



# Economic Geology: Lecture Notes

Assembled by:

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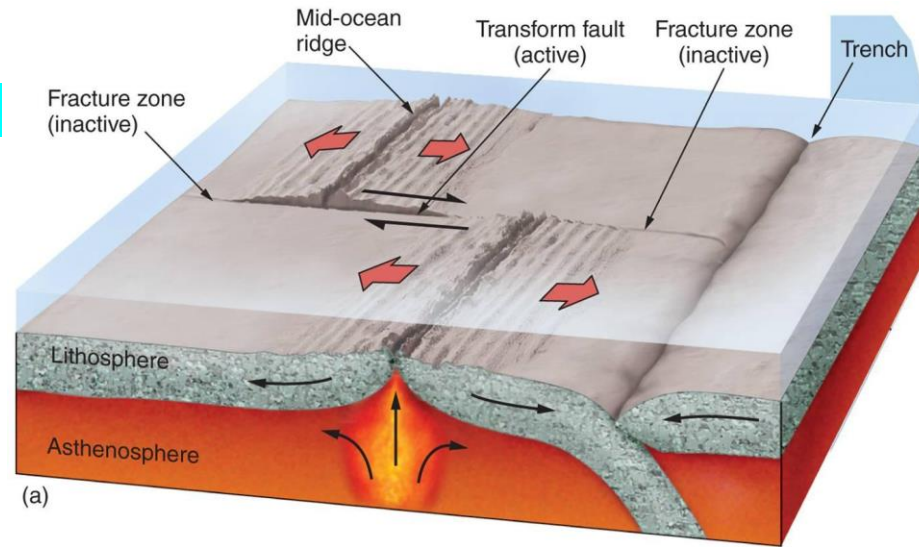
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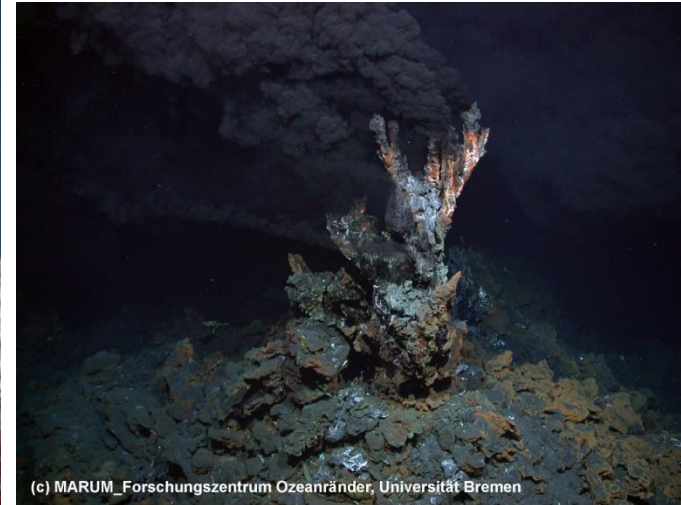
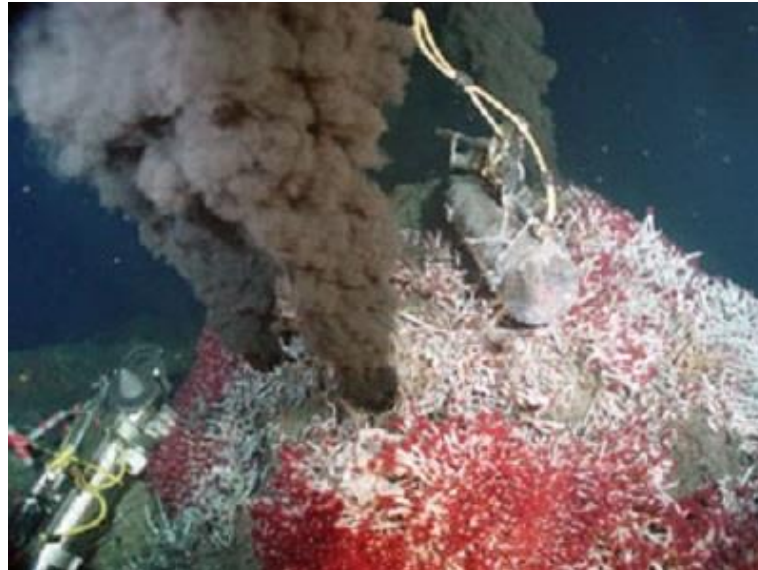
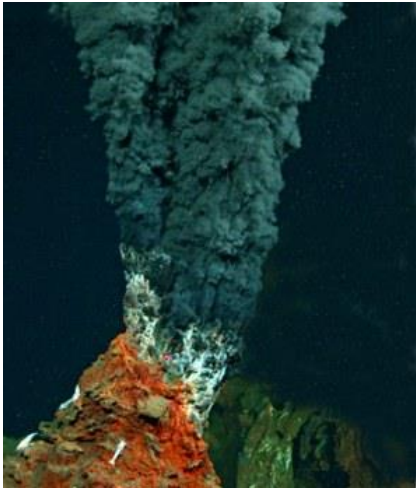
# Magmatic Ore Formation Systems

## 2. Ore deposits at mid-ocean ridges and in ophiolites

Exploration of **ocean floors** resulted not only in the recognition of plate tectonics but also in the discovery of conspicuous signs of **active ore forming systems** – the “black smokers”.



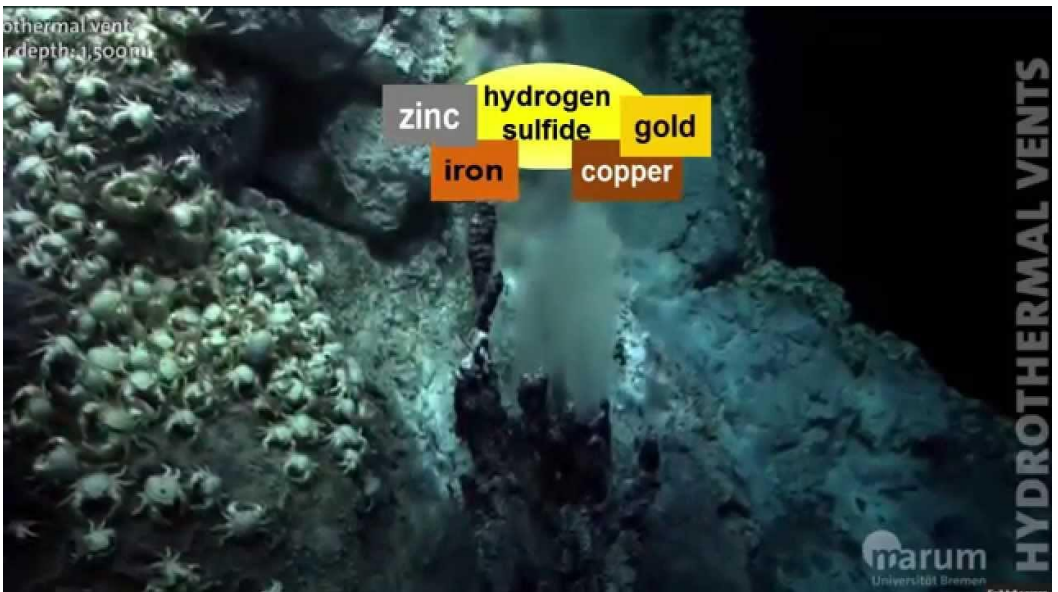
**Black smokers** are points of discharge of hot metalliferous solutions from the ocean floor. **Black smoker fields build NOW accumulations of metal sulphides on the ocean floor,** some of which may soon be economically exploitable.





# II. What are Black and White smokers?

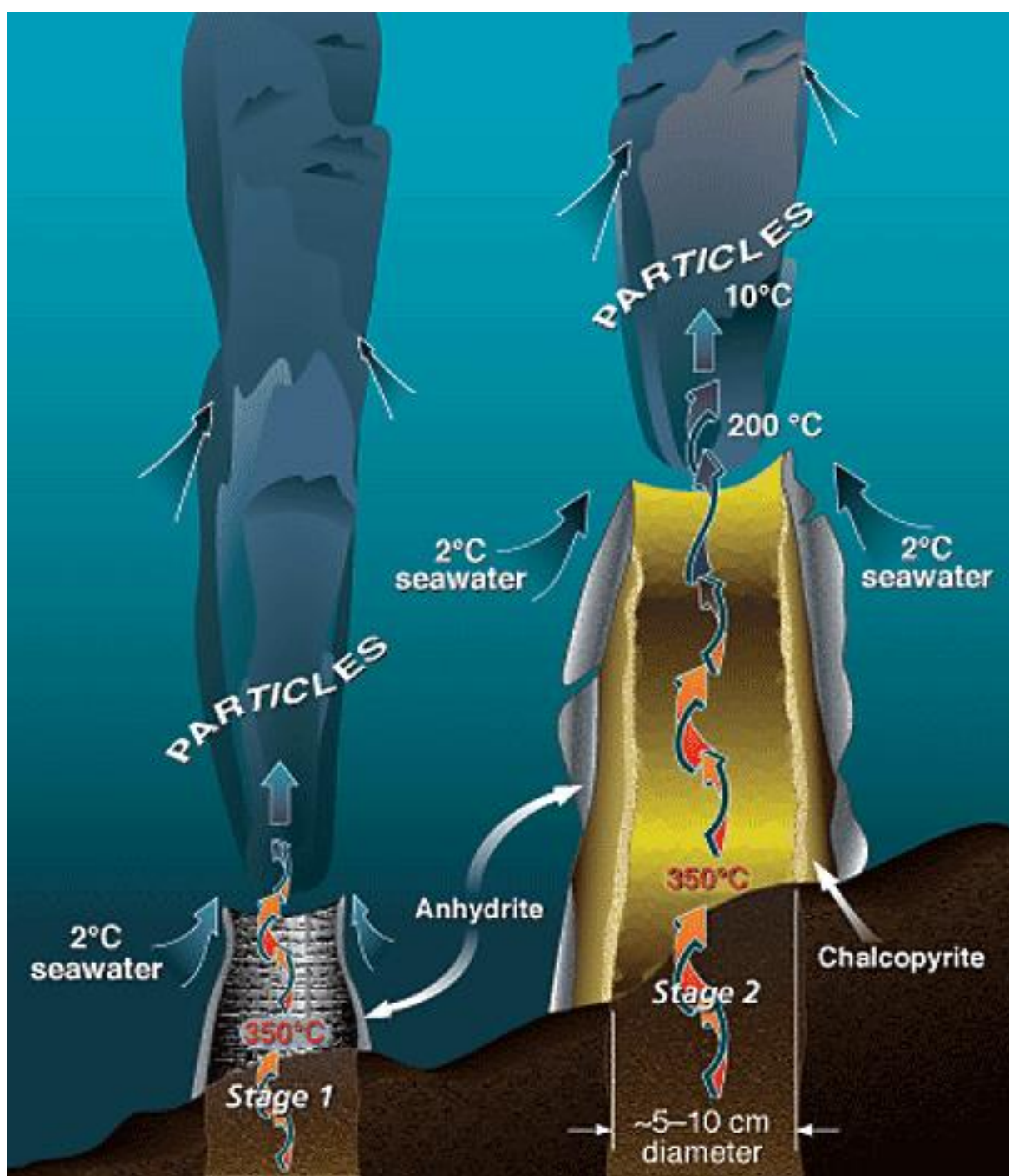
Black smokers are submarine vents/hydrothermal cones/chimneys that may reach a height of about 20m, built on outcrops of basalt. Black smokers are sea vents "geysers" that occur on the ocean floor and spew hot, mineral-rich water, that help support a diverse community of organisms. From an opening at the top, a high speed jet of hot fluid is ejected. The vents are tubes with zoned walls, from pyrite and chalcopyrite inside through sphalerite, marcasite, barite, anhydrite and amorphous SiO<sub>2</sub> to the exterior.



Over time, the height, width and thickness of a chimney structure builds around the vent flow while the temperature and chemical composition of the hydrothermal fluid varies. Concentric circles of various mineral zones form like tree rings in the chimney wall and evolve with changes in thermal and chemical gradients, as well as changes in chimney wall permeability. The different colors that can be seen in this sliced piece of hydrothermal vent structure reveal some of the different minerals that composed the vent wall.

The expulsion temperature of the **metalliferous solutions** is **350°C**. The hot Na-Ca-Cl fluids of the **black smokers** are reducing and have pH from 4–5, salinities from 0.1 to 3 times seawater, elevated **iron, copper, zinc, barium and SiO<sub>2</sub>**, and traces of **As, Cd, Li, Be, Cs, Mn, B, Cl, HCl, H<sub>2</sub>S, and CH<sub>4</sub>**.

Oxidation of sulphides by seawater “seafloor weathering” produces **vari-coloured ochreous alteration fragments**, which mainly consist of **iron-oxy-hydroxides** that assemble on the sea floor around the vents and build **gossan-like mounds (Gossan is oxidised surficial sulphide deposits)**.

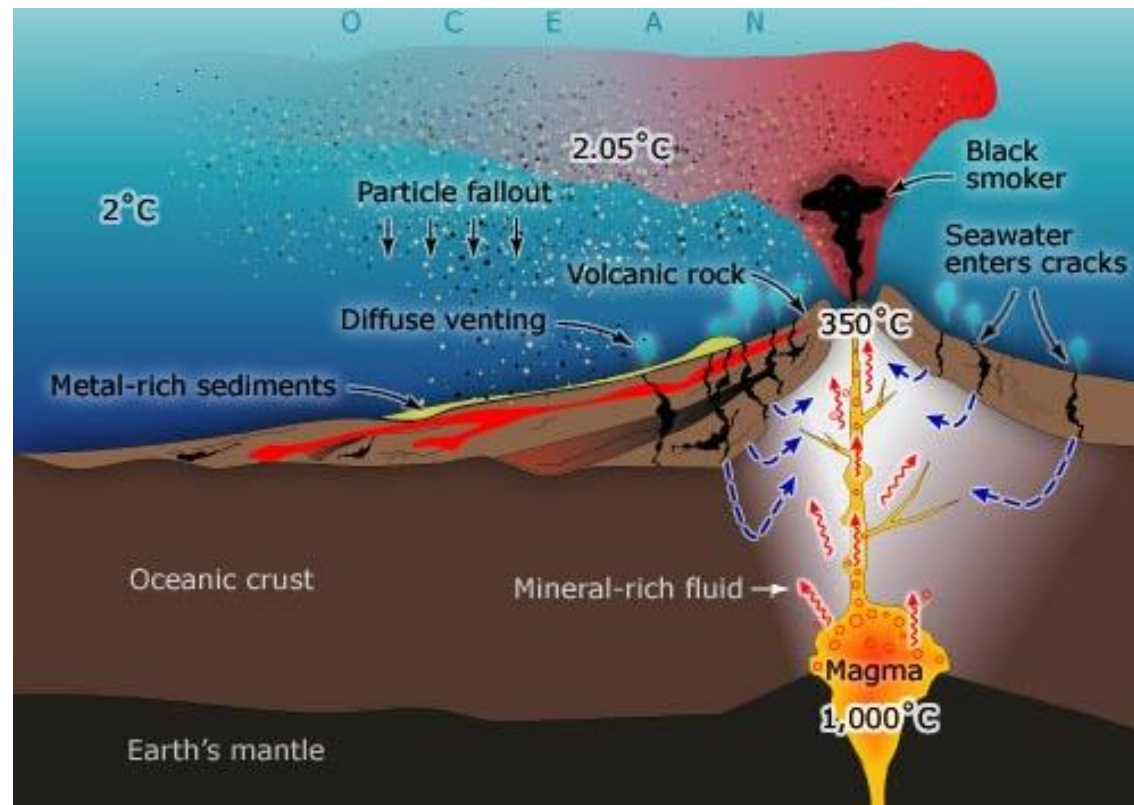




The ejected metalliferous solutions contain different solutes - a solute is a substance dissolved in another substance, known as a solvent. They are derived from various protoliths (original), possibly from magma. These solutes reflect different conditions of metalliferous solution/rock(vent) reactions.

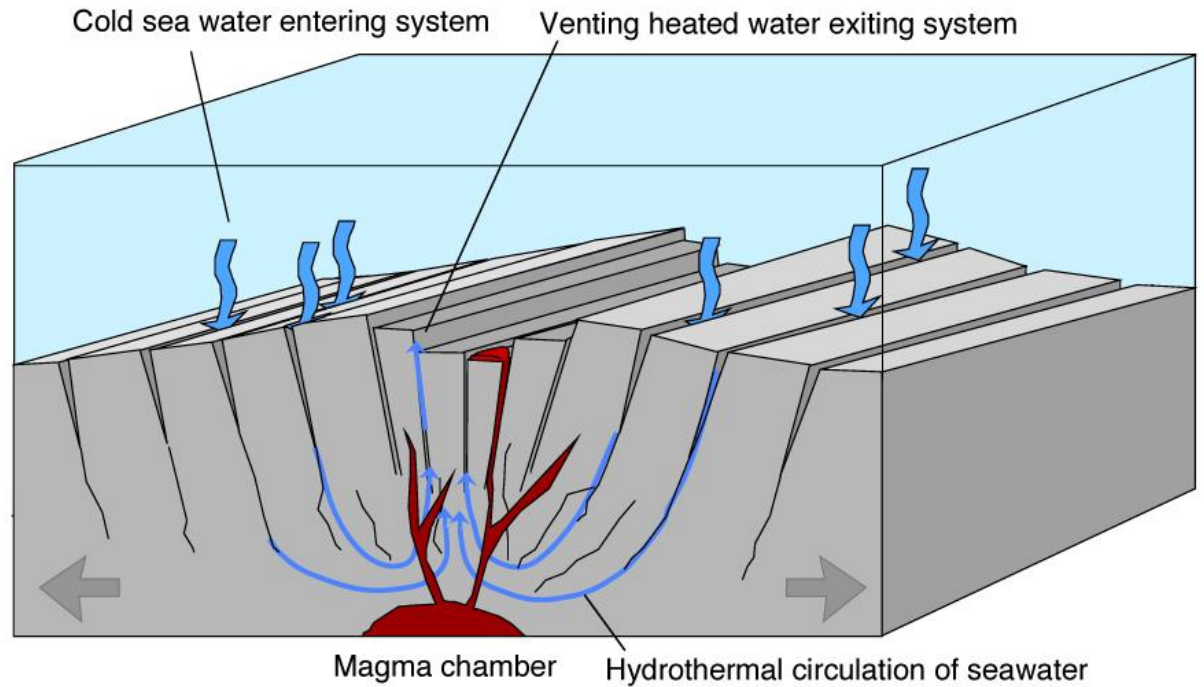
For example, copper is enriched in the solutions relative to iron under moderately oxidizing conditions, whereas a low  $O_2$  results in a high Fe/Cu ratio. If iron prevails, black or grey smoke-like plumes of amorphous iron sulphide and iron-manganese oxy hydroxides rise several hundred meters upwards and disperse over a distance of many kms. When zinc is concentrated in the fluids the smokers are bluish.

The properties of metalliferous solutions are changed by phase separation, boiling, alteration and mineral precipitation during rise to the seafloor. Upon discharge at the ocean floor, hot acidic fluids (metalliferous solution) mix with cold alkalic seawater, which results in immediate precipitation of solutes.

