# Remote sensing of heat: A Review of potentially useful methods and instruments in the quest for innovative exploration approaches

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Direct sensing of surface radiant heat, and buried temperature anomalies by remote methods deserves more attention because of the potential uses these methods can offer the geothermal exploration industry. Many instruments and methods exist, but their data have been largely ignored to date.

This paper provides a review of available, and yet to be tested methods, and their relative merits. In summing-up, focus is aimed at methods to measure surface radiant heat. There are ongoing challenges with data interpretation, new mathematical methods and software development.

Finally, a calibration range is advocated in one or more of Australia's more prospective regions for the purpose of testing and consolidating better use of geophysical methods, and developing diagnostic tools kits for exploration.

*Keywords*: Surface radiant heat, heat flow anomalies, Aster, airborne survey, SQUID, 3D modelling, Curie.

## Introduction

There is only token use of remote sensing technology in Australia for heat resource exploration. This seems strange given that field mapping, sampling and drilling are orders of magnitude more expensive. It is also true that the quantitative values from remote sensing are not believed by some workers, to reflect reality.

In estimating a thermal resource for a project via 3D modelling, one is required to input surface temperature, heat flow constraints, and rock property constraints (i.e., thermal conductivities and heat production rates). For all of these inputs, direct measurements need to be obtained to enable thermal modelling and interpolation of results but all of these inputs are typically under-sampled in the project area. The danger here is that local variation in geology and heat flow is generally not being accounted for. Therefore other methods to complete the picture of required inputs are required. This paper suggests complementary inputs can be achieved though acquisition of a well-calibrated and high resolution remotely sensed surface radiant heat map.

To reiterate the merits of this proposal:

1. Measuring any independent variable that reflects a property of the sub-surface geology will always make a contribution to the 3D geology earth model. So along with gravity, magnetics and radiometrics, why not measure surface radiant heat, as a potential means of understanding relative surface heat flow?
2. The rock properties required for a heat resource calculation are typically under sampled even though the variability is generally very high. Proxy measurements of surface heat flow, from remotely sensed surface radiant heat, may help elucidate populations of rocks with similar properties.

A common counter argument to the proposed use of surface radiant heat maps is that what happens at surface has little to do with what might be happening at a depth of say 3 kilometres, where, for e.g., there could be sedimentary layers "blanketing" the resource. Figure 1 illustrates this point. Different thermal gradients will exist in rock units of different thermal conductivity. This is the essence of the "hot dry rock" geothermal energy resource.

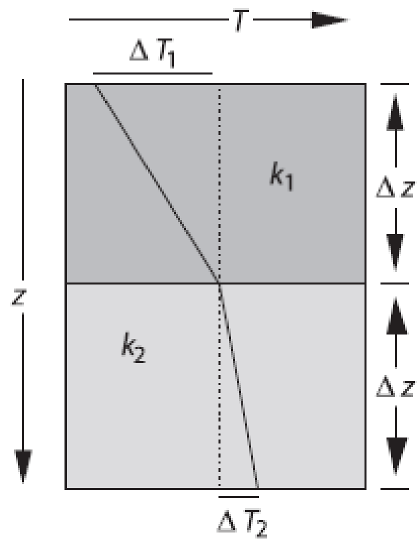


Figure 1. Cartoon illustrating how the geothermal gradient changes with depth if a low conductivity layer (k1) overlies a high thermal conductivity layer (k2). This is a special case of what is more generally known as heat refraction.

Like any other geothermal energy resource, this requires elevated rock temperatures to occur at anomalously shallow depths. For instance, this is achieved if a highly radioactive granite (with medium to high thermal conductivity) is thermally insulated from above by sedimentary cover of low thermal conductivity.

The current thrust in Australia is to find high value EGS resources that could provide significant base load electricity economically. Finding lower temperature heat and hot water resources for direct use (e.g., Cottesloe swimming pool, in W.A.) also has significance for the Australian economy long-term.

Both of these geological scenarios will have distinct surface signatures in terms of heat flow, holding clues to the thermal regime existing below, eg., a negative or a positive surface heat flow anomaly. Surface pattern recognition will be part of the improved innovative exploration methodology. In summary, remote sensing of surface radiant heat has an important part to play in the exploration of both geothermal energy scenarios.

## Earth's Heat Loss

In this section we review some principles of Earth's heat flow balance.

