Treasures from the deep earth

- Mineral deposits and their links to volcanoes

April 17th 2019

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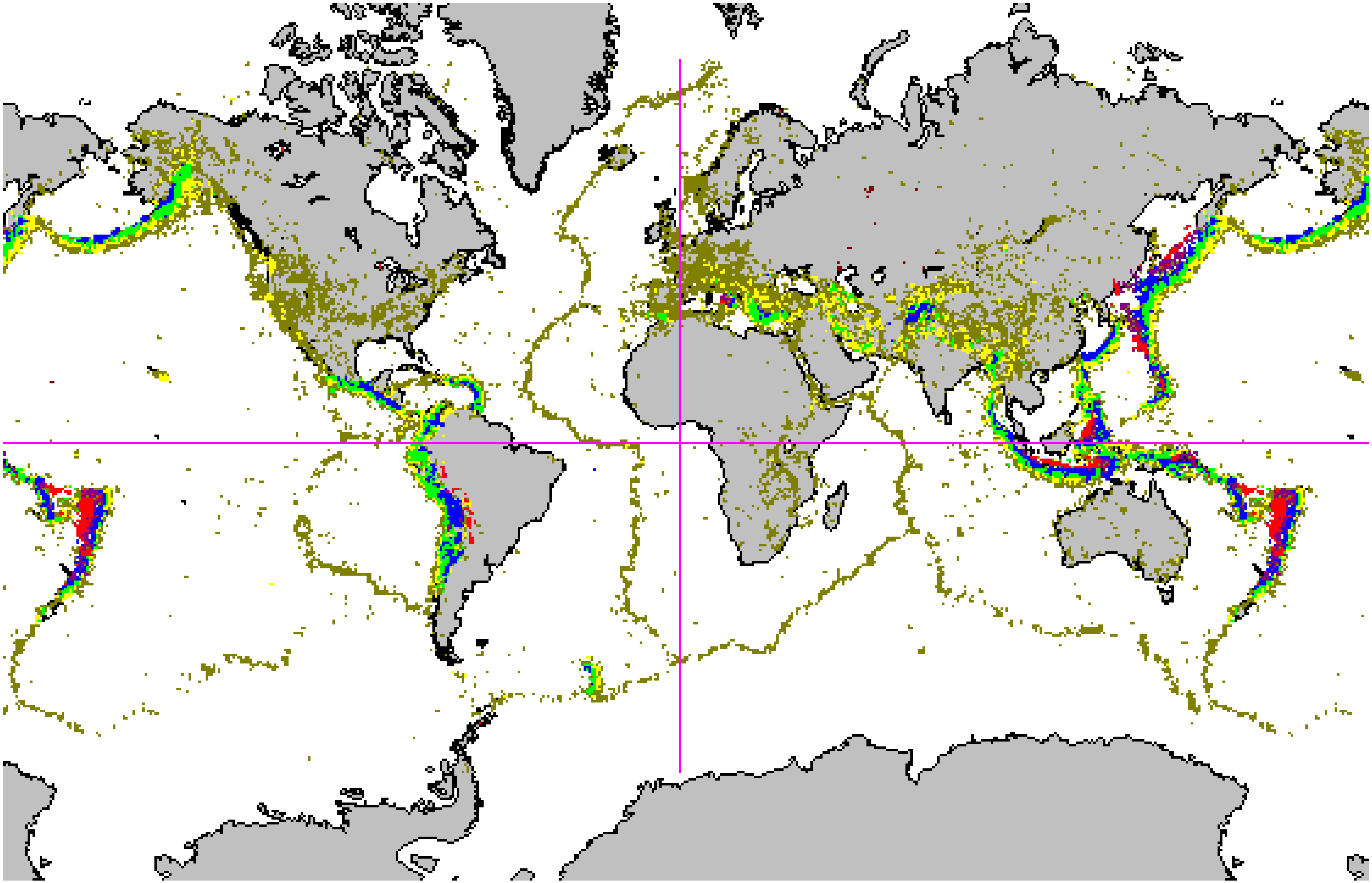
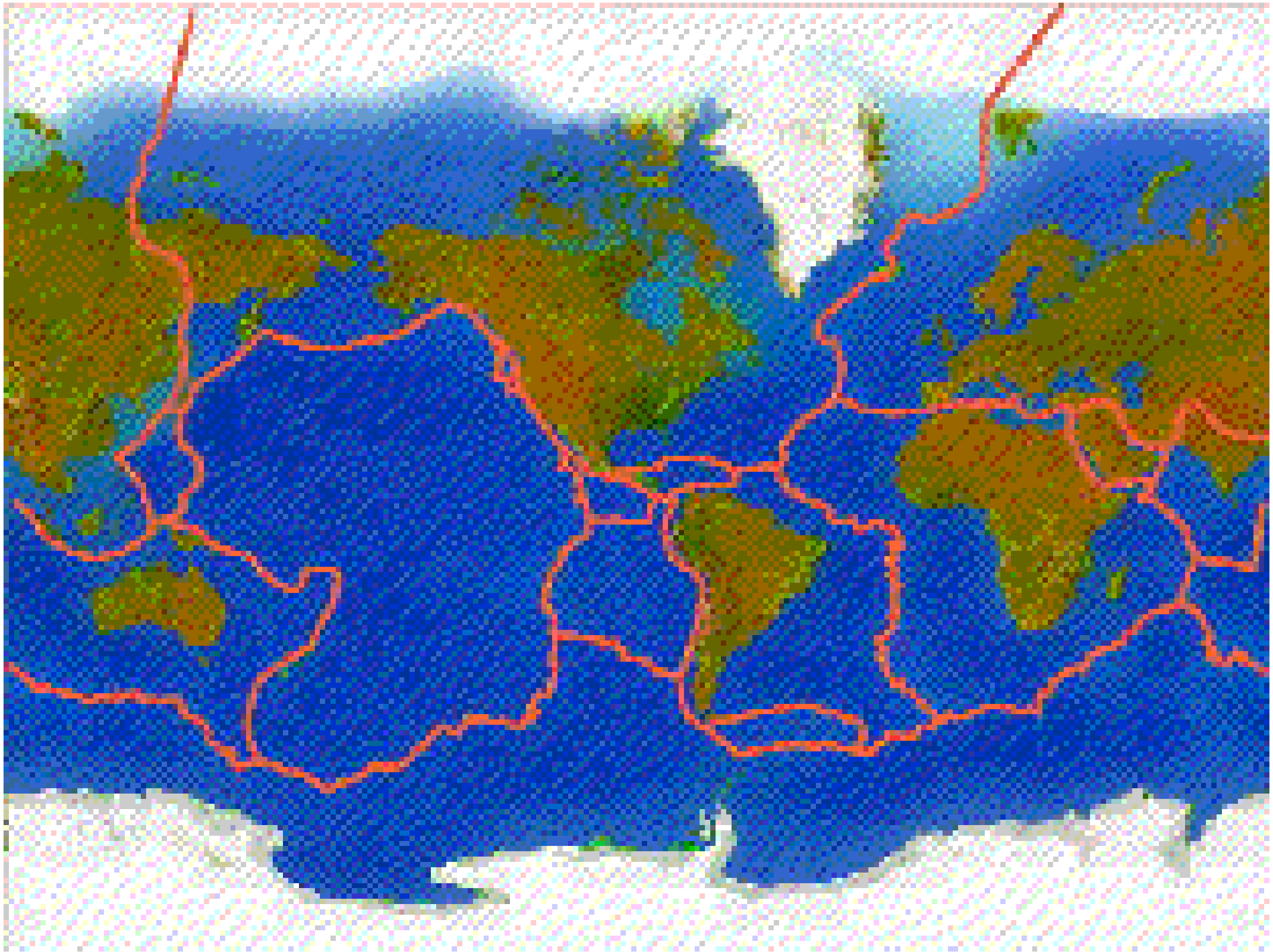
Thanks to Prof Sir Steve Sparks FRS and research colleagues…

Earth’s seismicity



The Earth’s tectonic plates



Volcanoes

- Cotopaxi Ecuador

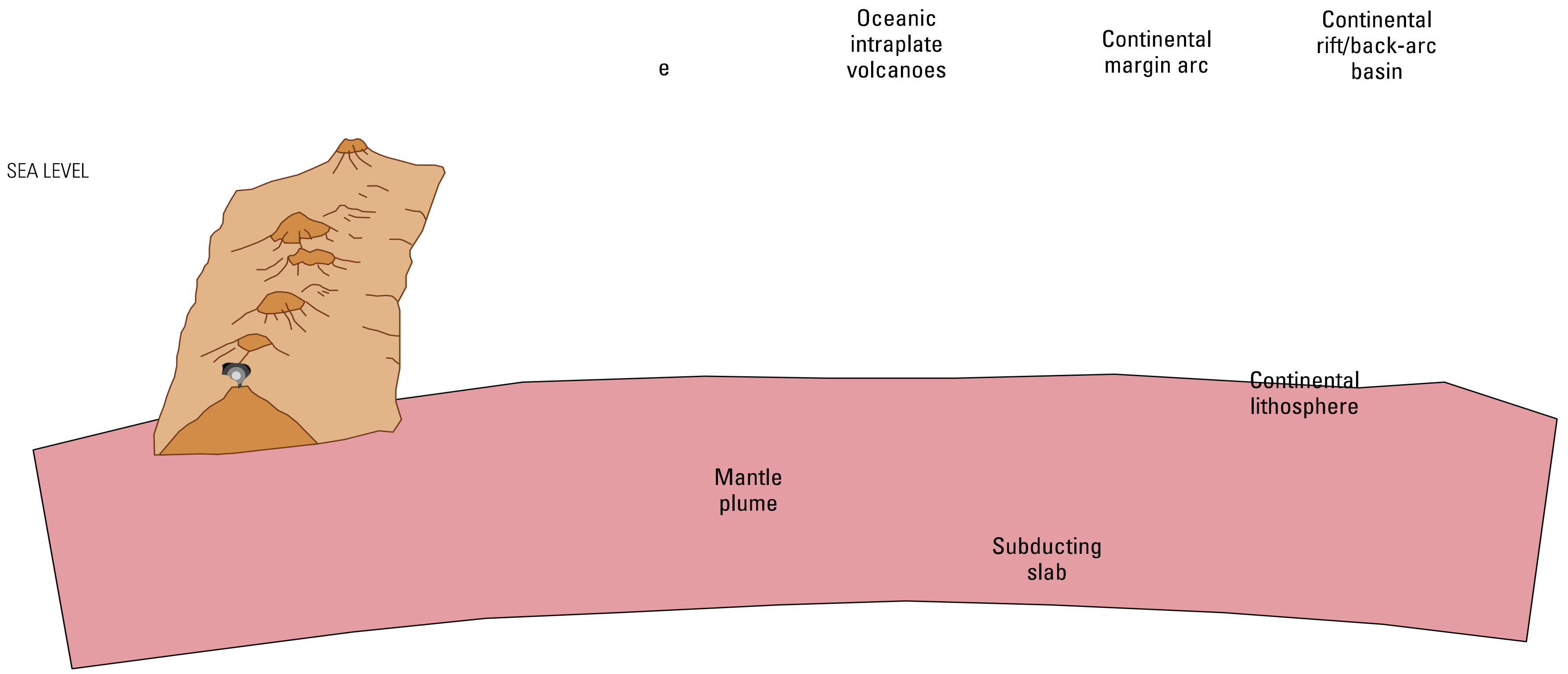
Fumaroles from volcanoes

- Solfatara vent site, Italy

Hotsprings associated with volcanoes

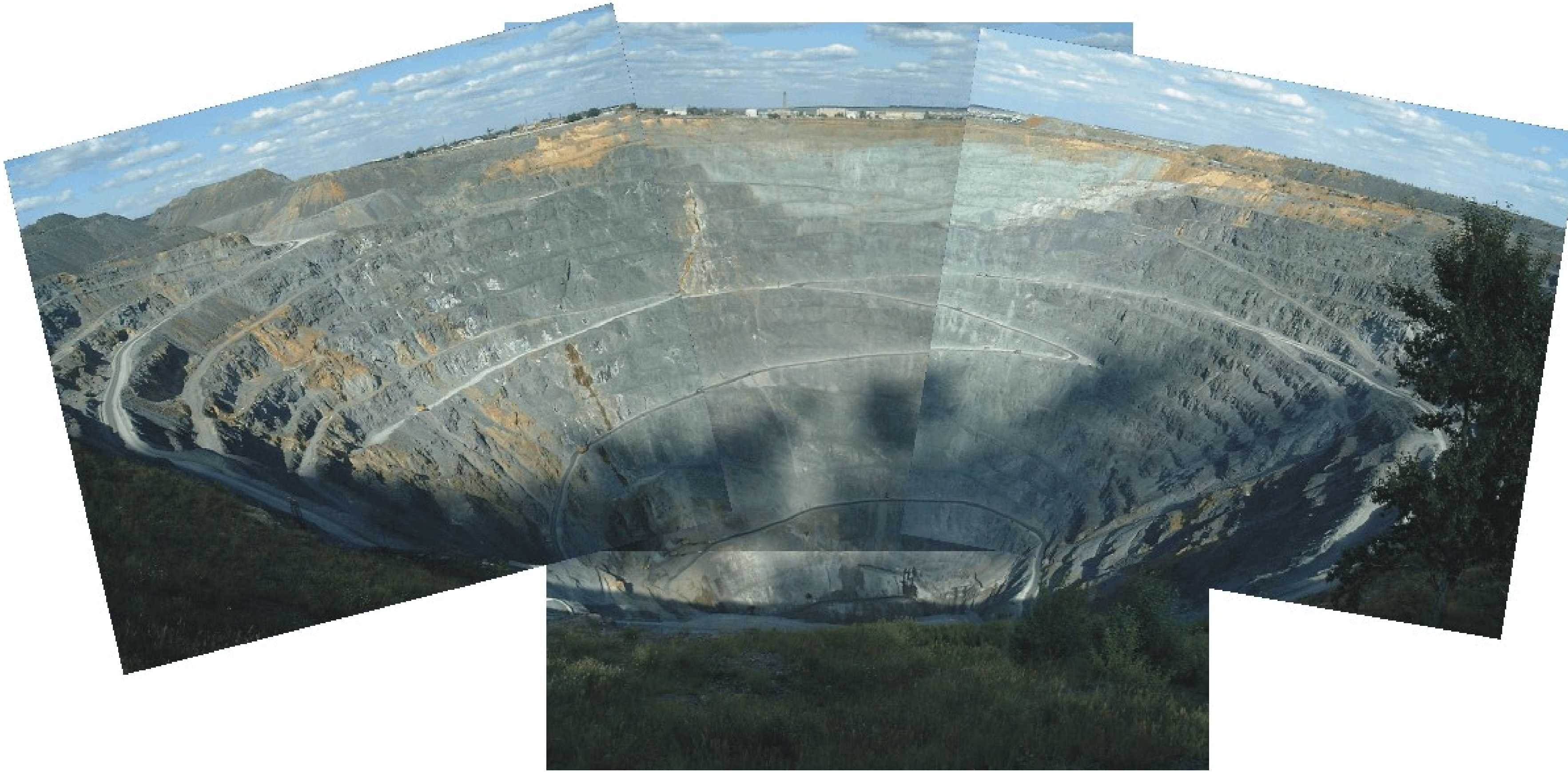
- North Island, New Zealand

Key tectonic settings for Earth's volcanoes



Shanks & Thurston 2012

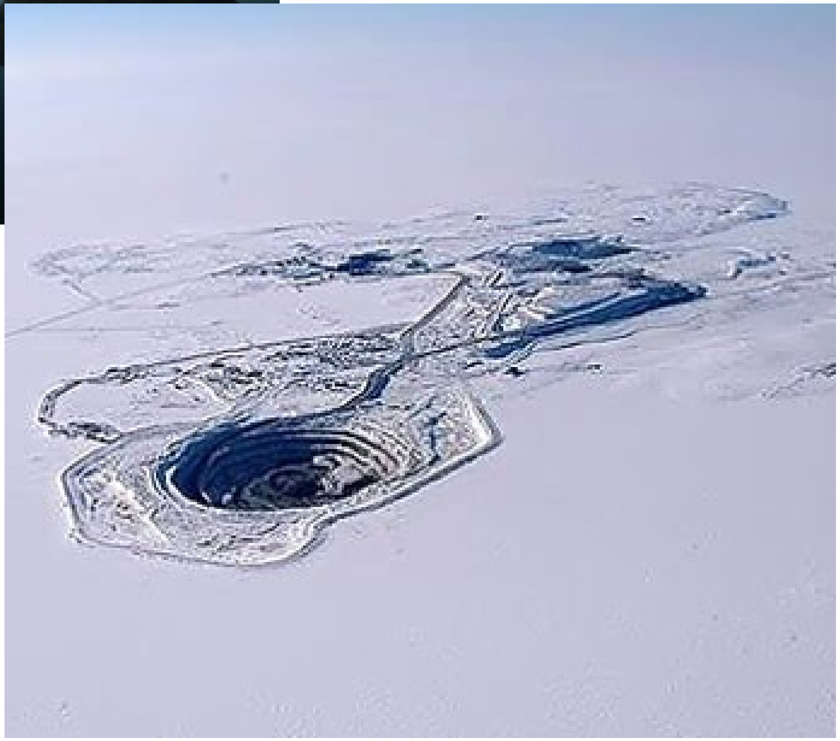
Sibay massive sulphide deposit, Urals



- 110 Mt @ 1.6% Cu, 0.4% Zn, 0.4g/t Au
- 470m deep open pit and underground working
- Output currently around 1.5 million tons ore per year


Chuquicamata porphyry Cu-Mo, Chile
• >Deposit contains > 2 Billion tonnes ore @ 0.7% Cu + Au
• 3 km long open pit, 400m deep
• Output currently around 350,000 tonnes of copper metal per year
Photo: CODELCO