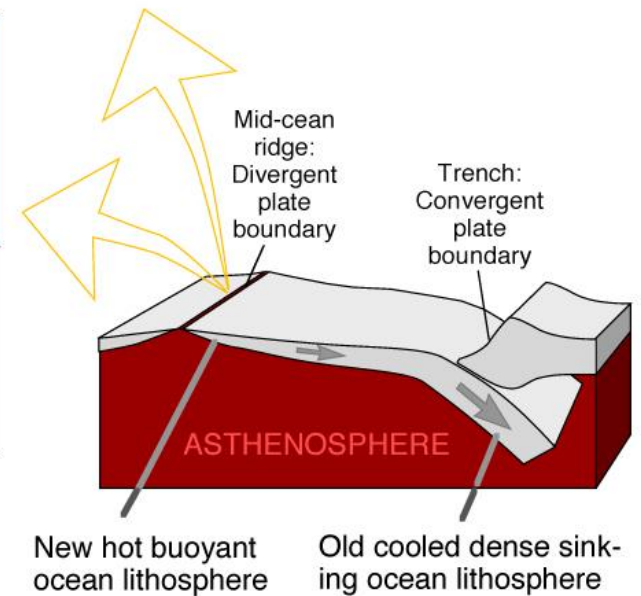
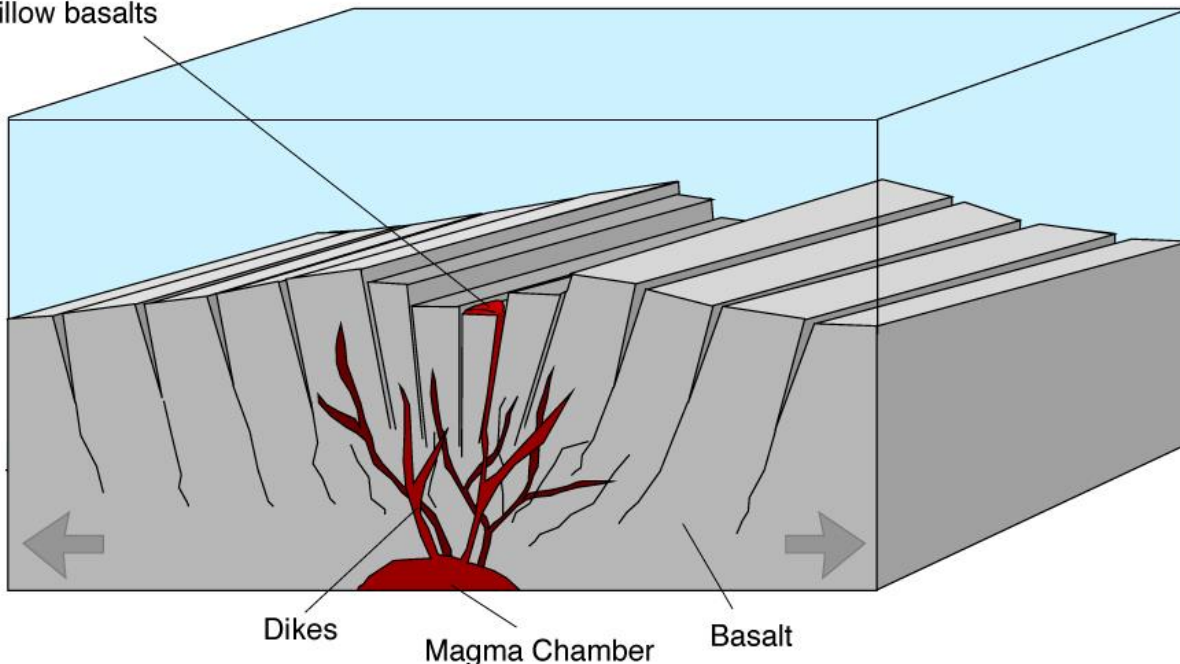


# A Mid-Ocean Ridge Vent or "Black Smoker", Part I

At the mid-ocean ridges, hot magma rises from Earth's interior as the two tectonic plates on each side of the ridge move apart. This rising magma ascends through planar ridge-parallel fractures. Most of it cools in those fractures to form sub-parallel criss-crossing dikes (hence "sheeted dikes"). However, some of it rises through those fractures to the sea floor, where it cools in blobs when it hits the cold seawater to form "pillow basalts". The heat of the magma also drives a hydrothermal circulation system discussed in Part II of this pair.

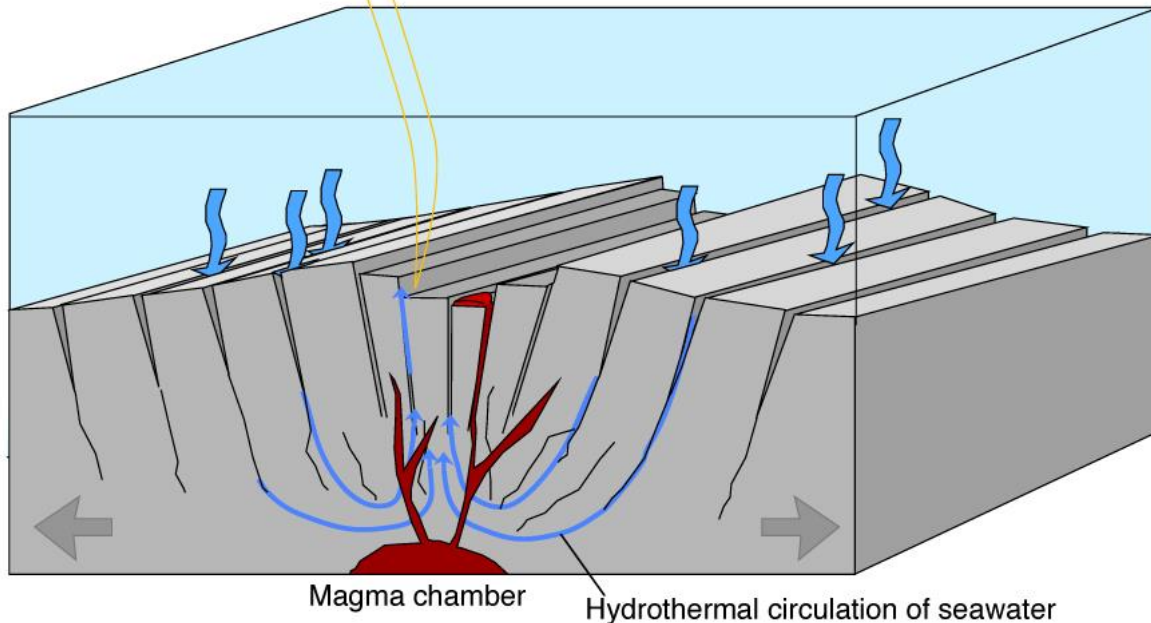
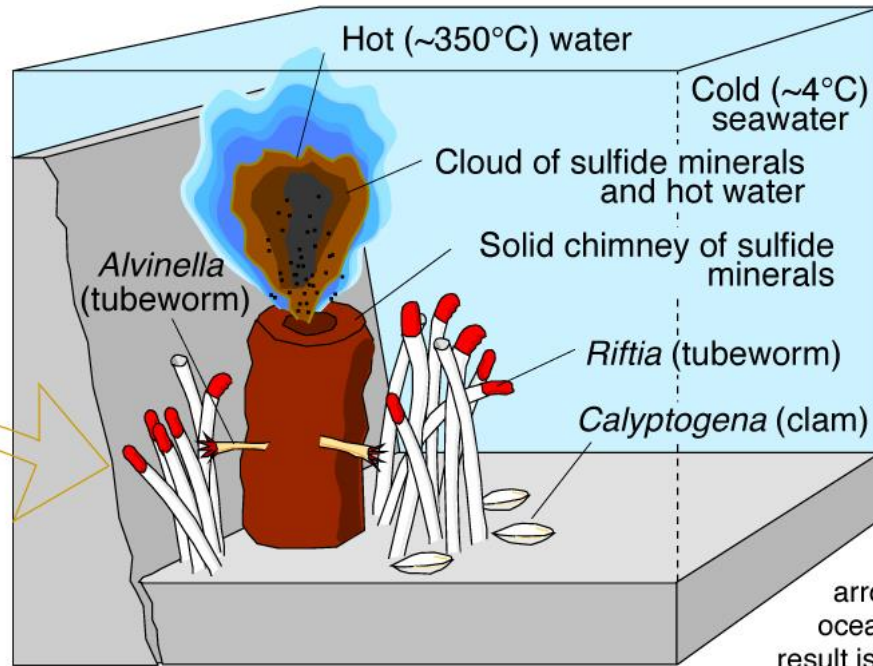
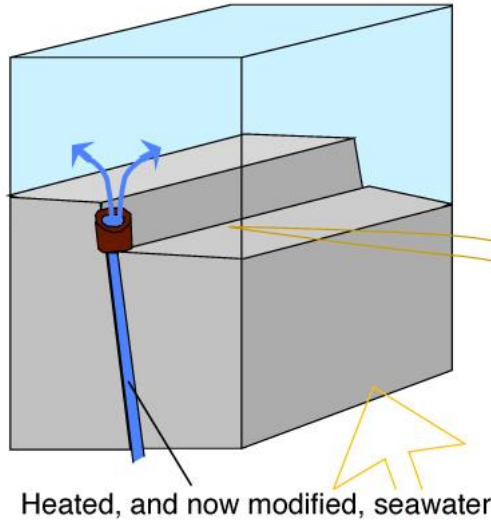


Pillow basalts





## A Mid-Ocean Ridge Vent or "Black Smoker", Part II



At the mid-ocean ridges, hot magma rises from Earth's interior as the two tectonic plates on each side of the ridge move apart. Heat from the magma chamber warms water in fractures in the center of the mid-ocean ridge, and that water therefore rises. Water from the flanks of the ridges moves inward to replace the rising water, and seawater (the wavy blue arrows at left) moves from the ocean into the seafloor. The result is circulation of water from the ocean into the ridge, heating, and ejection of that water at vents along the crest of the ridge. Sulfate ( $\text{SO}_4^{2-}$ ) in the seawater is chemically reduced to sulfide during this journey, with two results. First, iron, copper, and other sulfur-friendly elements are precipitated as sulfides where the water emerges, giving a chimney-like ring of sulfide minerals and a smoke-like cloud of mineral-laden water. Secondly, the emerging water is rich in hydrogen sulfide ( $\text{H}_2\text{S}$ ) that bacteria use in chemosynthesis. The flourishing bacteria are consumed by a variety of filter-feeding organisms, supporting intense, if geographically small, ecosystems near the vents.



## White smokers

White smoker vents discharge fluids between 100 and 300°C.

They form mainly:

- i) in the early stage of a newly established hydrothermal system (not enriched with metalliferous solvents yet); or
- ii) by sub-seafloor mixing of hot black smoker fluid with cooler waters.

The second probably leads to precipitation of sulphides at depth. Therefore, white smokers may indicate the presence of hidden stockwork and vein deposits of copper and zinc.

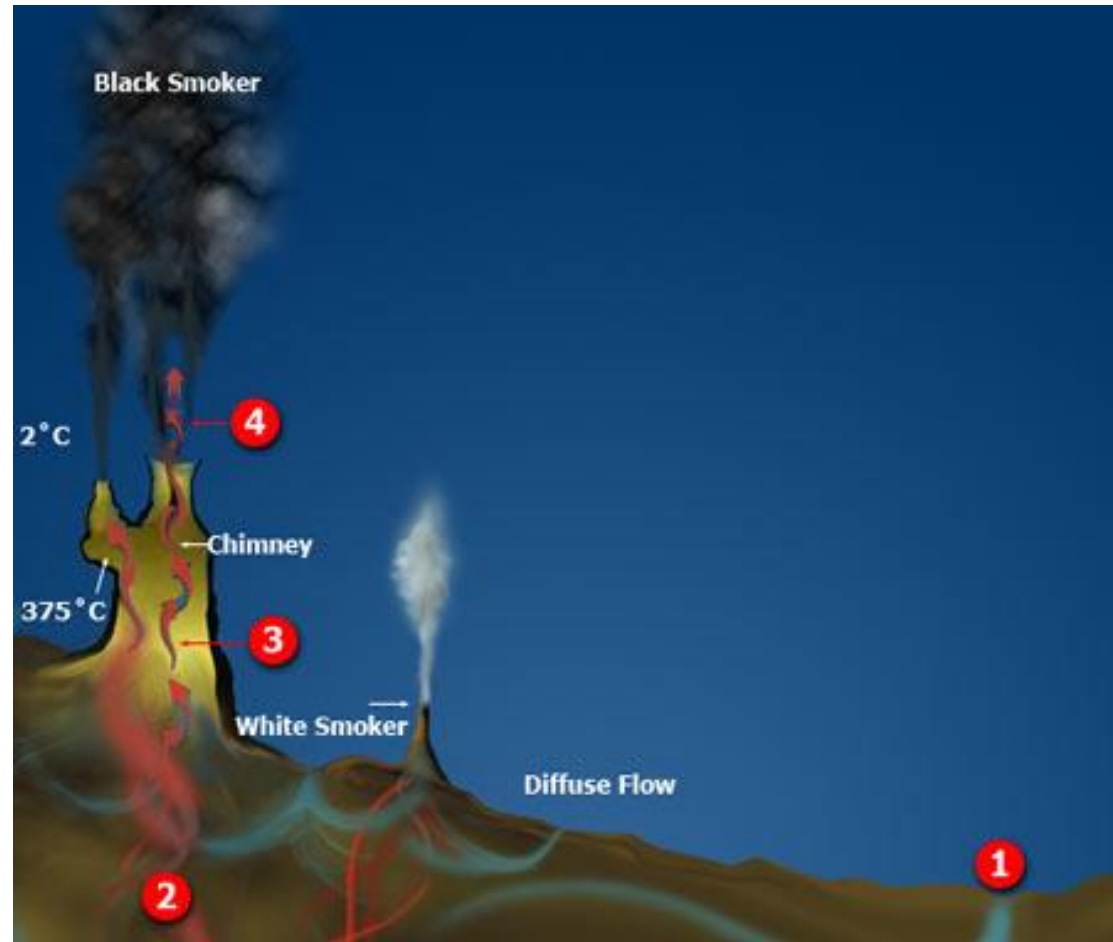


$\text{SiO}_2$ , barite and anhydrite are found in the white clouds (white smokers). So-called “snow-blower vents” emit dense clouds of white filaments of native sulphur that is produced from  $\text{H}_2\text{S}$  by sulphur-oxidizing bacteria.

### III. How are Black and White smokers formed?

1. **Cold seawater** ( $2^{\circ}\text{C}$ ) seeps down through **cracks** into the **ocean floor**.
2. The seawater continues to seep far in the ocean crust. Energy radiating up from molten rock deep beneath the ocean floor **raises the water's temperature to around  $350\text{-}400^{\circ}\text{C}$** . **As the water heats up, it reacts with the rocks in the ocean crust**. These chemical reactions change the water in the following way:

- I. **All oxygen is removed.**
- II. It becomes acidic.
- III. It picks up dissolved metals, including iron, copper and zinc.
- IV. It picks up hydrogen sulfide.

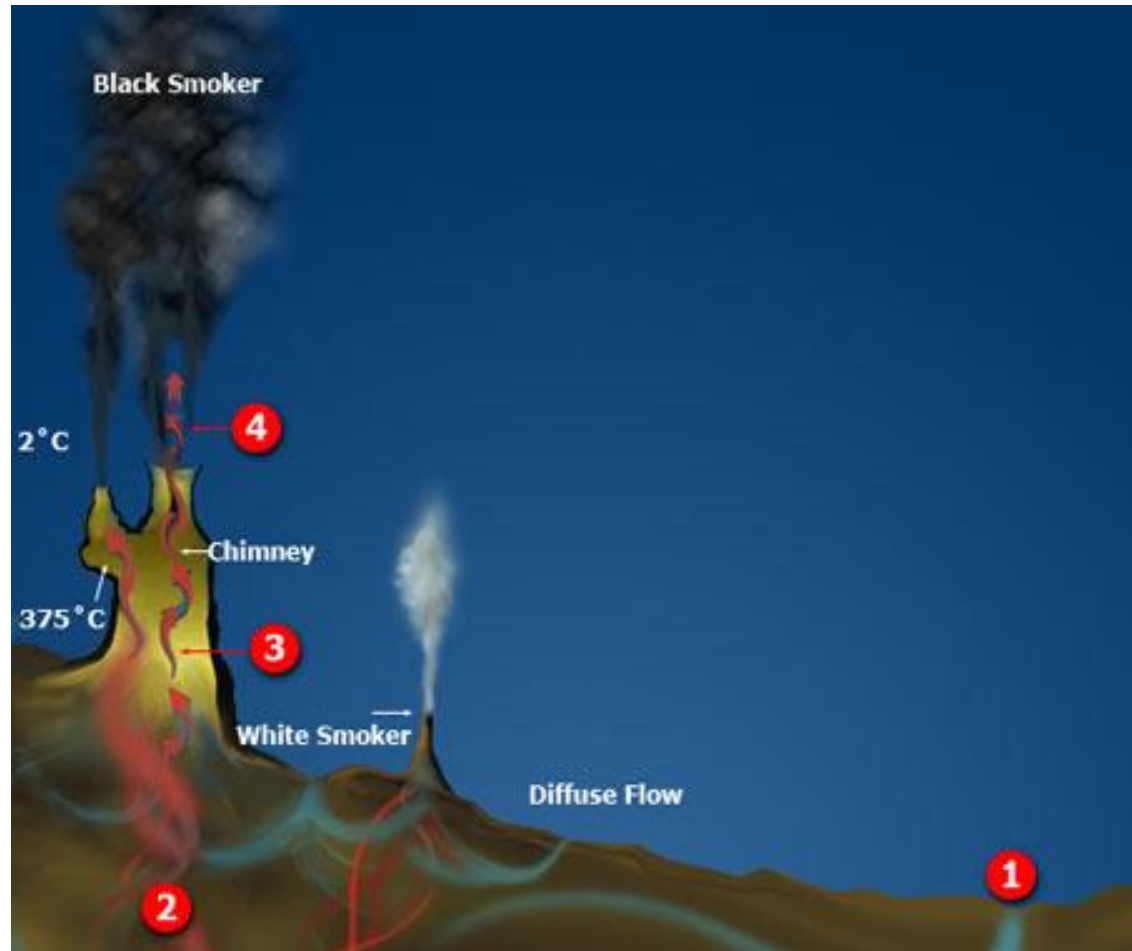


3. Hot liquids are less dense and therefore more buoyant than cold liquids. **So the hot hydrothermal fluids rise up through the ocean crust just as a hot-air balloon rises into the air**. The fluids carry **the dissolved metals and hydrogen sulfide with them**.

4. The **metalliferous hydrothermal fluids** exit the **chimney/vent** and **mix with the cold seawater**. The metals carried up in the fluids combine with sulfur to form **black minerals called metal sulfides**, and give the hydrothermal fluid the appearance of smoke. Many factors trigger this reaction. One factor is the cold temperature, and another is **the presence of oxygen in the seawater**. **Without oxygen, the minerals would never form.**

In **white smokers**, the hydrothermal fluids mix with seawater under the seafloor. Therefore, the black minerals form beneath the seafloor before the fluid exits the chimney. Other types of compounds, including silica, remain in the fluid. When the fluid exits the chimney, **the silica precipitates out.**

Another chemical reaction creates a white mineral called **anhydrite**. Both of these minerals turn the fluids that exit the chimney white.

