Economic Geology: Lecture Notes

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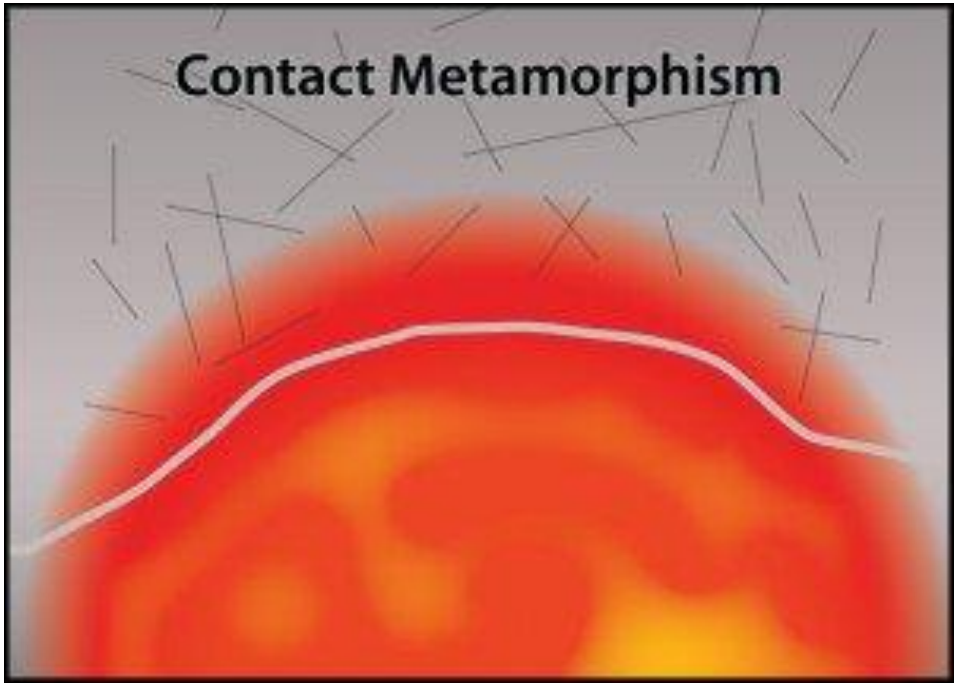
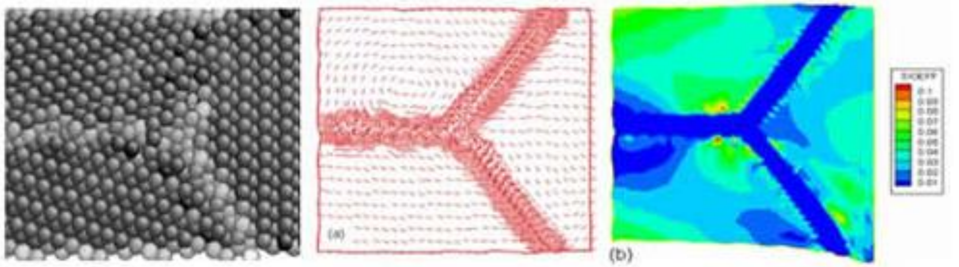
Metamorphic and metamorphosed ore deposits

Metamorphic ore deposits is a class that owes its economic interest to largely **isochemical metamorphic re equilibration and recrystallization of pre-existing material which had no use in its original state.** (e.g., transformation of alumina-rich claystones to kyanite/sillimanite deposits, or graphite flakes formed from dispersed bitumen).

Contact metamorphism of ore in the heated zone around magmatic bodies is usually static (i.e., in the absence of dynamic deformation). Exposure to high temperatures (with a maximum of 750°C) affects fabric, mineralogy and mineral chemistry (e.g. by driving off water and other volatiles). Fabric changes are confined to a general increase in grain size with rising temperature. Monomineralic ores recrystallize into triple grain boundary junctions at angles of 120°.

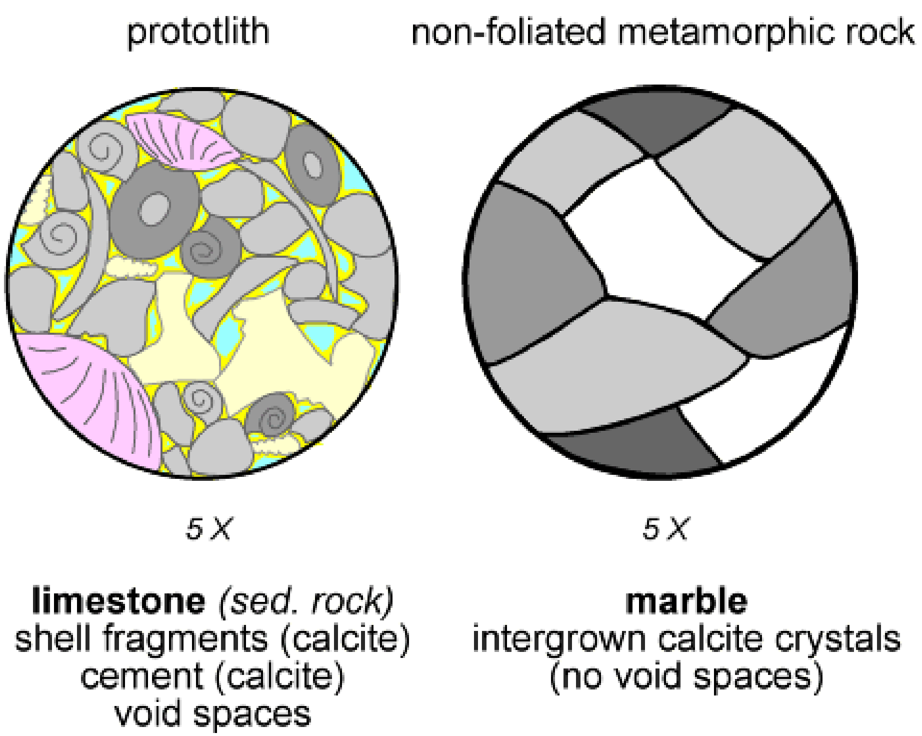


Increase of grain size by metamorphism is important in practice, because processing of coarse ore is less energy intensive.



Grain Boundary sliding and crystal rotation at the Triple Junction

Sulphur release (e.g. from pyrite) may induce formation of metamorphic pyrrhotite or even magnetite. Iron oxide ore at contacts may recrystallize to a different oxidation state (e.g. haematite to magnetite) controlled by the oxygen activity imposed by magma or by heated country rocks.

