PTt Modelling Exercise

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Overview

For this modelling exercise the programme 'ptt' was used to model the pressure-temperature-time paths of regional metamorphism. The programme accepts an input file with the appropriate parameters such as initial crustal thickness, crustal density, and specific heat. There are two ways of simulating PTt paths and the corresponding geotherms. One is via crustal thickening by a thrust sheet and the other is via homogeneous thickening. Both cases will be investigated.

1. Model evaluation for the case of thrusting.

(**a**) Geotherms are calculated as a function of time for a single representative set of conductivity, mantle heat flow, and heat production rate (Figure 1). No exhumation. The Tt paths for a rock above and below the thrust are also plotted (Figure 2).

Figure 1 shows that thermal equilibration is not completed after 150 Ma but the temperature difference does become gradually less.

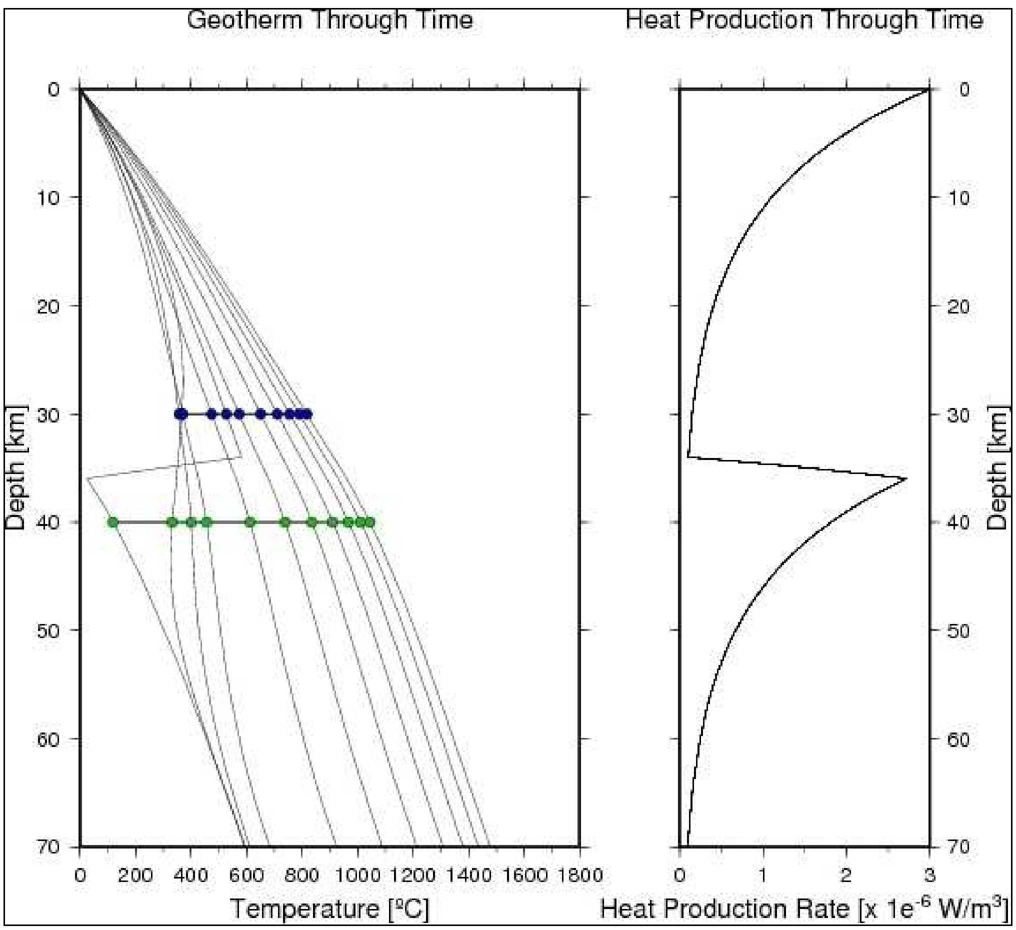

Figure 1 - Geotherms shown in left plot with the corresponding rocks above and below the thrust. On the right a plot is shown with the heat production rate versus depth. No exhumation. The last geotherm is at 150 Ma.

