Practical: Composition and Thermal Structure of the Lithospheric Mantle

Preliminary Information:

QT Resources recently discovered a new field of kimberlite pipes (The Thurman Field) in central Australia (Figure 1a). Eight kimberlite pipes have been discovered since December 2021 (Figure 1b). The pipes occur beneath approximately 20–35 meters of Aeolian sedimentary rocks (Eocene age). Geochronology was done on one representative kimberlite pipe (Mia) to determine the age of emplacement/eruption. The pipe returned a U-Pb perovskite age of 427 ± 5 Ma. To evaluate the potential for the Thurman Kimberlite Field to host diamond-bearing kimberlites, QT Resources conducted bulk samples for three of the pipes (Winston, Butch and Fabienne). Bulk samples of the pipes recovered approximately 50 mantle xenoliths of various rock types (lherzolites, harzburgites, and wehrlites etc.). Additionally, two rough octahedral diamonds (0.34ct and 0.12ct) were recovered from the Fabienne kimberlite pipe. Additionally, one rough fancy yellow diamond (0.75ct) was collected from a stream sediment sample approximately 10 km south-west of the Vincent kimberlite pipe. To improve the understanding of the diamond potential of the region, QT Resources have provided the mineralogical and compositional data for the mantle xenoliths. The data provided includes (a) the modal proportions of all minerals within the mantle xenoliths, and (b) the average chemical compositions (determined using EPMA) of olivine, clinopyroxene, orthopyroxene, and garnet, within each of the mantle xenoliths. Both sets of data are provided in spreadsheet SHEET 1. The oxide concentrations are reported on column H to AX. The cation concentrations per formula unit are reported on column BA to CR.

TASK 1: Using the modal proportions of the minerals in each mantle xenolith (column C to G in SHEET 1), construct a ternary diagram to determine what rock types they belong to (i.e., lherzolite, wehrlite, harzburgite, or dunite etc.) (see Figure 2 for an example). Remembering from the PART 1 lecture that the lithology (rock type) of mantle xenoliths provides important clues into the nature of the underlying lithospheric mantle. The ternary diagram is based on the modal proportions of olivine, orthopyroxene and clinopyroxene, therefore you must normalize these three minerals against one another. The normalized totals for the three minerals must sum to 100. Plot the normalized modal proportions (and corresponding sample names) into the YELLOW space in SHEET 2. The ternary diagram will plot your mineral proportions in the appropriate fields based on the normalized modal proportions (i.e., lherzolite, harzburgite, wehrlite etc.). Colour code the mantle xenoliths from each pipe so that you can determine what rock types occur for each location.

Q: What are the common rock types for the mantle xenoliths at each kimberlite pipe. Are there any major trends in the rock types of mantle xenoliths for the different kimberlite pipes within the Thurman Kimberlite Field? Discuss as group briefly.

TASK 2A We will now use geothermobarometry to calculate the equilibration pressure (P; kbar) and temperature (T; °C) of the mantle xenoliths using the cation concentrations of the minerals in SHEET 1. Calculate the temperature using the Taylor (1998) two-pyroxene solvus geothermometer (TA98). This geothermometer is suitable for mantle rock types that contain both clinopyroxene and orthopyroxene. This calibration is widely used by mantle petrologists interested in studying the thermal structure of the lithospheric mantle. The equation for the geothermometer is based on the cation concentrations in orthopyroxene and clinopyroxene, which change as a result of temperature. This equation is listed below.

Additionally, determine the pressures (kbar) of the mantle xenoliths using the Nickel and Green (1985) Al-in-garnet geobarometer (NG85). This geobarometer is suitable for mantle rock types that contain garnet and orthopyroxene. The geobarometer is based on the cation concentrations in garnet and orthopyroxene, which vary as a function of pressure. The equation is listed below BUT note that some of the in-put variables for the equation have already been calculated to save some time (dV, C and LnKd). Both the TA98 geothermometer and NG85 geobarometer equations require iteratively solving pressure and temperature simultaneously. Calculate the pressure and temperature for all mantle xenoliths using the two equations provided and make sure that the final estimate for each sample is iteratively solved. Plot the pressures and temperatures onto a scatter plot (pressure on y-axis in decreasing order and temperature on x-axis in increasing order) and colour code the xenoliths from each of the kimberlite pipes.