Earth's heat loss at present is about:

- 74% from plate activity,
- 9% from hot spots, and
- 17% from radiogenic heat lost from continental crust.

Typical heat flows at the Earths surface are between 0.001 W $m^{-2}$ and 0.1 W $m^{-2}$. The mean heat flow of all continents *qc* and that of the oceans *qo* , are:

$qc$ = 0.065 W $m^{-2}$

$qo$ = 0.101 W $m^{-2}$

(Stein, 1995, Stüwe, 2007).

This energy is directly emitted at the surface, together with heat being absorbed and re-emitted from external sources (see Figure 2). The direct sensing of this surface radiation (Figure 2), or "surface radiant heat" (the adopted terminology for this paper) is problematic, because the contribution of Earth heat loss is very small relative to all other factors. This is analogous to measuring gravity anomalies in an aeroplane, for which there are now several viable systems.

Figure 2 shows a cartoon of the inputs and outputs of the surface heat balance and gives approximate quantities during normal daylight hours. This model comes from NOAA and is a summary of the annual energy budget for the atmosphere.

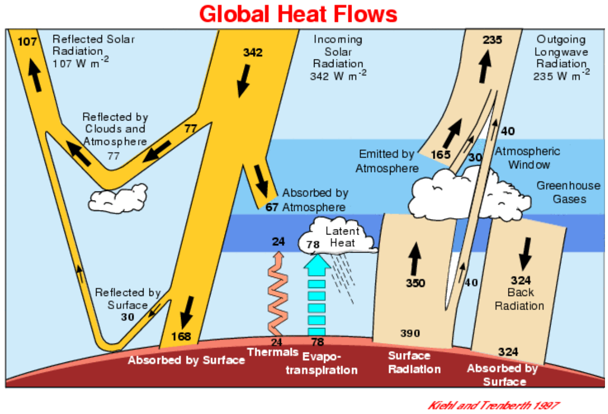


Figure 2. Global heat flows in Watts $m^{-2}$ during daylight hours. Critically, night-time or pre-drawn readings of surface radiation contain a far-reduced component of reflected solar radiation.

## Periodic Surface Temperature Fluctuations

Temperatures at the surface of Earth vary both in time and in space: daily and annual temperature fluctuations cause temporal variations and adiabatic gradients cause variations with surface elevation. While both may not be important in Australian geothermal energy problems, they are considered briefly here because they are important to account for when interpreting remotely sensed surface radiant heat (along with other surface effects such as moisture).

The relevance of temporal fluctuations may be studied by assuming that the diurnal or annual temperature variation at the surface is simply described by a cosine function:

$$T = \Delta T \cos(ft) \text{ at } \textit{the surface}$$

where $f$ is the frequency (i.e. 1 per day or 1 per year).

For these boundary conditions, there is an analytical solution of the heat flow equation given by:

$$T = T_0 + \Delta T e^{\left(-z\sqrt{f/(2\kappa)}\right)} \cos\left(ft - z\sqrt{f/(2\kappa)}\right)$$

where $T_0$ is the starting temperature at $t$ = 0, $f$ is the frequency (e.g. 1 per year) and $\Delta T$ is the annual temperature amplitude (e.g. 20 °C between summer maximum and mean annual temperature).

Annual fluctuations only influence temperatures at depths down to about 5 metres. Thus, annual and daily temperature fluctuation have to be accounted for in any remote sensing work and removed before 3D modeling is performed.

## A review of existing, potentially useful methods and instruments

### Satellite sensing of surface radiant heat

There are many contexts where either satellite, airborne or surface measurements clearly indicate unambiguous temperature anomalies in the sub-surface geology. Scenes gathered at night-time using thermal imagery are often quite good indicators of large scale sub-surface temperature anomalies.

ASTER, Landsat and NOAA satellite systems are used extensively by remote sensing specialists to help map geology. A considerable part of the measured signal is from the thermal infra-red (TIR) spectrum. For example, in Figure 3 below, a strongly negative thermal anomaly is imaged on surface in the Middle East. Here sub-surface hydrocarbons (poor thermal insulators) are creating a localised low heat flow anomaly that can be imaged on surface. Therefore, *from surface imagery alone* the ability to image thermal conductivity contrasts and gain clues about the possibility of strong heat refraction in occurring at depth, demonstrated here.