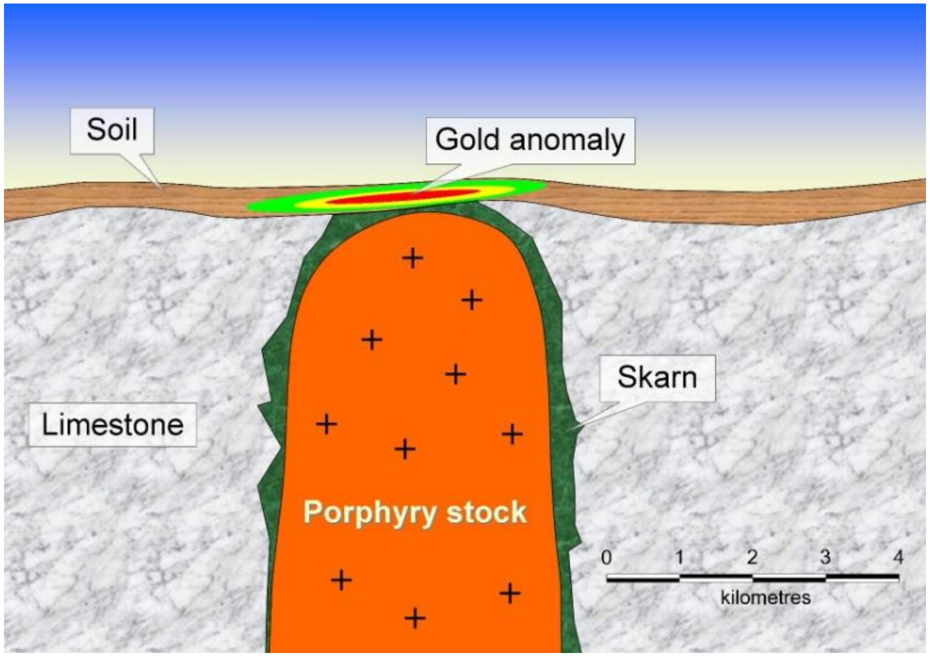


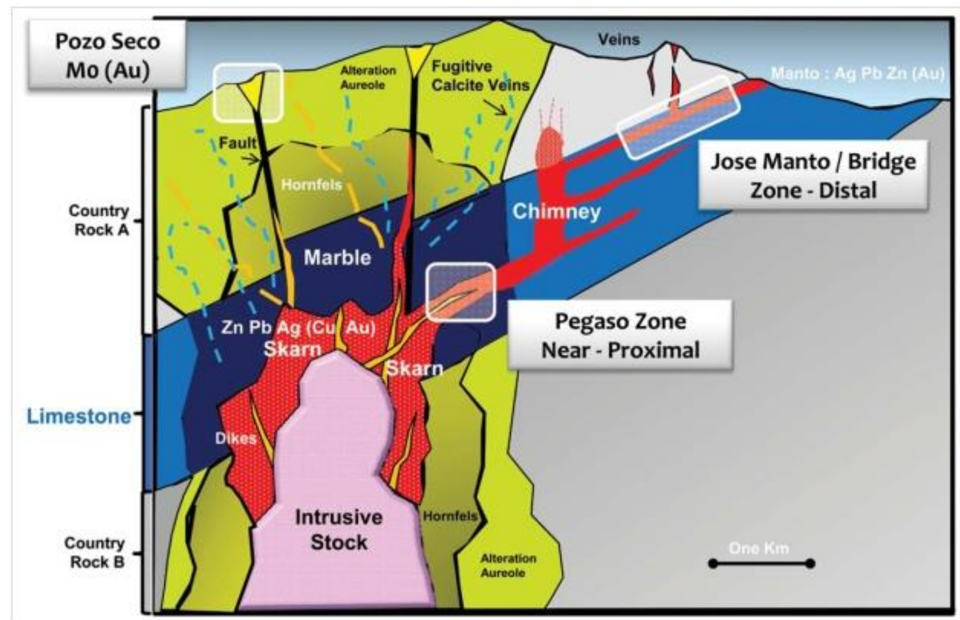
Oxidation/reduction and sulphidation/desulphidation reactions during metamorphism:

$$6Fe_2O_3 \text{ (haematite)} \leftrightarrow 4Fe_3O_4 \text{ (magnetite)} + O_{2(\text{Fluid})}$$

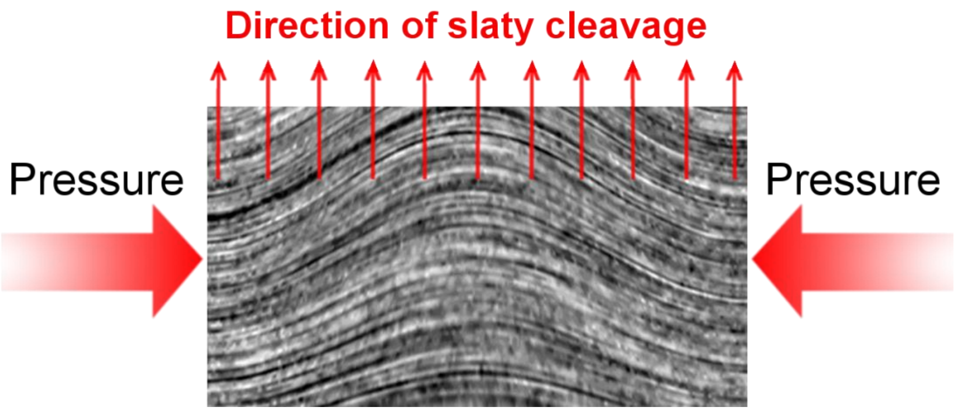
$$FeS_2 \text{ (pyrite)} + H_2 \leftrightarrow FeS \text{ (pyrrhotite)} + H_2S_{(\text{Fluid})}$$

Skarn and contact-metasomatic ore deposits are intimately related to thermal aureoles of magmatic intrusions. They may be said to be products of contact metamorphism, but the causal agent is the interaction with magmatic fluids and not simple change by heating. Therefore, it was discussed in the magmatic domain.