Equation for calculating temperature (°C):

$$\mathrm{T(°C)} = \frac{\left(24787 + 678\ \cdot\left(\frac{\mathrm{P}}{10}\right)\right)}{15.67 + 14.37\cdot \mathrm{Ti^{cpx}} + 3.69\cdot \mathrm{Fe^{cpx}} - 3.25\cdot(\mathrm{Al^{cpx}} + \mathrm{Cr^{cpx}} - \mathrm{Na^{cpx}}) + \mathrm{lnKd}} - 273$$

$$\mathrm{lnKd} = (\ln\left(\frac{\mathrm{a_{cpx}^{En}}}{\mathrm{a_{opx}^{En}}}\right))^2$$

$$\mathrm{a_{cpx}^{En}} = (1 - \mathrm{Ca^{cpx}} - \mathrm{Na^{cpx}})\cdot(1 - \mathrm{Al^{VI}}^{\mathrm{cpx}} - \mathrm{Cr^{cpx}} - \mathrm{Ti^{cpx}})\cdot(1 - \frac{\mathrm{Al^{IV}}^{\mathrm{cpx}}}{2})^2$$

$$\mathrm{Al^{VI}}^{\mathrm{cpx}} = \left(\frac{\mathrm{Al^{cpx}}}{2} - \frac{\mathrm{Cr^{cpx}}}{2} - \mathrm{Ti^{cpx}} + \frac{\mathrm{Na^{cpx}}}{2}\right)$$

$$\mathrm{Al^{IV}}^{\mathrm{cpx}} = \left(\frac{\mathrm{Al^{cpx}}}{2} + \frac{\mathrm{Cr^{cpx}}}{2} + \mathrm{Ti^{cpx}} - \frac{\mathrm{Na^{cpx}}}{2}\right)$$

$$\mathrm{a_{opx}^{En}} = (1 - \mathrm{Ca^{opx}} - \mathrm{Na^{opx}})\cdot(1 - \mathrm{Al^{VI}}^{\mathrm{opx}} - \mathrm{Cr^{opx}} - \mathrm{Ti^{opx}}\cdot(1 - \frac{\mathrm{Al^{IV}}^{\mathrm{opx}}}{2})^2$$

$$\mathrm{Al^{IV}}^{\mathrm{opx}} = \left(\frac{\mathrm{Al^{opx}}}{2} + \frac{\mathrm{Cr^{opx}}}{2} + \mathrm{Ti^{opx}} - \frac{\mathrm{Na^{opx}}}{2}\right)$$

$$\mathrm{Al^{VI}}^{\mathrm{opx}} = \left(\frac{\mathrm{Al^{opx}}}{2} - \frac{\mathrm{Cr^{opx}}}{2} - \mathrm{Ti^{opx}} + \frac{\mathrm{Na^{opx}}}{2}\right)$$

P is pressure in kbar

NOTE: X^{opx} refers to the cation concentration of element X in orthopyroxene.

Equation for calculating pressure (kbar):

$$\mathrm{P\ (kbar)} = \mathrm{dV}\cdot\left(\mathrm{C} + (\mathrm{T} + 273.15)\cdot\left(-1.9872\cdot\mathrm{lnKd} + 52.1\cdot\mathrm{Ca_{M2}^{grt}}\cdot\mathrm{Cr_{M1}^{grt}} - 3.23\right)\right)$$

$$\mathrm{lnKd} = \ln\left((1 - \mathrm{Ca}_{\mathrm{M2}}^{\mathrm{grt}})^3 \cdot {\mathrm{Al}_{\mathrm{M1}}^{\mathrm{grt}}}^2 / (\mathrm{opx}_{\mathrm{MF}}^{\mathrm{M1}} \cdot \mathrm{opx}_{\mathrm{MF}}^{\mathrm{M2}} \cdot D\right)$$