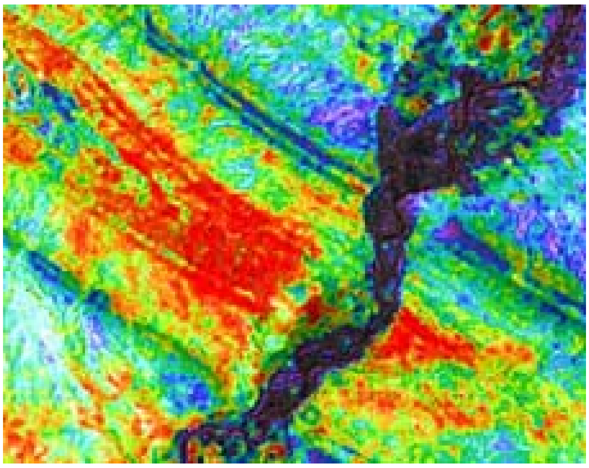

Figure 3. Night-time thermal imagery shows a strong negative (cold) thermal anomaly in the core of an anticline in the Middle East. In this case, sub-surface hydrocarbons with a low thermal conductivity are causing this surface expression.

Extensive use of ASTER NTIR or night-time thermal infra-red data from the northern Flinders Ranges (Beverly Mine Project area), has been used by Stamoulis 2006. This is a first attempt to minimize the effects of daytime temperatures on emissivity. In this example, paleo-channels have been located due to their lower sediment temperature, which is thought to be due to their higher moisture content (related to higher permeability and porosity in fluvial sediments). Figures 4a & 4b demonstrate the identification of temperature contrasts from the ASTER pre-enhanced temperature map. Surface expressions of palaeo-channels are not always evident from elevation, but their presence has been supported by field observations and drillhole data (Stamoulis 2006).

This work has been followed up in 2007 by Hou et. al. and now includes a publication of a state wide paleo-channel map. Temperature maps available as higher end ASTER products require minimal processing and can be integrated with existing data.

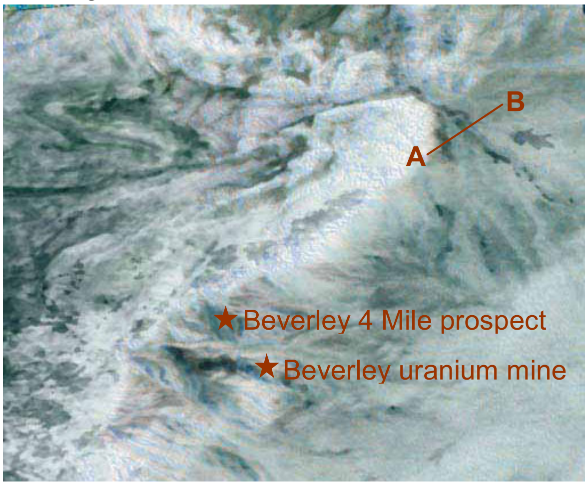


Figure 4a (after Stamoulis 2006). Aster NTIR system image from the Beverly project in the North Flinders Ranges. Dark areas indicate cooler temperatures. In areas of high elevation, colour contrasts are likely to indicate lithology variation. A-B refers to the profile in Fig 4b.

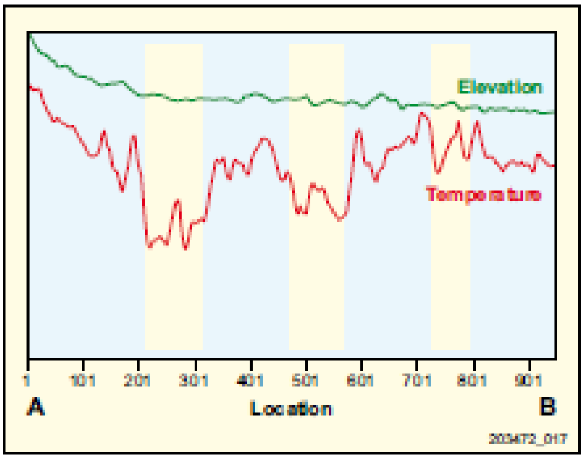


Figure 4b (after Stamoulis 2006). Sediment temperature contrasts are apparent despite no correlation with elevation, and these indicate the location of paleo-channels which are confirmed by drillhole data.