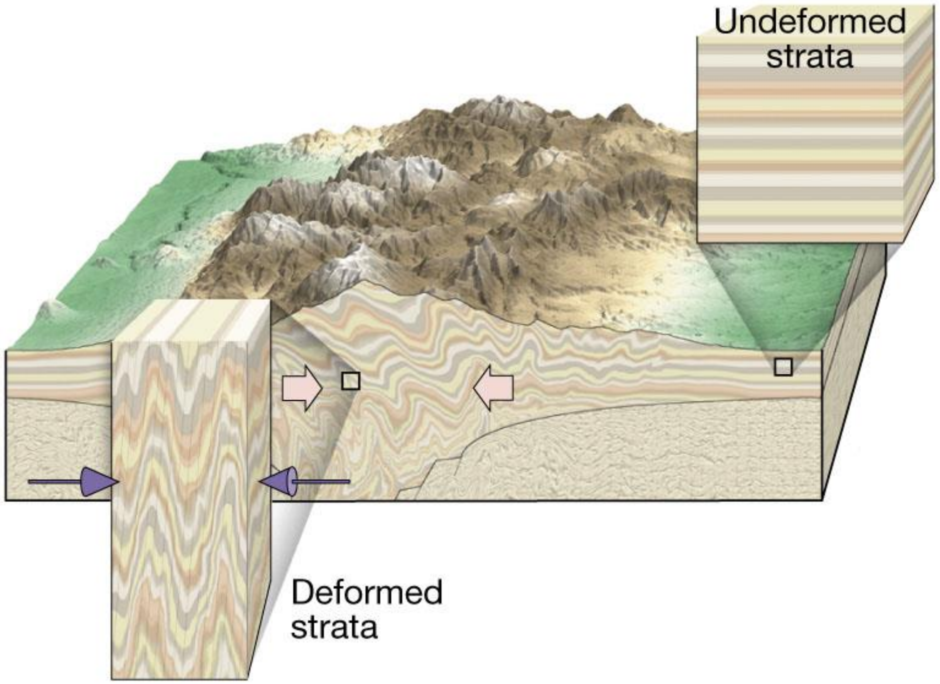




Orogenic (regional) metamorphism of ore deposits is common. Temperatures may reach 1100°C and pressures 30 kbar. Under these conditions, volatiles (water, etc.) are partly to wholly (at very high metamorphic grades) removed from the system. Metamorphic rocks exhibit grain coarsening, preferred orientation of minerals and a penetrative fabric (e.g. schistosity, foliation).



Under regional metamorphic conditions, oxides, especially of iron and manganese, react readily with carbonate and silicate minerals. This caused, for example, formation of the diagenetic-metamorphic skarn rocks in Sweden. Elevated Mn-contents of metamorphic silicates (garnet, pyroxene, stilpnomelane, etc.) conserve the geochemical halos of Sedex ore deposits and are useful prospecting tools.



Ores could also be formed from metamorphic fluids. The metamorphic fluids can be considered as solutions that are in equilibrium with host rocks, and although they are dilute, their sheer mass allows significant transfer of dissolved matter.

Metamorphic fluids originate primarily by chemical release (devolatilization). Increasing metamorphism, from sub-greenschist facies to anatexis, produces a steady flow of metamorphic dehydration fluids and a decrease of volatiles in the respective metamorphic rocks.

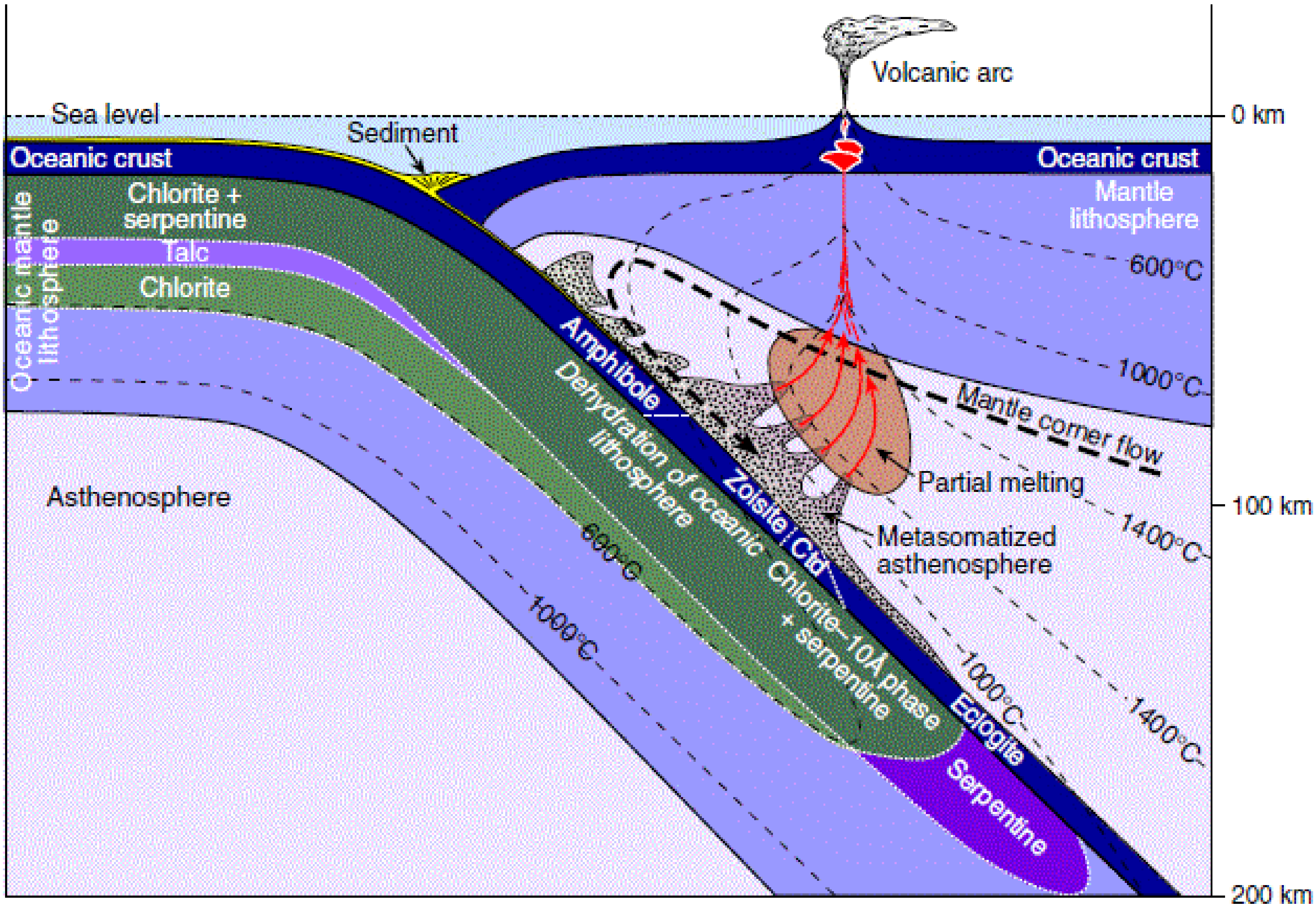
Shales contain 4 wt.% water in contrast to mica schist with 2%. By exothermic reactions, basalt assimilates water during the formation of greenschists to a maximum of 13%. Siliceous carbonates lose CO2 due to generation of metamorphic calcsilicate minerals.