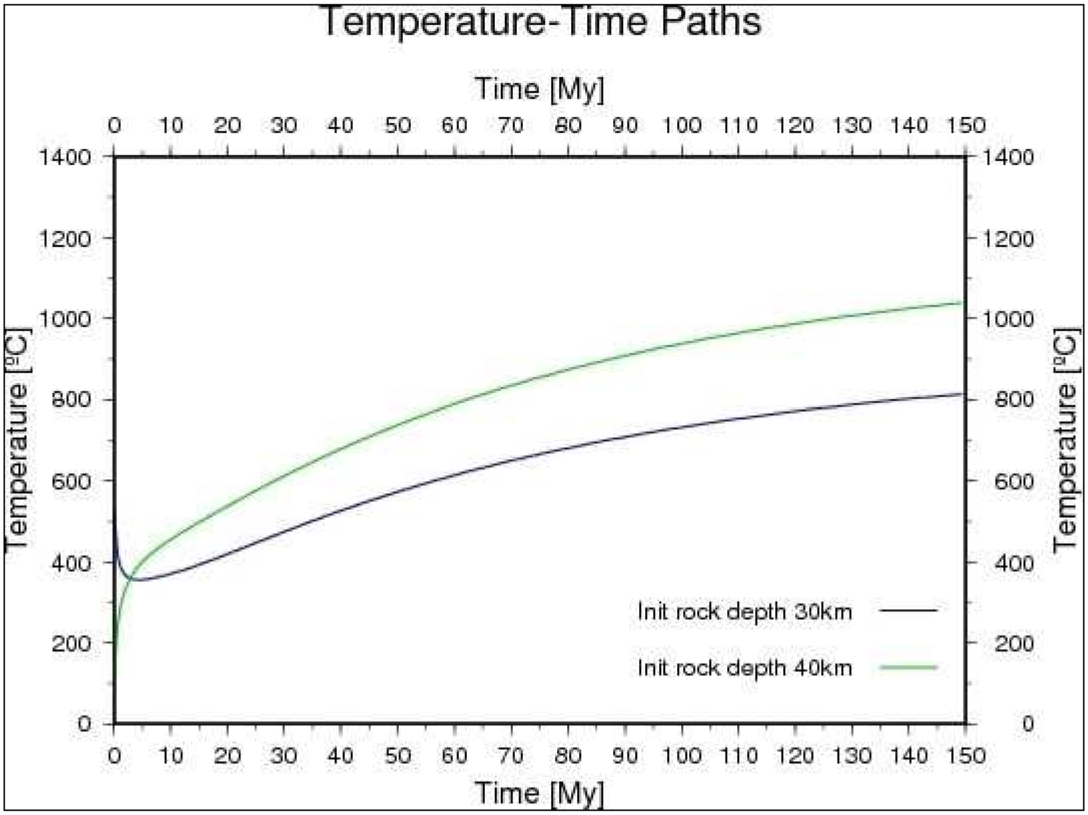

Figure 2 - The Tt paths for a rock below the thrust at 40km and a rock above the thrust at 30km. Note the initial inversion.

In figure 2 there is a conspicuous inversion of temperature below and above the thrust sheet. This is easy to explain because it is simply the geotherm that is stabilising. The rock that would first have been close to the surface suddenly ended up at 40 km below the surface and was still cool. It then heated up as thermal equilibration took place. The rock that was located below the thrust unit was hot already, but because it came into contact with the cold rocks after thrusting, it cooled down first before heating up again (see blue curve in figure 2).

(b) This time the effect of exhumation has been incorporated into the model. A representative rate of exhumation was taken at 0.1 $mmyr^{-1}$.

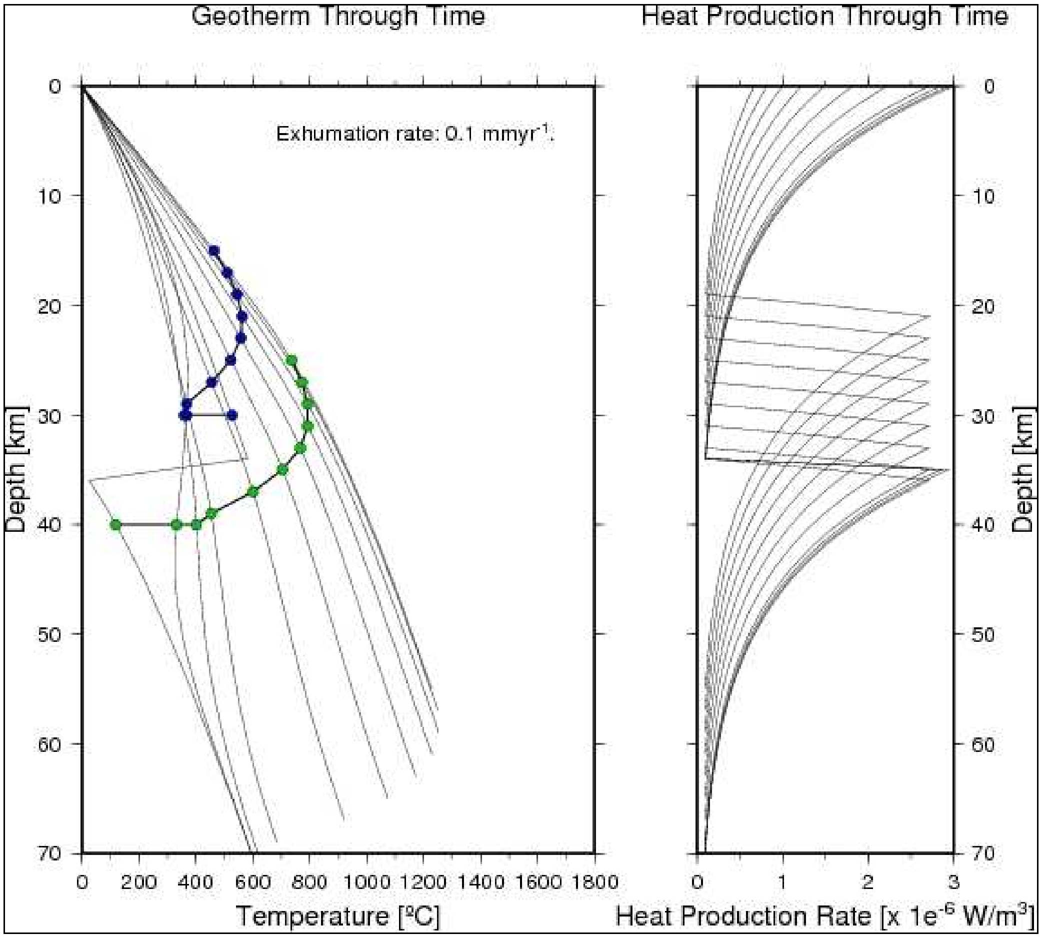

Figure 3 - Geotherms shown in left hand plot with the corresponding PTt paths for a rock above and a rock below the thrust. Last geotherms corresponds to 150 Ma. Exhumation rate is 0.1 $mmyr^{-1}$. On the right is shown the evolution of the heat production through time. As uplift takes place, heat production rate peak progressively comes closer to the surface.

Figure 3 shows what happens when exhumation does take place. It is fairly obvious to see that the rocks progressively come closer to the surface as time progresses. Exhumation also seems to have an effect on the peak heat production rate, which rises as time progresses.

Figure 4, on the other hand, shows what would happen if the exhumation rate were increased to 0.2 $mmyr^{-1}$. The rocks rise quicker to the surface as well as the heat production rate curve.