Several groups have developed technology for adjusting the Aster signal to correct for “Black Body” radiation in order to predict surface temperatures and/or heat flow associated with the outcropping geology. The RASTUS system by Neil Pendock is one example.

Black body effects must be removed from each Aster spectrum before the TIR imagery can be meaningfully interpreted. This is achieved by fitting and removing a blackbody curve from each of the TIR spectrums.

Afterwards, two outputs are available: a temperature image and a blackbody corrected data set. An example of this processing from India is shown below in Figure 5.

Further research can provide important information such as understanding temperature variations and properties of outcropping units. Applying such new knowledge will further improve interpretations where ASTER NTIR data is used and exploration targets will be better defined. ASTER data is very cheap to acquire compared to almost any other datasets.

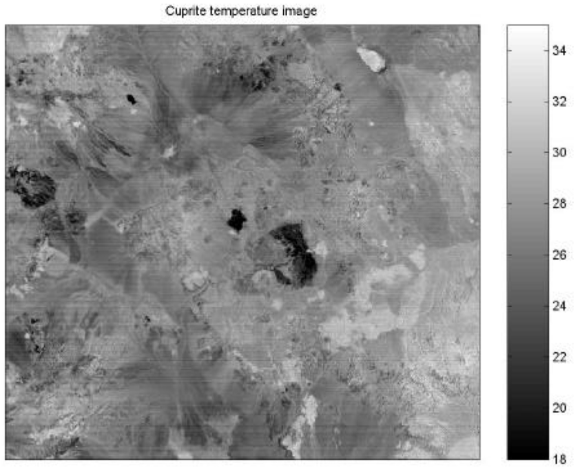


Figure 5 shows an example of a surface temperature map derived from pre-dawn Aster data using the RASTUS system. It shows over 16 degrees centigrade variation on the surface (temperature scale in ºC).

## Air Airborne sensing of magnetism for Curie T depths

The continental scale estimate of the temperature at 5 km depth mapped for Australia is due for another upgrade. This time the aim should be to extrapolate from the isolated deep well observations as before, but to also add in a blended contribution from the estimate of the depth to the Curie temperature (approximately 560 degrees).

This estimate can be made using the aero-magnetic observations and seeking the bottom or greatest depth to magnetic basement. While this is very dependent upon the quality of the observed magnetic data, we are fortunate in Australia, to have arguably the best observed regional magnetic datasets. If any country can get it right, Australia should be first. There is scope for new algorithms to emerge for this task.

## Airborne sensing of past and present high heat alteration effects

Another approach is to look at surface expressions of mineralogy that indicate where high heat alteration conditions have existed in the past. The mineralogy can be directly sensed using the reflectance of light and analysing wave-lengths (hyper spectral). Regional mapping can be used to differentiate granites through mica chemistry and mafic mineral content. (e.g., Pilbara Geology Mapping, WA.)

**Structure Control Of Alteration?**

**Above map of structural features derived from interpretation of 1:25,000 aerial photographs. Blue box shows location of scanner image.**

**Right Mineral index image pyrophyllite/ dickite/ sericite superimposed on the structural map.**

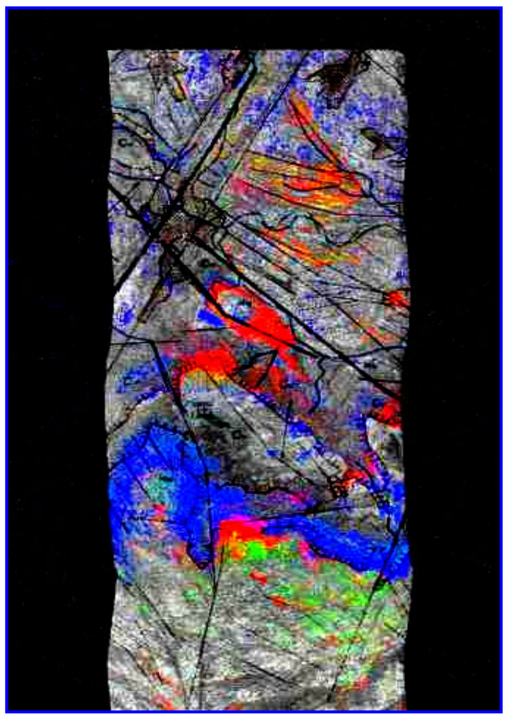

Figure 6. These images show methods adopted in the North Kimberley to analyse whether locations of mineral systems are controlled by structural features, or by alteration zones. Images courtesy of HyVista Corporation.