Example of dehydration reactions at the transition from greenschist to amphibolite:

$$\underset{(Fe,Mg)_5Al_2Si_3O_{10}(OH)_8}{4\ \text{Chlorite}} + \underset{Ca_2Al_3Si_3O_{12}(OH)}{18\ \text{Zoisite}} + \underset{SiO_2}{21\ \text{Quartz}}$$
$$= \underset{Ca_2(Fe,Mg)_3(Al)_2\ Al_2Si_6O_{22}(OH)_2}{5\ \text{Tschermakite-amphibole}}$$
$$+ \underset{CaAl_2Si_2O_8}{26\ \text{Anorthite}} + 20\,H_2O \qquad (1.25)$$

Water in metamorphic rocks occurs mainly in OH-groups of hydrous minerals and in fluid inclusions. Grain boundaries also host tiny inclusions. Some fluids fill open fissures and the pore space.

Fluids liberated from rocks undergoing prograde metamorphism acquire economically interesting trace metals (e.g. gold) or other elements (arsenic), either together with the volatiles H2O, F and Cl from the lattice of transforming minerals.



Volcanic arc
Sea level
0 km
Sediment
Oceanic crust
Oceanic crust
Chlorite + serpentine
Talc
Chlorite
Oceanic mantle lithosphere
Mantle lithosphere
600°C
1000°C
Mantle corner flow
Amphibole
Dehydration of oceanic lithosphere
Partial melting
100 km
1400°C
Zoisite / Ctd
Metasomatized asthenosphere
Asthenosphere
600°C
1000°C
Chlorite–10A phase + serpentine
1000°C
1400°C
Eclogite
Serpentine
200 km

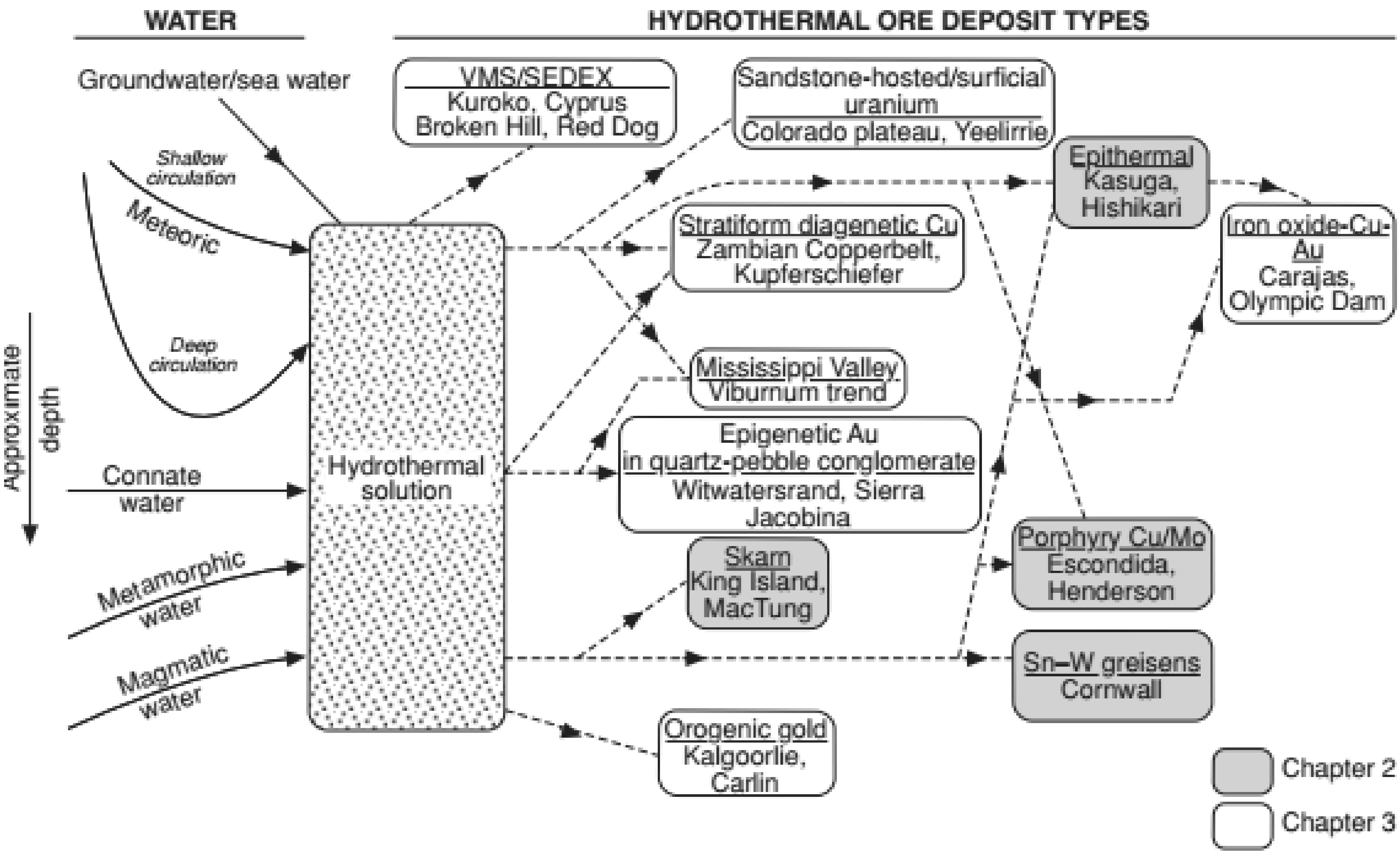
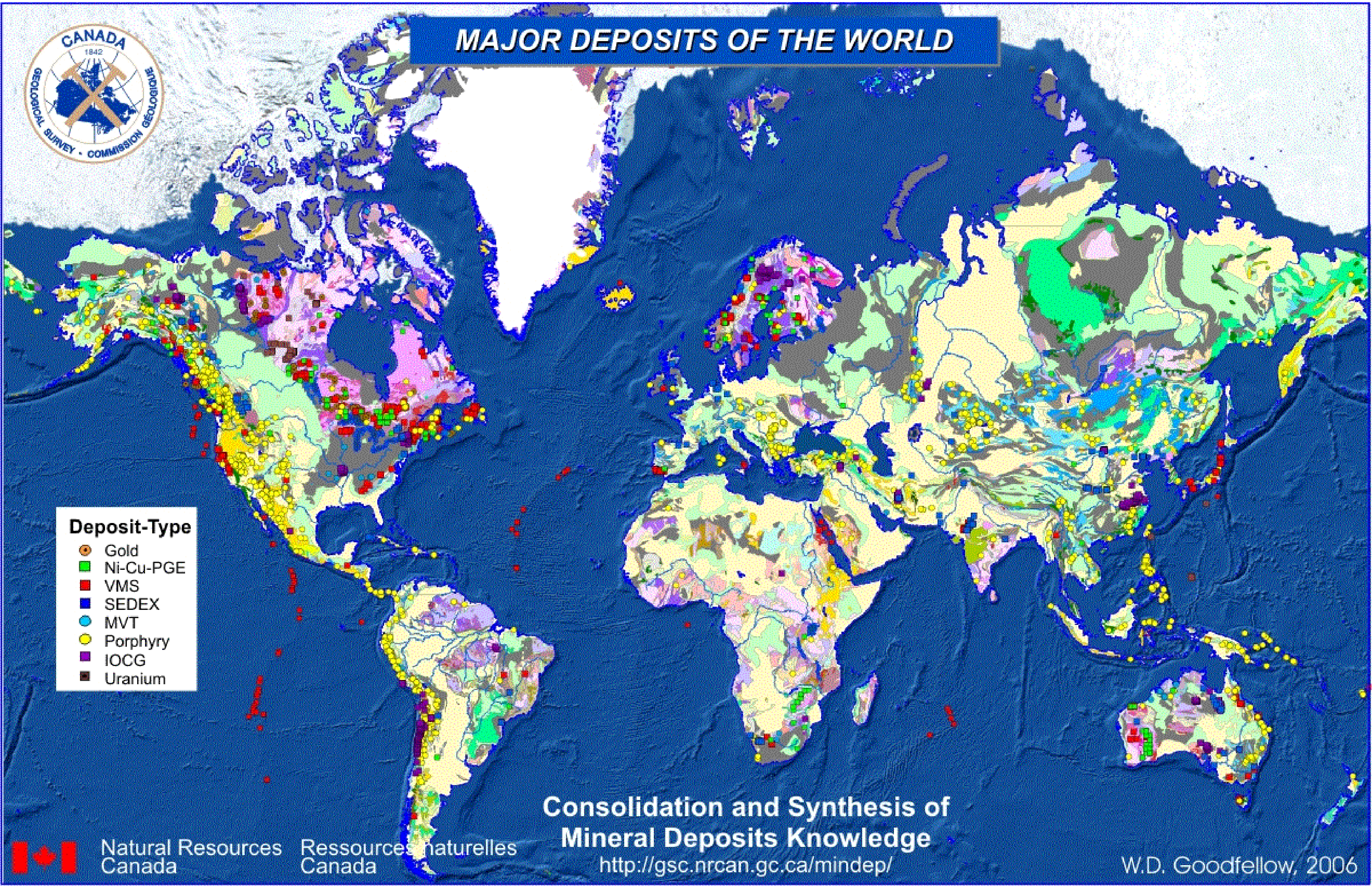


