Understanding Risks and Uncertainties in Geothermal Modelling: Constraining Thermal Conductivity Models

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Prediction of the rate at which temperature increases with depth in a sediment pile is an important tool in the evaluation of many geothermal prospects. Such prediction is typically carried out by geothermal modelling based on assumptions that can be made with regard to the interplay of heat-flow and lithological conductivity, from which estimates of geothermal gradient, and therefore absolute temperature, can be derived. Approaches to such modelling work may differ widely, with a correspondingly wide range of outcomes, bringing into question the reliability of geothermal modelling as a predictive tool.

This paper focuses on addressing some of the uncertainties and risks associated with thermal modelling.

Keywords: Geothermal modelling, conductivity, heat-flow.

Thermal Modelling

The thermal conductivity of a rock directly determines the efficiency (or otherwise) with which heat is propagated through it. This conductivity is lithology-dependent, and varies from layer to layer in a sediment pile according to the nature of the various lithologies present and their degree of compaction. The geothermal gradient within any single lithological unit results from the interplay of heat-flow with the thermal conductivity of that unit, broadly expressed thus:

$$Q/K = G$$

where

Q = heatflow (mW/m^2)

k = conductivity (cals/cm/sec)

G = geothermal gradient ($^oC/km$)

The temperature-depth profile at a given location in a sedimentary basin can therefore be thought of as the vertical summing of the geothermal gradients established within the individual layers within the sediment pile. Such a profile is, as we shall see, rarely linear.

Two primary methods are used for modelling geothermal systems based on the above relationship between heat-flow, conductivity and temperature:

- In the absence of existing well data, shallow (200-500m) wells are drilled, down-hole temperatures recorded, and conductivities measured in the laboratory from down-hole samples. The depths from which the temperatures and samples were taken, and the temperatures and conductivities appropriate to those depths, provide values for k and G in the equation described above, permitting a calculation of a notional value of heat-flow (Q) that can then be applied to the base of the sediment pile over the local area. The geothermal gradient that is obtained in the shallow section is typically extrapolated, or projected, to depth in the subsurface in order to provide estimates of drilling depths that would be required to reach commercially viable temperatures (typically 150 ^oC). This is referred to herein as the "***projected approach***"; and
- Where down-hole temperature and lithostratigraphic data are available from adjacent wells, such data can be input to a commercially available burial-history modelling software package, of the kind routinely used in petroleum exploration for the prediction of the degree and timing of source rock maturation, reservoir temperatures, and other mitigating geothermal properties. Such packages typically contain default thermal conductivities for end-member lithologies that can be mathematically averaged to reflect lithological mixtures as necessary, and thus do not rely on the laboratory measurement of conductivities on down-hole samples. Since such packages also take into account burial-compaction effects (in particular, increase in conductivity with increasing compaction), permitting the calculation of a temperature-depth profile from which predictions of depths to key isotherms can be made. This is referred to herein as the "***calculated approach***".

While both methods can be adapted to specific cases, both contain considerable uncertainties that can affect the predicted temperatures.

Projected versus Calculated Models

Thermal conductivity varies with rock type and properties (such as porosity), the latter being highly dependent on depth of burial, chiefly as a result of compaction. Assumptions concerning thermal conductivity measurements are therefore very important in thermal modelling, especially since stratigraphy, and therefore burial history (depth through time), show great lateral variation. Therefore, thermal modelling is necessarily location-specific, and generates a temperature-depth profile unique to the local

geology. However, the assumptions made about conductivity are very different according to the two approaches outlined above.

The projected approach uses input values of conductivity (k) measured directly on samples from shallow wells (200-500m), combined with measured temperatures and values of heat-flow (Q), to generate a geothermal gradient (G) in the shallow section that is then linearly extrapolated to depth (2000-5000m).

By contrast, the calculated approach takes, as its starting point, a stratigraphic sequence to depths of 2000-4000m, typically intersected by petroleum exploration wells or interpreted from seismic data tied to such wells. These sequences are entered into commercially available modelling software packages that utilise default (published), lithology-specific input conductivities that are made to vary with progressive burial and resulting compaction. A value of heat-flow is then calculated in such a way that, when it is applied to the lithological column, the resulting depth-temperature profile matches the down-hole temperatures (Horner-corrected for circulation effects) measured in the well at the time of drilling. This results in a predictive depth-temperature profile that is more accurately calibrated to the known temperature conditions at depth. The heat-flow calculated at the well location, by virtue of its constraint by measured temperature data, can then be used in offset locations more reliably than if it were derived from shallow, relatively uncompacted samples. Such modelling techniques are routine in the petroleum exploration industry.