The HYVISTA system has been used in the North Kimberley region of Australia for the detection of hydrothermal alteration associated with deep-seated high temperature granites. The question, “When did this alteration occur?” is not resolved by this sytem.

### Airborne sensing of radiometrics

The daughter products of natural radioactive decay in and around granitic rocks, includes radon gas. This is routinely observable during gamma ray airborne surveying, in Australia where there is granitic outcrop, on days of no rain and little wind.

This is thought of as noise and routinely discarded. The entire raw radiometrics surveying record for Australia contains quite a bit of this information. No systematic use of this record has been contemplated to date, with the possible exception of Geoscience Australia’s OESP Geothermal Programme.

### Ground sampling of radiometrics

Another daughter product from deep-seated radioactive decay is helium. This is not easily detected from an airborne system, but instruments do exist for ground surveying. This class of instrument is a chemical sniffer rather than an instrument based upon spectroscopy. Hot Dry Rocks market such an instrument.

Alternatively the direct detection of radon gas as an exploration tool is being used routinely in Namibia using the RADONTEX© system.

## Exploration Tools for the Future

### Innovations in remote sensing instruments

The pursuit of remotely-sensed data to help constrain deep sub-surface temperature predictions prior to drilling is not new, and is not restricted to the geothermal industry. For example, Shell are investigating various methods to help devise world temperature-depth maps in relation to sedimentary basins hosting hydrocarbons. Multidisciplinary approaches will eventually led to technology advances, benefiting a range of industries.

Many types of instruments are available. With the advent of SQUID (Super Conducting Interference Device) devices, the sensitivity and response time are now such that viable observation systems for direct measurement of surface radiant heat are evolving, and these are significantly more useful.

The classical direct heat measurement instruments are:

- Thermometer – temperatures and gradients
- Bolometer–surface radiant heat. This is the term coined by Langley of CIA fame for such an instrument which he invented in 1886.

Importantly, in the presence of significant water vapour, a bolometer is opaque to radiant heat through much of the thermal infrared band, as illustrated in figure 7 below.

Therefore, the greater the column of air, the more the heat signal would be attenuated, so satellite measurements are the least ideal. Low flying aircraft based systems are a good compromise for surveying.

A downward looking “telescope” that is in fact a bolometer, will yield more sensitive and precise measurements. At least 5 of the frequency peaks in Figure 7 should be chosen for measurement.

The German group IPHT from Jena manufacture such an instrument that would be very suitable. This instrument has never been deployed upon an aircraft, but rather on satellites. It is expected a prototype may emerge in 2010.

### What To Measure?

There are many sceptics to the notion of remote sensing of surface radiant heat and temperature. They claim that surface temperatures, in a spatial sense, do not vary very much when averaged over several days.

Remote sensing work using thermal infra red bands from satellite systems such as Aster indicate that there are significant spatial anomalies in surface radiant heat and temperature associated with locally outcropping geology (Figure 5).

These two positions (above) are not irreconcilable – we look to physics to explain how both observations can co-exist.

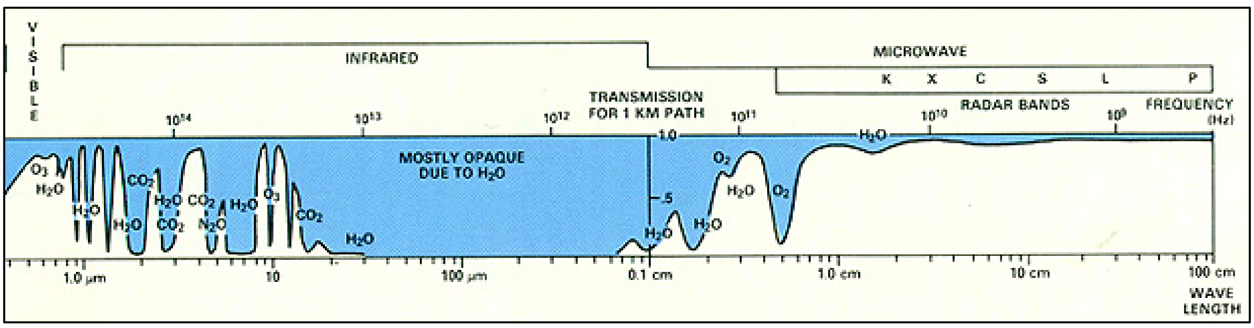


Figure 7. Shows the electro-magnetic spectrum and highlights in the thermal bands, those frequencies that cannot be measured due to water.

