Short course "Diamond as a messenger from the Earth's interior: natural samples and experiment"

Part 2:
What do we learn from diamonds?

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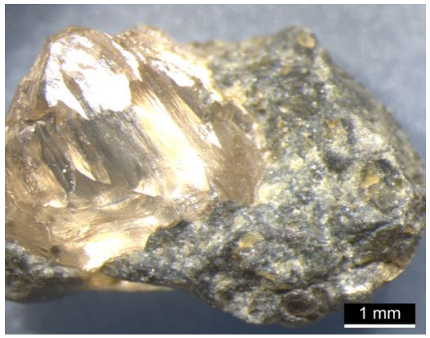
Inspiring Minds

Outline

- What do we know about diamond formation?
  - Phenocrysts or xenocrysts?
  - Complex growth – resorption patterns in natural diamonds
  - Role of oxidation – reduction processes
  - Role of carbon saturation in mantle fluids/melts
- Applications
  - Carbon isotopes – carbon cycle
  - Craton-formation
  - "window" into the mantle
  - How studies of diamond inclusions help in kimberlite prospecting and exploration

Phenocrysts or xenocrysts?



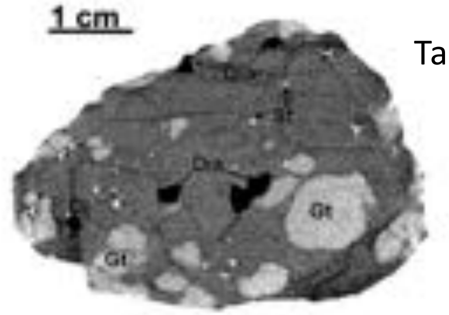


FIG. 1. HRXCT three-dimensional image of the eclogite xenolith U51, created by stacking the 80 two-dimensional

Taylor et al. (2000)

Diamond nucleation and growth by reduction of carbonate melts under high-pressure and high-temperature conditions

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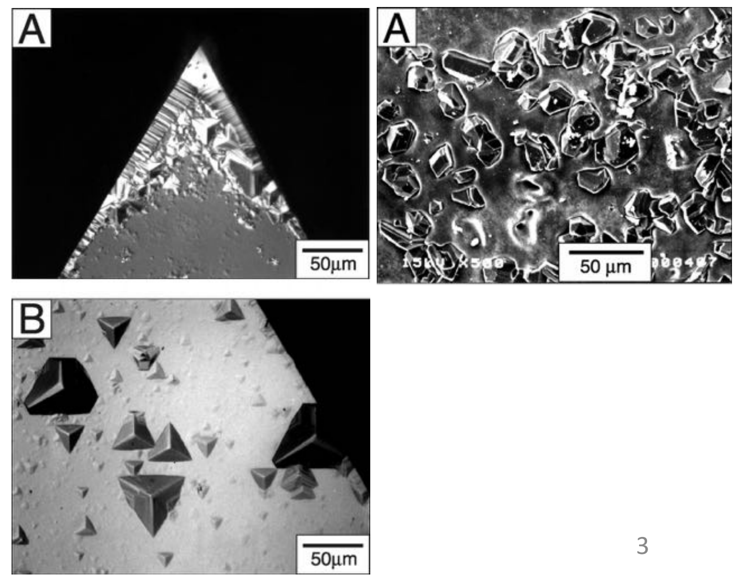
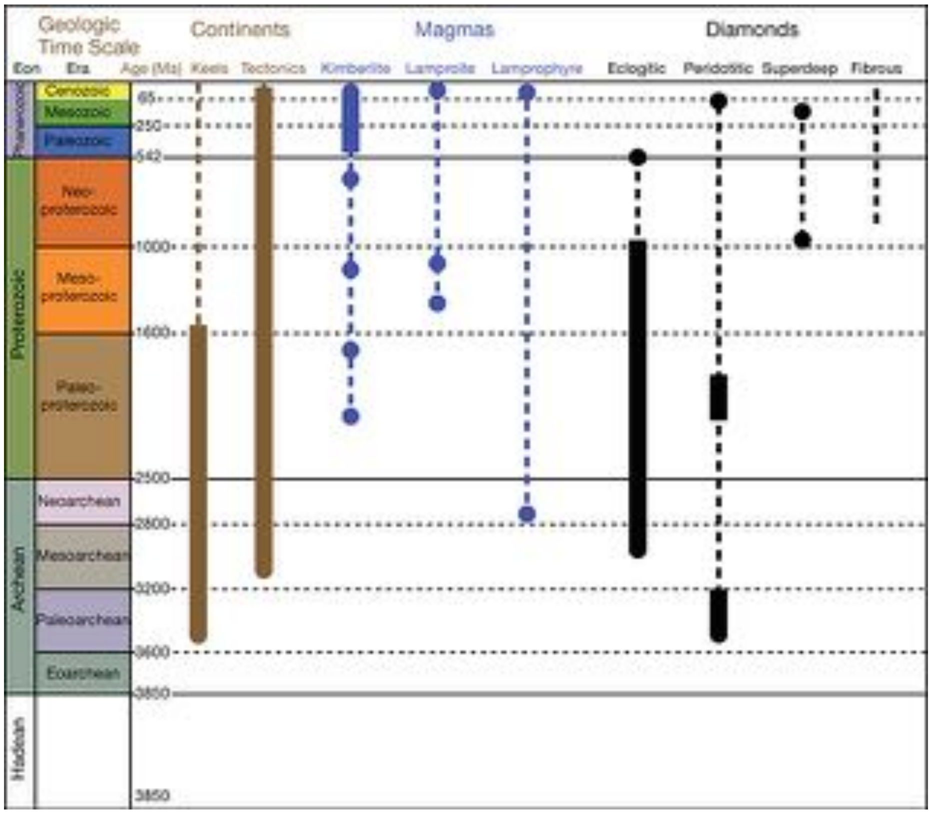
ABSTRACT

We report for the first time experimental evidence for the nucleation and growth of diamonds from carbonatitic melts by reduction in reactions with silicon metal or silicon carbide. Experiments were carried out in the $CaMg(CO_3)_2$-Si and $CaMg(CO_3)_2$-SiC systems at 7.7 GPa and temperatures of 1500–1800 °C. No graphite was added to the run powder as a carbon source; the carbonate-bearing melts supply the carbon for diamond formation. Diamond grows spontaneously from the carbonatitic melt by reducing reactions: $CaMg(CO_3)_2 + 2Si = CaMgSi_2O_6 + 2C$ in the $CaMg(CO_3)_2$-Si system, and $CaMg(CO_3)_2 + 2SiC = CaMgSi_2O_6 + 4C$ in the $CaMg(CO_3)_2$-SiC system. Our results provide strong experimental support for the view that some natural diamonds crystallized from carbonatitic melts by metasomatic reducing reactions with mantle solid phases.



Phenocrysts or xenocrysts?



From Shirey (2013) and Gurney et al. (2010)

From Gurney et al. (2010)

TABLE 1. Kimberlite Ages and Diamond Ages from Southern African Diamond Mines

Name of kimberlite	Emplacement age (Ma)	P-type Harzburgitic (Ga)	Archean E-type (Ga)	P-type Iherzolitic (Ga)	Proterozoic E-type (Ga)	FD	References
Premier	1180 ± 30	◇		~2.0	~2.0 ~1.2		1,2,3
Venetia	519	◆		~2.0	~2.0		3, 4
Jwaneng	235 ± 2	◆	~2.9		~1.5	✳	5, 6
Klipspringer	155	◇	~2.6				7
Finsch	118 ± 3	~3.3–3.2			1.58 ± 0.05		8, 9, 10
Orapa	93.1	◇	~2.9		0.99 ± 0.05	✳	10, 11
Kimberley pool	95	~3.3– 3.2	2.89 ± 0.06				8, 12
Koffiefontein	90.4	◆	~2.9		~1.1		13
Jagersfontein	86	◇			~1.7 ~1.1		14

TABLE 2. Kimberlite Ages and Diamond Ages from Slave Province Kimberlites and Diamond Mines (*)

Name of kimberlite	Emplacement age (Ma)	P-type harzburgitic (Ga)	P-type Iherzolitic	E-type (Ga)	FD	References
Anuri	613					1
Gahcho Kué	542	◆				2
Snap Lake*	533–535	◆		◇	✳	3
Victoria Island	256–286					2
Jericho	172.3	◇		◆		4
Diavik*	55	~3.5–3.3		2.2–1.8	✳	5,6
Panda*	53	3.5.± 0.17		◇	✳	7,8