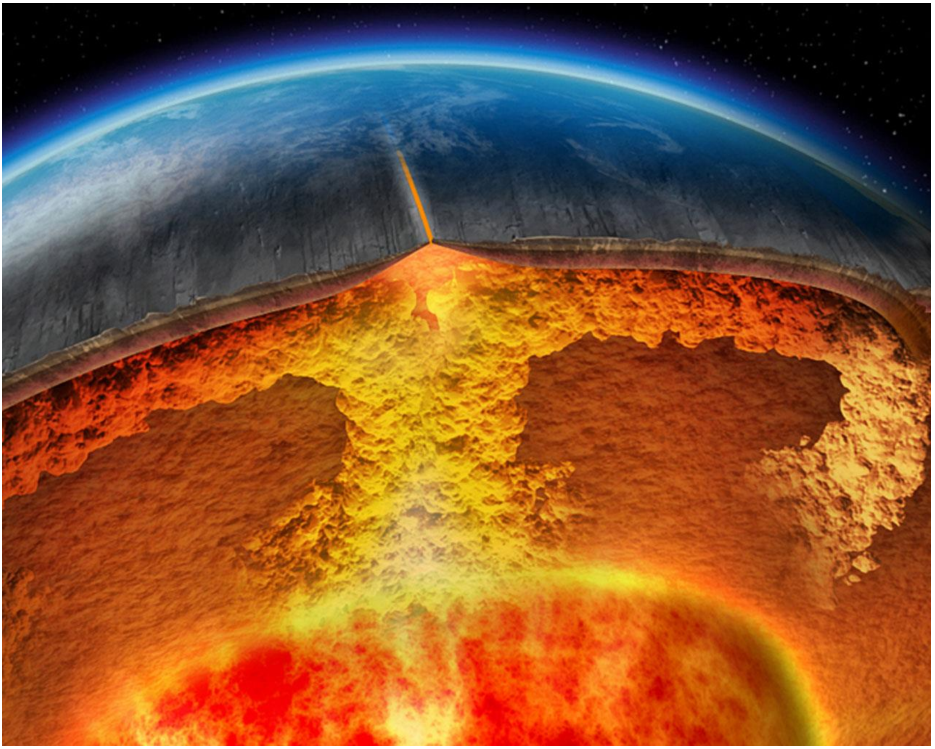
Diagram illustrating the relationship between different fluid types and various hydrothermal ore deposit types