For those familiar with gliding, thermals form over "Black Bodies" and strong updrafts can exist over areas of high heat emittance even though surface temperatures may not vary greatly.

### Known obstacles to the remote sensing of surface radiant heat

Among the obvious issues to overcome are:

- effect of evapo-transpiration
- Albedo effect
- Black body corrections
- ground water and its influence in masking
- clarification of transient vs. steady state measurements
- what quantity is being measured and how does it compare with other measurements using different physical principals

There are already many examples of published techniques for dealing with these issues. For example, the US Geological Survey via Ken Watson (1992) has investigated removal of the Albedo using innovative Fast Fourier Transform filtering techniques.

There are many examples in observational geophysics where the anomaly to be measured is less than $10^{-5}$ of the gross amplitude. Heat anomalies are just another challenge of this nature.

Overcoming these and other challenges including: data interpretation and software development are all required to ensure proposed future methods deliver useful outcomes for EGS explorers in Australia.

## A Proposal For An Australian Calibration Range

My proposal to the AGEG community is to set up calibration ranges in at least two settings representative of Australian conditions.

Examples of other calibration ranges are available from the work of our overseas counterparts (Figure 7), but we require our own range to test specific geological and geophysical issues arising here on the Australian continent, where we are leading the world in EGS exploration.

In conventional geothermal systems, there is usually an easily discernable expression of near surface heat. Figure 8 shows a calibration or test range set up in Nevada by the US Geological Survey (Kratt, et. al. 2008). Here Aster satellite data, pattern drilling of short length test holes, some deeper drilling and locations of known "hot" geological structures such as geysers are shown.

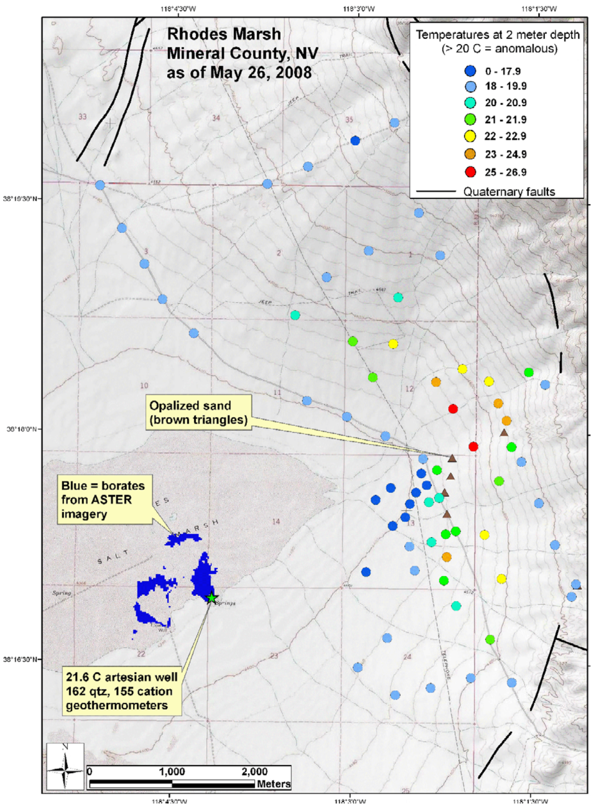


Figure 8. Shows the general layout for what can be described as a calibration range in Nevada, USA.

Two calibration ranges are proposed for Australia:

## Range 1

Northern Flinders Ranges (South Australia) where there are known high-heat producing granites, due to radiogenic contribution. The aim is to conduct a detailed field mapping exercise to acquire surface heat and temperature measurements and rock properties on say a 200m grid basis for a 5km x 5km area. The study area should cover both exposed and covered granites. The weather conditions, time of day, cloud cover and soil moisture are also factors to be recorded.

## Range 2

Onshore PortCampbell (south-western Victoria) where there are suspected oil seeps associated with faulting. There are also many deeper oil exploration wells in this area.

An initiative to get the ball rolling could be funded by government sources. All datasets go in to the public domain and any party that wants to try out their technique in the test range can have access to all the past data.

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