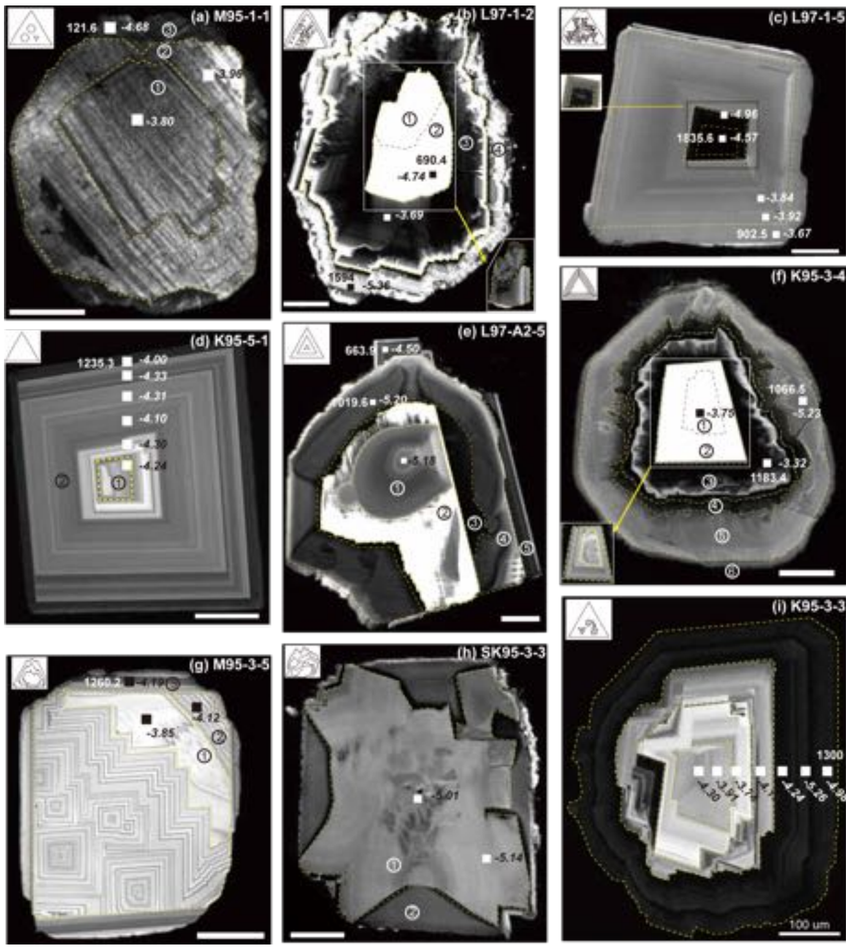
TABLE 3. Kimberlite Ages and Diamond Ages from Kimberlites of the Siberian Craton

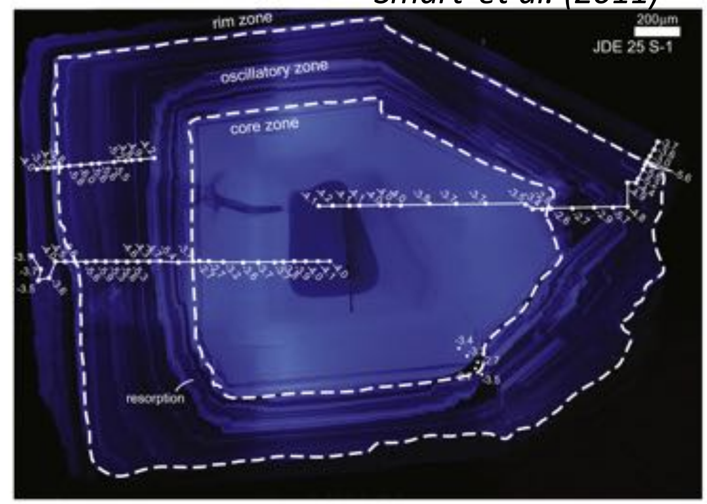
Name of kimberlite	Emplacement age (Ma)	P-type harzburgitic (Ga)	E-type (Ga)	P-type Iherzolitic (Ga)	FD	References
Chomur) (Upper Olenek	436-421					
Nakyn	364	◆				
Udachnaya (Daldyn)	361 ± 6	~3.5 – 3.1	2.9 ± 0.4	~2.01 ± 0.06	✳	1,2, 3
Yubileynaya (Alakit)	358	◆			✳	
Mir (Malo-Botuoba)	360	◆			✳	
23 Party Congress (Malo-Botuoba)		◆				
Upper Muna	345					
Kharamai	235					
Kuoika	128–148					

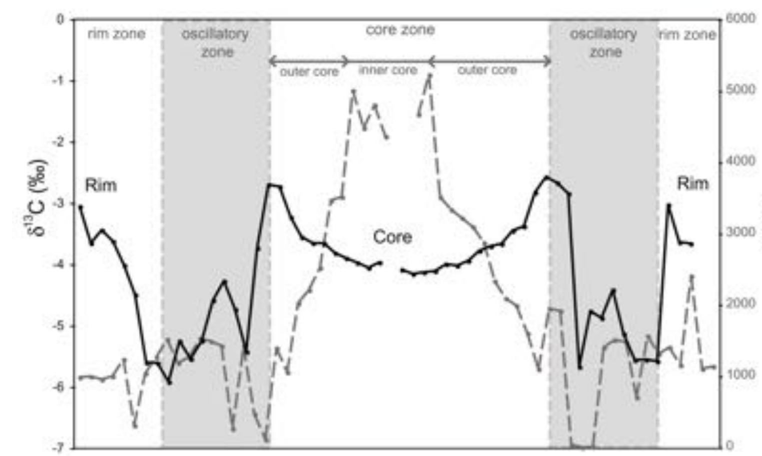
References: For kimberlite ages see compilation by Griffin et al. (1999); Inclusion ages: 1 = Pearson et al. (1999), 2 = Pearson et al. (1995), 3 = Richardson and Harris (199?)

Complex growth – resorption patterns in natural diamonds

Smart et al. (2011)



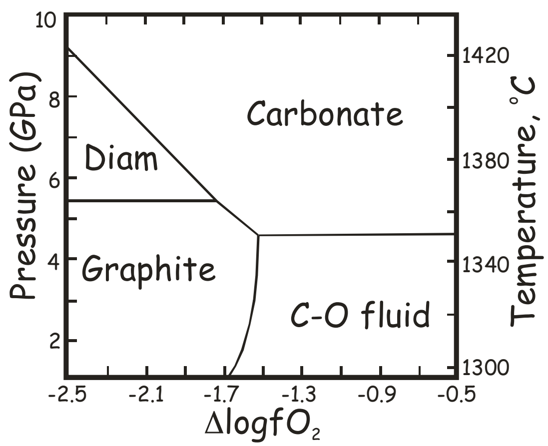




Role of carbon saturation in mantle fluids/melts

Diamond may form in Earth's mantle by a variety of processes (Stachel and Luth, 2015):

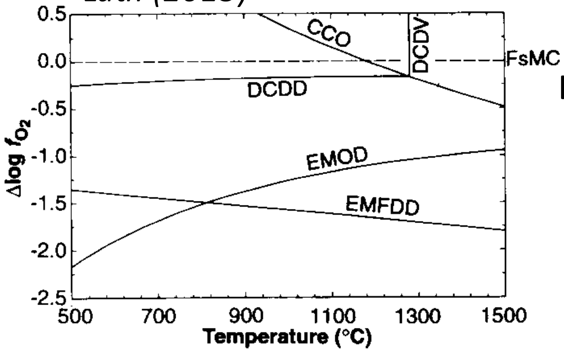
- recrystallization of the low-pressure graphite polymorph,
- Precipitation from a fluid or melt saturated with carbon,
- by oxidation–reduction reactions involving carbonate or methane.



Frost & Wood, 1997

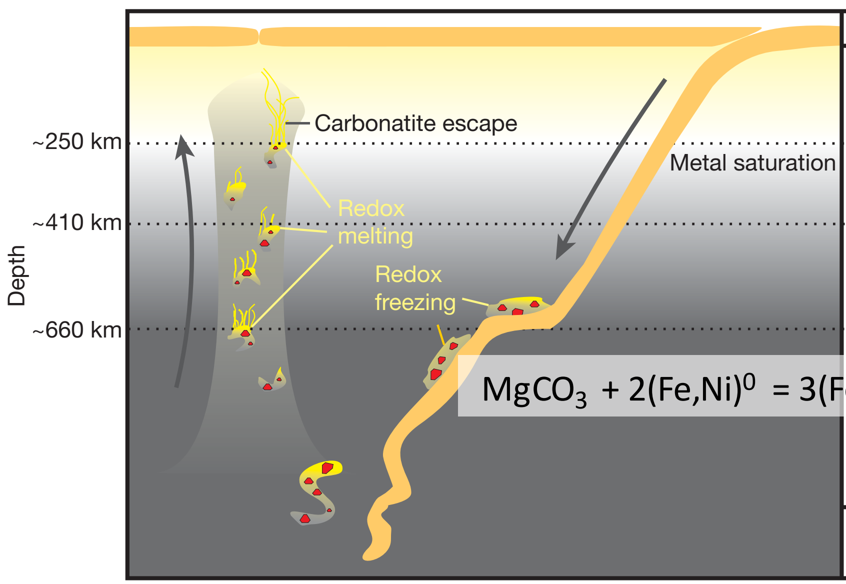
Oxidation – reduction processes

Luth (2013)