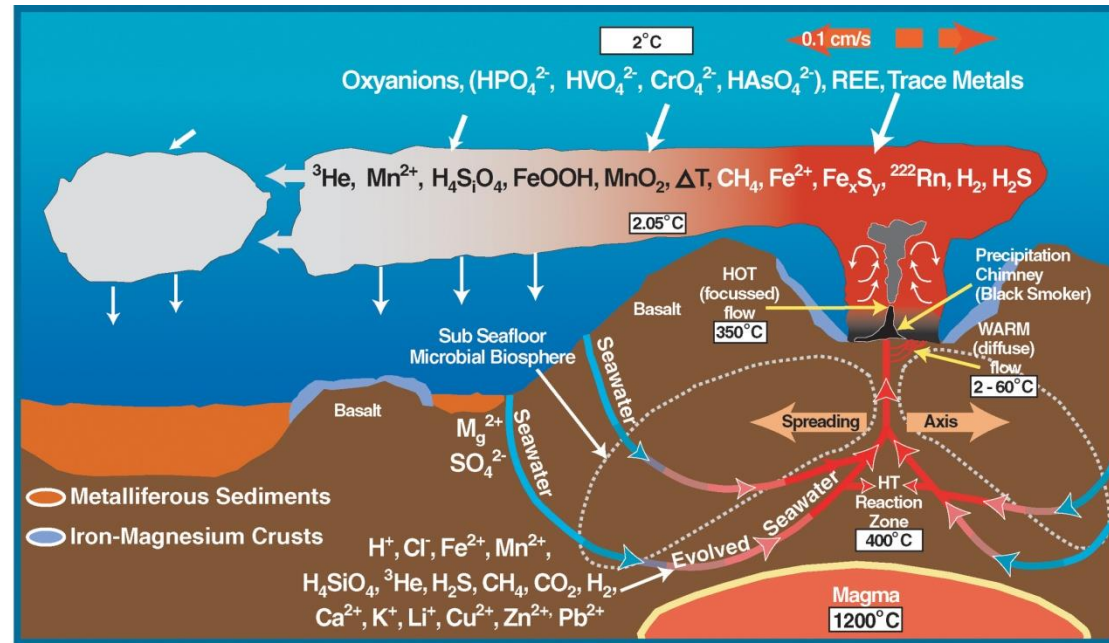




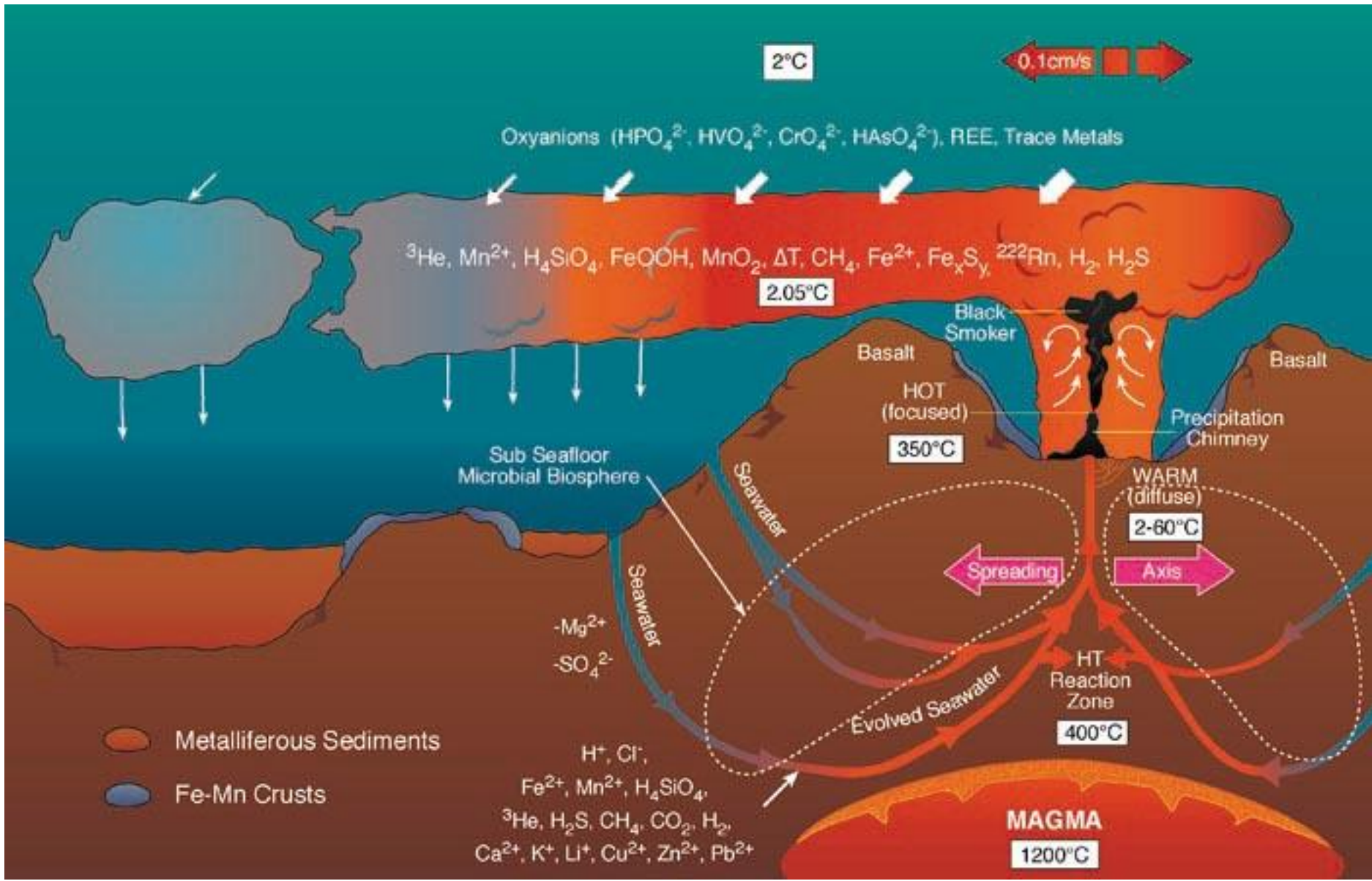
In other words, the origin of mid-ocean submarine hydrothermal systems is mainly seawater convection in hot young oceanic crust, on top or above the flanks of shallow magma bodies 1 to 3km below the seafloor.

The seawater flows downwards to more than 3km depth through the fractures developed due to the convection current and divergent plate boundaries. At higher temperature and deeper levels, the descending seawater reacts with basalts causing ocean floor greenschist facies metamorphism.

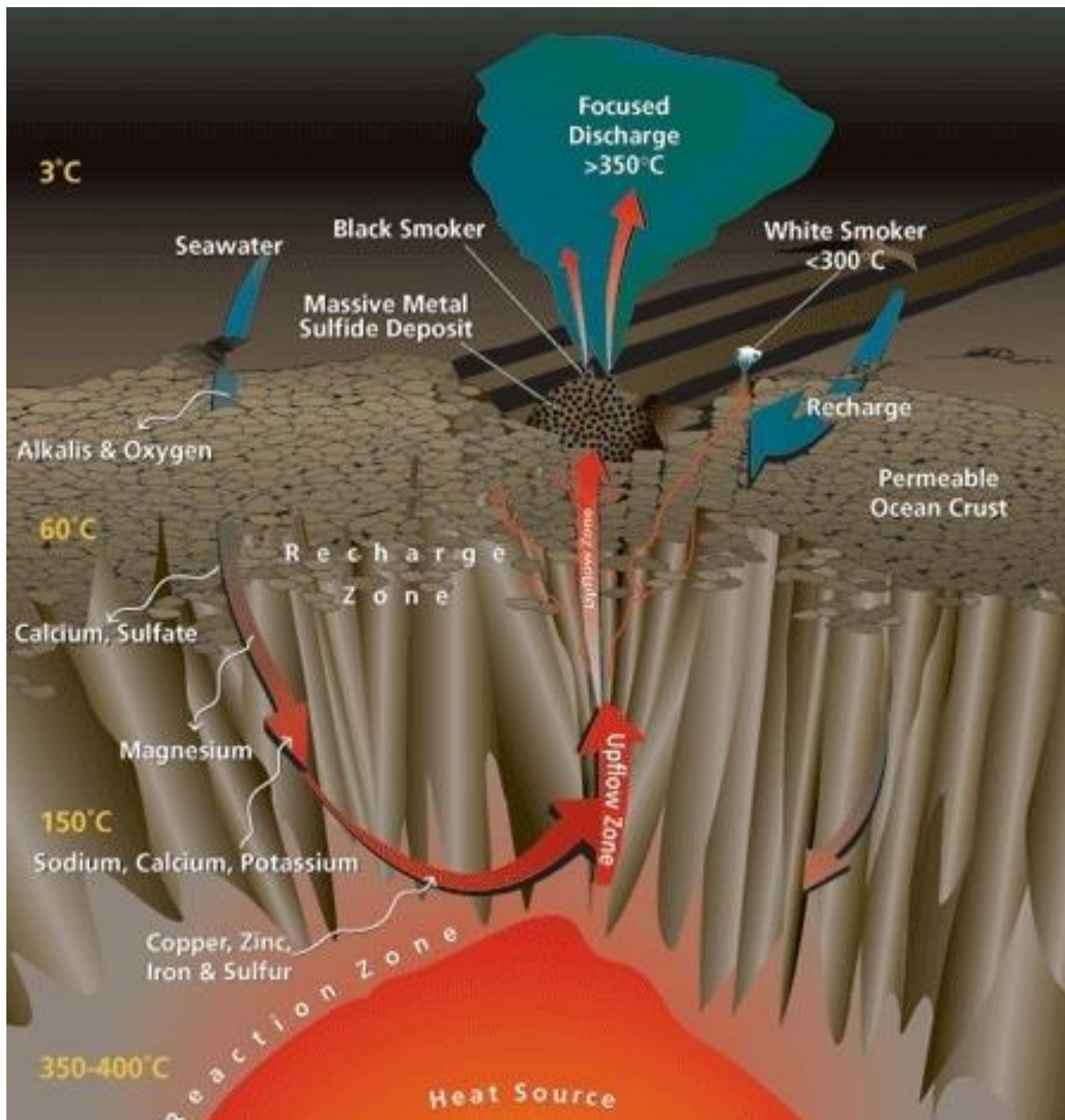
Water oxygen is rapidly consumed by reaction with Fe(II) and new hydrated minerals incorporating OH are formed (e.g. chlorite, amphibole). Consequently, the H<sup>+</sup> increased in the fluid increasing its acidity. The acid water dissolves metals and sulphur of the country rocks.



Although most of the emitted metals are diluted in ocean water and sediments, approximately 250 metalliferous bodies of economic mass and grade have meanwhile been discovered.



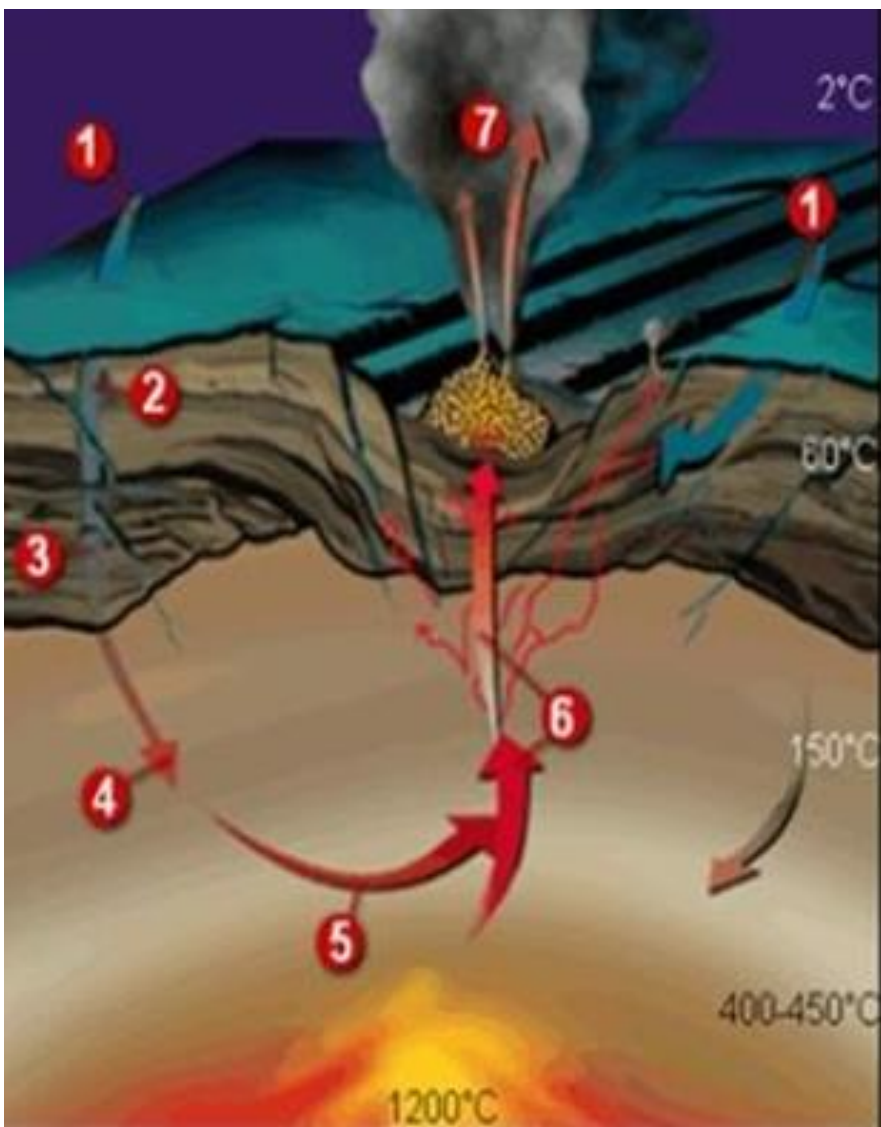
Interaction of seawater, hot crust drives chemistry of hydrothermal vents. When intruding magma cracks crustal rock beneath the ocean, seawater rushes in to react with the rock, becomes heated, and rises to the seafloor where it escapes from hydrothermal vents to form plumes known as black smokers. Within the plumes, which sometimes travel thousands of miles from the vent, further chemical reactions produce metal-rich particulates that settle on the ocean floor.



Cold seawater enters the crust in the recharge zone heats up and gets acidic with proceeding descent in the crust until it reaches the reaction zone where metal mobilization occurs.

The metalbearing fluids rise to the seafloor along the high temperature up-flow zone, where metal precipitation occurs due to fluid-seawater mixing. Fluid venting – sea vent "geysers" – occur on the seafloor spreading and may also occur in other tectonic settings, including magmatic arcs above subduction zones, hotspot ocean island volcanoes and dewatering sediments of active and passive continental margins.



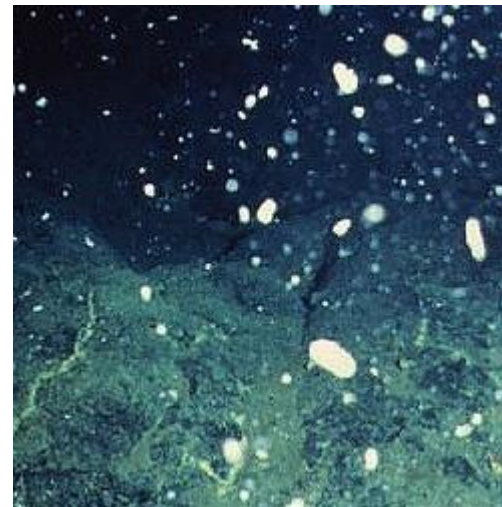
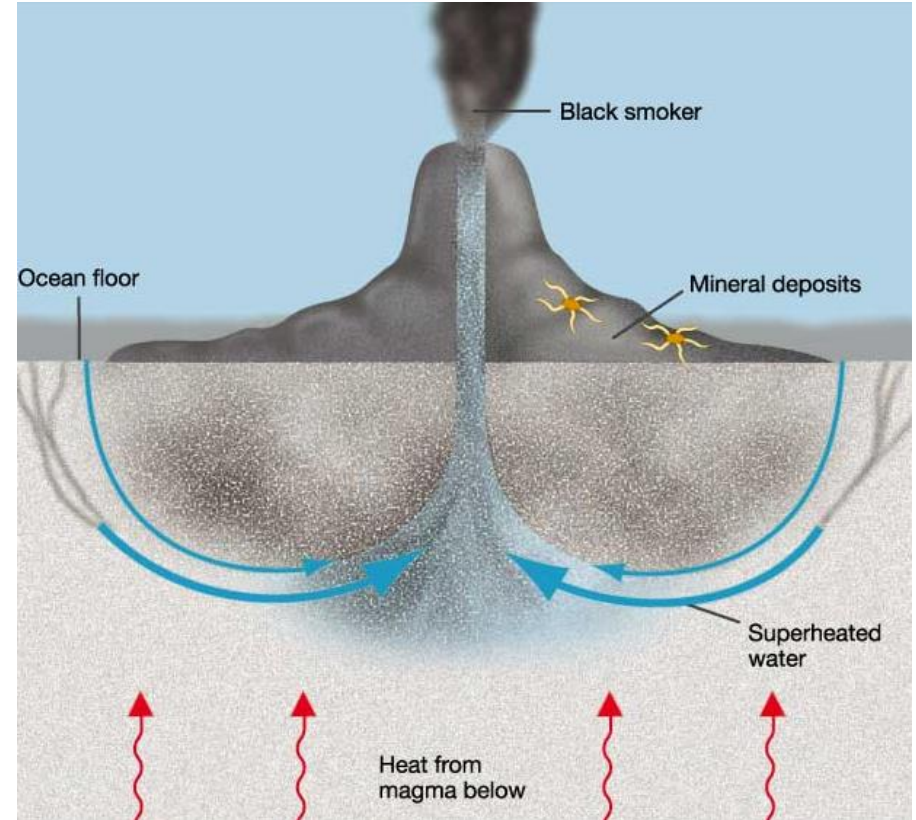


- 1 influx of cold seawater (recharge)
- 2 alteration of oceanic crust (<150°C)
- 3  $\text{H}_2\text{O} = \text{H}^+ + \text{OH}^-$  (>150°C)
- 4 excess  $\text{H}^+$  --> pH drop to ~ 3 (acid)
- 5 heating of seawater to ~ 450°C  
seawater  $\text{SO}_4^{2-} \rightarrow \text{H}_2\text{S}$  ( $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$ )
- 6 leaching of Cu, Zn, Fe, Au, S etc. from the surrounding rock
- 7 formation of hydrothermal precipitates due to mixing of hot fluid with cold seawater (discharge) – black smokers

Scientists are enthralled by the unusual life that inhabits the vent sites. Since temperatures are so high in the vents, it is amazing that it can support life forms.

