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Conversion of thermal infrared surveys to heat flow: Comparisons from Dixie Valley, Nevada, and Wairakei, New Zealand

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ABSTRACT

Shallow soil temperature were measured at Dixie Valley geothermal field between 27-29 October, 1998 in order to assist interpretation of pre-dawn, airborne thermal infrared (TIR) imagery acquired three months earlier. Measurements at the surface, 1 cm and 10 cm depth were made on the Senator thermal area at predawn, and intermittently during the three days at three stations at depths up to 1 m. The latter measurements indicated a thermal diffusivity for the soil of ~0.5×10^{-6} m^2/s. A comparison between surface temperatures measured with a hand-held TIR sensor and a thermistor at 1 cm depth confirmed the same magnitude of temperature anomaly over lightly vegetated and bare ground. On thermal ground, the near-surface temperature gradient increased linearly with surface temperature above about 15°C. The linear relationship derived from the Senator thermal area is similar to that observed at Wairakei field. Comparisons with total heat flow measurements from Wairakei field imply the surface heat flow may be predominantly conductive for surface temperatures up to ~80°C and heat flows of up to ~300 W/m^2. The thermal effects of observed non-condensible gas fluxes through the soil are shown to be negligible. At low temperatures, factors such as emissivity, thermal conductivity and ambient temperature are important uncertainties; at high temperatures, convective heat losses become important.

Introduction

During the summer of 1998, an airborne thermal infrared (TIR) survey was flown immediately prior to dawn over Dixie Valley

