Data Repository Item DR1

Cooling Rate Models

Cooling rate models for intrusions contain many uncertainties, such as: three-dimensional shape of the body; conduction versus convection in the magma chamber; conductivity of wall rocks (especially changes in value as a function of temperature (Nabelek et al., 2012); depth of emplacement; extent of melting of the country rock; among others. If that magma chamber has been filled by multiple pulses of magma over a protracted period of time, the calculations become extremely difficult to quantify. The last issue is dominant in modelling the cooling of the Bushveld Complex.

The model developed was based on that of Shaw et al. (1977). They divided a vertical section of the Earth into a great many thin layers. They gave an initial temperature to each layer (thermal gradient). They then added a layer of magma within this package that was equally divided (mathematically) into many thin layers, again each given a specified temperature. The cooling model then consisted of:

1. calculating the temperature difference between each adjacent layer;
2. calculating the energy flow from one layer to the next in a short interval of time based on that temperature difference;
3. determining the new temperatures of the two layers after that interval of time;
4. repeating this process for each pair of layers downward; thus completing the first (very small time) cycle of cooling.
5. calculations 1 to 4 were repeated (for many iterations) for short intervals of time.

That model was adopted and adapted by Walraven (1987). He included the possibility of adding more magma at any given time, at any given depth, at any given temperature. It included the latent heat of crystallization of the magma and latent heat of melting of surrounding rocks (at chosen solidus and liquidus temperatures), using linear crystallization and fusion as a function of temperature. Other options in the programme included:

1. energy from radioactive decay in wall rocks
2. convection or conduction for energy transfer within the magma
3. accumulation of layers on the floor or roof (with conduction values as per solid rock).

There is one important assumption, namely that the area is infinite compared to thickness. Hence, there is no energy loss from the sides, only from top and bottom. The Bushveld is at least 300 by 200 km in area, and not more than 8 km thick. Hence, this approximation is considered reasonable.

Given all these assumptions and variables, it is not possible to claim a huge precision. However, the model presented in the text is considered a reasonable estimate of processes.
References


Data Repository Item DR2

There are two issues that can affect the modelling of the rate of cooling of the intrusion, which are reviewed here, but it is shown below that they have little effect on the model presented, and so are not included in the main text.

Finally, we discuss why we feel that a bottom-up retention of palaeomagnetic reversals, as used in volcanic stratigraphy, is not consistent with the cooling of a large intrusion.

Thickness Of The Roof

The proposed model assumes that the roof was 2 km thick. We have repeated these calculations, using thicknesses for the roof of 1 km and 4 km. Using a 1 km-thick roof, the heat loss through the roof is greater, but there is almost no change at the base. As a result, the length of time taken for the hottest part of the intrusion to cool below its Curie temperature would have been at about 200,000 years in Fig. 4 (total elapsed time of 380,000 years), and the final unit to so cool would have been at 7 km depth. Assuming a 4 km-thick roof, the time sequence analogous to that shown in Fig. 4 would be expanded to 650,000 years, and the final section to cool below the Curie temperature would be at 5 km depth. The exact roof thickness is not known and so there is a small uncertainty in the cooling rates, but a 2 km-thick roof is consistent with geological observations that the roof was the Rooiberg Group of lavas (Schweitzer et al., 1997).

Bushveld Granite

Intruding close to the top of the Bushveld Complex is a 2 km-thick granite sheet. Its age is not distinguishable from that of the mafic rocks given the analytical uncertainty at 2056 my. However, it can be seen from the above thermal profiles that a difference in age of less than a few hundred thousand years between the end of the mafic phase and the addition of granite would influence the cooling profile. At one extreme, it could be suggested that the granite was emplaced immediately as the mafic solidified (but had not cooled below 900°C). Such a model would add 2 km to the top of Fig. 2. The temperature of the granite magma has been inferred to be 900°C (Kleeman and Twist, 1989). This additional hot material would have caused a decrease in the cooling rate, and would have become comparable to that of envisaging a roof 4 km thick, as discussed above, which changes the overall time interval, but not the sense of the process. At the other extreme, it could be envisaged that the granite magma was emplaced after the mafic rocks had cooled significantly, specifically below the Curie temperatures of the uppermost rocks. It could then be argued that the granite magma may have reheated the uppermost rocks above their Curie temperatures, and so the magnetism could have been reset. The vertical section into the mafic rocks that the 900°C granite
could have reheated above the Curie temperature would depend upon how cool the mafic rocks had become prior to the granite emplacement. However, because the uppermost 1.5 km of the mafic rocks all have the same magnetic orientation (within the limitations of the data), there is no evidence for such a reheating and resetting. Whereas such a process cannot be excluded, there is no evidence to make its effect necessary. Obviously, a palaeomagnetic study of the rocks at the base of the granite sheet would be of great interest in this regard.

**Bottom-Up Palaeomagnetic Model**

In the original study of this palaeomagnetic data seven reversals were proposed (Letts et al., 2009). It was implicit that the oldest reversal was at the base, as is commonly assumed in previous studies of volcanic rocks. This model requires that each section of the intrusion with a specific polarity must have cooled below its Curie temperature before the next pulse of magma, and furthermore, was not reheated above that temperature. Thus each pulse of magma should have differentiated to produce a complete range of 100*Mg/(Mg+Fe) values in the mafic minerals and An content in the plagioclase. Such dramatic trends of differentiation are totally lacking in the Bushveld Complex (Eales and Cawthorn, 1996). Also, if there had been on average one intrusion about 1 km thick every 0.2 million years it would have totally crystallized and cooled very substantially. Thus, subsequent injections of magma ought to have chilled against the previous body, as identified in the Kap Edvard Holm gabbro complex, Greenland (Tegner et al., 1993). However, they noted that the pre-existing magma had not totally solidified (based on 100*Mg/(Mg+Fe) value of the mafic minerals and An content of the plagioclase). They argued that a difference in temperature of a mere 50°C was adequate to cause quenching of the hotter magma. No finer grained layers are observed in the Bushveld Complex. Hence, we argue that the bottom-up palaeomagnetic model creates more significant petrological problems than the combined top-down (dominant) and bottom-up (minor) model discussed here.

**References**