One type of organism that can thrive alone or in symbiotic relationships with other organisms is the extreme **thermophilic microbes**. Microbe particles being spewed from the smokers.

Many other organisms survival in the **deep sea vents** is dependent upon microbes. Without the microbes, they would not be able to produce nourishment for themselves. Microbes that are found in the giant tubeworms and mussels are sulfur-oxidizing bacteria that gain energy by the metabolism of inorganic compounds.



**Thermophilic** microbes.



Shrimp and crabs living among black smoker spires.

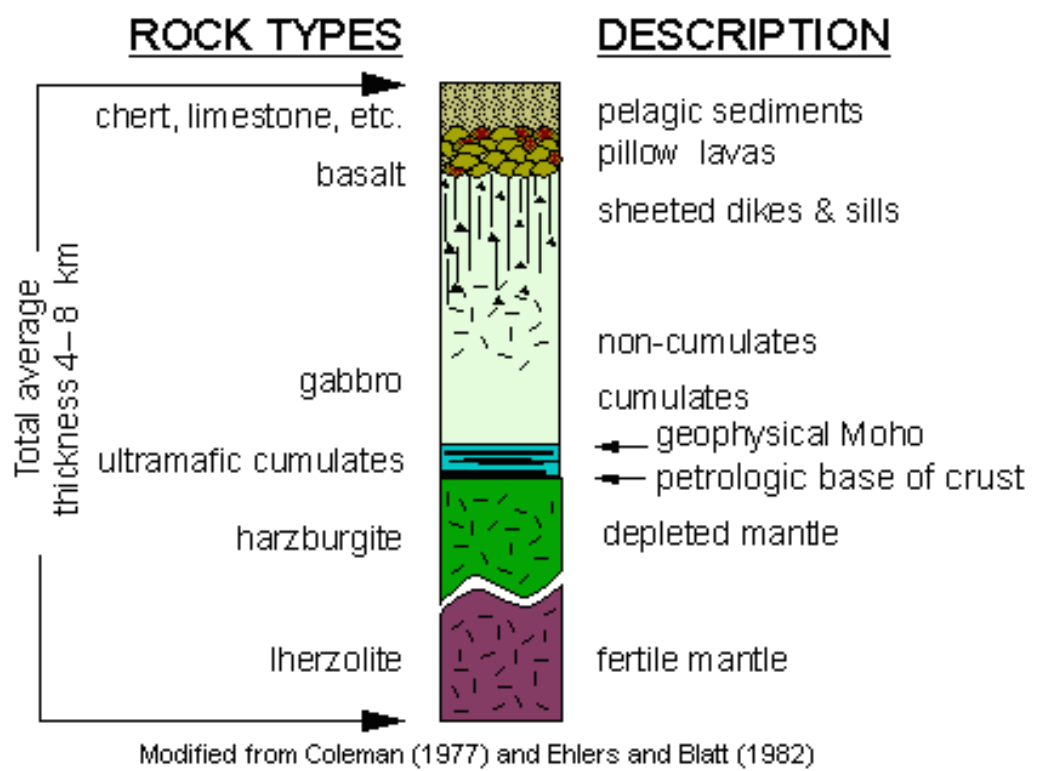
# IV. Ores in Ophiolites

Ophiolites are fragments of oceanic crust and mantle that have been transported (obducted) as thrust sheets (nappes) towards continental masses. The tectonic emplacement was normally associated with dismemberment of the original succession.

A complete ophiolite sequence was described before.

Tectonized (foliated) harzburgite and the lower cumulates host dunite bodies that may contain massive and disseminated chromite ore. Dunite in harzburgite can be understood as lag segregation from rising basaltic melt diapirs.

## IDEALIZED CROSS-SECTION OF AN OPHIOLITE

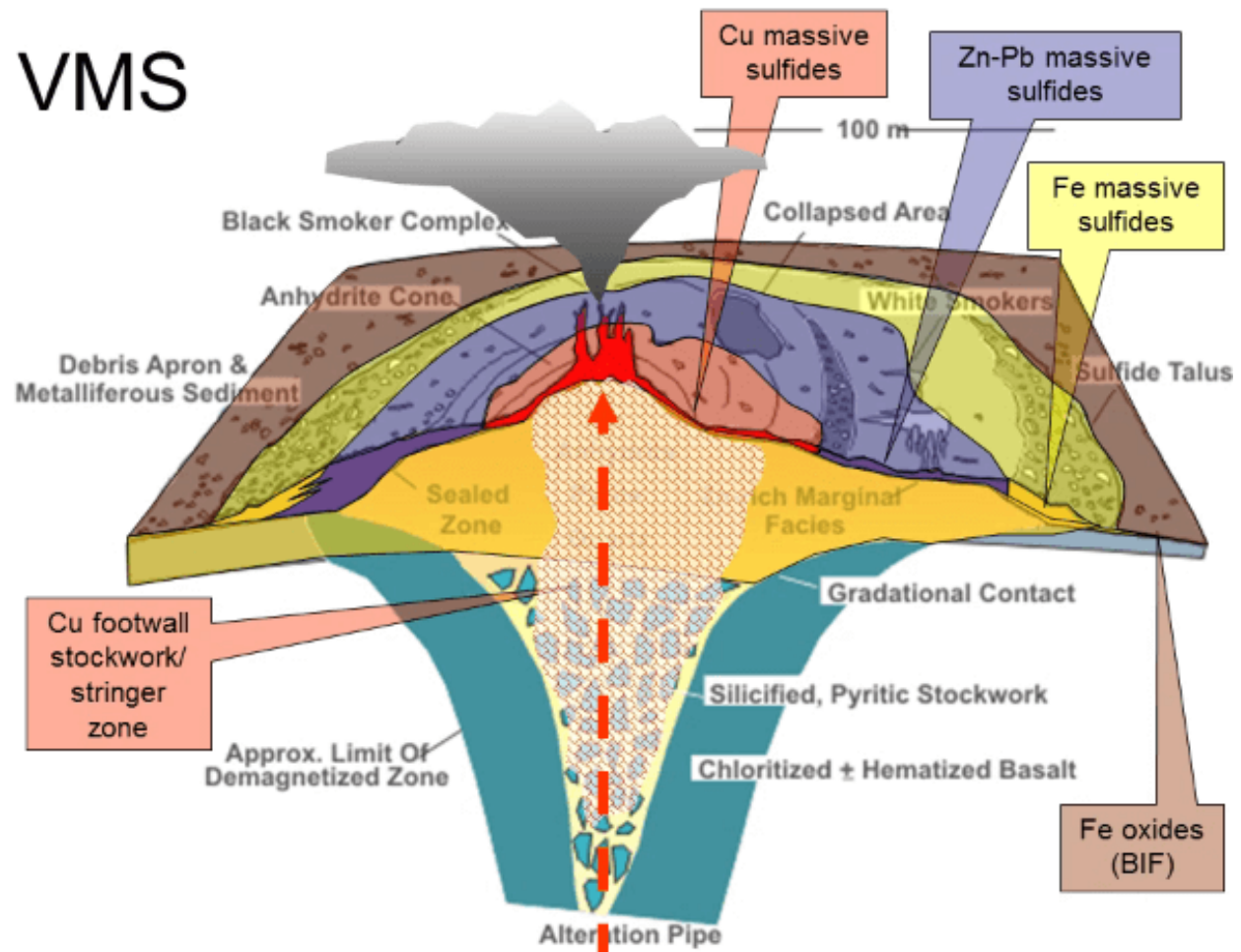


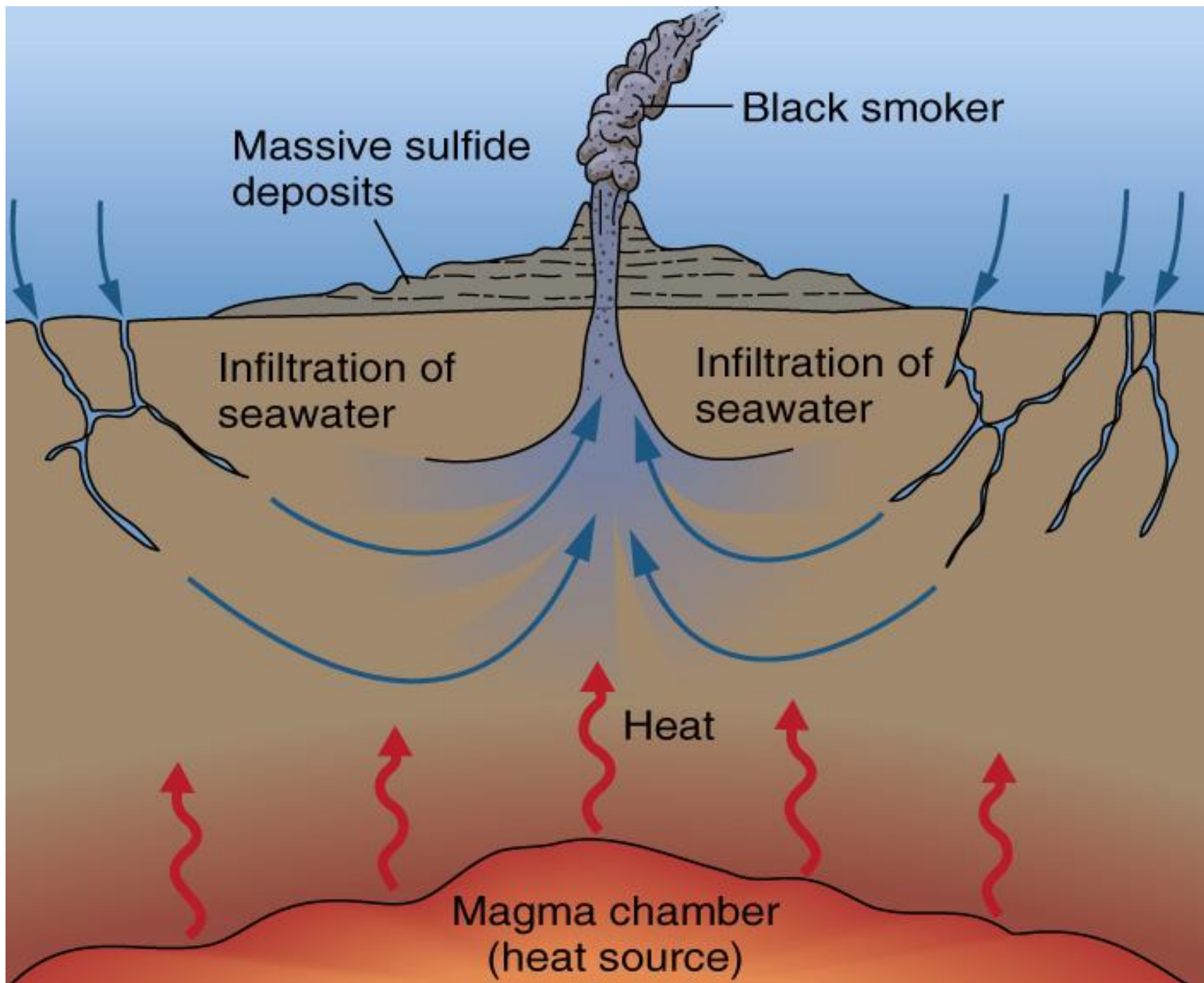
**Chromitites** originate from dunite by liquid-liquid immiscibility. Because of ductile shearing in the oceanic mantle, both dunites and chromite orebodies are strongly deformed, resulting in lenticular pod-like shapes.



# V. Volcanic-hosted Massive Sulphide (VMS) = Volcanogenic Massive Sulfide

This is comparable to ancient **volcanic-hosted massive sulphide (VMS)** deposits of **obducted ophiolites** (the Cyprus type). In the shallow crust beneath vent fields, large Cu, Zn and Au accumulations are probably formed by precipitation because of boiling and vapour loss during de-pressurization. Metalliferous mud in several depressions of the Red Sea represents the largest known submarine base metal mineralization.

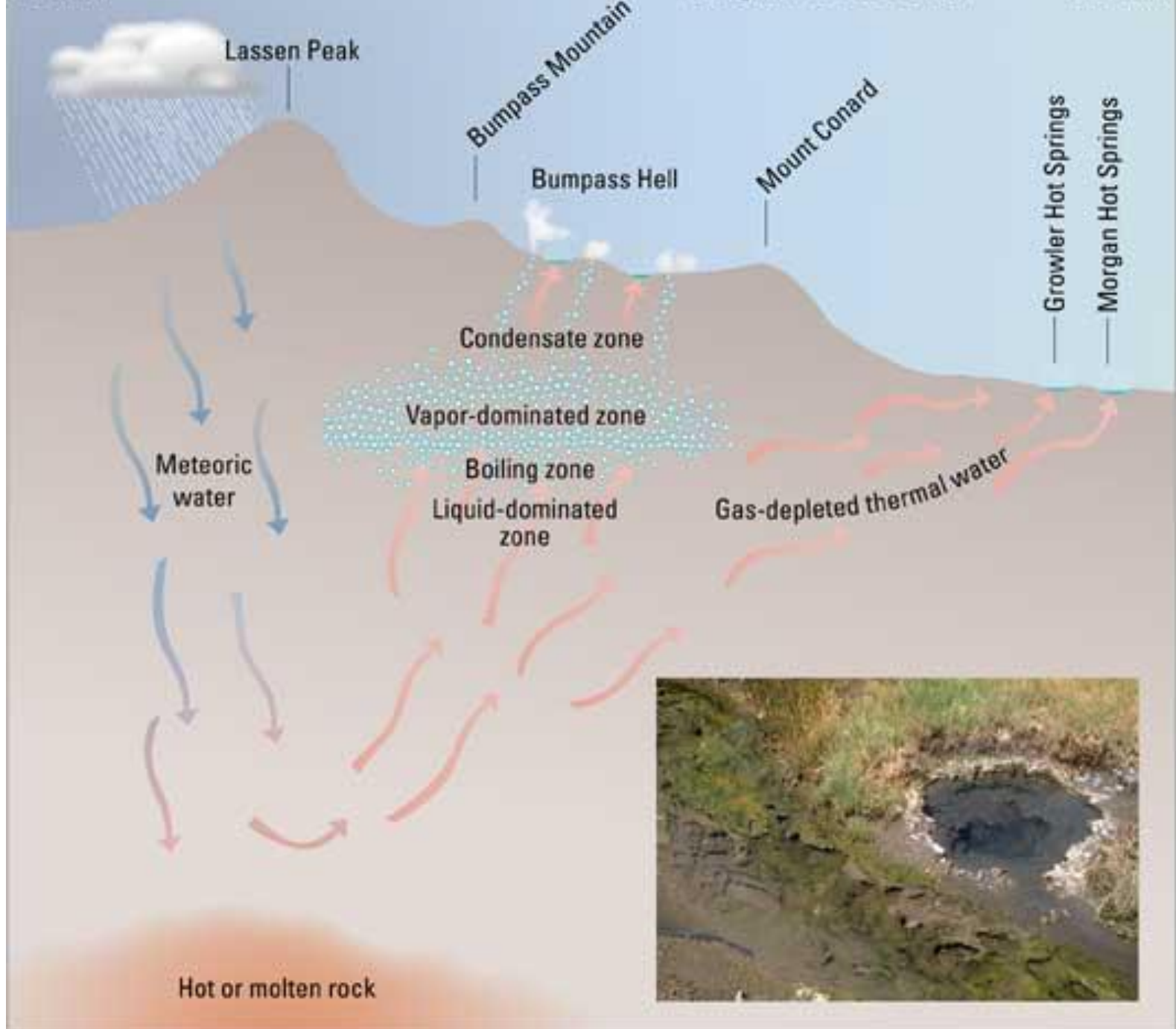




North

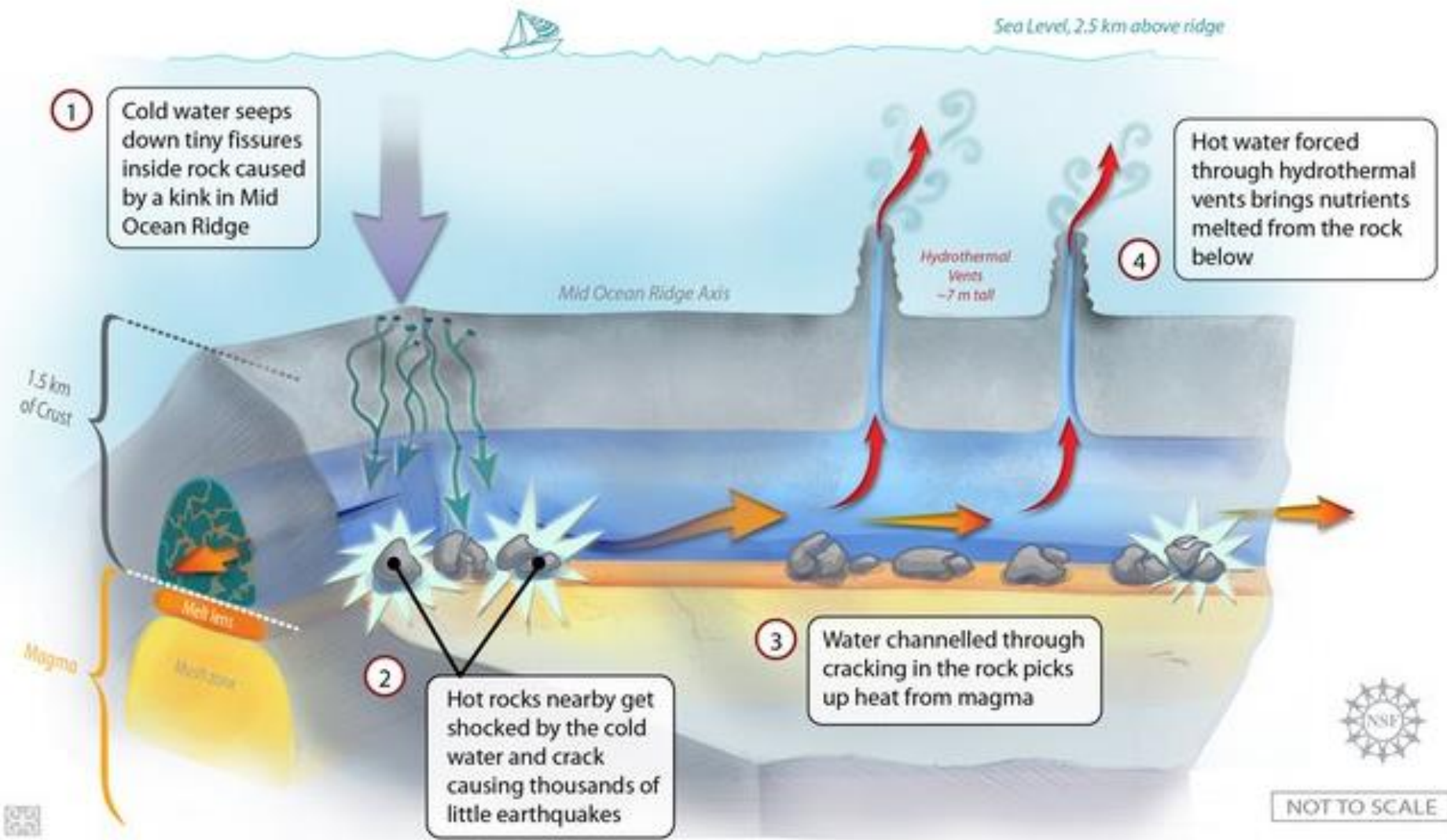
(diagram not to scale)