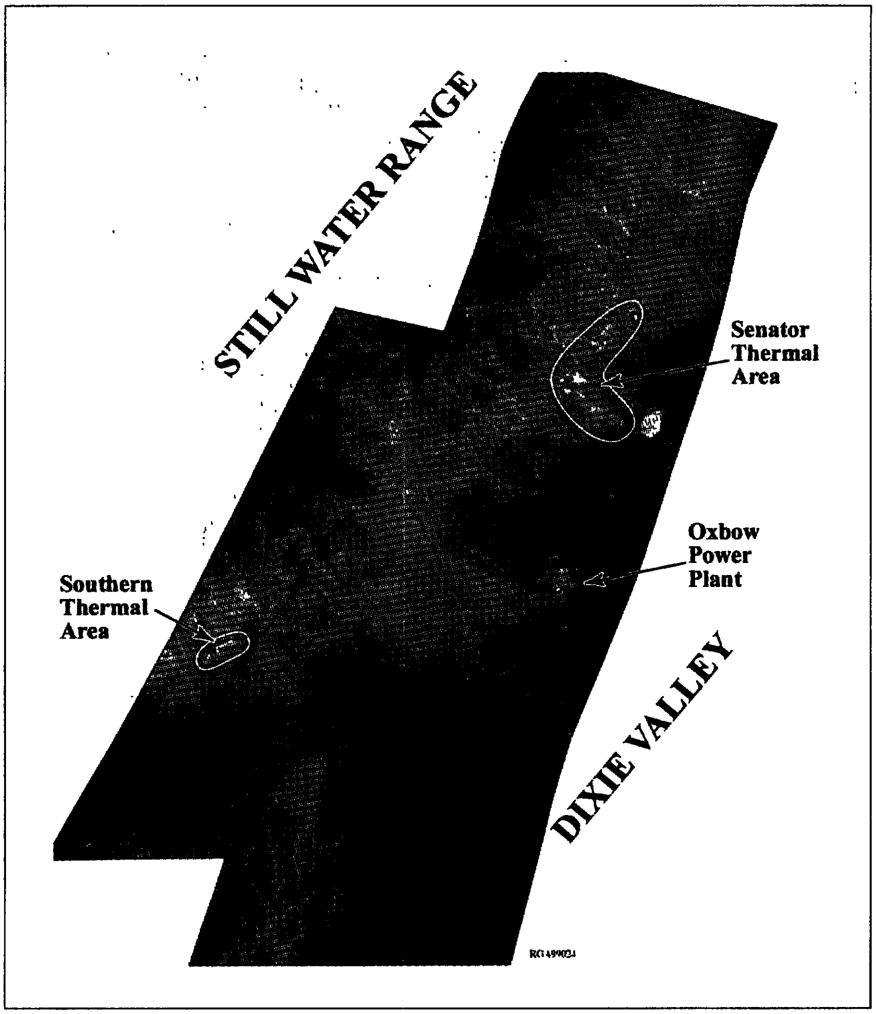

Figure 1. Unprocessed thermal infrared image of part of Dixie Valley field. There are two areas of thermal activity identifiable on this image (labeled). This paper concentrates on the area of increased thermal activity around the Senator fumarole and the adjacent fan. Light tones indicate higher surface temperature.

geothermal field to assist mapping of the changes known to be occurring in the thermal activity. Part of the unprocessed TIR image, acquired by NASA with their ATLAS multi-spectral sensor at a height of 2600 m above the valley floor, is shown as Figure 1, previous page. The two areas of known thermal activity are clearly identifiable, as are roads, pipelines and a newly formed pond due to subsidence at the base of the Senator thermal area. Variations in surface temperature can be caused by many factors including the effects of diurnal atmospheric temperature variations, the degree of exposure to solar heating and the emissivity of the surface, and cooling effects caused by vegetation or varying soil moisture content.

To assist quantitative interpretation of the TIR imagery, ground-truth soil temperature and gradient measurements were subsequently made over the Senator fan (i.e. area containing the Senator thermal area and the Senator fumarole) between October 27-29, 1998. These comprised infrared measurements of the ground surface and vegetation with a hand-held sensor, and temperatures measured at 1 cm, 10 cm and 1 m depth with a thermistor sensor. They have allowed an estimate of the thermal diffusivity of the soil, and the relationship between surface temperature and conductive heat flow to be inferred. In this paper we report on the preliminary findings from these measurements, and compare these with similar measurements made at Wairakei field two decades earlier (Allis, 1979). The interpretation of the airborne TIR imagery from Dixie Valley will be reported elsewhere.

Temperature Transients at < 1 m depth in hot ground

Both the airborne TIR imagery, as well as most of the ground truth measurements were collected immediately prior to dawn so that solar heating effects from the previous day were minimized. Even so, changes in temperature with time around the time of the surveys can cause significant transient effects that need to be considered when interpreting subsurface data collected as ground-truth. Both increasing attenuation of the temperature variations and increasing phase lag occur with increasing depth. The changes in air temperature around the time of the ground truth survey at Dixie Valley are shown in Figure 2, along with those recorded at the time of the airborne TIR image acquisition.

In order to observe the conductive attenuation of the daily temperature wave with increasing depth, and potential effects of convective heat flow, three temperature-monitoring stations were set up at around the Senator fan. These were sited in cold, warm, and hot ground for the period 27–29 October 1998. Each station comprised a cluster of 1.2 cm diameter water-filled pipes set at varying depths. The stations were monitored at widely spaced times during the day. Figure 3 summarizes the results from the three stations.

The cold ground Station C shows the expected gradual decrease in diurnal temperature variations with depth. This thermal behavior is not seen at Station B or Station A. These two stations are several meters apart, at increasing distance from a patch of weakly steaming ground. Station A is dominated by the vertical movement of steam (96°C) between 1 m and 30 cm depth, with an overlying boundary zone where steam condensation is presumably occurring. Station B also has a broadly convex-upwards shape suggestive of thermal effects resulting from upward migration of warm vapor. The 10 cm depth temperatures in Station B appear anomalously warm, and could be influenced by lateral heat flow effects.