Dol + Coes = Di + Dia + O_2

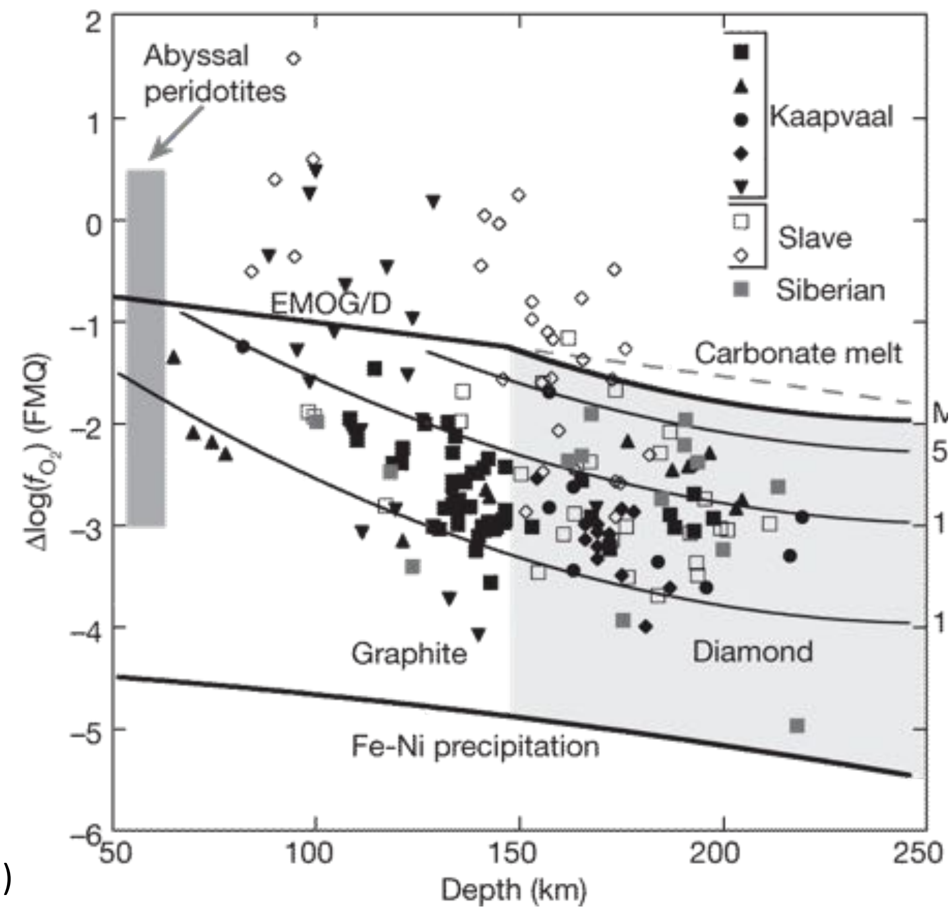
En + Mgn = Ol + Dia + O_2



$MgCO_3 + 2(Fe,Ni)^0 = 3(Fe,Ni,Mg)O + C$

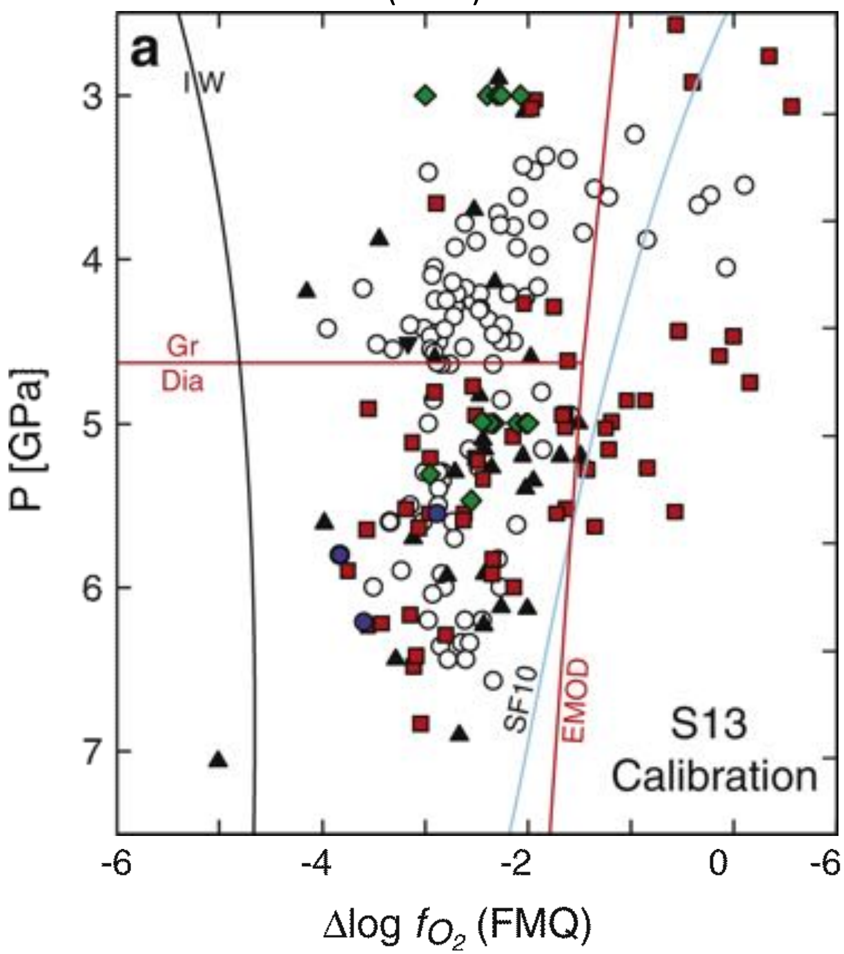
Rohrbach and Schmidt (2011)

Stagno et al. (2013)

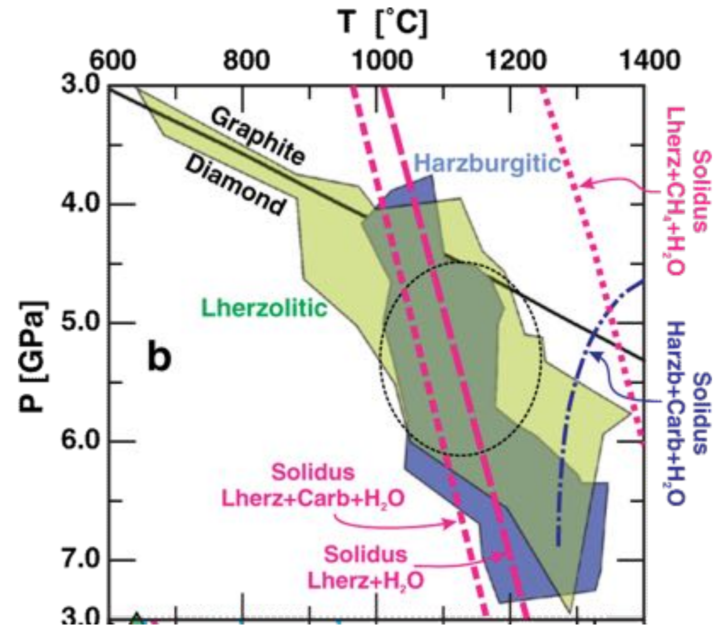


Carbon saturation in mantle fluids/melts

Stachel and Luth (2015)



Stachel and Luth (2015)



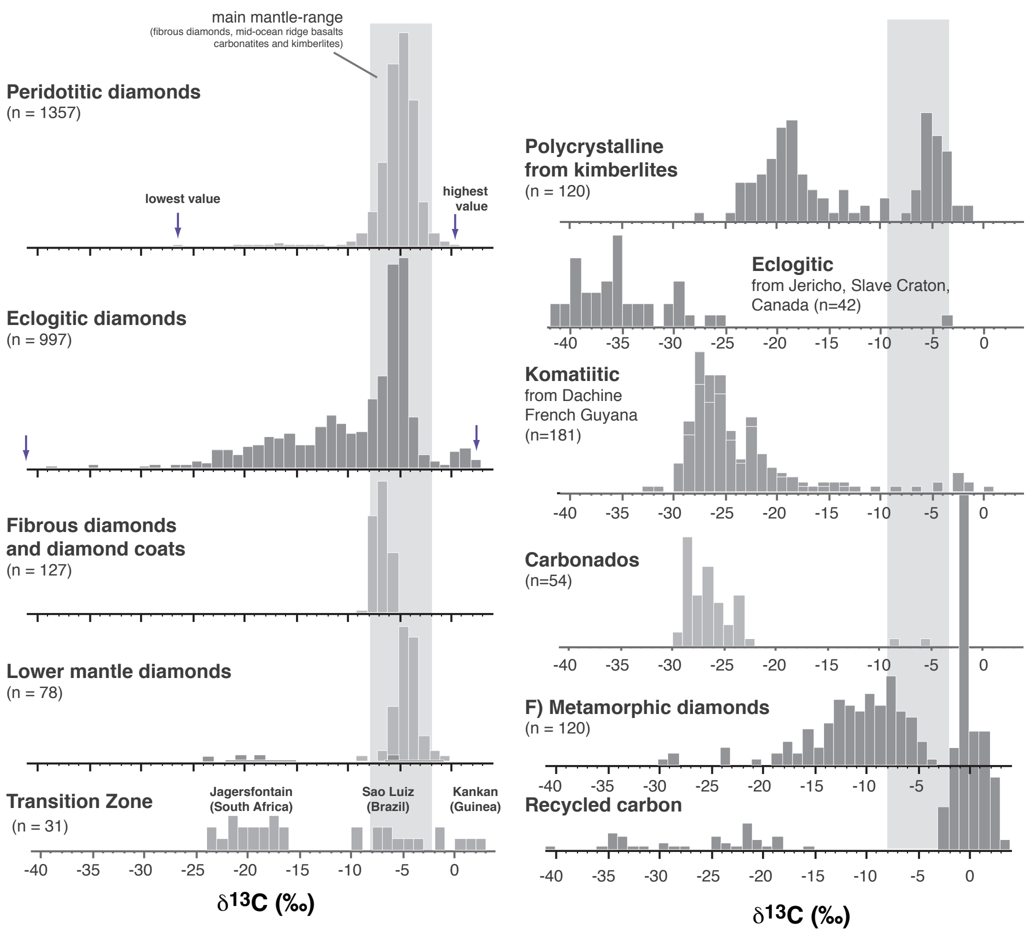
Harzburgite:

