THE EFFECT OF DIFFERENTIAL MINERAL COMPRESSIBILITY ON DIAMOND INCLUSION THERMOBAROMETRY

David Phillips[1] and Jeff Harris[2]
[1] The University of Melbourne, Australia; [2]The University of Glasgow, Scotland

INTRODUCTION

The determination of temperatures and pressures from co-existing mineral inclusions in diamonds provides valuable information on the depth and thermal conditions associated with the diamond-bearing mantle (e.g. Boyd et al., 1985; Viljoen et al., 1999). In most cases, experimental or empirical thermometers and barometers are applied to pairs of *non-touching* silicate inclusions (e.g. garnet-orthopyroxene, garnet-olivine and garnet-clinopyroxene). Provided these are unaltered equilibrium assemblages, the application of appropriate thermobarometers should constrain the pressure and temperature conditions that prevailed at the time of diamond crystallization. However, some diamonds contain *touching* inclusion pairs that may re-equilibrate in response to changing mantle temperatures and pressures, as long as there is sufficient time for chemical reactions to occur (e.g. Phillips et al., 1995; Sobolev et al., 1997). Consequently, touching inclusions have the potential to provide information on the post-crystallisation thermal and tectonic history of the diamond-bearing mantle. For example, Phillips et al. (1995) concluded that temperature differences between touching and non-touching inclusions from Kimberley mine diamonds were due to cooling of the mantle subsequent to diamond formation. Sobolev et al. (1997) have suggested that some touching inclusions could record elevated temperatures related to interaction with the transporting kimberlite melt.

Although it is expected that changes in external mantle temperatures will be effectively transmitted to inclusions contained in diamond, this may not be the case for variations in the confining pressure. Diamond is characterised by a much lower thermal expansivity than typical silicate inclusions such as garnet and pyroxene. Therefore, if the diamond does not fracture or undergo viscous flow, the inclusion volume will be dictated by the compressibility of the host diamond (see Zhang, 1998 for theoretical discussion). Consequent changes in mantle pressure/temperature could then produce internal pressures that differ from external conditions, leading to erroneous pressure estimates for mineral inclusions.

In this study, we evaluate the magnitude of this effect from thermodynamic modeling as well as thermobarometric results obtained from touching and non-touching silicate inclusions extracted from diamonds from the Kimberley Mines, South Africa.

THERMODYNAMIC MODELS

The potential effects of differential thermal compressibility were modeled using two different approaches: 1) the elastic stress model of Zhang (1998); and 2) the THERMOCALC software package (e.g. Powell et al., 1998) and the thermodynamic dataset of Holland and Powell (1998). Input parameters to the models assumed diamond crystallisation and equilibrium inclusion encapsulation at 1250°C and 6.0GPa. (The choice of these conditions will become apparent in the discussion on the Kimberley inclusion

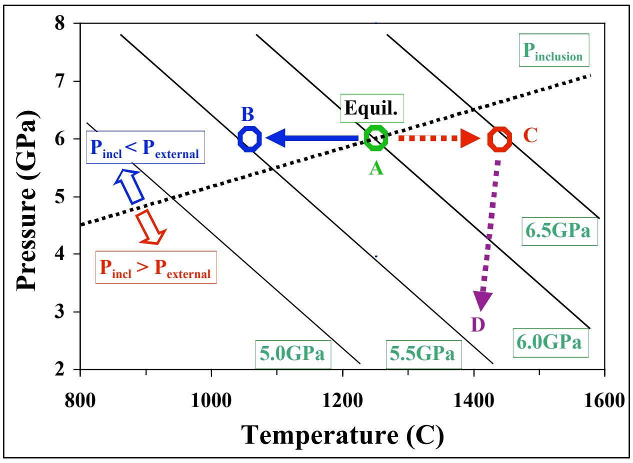

Figure 1: Calculated internal pressure for silicate mineral inclusions in diamond as a function of changing external temperature and pressure. Equilibrium conditions at the time of diamond crystallization and inclusion encapsulation are assumed to be 1250°C and 6.0GPa (A). Subsequent mantle cooling and a decrease in temperature to 1050°C at constant pressure, would cause a reduction of the internal pressure to ~5.6GPa (B). A corresponding increase in external temperature (1450°C; constant P), as might be expected during kimberlite eruption, would increase internal pressure to ~6.4GPa (C). Rapid (adiabatic) eruption to surface (D) would cause a much smaller change in internal pressure; however subsequent quenching may prevent chemical equilibration.

results). Due to the low compressibility of diamond relative to silicate inclusions, the volume occupied by the inclusion remains relatively constant and internal pressure experienced by the silicate inclusions can be modified by changes in external mantle temperatures. Both modeling approaches yielded similar results indicating that cooling or heating of the mantle would cause a corresponding reduction/increase in internal inclusion pressure of ~0.2GPa/100°C, respectively (Fig. 1). Adiabatic transport of diamonds to the surface by the host kimberlite magma causes a rapid reduction in external confining pressure; however, changes in internal pressure are much more subdued (Fig. 1). This results in a large differential between external and internal pressures and it is at this point that the inclusion is most vulnerable to decrepitation.