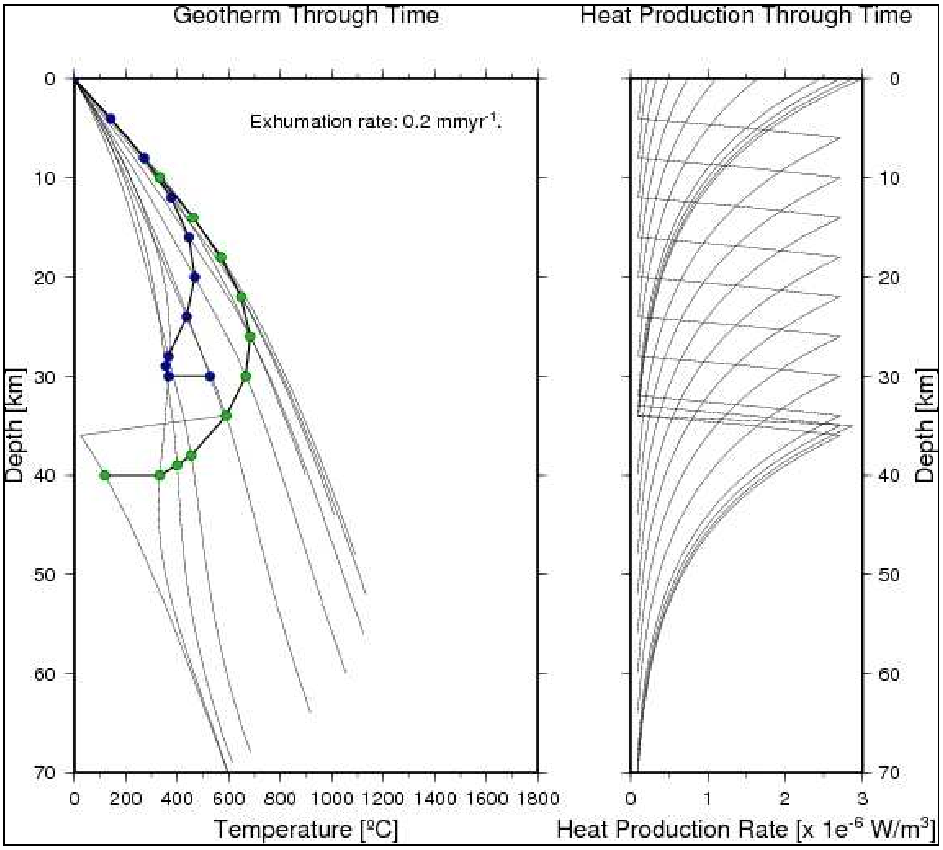

Figure 4 - Geotherms shown in left hand plot with the corresponding PTt paths for a rock above and a rock below the thrust. Last geotherms corresponds to 150 Ma. Exhumation rate is 0.2 mmyr^{-1}. On the right is shown the evolution of the heat production through time. As uplift takes place, heat production rate peak progressively comes closer to the surface.

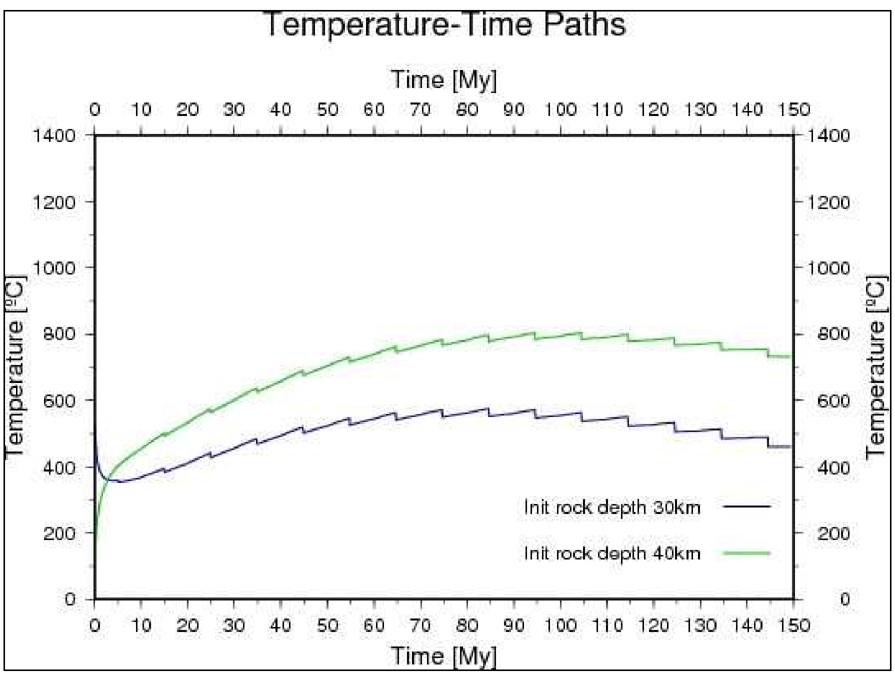

Figure 5 - The Tt paths for a rock below the thrust at 40km and a rock above the thrust at 30km. Note the initial inversion and the steps in the curves.

Figure 5 is most intruiging. It very much resembles figure 2 but the peak temperature conditions are much earlier at about 90 - 100 My after thrusting. Also the curves display 10 My steps. This is probably attributed to the evolution of heat production through time. But I am not certain in what way. Maybe because the heat production curves in figure 3 also display step wise increase in heat production closer to the surface as time progresses.

The conductivity can be varied from a mimimum to a maximum. The effect of these extremes can be seen in figure 6.