A comparison of the outcomes typical of these two approaches was made on wells from the Perth Basin, Bass Basin and the Vulcan Sub-basin.

In the well from the Perth Basin (Figure 1), two down-hole temperatures (Horner-corrected for drilling circulation effects) were available together with a comprehensive stratigraphy. These data were input to Genesis^{TM}, a commercially available interactive thermal modelling package used by 3D-GEO Pty Ltd. Heat-flow input to the base of the sediment pile was varied until a temperature-depth profile (in blue) was obtained that was commensurate with, and therefore calibrated to, the measured down-hole temperatures.

The two most important features of the predicted temperature-depth curve are (a) its non-uniform slope as it responds to changes in lithological conductivity from one formation to the next, and (b) the general steepening of the slope (decrease in geothermal gradient) with depth as it responds to increasing lithological conductivity with increasing compaction (porosity-reduction).

The predicted depth-temperature profile (in blue) is compared in Figure 1 to that which might result from the "projected" approach (red dotted line), which may have been required had the well, and the data available from it, not existed. According to this approach, a temperature-depth profile derived at shallow levels is extrapolated linearly downwards. As Figure 1 shows, in the shallower part of the sequence (above 2500m), both curves approximately coincide, and match the shallower down-hole temperature. However, as you go deeper in the profile, the temperature-depth profile projected linearly from the shallow section deviates significantly from the calculated (blue) curve. At the bottom of the hole, the blue (calculated) curve intersects the measured down-hole temperature (approx 142^{o}C), while the projected curve indicates a temperature of 160^{o}C, some 18^{o}C higher than that measured. Another result is that the depth to an economic target of 150 ^{o}C varies by 540 m between the two models. Figure 1. Comparison between the projected and calculated approach from the Perth Basin.

The projected approach therefore has the very obvious effect of being too optimistic in its estimate of the drilling depths required to reach commercially desirable temperatures. A comparison of the two modelling approaches in the Durroon Sub-Basin in southern Australia and the Vulcan Sub-Basin in the Timor Sea show a similar relationship (Figure 2). The calculated curve fits well with measured temperature, whereas the projected linear profile deviates significantly. Here, two linear temperature profiles are compared to the calculated trend, one based on 300 mssf (in red), the other from 500 mssf (in purple). Both profiles deviate significantly from the calculated curve at depth, with up to 1.2 km difference between where the predicted gradients intersect the target 150^{o}C. (Note that two corrected BHTs were available from the well, the calculated curve being calibrated to the more reliable one based on other calibration data. The higher of the two temperatures, which is considered to be over-corrected, coincidentally fits with the profile projected from 500m).

An example from the Vulcan Sub-Basin in offshore NW Australia shows a similar comparison with the 300-500 mssf extrapolations (Figure 3), with a similar outcome (significant overestimation of temperature by the "projected" approach).

The calculated approach is only possible where deep well data are available, and, like all modelling exercises, is prone to numerous sources of error in terms of its input assumptions. However, it does at least take account of the non-uniform nature of temperature-depth profiles with depth. While, in

