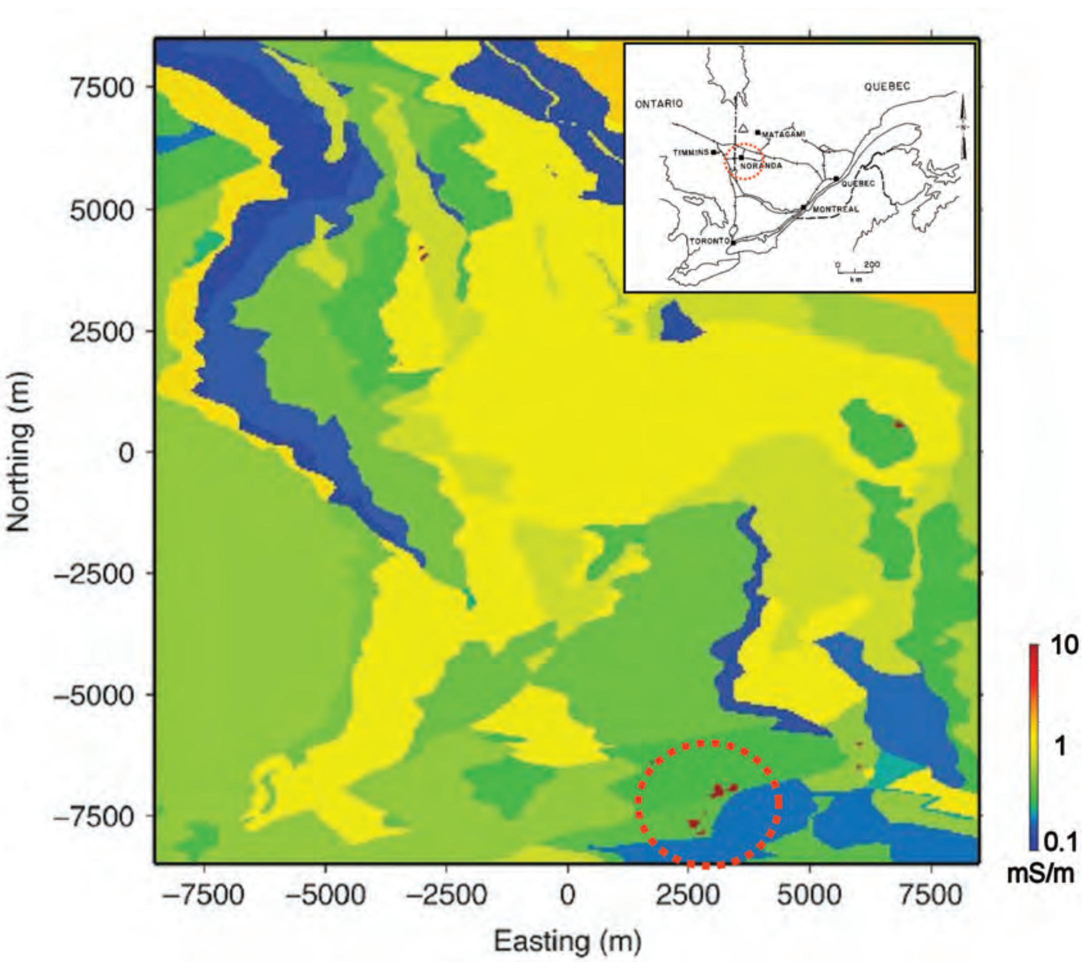

FIG. 28. ZTEM conductivity model of the Noranda camp; various geologic units have conductivity ascribed to them; Noranda VHMS deposits (red) in southeast corner of image are highlighted by dashed red circle. From Holtham and Oldenburg (2012).

in defining specific signatures, but their cost of acquisition is such that they would seldom be considered a primary search tool. Government-supported programs such as the PACE in South Australia (Tyne, 2013) have been used to generate pre-competitive geoscience data; adding semiregional MT and seismic surveys would seem a reasonable extension of their already proactive approach to support the exploration industry. Industry could then do fill-in work, either concurrent with government surveys or at a later date.

Whereas the technology needed to look for mineral systems signatures appears viable, there are serious human resources, corporate, and fiscal issues facing the exploration community that must be recognized and addressed before the industry can work effectively in exploration for deposits under cover. New collaborative models between the producers, speculative investors, governments, and explorers are needed. Producers have a long-term need for new resources and can justify risk capital to achieve this requirement. Speculative investors might appear as fair weather friends of exploration but their contribution is too significant not to have their buy-in going forward. Governments must be more proactive in facilitating greenfields exploration, in particular, as it offers the best return on investment in the long term. Explorers provide the technical savvy and experience base to carry out complex programs but require a level of consistent funding to maintain capabilities over time. Without such collaboration, one must be far less optimistic about the future of mining industry.

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