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Constraints on the depth and thermal history of cratonic lithosphere from peridotite xenoliths, xenocrysts and seismology

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ABSTRACT

Despite the relatively long-standing availability of numerical approaches for estimating palaeogeotherms using peridotite xenolith Pressure–Temperature (P–T) data, the practise of fitting xenolith P–T arrays to simple models of lithospheric heat generation, in a non-quantitative manner, remains widespread. The lack of quantification in both the magnitude and uncertainty of heat flow and lithosphere thickness estimates leads to difficulty in evaluating proposed models for lithosphere evolution on a local and regional scale.

Here, we explore the advantages of using a numerical approach to palaeogeotherm fitting, in terms of the ability to make objective comparisons of the effect that differing thermobarometer combinations and varying states of mineral and textural equilibrium have on the shape of the palaeogeotherm, and the resulting estimates of lithospheric thickness and heat flow. We also make quantitative comparisons between lithospheric mantle properties estimated using peridotite xenoliths versus single mineral xenocrysts. Using two reference peridotite xenolith databases from Bultfontein (S. Africa) and Somerset Island (Canada) we show that the same lithospheric mantle properties are predicted using harzburgite versus lherzolite thermobarometry methods. Filtering mineral data for the effects of inter-mineral disequilibrium does not produce significantly different palaeogeotherms but does increase the quality of fit of the palaeogeotherm to the P–T data, allowing more confidence to be placed in comparisons between locations. Palaeogeotherms calculated using xenocryst data, screened for peridotitic affinities, show misfits that are 2–3 times greater than those obtained using xenoliths. Lithospheric properties calculated from the Somerset Island xenocryst-based geotherm yield results that are within error of the xenolith estimate.

A mutually consistent and quantitative palaeogeotherm fitting approach is used to evaluate existing hypotheses for the evolution of the southern African lithosphere. We find very similar estimates for the heat flow and thickness of the lithosphere between SW Namibia (off-craton) and Bultfontein (on-craton). This supports suggestions of a cratonic thermal regime and equivalent lithospheric thickness across that region of southern Africa at the time of kimberlite sampling, with concurrent local thermal disturbance evident in Namibia. Complimentary, novel, seismically-obtained geotherm estimates show that the lithosphere in Namibia is now significantly thinner than the estimate at 70 Ma obtained from xenolith thermobarometry.

1. Introduction

The estimation of palaeogeotherms from mantle xenolith Pressure–Temperature (P–T) data has been an integral part of studying the ancient roots of continents for over 30 years (Boyd, 1973). While thermobarometry methods have steadily evolved and have been subject to intense scrutiny (e.g., Brey and Köhler, 1990; Finnerty and Boyd, 1984; Nimis and Grütter, 2009), the most commonly-used method for estimating mantle palaeogeotherms from these P–T data has remained the same (Pollack and Chapman, 1977). This is surprising in the light of improved understanding of the thermal properties of the lithospheric mantle (e.g., Hofmeister, 1999; Jaupart et al., 1998), and advancing computational techniques. There have been multiple efforts to formulate more accurate palaeogeotherms (e.g. McKenzie and Bickle, 1988; McKenzie et al., 2005; Michaut et al., 2007; Rudnick and Nyblade, 1999; Russell et al., 2001) but these are often specific to particular localities and datasets, and have not been widely adopted. In this contribution, we compare the extensively-used Pollack and Chapman (1977; PC77) formulation that is usually fitted to data in a qualitative manner, with a modern, numerical palaeogeotherm fitting program, *FITPLOT* (McKenzie and Bickle, 1988; McKenzie et al., 2005) that can be applied to P–T data from a variety of localities. In this way, we aim to

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show the limitations of the PC77 approach, as commonly used by petrologists, and highlight the advantages of using more quantitative fitting methods to estimate palaeogeotherms from peridotite xenolith data. We show how these more quantitative fits allow objective evaluation of different models for regional lithosphere evolution, using a specific case study. In addition, the quantitative nature of the fitting method we adopt allows an evaluation of the relative accuracy and precision of palaeogeotherms derived from single-cpx xenocryst chemical data versus those derived from multi-phase peridotite xenoliths.

We also compare seismically-obtained geotherm parameterizations (c.f. Preistley and McKenzie, 2006) to those made using peridotite xenolith thermobarometry, to evaluate alternate methods of obtaining lithosphere thickness and thermal properties.

2. Mantle palaeogeotherms

Mantle palaeogeotherms derived from peridotite xenolith thermobarometry can be used to directly estimate information about the properties of the lithosphere at the time of eruption of the kimberlite, such as lithospheric thickness and thermal state. A geotherm is a description of the changing temperature of the Earth between the surface and the convecting mantle interior. Temperature increases fairly rapidly with depth within the crust; then reduces to a more linear gradient increase in the lithospheric mantle. The mantle lithosphere — where the Rayleigh number is much less than critical and therefore heat is transported by conduction — moves rigidly with respect to the crust above and is known as the Mechanical Boundary Layer (MBL; McKenzie and Bickle, 1988). As the geotherm curve approaches the ambient temperature of the asthenosphere, the gradient increases until it is parallel with the asthenospheric isentrope. The region in which this occurs has a Rayleigh number close to critical and is known as the Thermal Boundary Layer (TBL). Within this layer, heat is transported by both conduction and convection. The base of both these different regions of heat-flow (MBL, TBL) can be used to define different types of lithosphere. In this study we use the general term “lithospheric thickness”, to be consistent with common terminology used in mantle geotherm studies. This “lithospheric thickness” is the depth where the projection of the MBL (i.e. conductive) geotherm intersects the isentrope; this value falling within the TBL (see: Michaut et al., 2009, their Fig. 1). As pointed out by Rudnick and Nyblade (1999), any geotherm which does not meet the isentrope cannot be an accurate description of the way in which heat is conducted between the asthenosphere (represented by the isentrope) and the surface of the Earth.