Quantitative analysis of the attenuation of temperature variations with depth in Station C indicates a thermal diffusivity of 0.5×10^{-6} m^2/s (± 50% uncertainty, Allis *et al.*, in prep.). The important qualitative observation for the thermal structure at

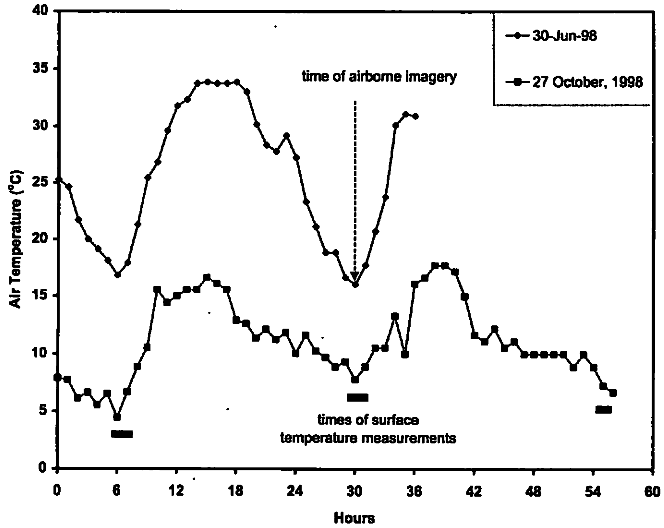

Figure 2. Comparison of the atmospheric temperature trends measured near the power station around the time of the airborne image acquisition (July, 1, 1998) and the time of ground-truth measurements (October 27 – 29, 1998). The time axis starts at midnight on the indicated date.

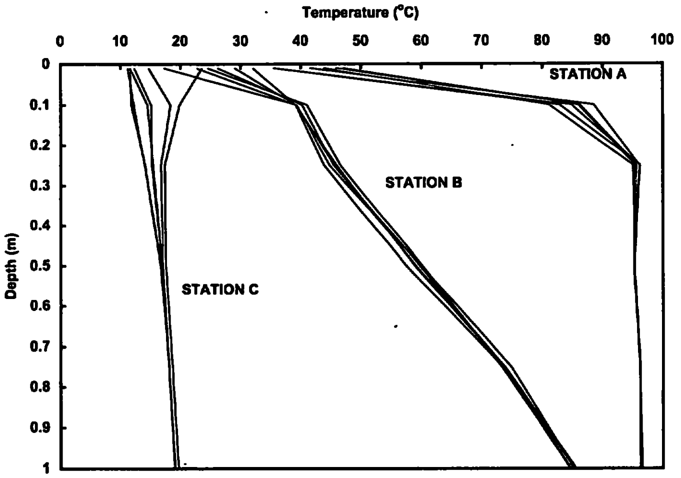

Figure 3. Summary of temperatures measured at three 1-meter depth monitoring sites in hot (A), warm (B) and cold ground (C). These sites are shown on Figure 1. Note the increase in surface temperature with increasing surface temperature gradient.

all three stations is that with increasing subsurface temperature, both the surface temperature and the near-surface temperature gradient increase. The temperature gradient between 0 and 0.1 m depth increases from around zero at Station C (influenced by the time of day), to around 4°C/cm at Station A with the corresponding surface temperature increasing from 15 to 40°C. For a typical soil conductivity of 0.5 W/mK (Clark, 1966; a 50% uncertainty is likely), the conductive heat flow implied by the maximum gradient is 200 W/m^2. At Station C, the gradient of 4°C/m between 0.5 and 1.0 m depth implies a conductive heat flow of 2 W/m^2. Significant additional heat could be flowing convectively to the surface at Station A, with visibly steaming cracks present at less than 1 m from the station.

The 4°C/m gradient below 0.5 m depth in Station C is mostly due to the annual variation in ground surface temperature. Although the amplitude of the annual wave on the ground surface is unknown at Dixie Valley, an estimate using a sinusoid with a mean annual temperature of 15°C and a 5°C amplitude peaking in late July, predicts a 4°C/m gradient 3 months later (i.e. at the time of these ground-truth surveys). The gradient in temperature at Station C is therefore dominated by the annual variation in temperature, and not by the station's location in the vicinity of the geothermal field.

The qualitative relationships between surface temperature, near-surface temperature gradient, and conductive heat flow in Figure 3 provide the basis for the surface temperature measurements made on the Senator fan, as discussed below.