South





# NEW MODEL FOR WATER DYNAMICS OF DEEP-SEA HYDROTHERMAL VENTS



## **In conclusion:**

Ore deposits in ophiolites include two major groups:

- i) **Chromite** and in rare cases with co-precipitated exploitable **platinum** and
- ii) **exhalative volcanic massive sulphide (VMS)** deposits of iron, copper and zinc sulphides (Ag and Au, but note the virtual absence of Pb), **including possible underlying stockwork ore.**

Ophiolites host other important mineralizations that they have “acquired” during obduction, nappe transport, deformation, metamorphism and finally weathering. These include **asbestos, magnesite, gold (in listvaenite), talc, and lateritic Ni-(Cr-Co-Fe) ore in deeply weathered soil profiles.**



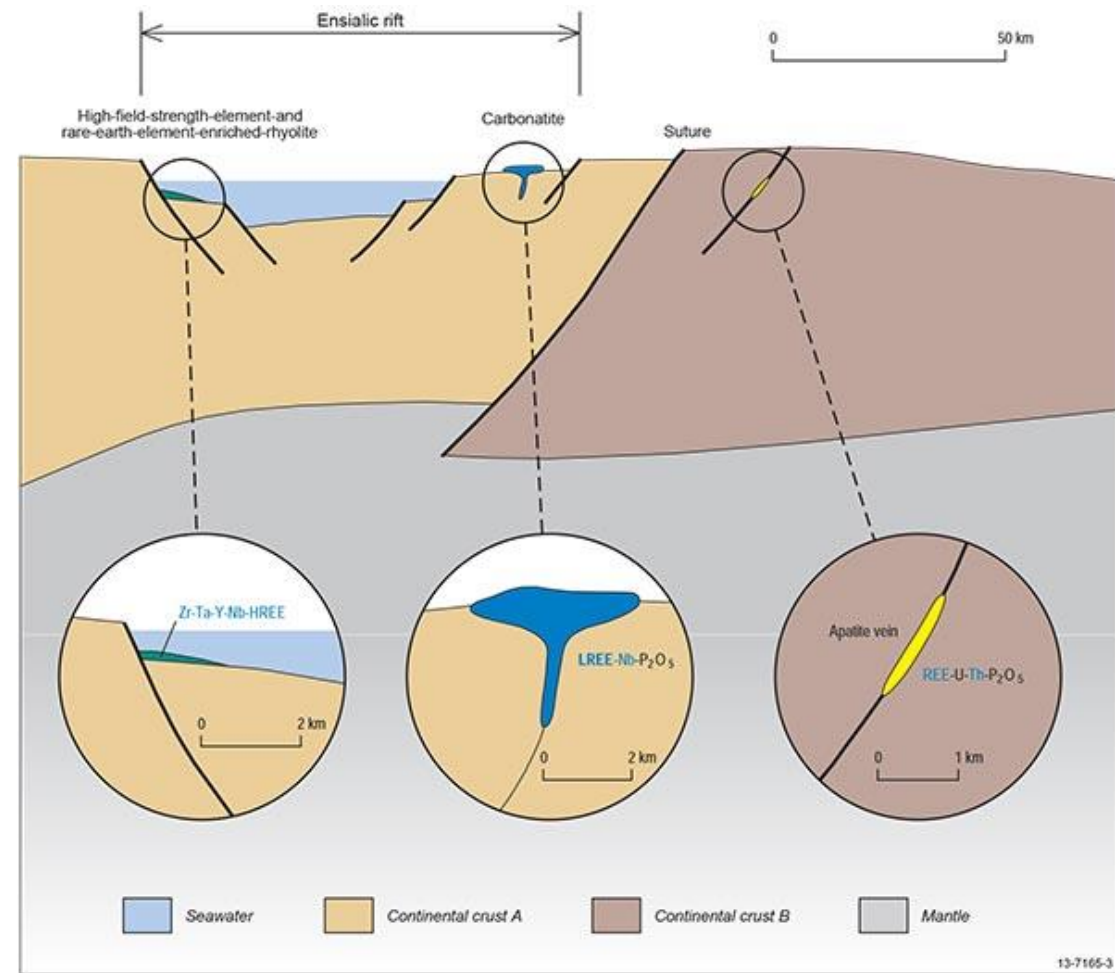


### 3. Ore formation related to alkaline magmatic rocks, carbonatites and kimberlites

Rocks of alkaline affinity generally have low  $\text{SiO}_2$  and high alkali element content, especially of sodium and potassium. They occur mainly in continents, and rarely within oceanic plates.

An anorogenic setting is affirmed by the existence of these rocks near continental rifts, over heat anomalies of the mantle (hot spots, plumes, superplumes).

The alkaline magmas originate by a low degree of partial melting of enriched mantle material may stem from subducted oceanic crust, or more probably, from metasomatized lithospheric mantle.



**Nephelinite (alkaline) magma** is the most common mafic alkaline liquid that crystallizes to give a range of igneous rocks (termed the ijolite suite). They are typically associated with the much rarer carbonatites that have a more prominent metallogenetic role than the ijolite rocks.

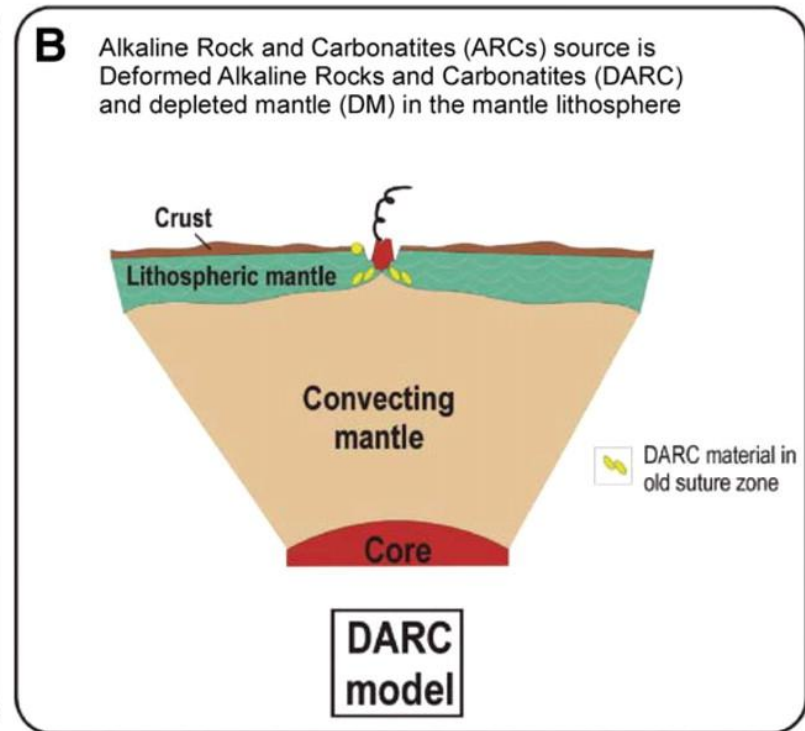
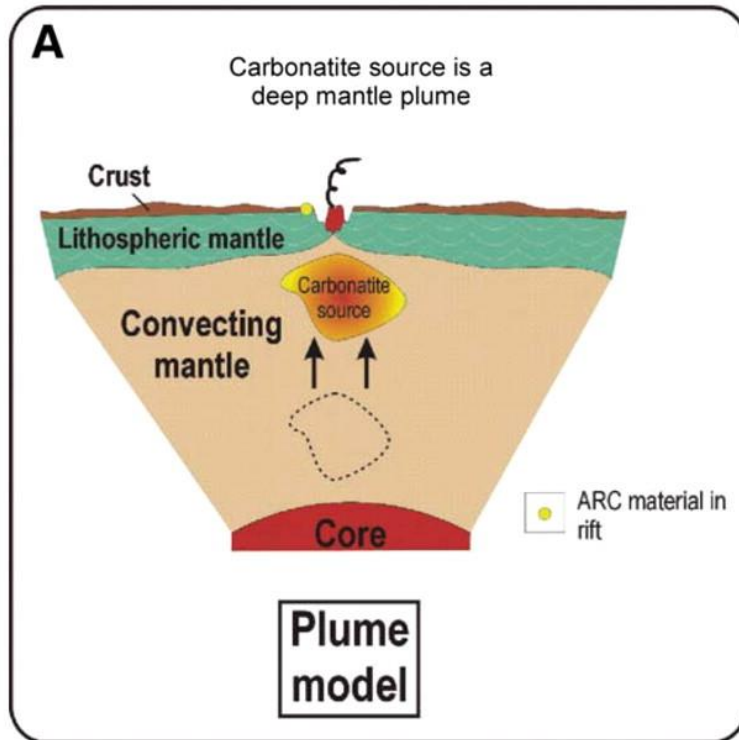
Table 19-1. Nomenclature of some alkaline igneous rocks (mostly volcanic/hypabyssal)

<b>Basanite</b>	feldspathoid-bearing basalt. Usually contains nepheline, but may have leucite + olivine
<b>Tephrite</b>	olivine-free basanite
<b>Leucitite</b>	a volcanic rock that contains leucite + clinopyroxene ± olivine. It typically lacks feldspar
<b>Nephelinitite</b>	a volcanic rock that contains nepheline + clinopyroxene ± olivine. It typically lacks feldspar. Fig. 14-2
<b>Ürtite</b>	plutonic nepheline-pyroxene (aegirine-augite) rock with over 70% nepheline and no feldspar
<b>Ijolite</b>	plutonic nepheline-pyroxene rock with 30-70% nepheline
<b>Melilitite</b>	a predominantly melilite - clinopyroxene volcanic (if > 10% olivine they are called olivine melilitites)
<b>Shoshonite</b>	K-rich basalt with K-feldspar ± leucite
<b>Phonolite</b>	felsic alkaline volcanic with alkali feldspar + nepheline. See Fig. 14-2. (plutonic = nepheline syenite)
<b>Comendite</b>	peralkaline rhyolite with molar $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{Al}_2\text{O}_3$ slightly > 1. May contain Na-pyroxene or amphibole
<b>Pantellerite</b>	peralkaline rhyolite with molar $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{Al}_2\text{O}_3 = 1.6 - 1.8$ . Contains Na-pyroxene or amphibole
<b>Lamproite</b>	a group of peralkaline, volatile-rich, ultrapotassic, volcanic to hypabyssal rocks. The mineralogy is variable, but most contain phenocrysts of olivine + phlogopite ± leucite ± K-richterite ± clinopyroxene ± sanidine. Table 19-6
<b>Lamprophyre</b>	a diverse group of dark, porphyritic, mafic to ultramafic hypabyssal (or occasionally volcanic), commonly highly potassic ( $\text{K} > \text{Al}$ ) rocks. They are normally rich in alkalis, volatiles, Sr, Ba and Ti, with biotite-phlogopite and/or amphibole phenocrysts. They typically occur as shallow dikes, sills, plugs, or stocks. Table 19-7
<b>Kimberlite</b>	a complex group of hybrid volatile-rich (dominantly $\text{CO}_2$ ), potassic, ultramafic rocks with a fine-grained matrix and macrocrysts of olivine and several of the following: ilmenite, garnet, diopside, phlogopite, enstatite, chromite. Xenocrysts and xenoliths are also common
<b>Group I kimberlite</b>	is typically $\text{CO}_2$ -rich and less potassic than Group 2 kimberlite
<b>Group II kimberlite (orangeite)</b>	is typically $\text{H}_2\text{O}$ -rich and has a mica-rich matrix (also with calcite, diopside, apatite)
<b>Carbonatite</b>	an igneous rock composed principally of carbonate (most commonly calcite, ankerite, and/or dolomite), and often with any of clinopyroxene alkalic amphibole, biotite, apatite, and magnetite. The Ca-Mg-rich carbonatites are technically not alkaline, but are commonly associated with, and thus included with, the alkaline rocks. Table 19-3

For more details, see Sørensen (1974), Streckeisen (1978), and Woolley *et al.* (1996)

**Alkaline magma is plumed-out** from the **sub-continental mantle lithosphere** by rising the mantle temperature, falling pressure, or under the influence of volatile (mantle metasomatism). **A subducted crust is also a possible source.**

**“Shallow” carbonatitic and deep kimberlitic melts with high CO<sub>2</sub> and low H<sub>2</sub>O content originate in lithospheric mantle at 120–260km depth. The high gas content (CO<sub>2</sub> and low H<sub>2</sub>O) facilitates rapid rise of magma diapirs to the surface where eruption takes place.**



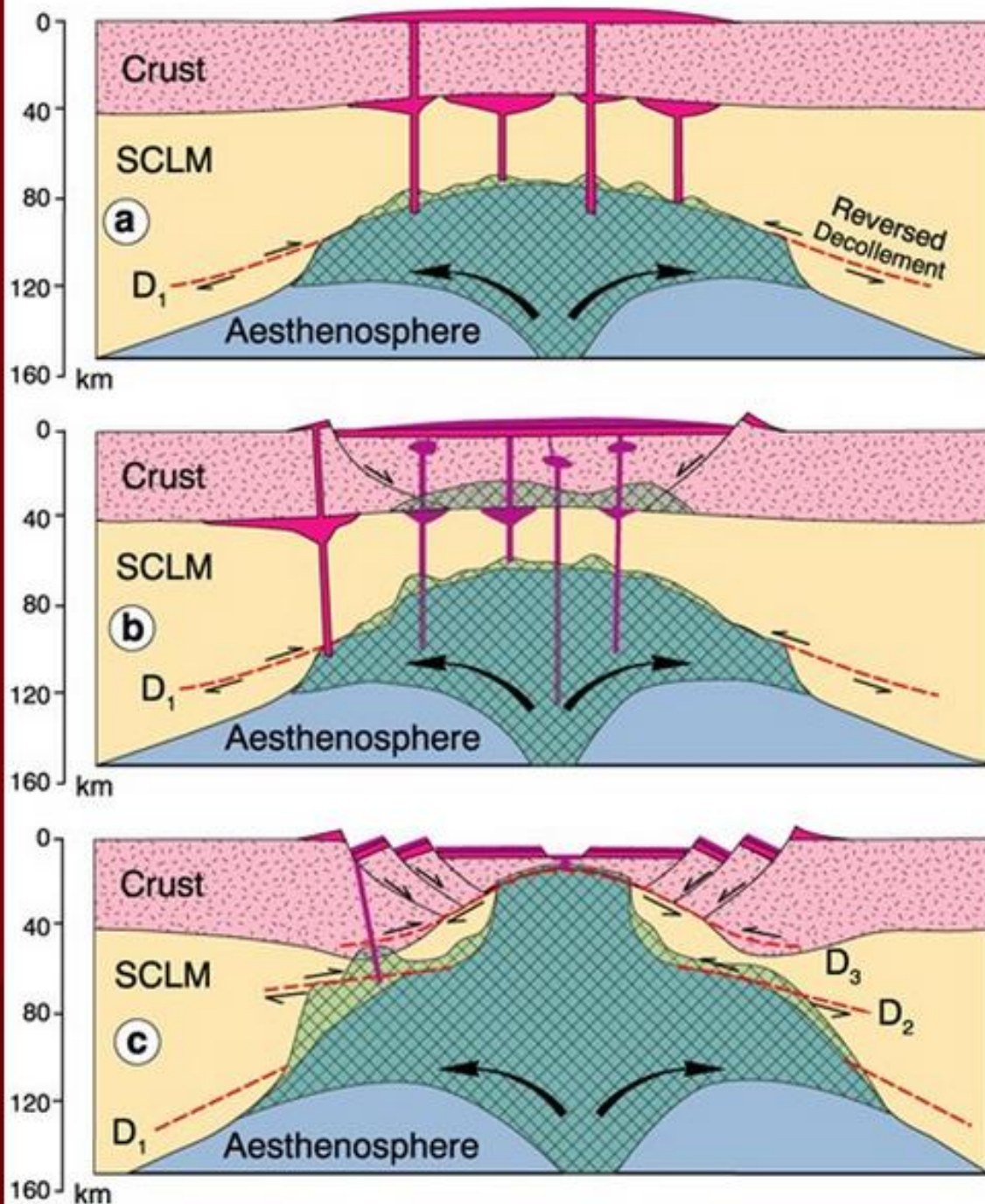
Two current hypotheses about the origin of **Alkaline Rocks and Carbonatites (ARCS)**. **A: In the plume model**, ARCs are derived from mantle plumes (here defined simply as magma sources of distinctive chemical composition within the convecting mantle). **B: In the Deformed Alkaline Rocks and Carbonatites (DARC) model**, ARCs are derived from melting that involves deformed alkaline rock and carbonatite material that was carried into the lithospheric mantle during an ancient subduction episode.



**Figure 19-9. . a. Pre-rift stage** asthenospheric mantle diapir rises (forcefully or passively) into the lithosphere. Decompression melting (cross-hatch-green indicate areas undergoing partial melting) produces variably alkaline melts. Some partial melting of the metasomatized sub-continental lithospheric mantle (SCLM) may also occur. Reversed decollements ( $D_1$ ) provide room for the diapir.

**b. Rift stage:** development of continental rifting, eruption of alkaline magmas (red) mostly from a deep asthenospheric source. Rise of hot asthenosphere induces some crustal anatexis. Rift valleys accumulate volcanics and volcanoclastic material

**c. A far stage**, in which asthenospheric ascent reaches crustal levels. This is transitional to the development of oceanic crust.



## VI. Carbonatites

**Carbonatites** are igneous rocks with more than 50% of carbonate minerals. They are further subdivided depending on the nature of the carbonates (calcite, dolomite, and ankerite) and the silicate phases (biotite, pyroxene, amphibole, etc.). The formation of carbonatite-alkali complexes is probably controlled by:

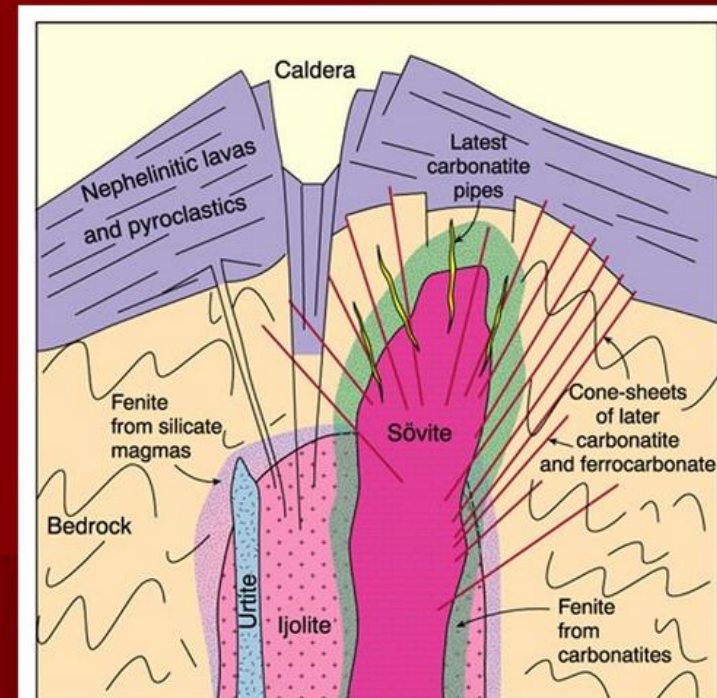
1. fractional crystallization and
2. unmixing of carbonate and silicate melts in the crust.
3. very low degree of melting in the mantle at elevated  $\text{CO}_2$  content, temperatures of  $930\text{--}1080^\circ\text{C}$  and pressures of  $21\text{--}30$  kbar (Bailey 1993).

