A METHOD FOR CALIBRATING AUSTRALIAN TEMPERATURE-DEPTH MODELS

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The Australian geothermal industry is moving rapidly, and in that process requires a lot from geophysics to aid in characterising regional prospectivity for exploitable heat resources.

Various groups are using hybrid methods to estimate 'Curie point' temperatures at depth, or alternatively, the temperature at 5 kilometres below the surface. Deep drilling observations and airborne magnetic compilations are the key components, together with a basement geology interpretation. Several generations of this work are already published with more to come.

A method to test these maps and also help characterise uncertainty is proposed based upon a deep 3D continental model scale, extending to the lithosphere. Variable surface temperature and heat flow grids, based upon remote sensing are used, together with a simple lithosphere boundary condition. The heat diffusion is then employed to test the temperature-depth maps. Progress on applying this method to Australia is reported.

Key words: Sensing Heat Flow Anomalies, EM spectrum, High Energy photons, Continental scale 3d Geology models

Introduction

Not enough attention is paid to the influences of heat, both on-going and its history, in the field of exploration geoscience. Scant regard is paid to heat alteration mineral products, unless it is obviously a primary indicator of an economically viable resource. A more holistic approach to creating 3D earth models that embrace all aspects of heat and its influence on rocks is required. The challenge (Stein) is the classical one of using the measured temperature and temperature gradient at an object's surface to infer the temperature field at depth, T(x,t), a function of position x and time t. Near the earth's surface, the temperature gradient is essentially vertical, so the outward heat flow qs is the product of the vertical gradient of the temperature T(z), which is most everywhere positive downwards (temperature increases with depth z), and the measured or estimated thermal conductivity of the material, k.

Australian developments

The systematic gathering of borehole observations of downhole temperatures, rock heat conductivities and temperature gradients with depth below surface were the basis of producing the first generations of predicted temperatures 5km below the surface for the Australian continent (Chopra & Holgate, 2005)., see figure 1.

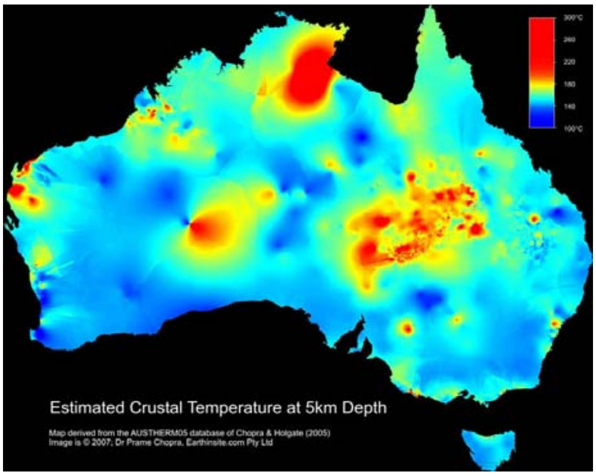

Figure 1: Map of estimated crustal temperatures at a depth of five kilometres.

Maus, 1997 developed the idea that compilations of the magnetic anomaly map could form the basis for estimating the depth to the Curie point. This requires a technique to find the bottoms of causative bodies. A moving window method using a modified Spector-Grant type algorithm was initially proposed for this task.

In recent times, Geoscience Australia has produced the 5th generation magnetic anomaly grid and with this edition there is much greater confidence that the longer wavelength anomalies (greater than 50 km) are faithfully reproduced. This follows from the AWAGS survey, funded by the "Securing Australia's Energy" initiative. Also, more theoretical work has been done on automatic depth to basement techniques, such that the ability to separate top/bottom and centres of causative bodies. (see Stavrev and Reid 2007).

Several groups have formed to tackle this problem and the recently reported progress from the USGS team (Bouligand et al 2009) is encouraging. In this work, a variety of approaches were applied to the California/Utah/Nevada region where over 25% of all geothermal power station capacity for the world is located. These heat sources are labelled "conventional" as they follow from near surface volcanic sources associated with the Rocky Mountains and Yellowstone.

In Australia, a significant initiative is being mounted around the so-called South Australia Heat Flow anomaly. This was first recognized by Sandiford 1998, as the burial of a basement sequence enriched in heat producing elements during thermal subsidence following rifting. This major rift in the Australian continent from Adelaide north to the Cooper Basin, has a massive granitic intrusion which is Uranium rich. Naturally occurring low grade thermo-nuclear heating of this granite peaks at around 4 km deep. This type of play is termed an Enhanced Geothermal System.