Surface Temperature and Gradient Trends

Pre-dawn ground surface temperature measurements comprised 1 cm and 10 cm depth soil temperatures, and infra-red (IR) temperatures of both the adjacent fan soil surface as well as the vegetation. The soil temperatures were measured with a thermistor probe (accuracy 0.2°C), and the hand-held commercial IR probe had an accuracy of 0.5°C.

A comparison of the 1 cm depth temperatures and the IR surface temperatures is shown in Figure 4. None of the measurements has been corrected for the temperature variations with time. There is no significant difference between IR measurements on the road (compacted fan material) and the adjacent undisturbed bare fan. However, both IR temperatures are an average of 1°C cooler than the 1 cm depth measurements for temperatures up to about 10°C above ambient temperature on non-thermal ground. Part of the difference could be due to the shallow temperature gradient present in the soil at the time of the surveys, and the requirement for the thermistor probe to actually be under the surface (i.e. at 1 cm depth) in order to equilibrate rapidly with the soil temperature. Irrespective of the reason, Figure 4 confirms that airborne IR measurements over the lightly vegetated fan should show a thermal anomaly similar in magnitude to the soil temperature at 1 cm depth.

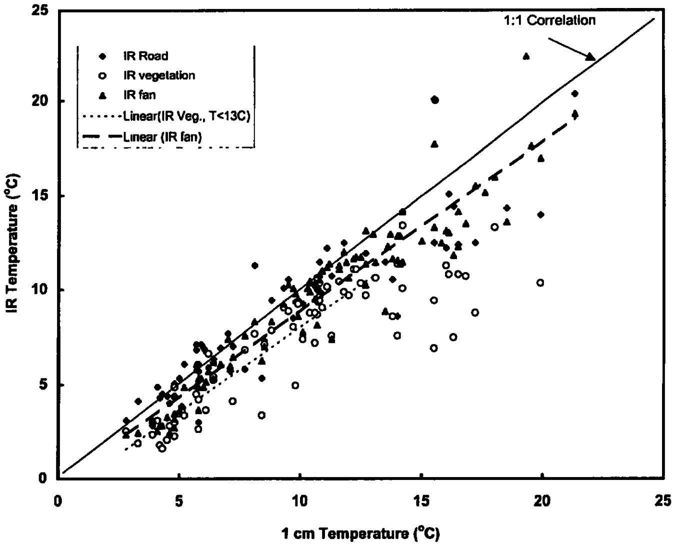

Figure 4. Comparison between the soil temperature measured at 1 cm depth and the infrared surface temperature on nearby thermal ground and nearby vegetation on the Senator fan, Dixie Valley (October 27-29, 1998). There is no significant difference between the IR road and IR bare ground temperatures. The correlation (R^2 = 0.9) between bare ground IR temperatures and 1 cm temperatures provides a quantitative basis for using airborne IR imagery for mapping soil temperature variations on the lightly vegetated fan.

The IR temperature of the vegetation is systematically about 2°C lower than the 1 cm temperatures for locations where the 1 cm temperatures < 10°C above the cold ground ambient temperature (3-5°C; Figure 4). At higher ground temperatures there is little correlation with the soil temperature. This is attributed to the vegetation temperature more closely reflecting atmospheric temperature rather than soil temperature. The vegetation density is low over much of the Senator fan due to earlier die-back (Bergfeld *et al.*, 1998; Johnson and Nash, 1998). The thermal effects of vegetation on the airborne thermal imagery in this area are therefore not likely to be significant.

The 1 cm and 10 cm depth soil temperature measurements were made over a 2-3 hour period at predawn on the 27th and 28th October. Because air temperature was varying during the measurement period, and between the two days, correction is needed for the transient thermal effects. This correction used a sinusoidal surface temperature function fitted to the known trend in atmospheric temperature, and a soil thermal diffusivity of 0.5 x 10^{-6} m^2/s. The correction causes the seven readings at a base station during the two days to have a mean temperature at 1 cm depth of 6.8 ± 0.7 °C (1 s.d.), and the mean gradient between 1 and 10 cm depth to be 0.46 ± 0.05 °C/cm. These uncertainties are considered indicative of the uncertainties in the corrected surface temperatures and temperature gradients discussed below.

