Heat flow: The neglected potential field for mineral exploration

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SUMMARY

This paper argues that heat flow is a valid 'potential field method' for mineral exploration. Certain ore deposits, most notably iron oxide copper gold uranium (IOCG-U) deposits, demonstrably affect the local heat flow and ground temperature conditions. The physics of steady state conductive heat flow is mathematically the same as gravitational acceleration, with buried heat sources analogous to buried masses. Detecting the surface signature of a buried heat source can therefore yield direct evidence of an ore body. The physics is robust, appropriate tools exist for the collection of heat flow data for exploration, and some simple strategies could yield valuable additional information about the subsurface for small marginal cost.

Key words: Heat flow, IOCG-U, potential fields

INTRODUCTION

Some ore bodies can affect the flow of heat flow and distribution of temperature in the ground around them. This simple fact points to an opportunity to use heat flow as an independent exploration tool for certain ore types. This opportunity, however, has so far been poorly exploited, even though the marginal cost of including heat flow measurements in broader exploration programs would often be very small compared to the value of the additional information they could provide.

Extensive investigation and development of gravity, magnetics, seismic, EM and electrical geophysical methods have turned these into routine and valuable exploration tools for all sorts of mineral and energy commodities. Heat flow, however, is rarely considered part of the geophysics toolkit. Even my 'bible' of practical geophysics (Telford *et al.*, 1991) includes just a couple of short paragraphs about 'thermal logging' in all of its almost 800 pages. But heat flow measurements provide independent data that are particularly relevant to some economically important ore deposits; most notably iron oxide copper gold uranium (IOCG-U) deposits such as Olympic Dam, Carrapateena, Prominent Hill and others. Radioactive isotopes of uranium (as well as thorium, potassium and some other minor elements) generate low levels of heat as they undergo spontaneous fission. The elevated concentrations of these elements found in many IOCG deposits represent significant heat sources relative to the background flow of heat from the Earth's mantle.

This paper is certainly not the first to suggest this. Sass *et al.* (1981) investigated the link between heat flow and sediment-hosted uranium; Houseman *et al.* (1989) illustrated a clear correlation between heat flow and IOCG-U deposits on the Stuart Shelf; and Matthews and Beardsmore (2006) presented a theoretical argument for using heat flow as an IOCG-U exploration tool. But the author is only aware of a single exploration company (Western Mining Corporation) that has trialled heat flow as a exploration tool in Australia. One has to question why this is the case.

I believe the key barriers to using heat flow as an exploration tool are: (a) a lack of awareness of the opportunity; (b) a lack of adequate equipment and experienced practitioners; (c) a mismatch between common exploration procedures and the requirements for quality heat flow data collection. Of these, the first is arguably the most pervasive barrier. This paper aims to present the theoretical justification for using heat flow as an exploration tool, and provide some practical guidance to how it can be adopted.

CONDUCTIVE HEAT FLOW IS A POTENTIAL FIELD

The steady state conduction of heat forms a potential field that can be described in a mathematical form analogous to a gravitational potential field. I do not intend to reproduce the entire mathematical underpinnings of the gravitational survey technique here. These can be found in sources such as Telford *et al.* (1991) and a myriad others. It should suffice to state that the gravitational potential at any given location, $\boldsymbol{r}$, within a dense body varies according to Poisson's equation:

$$\nabla^2 U_r = 4\pi G \rho_r \quad (1)$$

where ∇^2 = 'grad-squared' or the second spatial derivative, U_r = gravitational potential at location $\boldsymbol{r}$ (J kg^{-1}), G = universal gravitational constant (6.67408×10^{-11} m^3 kg^{-1} s^{-2}) and ρ = density at location, $\boldsymbol{r}$ (kg m^{-3}). Gravity is considered a 'potential field' because all points of equal U can always be connected to form a smooth surface.

In 'free space' (points of zero density), Equation 1 reduces to Laplace's equation:

$$\nabla^2 U_r = 0 \qquad (2)$$

In practice, we typically make measurements at the Earth's surface of the 'acceleration due to gravity', $\boldsymbol{g}$ (m s^{-2}), which is a vector with magnitude equal to the first spatial derivative of U_r in a direction perpendicular to the equi-potential surface.

$$\boldsymbol{g} = -\nabla U_r \qquad (3)$$

The 'negative' sign indicates that gravitational acceleration decreases as gravitational potential increases.