- Xenoliths P-T below solidus → Diamond growth from fluid
- extremely limited redox buffering capacity of cratonic peridotites → redox reactions cannot produce notable diamond growth

What can we learn from diamonds?

- Carbon cycle
- Formation of cratons
- “Window” into the mantle
- Kimberlite exploration

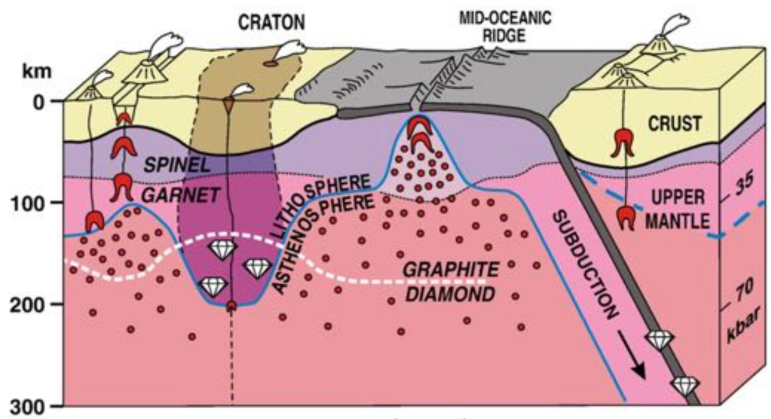
Carbon isotopes – carbon cycle



From Shirey et al. (2013)

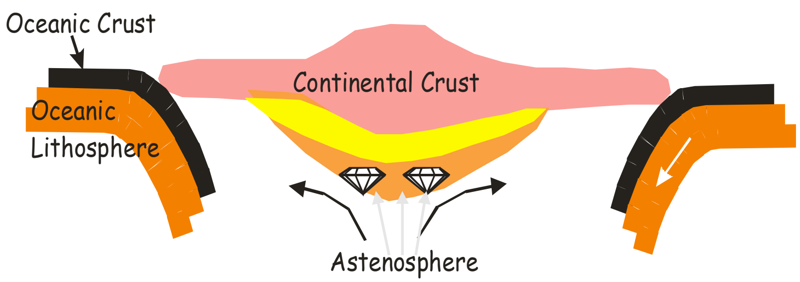
- Worldwide carbon isotopic composition of diamonds ranges from −41 to +5‰, close to the range in sedimentary rocks.
- ~72% of diamonds have carbon isotopic composition within of −8 to −2‰ (mean −5‰) = similar to mantle-derived rocks (mid-ocean ridge basalts, ocean island basalts, carbonatites, kimberlites).

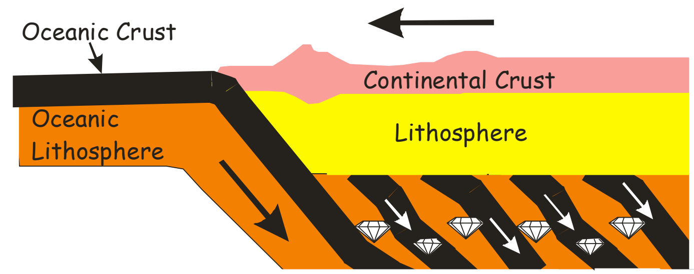
Formation of cratons



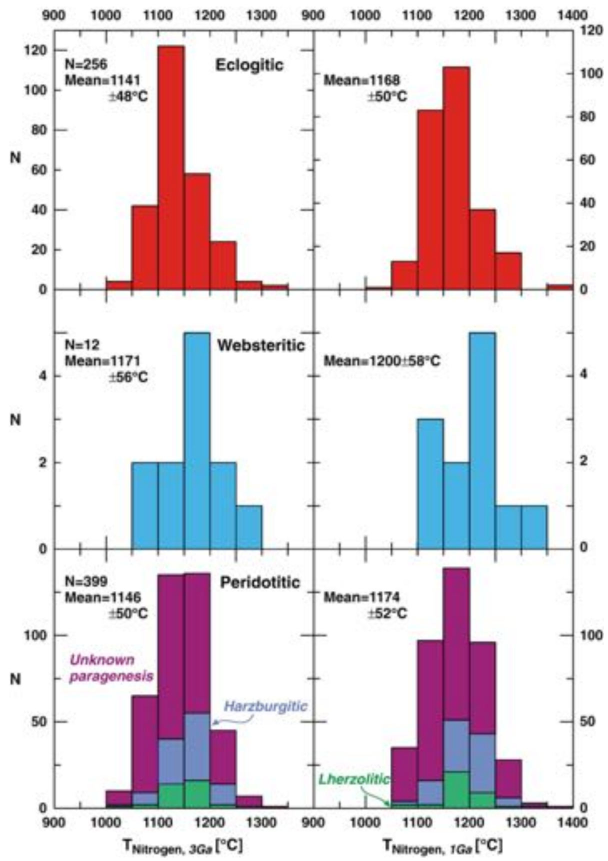
From Stachel and Harris (2008)

Underthrusting of oceanic slabs or upwelling plume magmatism ?



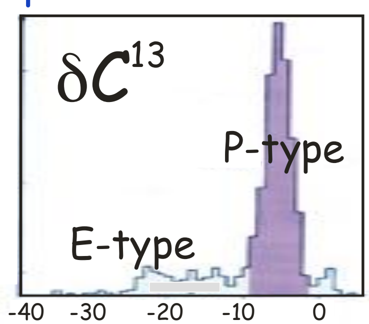


Formation of cratons

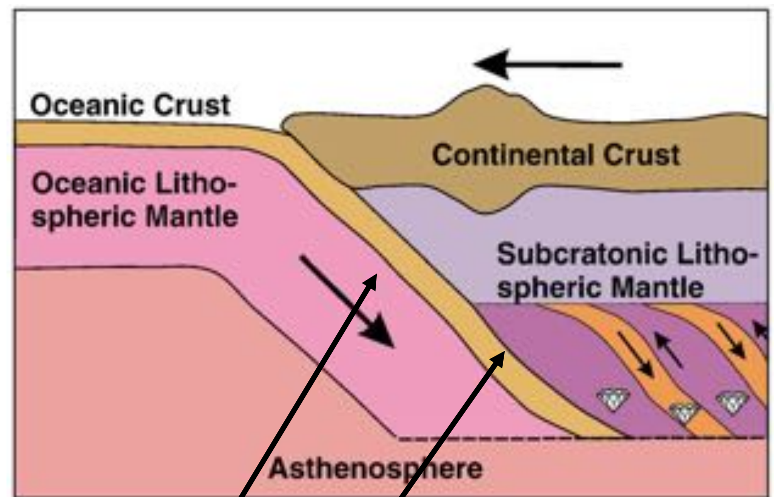


From Stachel and Harris (2008)

Mantle residence temperatures for peridotitic, websteritic and eclogitic diamonds based on the nitrogen thermometer shows that diamonds forming in very distinct environments (peridotite vs. eclogite) show identical equilibration temperatures.