Assuming the thermal conductivity of the soil to be 0.5 W/m°C (dry soil, Clark, 1966), the corrected gradients can be converted to conductive heat flow values. There could be a systematic error of up to 50% in these heat flow values due to the assumed thermal conductivity value, but relative heat flow values will be more accurate. Plots of the relationship between heat flow and surface temperature, and heat flow and 10 cm temperature reveal a surprising result (Figure 5, overleaf). There appears to be no relationship between surface temperature and the conductive heat flow up to almost 10°C above ambient temperature. This means that both the 1cm and the 10 cm temperatures varied by the same amount, along most of the survey lines across the fan. The 0.4°C/cm average gradient for the

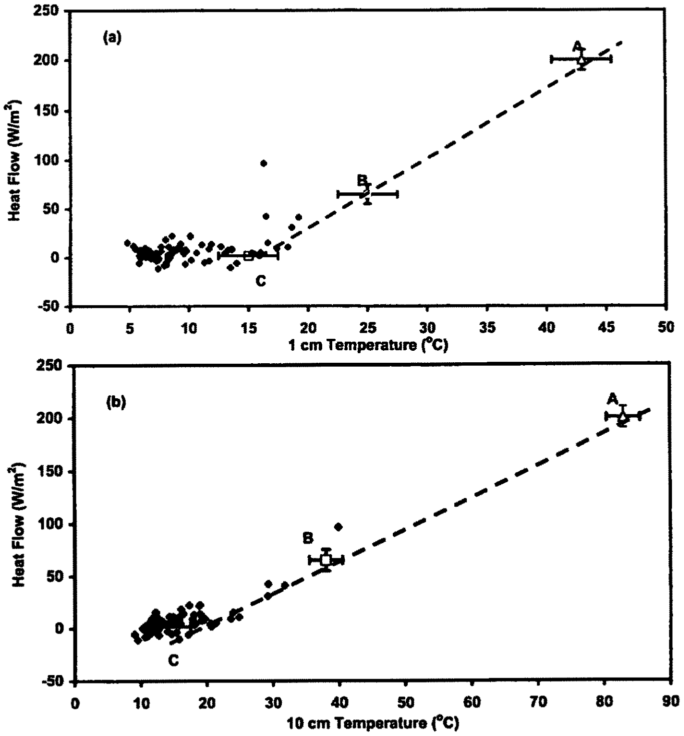

Figure 5. Comparisons between the temperatures at 1 cm, 10 cm depth, and the conductive surface heat flow (derived from the temperature gradient between 1 and 10 cm depth). The three points with error bars are from Stations A-C. The scatter of points in the upper graph with a surface temperature of < 15°C is attributed to the effects of micro-climatic warming at higher elevation on the fan.

time of the surveys, equivalent to 2 W/m² average conductive heat flow, is therefore no different to that observed in non-thermal ground away from the fan.

The simplest interpretation is that the ground surface temperature on these parts of the fan is warmer than that near the valley floor due to the pre-dawn air temperature being warmer on the fan. Evidence that the 10 cm soil temperature rises significantly above the background gradient is only seen when the surface ground temperatures were above 13-15°C. Here elevated surface temperatures can be attributed to elevated heat flow from depth. The cause of the anomalously warm air temperatures is attributed to the presence of a micro-climate with a temperature inversion. The micro-climate was probably caused by cold air drainage from the Stillwater Range earlier in the evening. This resulted in a lower-valley cold-air sink which displaced warmer air to higher altitudes eventually moving up the fan as the drainage decreased.

The elevation of the Senator fumarole where most of the steaming ground is located is 100 m higher than Base Station D. This micro-climatic warming of the air and ground temperatures around the thermal areas on the Senator fan means that the outer boundary zones of surface thermal anomalies may be in error if lateral changes in ambient temperature are not considered.