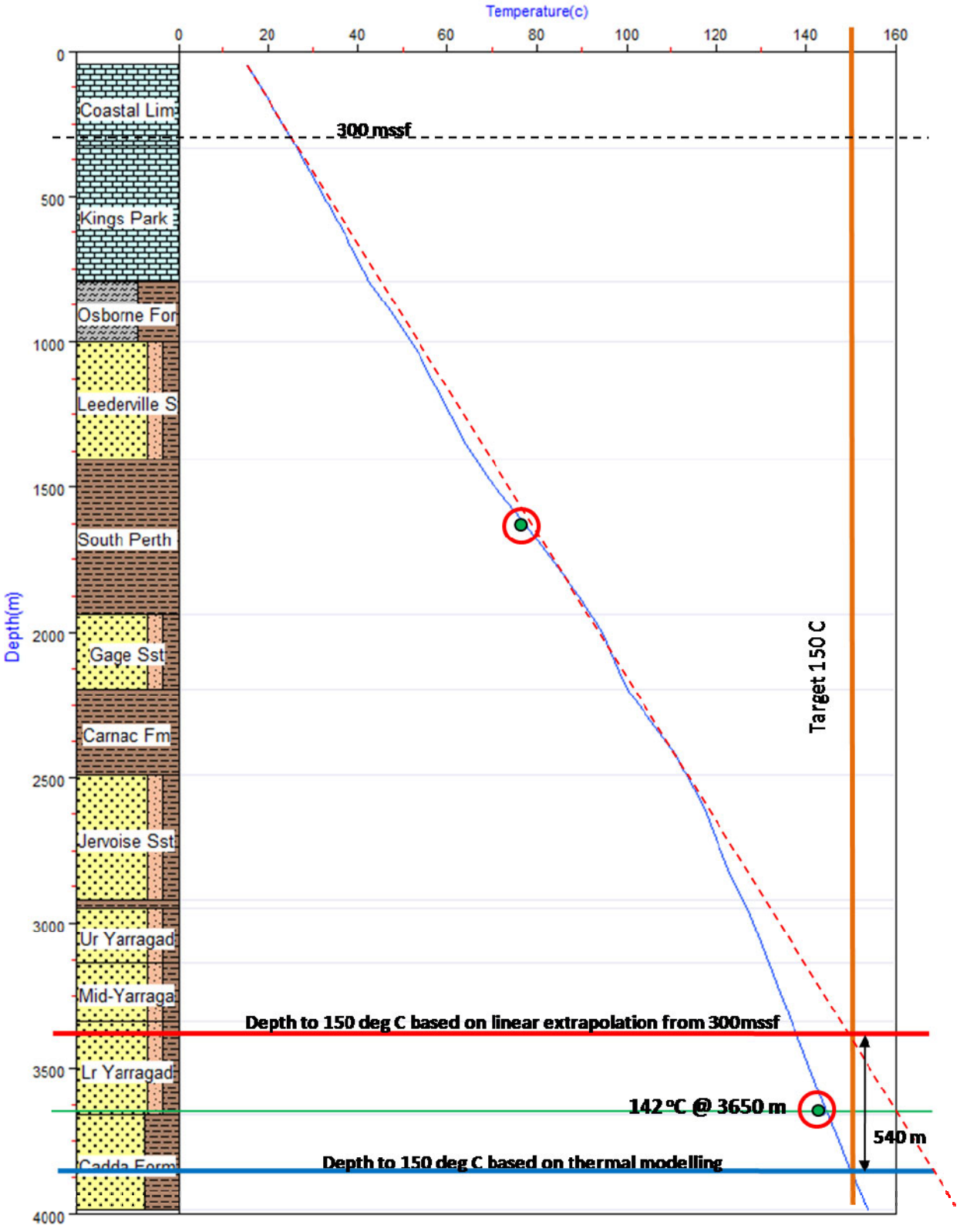


Figure 1. Comparison between the projected and calculated approach from the Perth Basin.

defence of the projected approach, it might be said that it is useful in areas in which no deep-drilling data are available, it is clear from the comparisons shown in Figures 1, 2 and 3 that it is almost inevitably prone to under-estimation of the drilling depths required to reach temperatures of commercial significance. Otherwise put, if the wells shown in these figures had not existed, and the projected approach was applied to the problem of predicting depths to 150°C, the results would have been grossly misleading.