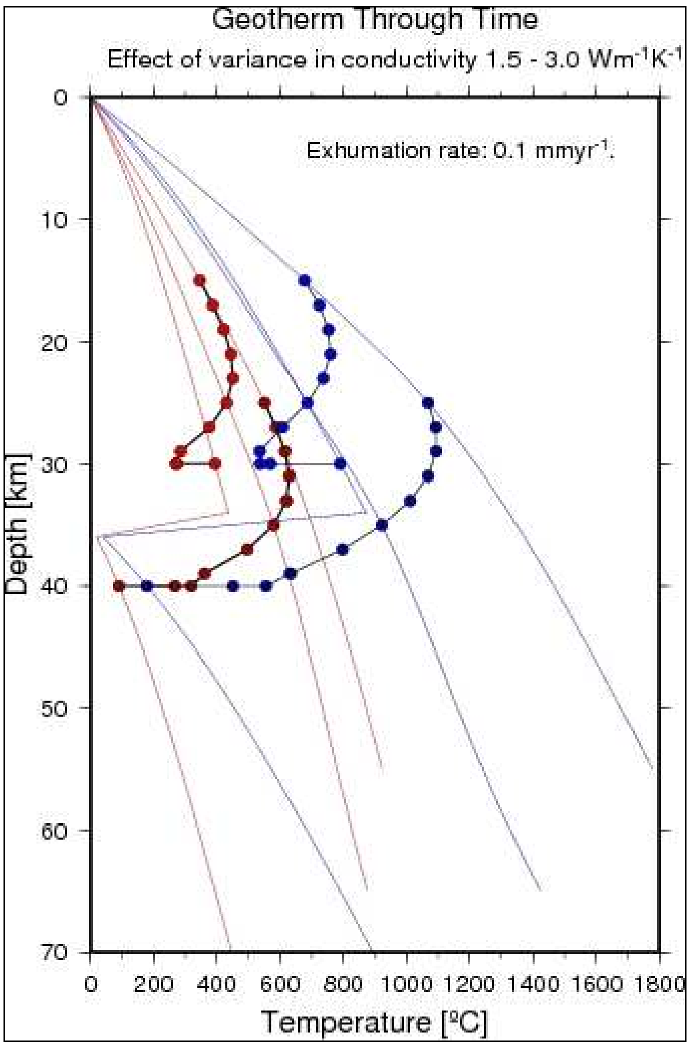

Figure 6 – The blue points represent the PTt path with a high conductivity whereas the red points represent the PTt path with a low conductivity. Last geotherm is 150 Ma. Exhumation rate is 0.1 mmyr^{-1}.

Figure 6 shows that for high conductivities we can expect the rocks to reach higher temperatures with the corresponding PTt paths. The maximum temperature attained is 1100˚C for a rock at an initial depth of 40 km as opposed to only 600˚C for a rock at 40 km but experiencing a low conductivity. Cooling starts when 9 km of exhumation has taken place for both rocks.

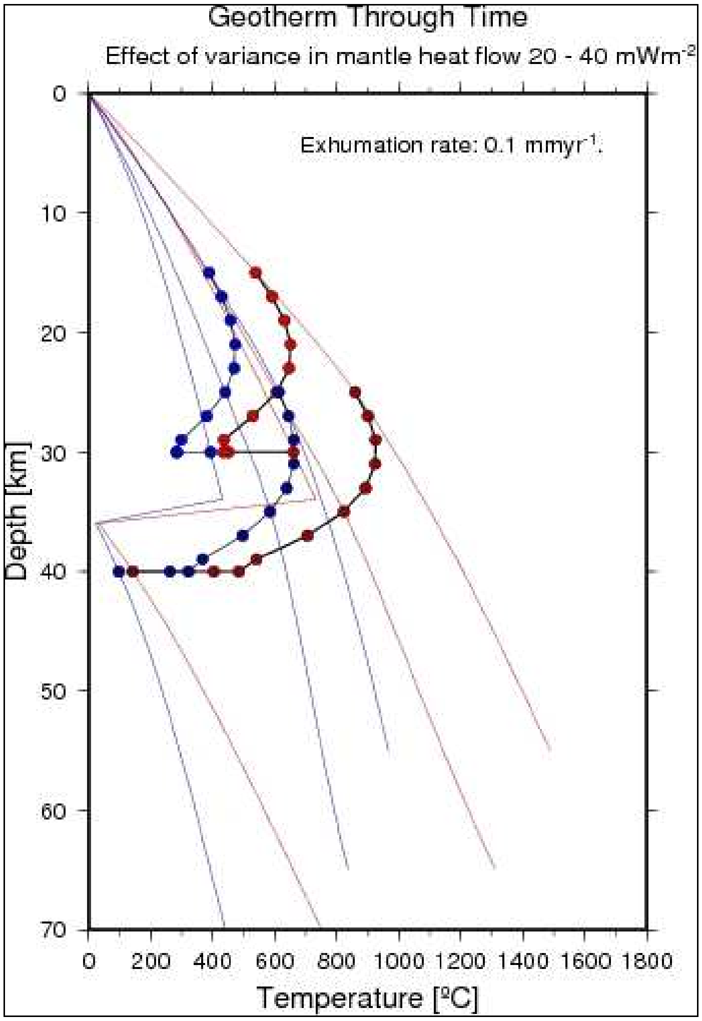

Figure 7 – The blue points represent low mantle heat flow whereas the red points represent high mantle heat flow. Last geotherm is 150 Ma. Exhumation rate is 0.1 mmyr^{-1}.

In turn the mantle heat flow can be varied from one extreme to another. Figure 7 shows the effect of a minimum and a maximum mantle heat flow. Note that the maximum temperature is not as high this time at around 950˚C instead of 1100˚C in figure 6. The cooling still starts after 9 km of exhumation however.

Lastly, figure 8 shows the variance of a minimum heat production to a maximum. The maximum temperature attained is about 900˚C and the cooling starts after about 9 km of exhumation as well. There is, however, greater difference with figure 7, which is that the difference between the low and high extremes of heat production has less an effect on the PTt paths (and geotherms) than difference between a low and a high mantle heat flow.