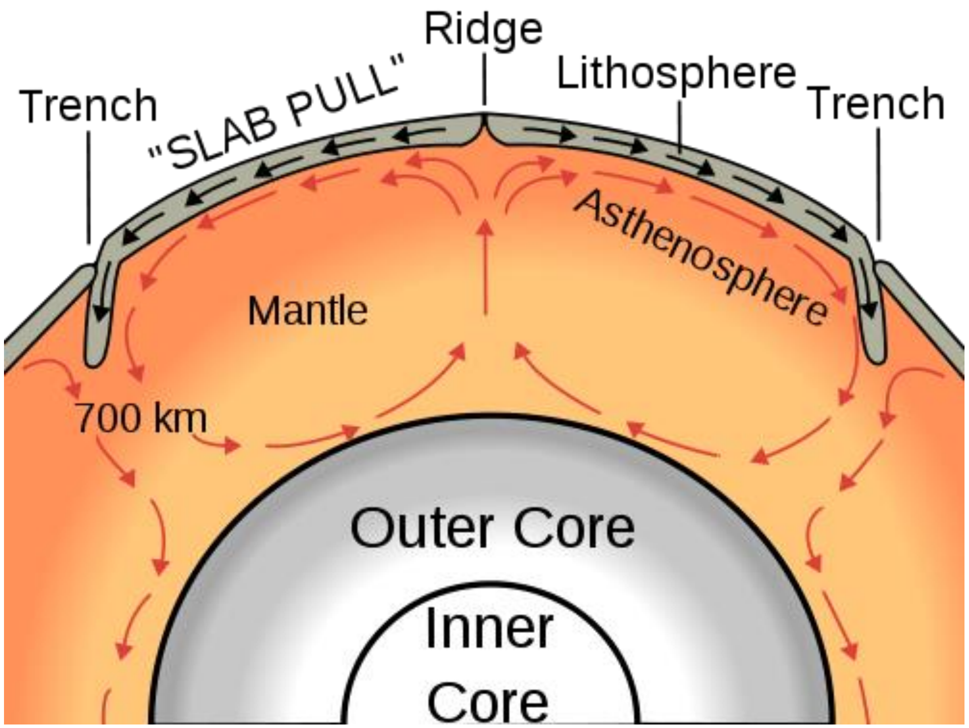


Map of world showing the distribution of major deposits.

Metallogeny and plate tectonics

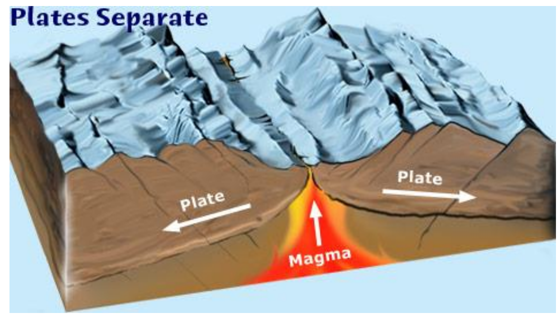
The new concept of plate tectonics recognized that the lithosphere is divided into a number of rigid plates, which display considerable lateral movement. The engine of plate tectonics is convective cooling of the mantle. The resulting lithosphere is in part recycled back into the mantle. Extensional and compressional interactions at plate boundaries are the cause of profusely fertile metallogenetic systems.

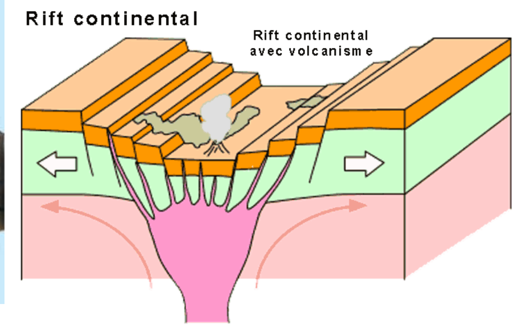




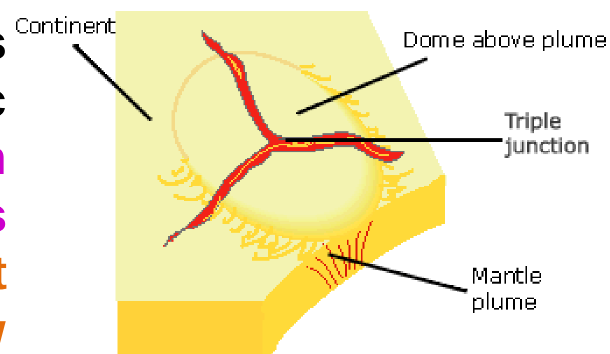
1- The formation of intracontinental rifts, aulacogens and large sedimentary basins (incipient divergent plate boundaries - Extensional setting)

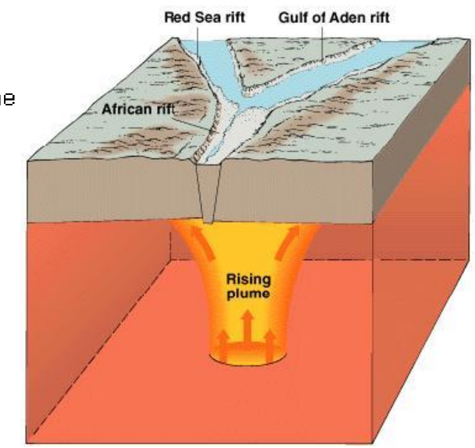
Rifts originate by extensional deformation of lithospheric plates and may or may not evolve into a new plate boundary. Rifting causes: i) thinning of the crust, ii) upflow of hot mantle and iii) updoming of rift shoulders.