With this caveat in mind, the linear relationship between near-surface conductive heat flow and surface ground temperature is mostly based on the three 1 m temperature monitoring sites (Stations A – C; Figure 5). The equation for the line is:

$$Q_c\ (\mathrm{W/m^2}) = 7\ (T_1 - T_{amb}) \qquad (1)$$

where Q_c is the total conductive heat flow, T_1 is the temperature at 1 cm depth in °C, and T_{amb} is the ambient temperature, in this case approximately 15°C. Equation 1 theoretically provides a simple way for converting TIR anomalies in heat flow anomalies, but in practice it needs to be applied cautiously in view of the uncertainties. These uncertainties are discussed below.

Comparison with Wairakei Field

Despite the paucity of data from Dixie Valley, Equation 1 is similar to that determined in a more detailed study of the shallow thermal regime in a thermal area of Wairakei field, New Zealand (Allis, 1979; Figure 6). The soil in the Wairakei study area was dry and pumiceous, with a thermal conductivity of 0.6 W/m°C. The Wairakei study showed that the near-surface conductive heat flow increased almost linearly up to a temperature of 60 – 80°C at which stage the conductive heat flow decreased with a further increase in ground temperature. The temperature of this transition from predominantly conductive to increasingly convective heat flow was found to *decrease* with *increasing* depth, being as low as 30 – 40°C at 1 m depth (Allis, 1979). The reason for this is thought to be the increased magnitude of the conductive heat flow when the upper boundary zone to the convecting steam and vapor is thin. In thin boundary zones all the subsurface convective heat flow from depth may be balanced by a high conductive heat flow at the surface.

When the two Dixie Valley lines from Figure 5a,b are superimposed on the Wairakei data, there is reasonable agreement, particularly in the relationship between surface temperature (1 cm depth) and conductive heat flow (Figure 6). The match between the 10 cm depth line and the 10 cm data at Wairakei would be improved if the thermal conductivity of Dixie Valley soil is 10 – 15% higher than that assumed (0.5 W/m°C). Measurements with a calorimeter sitting on the ground surface at

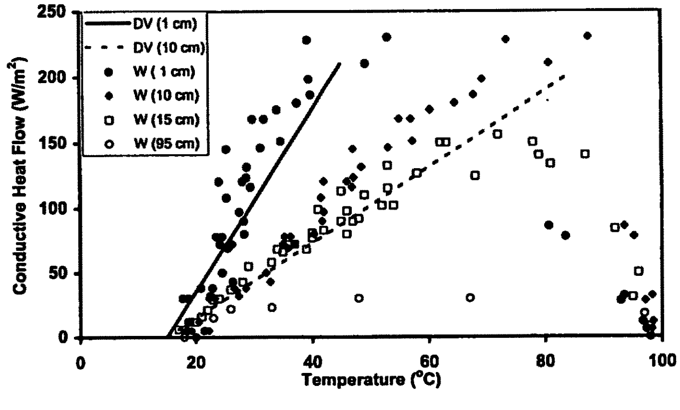

Figure 6. Comparison between the near-surface thermal regimes adjacent to thermal areas at Dixie Valley (DV) and those at Wairakei field, New Zealand (W). The two lines are from Figure 5. All 1 cm and 10 cm depth data have their heat flows determined from the temperature gradient between 1 and 10 cm depth. The 15 cm W data uses the gradient between 10 and 20 cm depth; the 95 cm W data uses the gradient between 90 and 100 cm depth. The similarity in the DV and W 1 cm depth temperature-heat flow trends suggests that the relationship may be widely applicable.

Wairakei field have indicated that for temperatures up to 70°C at 15 cm depth, the total heat flow is similar to the conductive heat flow. That is, the advective steam flow at the ground surface is insignificant because most steam flow has condensed at greater depth. It will be shown below that there are also negligible thermal effects from the observed non-condensible gas flux through the soil.

The similarity of the surface temperature – heat flow relationships between the two areas is partly a consequence of similar thermal properties of the soil, and partly due to the similar average temperature at time of data acquisition (15 – 20°C in both cases). Large variations in the ambient temperature outside this range probably cause the slope of the line to change due to the surface soil temperature at high temperature being more controlled by convecting steam rather than atmospheric temperature.