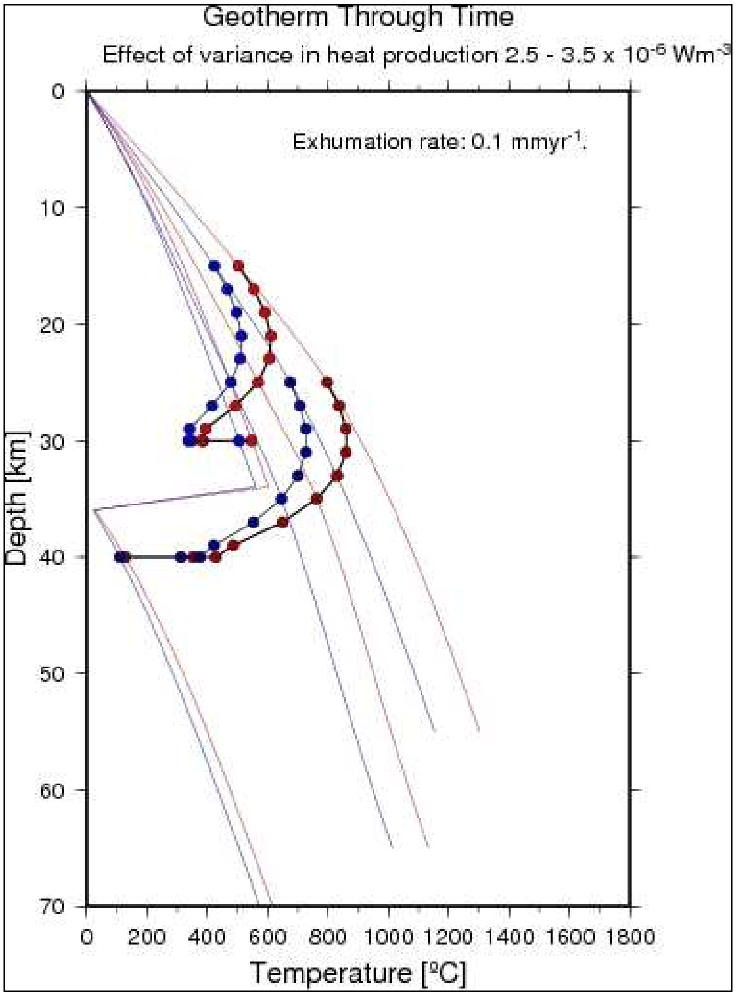

Figure 8 - The blue points represent low heat production whereas the red points represent high heat production. Last geotherm is 150 Ma. Exhumation rate is 0.1 mmyr^{-1}.

To conclude, changes in conductivity has the greatest effect on PTt paths (and corresponding geotherms), then changes in mantle heat flow, and lastly changes in heat production which has the least effect. The same sequence goes for the maximum temperature attainable for a given rock at a given depth.

The maximum temperature attained is an important parameter because it is the guide to the degree of effect the variance in conductivity, mantle heat flow, heat production and exhumation.

2. Model evaluation for the case of homogeneous thickening

This time the lithosphere is thickened by a factor of 2, which means the lithosphere will have the same thickness as in part 1, but the process of lithospheric thickening is different.

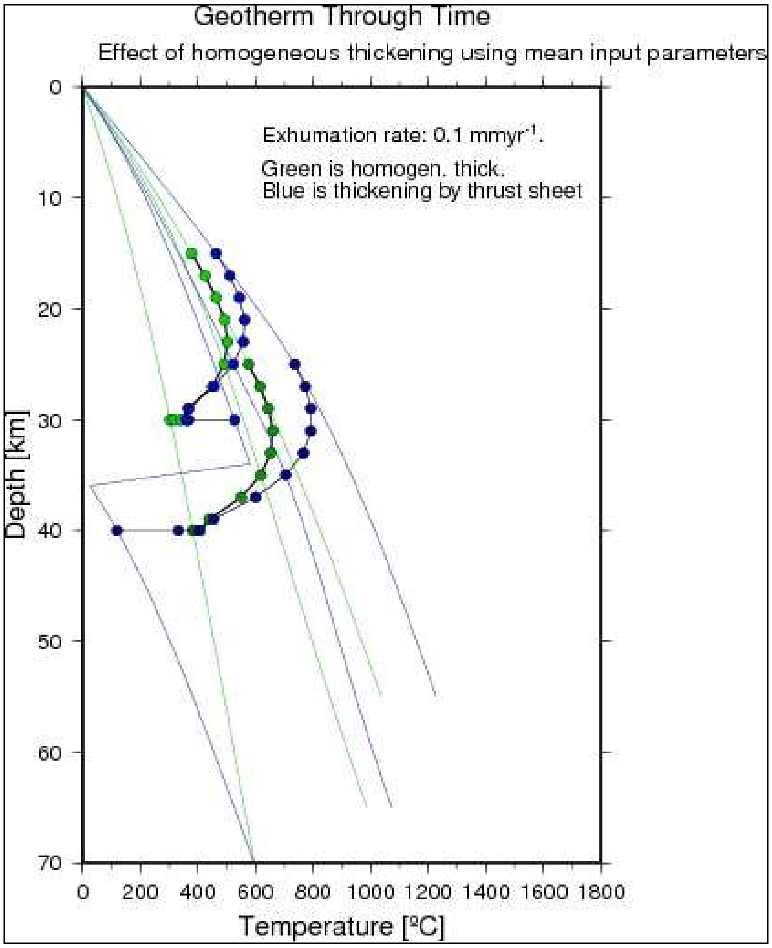

Figure 9 – As the plot shows, the green geotherms and PTt points are for the case of homogeneous thickening whereas the blue geotherms and PTt points correspond to the case of thickening by a thrust sheet. The last geotherm is 150Ma. Exhumation rate is 0.1 mmyr^{-1}.