Diavik diamond mine, Canada



- 39 million tonnes of kimberlite containing 95 million carats of diamond

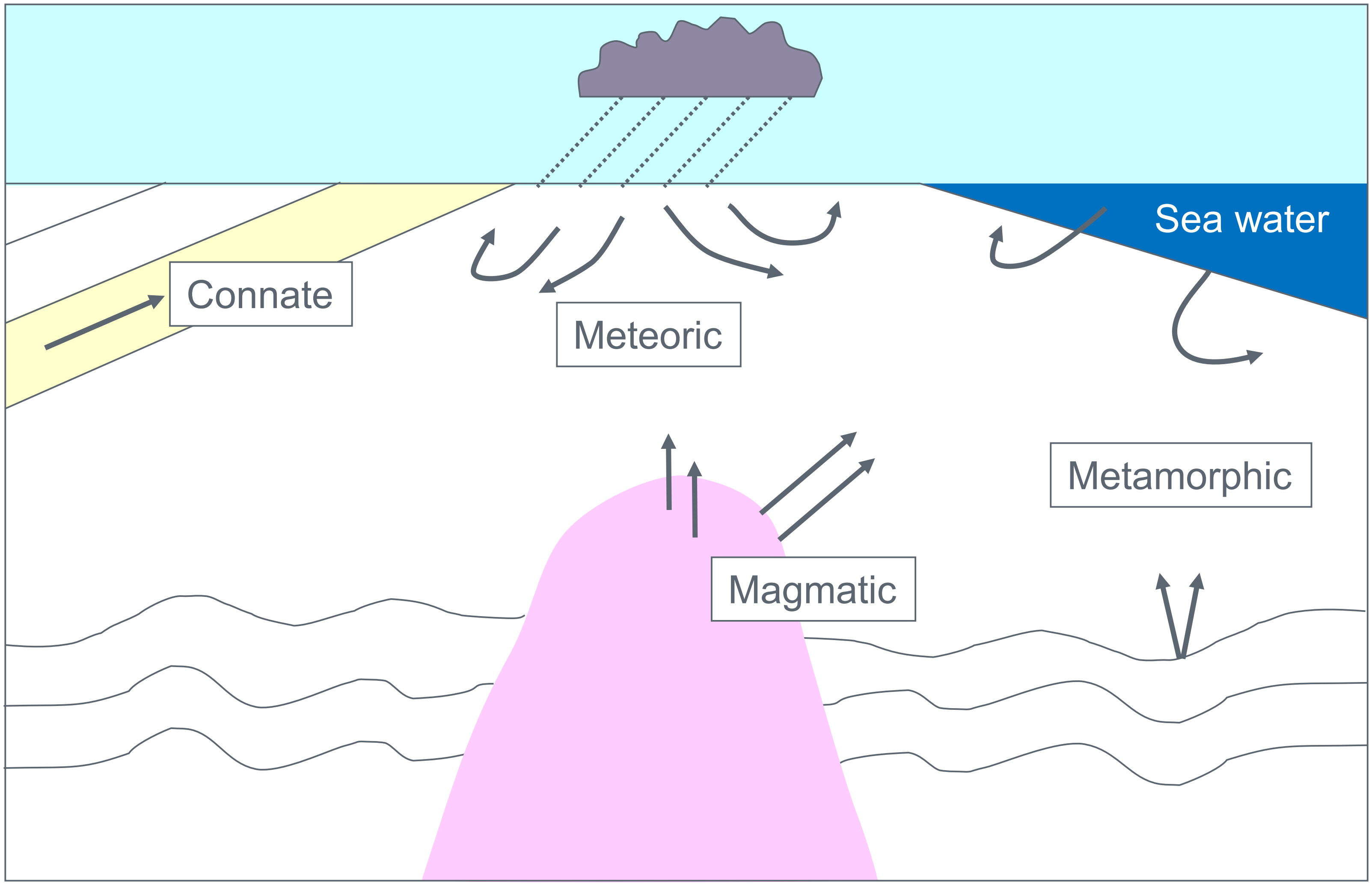
Photos: Rio Tinto

Kambalda Nickel Australia

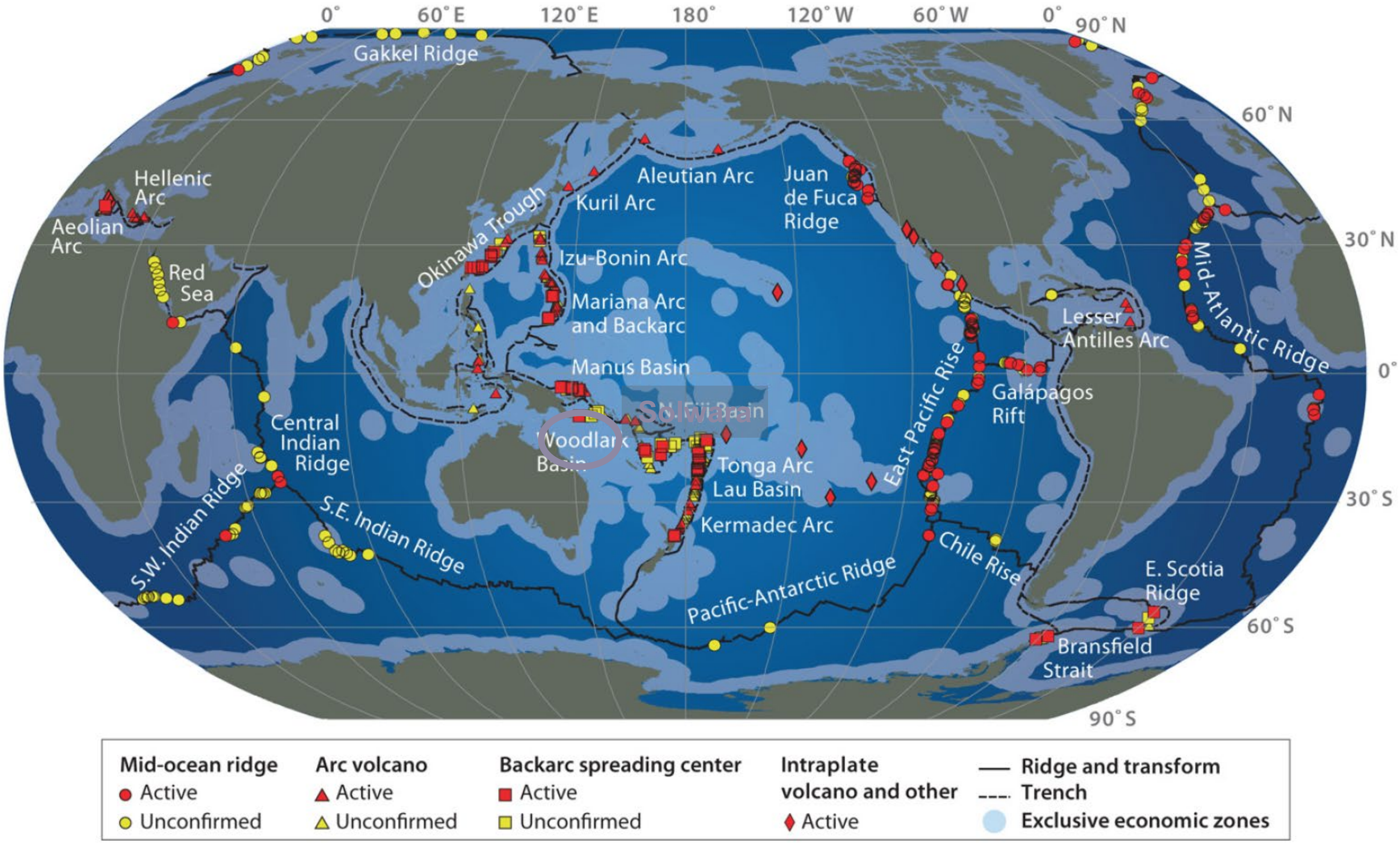
- Massive Ni-Cu sulphide ore Kambalda
- The region has resources of more than 90 million tonnes of ore at a grade of >2.5% Ni
- Related to Archean (2700 million year old) komatiite lava flows

Photos: CSIRO

Diverse water sources in the Earth's crust

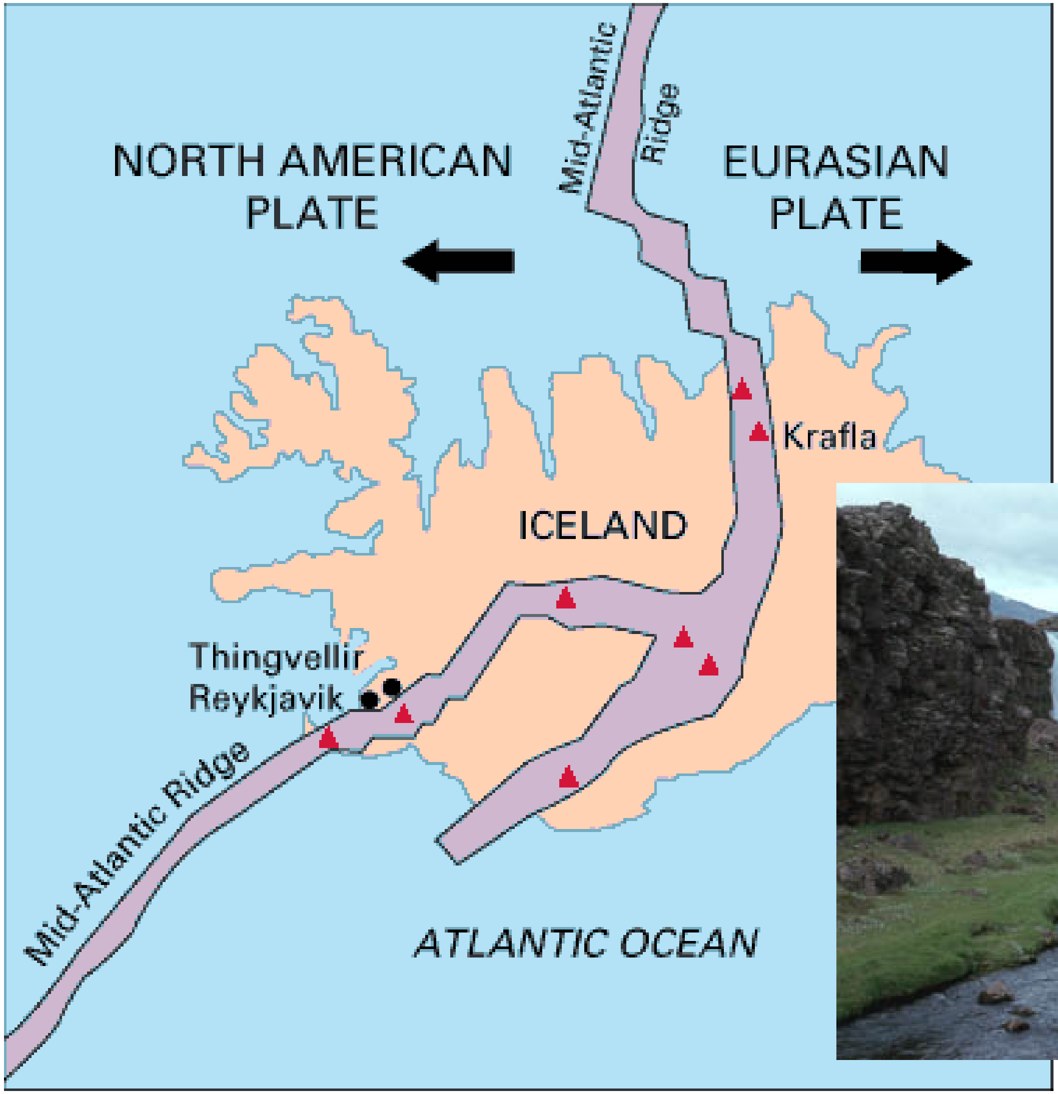


Seafloor high temperature vents



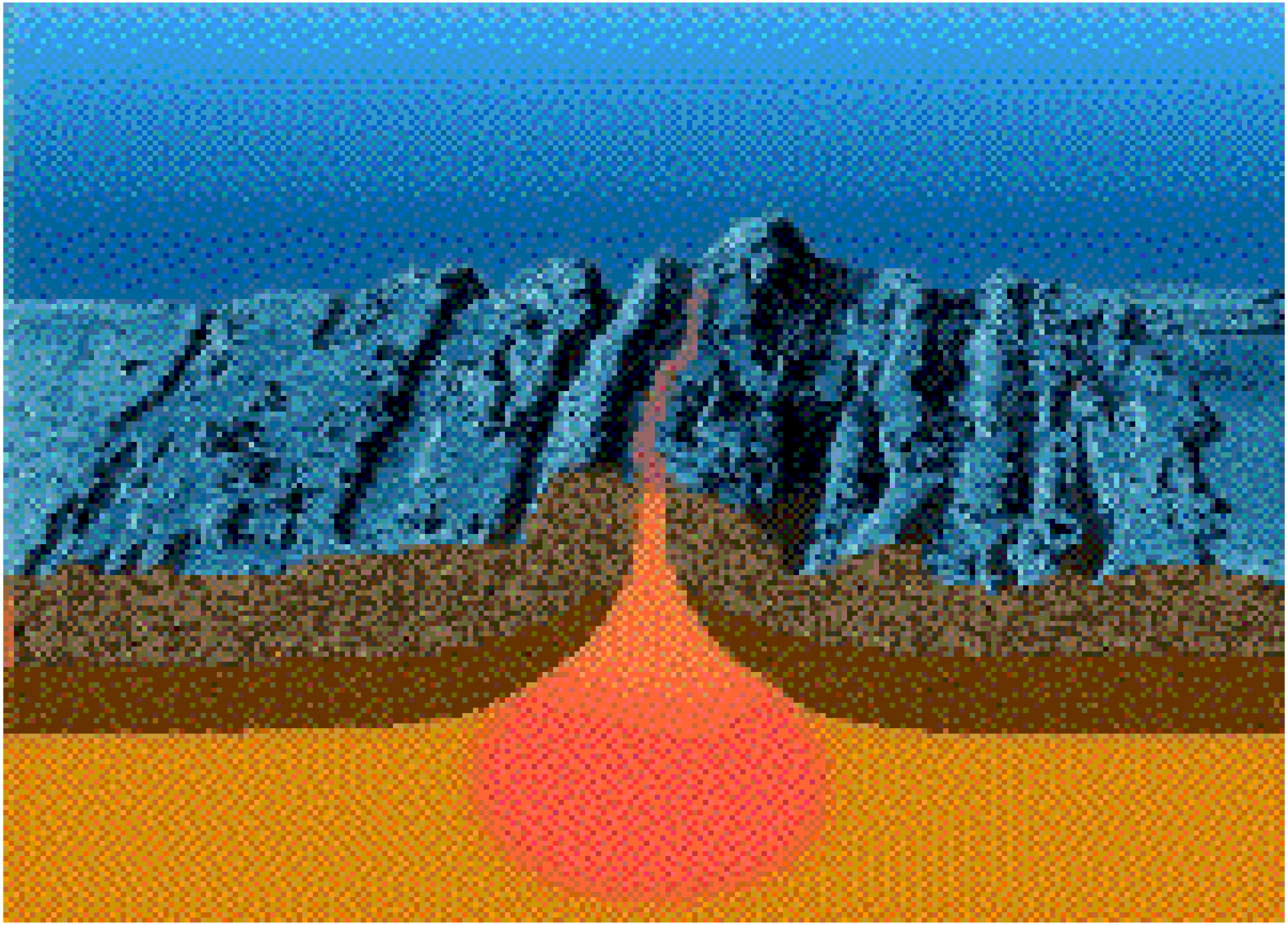
Hannington et al. 2011

Mid Atlantic Rift crosses Iceland



Thingvellir, Iceland

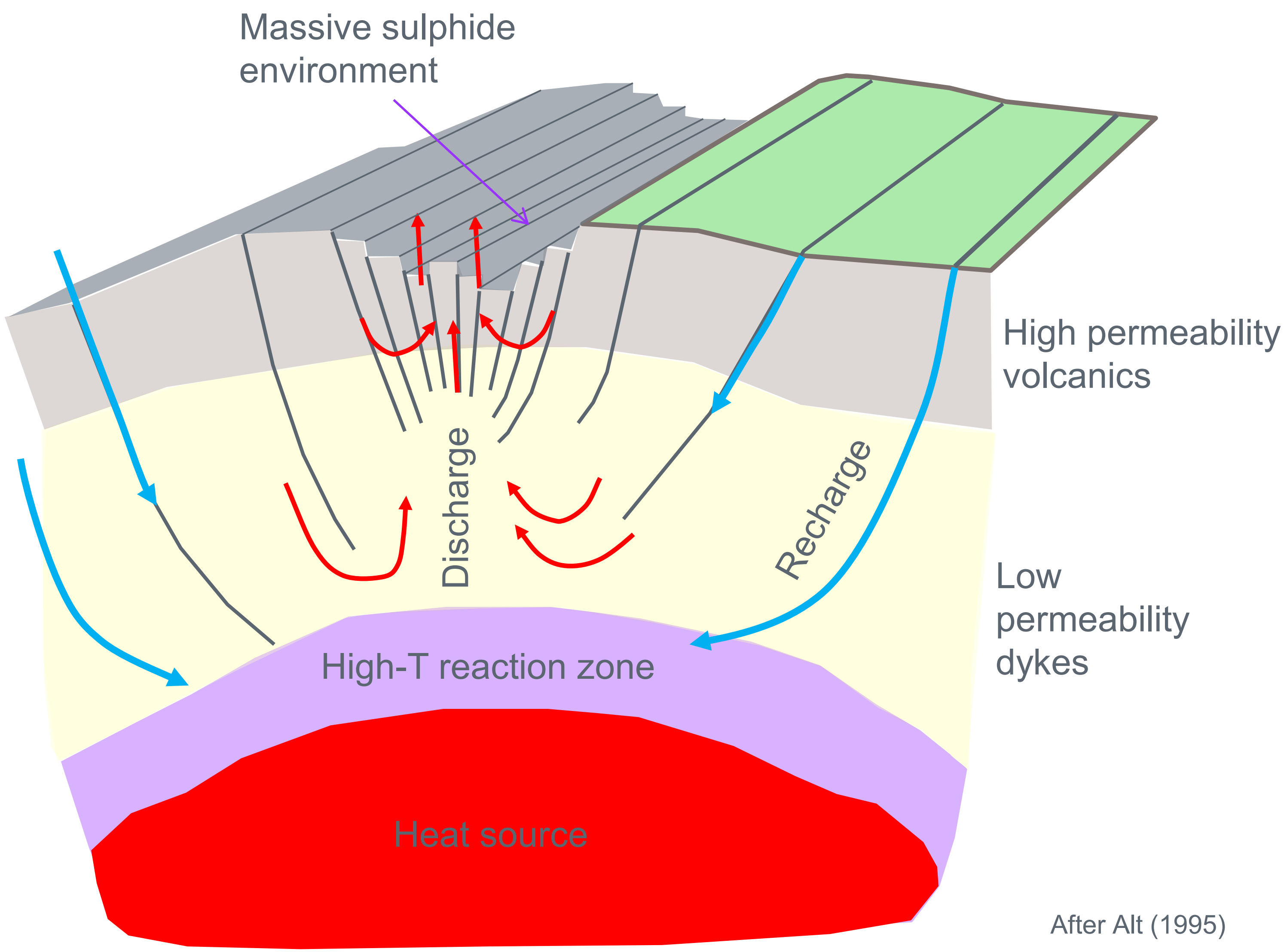
Seafloor spreading causes extension and volcanism