A practical outcome of the above relationships is that we can infer details about the distribution of bodies of anomalous mass within the Earth from measurements of the gravitational acceleration at the Earth's surface. If we can constrain the volume of the body containing the anomalous mass (and hence the body's density) then we can infer the distance (or depth) to the body. Alternatively, if we can constrain the depth to the body, we can infer its density.

Let's now compare Equation 1 to the steady state conductive heat flow equation, which is also a formulation of Poisson's equation:

$$\nabla^2 T_r = -A_r / \lambda \qquad (4)$$

where T_r = temperature at location $\boldsymbol{r}$ (K), A_r = internal heat generation at location $\boldsymbol{r}$ (W m^{-3}) and λ = thermal conductivity (W m^{-1} K^{-1}). Steady state conductive heat flow is considered a 'potential field' because all points of equal T can always be connected to form a smooth (isothermal) surface.

The heat flow equation also reduces to a formulation of Laplace's equation at points of zero heat generation:

$$\nabla^2 T_r = 0 \qquad (5)$$

We can (and do) also consider the 'temperature gradient', $\boldsymbol{\gamma}$ (K m^{-1}), as a useful parameter. Temperature gradient is a vector with magnitude equal to the first spatial derivative of T_r in a direction perpendicular to the isothermal surface:

$$\boldsymbol{\gamma} = \nabla T_r \qquad (6)$$

By convention, a positive gradient is in the direction of increasing temperature. Table 1 summarizes the mathematical analogues between gravity (Equations 1–3) and steady state conductive heat flow (Equations 4–6).

Gravitational field term	**Analogous temperature field term**
Gravitational potential, U (J kg^{-1})	Temperature, T (K)
Gravitational acceleration vector, $\boldsymbol{g}$ (m s^{-2})	Temperature gradient vector, $\boldsymbol{\gamma}$ (K m^{-1})
Density, ρ (kg m^{-3})	Internal heat generation, A (W m^{-3})
Mass (kg)	Heating rate (W)
Universal gravitational constant, G (m^3 kg^{-1} s^{-2})	Thermal conductivity, λ (W m^{-1} K^{-1})
Body of anomalous mass	Body that generates heat at an anomalous rate

Table 1: Analogous terms for gravity and steady state conductive heat flow

The mathematics implies that, in steady state conductive settings, temperature behaves in a way analogous to gravitational potential. While the above does not constitute a formal proof, the conclusion is, in fact, theoretically sound and it is possible to restate one of the above paragraphs in analogous terms; "As a consequence of the above relationships, we can infer details about the distribution of bodies *generating heat at anomalous rates* within the Earth from measurements of the *temperature gradient* at the Earth's surface. If we can constrain the volume of the body *generating the heat* (and hence the body's *internal heat generation*) then we can infer the distance (or depth) to the body. Alternatively, if we can constrain the depth to the body, we can infer its *internal heat generation*." This had profound implications when we are exploring for a commodity that generates (or absorbs) heat.

While there are striking mathematical similarities between gravity and steady state conductive heat flow, there are also some important differences that impact on the practical application of the two potential fields to geophysical exploration. Chief amongst these is the fact that G is a universal constant while the analogous λ varies with location in space. It is, therefore, necessary to reformulate Equation 4 and Equation 5 to allow for spatial variation in λ. Equation 4 can be rewritten:

$$\nabla (\lambda_r \nabla T_r) = -A_r \quad \text{or} \quad \nabla (\lambda_r \boldsymbol{\gamma}_r) = -A_r \quad \text{or} \quad \nabla \boldsymbol{Q}_r = A_r \qquad (7)$$

where the heat flow vector, $\boldsymbol{Q}_r$ (W m^{-2}), is the product of thermal conductivity (λ_r) and the thermal gradient vector ($\boldsymbol{\gamma}_r$) in a direction opposite to the thermal gradient. At points of zero heat generation, Equation 5 can be rewritten:

$$\nabla \boldsymbol{Q}_r = 0 \qquad (8)$$

Equation 7 and Equation 8 can be paraphrased as, "Total heat flow increases in the presence of a heat source, but otherwise remains constant." Heat generated underground increases the total heat flow towards the Earth's surface. This fundamental physics tells us that, in a steady state conductive setting, a buried heat source results in a positive surface heat flow anomaly directly above it.