Origin of cratonic lithosphere during Archean subduction events



From Stachel and Harris (2008) and Helmstaedt and Schulze (1989)

Peridotites

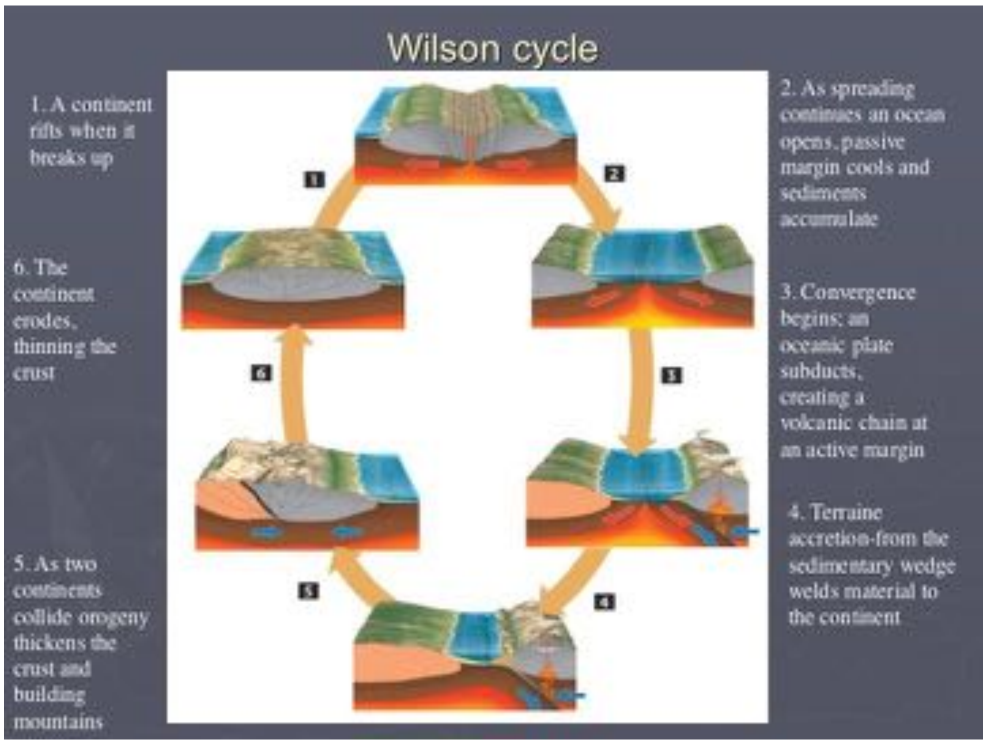
Eclogites

P-type Dia

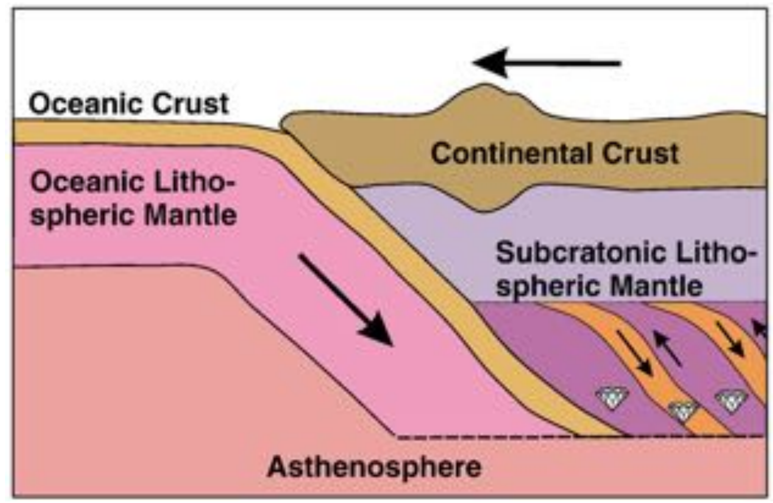
E-type Dia

When plate tectonics has started?

Insights from diamond ages



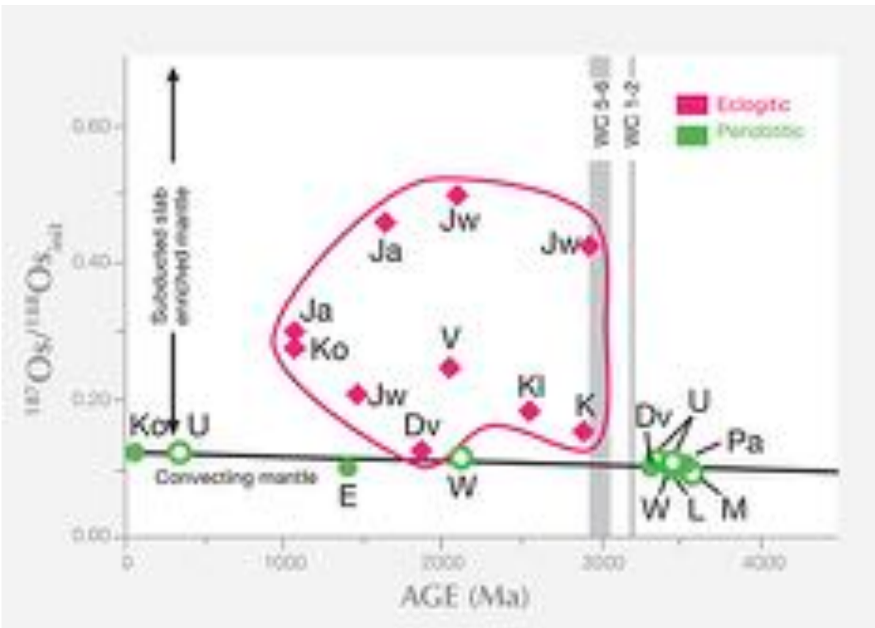
Diamonds as a "time-capsule" of ancient processes



From Stachel and Harris (2008) and Helmstaedt and Schulze (1989)

When plate tectonics has started?

Insights from diamond ages

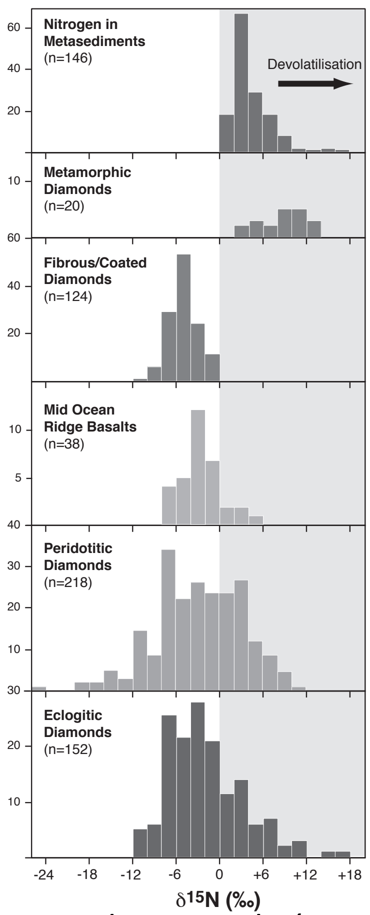


Shirey and Shigley (2013)

- Significant difference in age between E- and P-type diamonds: no eclogitic diamonds (E-type) older than 3 billion years
- E-type diamonds (3 Ga) capture the first record of basaltic rock (eclogite is a basalt at high pressure metamorphism) in the mantle keel of the continents.
- This indicates ocean basin closure and continental collision (modern plate tectonics or Wilson Cycle), because
- Basalt is derived from the ocean floor and is incorporated into the mantle keel during collision.
- Mark a transition from a planet dominated by vertical geodynamic processes (plumes) to lateral tectonics and subduction.

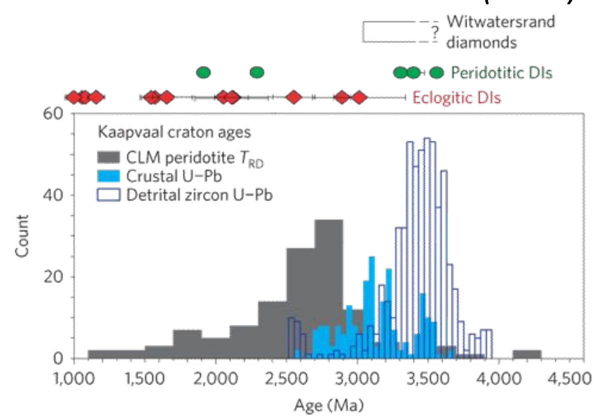
When plate tectonics has started?