**Carbonatites** occur as both intrusive and extrusive bodies - the former as plutonic and hypabyssal dikes, sills, sheets, pipes, stocks, and more irregular bodies; the latter as flows and pyroclastics.

**Ijolite** plutonic nepheline-pyroxene rock with 30-70% nepheline  
**Urtite** plutonic nepheline-pyroxene (aegirine-augite) rock with over 70% nepheline and no feldspar

### Carbonatites

Figure 19-11. Idealized cross section of a carbonatite-alkaline silicate complex with early ijolite cut by more evolved urtite. Carbonatite (most commonly calcitic Sovite) intrudes the silicate plutons, and is itself cut by later dikes or cone sheets of carbonatite and ferrocarnatite. The last events in many complexes are late pods of Fe and REE-rich carbonatites. A fenite aureole surrounds the carbonatite phases and perhaps also the alkaline silicate magmas. After Le Bas (1987) Carbonatite magmas. *Mineral. Mag.*, 44, 133-40. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

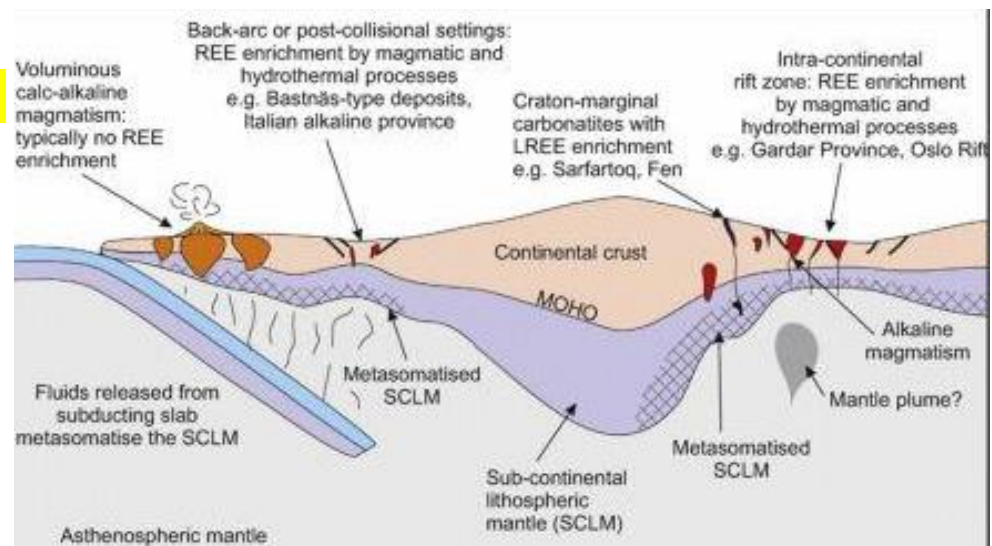




## There are three possible models for the generation of carbonatitic magmas:

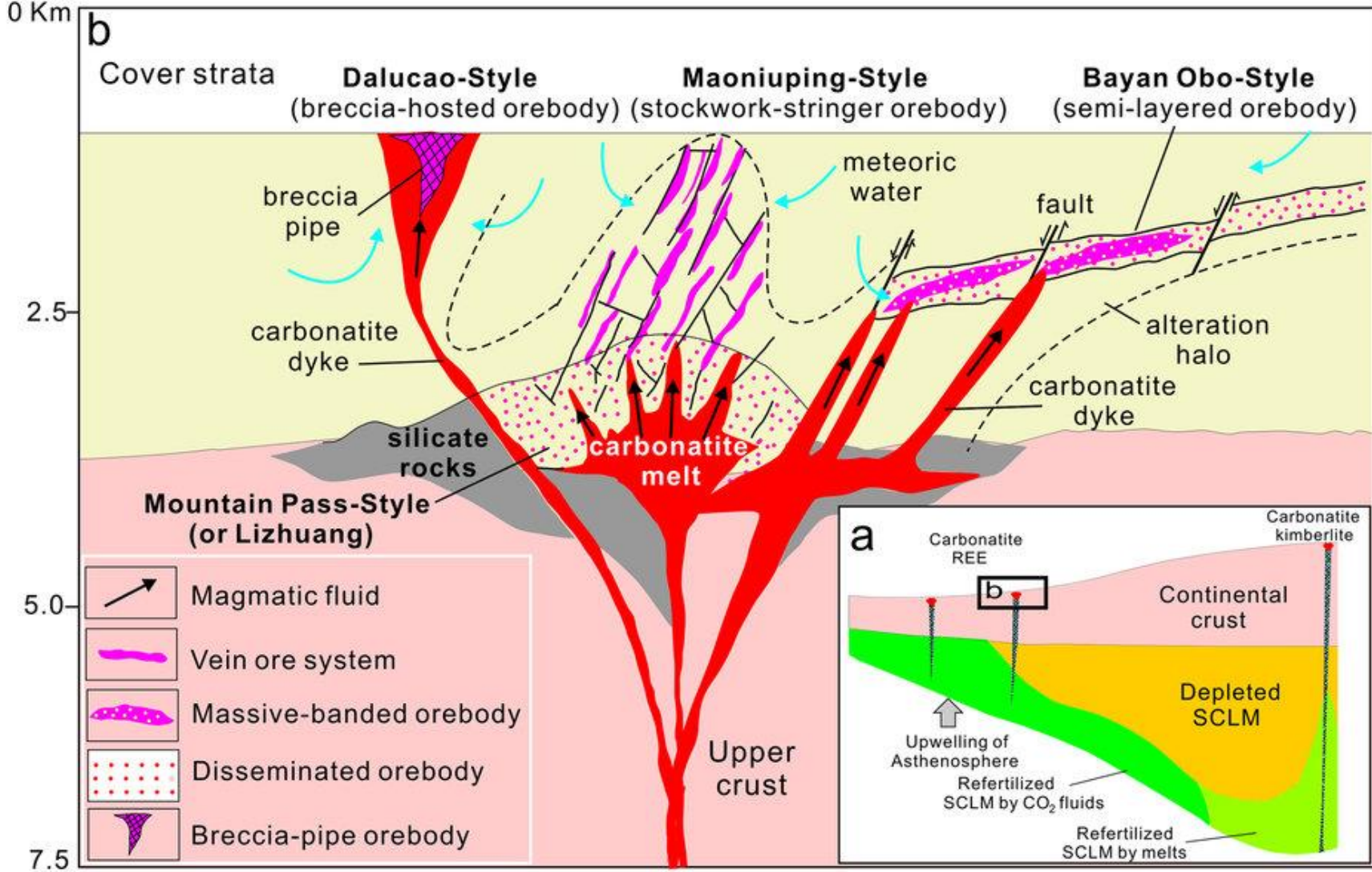
- direct partial melting of the upper mantle peridotite induced by addition of  $\text{CO}_2$ ,
- fractional crystallization of a nepheline normative, silica-undersaturated, relatively alkali rich silicate magma containing dissolved  $\text{CO}_2$  and probably also  $\text{H}_2\text{O}$ ; and
- separation of an immiscible carbonatite melt from an alkali-rich or Ca-rich silicate magma.

Field relations do not support the fractional crystallization model either, because carbonatites are not found associated with a differentiated series of silicate rocks. **The liquid immiscibility model, on the other hand, is supported by several lines of field and chemical evidence.**



The chemical diversity of carbonatites is also quite compatible with a **liquid immiscibility origin**. Factors that contribute to the diversity are: (a) chemical composition of the parental magma; (b) pressure and temperature at which liquid immiscibility may take place; (c) crystal fractionation of carbonate minerals (calcite and/or dolomite) and the early precipitation of a range of minerals such as apatite, magnetite, bastnasite, baddeleyite, and pyrochlore; (d) loss of alkalis by fenitization; and (e) contamination by adjacent country rocks.





a) Upwelling of asthenosphere triggers the melting of refertilized SCLM that was previously metasomatized by CO<sub>2</sub>-rich fluids derived from marine sediments associated with “fossil” subduction zones. The subducted sediments released their REEs into CO<sub>2</sub>-rich fluids that metasomatized old depleted or enriched SCLM to form an unusually REE-rich, carbonated mantle source, which then produced carbonatite melts or CO<sub>2</sub>-rich silicate melts. The margins of the craton experience low degrees of partial melting, and the melts ascend through fracture zones into the overriding crust. (b) Schematic illustration of models of CARD formation, including a variety of orebodies formed by fluids exsolved from REE-rich carbonatitic magmas emplaced at shallow crustal levels. Lateral migration, replacement, open-space filling, and focused discharges of ore-forming fluids produced semi-stratabound (Bayan Obo-style), disseminated (Lizhuang or Mountain Pass-style) stringer-stockwork (Maoniuping-style) and breccia pipe (Dalucao-style) orebodies with associated fenitization and K-silicate alterations, respectively.

Anomalous amounts of rare earth elements (REE) are remarkable features of carbonatites, especially of the light REE Elements (lanthanum to samarium), P, F, Th, Ti, Ba, Sr, and Zr. Half of all known carbonatites occur along the East African Rift System.

Metals exploited from complex intrusions of carbonatite, alkali-pyroxenites and nepheline syenites include:

- I. **Metallic**, such as copper, rare earth elements, iron-titanium-vanadium, uranium-thorium and zirconium;
- II. **Non-metallic**, such as vermiculite, apatite, fluorite and barite, and limestone.

Nepheline syenite is a good source for Al in ceramics industry.

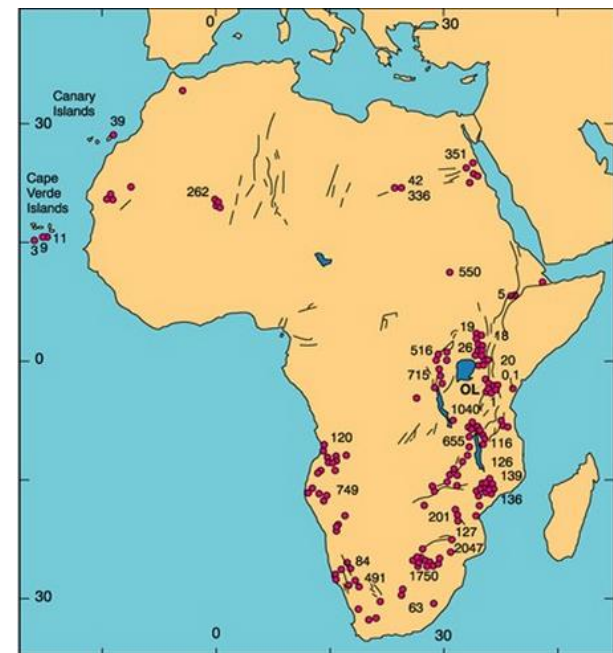


Table 19-4. Some Minerals in Carbonatites.

<b>Carbonates</b>	<b>Sulfides</b>
Calcite	Pyrrhotite
Dolomite	Pyrite
Ankerite	Galena
Siderite	Sphalerite
Strontanite	<b>Oxides-Hydroxides</b>
Bastnäsite (Ce,La)FCO <sub>3</sub> )	Magnetite
* Nyerereite ((Na,K) <sub>2</sub> Ca(CO <sub>3</sub> ) <sub>2</sub> )	Pyrochlore
* Gregoryite ((Na,K) <sub>2</sub> CO <sub>3</sub> )	Perovskite
<b>Silicates</b>	Hematite
Pyroxene	Ilmenite
Aegirine-augite	Rutile
Diopside	Baddeleyite
Augite	Pyrolusite
Olivine	<b>Halides</b>
Monticellite	Fluorite
Alkali amphibole	<b>Phosphates</b>
Allanite	Apatite
Andradite	Monazite
Phlogopite	
Zircon	

The most important mineral products of **carbonatites** probably are calcite for cement and apatite for phosphatic fertilizer. Many carbonatites contain traces of **Th-bearing monazite, pyrochlore, and uranothorianite**, which are useful for outlining carbonatite bodies by **radiometric surveys**. **The principal metals for which the carbonatites are considered a major resource are niobium and REE**; some carbonatites also contain significant concentrations of **Fe (magnetite, hematite), Ti (rutile, brookite, ilmenite, perovskite), Cu sulfides, barite, fluorite, and strontianite**, which may be recoverable as byproducts. **Pyrochlore (CaNaNb<sub>2</sub>O<sub>6</sub>F) is by far the most abundant primary niobium mineral in carbonatite associations and it is found in nearly all rock types of carbonatite complexes in accessory amounts.**



		METAL	OXIDE	NAME	USAGE
		<b>Sc</b>		<b>Scandium</b>	X-ray tubes, catalysts for polymerisation, hardened Ni-Cr superalloys, dental porcelain.
		<b>Zr</b>	ZrO <sub>2</sub>	<b>Zirconium</b>	Zirconium is used as an alloying agent due to its high resistance to corrosion.
		<b>Nb</b>	Nb <sub>2</sub> O <sub>3</sub>	<b>Niobium</b>	Niobium is used mostly in alloys, the largest part in special steel such as that used in gas pipelines.
RARE EARTH ELEMENT (LANTHANIDES)	LIGHT REE'S	<b>La</b>	La <sub>2</sub> O <sub>3</sub>	<b>Lanthanum</b>	Ceramic glazes, high quality optical glass, camera lenses, microwave crystals, ceramic capacitors.
		<b>Ce</b>	Ce <sub>2</sub> O <sub>3</sub>	<b>Cerium</b>	Glass polishing, petroleum cracking catalysts, alloys - with iron for sparking flints for lighters, with aluminium, magnesium and steel for improving heat and strength properties, radiation shielding.
		<b>Pr</b>	Pr <sub>2</sub> O <sub>3</sub>	<b>Praseodymium</b>	Yellow ceramic pigments, tiles, ceramic capacitors. With neodymium in combination for goggles to shield glass makers against sodium glare, permanent magnets, cryogenic refrigerant.
		<b>Nd</b>	Nd <sub>2</sub> O <sub>3</sub>	<b>Neodymium</b>	Ceramic capacitors, glazes and coloured glass, lasers, high strength permanent magnets as neodymium-iron-boron alloy, petroleum cracking catalysts.
		<b>Pm</b>	Pm <sub>2</sub> O <sub>3</sub>	<b>Promethium</b>	Radioactive promethium in batteries to power watches, guided missile instruments.
		<b>Sm</b>	Sm <sub>2</sub> O <sub>3</sub>	<b>Samarium</b>	In highly magnetic alloys for permanent magnet as Samarium-Cobalt alloy; probably will be superseded by neodymium. Glass lasers. Reactor control and neutron shielding.
	HEAVY REE'S	<b>Eu</b>	Eu <sub>2</sub> O <sub>3</sub>	<b>Europium</b>	Control rods in nuclear reactors. Coloured lamps, cathode ray tubes. Red phosphor in TV tubes.
		<b>Gd</b>	Gd <sub>2</sub> O <sub>3</sub>	<b>Gadolinium</b>	Solid state lasers, constituent of computer memory chips, high temperature refractories.
		<b>Tb</b>	Tb <sub>2</sub> O <sub>3</sub>	<b>Terbium</b>	Cathode ray tubes, magnets, optical computer memories; hard disk components.
		<b>Dy</b>	Dy <sub>2</sub> O <sub>3</sub>	<b>Dysprosium</b>	Controls nuclear reactors. Alloyed with neodymium for permanent magnets. Catalysts.
		<b>Ho</b>	Ho <sub>2</sub> O <sub>3</sub>	<b>Holmium</b>	Controls nuclear reactors; catalysts; refractories.
		<b>Er</b>	Er <sub>2</sub> O <sub>3</sub>	<b>Erbium</b>	In ceramics to produce a pink glaze; infra-red absorbing glasses.
		<b>Tm</b>	Tm <sub>2</sub> O <sub>3</sub>	<b>Thulium</b>	X-ray source in portable X-ray machines.
		<b>Yb</b>	Yb <sub>2</sub> O <sub>3</sub>	<b>Ytterbium</b>	Practical values presently unknown. Research.
	<b>Lu</b>	Lu <sub>2</sub> O <sub>3</sub>	<b>Lutetium</b>	Deoxidiser in stainless steel production, rechargeable batteries, medical uses, red phosphors for colour television, superconductors.	
	<b>Y</b>	Y <sub>2</sub> O <sub>3</sub>	<b>Yttrium</b>	Deoxidiser in stainless steel production, rechargeable batteries, medical uses, red phosphors for TV.	
	<b>Hf</b>	HfO <sub>2</sub>	<b>Hafnium</b>	Hafnium is used in filaments, electrodes, and semiconductor fabrication processes for circuits	

*Acronyms used throughout this press release are defined below:*

**REE** rare earth elements, lanthanum to lutetium by atomic weight plus yttrium

**LREE** light rare earth elements, lanthanum to samarium by atomic weight

**HREE** heavy rare earth elements, europium to lutetium plus yttrium

**TREO** rare earth elements, calculated as oxides, including lanthanum to lutetium plus yttrium

**HREO** heavy rare earth elements, as per HREE above, calculated as oxides

**LREO** light rare earth elements, as per LREE above, calculated as oxides



# Kimberlite Pipe

Kimberlite Sample rich in Olivine



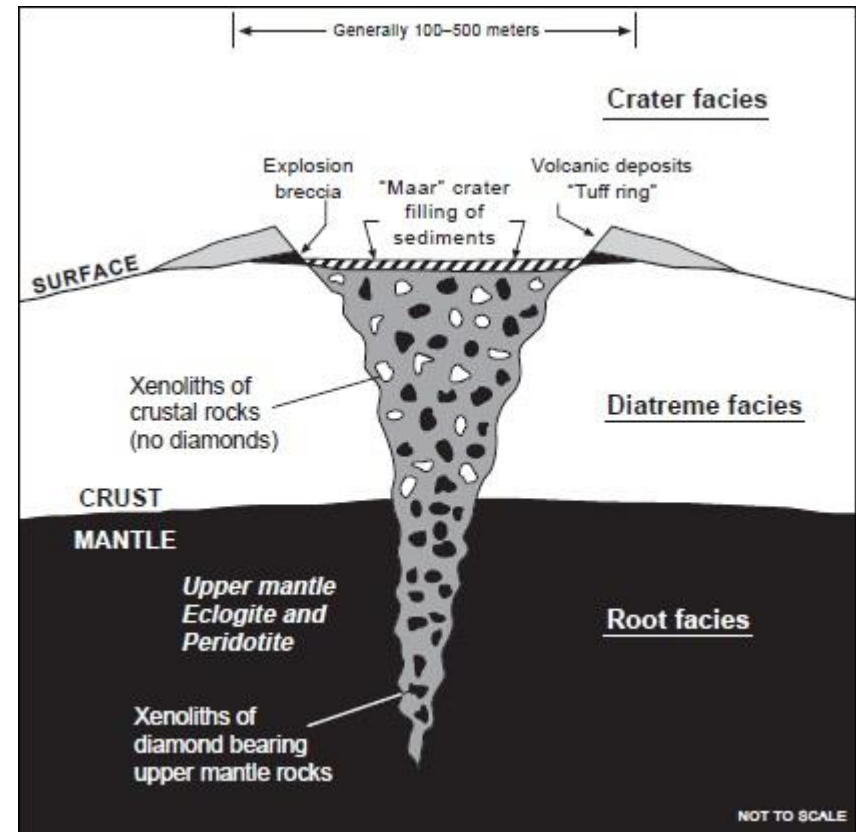
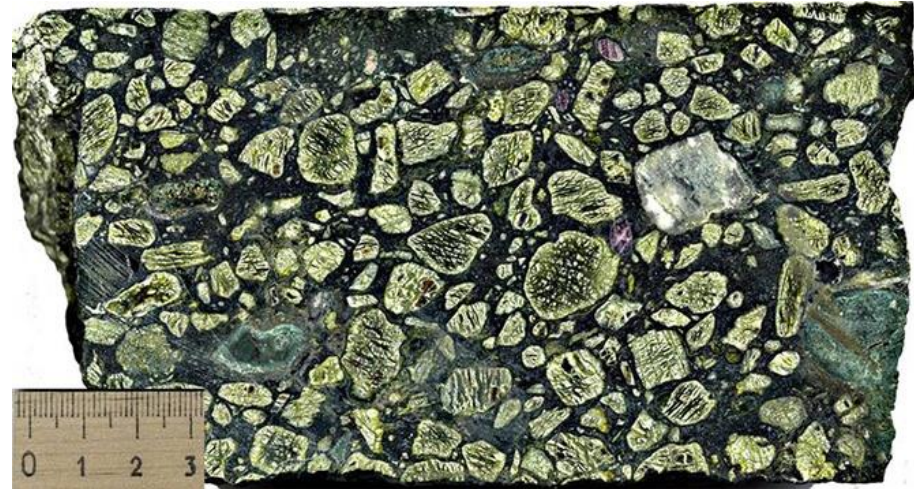


## VII. Kimberlites

Kimberlites are derived from the Earth's mantle at more than 140km depth. They are petrographically variable rocks comprise strongly altered breccias and tuffs.