Underwater volcanoes

Pillow lavas forming under the ocean - Iceland

Extensional settings - sub-seafloor circulation of seawater



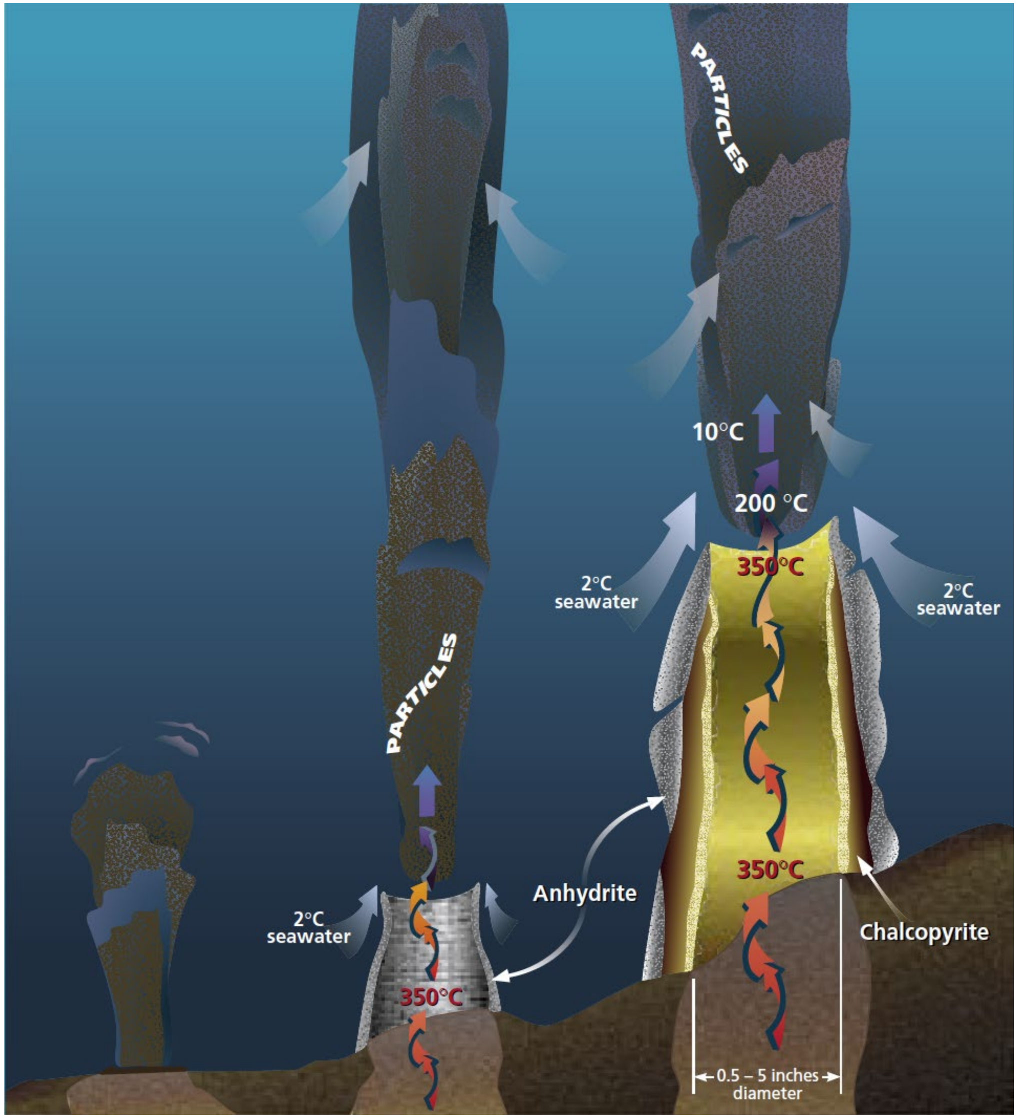
After Alt (1995)

Deep ocean black smokers

Black smoke = fine grained sulphide minerals

Deep ocean black smokers

Black smoker chimneys develop on the seafloor

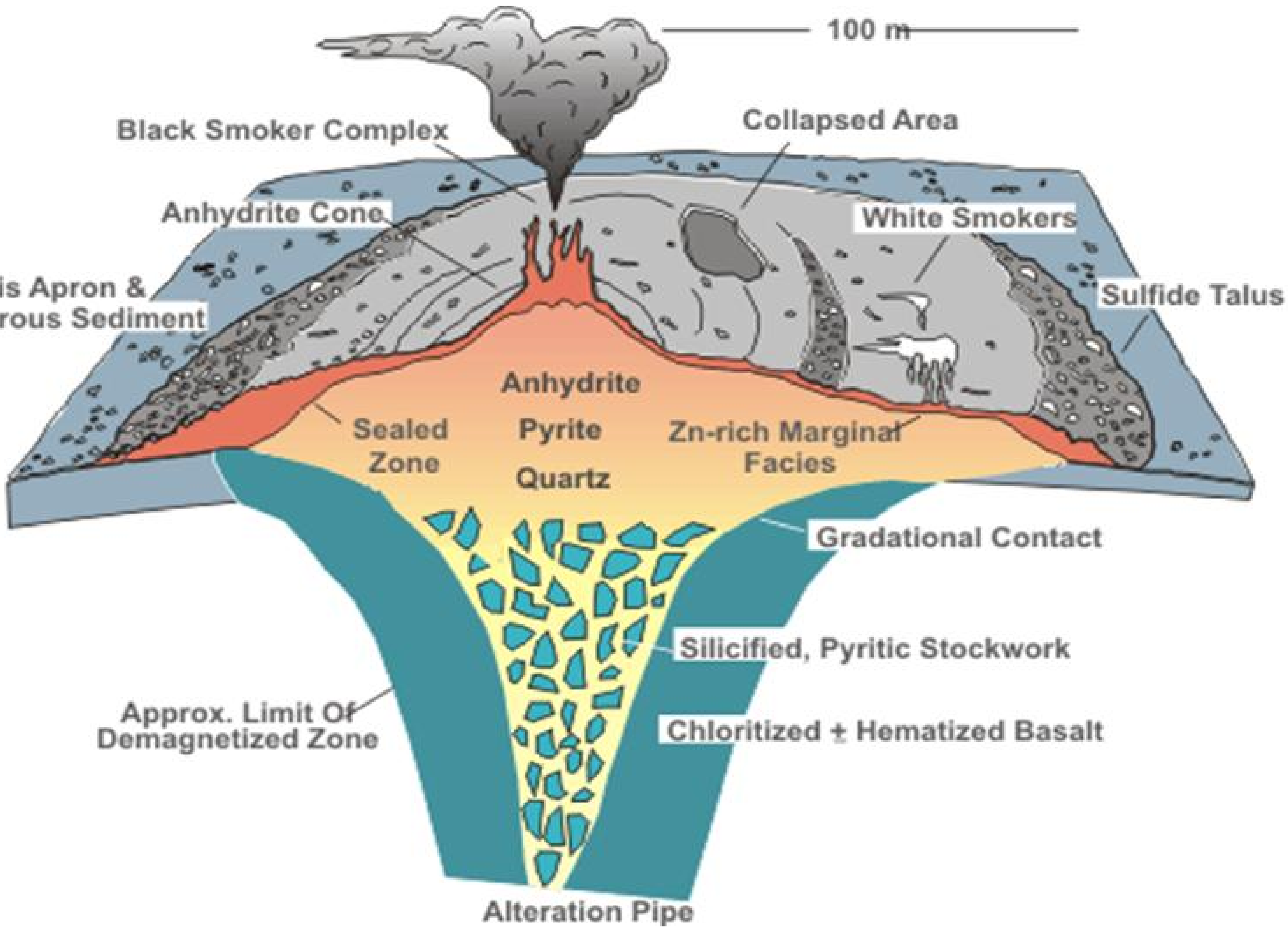


- High temperature heated seawater rises onto the seafloor at > 350° C
- Minerals including metal sulphides are zoned around the open core of the chimney

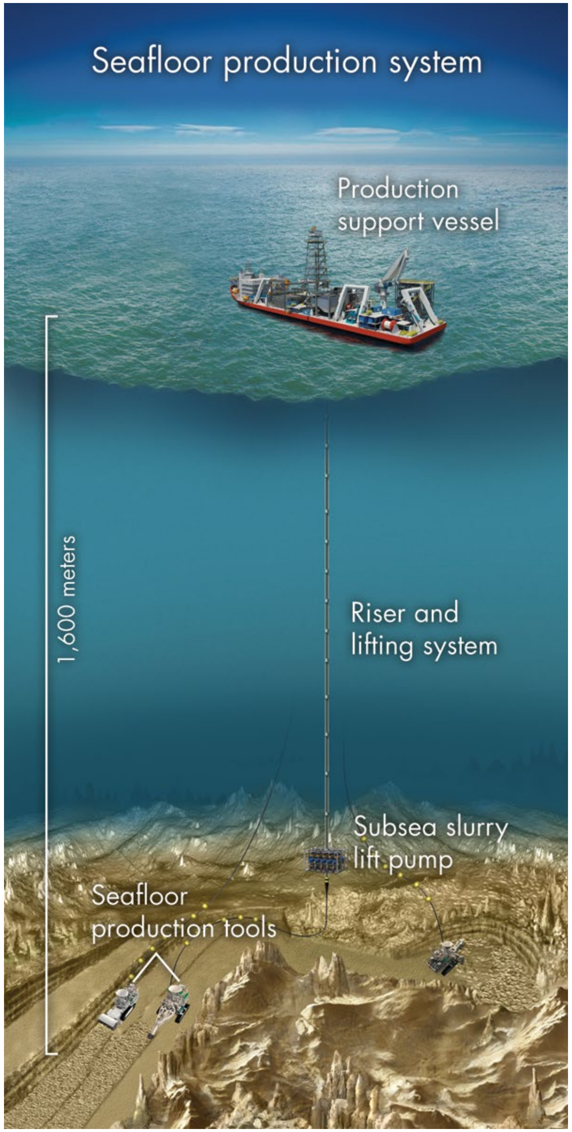
(after Meg Tivey)

Sulphide deposits drilled on the seafloor

Anatomy of the sulphide deposits – TAG – Mid Atlantic

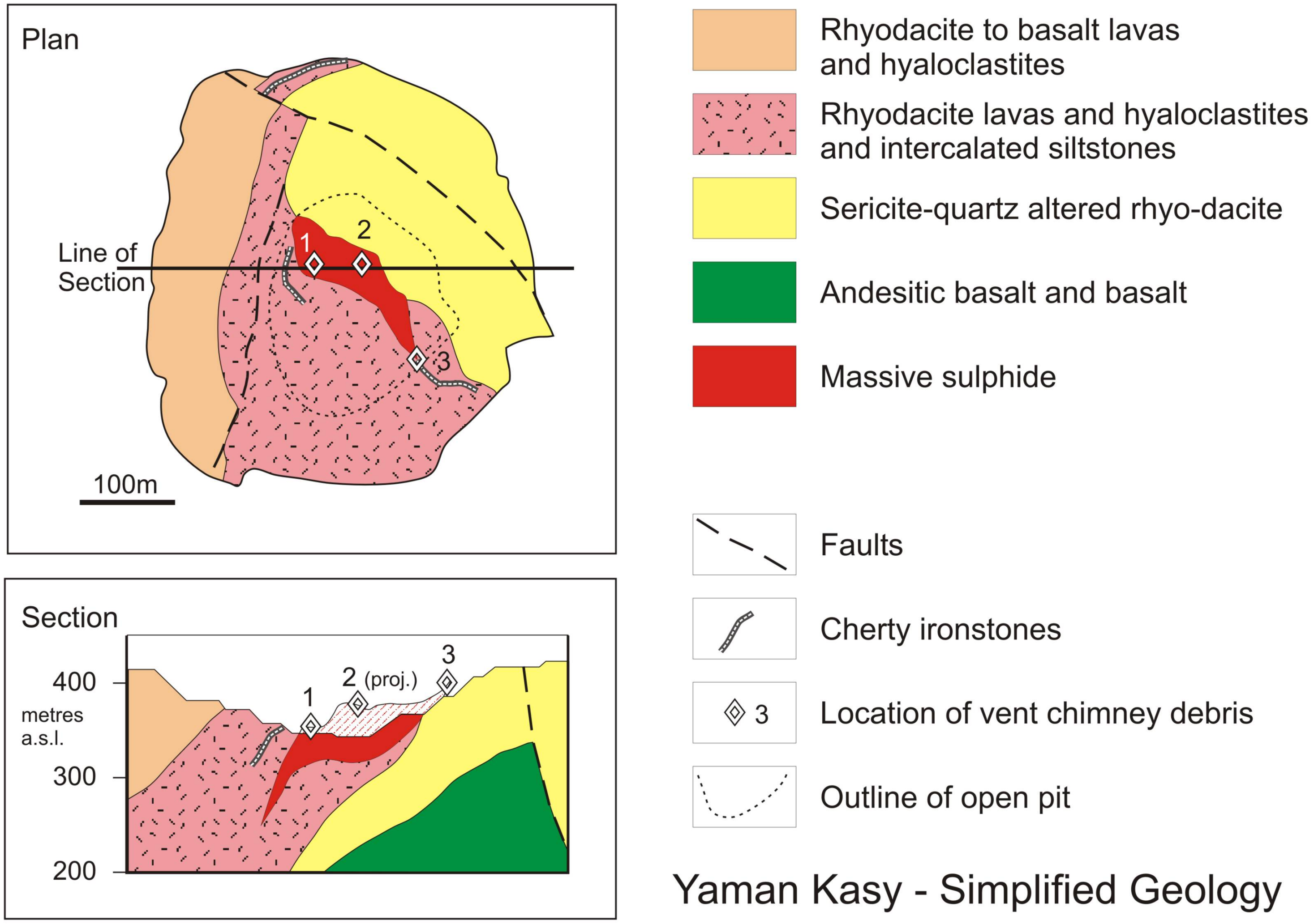


From Hannington et al. 1995



Nautilus Minerals have permits for offshore sulphide deposits in PNG

Yaman Kasy, Russia – a well preserved 420 million year old example



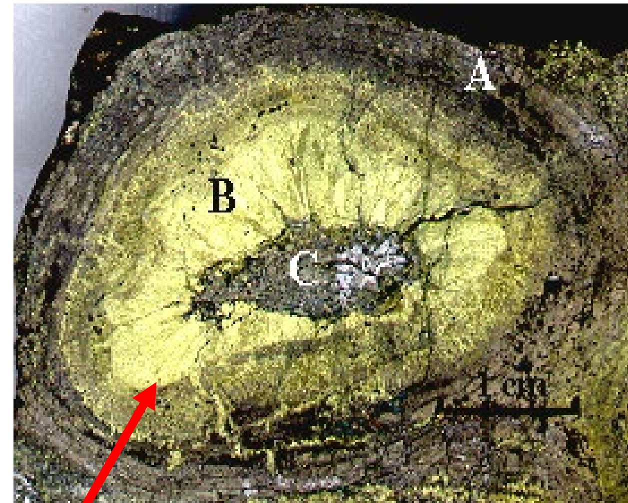
Herrington et al. 2005

Primary deposition features seen in the Yaman Kasy deposit

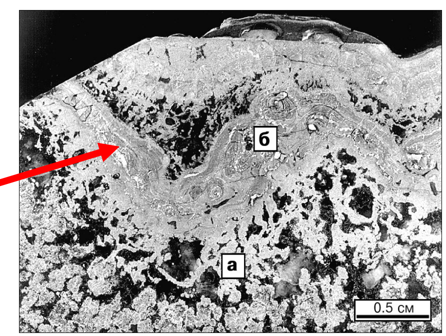
After Little et al. 1997
Herrington et al. 1998