Figure 9 displays the comparison of homogeneous thickening versus thickening by a thrust sheet. The first important observation is that the initial geotherm for homogeneous thickening is straight as opposed to the geotherm of the other case. This is no surprise for obvious reasons in the geometry of the process of lithosperic thickening for each case. The second important observation is that the maximum temperature attained is higher for the case for thickening by a thrust sheet. This is possible because emplacing a whole section of crust onto another section of crust doubles the amount of radioactive elements in the crust / lithosphere. For homogenous thickening this is not the case. More radioactive elements in the crust mean a higher heat production and thus higher temperatures. The third and last important observation is the moment cooling starts, which is not at the same time for both models. For the case of homogeneous thickening, cooling starts about after 1 – 2 km of exhumation earlier than for the other case. The reason for this difference probably has to do with the same idea of fewer radioactive elements in the crust, but I cannot say for sure.

The major controls on temperature experienced by a buried rock are therefore exhumation, changes in conductivity, mantle heat flow, and heat production. But without doubt there are many others.

One might argue that these models do not have a realistic initial thermal structure. For the model of thickening by a thrust sheet we have the crust with 0˚C on top when instantly a copy of the crust is emplaced on top of the original crust. One might wonder is this realistic? The reason we can do this is because on the short time scale when trusting takes place, the geotherm cannot adapt itself quickly enough due to the low rate of conductivity in the crust. Hence we can assume that this model is representative, yet a simplification of the real world. For the homogeneous thickening case, the initial thermal structure is a normal geotherm that still needs to equilibrate. Whether this is realistic is arguable, but also this model is just a simplified end member of all the possible ways a crust can thicken.

The general form of the modelled PTt path with exhumation implies that the conditions during metamorphism are such that first the temperature reaches a thermal maximum as well as a decrease in depth after that the rocks cool down and are brought to the surface. This means that HP/LT metamorphism can occur initially, and that later HT/LP metamorphism might follow before the rocks are brought to the surface.

Application of the model: the Eastern Alps

3. Can the observed blueschist facies metamorphism be a result of overthrusting?

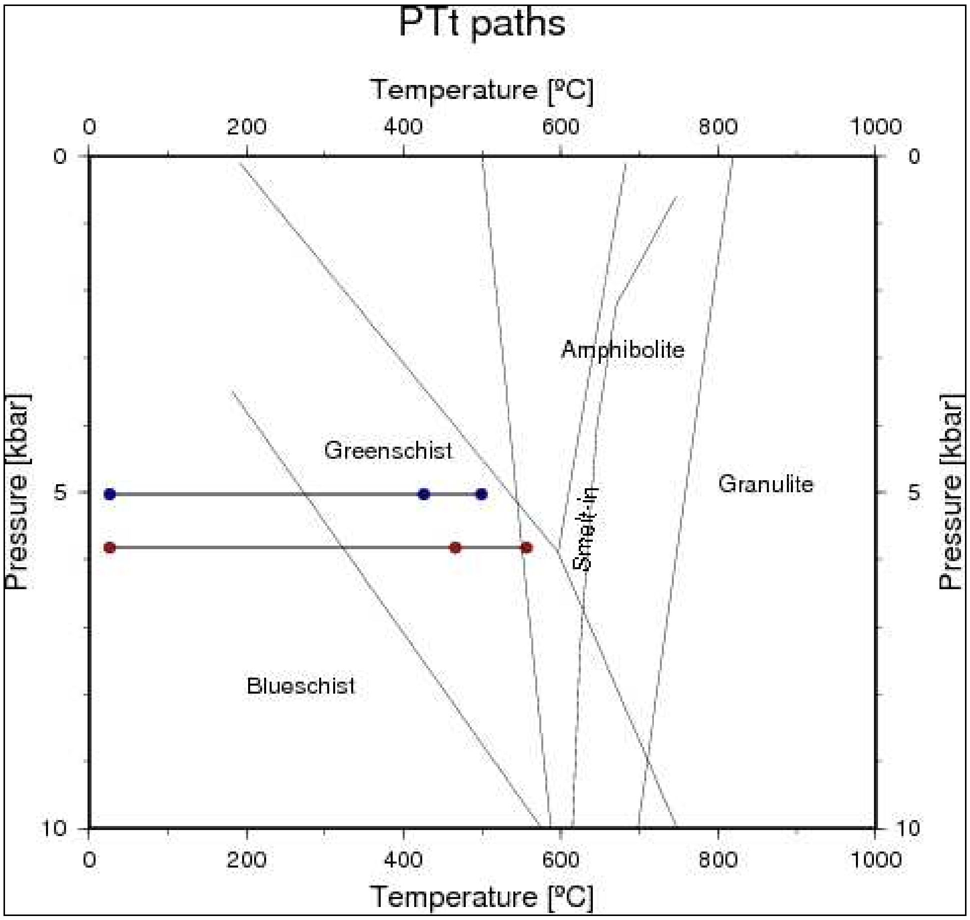

Figure 10 – A PT diagram showing the effect of overthusting for a thrust unit of 18 km thick (blue) and for a thrust unit of 21 km thick (red). The first point is at 0 My, the middle point at 35 My, and the last point is at 65 My. These are connected and represent the PTt history without exhumation.

As figure 10 shows, blueschist facies metamorphism can indeed occur as a result of crustal thickening by a thrust sheet before the temperature becomes too high. The same can be seen in figure 11 form a temperature-time perspective.