HEAT FLOW AND ORE BODIES

Heat flow only represents a useful geophysical exploration tool if (a) the commodity we are exploring for generates (or absorbs) heat at a rate detectable against 'background' heat flow, and (b) our assumption of pure steady state conduction is valid. Regarding the first condition, the average global continental heat flow is about 0.065 W m^{-2}, or 65 mW m^{-2} (Pollack *et al.*, 1993). Let's arbitrarily assume that a 'detectable' heat source is one that contributes at least an additional 5 mW m^{-2} to the background flow. The internal heat generation of continental rocks is typically in the range 10^{-6} – 10^{-5} W m^{-3} (Beardsmore and Cull, 2001), or 1–10 μW m^{-3}. At 1 μW m^{-3}, a 5000 m thickness of rock would be needed to generate an additional 5 mW m^{-2} surface heat flow; but only 500 m of rock at 10 μW m^{-3}.

The Prominent Hill IOCG-U deposit to the northwest of Olympic Dam in South Australia has a vertical thickness of about 700 m (Oxiana Ltd, 2005). Assuming that radioactive isotopic abundances in the ore body are similar to other IOCG-U ore bodies, we can approximate them as 100 ppm U, 50 ppm Th, and 1.7% K_2O. From these, we can estimate the average heat generation of the ore body at 60 μW m^{-3}. 700 m of ore generating 60 μW m^{-3} potentially adds up to 42 mW m^{-2} to surface heat flow. The maximum anomaly would only be achieved, however, if the ore body covered a significant lateral area. In more realistic scenarios, anomalous heat sources have limited lateral extent and part of the heat disperses sideways to result in a characteristic 'bell-shaped' surface anomaly. Matthews and Beardsmore (2006) illustrated this point (Figure 1).

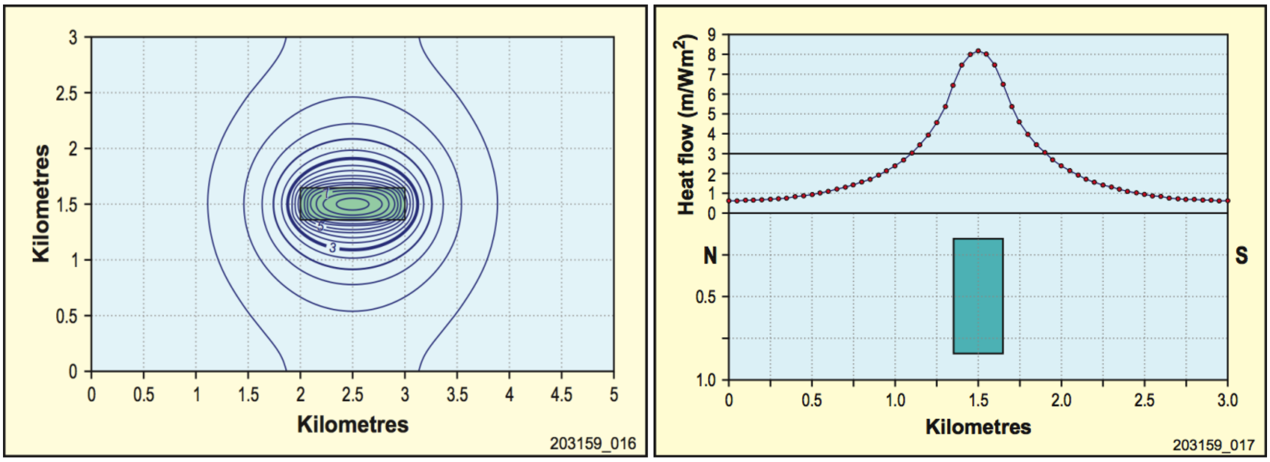

Figure 1: Theoretical distribution of anomalous surface heat flow above a buried heat source approximating the Prominent Hill ore body. The shape of the anomaly is indistinguishable from a gravity anomaly above a buried anomalous mass. From Matthews and Beardsmore (2006).