Vent fauna

Sulphide talus breccia

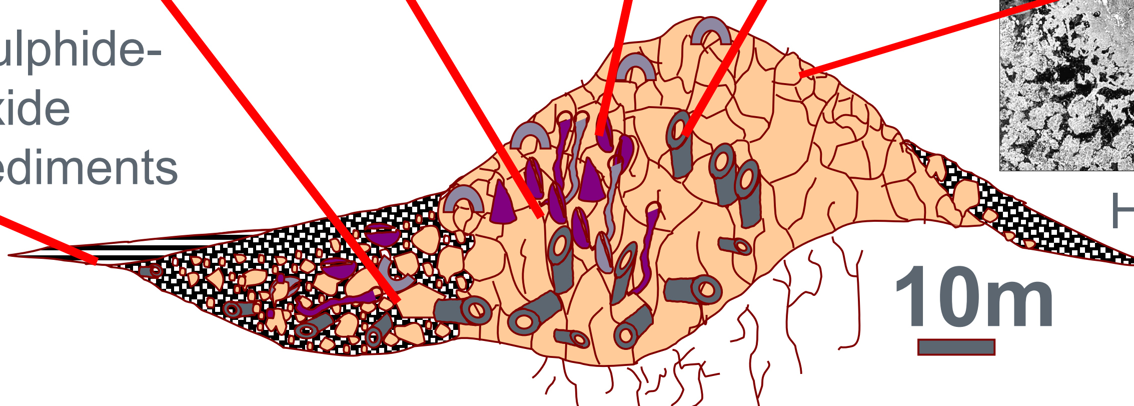


Vent chimney

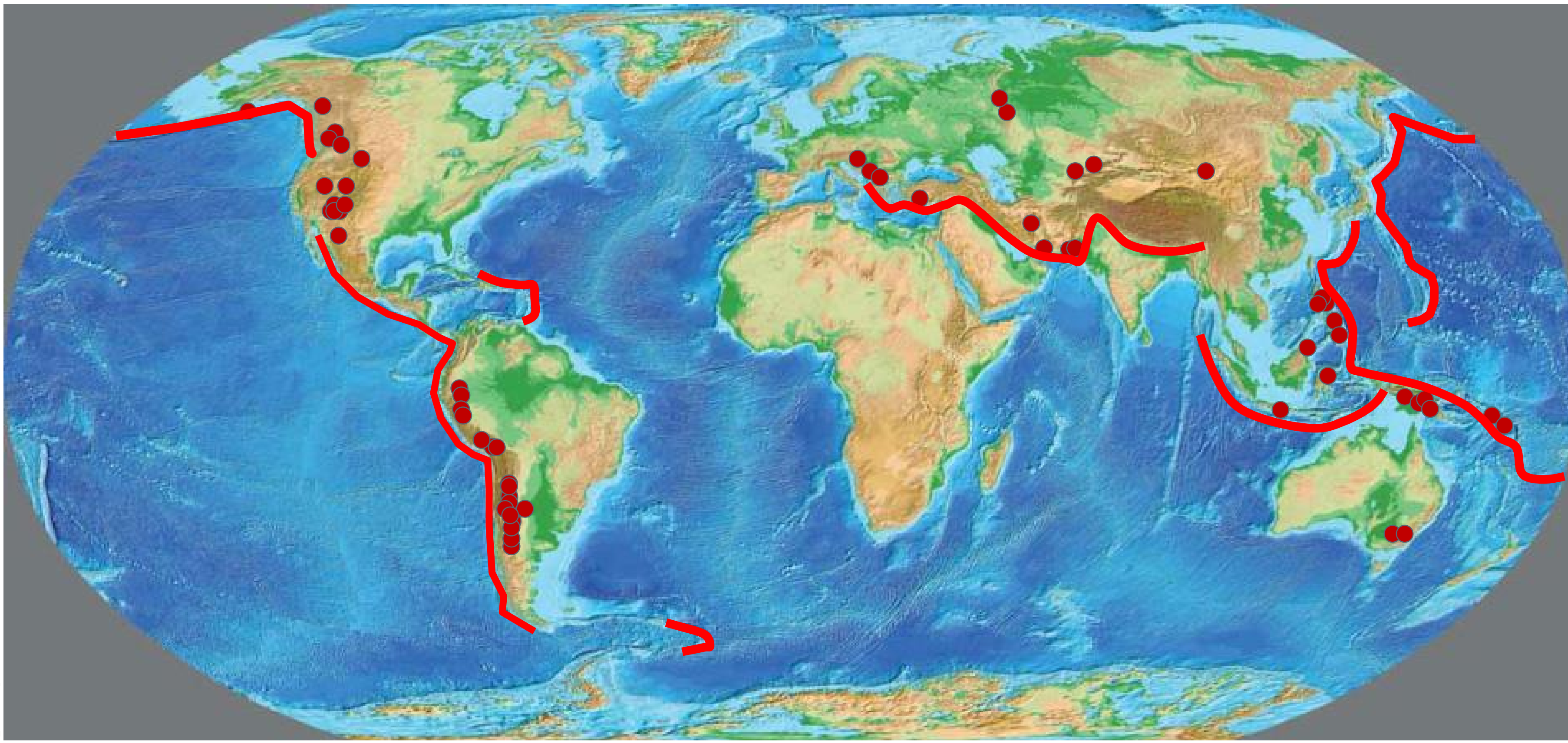


Hydrothermal crust

Sulphide-oxide sediments



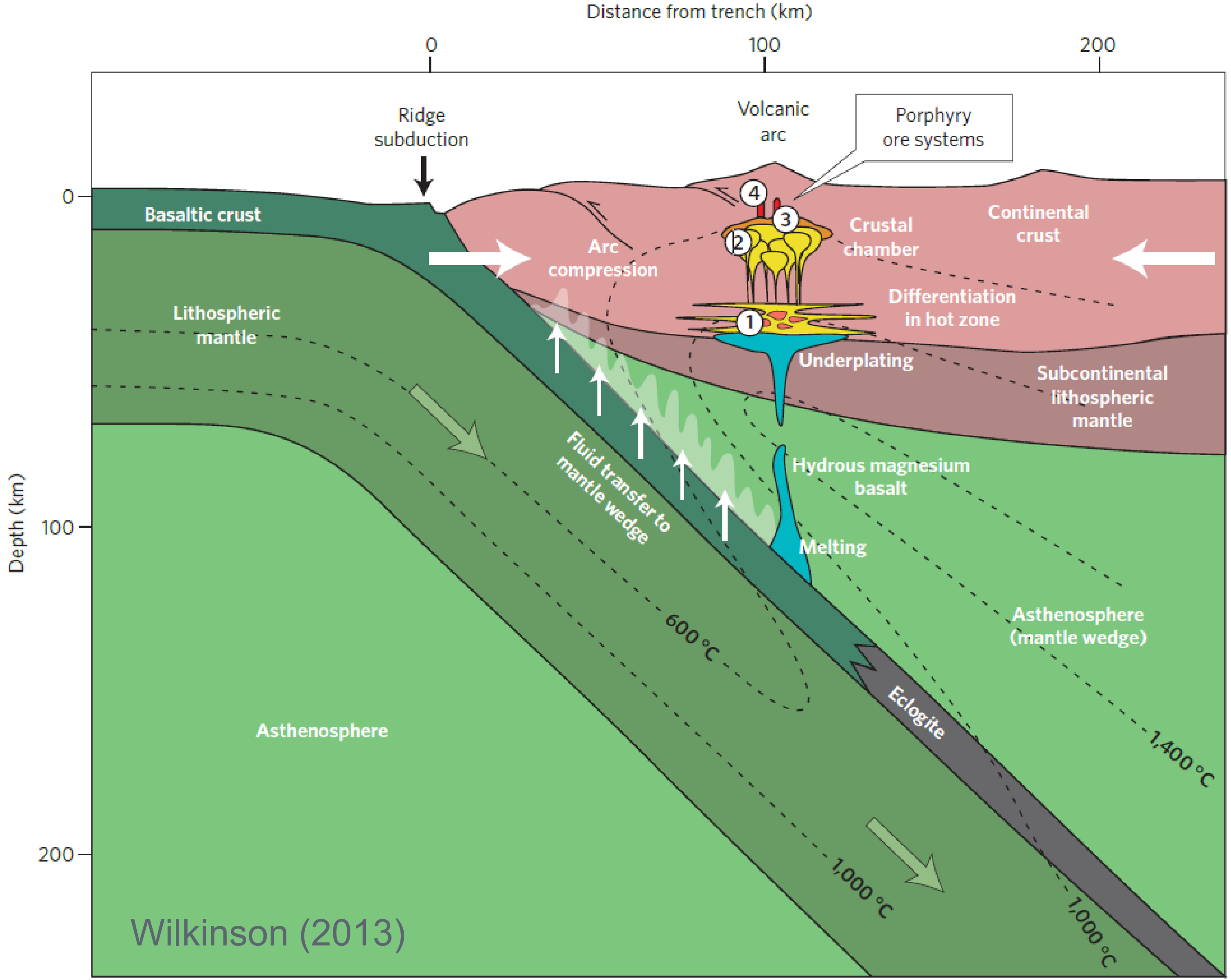
Arc volcanoes and giant copper deposits



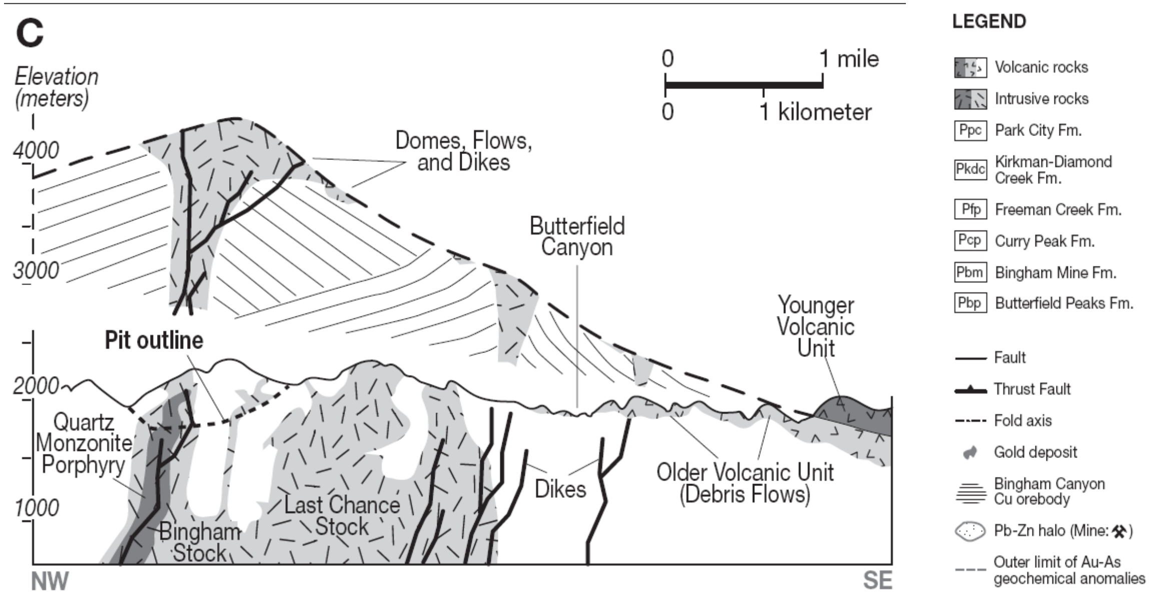
Porphyry Copper Deposit

Subduction (convergent)

Magma also generated at subduction zones



World's largest porphyry copper mine Bingham Canyon likely sits under a volcano like Soufriere Hills, Montserrat



Landtwing et al. 2010


Los Bronces Porphyry Cu-Mo, Chile
Photo: Matt Loader

Los Bronces Porphyry, Chile

Thin quartz-sulphide veinlet in altered porphyry host rock

La Paloma (Los Sulfatos) 213 metres of core @ 7.42% Cu

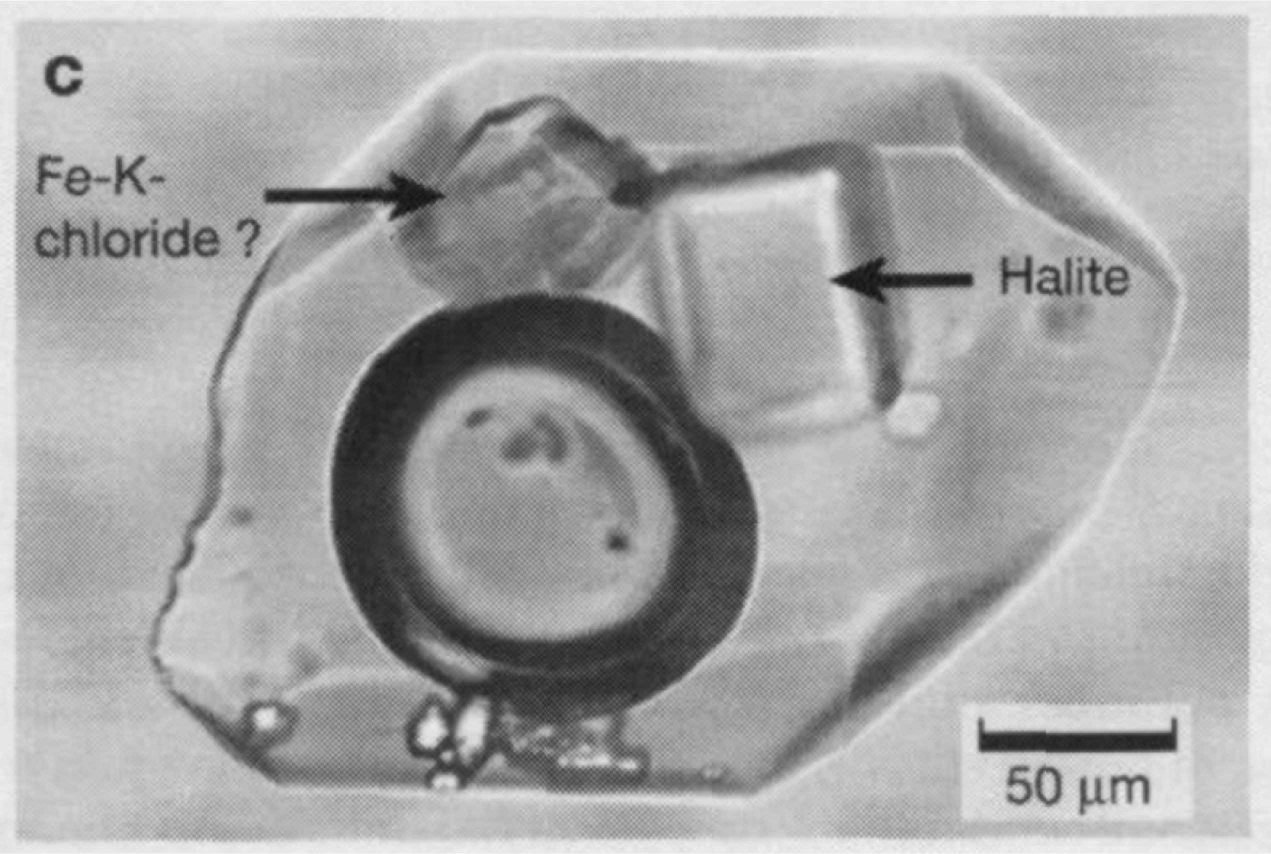
Los Bronces Porphyry, Chile

Anhydrite-chalcopyrite cemented porphyry breccia

Miarolitic Cavities – this means melt and fluid together

Amazonite feldspar and quartz crystals, Pikes Peak, USA

Fluid inclusions found in porphyry crystals



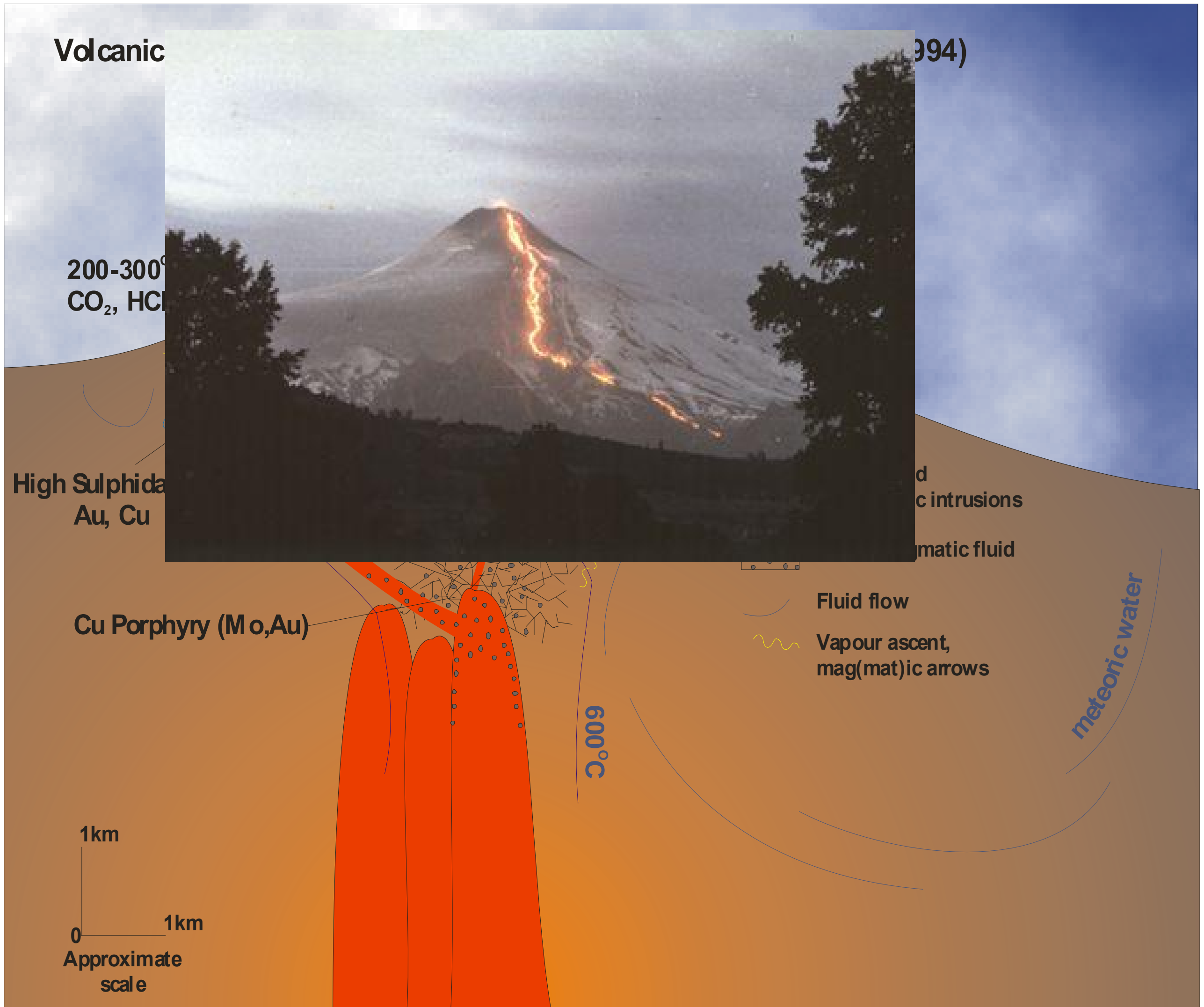
Audétat et al., 2000. Causes for large-scale metal zonation around mineralized plutons: Fluid inclusion LA-ICP-MS evidence from the Mole Granite, Australia. Econ. Geol., 95: 1563-1581.