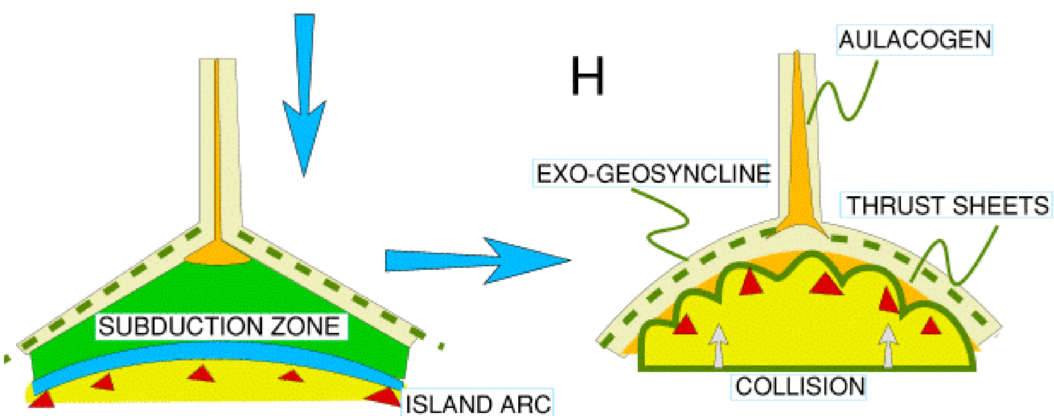


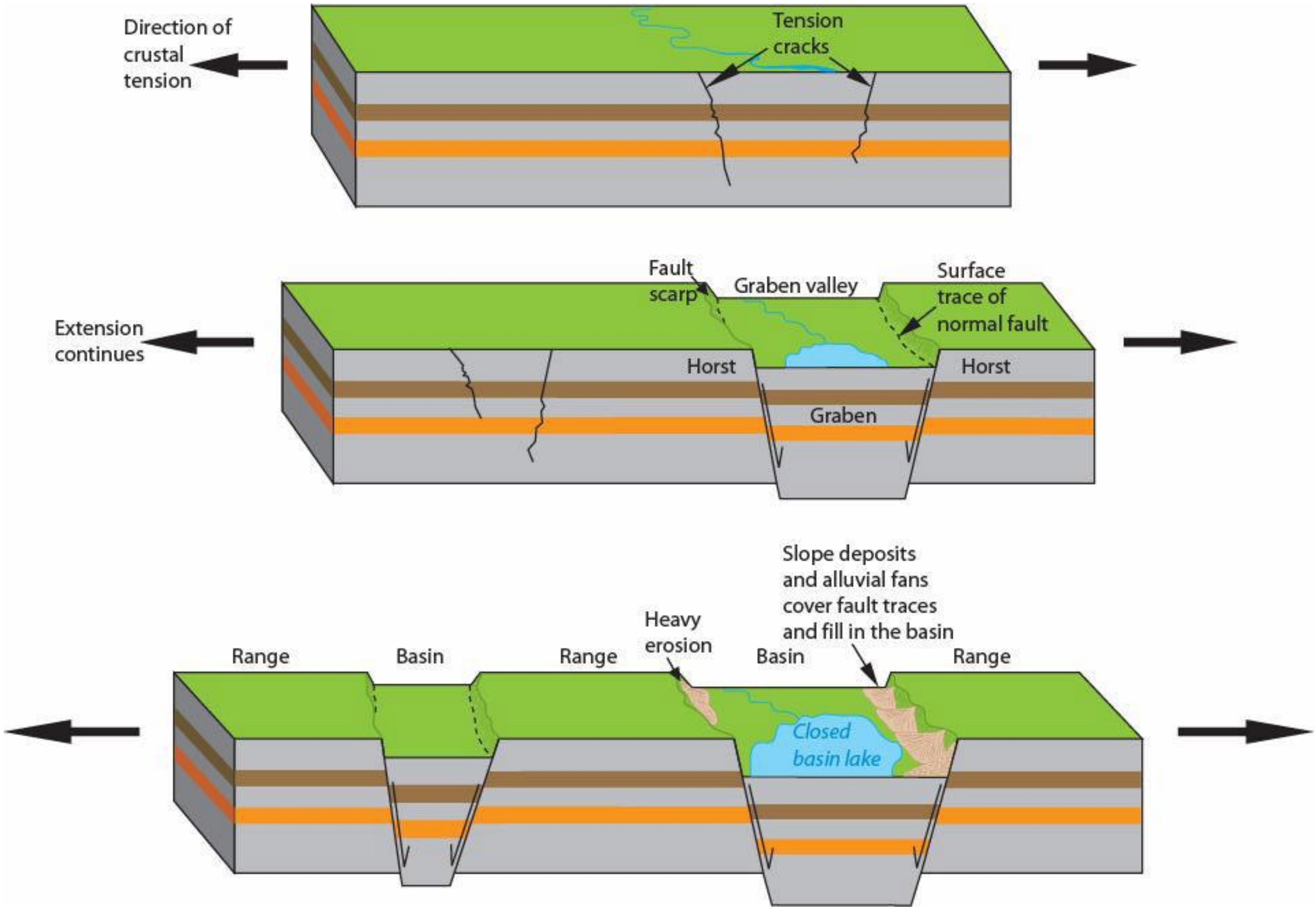
Volcanic activity within the rifts is often organized into large volcanic centres "hot spots". Hot spots can be the origin of three diverging rifts (triple junction). Two of the three rift arms may widen to form a new ocean, whereas the third remains inactive and is called a failed rift arm.





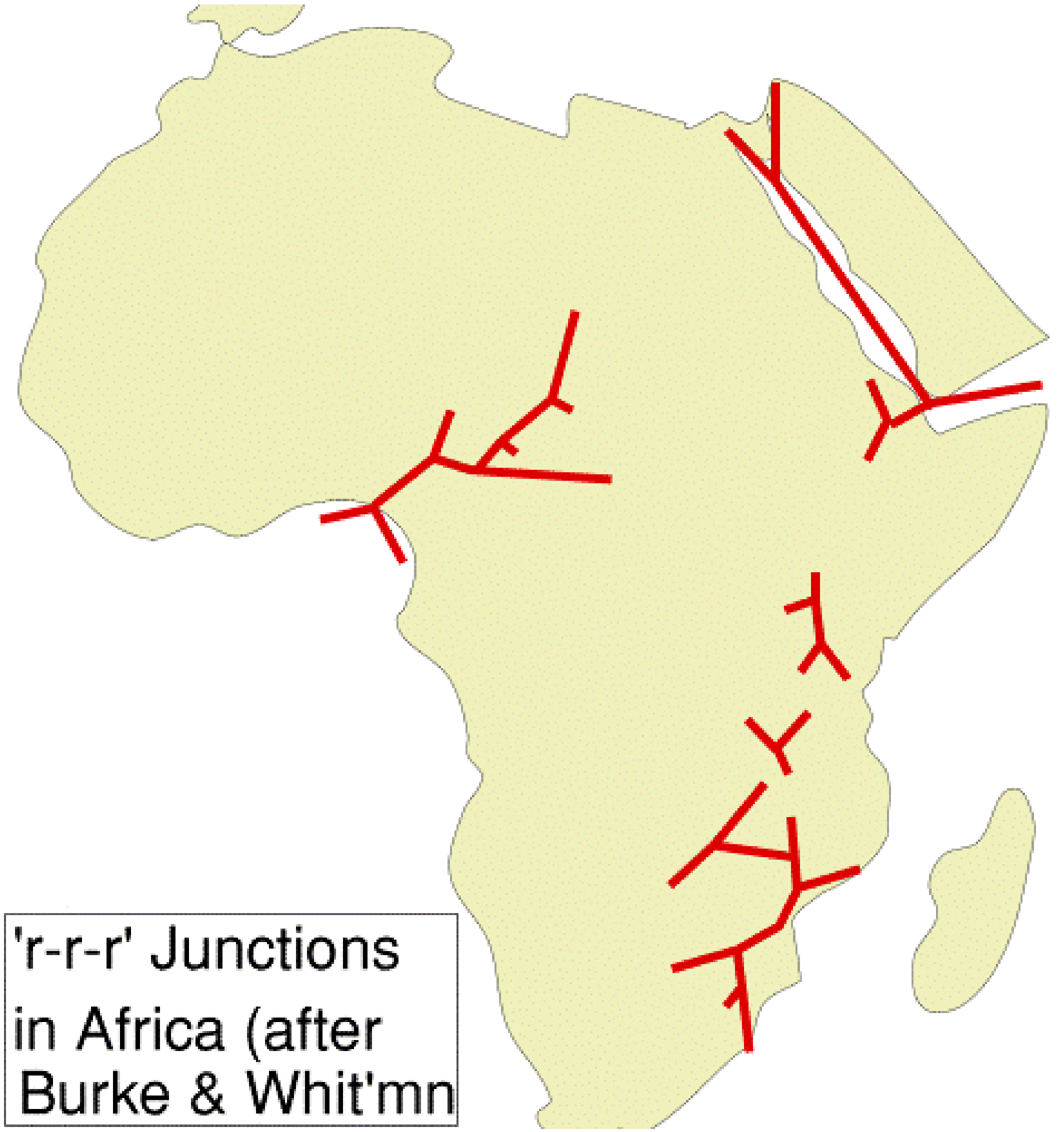
Several failed rift arms display thick sediments. Also, considerable intrusive activity may occur. Settings like this have been called aulacogens (failed arm).