Steady state conductive heat flow theory is backed up by observations of heat flow on the Stuart Shelf in South Australia. Houseman *et al.* (1989) combined temperature logs from 63 boreholes with 73 thermal conductivity measurements on core samples to derive 63 estimates of heat flow on the Stuart Shelf. They observed significant positive heat flow anomalies above the known Olympic Dam and Acropolis IOCG-U deposits (Figure 2).

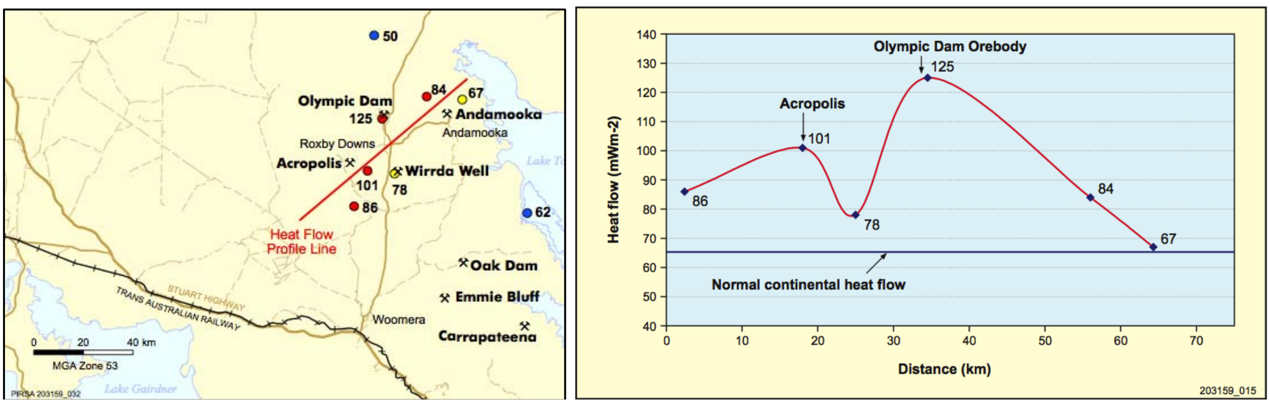

Figure 2: Cross section of heat flow values from the Stuart Shelf, South Australia, published by Houseman *et al.* (1989). From Matthews and Beardsmore (2006).

LIMITATIONS, COMPLICATIONS AND STRATEGIES FOR HEAT FLOW EXPLORATION

There are practical challenges to using heat flow to explore for mineral deposits. The first challenge is that a heat flow 'measurement' is relatively difficult to obtain. This is best illustrated by comparison with measurements of gravitational acceleration at the Earth's surface.

Gravity meters provide a rapid and portable means by which to measure the vertical component of gravitational acceleration at any given point on the Earth's surface. The author's personal experience is that up to 20 gravity readings can be obtained in a single day with little or no previous preparation of the survey sites. The derivation of vertical heat flow, however, requires separate measurements of vertical thermal gradient and thermal conductivity. Thermal gradient can only be calculated from measurements of temperature at two or more discrete depths. This requires that instruments be penetrated into the ground, typically down a borehole. The requirement for a borehole immediately makes a heat flow 'measurement' far more logistically challenging than a gravity measurement. In addition, while the gravitational constant, G, is (obviously) a constant, thermal conductivity is a variable. Ideally, it should be measured in a laboratory using rock samples representative of the interval over which thermal gradient was calculated. When such rock samples are not available, conductivity can also be estimated from previous measurements of the same rock type, although the uncertainty of such estimates is higher than for actual measurements. Clearly, a single heat flow calculation might only be achieved after a substantial drilling, coring, logging and testing program.

Another challenge is that the assumption of pure steady state conductive heat flow does not always hold true. Any departure from those conditions also means a departure from the mathematical analogy with gravity. The daily and seasonal solar cycles introduce a time-varying component to heat flow, invalidating the 'steady state' assumption in the top 30 m or so of the Earth's surface (Beardsmore and Cull, 2001). Borehole measurements must generally be obtained from greater depths to avoid the disturbance. Even at depths away from the surface disturbance, groundwater flow can transfer heat by advection, in which case the assumption of 'pure conduction' is invalidated.