NATURAL HISTORY MUSEUM

Magma Mingling (Hybrid Rocks)

Magma mingling often the trigger for eruption – also brings in more sulphur!

Porphyry copper deposits linked to strato-volcanoes



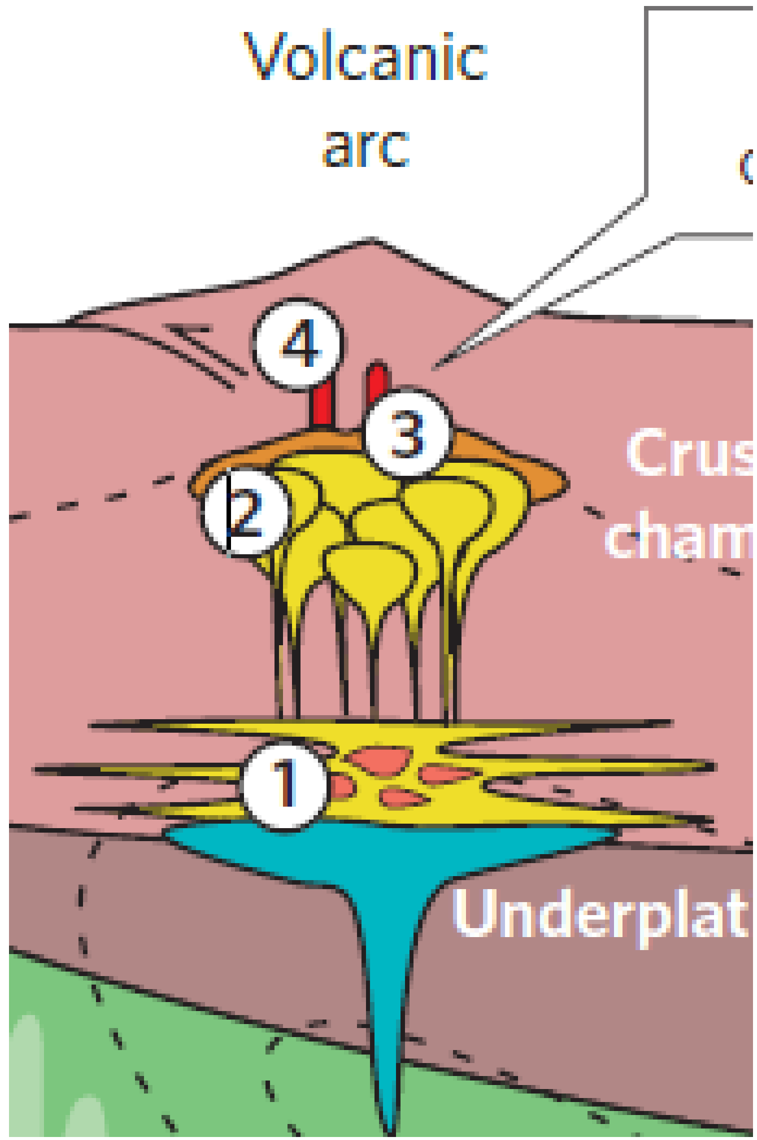
Porphyry magma evolution

4 Porphyry Cu deposits form above intrusions which come off the tops of these magma chambers. Fluids rise through intrusions

3 Fluids dissolved in the magma come out of solution, metals get concentrated in the fluids

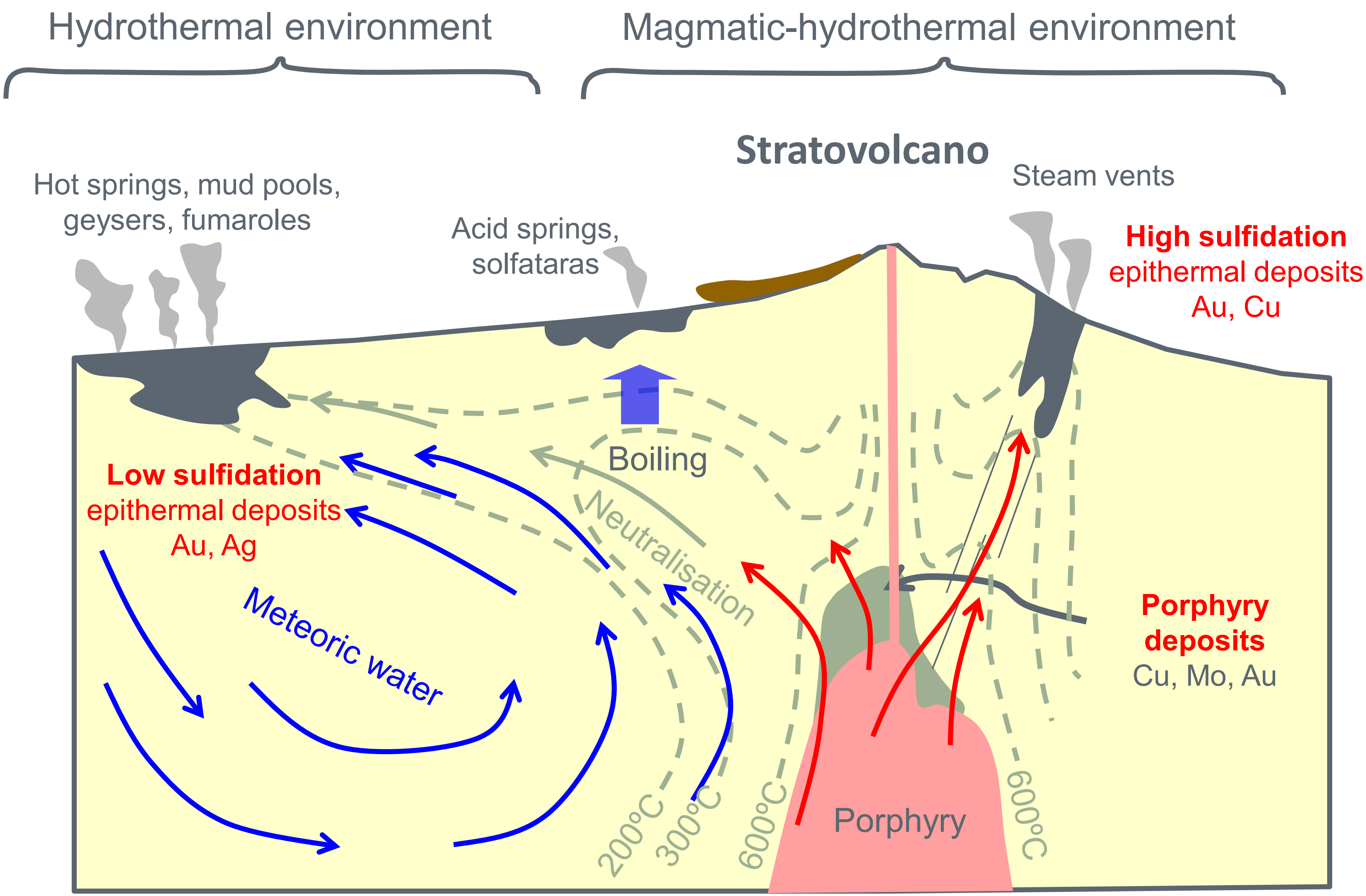
2 Magmas rise through the crust to form magma chambers, which grow incrementally

1 Magmas stall at the base of the crust (density contrast), where they cool, crystallise and fractionate (become more **felsic**)



From: Wilkinson 2013

Hydrothermal flow around porphyry – stratovolcano systems



(from Hedenquist et al. 1996)

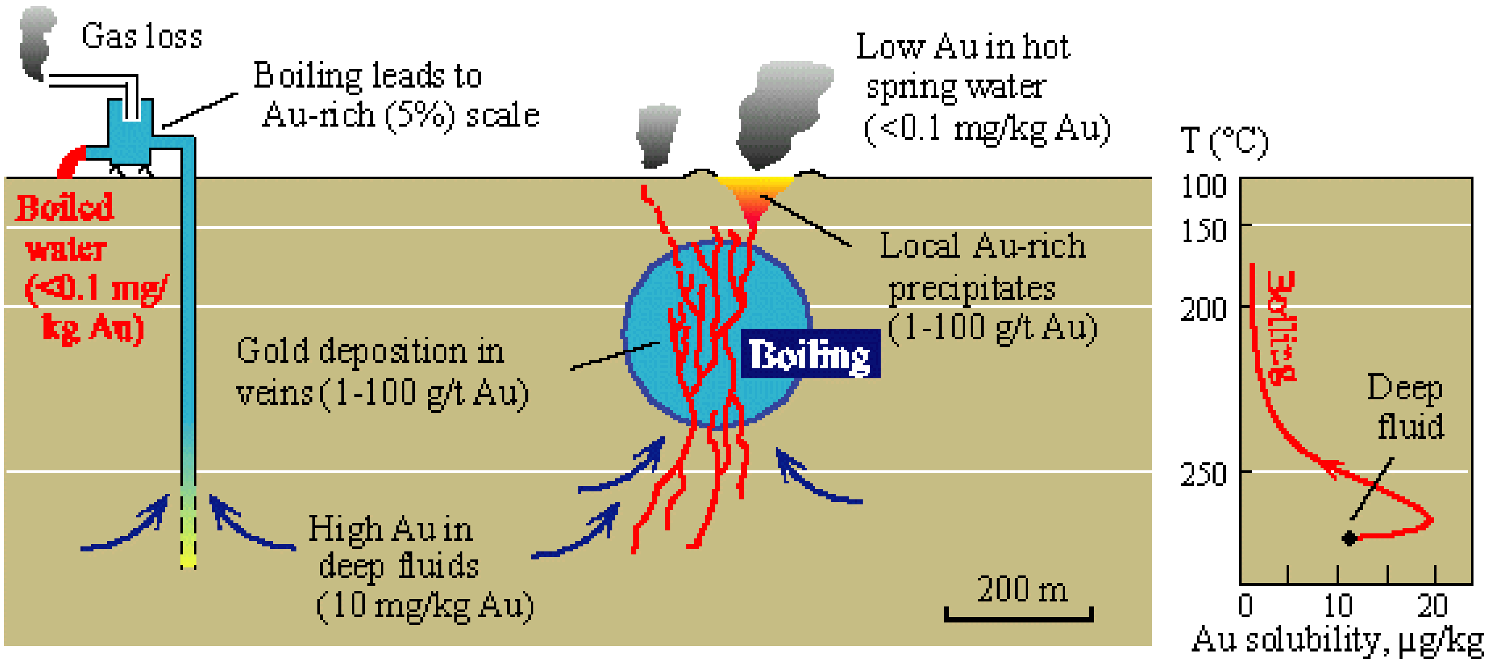
Hotsprings associated with volcanoes

Wairakei_geothermal_power_station, New Zealand

Champagne Pool, Rotorua, New Zealand

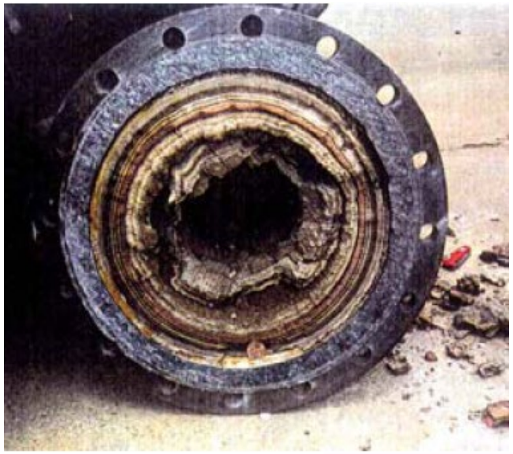
- North Island, New Zealand

Epithermal Au-Ag – Boiling as a precipitation mechanism



- Gold-in deep waters (prior to boiling and gas loss) 10 mg/kg
- Hot spring waters contain <0.1 mg/kg Au

(from Hedenquist et al. 1996)



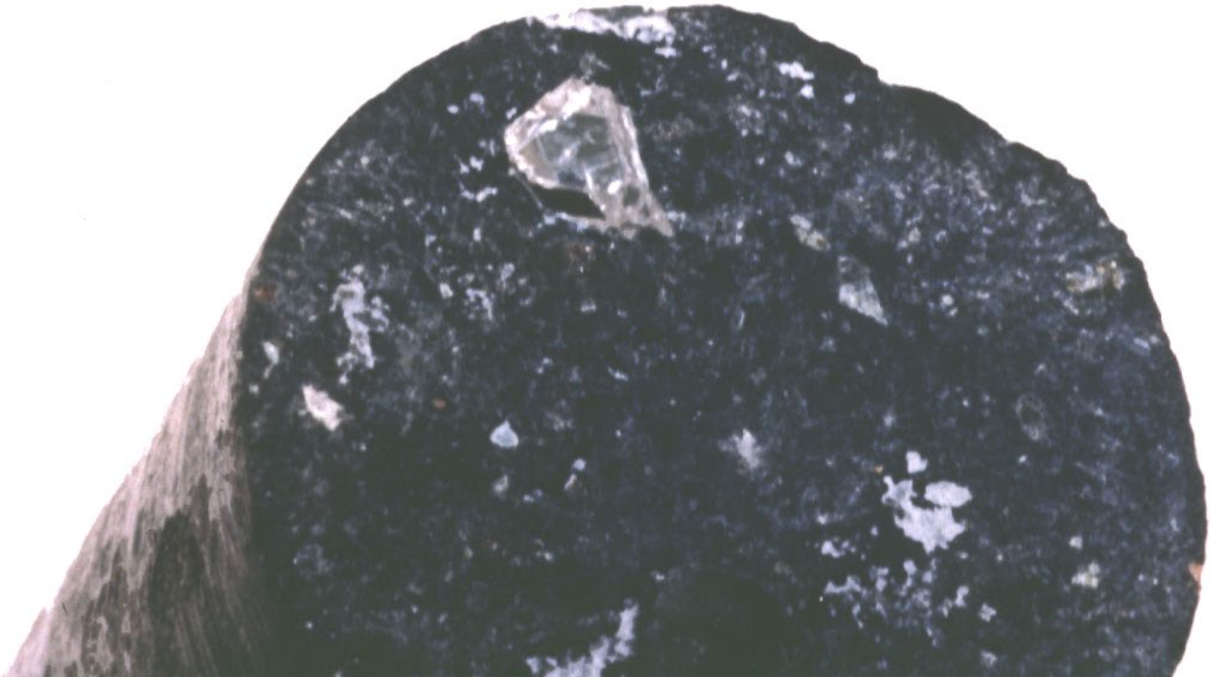
Gold-rich pipe scale
from geothermal pipes

Diamonds – gem quality stones

Alluvial Diamonds: River Gravels

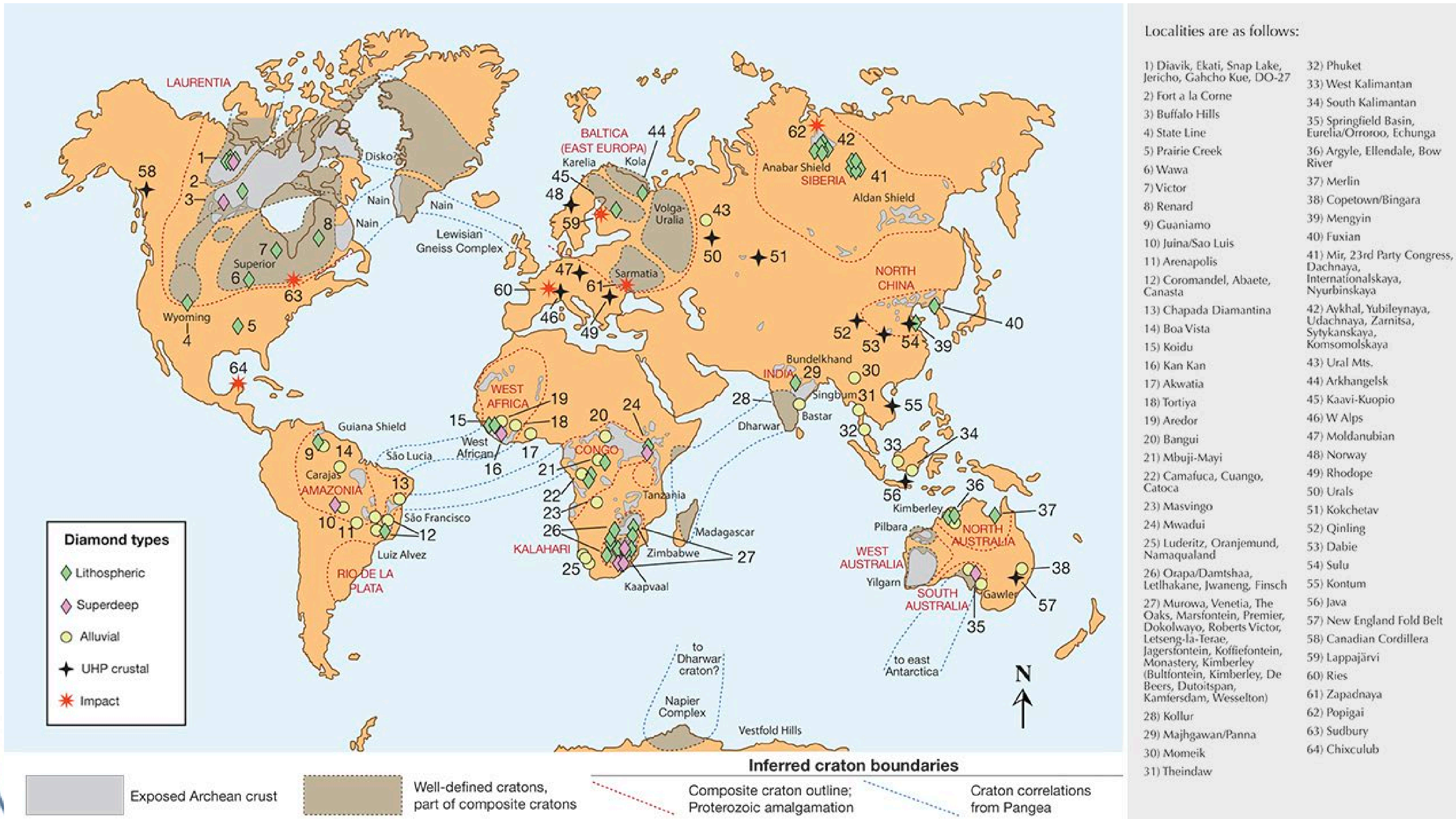
Historically diamonds recovered from river gravels – particularly gem-quality