Geochemistry

It is mainly the oil industry that has come to realise just how important the heat history of rocks and sedimentary packages is, in the prospectively of basins for oil or gas finds.

Observationally, the key technique is defining the mineral alteration products and from experiment, just what must have been the heat history to have left this legacy. Diamond exploration has also traditionally looked for indicator minerals that imply the necessary heat history.

Structural geology

Most structural geology phenomena have an underlying genesis where heat has played a major role.

1. A deep pipe from the mantle to the surface can form as nature "vents" heat in explosive events. Kimberlite pipes retain a record of heat altered minerals that can be interpreted for temperatures during formation.
2. Granite intrusions in general.
3. All tectonic and plate scale movements are thought to be manifestations of heat circulation effects in the mantle.
4. Volcanic activity is mostly associated with crustal faulting, often on a plate boundary. Basalt flows and flood plains, and sills are remnants of this activity.
5. Rifting or failed rifts.

Observational geophysics

All the measurable geophysical phenomena such as gravity, magnetics, deep crustal seismic and radiometrics can indirectly be used to help interpret structural geology and define heat province boundaries.

Missing from these lower cost, bulk observational methods, is a viable methodology to either directly or indirectly observe heat or temperature. This would lead to near surface temperature and/or heat flow maps that significantly improve upon Figure 1. So what is the physics and why do we struggle with this challenge?

Electro-magnetic spectrum

Thermal radiation is emitted by all substances above absolute zero and includes visible and infrared radiation and some ultra-violet radiation. Thermal radiation occurs in solids, liquids, and gases, at the speed of light and has no attenuation in a vacuum. Thermal radiation can occur between two bodies with a colder medium in between. Actually, the electromagnetic spectrum can be expressed in terms of energy, wavelength, or frequency. Each way of thinking about the EM spectrum is related to the others in a precise mathematical way.

	Wavelength (m)	Frequency (Hz)	Energy (J)
Radio	$> 1 \times 10^{-1}$	$< 3 \times 10^{9}$	$< 2 \times 10^{-24}$
Microwave	$1 \times 10^{-3} - 1 \times 10^{-1}$	$3 \times 10^{9} - 3 \times 10^{11}$	$2 \times 10^{-24} - 2 \times 10^{-22}$
Infrared	$7 \times 10^{-7} - 1 \times 10^{-3}$	$3 \times 10^{11} - 4 \times 10^{14}$	$2 \times 10^{-22} - 3 \times 10^{-19}$
Optical	$4 \times 10^{-7} - 7 \times 10^{-7}$	$4 \times 10^{14} - 7.5 \times 10^{14}$	$3 \times 10^{-19} - 5 \times 10^{-19}$
UV	$1 \times 10^{-8} - 4 \times 10^{-7}$	$7.5 \times 10^{14} - 3 \times 10^{16}$	$5 \times 10^{-19} - 2 \times 10^{-17}$
X-ray	$1 \times 10^{-11} - 1 \times 10^{-8}$	$3 \times 10^{16} - 3 \times 10^{19}$	$2 \times 10^{-17} - 2 \times 10^{-14}$
Gamma-ray	$< 1 \times 10^{-11}$	$> 3 \times 10^{19}$	$> 2 \times 10^{-14}$

Table 1 : shows these relationships..

So why do we have three ways of describing things, each with a different set of physical units? After all, frequency is measured in cycles per second, wavelength is measured in meters, and energy is measured in electron volts and is inversely proportional to the wavelength.

By convention, gamma-rays are reported in electron volts, with the highest energy going to the right hand side. Figure 2 below has the order reversed, and shows the EM spectrum wavelengths increasing to the right, in what is the conventional manner for visible light, heat etc.

This traditional view also is somewhat misleading with the label "thermal radiation". This type of heat is arguably the least well understood. While at the same time, most people are very familiar with the weather and sensing radiant heat. The body is receptive, largely due to the interaction of parts of the EM spectrum with water and to a lesser extent, other organic molecules. With this in mind, it is normal to associate heat with infra-red band, terra-hertz band and the ultra-violet bands (sun-burn). We have evolved to sense visible light which radiates from the sun due to thermal black body radiation at 5800K. What this is really showing is the range of Plank's law (see Figure 3) and how parts of the spectrum relate to "black body" radiation from the Earth. As can be seen, microwaves are not considered to be thermal radiation, yet clearly that have a very effective capacity to "heat". At the high end of the energy scale, gamma rays are part of the mix in nuclear power plants that, of course, generate heat prior to conversion to electricity.