A third challenge involves ensuring data quality. The temperature measured within a borehole does not necessarily represent the 'virgin' temperature of the rock surrounding the hole. The circulation of drilling fluid easily disturbs temperature, and a certain period of time is typically required before the hole can thermally re-equilibrate with the rock; three times the drilling time is a useful 'rule of thumb.' Furthermore, temperature should be logged *down* the hole at a slow speed to minimise disturbance of the drilling fluid prior to measurement. This need for re-equilibration and careful logging procedure is often incompatible with standard logging programs that tend to collect data upwards from the bottom of the hole, rapidly, and as soon as possible after drilling. Good heat flow measurements increase the cost of a drilling program by way of casing material or extended rig time on site.

Finally, temperature-logging tools and thermal conductivity devices need to be of sufficient accuracy and precision for heat flow measurements. Many standard 'temperature tools' fail this test. Poor temperature and conductivity measurements translate directly into unreliable heat flow values.

But the potential value to be obtained from heat flow measurements can outweigh the added cost and effort involved in collecting and analysing quality data. Imagine a case where a company spends hundreds of thousands of dollars to drill an exploration borehole in a location based on gravity, magnetics or EM data in the hope of intersecting an IOCG-U ore body. The drilling is unsuccessful in that the bore does not intersect any commercial grade ore. This was exactly the case for an unsuccessful hole drilled by Tasman Resources under South Australia's 'Program for Accelerated Exploration' ('PACE') in 2004 (Figure 3).

> In summary, there appears to be no simple explanation for the lack of conductive rocks in TI 8. It seems most likely that the potential zone of interest may have been just missed by TI 8, or the conductive response in the AMT may be due to saline groundwater associated with faulting on the eastern margin of the Titan system.
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> The possibly of a "near miss" scenario could be further investigated by downhole probing of TI 8 by EM or perhaps MMR techniques, but these techniques have already been trialled at Titan, with inconclusive results, and they also proved to be relatively expensive.

Figure 3: Extract from a drilling report to the South Australian Government (Tasman Resources, 2006).

Was TI 8 unsuccessful because it missed the ore or because there is no ore? A heat flow measurement in the hole might have answered that question. Elevated heat flow would have supported a 'near miss' scenario, while background heat flow would have suggested a barren target. The value of such information would be apparent in assessing the risk of drilling another hole into the same target. For that reason alone, I would argue that a heat flow measurements should be factored into the cost of any hole drilled for IOCG-U exploration. The marginal cost of including a heat flow measurement would typically be small (<10%).

The above challenges of measuring heat flow in boreholes would be largely circumvented if there were a tool for measuring surface heat flow without a borehole. Hot Dry Rocks Pty Ltd has been slowly working on such a tool with a series of partners for at least the past 10 years (Figure 4). Beardsmore and Antriasian (2015) provided the most recent update on our progress. Since that time, we have successfully delineated surface heat flow variations across four hydrothermal systems in Mexico to a precision of about 100 mW/m^2. This is still about an order of magnitude too coarse for detecting IOCG-U bodies. However, the limiting factor on precision is now data processing, which is currently very manual, time consuming and simplistic. Our plans to improve the data processing process and algorithms should also bring about an improvement in precision and bring us a step closer to being able to perform regional heat flow reconnaissance for IOCG-U bodies without boreholes.

Figure 4: The author field trialling a shallow heat flow probe in South Australia in 2012.

CONCLUSIONS

Steady state conductive heat flow could be exploited as a potential field geophysical exploration technique for problems involving underground heat sources and sinks. The challenges in doing so are more behavioural than technical, with the basic tools already readily available for borehole heat flow measurements. Such measurements performed as a routine test in bores targeting IOCG-U deposits could discriminate between barren targets and 'near misses', with multiple bores providing vector information towards the nearest heat source. While not discussed explicitly in this paper, heat flow could also be used to investigate other mineral-related phenomena. These could include highly thermally conductive bodies (e.g. metallic ores, salt diapirs), which tend to focus heat flow through refraction and result in a heat flow peak rimmed by a heat flow trough; oxidising sulphide bodies, which generate heat; underground coal files; active hydrothermal systems; and others.

The possible emergence in the coming years of a tool for carrying out surface heat flow reconnaissance could finally raise conductive heat flow surveys to a similar status to their potential field cousins, gravity and magnetics.

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