Diamonds from kimberlite



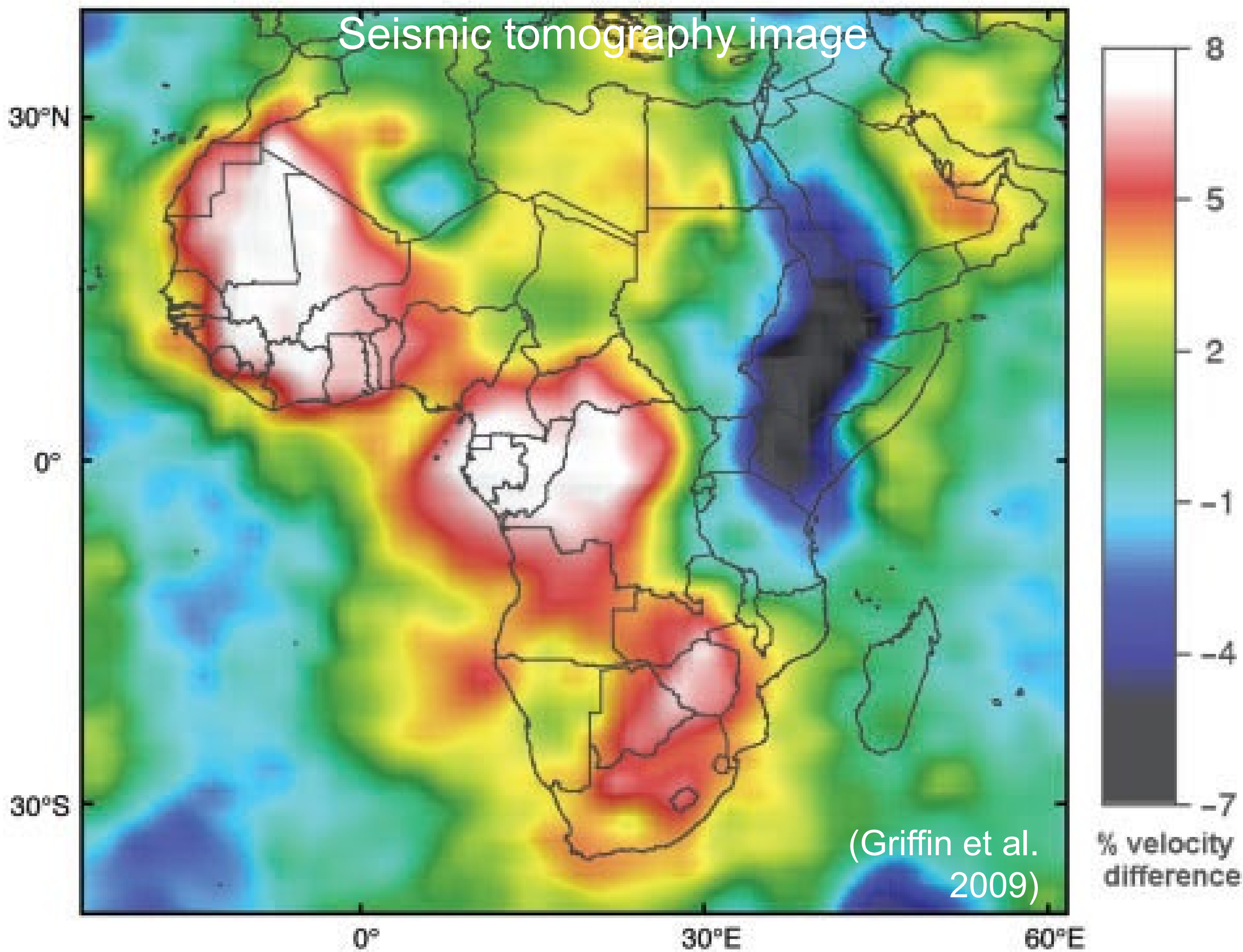
Diamonds in a drill core from Aber Resources A-154 kimberlite pipe in northern Canada - extremely rare occurrence!

Geographic distribution of known diamond deposits – Relationship to cratons



Shirey & Shigley 2013

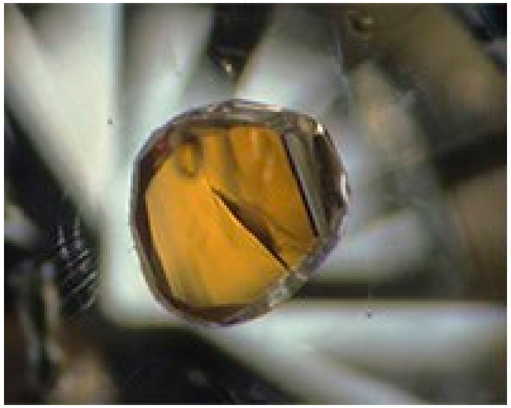
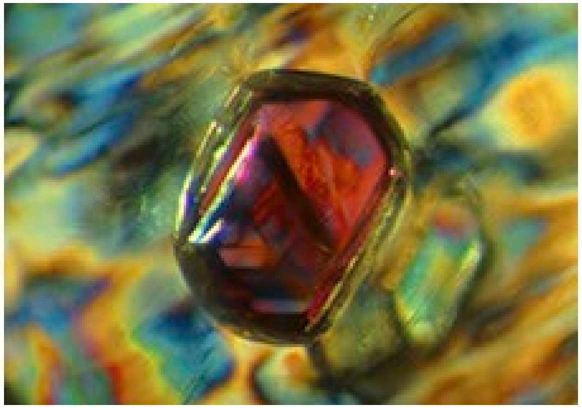
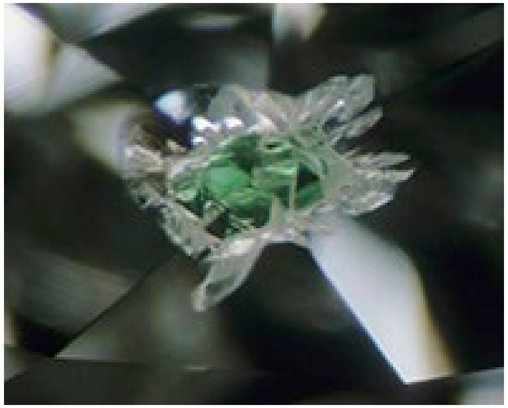
Geographic distribution of known diamond deposits – Relationship to thickest crust



‘Clifford’s Rule’

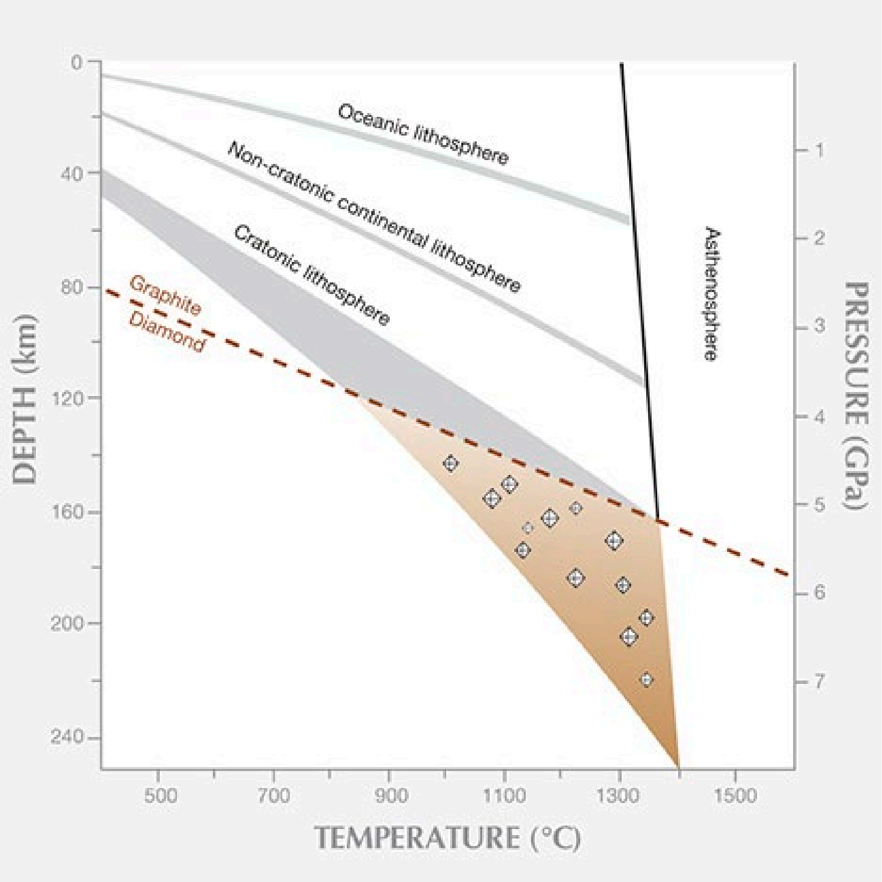
- This relationship, first formalized by Clifford (1966) and known as Clifford’s Rule:
  - Diamondiferous kimberlites erupted through the oldest Archean portions of the cratons
  - Non-diamondiferous kimberlites erupted through younger cratonic rocks
- ‘Clifford’s Rule’ is best shown in the Kaapvaal craton, where all of the diamondiferous kimberlites are “on-craton” and all of the “off-craton” kimberlites are diamond-free.

Diamonds – history from inclusions

- Mineral inclusions in diamonds have revealed much about how they have formed
- Indicate that they have formed up to 800 km below the surface

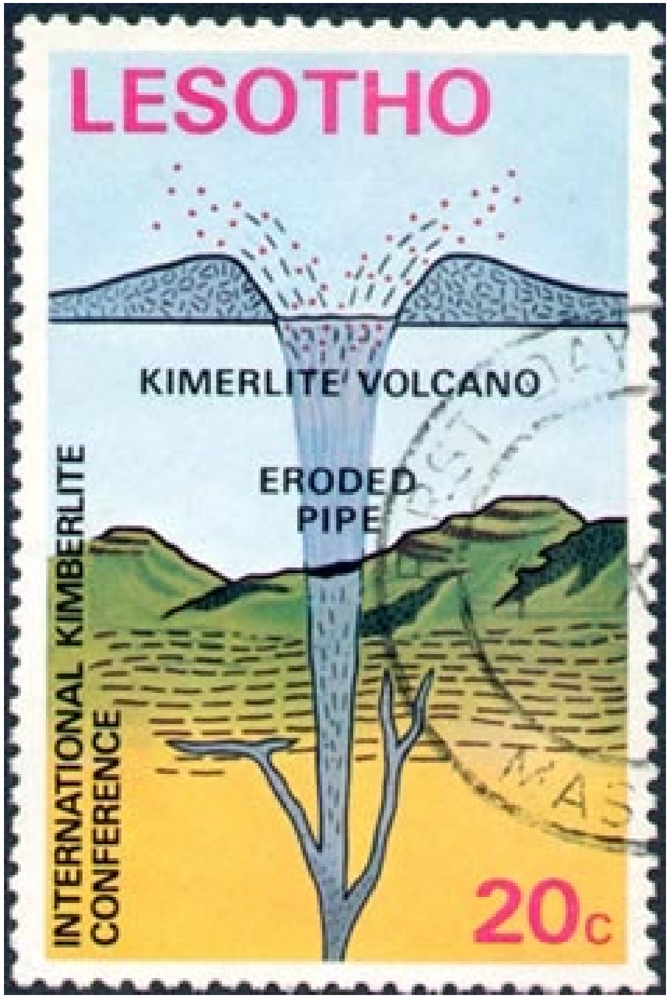
Diamonds – stability field in the mantle

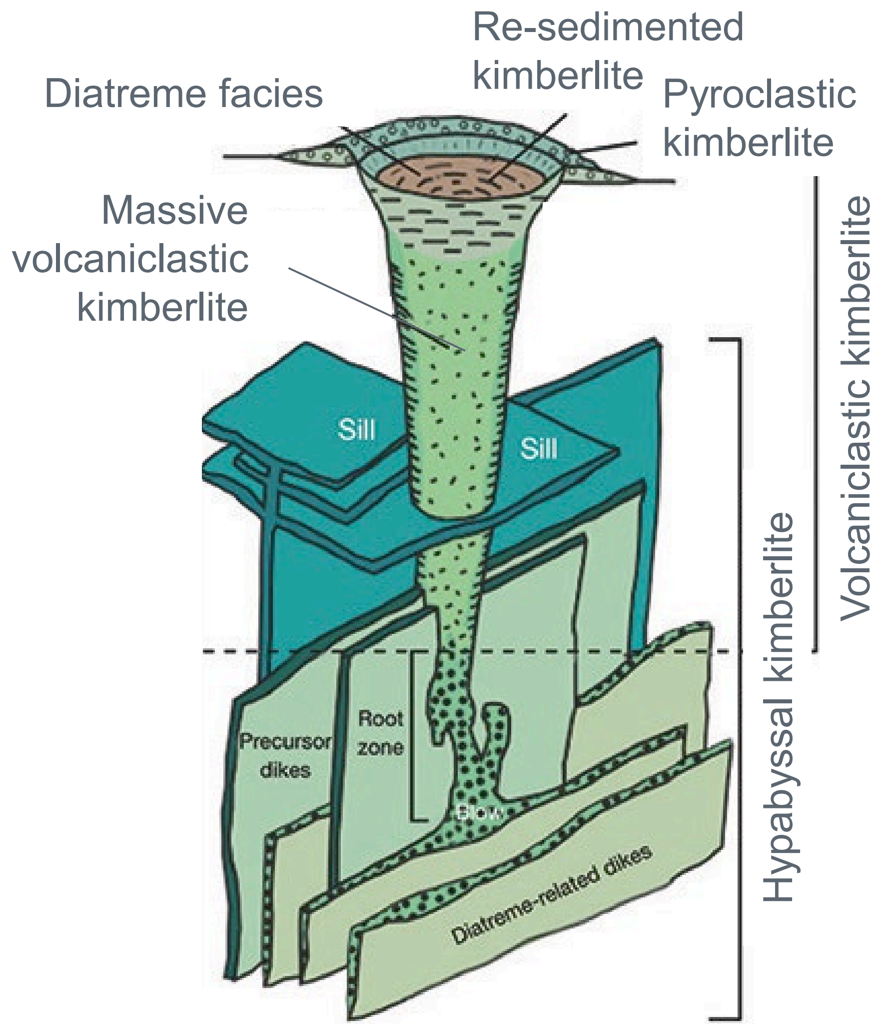


(After Tappert & Tappert 2011)

- Diagram showing stability field for diamond in the lithosphere
- Note that the asthenosphere (convecting mantle) is too hot to preserve diamonds