$$\mathrm{opx}_{\mathrm{MF}}^{\mathrm{M1}} = 1 - \mathrm{opx}^{\mathrm{jad}} - \mathrm{Cr}^{\mathrm{opx}} - \mathrm{Ti}^{\mathrm{opx}}$$

$$\mathrm{opx}^{\mathrm{jad}} = \mathrm{Na}^{\mathrm{opx}} - \mathrm{Cr}^{\mathrm{opx}} - 2 \cdot \mathrm{Ti}^{\mathrm{opx}}$$

$$\mathrm{opx}_{\mathrm{MF}}^{\mathrm{M2}} = 1 - \mathrm{Ca}^{\mathrm{opx}} - \mathrm{Na}^{\mathrm{opx}} - \mathrm{Mn}^{\mathrm{opx}}$$

$$\mathrm{Al}_{\mathrm{M1}}^{\mathrm{grt}} = \mathrm{Al}^{\mathrm{grt}} / (\mathrm{Cr}^{\mathrm{grt}} + \mathrm{Al}^{\mathrm{grt}})$$

$$\mathrm{Ca}_{\mathrm{M2}}^{\mathrm{grt}} = \mathrm{Ca}^{\mathrm{grt}} / (\mathrm{Ca}^{\mathrm{grt}} + \mathrm{Fe}^{\mathrm{grt}} + \mathrm{Mg}^{\mathrm{grt}} + \mathrm{Mn}^{\mathrm{grt}})$$

$$\mathrm{Cr}_{\mathrm{M1}}^{\mathrm{grt}} = \mathrm{Cr}^{\mathrm{grt}} / (\mathrm{Cr}^{\mathrm{grt}} + \mathrm{Al}^{\mathrm{grt}})$$

Variables dV, C and D are provided already in the spreadsheet

T is temperature is °C

NOTE: X^{grt} refers to the cation concentration of element X in garnet.

Q: What is the pressure and range of the mantle xenoliths from each kimberlite pipe? Which kimberlite pipe(s) contain the mantle xenoliths with the highest pressures and temperatures? What is a possible explanation for the lack of high-pressure mantle xenoliths from the Winston kimberlite pipe?

Q: Using the rock types determined from the previous question, are there any major trends in the lithology (rock type) of mantle xenoliths as a function of their pressure and/or location?

TASK 2B: Add the graphite-diamond phase transition onto your plot in order to determine whether any of the mantle xenoliths came from lithospheric depths where diamond was stable. Laboratory experiments have determined the approximate phase transition from graphite (lower pressure) to diamond (higher pressure) (Figure 3). Use the information on Figure 3 to derive an approximate line for the graphite-diamond transition. This will require using data points on the Figure 3 to fit a straight line onto your plot that shows the graphite-diamond phase transition.

Q Do any of the mantle xenoliths record equilibration pressures and temperatures that fall within the diamond stability field? If so, which kimberlite pipe(s) contained the most mantle xenoliths from the diamond stability field? Where do these kimberlites occur within the Thurman Kimberlite Field.

Q What do the results tell us about possible variations in lithospheric structure throughout the Thurman Kimberlite Field? If you were responsible for evaluating the diamond potential of additional kimberlite pipes within Thurman Kimberlite Field, which pipes would you suggest?

Q Based on these results do you think that the rough fancy yellow diamond (0.75 ct.) that was found near the Vincent Kimberlite was from this area of the Thurman Kimberlite Field?

TASK 3 We will further explore the lithospheric structure beneath the Thurman Kimberlite Field by plotting a simplified paleogeotherm to the pressure and temperature data of mantle xenoliths from each kimberlite pipe. First, we must add the pressure and temperature range of the mantle adiabat for a chosen mantle potential temperature (Tp). Tp is the temperature the mantle would have at the surface, if it ascended along an adiabat without undergoing melting (Figure 4). The adiabat can be used to compare the temperature of the mantle between different locations. The pressure and temperature that a paleogeotherm gradient intersects the mantle adiabat provides an estimate of where the mantle has changed from conductive heat transfer to convective heat transfer, and thus constrains the lithosphere–asthenosphere boundary (LAB). To your Figure, add a mantle adiabat with a mantle Tp of 1330 C. To add the adiabat, consider the simple relationship:

T = 1.7033(P) + 1330, where T is the temperature (C) of the adiabat, and pressure is in kbar. Use this equation to calculate the temperature of the adiabat using a range of pressures. Add the pressures and temperature in a separate set of columns and add the line to your current Figure.