Many of the PC77 palaeogeotherms that appear to fit peridotite xenolith P–T datasets (30–40 mW m^{-2}) do not cross the isentrope at any point and therefore it is not possible to estimate lithospheric thickness from the intersection of the geotherm with the isentrope. In these cases, other methods must be used to assess lithosphere thickness, such as the deepest xenolith erupted (Finnerty and Boyd, 1984). It is unlikely that kimberlites sample the lithosphere in a consistent and representative manner; this is clear from the variable spread in P–T data points produced by different kimberlite localities. Therefore, it is difficult to assess the accuracy of lithosphere thicknesses estimated using this method. A further problem is that PC77 palaeogeotherms are not unique for a given P–T array because they are calculated without reference to the P–T data, and the best-fit is estimated qualitatively by eye. As a result, two PC77 palaeogeotherms, with different surface heat flow, will often appear to fit the P–T data array equally well. Together, these problems create significant uncertainty when using PC77 palaeogeotherms as a tool for investigating craton evolution and diamond potential. Despite the lack of quantitative application of the PC77 formulation by many petrologists, far-reaching conclusions are often made on the basis of evidence provided by such palaeogeotherms, regardless of the fact that they were not initially intended for this purpose.

A palaeogeotherm formulation that is calculated using P–T data, that intersects the convecting mantle isentrope, and which provides some estimate of its accuracy would improve our assessment of the properties of the lithospheric mantle obtained using xenolith data. We aim to compare the results of such a quantitative fitting method: *FITPLOT* (McKenzie and Bickle, 1988; McKenzie et al., 2005) with those obtained using the commonly applied PC77 approach and other techniques, in order to assess its potential as a tool for evaluating the thermal evolution of cratonic regions. We evaluate the effects on resultant estimates of the lithosphere thickness and other palaeogeotherm parameters (e.g. shape, “diamond window” thickness and heat flow). We also use the ability of the *FITPLOT* technique to produce unique palaeogeotherm fits from individual P–T arrays to quantitatively investigate the effects that using a) different thermobarometer combinations, b) non-equilibrated xenoliths, and c) xenolith-and xenocryst-derived P–T estimates have on the shape of the palaeogeotherm.

3. Methods

3.1. Xenolith and xenocryst suites

Data from four suites of garnet peridotite xenoliths and two suites of single-cpx xenocryst data were used. These suites were chosen based on the abundance of samples from a wide range in depth, and, for two localities, the availability of complimentary xenocryst data for comparison. Published xenolith suites used are from Finsch (Gibson et al., 2008; Lazarov et al., 2009; Skinner, 1989), Bultfontein (Boyd and Nixon, 1978; Simon et al., 2007), Somerset Island (Schmidberger, 2001; Schmidberger and Francis, 1999), and Gibeon (Boyd et al., 2004; Franz et al., 1996a,b). In addition to these, new mineral chemical data are included in this study from Somerset Island (see Supplementary data).

We use clinopyroxene xenocrysts from Somerset Island and Bultfontein, which have been screened for peridotitic association (3.3.3). The Somerset Island dataset is from this study, and the Bultfontein xenocryst dataset was obtained courtesy of DeBeers.

3.2. Computation of the palaeogeotherm, and previous computation-based palaeogeotherm fits

We re-calculated P–T estimates from xenolith major-element data, rather than using published P–T values. Fe^{3+} content of constituent minerals was assumed to be zero. The spreadsheet ‘ptexl3’ was used to calculate pressures and temperatures which were then used as input data for palaeogeotherm fitting using the *FITPLOT* program.

FITPLOT, was written by McKenzie in 1988 (McKenzie and Bickle, 1988), and expanded by McKenzie et al. (2005); a more comprehensive description of the way that the geotherm is calculated can be found there, and in the supplementary data. In brief, *FITPLOT* uses equations describing the thermal properties of the lithospheric mantle, together with a range of input parameters for the crust and mantle (Section 3.3; and supplementary data) to iterate a series of discrete palaeogeotherms with varying Mechanical Boundary Layer (MBL) thicknesses. In this MBL, thermal conductivity varies with temperature. In the TBL, the temperature variation with depth depends on the viscosity.

Importantly, the quantitative fit to the P–T data is obtained by calculating the misfit for each of these calculated palaeogeotherms to the input P–T array, using a root mean square distribution of ΔT from the calculated palaeogeotherm line. The palaeogeotherm output by the program is that which shows the lowest misfit (ΔT) with the input Pressure–Temperature data. Additionally, the lithospheric thickness