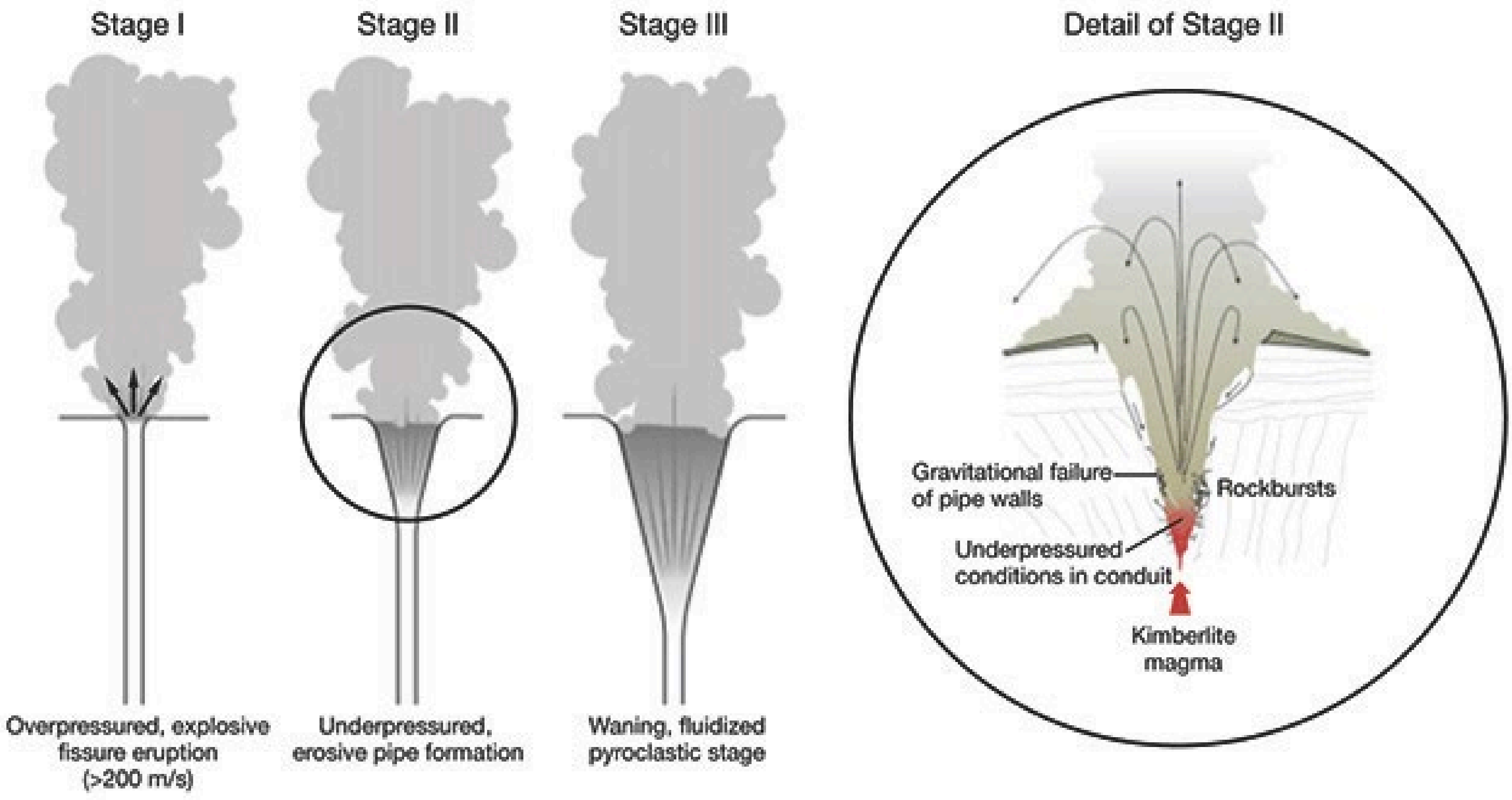
Kimberlite volcano





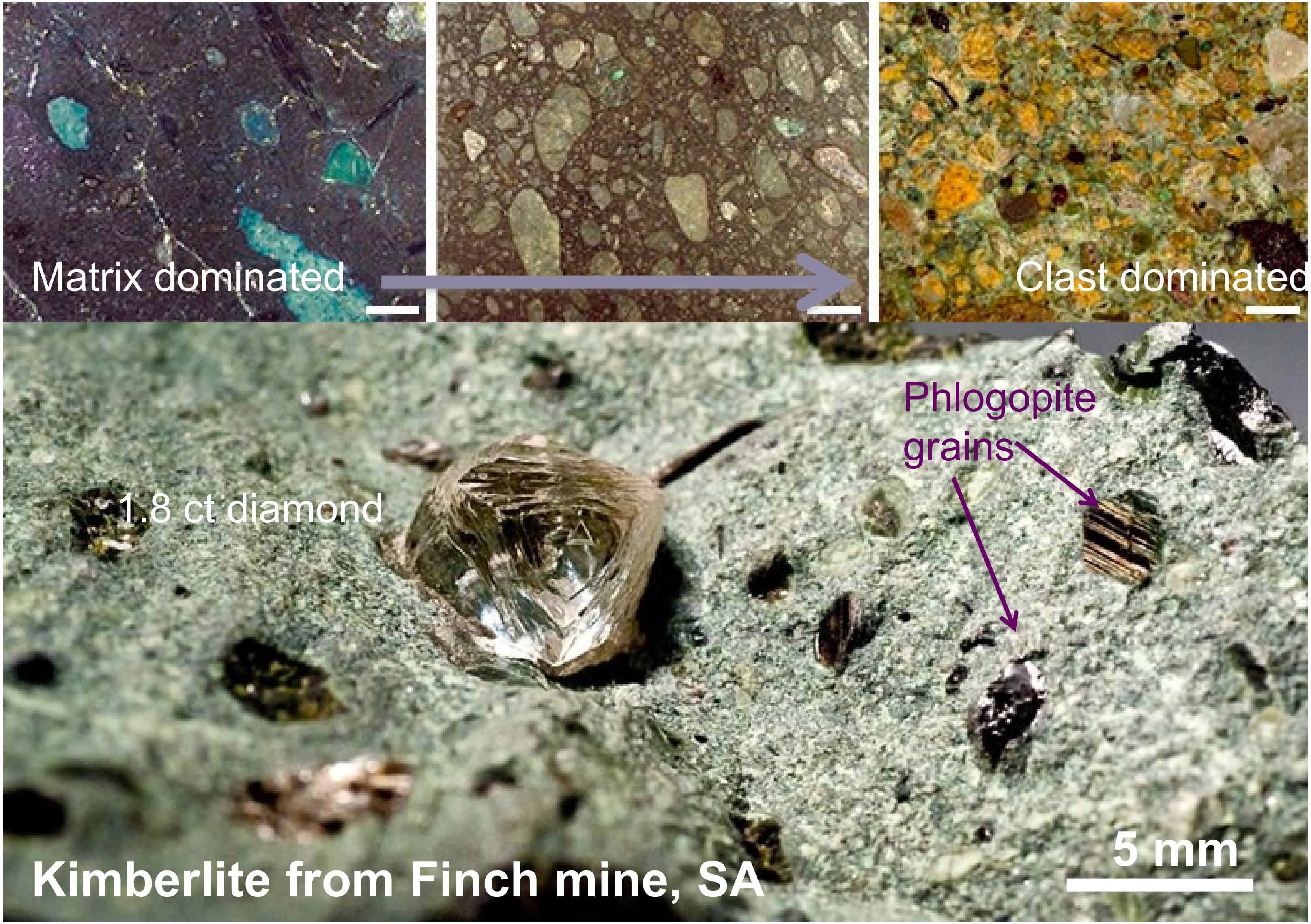
From Kjarsgaard (2007)

Formation of kimberlites



From Sparks et al (2006)

Kimberlite host rock

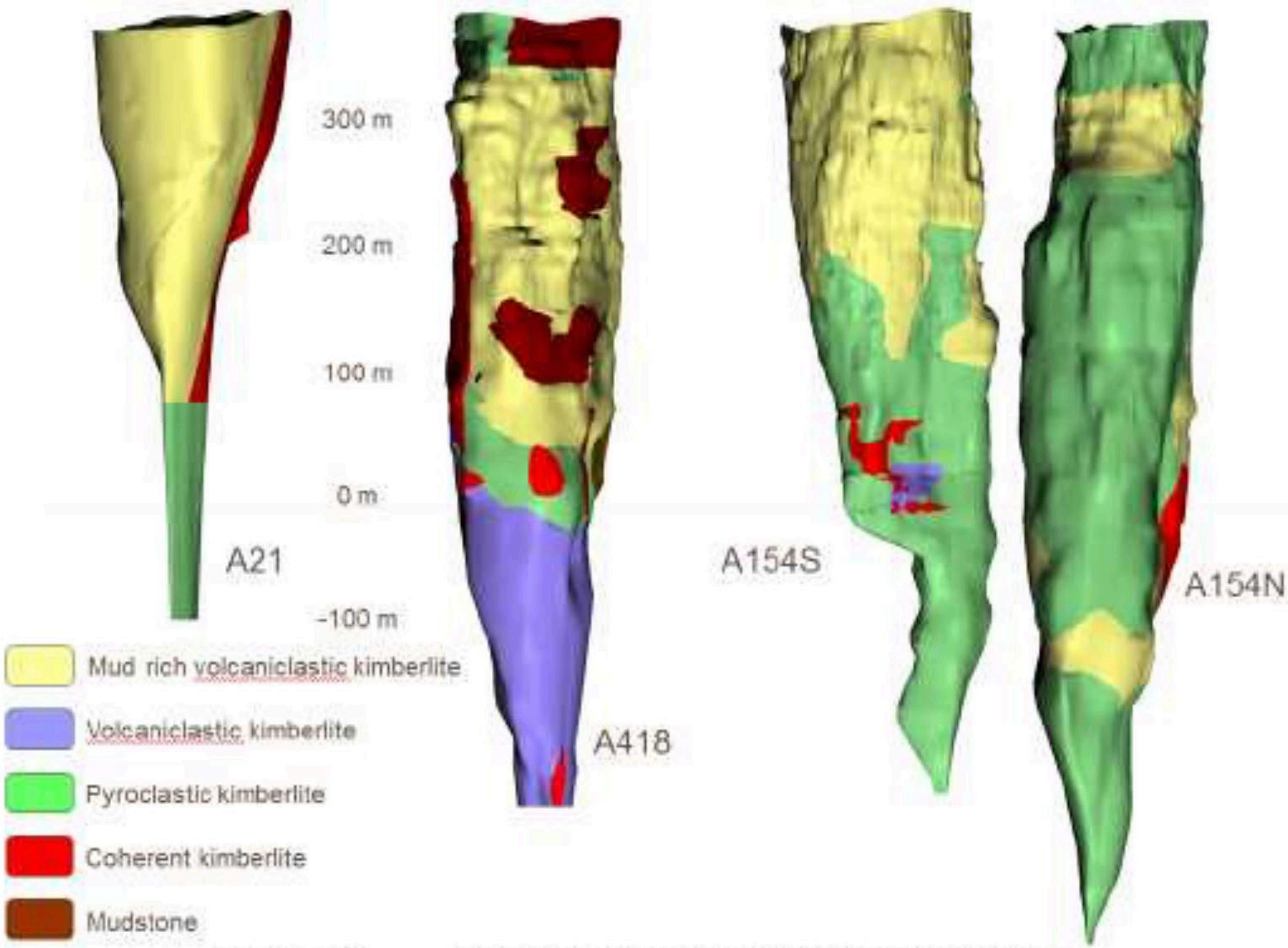


From Shirey et al. (2013)

Ekati mine Canada

Multiple kimberlite pipes

Ekati mine Canada

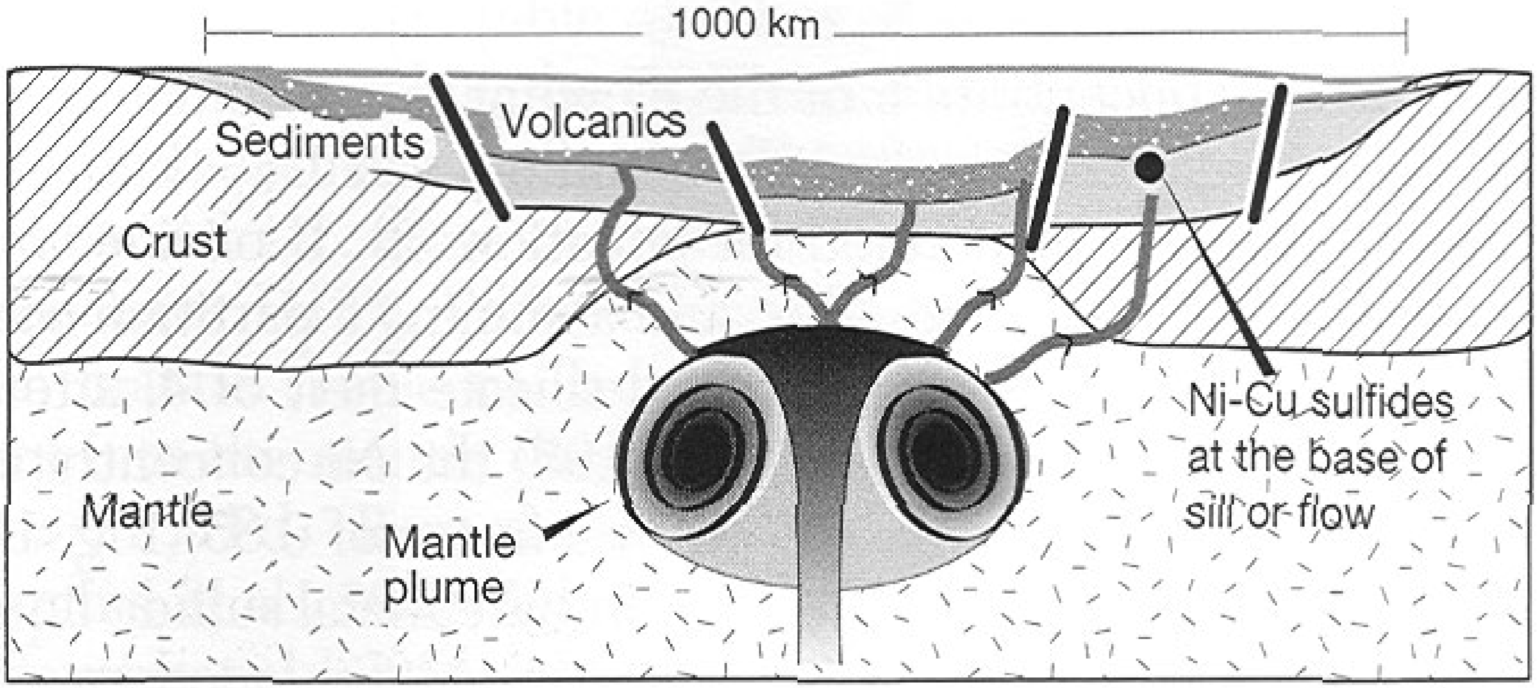


Diverse styles of kimberlite pipes

Yip & Thompson 2015

Mantle plumes, volcanoes and ores

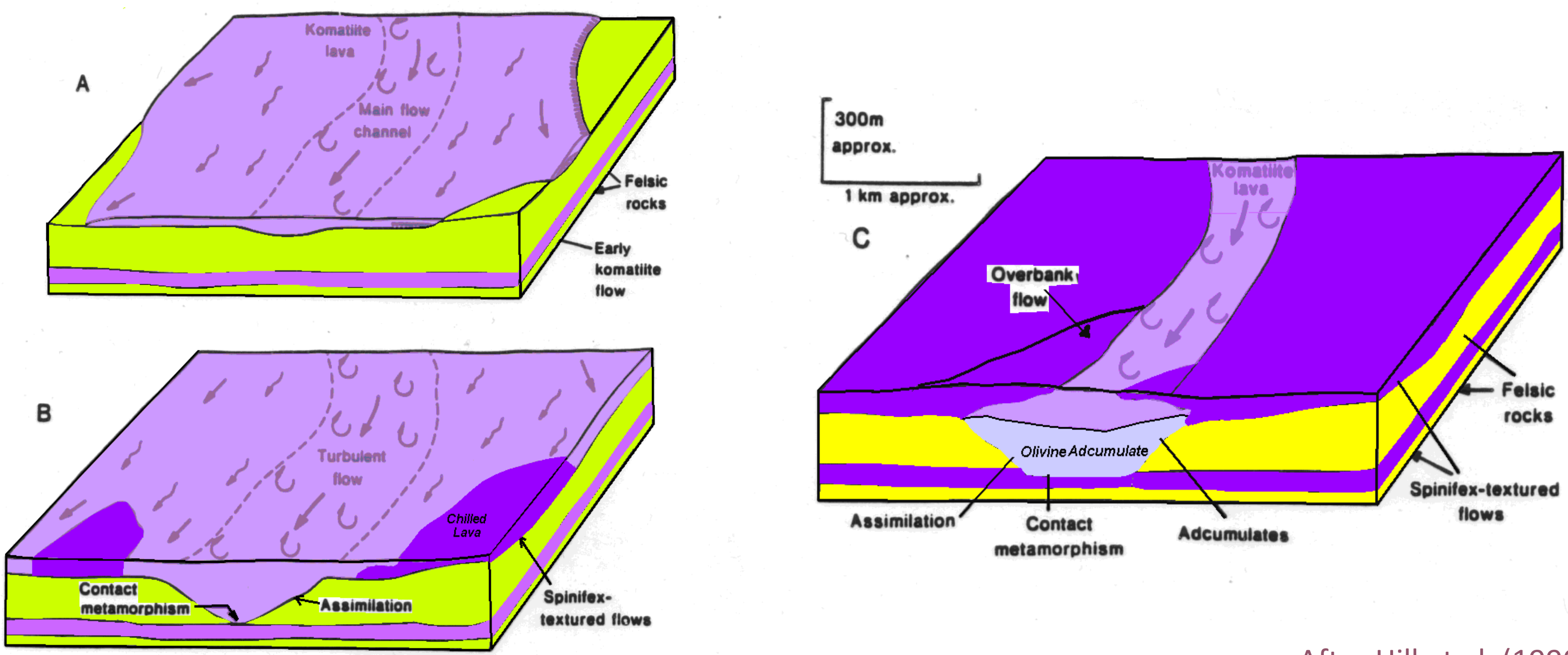
- In the geological record we have evidence for times when ‘plumes’ from the deep mantle have given rise to mineral deposits
- This demands that very primitive, deeply sourced melts are able to penetrate up through the crust



Lightfoot et al. 2005

Sulphide deposits in komatiite lavas

- **Very special case** – Komatiite lava hosted magmatic sulphides
- Extremely hot lava flows in Precambrian – ability to get to the surface of the hot early Earth and form flows
- These lavas thermally erode the rocks they erupt on to assimilating the footwall rocks



After Hill et al. (1990)

Komatiites – very high temp lavas

- Distinctive ‘spinifex texture’ forms as olivine or pyroxene grows in very high temperature lava (up to 1700 ^{o}C) as it quenches
- Impossible to erupt now on Earth