From a geophysical point of view, any EM emission from the Earth could be harnessed to extract heat. The challenge of how to do this is largely an engineering problem.

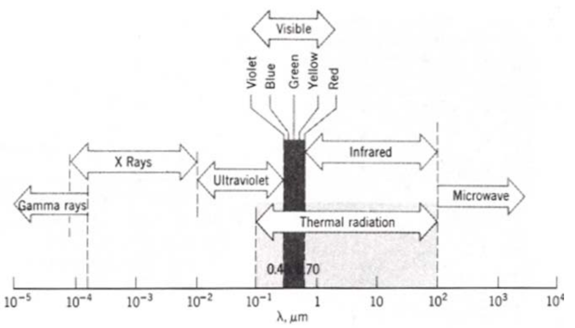

Figure 2. Radiation Spectrum, showing wavelengths. Note, it is not usual to think of thermal radiation extending into the higher energy parts of the spectrum e.g. X Rays.

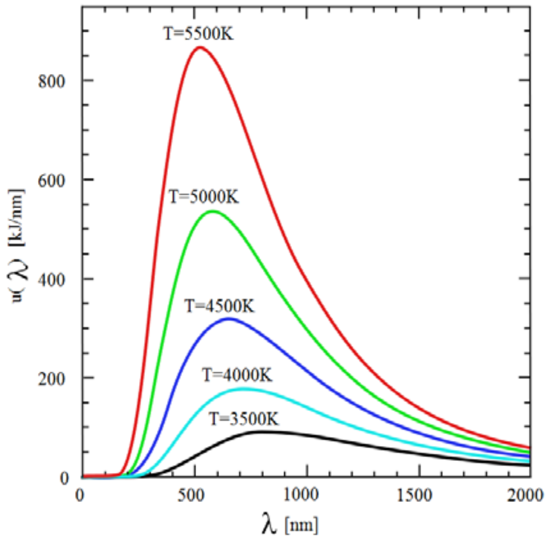

Figure 3 Plank's law and Black Body radiation. At normal surface temperatures of the Earth, the range of wavelengths still emitting radiation is large, while the overall energy (the area under the curve), falls off dramatically.

There are two types of radiation categories

- Volumetric phenomenon – radiation emitted or absorbed throughout gases, transparent solids, some fluids
- Surface phenomenon – radiation to/from solid or liquid surface.

Initially, heat is emitted from the surface of the earth and then it is "attenuated" and absorbed in the atmosphere.
The magnitude of the radiation varies with wavelength – it's spectral. The wavelength of the radiation is a major factor in what its effects will be. This is illustrated in Figure 4.

Radiation is made up of a continuous, non-uniform distribution of monochromatic (single-wavelength) components.

The magnitude and spectral distribution (how the radiation varies with wavelength) varies with temperature and type of emitting surface. We are interested in the continental crust and regional variations due to the age and composition of the rocks.

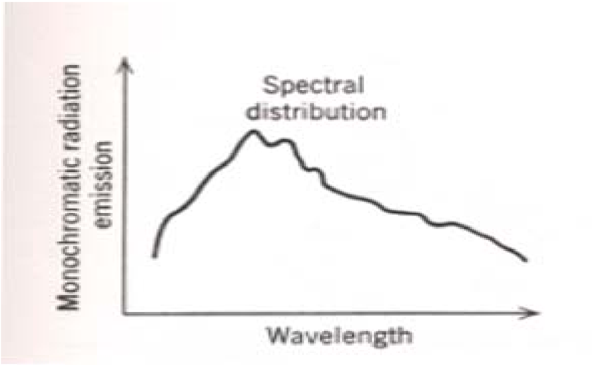

Figure 4. Shows varying emissivity with wavelengths

Radioactive (crustal) heat production

The continental crust contains a relatively high density of radioactive isotopes, primarily those of uranium, thorium, and potassium.

Hence, within a region the heat flow depends on
(1) radioactivity in the crust,
(2) tectonic setting, and
(3) heat flux from the mantle below.

For a given area, termed a heat-flow province, the measured heat flow "q" varies linearly with the near surface radioactive heat production.

The technology to observe radiometrics emissions from the earth or gamma-rays has traditionally always ignored the "low channels", due to high counts and diurnal effects, often labelled "skyshine". Very few observations using these instruments have ever been done at night, when these diurnal effects are minimised. With the newer hardware now available and the sensitivities and counting capacities increased, a 66 litre system, designed for 1024 channels and/or a GeLi purpose built system, would be able to observe a considerable portion of the "thermal radiation" tail. The first channel of a radiometrics instrument covers most of the conventional EM spectrum, covering from 0 to 12 keV. Figure 5 recasts the EM spectra into the form favoured for measuring gamma rays.