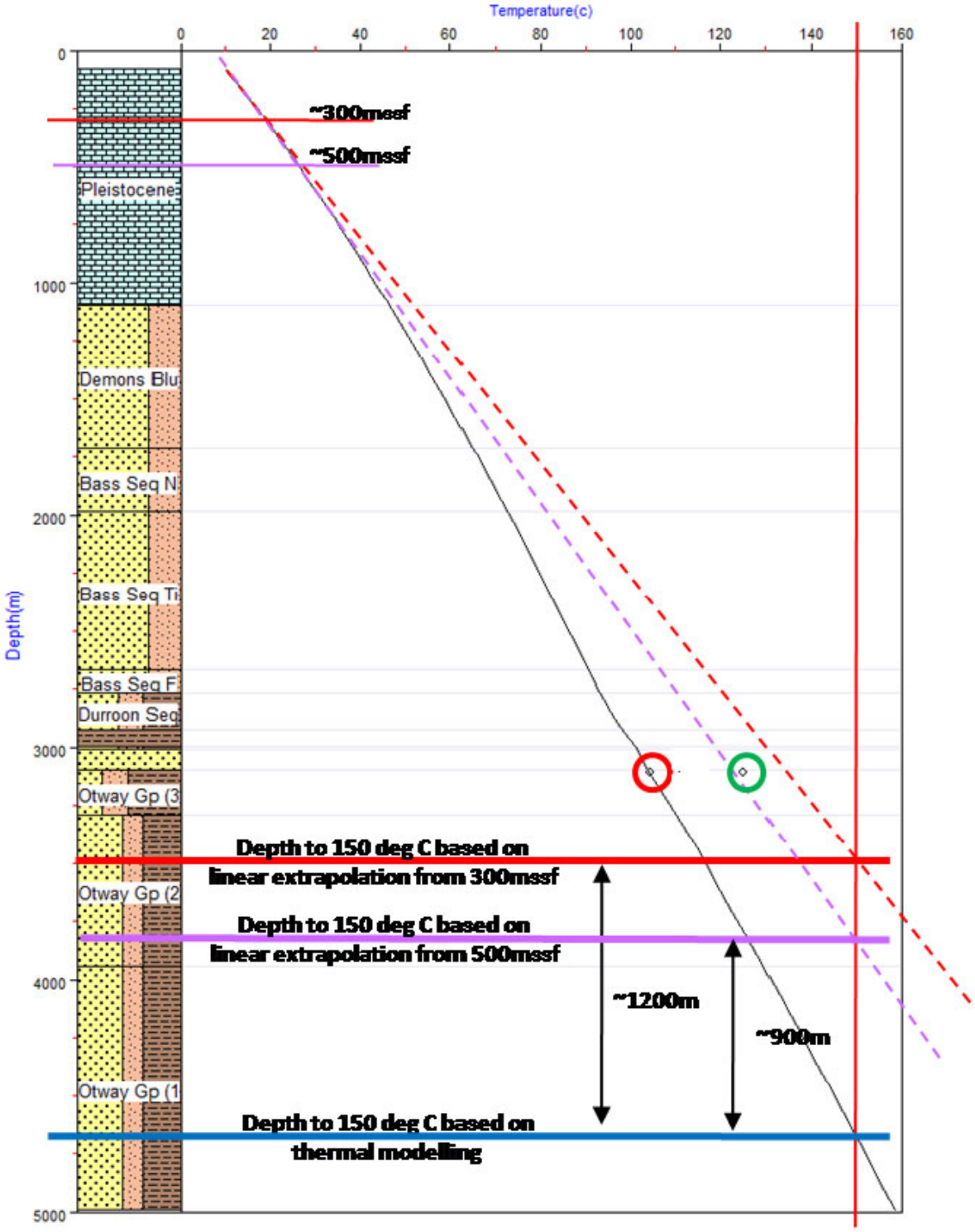


Figure 2. Comparison between the projected and calculated approach from the Durroon Sub-basin. Modelled approximately to basement. Red temperature plot corresponds to Horner corrected temperature. Green temperature plot corresponds to an arbitrary 25% correction applied by the previous modelling attempts.

Conclusions

For the reasons outlined above, the calculated approach accounts for variations in conductivity with both lithostratigraphy and depth (and therefore compaction), and uses measured down-hole temperatures to constrain and calibrate the magnitude of heat-flow being conducted through the sediment pile. The resulting depth-temperature profile is therefore necessarily more consistent with geothermal gradients observed basin-wide. By contrast, the "projected" approach may predict, depth for depth, significantly higher temperatures compared with the "calculated" approach, mainly because the conductivities acquired at shallow levels are anomalously low, and are assumed to be continuous with depth (unaffected by lithological variation or burial-compaction). The