Basically, Kimberlites are porphyric,  $\text{SiO}_2$ -undersaturated, K-rich (1–3 wt.%  $\text{K}_2\text{O}$ ) peridotites with xenoliths, and xenocrysts of diamond and olivine in a carbonated and serpentinized groundmass.

Kimberlites are chaotic mixtures of xenoliths of crustal rocks and mantle minerals released from the xenolith crumbling during eruption, phenocryst minerals, alteration minerals of these previous phases such as serpentine, and pieces of preexisting kimberlite. Kimberlite is a hybrid rock, which does not consider a true representation of melt composition.

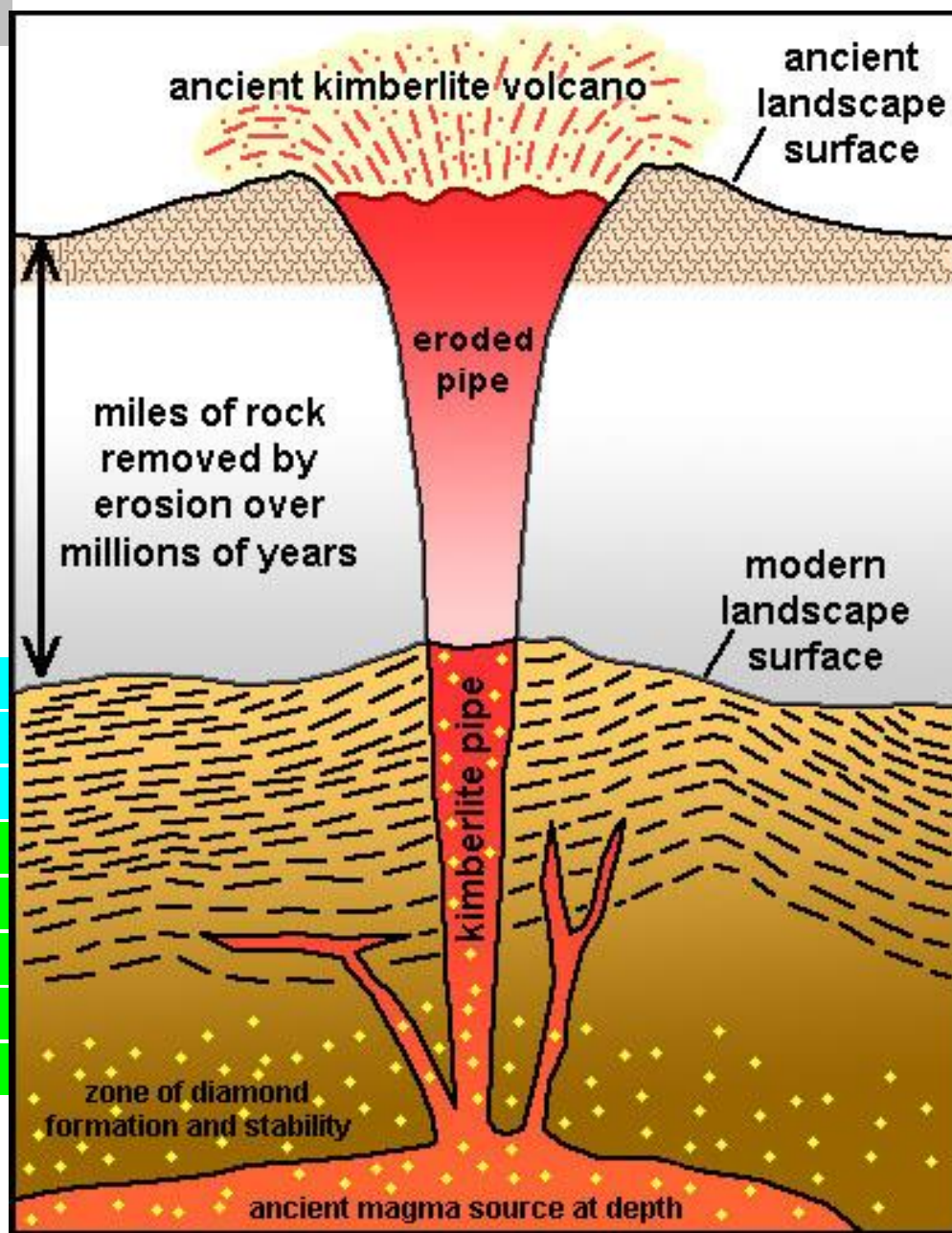


Kimberlite Pipe (diatreme)



**Diamonds** are formed under hot and high pressure conditions. Physical and chemical conditions where diamonds form only exist in the **mantle**. In the upper mantle, diamonds may be a common mineral!

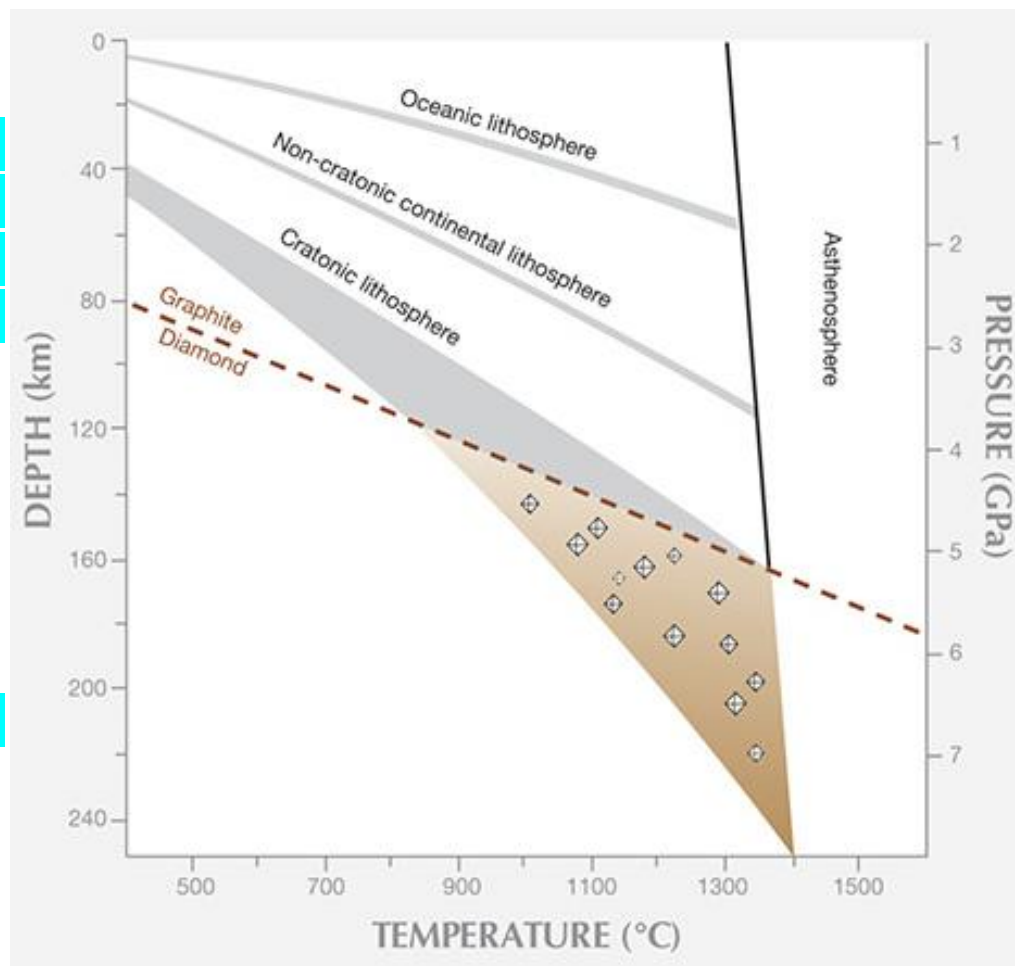
**Diamond** is associated with volcanic features called **diatremes**. A diatreme is a **long, vertical pipe** formed when **gas-filled magma** forces its way through the crust to explosively erupt at the surface. **Kimberlite** is a special kind of igneous rock associated with some diatremes that sometimes contain diamonds. **Diamonds** are **xenoliths** carried up from deep sources in the mantle, and often occur in association with other gem minerals including **garnet, spinel and diopside** inside the kimberlite. They are most extensively mined from Kimberlite pipes or from alluvial gravels derived downstream from diamond source areas.



**Diamond-bearing Kimberlite pipes are diatremes that originate in the mantle.**

Whenever **carbon** occurs as a free species, **diamonds** have the potential to form. **Diamonds** are stable under the high pressure and temperature conditions that are only met at great depth in the earth's mantle.

**Continental regions** that long ago ceased participating in active plate tectonic processes such as *rifting, mountain building, or subduction* are known as **continental cratons** and has the *Archean age*. **Diamonds** always occur within the Cratons, especially those hosting *Kimberlite*, the main carrier and hence “ore” of gem-quality diamond. Withering of *Kimberlite*, releases the diamonds to the *regolith*. When transported by rivers, the *alluvial diamonds* are concentrated in the *placer*.



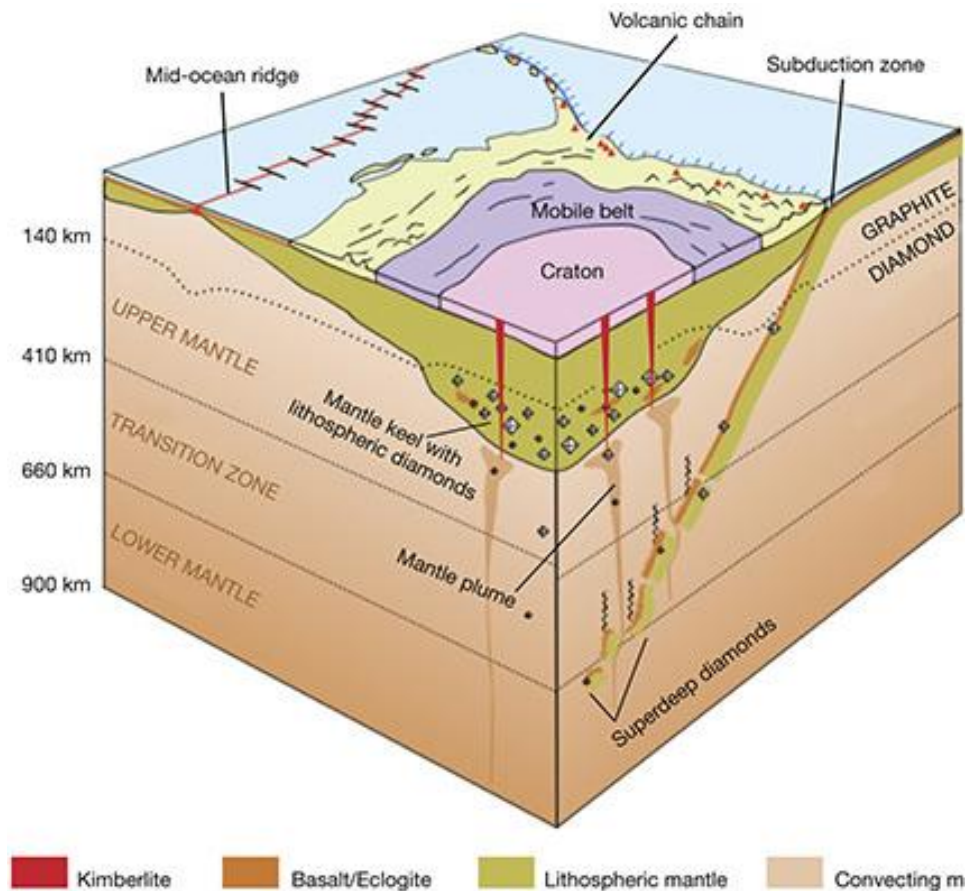
This phase diagram depicts the stability fields of graphite and diamond in relation to the convecting mantle (asthenosphere) and the lithospheric mantle. Note that only the cratonic lithospheric keel is cold enough at high enough pressures to retain diamonds.

Economically important kimberlites appear to be localized in regions underlain by portions of the cratons which are older than 2.4 Ga. These include the diamond-bearing kimberlites of Africa (Angola, Botswana, Lesotho, Sierra Leone, South Africa, Swaziland, Tanzania), Russia (Yakutia), Australia (Western Australia), and the recently discovered kimberlite pipes in Canada (NWT). Kimberlites are also believed to be the ultimate source of diamonds found in placer deposits, which have supplied about 90% of the world's diamond output. Some kimberlites are non-diamondiferous either because the magma was generated outside the P-T stability field of diamond or because the magma never picked up any diamond xenocryst due to the non-uniform distribution of diamonds in the upper mantle.



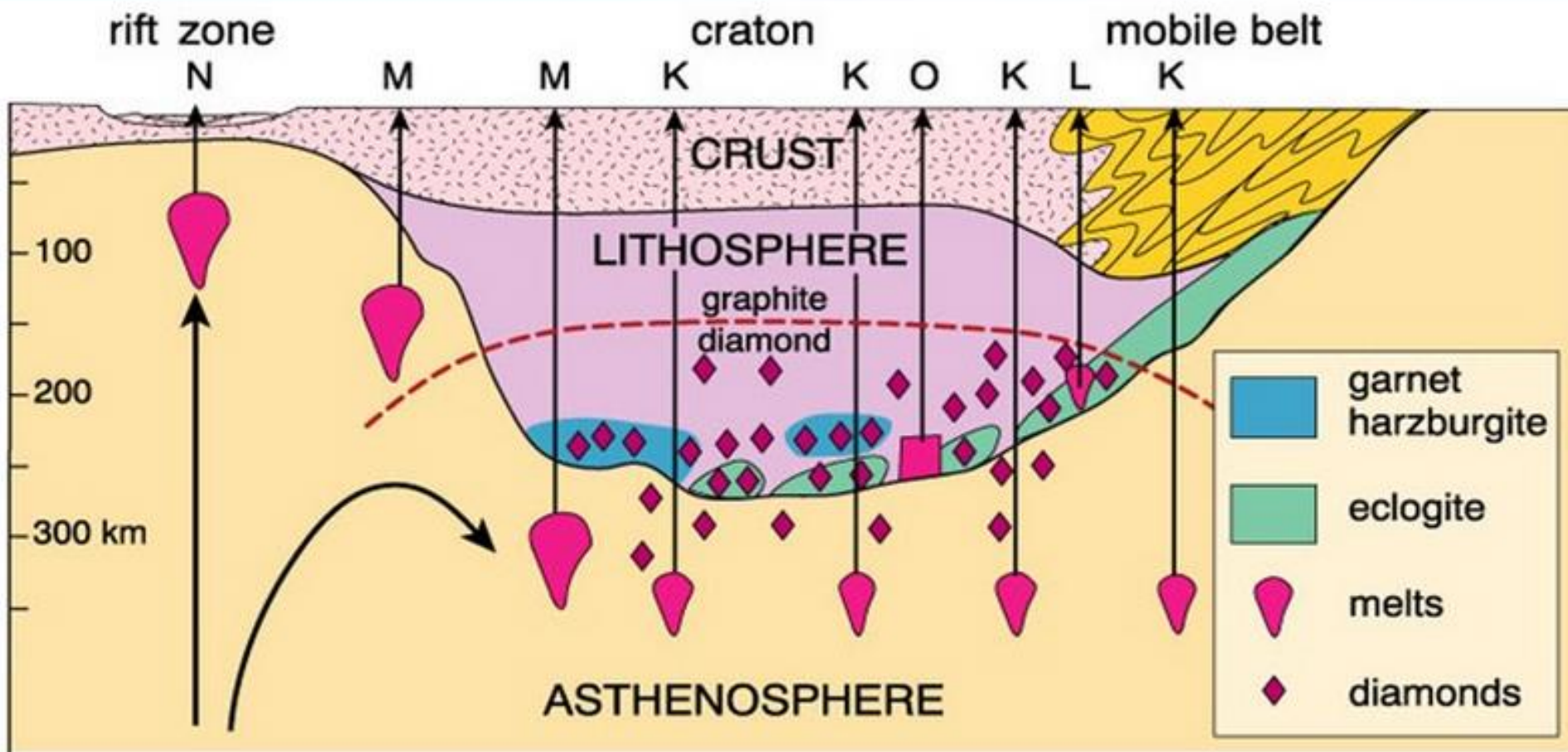
## VIII. Diamonds in tectonically stable environment (Mantle keel beneath craton)

The mantle keel under each craton is at high enough **pressure** and comparatively low temperature to **allow diamonds to crystallize whenever they receive fluids saturated in carbon** from the underlying convecting mantle. **The keel bottom can be viewed as an “ice box” to store diamonds and keep them from entering mantle circulation, to be sampled by a rising Kimberlite magma (the Phenocryst model).** The **Kimberlite** eruptions that transport diamonds to the surface also carry samples of lithospheric mantle rocks called **xenoliths**. **Both peridotite and eclogite contain diamonds, but intact peridotites subducted to the surface – ophiolites - with their diamonds are rare, while eclogites (high pressure metamorphosed basalt/gabbro) with their diamonds in place are common.**



The relationship between a continental craton, its lithospheric mantle keel (the thick portion of the lithospheric mantle under the craton), and diamond stability regions in the keel and the convecting mantle. Under the right conditions of low oxidation, diamonds can form in the convecting mantle, the subducting slab, and the mantle keel.