Komatiite volcanoes

Nickel-Copper sulphide deposits in lava flows

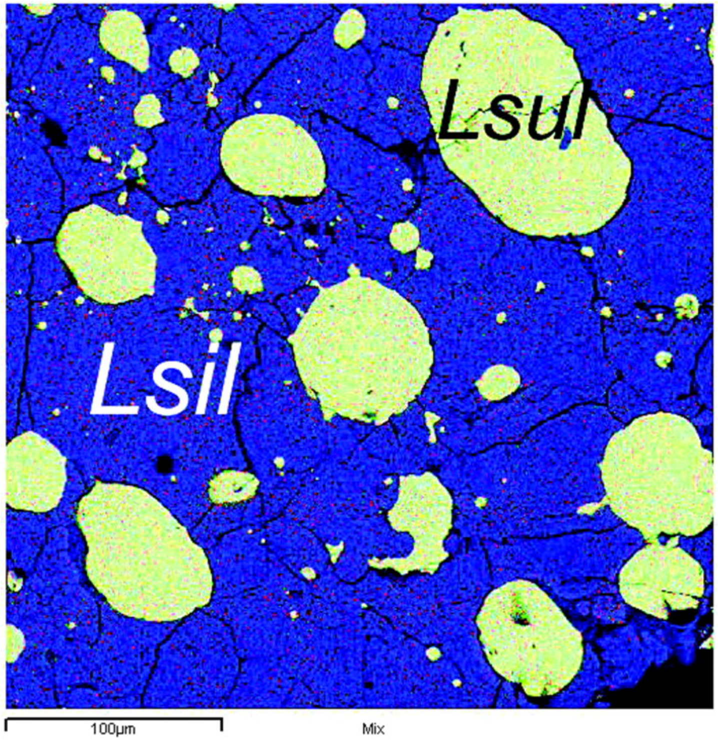
As a very primitive magma evolves, one phase can segregate from another = immiscibility

- like oil separates from water

Experiments have simulated this process

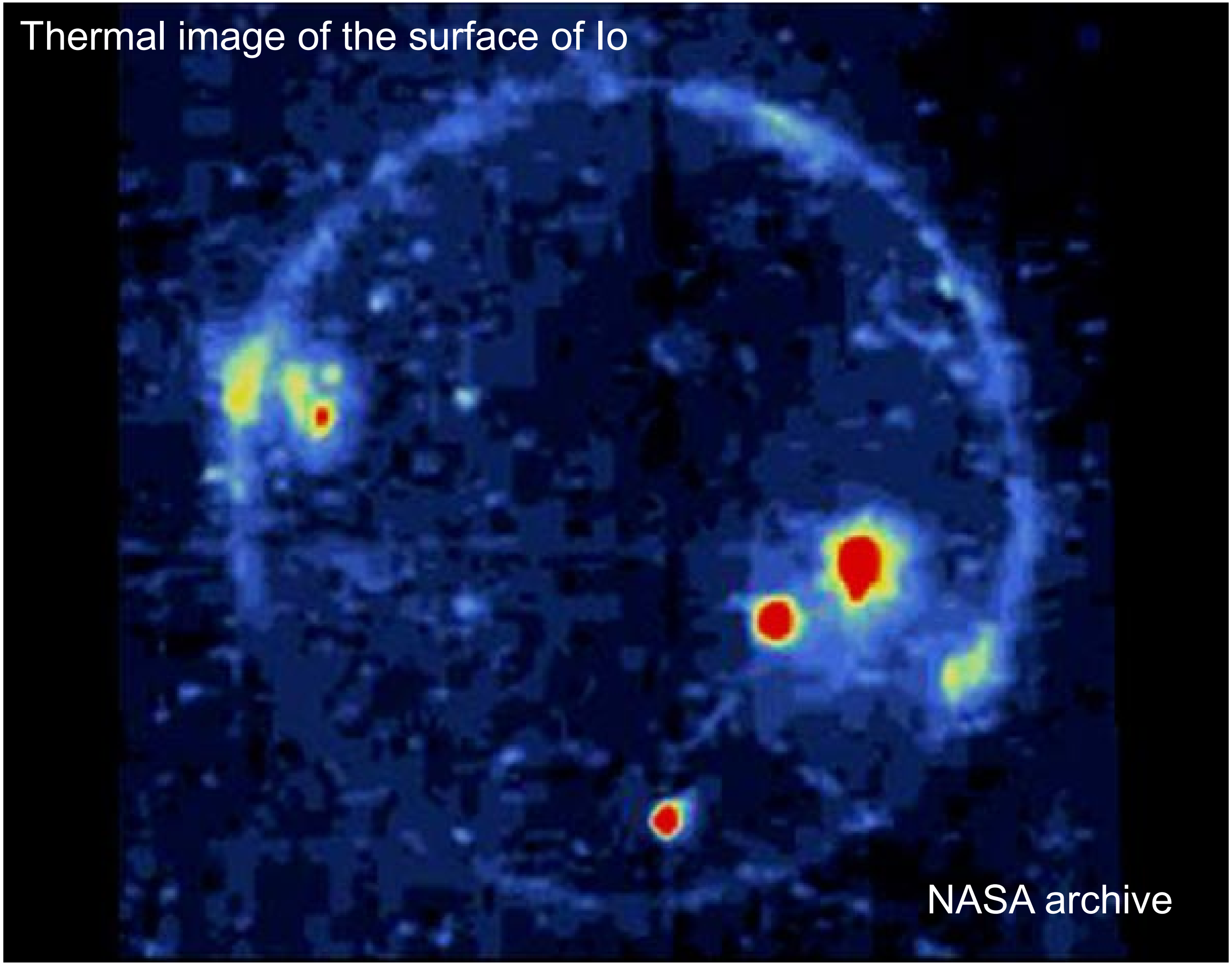
This phenomenon is linked to:

a) Temperature changes (cooling)
b) Changes to the chemistry of the lava (e.g. add sulphur or silica)

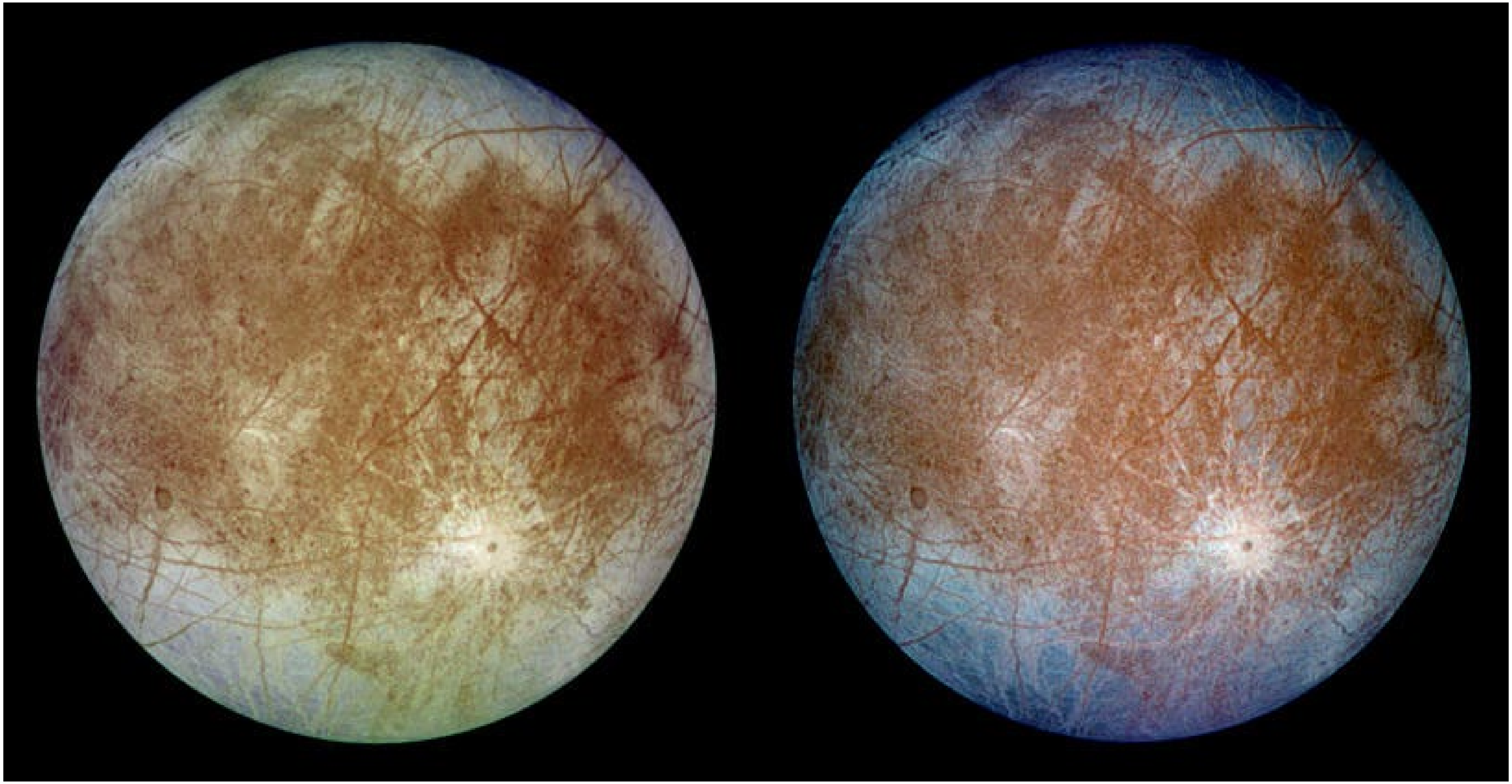


Scanning electron microscope image of the immiscible silicate and sulfide melts after quenching
From Shushkanova & Litvin 2008

Komatiites forming today on Io

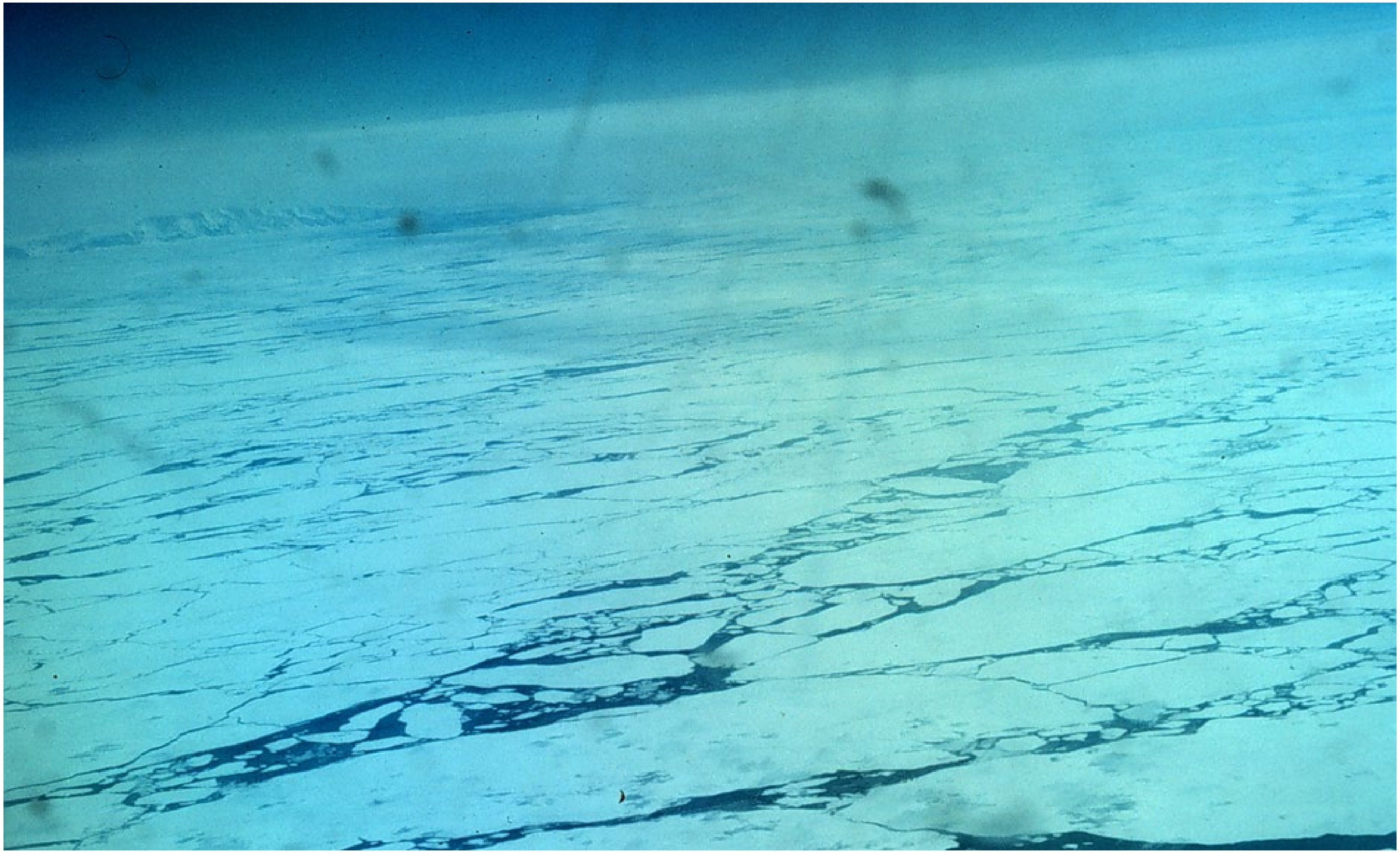


Evidence for volcanoes on Europa



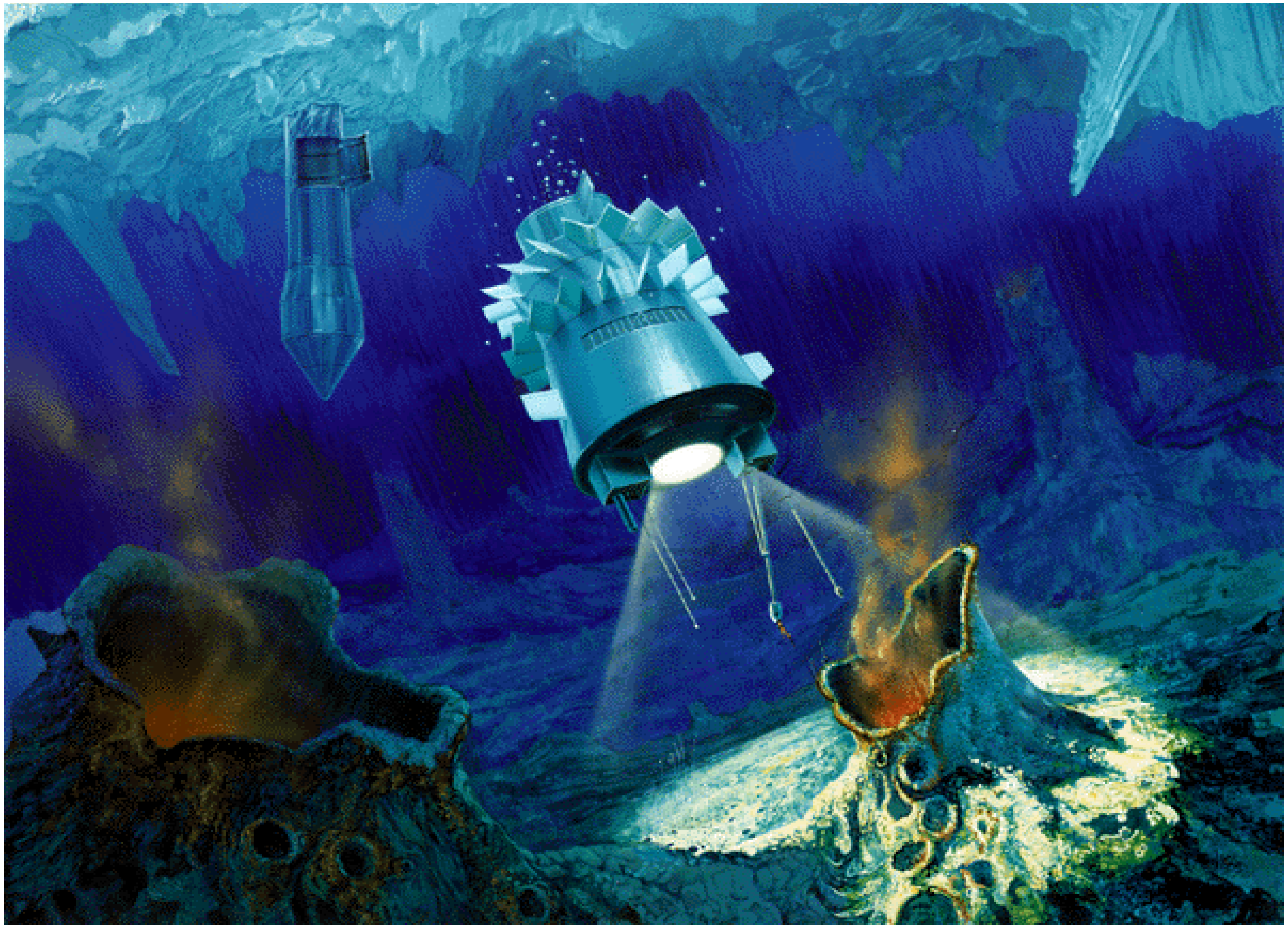
Patterned surface ice – points to a liquid ocean below?

Evidence for volcanoes on Europa



Similar ice patterns seen in the Arctic

Evidence for volcanoes on Europa



In the ocean beneath – there is a good chance of volcanoes and hydrothermal vents – sulphide deposits? maybe life?

Mars has huge volcanoes

No longer active but may equate to early earth volcanoes

Summing up

- Volcanoes are the manifestation of a geologically active planet, evidence of a planet both maturing and recycling material between the mantle and the crust
- Magmatic processes underlying volcanoes are often responsible for recycling and concentrating metals and other elements into economic concentrations
- Water is key component in many of the geological processes linked to formation of volcanoes
- Water helps to drive some crustal volcanic systems and in many cases is essential for the formation of many the useful mineral deposits formed
- Planetary exploration offers some answers to early Earth questions