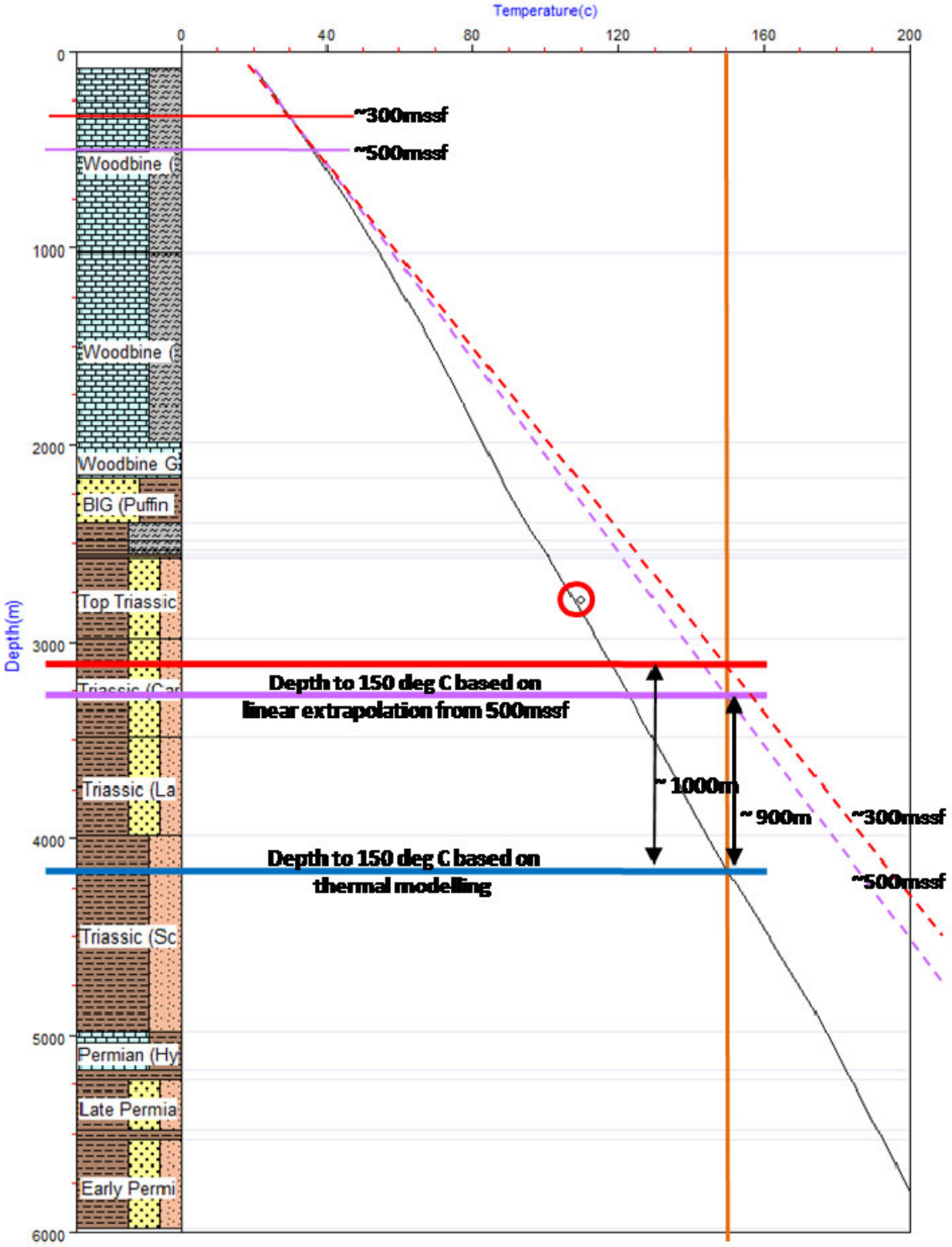


Figure 3. Comparison between the projected and calculated approach from the Vulcan Sub-Basin. Profile modelled to approximate basement.

temperatures predicted at depth by linear extrapolation may therefore significantly higher than those predicted by the "calculated" method, and as such are in danger of predicting the economic target (eg. 140 or 150 ^{o}C) at optimistically shallow levels, and of overestimating geothermal potential.

While both methods have considerable risks and uncertainties associated with them, and while measuring the conductivity in the projected

approach may seem more precise, it is likely to be less accurate than the temperature estimates obtained from the "calculated" approach. However, the "projected" technique may be best suited for areas where calibration data are limited.

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