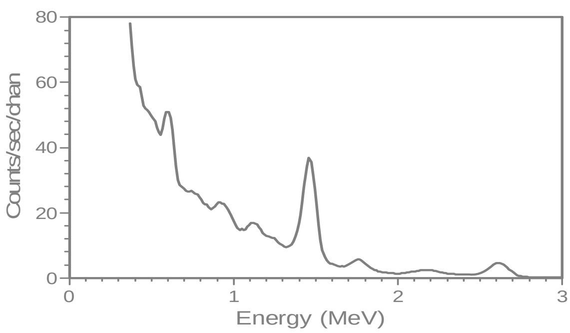

Figure 5 Typical Gamma Ray spectrum view, observed remotely within 100 m. of ground.

Attenuation of signal

Radiant energy from the earth is readily absorbed and attenuated in the lower atmosphere. At lower energies, the photoelectric effect is mostly responsible for this. Radiometric airborne surveys are conducted at flying heights of around 100m, to ensure emissions characteristic of particular minerals can be observed before this attenuation smooths the characteristic spectral peaks. This required observation distance reduces as the energy of the photons reduces, if individual characteristics are to be seen. If one re-examines the generalized "Black Body" diffuse curve at 300 degrees Kelvin, it is very smooth and covers a broad range of energies, with no possibility of peaks from good emitting minerals.
This appears to be an area that requires either more research, or practical observations in differing terrains and natural light conditions. Towards the classic heat portion of the spectrum, bolometers exist that have been deployed at large distances, to observe that portion of the spectrum. (TIMS, ASTER etc.) The reason these show any signal, is that wavelengths are chosen that minimize absorption with water vapour.

Modelling construts

The oceanic lithosphere is relatively uniform in composition, and little heat is generated within it by radioactivity, oceanic heat flow is essentially a simple function of age. In contrast, a continental crust is heterogeneous in composition, due to its much longer tectonic history. Moreover, the heat flow depends critically on radioactive heat production in the crust. The two primary effects are thus that continental heat flow is proportional to the surface crustal radioactivity in a given region, and decreases with the time since the last major tectonic event.

A rational way to construct a 3D continental scale earth model that is to serve the purpose of constraining the complexity while still honouring the important factors is to use the new radiometrics map of Australia, to define tectonic and cratonic provinces characterised by the radiogenic rock content. The big unknown is the depth extent of each of these units. It is also here that geophysics is needed to play a part. To date, see Figure 1, no geological influences are taken into account when interpolating the temperatures away from observation points.
At the same time, great strides are being made to construct large scale 3D solid geology models that are consistent with structural geology observations and all the geophysical datasets.

In Australia, we have 3D models for Tasmania, most of Victoria, and about one third of South Australia. (Preliminary 3D geological models of the Curnamona basin and Gawler craton). In addition, some purpose built 3D heat/geology models for the Cooper basin have been constructed with a view to characterising the heat flow domains and defining uncertainties on this resource.

Numerical/computational complexities

A current challenge is thus to deal with all these complexities, deciding on the 4 or 5 most important aspects of the geoscience, and construct more realistic and therefore useful models. It turns out there is a barrier with the numerical methods used to solve the heat diffusion equation. The methods do not scale well. For simple situations, all is well, but when the requirements of 3D, structural geology, material inhomogeneity and continental scale are stated, no really viable techniques present themselves. For this reason, leading edge numerical methods, using Fast Fourier transforms etc., are being followed up. Two significant recent publications point the way here. Caratori 2009, elegantly shows how gravity and magnetic forward modelling in 3D can be rapidly achieved using 3D FFT methods. Li, 2007, looks at faster methods for the heat diffusion equation, but just the homogenous case.

Conclusions

Craton scale and larger 3D numerical models, with structural geology constraints, properties and boundary conditions of measured surface heat flows, and more fuzzy "Curie Point" depths, can be integrated to create heat flow anomaly maps that will be a vast improvement on the existing practise.

The EM spectra and its measurement continue to provide challenges and insights into whole earth processes. The ability to interpret the EM spectra from the standpoint of extracting information about crustal heat deserves more thought and development.

A better understanding of how Plank's Law and the physics implied by it would be important in interpreting non-solar influenced earth heat emissions.

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