Furthermore, fit a linear gradient to the mantle xenolith pressure and temperature estimates for each kimberlite pipe. Play around with the forecast options for the line to increase its projection and to see where it intercepts the mantle adiabat. Using a linear relationship for pressure and temperature for the paleogeotherm is likely to be reasonable approximation, although more advanced programs can produce a reliable set of paleogeotherms, such as FITPLOT (Mather et al. 2011). For this exercise a simple linear fit in excel will suffice.

Q What is the pressure (and depth in kilometres) of the lithosphere–asthenosphere boundary beneath each of the kimberlite pipes for the time of eruption? Convert pressure (kbar or GPa) to kilometres by assuming 1 kbar = 3 km in depth. How does the lithosphere thickness at the time of eruption vary between the kimberlite pipes?

Q What is the approximate change in lithosphere thickness between the Winston and Butch kimberlite pipes, and what does this difference tell us about the change in lithospheric structure across the Kimberlite Field.

TASK 4: As mentioned in the *Preliminary information*, the emplacement of kimberlite pipes at the Thurman Kimberlite Field occured at 427 ± 5 Ma. The paleogeotherms reported above have provided us with insights into the thickness and thermal structure of the mantle for this period only, but how do they compare with the present day thermal structure and lithospheric thickness of the region? One way of determining the present day thickness of the lithospheric mantle is from seismic tomography models which estimate the LAB depth based on surface waves and the relationship between depth, Vs and T (°C) of the lithosphere (see Priestley et al. 2024; EPSL). In SHEET 3 the latitude (LAT), longitude (LON) and LAB depth (LAB) (km) are reported. These values are taken from a regional model from Hoggard et al. (2020).

The latitude and longitude for the Fabienne and Winston kimberlite pipes are reported in Table 1. The Table contains an empty column for your xenolith LAB estimates. Additionally, LAB estimates and latitude (LAT), longitude (LON) are provided for an additional three pipes, which have been taken from previous studies on the xenoliths. The format for all latitude and longitude points are the same (decimal degrees) however, the data in SHEET 3 is only to one decimal place. Find the present-day LAB depth from the SHEET 3 datafile for the appropriate latitude and longitude of kimberlite pipes in Table 1 and compare the present day LAB with the xenolith based LAB estimate.

Q How does the depth of the LAB at the time of eruption (xenolith LAB) compare with the present-day LAB taken determined from seismic methods, and how do these results vary between the various pipes?

Q Are there any notable changes in present-day LAB depth across the Thurman Kimberlite Field? Provide a possible explanation for any changes in the lithospheric thickness over time. Also, take into consideration that paleogeotherms and seismic LAB models likely have uncertainties in the order of 10–20 km. If the lithosphere has not changed since the eruption of the kimberlites, how might this be explained?

Q: If the lithospheric thickness had decreased by 50 km since the eruption, what might be a possible explanation for this? Conversely, what may be an explanation for similar (+50 km) amounts of thickening of the lithosphere?

TASK 5: The estimates for pressure and temperature of the mantle xenoliths can be used in conjunction with the measured concentrations of different elements to see how the chemistry of the mantle varies between different pipes and, with increasing depth. This can be particularly important for identifying regions of anomalous geochemical enrichment, which may be responsible for anomalous features observed in geophysical datasets (i.e., magnetotellurics, seismic tomography, S-receiver functions). Trace element concentrations (in ppm, parts per million) for clinopyroxenes are reported in SHEET 4 for the same xenoliths reported in SHEET 1. Copy over the pressure and temperature data from SHEET 1 into SHEET 4 (keeping the same order). Explore how the chemical compositions of clinopyroxenes vary with increasing pressure and temperature, and between the different kimberlite pipes. Report any systematic changes or notable trends in the chemical compositions of the clinopyroxenes. Use a periodic table to familiarize yourself with the elements reported in SHEET 4. A periodic table with different element properties (density, atomic radii, bulk modulus, bond length, valence state etc.) can be accessed from (https://www.webelements.com/periodicity/contents/).