Equation 1 may be used to gain a first-order estimate of the *total* heat flow from a map of surface temperatures, as long as the effects of actively steaming ground are considered separately. This expression predicts a heat flow of 500 W/m^2 for a surface temperature of 90°C. The calorimeter experiments of Dawson, (1964) at Wairakei field measured *total* surface heat flow values of 300 – 400 W/m^2 for soil temperatures at 15 cm depth of >90°C. The *surface* temperature during these measurements is unknown, but it would have been less than 90°C. Allis (1981) simplified Dawson's thermal ground classification, and had a "medium" grade of thermal ground where the surface heat flow was 500 W/m^2 for soil temperatures in the range 80 – 97°C at depths of 7 – 15 cm respectively. "High" grade thermal ground which applied to steaming ground had a much higher heat flow weighting factor. Under this classification, Equation 1 may give the correct order of magnitude total heat flow from low and medium grade thermal ground. An additional component of heat flow will be necessary for actively steaming ground. In such cases cool atmospheric steam may obscure true ground temperatures acquired by airborne TIR surveys, so ground inspection of such areas is required.

Thermal effects of CO_2 flux

The apparently linear relationship between conductive heat flow and surface temperature raises a question about thermal effects of the non-condensible gas flux through the soil, and whether this could be contributing to the total surface heat flow. The dominant component of these gases CO_2. Bergfeld *et al.* (1998) showed that there is a weak correlation between soil temperature and CO_2 flux on the Senator fan, particularly close to the most active areas of steaming ground. The observed CO_2 flux ranged from less than 0.01 to a maximum of 0.2 kg/m^2/day. This gas flux is inferred to have caused the vegetation over a large part of the fan to die back (Bergfeld *et al.* 1998; Johnson and Nash, 1998). A simple check on the advective effects of warm CO_2 can be made if its specific heat can be assumed to be constant. This is reasonable if the CO_2 is rising to the ground surface at close to atmospheric pressure after separating from the groundwater table. The analytical expression for one-dimensional fluid flow through porous media (Bredehoft and Papadopulos, 1965) has been used for this calculation, together with an empirical expression for the specific heat of CO_2 at constant (zero) pressure (Sweigert *et al.*, 1946). This latter expression yields a specific heat value of 0.5 kJ/kg°C (± 0.1) for a CO_2 temperature between 0 and 150°C.

The effect of upflowing CO_2 on soil temperatures has been modeled assuming a water table at 100 m depth, at a temperature of 100°C. The results (Figure 7) show that the undisturbed conductive temperature gradient becomes significantly affected for mass flows of more than 300 kg/m^2/day. A shallower water table could lower this threshold slightly, but it is not going to alter the conclusion that CO_2 mass flows of less than 1 kg/m^2/day have no effect on shallow soil temperatures. If soil temperatures are less than the boiling temperature so there is negligible flow of steam to the ground surface, based on the CO^2 fluxes measured on the Senator fan, the total heat flow is likely to be predominantly conductive.

Although the shallow thermal regime on the Senator fan has not been affected by the non-condensible gas flux, the vegetation clearly has been affected. The relatively large area of vegetation die-back on the Senator fan, and the lack of a corresponding shallow temperature gradient anomaly, is presumably due to an elevated flux of CO_2 sufficient to acidify the soil but not raise the temperature.