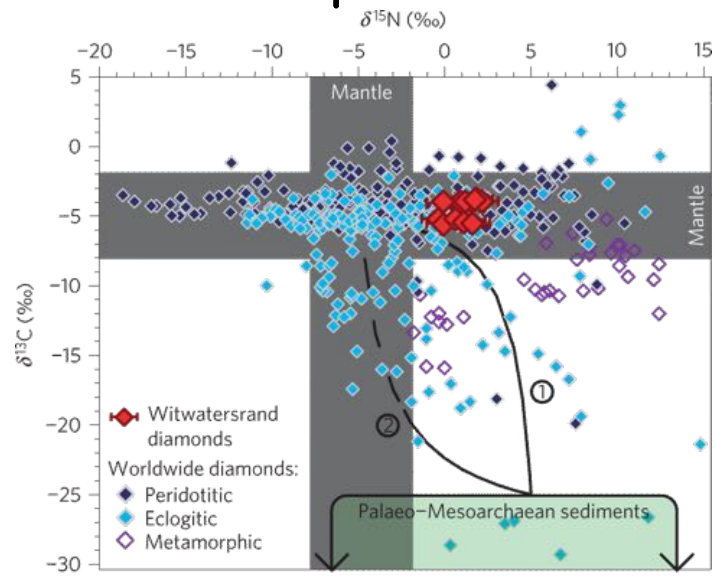
Insights from nitrogen and carbon isotopes



From Shirey et al. (2013)

From Smart et al. (2016)



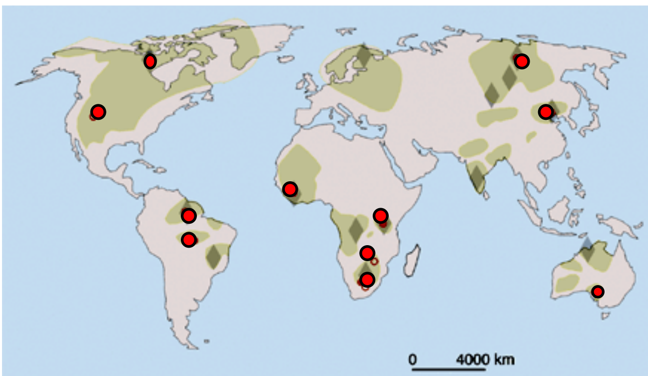


- Witwatersrand diamonds have enriched nitrogen but mantle carbon isotopic compositions.
- This nitrogen values suggest contamination of the mantle by nitrogen-rich Archaean sediments.
- Modern-style plate tectonics operated as early as 3.5 billion years ago

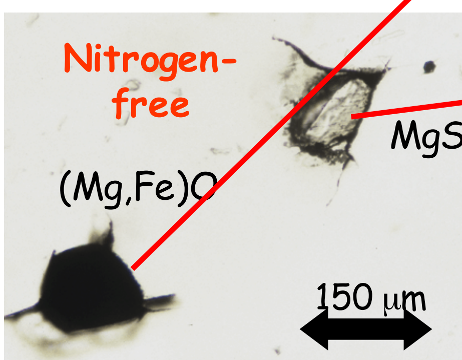
"Window" into the mantle

Lower mantle inclusions

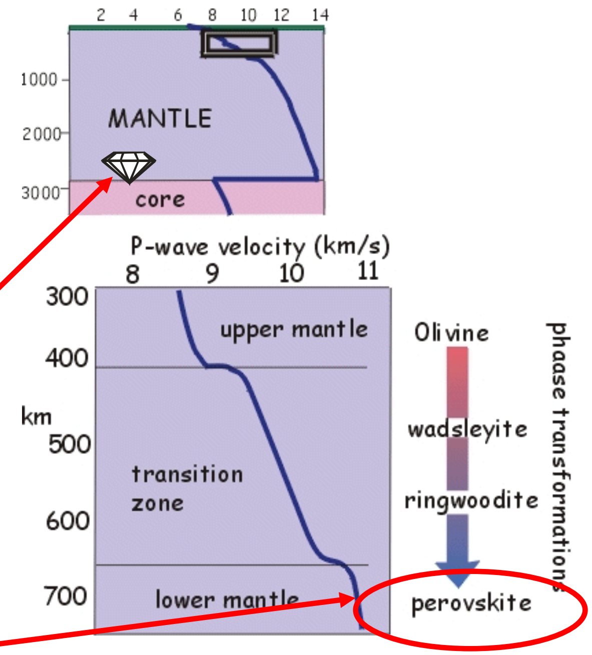
Occurences



Mineral Assemblage

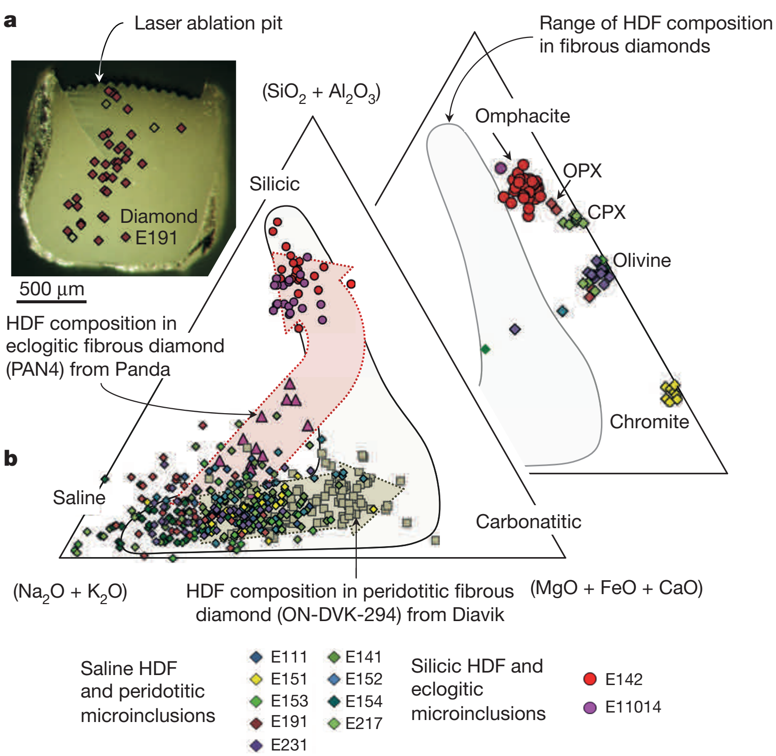


McCammon, 2001



1. Material exchange
2. Material uplift from the base of the lower mantle
3. Upper and Lower mantle are chemically different

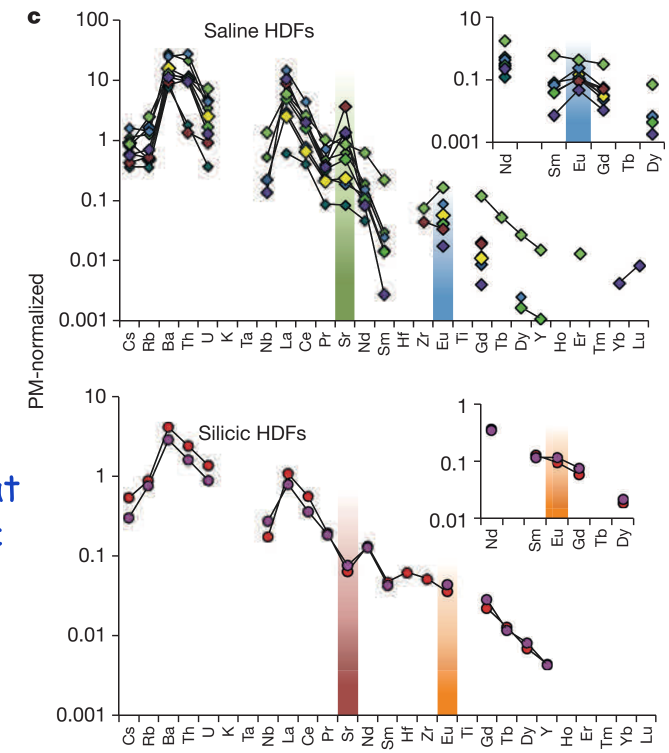
Composition of fluids in diamonds



Weiss (2015)

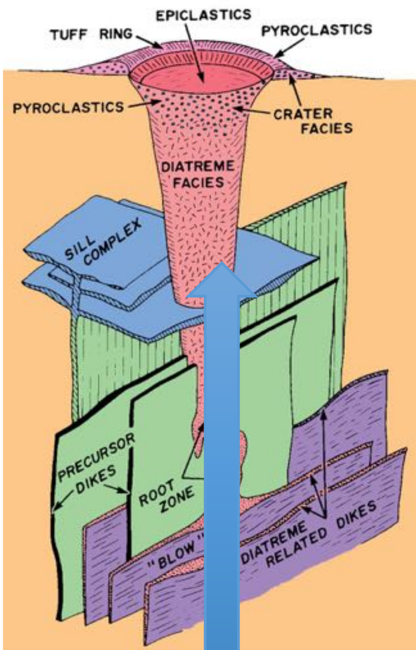
[Fibrous diamonds from Ekati Mine, Canada:]

- Diamonds can trap fluids percolating through lithosphere
- Saline fluids as parental to silicic and carbonatitic deep mantle melts
- The timing of diamond formation suggest that a subducting Mesozoic plate under western North
- America is the source of the fluids

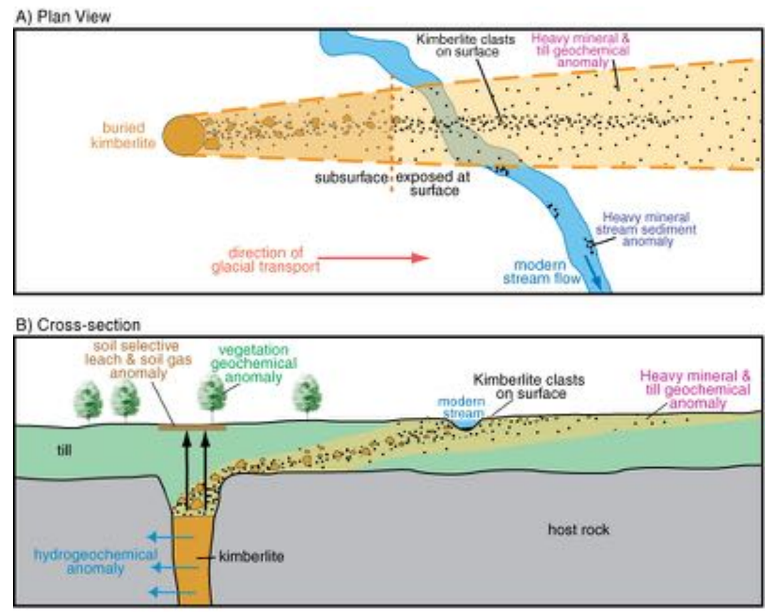


Weiss (2015)