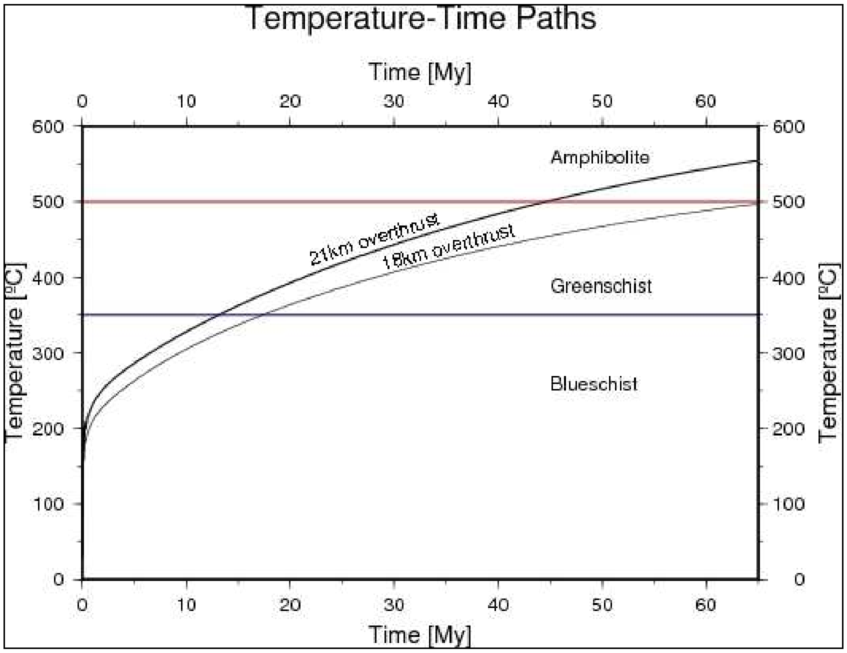

Figure 11 – Tt paths for the case of 21 and 18 km of overthrusting. Note that both curves exist in the blueschist facies field for 10 – 16 My.

4. Would the amphibolite facies metamorphism be expected after 35 My?

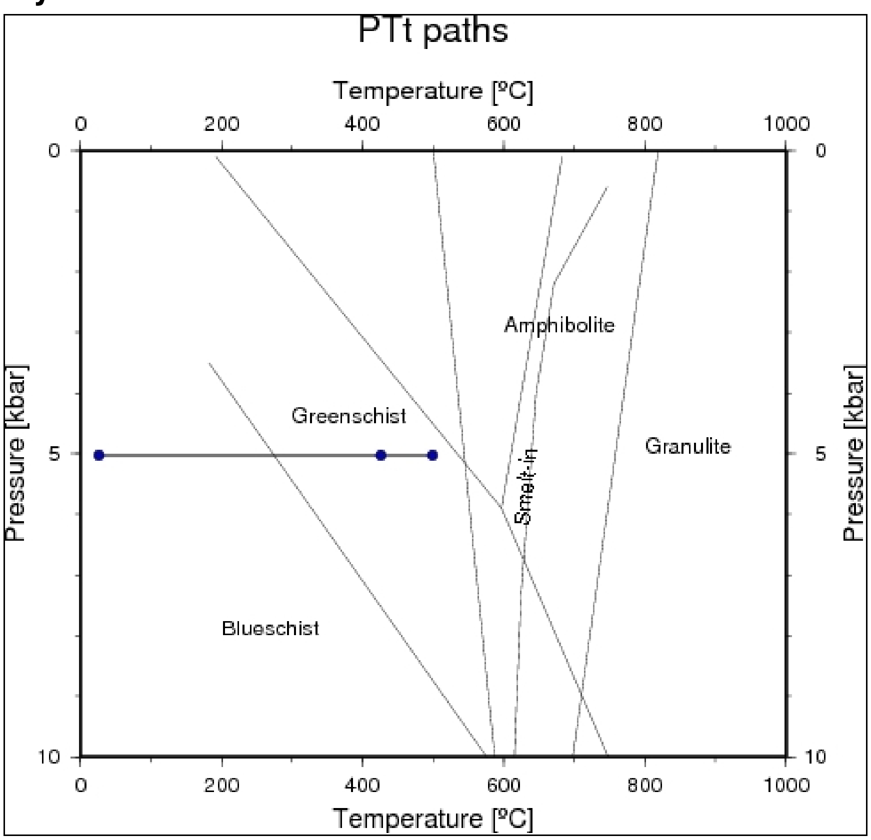

Figure 12 - A PT diagram showing the effect of overthusting for a thrust unit of 18 km thick (blue).

Figure 12 shows that amphibolite facies metamorphism is **not** expected after 35My. It is not even expected after the full 65 My of evolution. In order to investigate this further I thought I could change some parameters such as a minimum in conductivity, and a maximum in mantle heat flow and heat production to give the desired effect. Figure 13 shows that if the conductivity of the rocks is low, then it is possible to get amphibolite facies metamorphism.