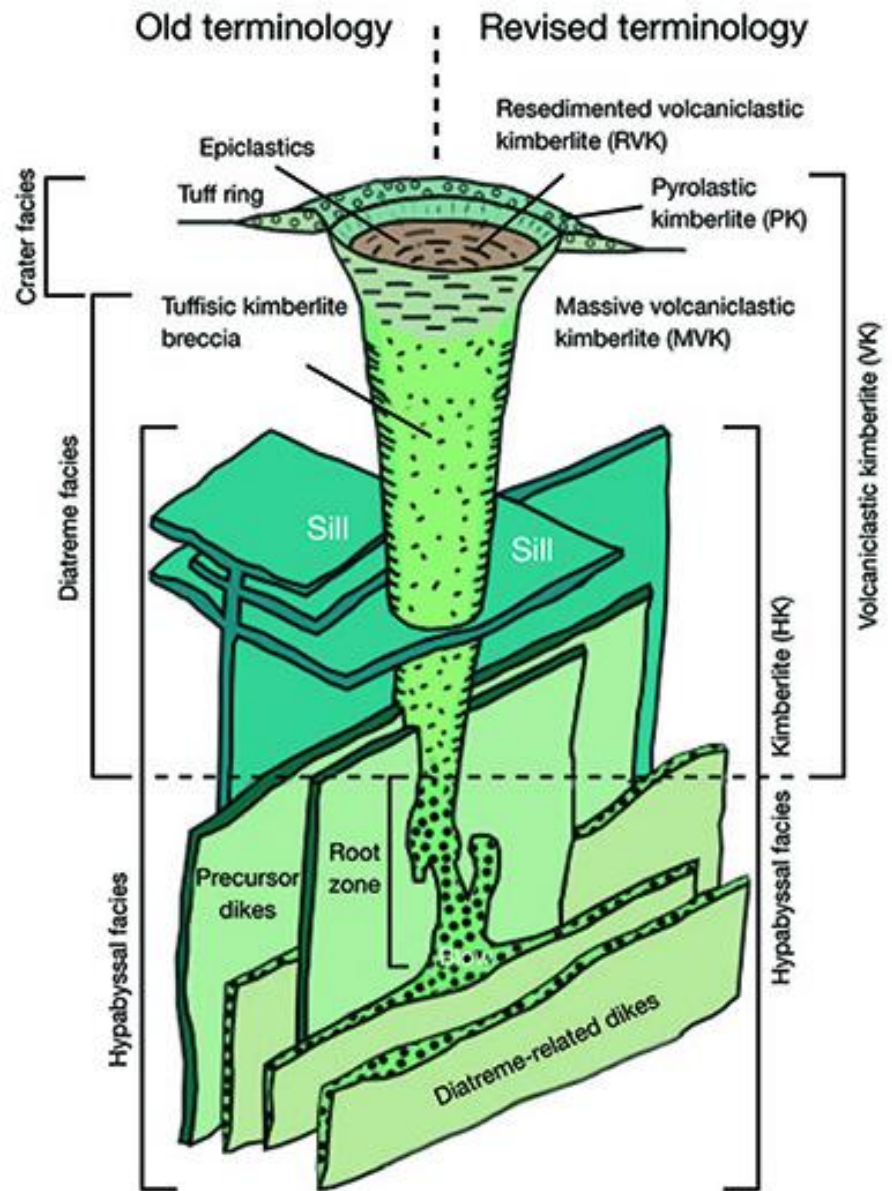
# Kimberlites



**Figure 19-20b.** Hypothetical cross section of an Archean craton with an extinct ancient mobile belt (once associated with subduction) and a young rift. The low cratonal geotherm causes the graphite-diamond transition to rise in the central portion. Lithospheric diamonds therefore occur only in the peridotites and eclogites of the deep cratonal root, where they are then incorporated by rising magmas (mostly kimberlitic- "K"). Lithospheric orangeites ("O") and some lamproites ("L") may also scavenge diamonds. Melilitites ("M") are generated by more extensive partial melting of the asthenosphere. Depending on the depth of segregation they may contain diamonds. Nephelinites ("N") and associated carbonatites develop from extensive partial melting at shallow depths in rift areas. After Mitchell (1995) *Kimberlites, Orangeites, and Related Rocks*. Plenum, New York. Winter (2001) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

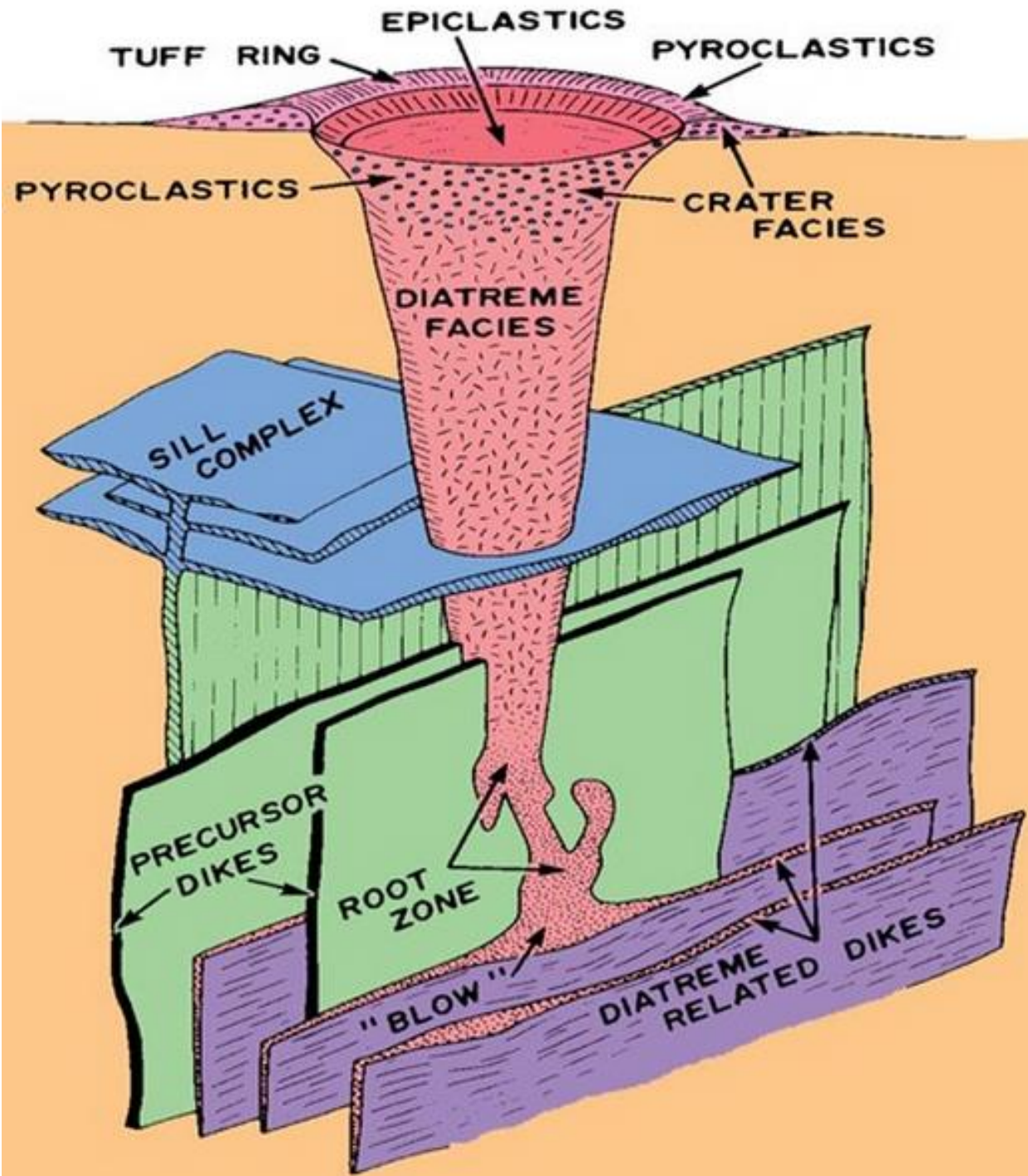


A kimberlite magma can start at depths as great as 200–300 km, but must be generated at least below the depths where diamonds are stable (greater than 140 km) in order to pick them up from their lithospheric source. The kimberlite magma propagates upward through the lithosphere by hydraulically fracturing the overlying rock. It moves at relatively high velocity (4 to 20 m/sec). The evolution of the kimberlite magma from its deep mantle source is associated with changing the magma composition (siliceous or carbonaceous), and gaseous contents ( $H_2O+CO_2$ ). Kimberlites occur most frequently in sub-volcanic pipes and occasionally in sills and dykes.



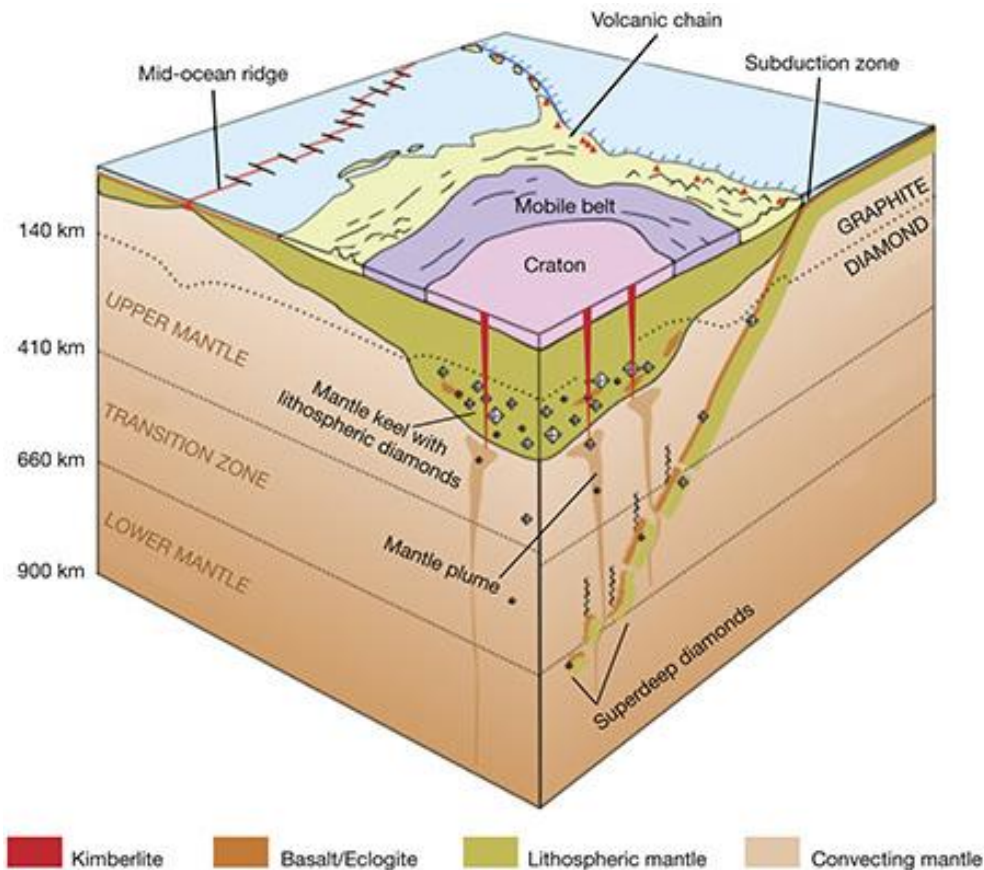
A kimberlite pipe shows dikes and sills related to different levels of intrusion of kimberlitic magma and the kimberlite types exposed at different levels. Examples of shallower pyroclastic kimberlite (erupted into the air) versus deeper or hypabyssal kimberlite (crystallized several kilometers below the earth's surface).



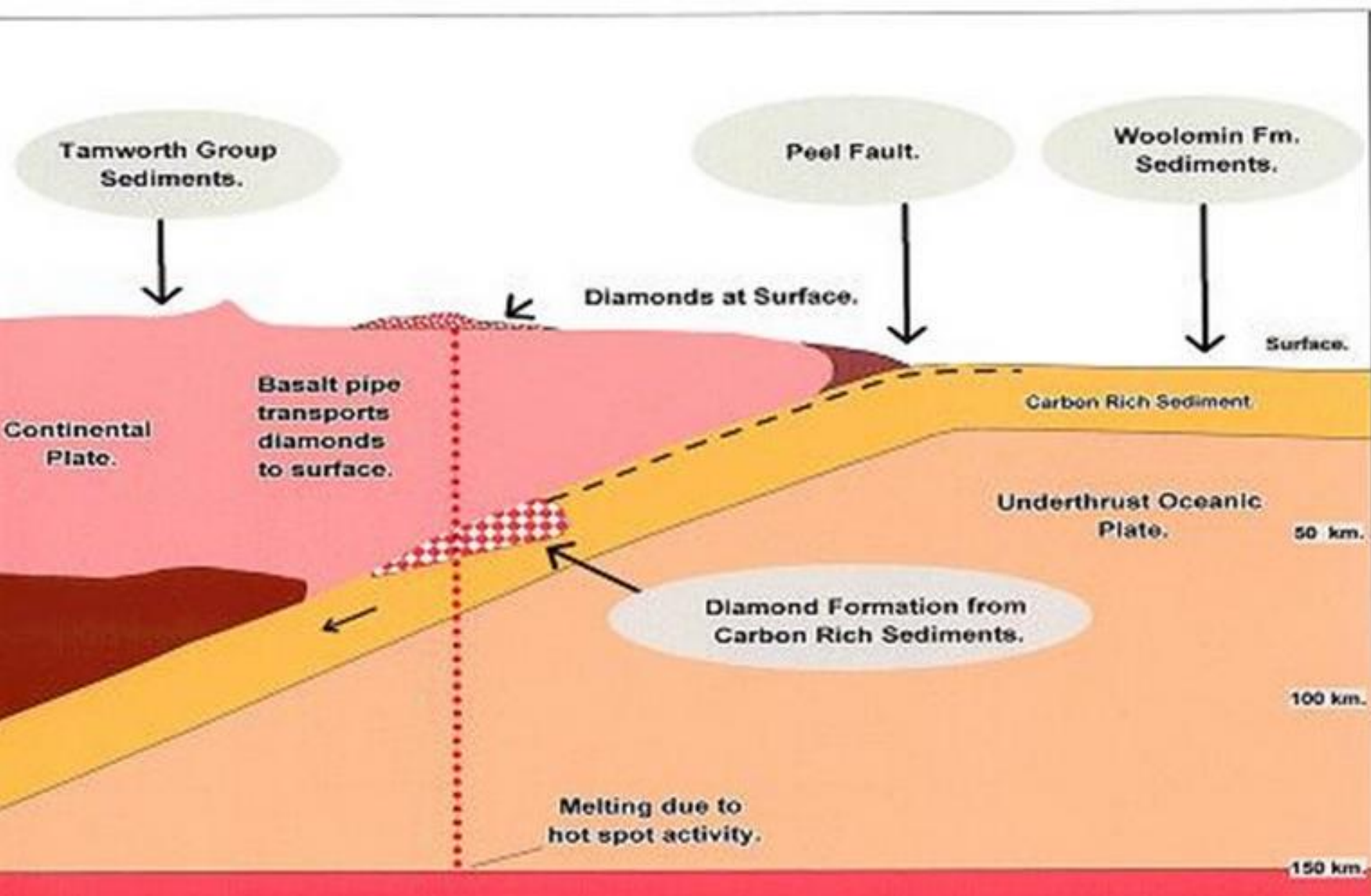


## IX. Diamond at tectonically unstable environment

Diamond is destroyed in the volcanism, mountain-building, and intrusive magmatism near the earth's surface, where pressures, temperatures, and oxidizing conditions are not suitable for diamond to crystallize or remain stable. However, diamonds can be found in non-kimberlitic rocks formed in tectonic areas that were once active. Subduction-related (non-kimberlitic) magma type can carry diamonds from the mantle. Late-stage subduction-related magma can produce a rock called a lamprophyre and lamproite as dikes carrying diamonds.



# SUBDUCTION DIAMOND MODEL





## X. Magmas Carrying Diamonds

**Diamonds** are known to be carried to the earth's surface in only three rare types of magmas: **kimberlite, lamproite, and lamprophyre**. Of the three types, kimberlites are by far the most important, with several hundred diamondiferous kimberlites known. In general, all three magma types are: (1) derived by small amounts of melting deep within the mantle; (2) relatively high in volatile (H<sub>2</sub>O, CO<sub>2</sub>, F, or Cl) contents; (3) MgO-rich; (4) marked by rapid eruption; and (5) less oxidizing than more common basaltic magma.

**TABLE 2.** Characteristics of known diamond-carrying magmas.

Characteristic	Kimberlite	Lamproite	Lamprophyre
Color of rock in outcrop	Green, dark bluish green	Dark gray, black	Dark gray, black
Volatiles	CO <sub>2</sub> >H <sub>2</sub> O, halogens (Cl, F)	H <sub>2</sub> O>CO <sub>2</sub> , halogens	H <sub>2</sub> O>CO <sub>2</sub> , halogens
Composition	Not peralkaline, hybrid, K <sub>2</sub> O>Na <sub>2</sub> O	Peralkaline, hybrid to magmatic	Peralkaline, magmatic
Setting	Cratonic	Mobile belt, craton margin	Subduction zone
Depth of origin	200–300 km mantle, can be sourced >400–700 km	>140 km, but probably not much deeper	>140 km, but probably not much deeper
Eruptive style	Explosive volcanic pipes, pyroclastic	Small volcanic pipes and cones	Dikes
Diagnostic phenocryst minerals	Olivine	Ti-phlogopite	Biotite, amphibole
Typical matrix mineralogy	Olivine, carbonate	Phlogopite	Feldspar
Diamond potential	Common, can range to high diamond grade	Rare, but can range to high diamond grade	Rare, few diamondiferous known

*Notes: A hybrid composition is one that is substantially modified by incorporation of early-crystallizing minerals, xenoliths, and pieces of country rock so that determining a real magmatic composition is difficult; magmatic composition can be directly related to its igneous source.*

## XI. Why Carbonatites do not carry Diamond?

The **diamond-bearing rocks** are distinguished from the related **carbonatites** by having an *igneous* carbonate mineral abundance of less than 50%. Experiments show that kimberlites and carbonatites can form a continuum—together in which carbonatites may beget kimberlites. **Carbonatites may be a ready source of diamond-forming fluids. But at the earth's surface, carbonatites are almost never diamond-bearing. The simple reason is that their carbon, i.e., the carbonatite carbon, is locked up in the carbonate mineral calcite (CaCO<sub>3</sub>), which simply has too much oxygen to allow carbon to exist in the elemental form needed to stabilize diamond.**

**End of Lecture**