Kimberlite prospecting and exploration



- Pyrope Garnet
- Chromite
- Ilmenite
- Chrome-diopside
- (Olivine)
- Heavy minerals, resistant to chemical and mechanical weathering



McClenaghan & Kjarsgaard, 2007

Diamond grade of a kimberlite depends on:

- How much diamond-bearing peridotite and eclogite are present
- What the diamond grade of the source rocks were
- How well the diamonds were preserved during transportation to the surface

Indicator minerals:

- Recognition of mineral composition known to be associated with diamond
- Confirmation that these are derived from the diamond stability field ("diamond window")

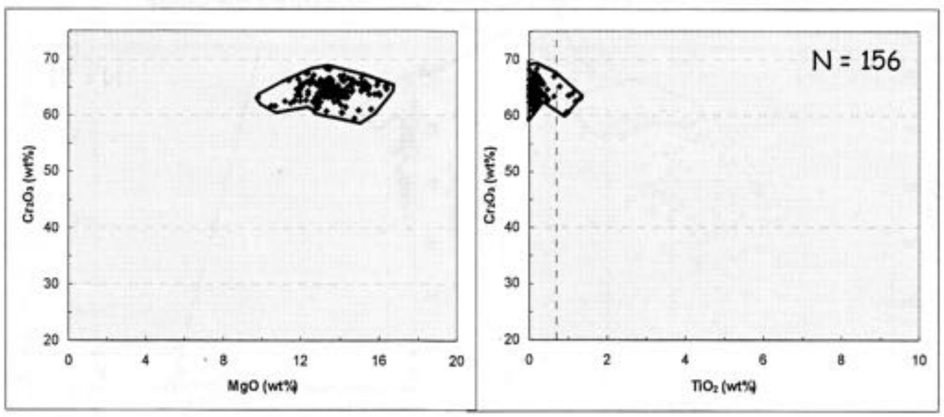
Mineral composition

- Assessment of the quantity of high-interest mantle minerals sampled and preserved by kimberlite

Mineral abundance

Recognition of mineral composition known to be associated with diamond

Chromites Inclusions in Diamond

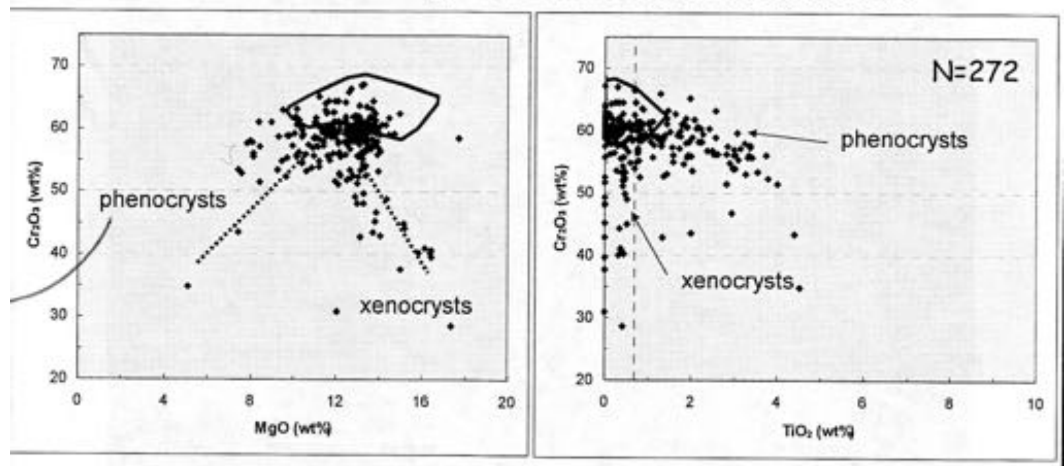


Data - compilation from published research

Mineral Services

Kimberlitic Chromite Compositions

Chromites from a typical diamondiferous kimberlite

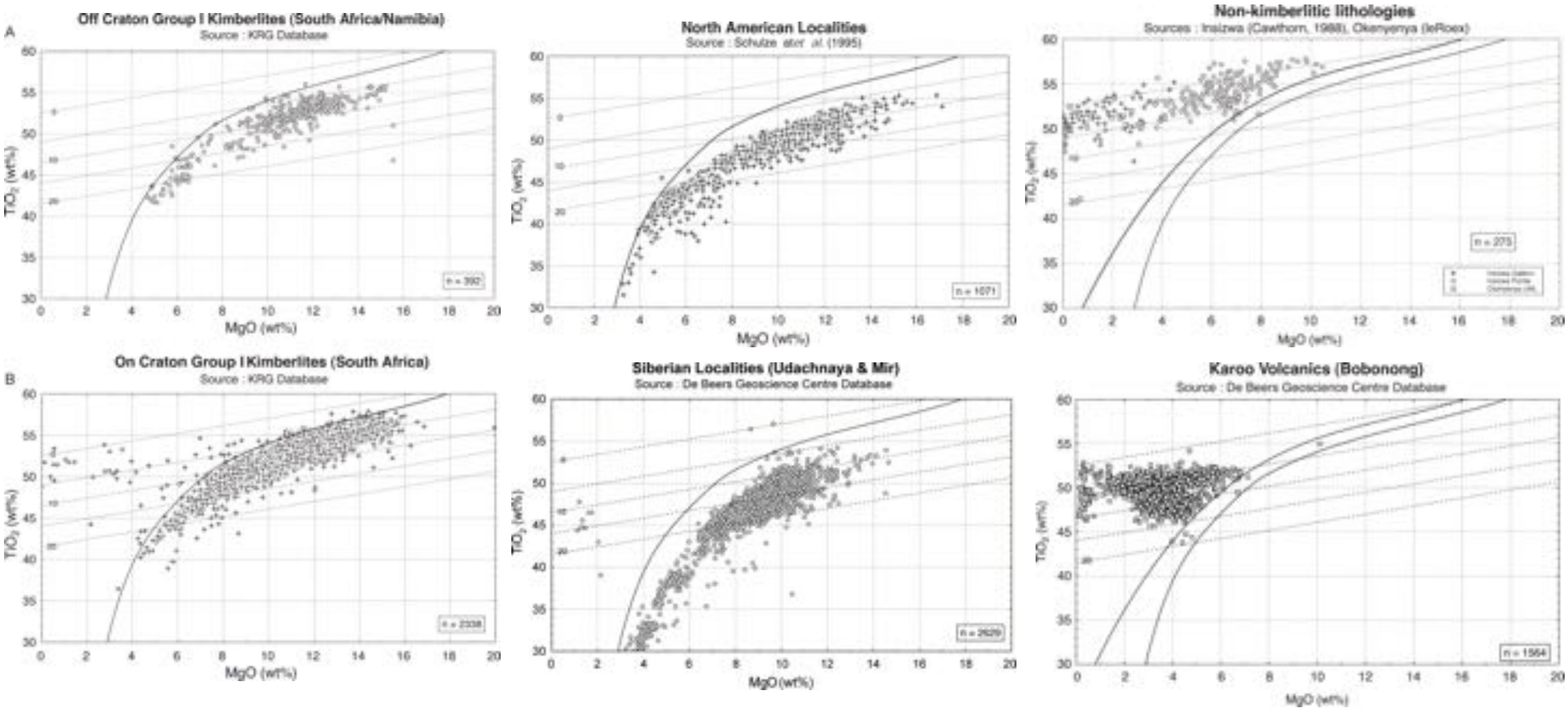


Data - Mineral Services database

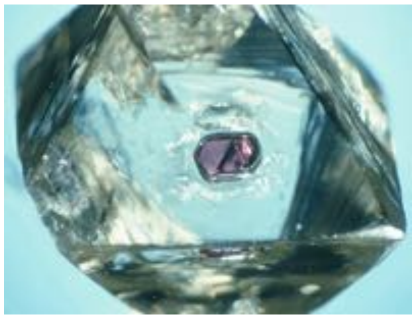
Mineral Services

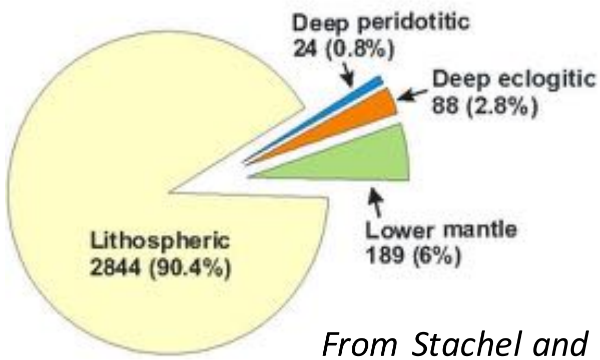
Recognition of mineral composition known to be associated with diamond