DIAMOND INCLUSION THERMO-BAROMETRY

Kimberley Pool diamonds yielded a predominance of peridotitic paragenesis inclusions and an unusually large number of touching and non-touching inclusion pairs (Phillips et al., 1995). Electron microprobe analyses of these assemblages revealed distinct compositional differences that were attributed to differences in mantle equlibration conditions. With few exceptions, the Mg/(Mg+Fe) ratios of non-touching garnets co-existing with separate olivine and pyroxene inclusions are higher than those of garnets intergrown with other silicates (Fig. 2). This observation is consistent with the non-touching assemblages having higher equlibration temperatures. In addition, the aluminium contents of non-touching orthopyroxene

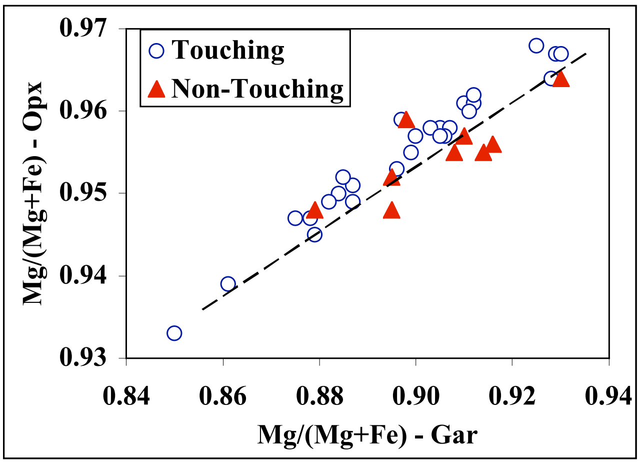

Figure 2: Mg/(Mg+Fe) ratios of co-existing garnet and orthopyroxene inclusions from Kimberley Pool diamonds. Most touching garnet inclusions exhibit lower mg ratios, consistent with lower equilibration temperatures.

inclusions are generally higher than in touching inclusions, implying that the former also experienced elevated equilibrium pressures (Phillips et al., 1995; Girnis et al., 1999). Thermobarometry determinations of 33 touching and 20 non-touching inclusions assemblages were made using the Fe-Mg exchange thermometers of O'Neill and Wood (1979; gar-oli), Harley (1984; gar-opx) and Krogh (1989; gar-cpx)) and the Al-in-opx barometer of Brey and Kohler (1990). Non-touching mineral pairs generally yielded higher temperatures and pressures with average values of 1240°C and 6.1GPa, compared to 1070˚C and 5.3GPa for touching inclusion assemblages (Fig. 3). The difference between the two inclusion groups is thus 170°C and 0.8GPa.

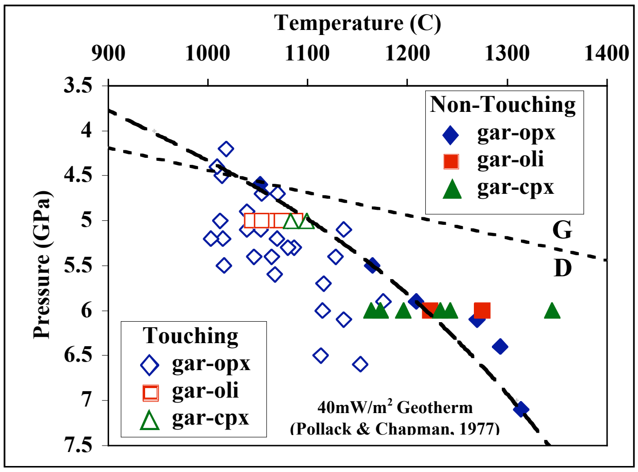

Figure 3: Temperature and pressure determinations for touching and non-touching inclusion assemblages from Kimberley Pool diamonds. Also plotted are the diamond/graphite phase boundary and the conductive geothermal gradient, based on a surface heat flow of $40mW/m^2$ (Pollack and Chapman, 1977).

DISCUSSION

The discrepancy in temperature estimates between the two inclusion groups is readily reconciled in terms of mantle cooling subsequent to diamond crystallization, and there is no evidence to indicate significant heating related to interaction with the kimberlite magma. The apparent pressure difference (~8kb) could be an artifact of the geobarometer used or it may be due to uplift of part of the mantle, subsequent to diamond crystallisation. If diamond formation occurred more than 3.0Ga ago, differential movements of ~20km might not be unexpected. However, uplift of this magnitude is not manifest in the overlying crust. Based on the modeling constraints, it seems likely that at least some portion of the apparent discrepancy in calculated pressures relates to differences in the thermal compressibility between diamond and silicate inclusions. While the value of 8kb is greater than that predicted from the thermodynamic modeling, it must be noted that the calculated pressures are average values and individual thermobarometric estimates are subject to relatively large uncertainties, typically ±50°C and ± 2kb.

In conclusion, thermodynamic modeling suggests that differential compressibility between diamonds and their inclusions is likely to have a discernable effect on 'internal' inclusion pressure estimates. As most thermometers have some pressure dependence, temperature estimates will also be slightly affected. These results have implications not only for the interpretation of thermobarometric results from diamond inclusions, but also for pressure/temperature calculations of metamorphic rocks in which minerals are included in one another.

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Contact: D Phillips, School of Earth Sciences, The University of Melbourne, Parkville, VIC, 3010, Australia, E-mail: dphillip@unimelb.edu.au.