Q: How do the concentrations of trace elements in clinopyroxene vary with pressure and temperature beneath each of the three kimberlite pipes? Report and discuss any notable trends.

Q: How might we assess the degree of melt depletion beneath the three pipes? Use the major and minor oxide concentrations, and any suitable trace elements to evaluate which sections of the mantle are more geochemically depleted.

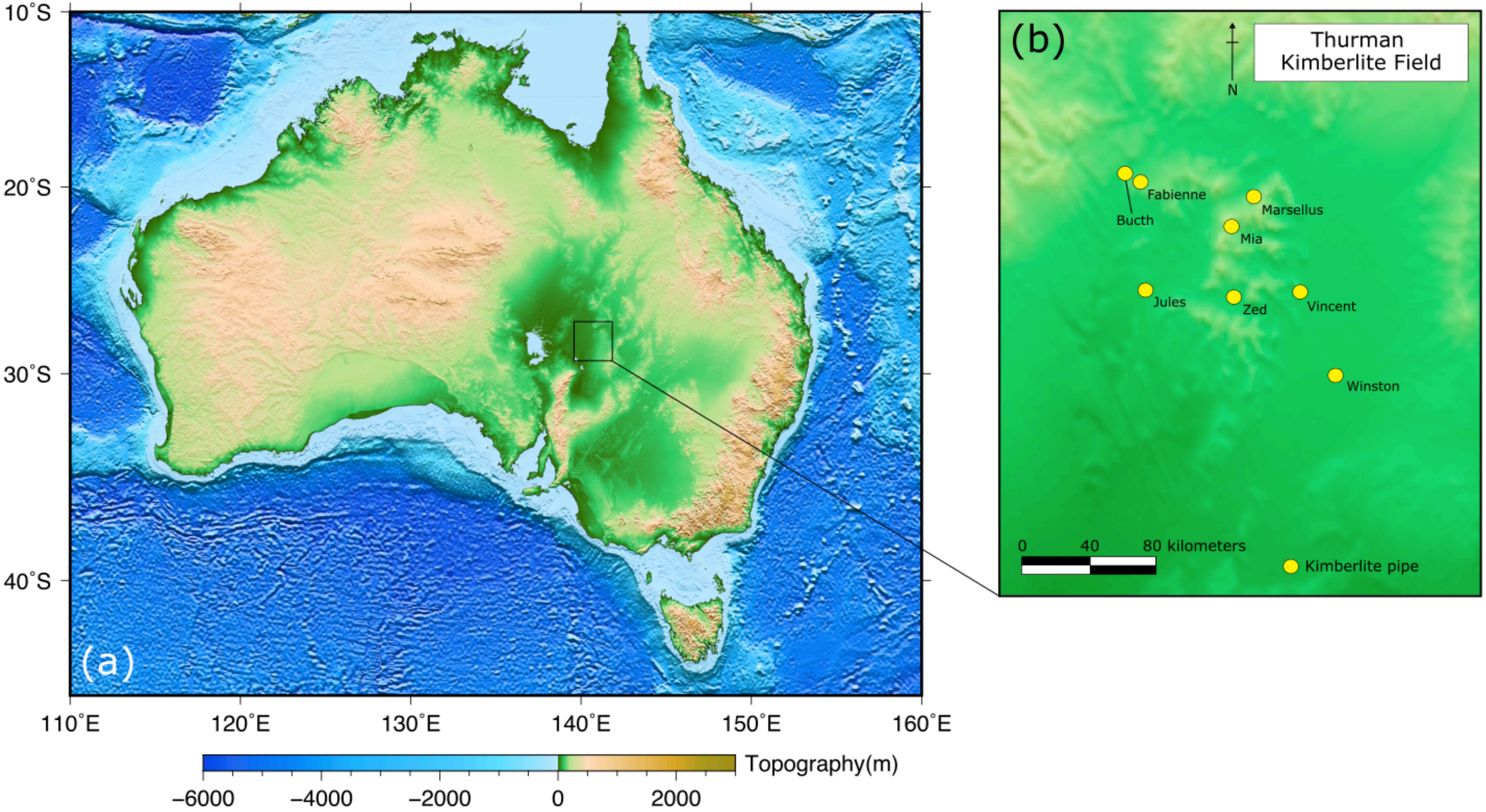
10˚S
20˚S
30˚S
40˚S
110˚E
120˚E
130˚E
140˚E
150˚E
160˚E
(a)
−6000
−4000
−2000
0
2000
Topography(m)
(b)
N
Thurman Kimberlite Field
Fabienne
Bucth
Marsellus
Mia
Jules
Zed
Vincent
Winston
0
40
80 kilometers
Kimberlite pipe