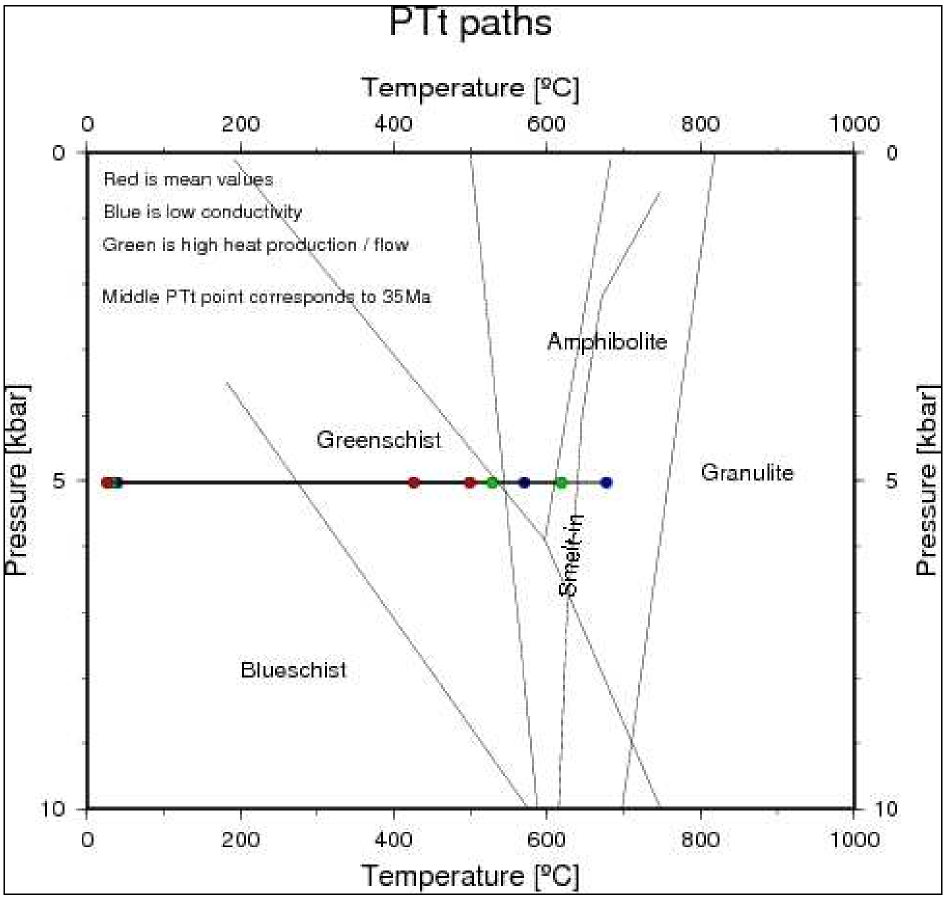

Figure 13 – Same as figure 12 but this time the conductivity of the lithospheric rocks was decreased to a low(blue). When a maximum mantle heat flow combined with a maximum heat production is inserted into the model, the increased temperature effect is less.

However, if we keep conductivity as a mean value and increase the mantle heat flow and heat production to a maximum, the desired effect is not enough. That is, at the middle point corresponding to 35 My the rocks are supposed to undergo amphibolite facies metamorphism but this does not occur. This means that the conductivity of the crust must have been less than average.

5. Can amphibolite facies metamorphism occur with the added effect of exhumation? Would an 'exhumation time lag' do the trick?

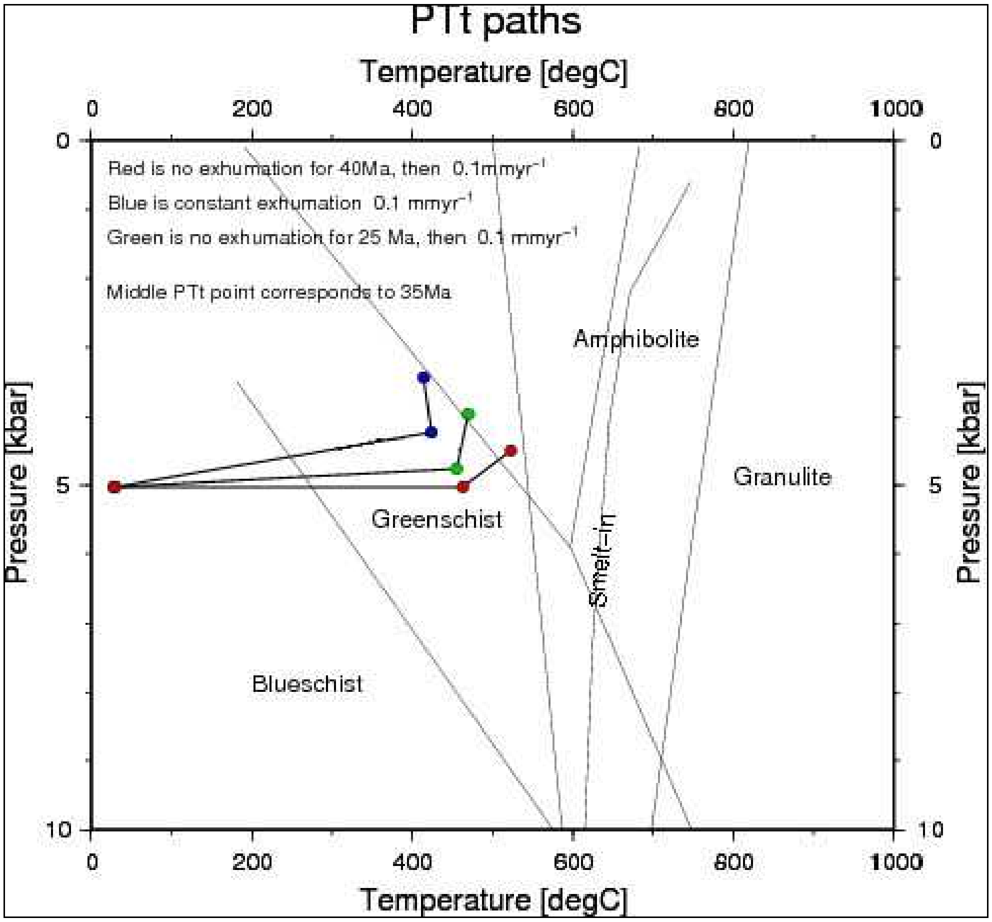

Figure 14 – The same type of PT diagram with PTt paths where the middle point should represent the onset of amphibolite facies metamorphism. The blue PTt points are shown with constant exhumation of 0.1mmyr^{-1}. The red PTt points represent no exhumation for 40Ma, then 0.1mmyr^{-1}. Finally the green PTt points represent no exhumation for 25 Ma, then 0.1mmyr^{-1}. Thermal conductivity is 2.0 Wm^{-1}K^{-1}. The other parameters are averages and defaults.

As figure 14 shows, there is no way amphibolite facies metamorphism can occur with the effect of exhumation. Not at a pressure of 5 kbar and around 500˚C. In fact, the last point representing 65 Ma should be located back at the surface. In other words, the model proposed here is inadequate, too simplified, and cannot not explain the observations made in the field.