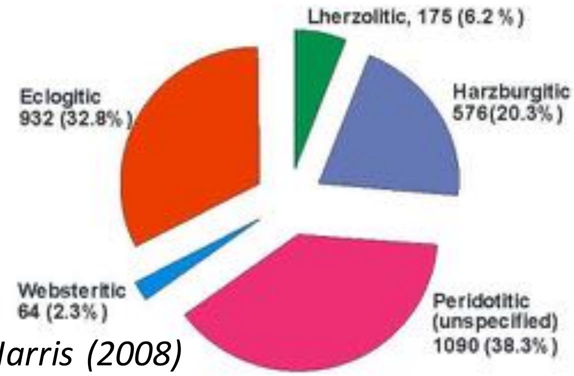
Ilmenite



Diamond Inclusions





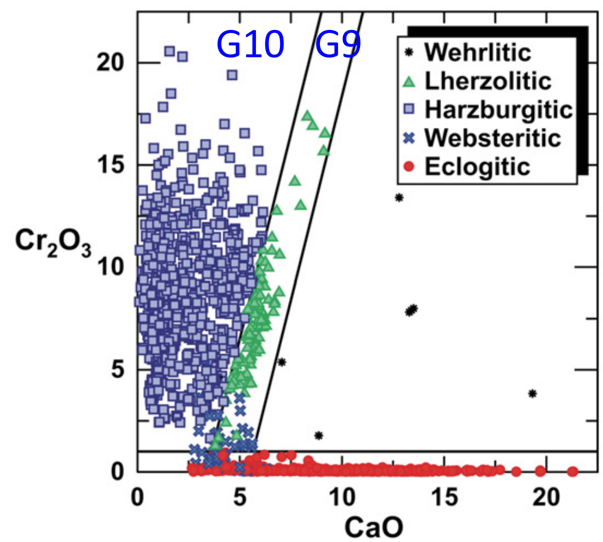


From Stachel and Harris (2008)

Garnets

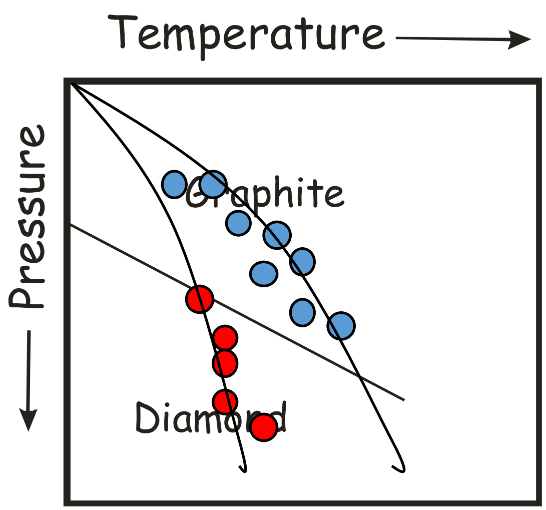
The mantle source :
- Rich in carbon?
- In diamond stability field ("diamond window")?

1. Peridotite association vs. Eclogite association
2. Peridotite xenoliths:
   Grt harzburgite > Spl harzburgite > Grt lherzolite
1. About 32-fold preferential association of carbon for depleted harzburgite over lherzolite



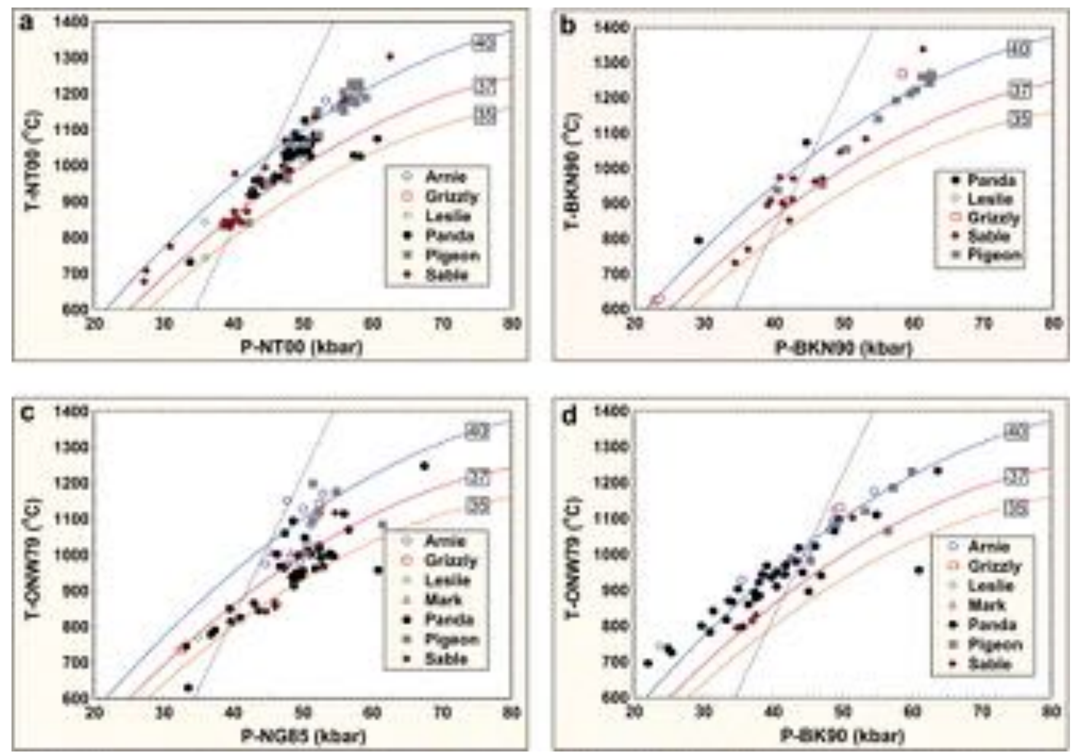
From Stachel and Harris (2008)

Garnets: "diamond window"

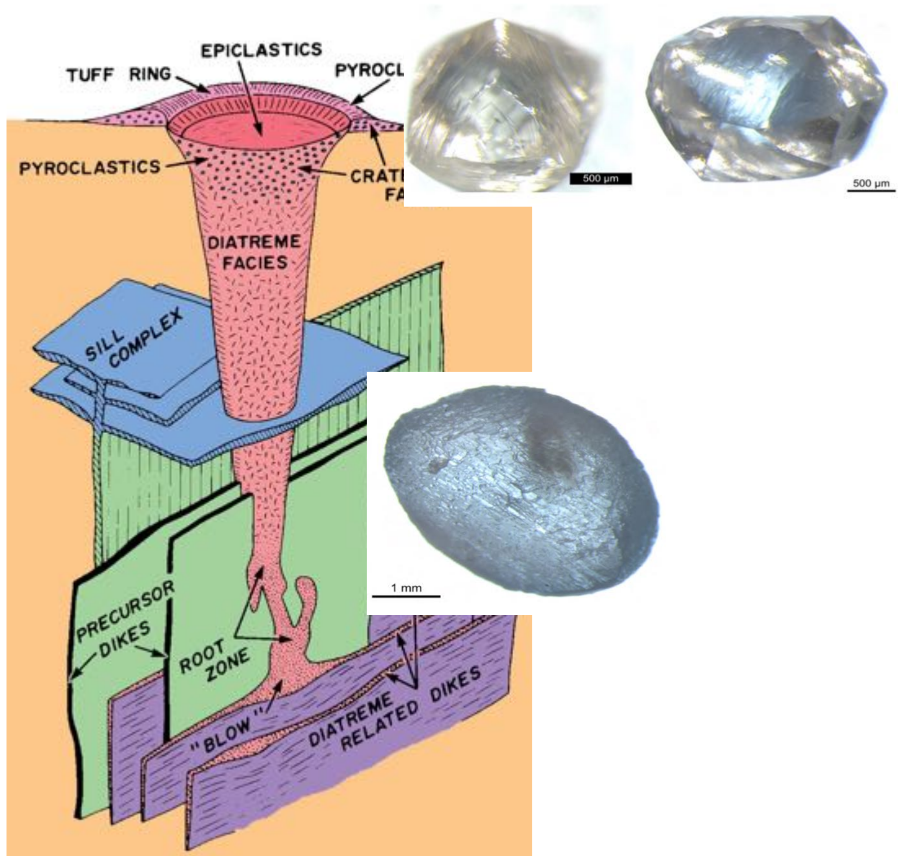


Thermobarometery
- Garnet
- Chrome Diopside
- Enstatite

Ni in Garnet thermometer:
-well-calibrated, reliable
- single grain thermobarometer



Diamond preservation in kimberlite



After Mitchell (1986)


Thank you!