Figure 1a. (previous page) (a) Topographic map of the Australian and, (b) the location of the recently discovered Thurman Kimberlite Field. Yellow symbols (circles) are the locations of kimberlite pipes from the Thurman Kimberlite Field. (Figure a Modified after Scholz and Zhang et al. (2024).

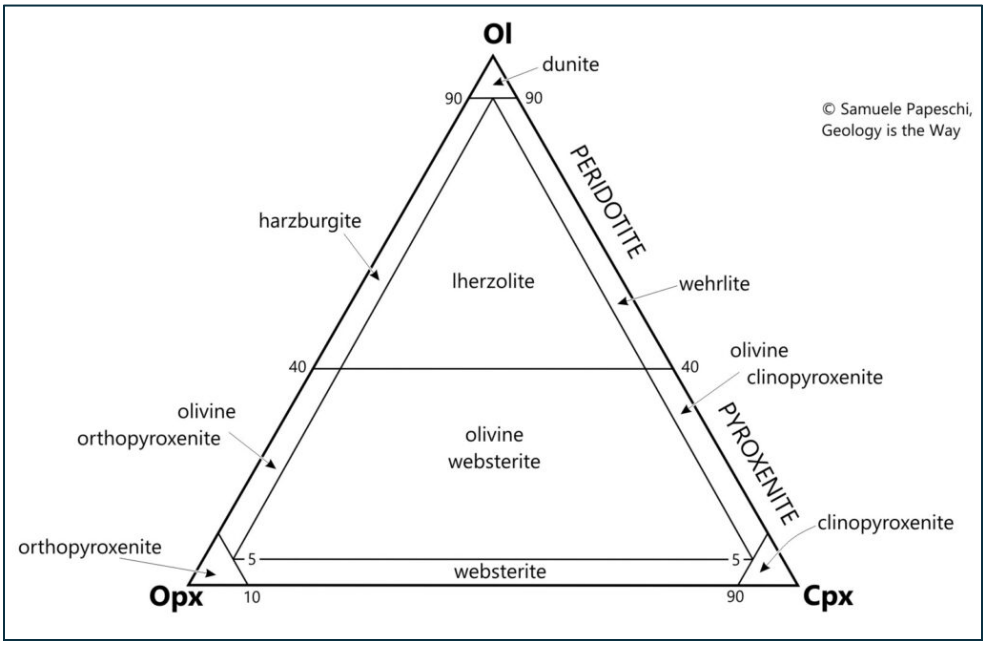

Figure 2 Ternary diagram showing the different mantle rock types for peridotite and pyroxenite based on different modal proportions of olivine, clinopyroxene and orthopyroxene. Each axis is the modal proportion of the mineral (as percentage).