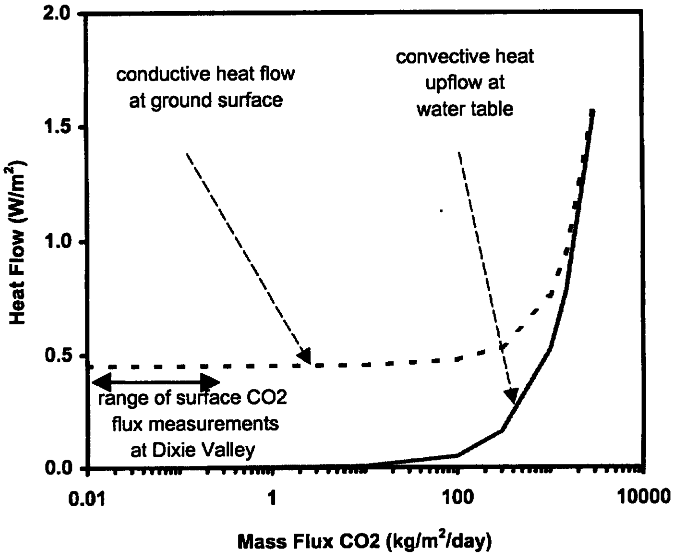

Figure 7. Thermal effects of CO_2 flux through the soil from a source at 100 m depth at 100°C, and pressure at < 100 m depth at atmospheric pressure. The thermal effects of CO_2 become significant only at fluxes at least two orders of magnitude above the highest observed in the soil at Dixie Valley.

Conclusions

The linear heat flow relationship suggested by the shallow soil temperature data from thermal areas of Dixie Valley and Wairakei geothermal fields may provide a simple method for converting TIR imagery into surface heat flow maps. However there are significant limitations and uncertainties in this conversion. The limitations can be summarized as an ambient temperature of 15-20°C, surface soil temperature less than 90°C, surface soil thermal conductivity of ~0.5 W/m°C, and minimal disturbing effects from solar heating, varying emissivity or recent rainfall. Uncertainties increase towards the outer boundaries of the thermal anomaly due to all the above effects, as well as possible micro-climatic warming of the ground-surface, as observed during the ground-truth surveys at Dixie Valley reported here. Uncertainties will also exist at very high ground temperatures with airborne imagery because of the obscuring effects of cool steam clouds.

Further research into the relationship between surface heat flow and surface temperature is warranted based on the results of this study. The emphasis needs to be on the thermal conductivity of the soil, and its variation with time at a particular site (e.g. varying moisture content), and more detailed measurements of the temperature gradient in the upper few cm of soil in comparison to the surface temperature changes. These measurements should clarify mode of heat transport.

Despite the uncertainties in this study, a relationship similar to that developed here for Dixie Valley and Wairakei fields may be able to be applied to any geothermal area, in particular where quantitative mapping of the surface thermal changes is required.

Acknowledgements

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References

Allis, R.G., 1979. "Heat flow and temperature investigations in thermal ground." Geophysics Division Report 135, Dept. of Scientific and Industrial Research, New Zealand, pp.28.

Allis, R.G. 1981. "Changes in heat flow associated with exploitation of Wairakei field, New Zealand." *New Zealand Jl. Geology and Geophysics,* 24, 1-19.

Allis, R.G., Nash, G., Johnson, S., Luvall, J.C., and Estes, M. 1999. "Mapping changes in surface thermal activity at Dixie Valley geothermal field, Nevada." *In prep.*

Bergfeld, D., Goff. F., Janik, C., and Johnson, S.D. 1998. " CO2 flux measurements across portions of the Dixie Valley geothermal system, Nevada." *Geothermal Resources Council Trans.,* 22, 107-111.

Bredehoft J.D. and Papadopulos, I.S. 1965. "Rates of vertical groundwater estimated from the Earth's thermal profile." *Water Resources Research,* 1, 325-328.

Clark, S.P. 1966. Handbook of Physical Constants. Thermal Conductivity. Memoir 97, Geol. Soc. Amer., 459-482.

Dawson, G.B. 1964. "The nature and assessment of heat flows from hydrothermal areas." New Zealand Jl. *Geol. & Geophys.,* 7, 155-171.

Johnson, G.W. and Nash, G.D. 1998. "Unmixing of AVRIS hyperspectral data from Dixie Valley, Nevada." *Proc. 23rd Workshop on Geothermal Reservoir Engineering,* 240 – 245.

Sweigert, R.L. Weber, P. and Allen, R.L. 1946. "Thermodynamic properties of gases: carbon dioxide." *Industrial Eng. Chem.,* 38.s