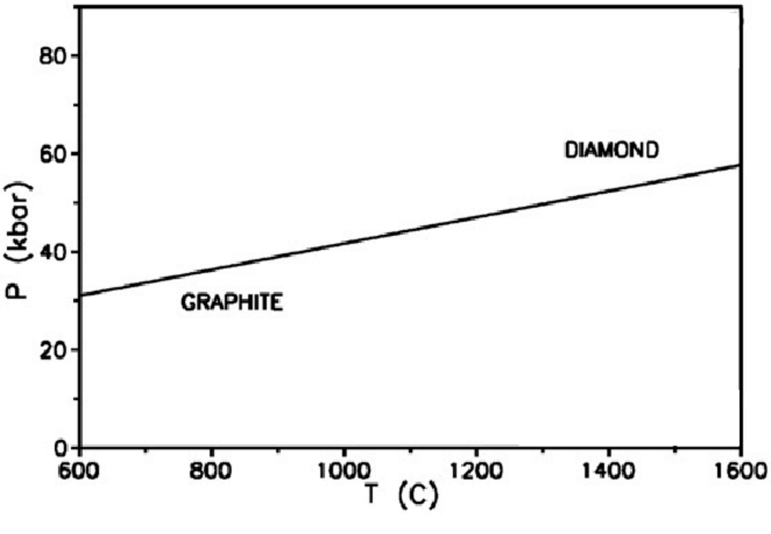

Figure 3 (previous page). Simplified diagram showing the pressure and temperature of the graphite-diamond transition.

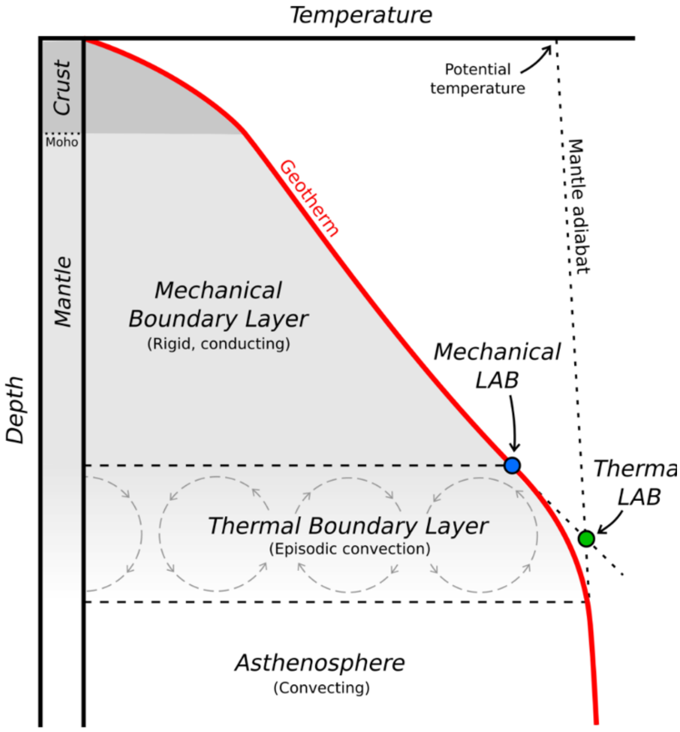

Figure 4. Simplified diagram showing a paleogeotherm/geotherm, the mantle adiabat, and mantle potential temperature. Note that the paleogeotherm intersects the mantle adiabat at the thermal LAB. After Hoggard et al. (pers. Comms). The mantle adiabat projects down from the potential temperature at the surface.

Table 1. Latitude and longitude (decimal degree) for kimberlites from the Thurman Kimberlite Field. Xenolith LAB for the Fabienne and Winston pipes are to be taken from your paleogeotherm models. The Xenolith LAB for Mia, Zed and Vincent pipes come from previously published estimates. Determine the present day LAB at the correct latitude and longitude for each of the pipes by using the seismic LAB estimates reported in SHEET 3

Pipe name	**Latitude**	**Longitude**	**Xenolith LAB**	**Present Day LAB**
Winston	-25.8	140.0		
Fabienne	-24.4	136.3		
Mia	-24.7	137.5	183	
Zed	-24.9	138.1	173	
Vincent	-25.1	137.8	170	