Crustal extension causes the earth's crust to rift, creating horsts and grabens. This basin and range topography occurs along a normal fault.

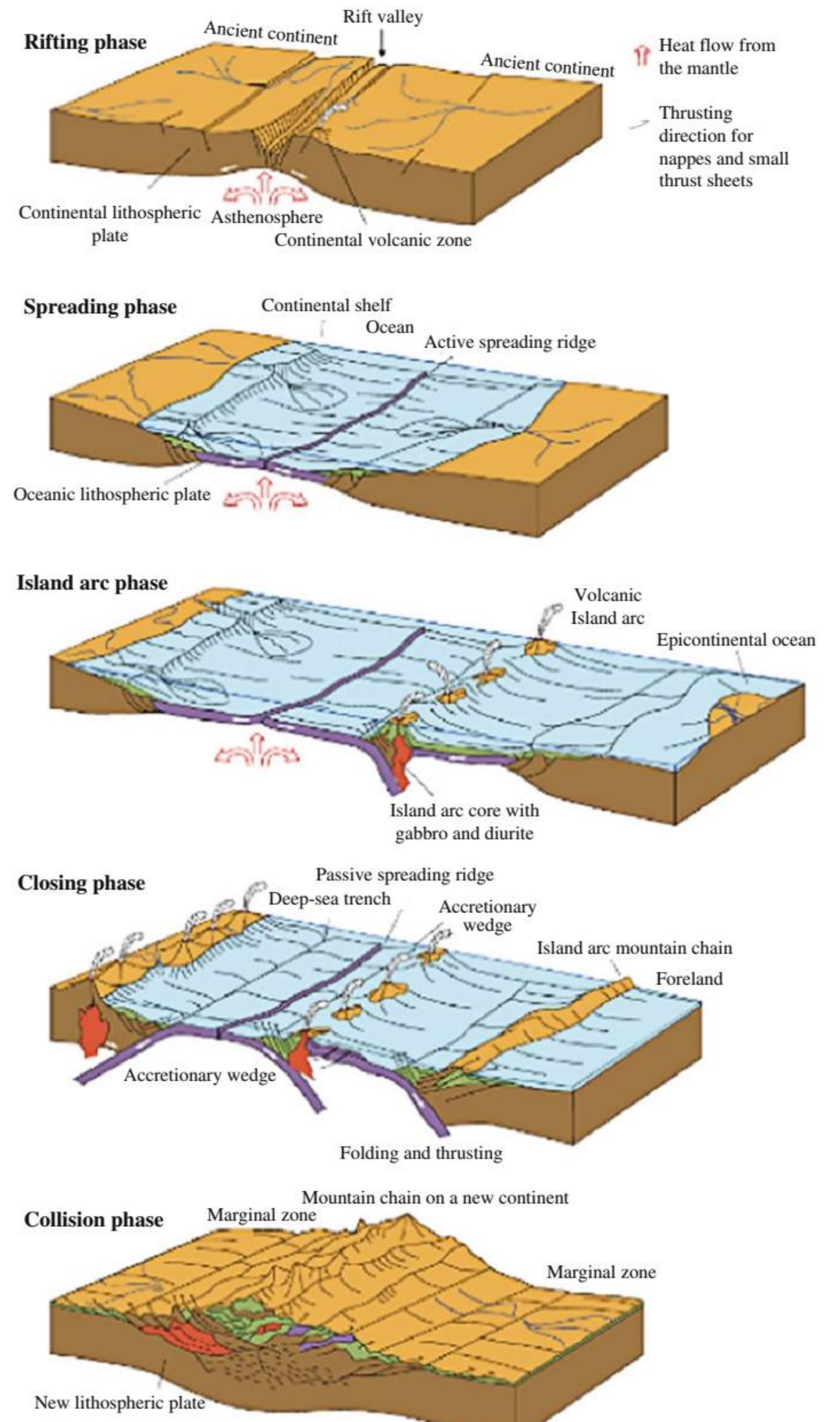
Africa is thought to have been split by a series of rift valleys in various states of development. Those in East Africa are still in thick crust. Those in West Africa are associated with thick oil-bearing sediments. In the Red Sea area the rifting has gone so far as to form a narrow ocean. In the south-east Madagascar has been completely separated from Africa by rifting.



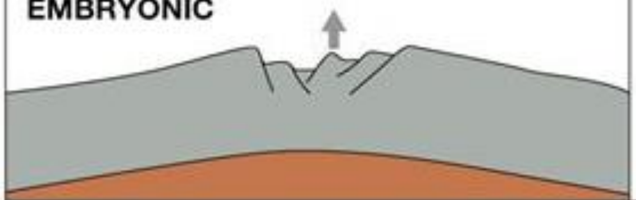
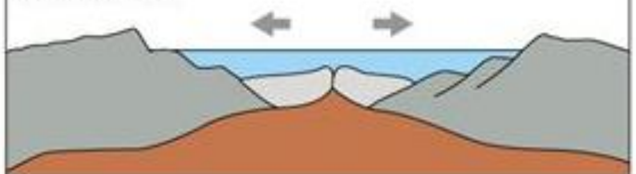
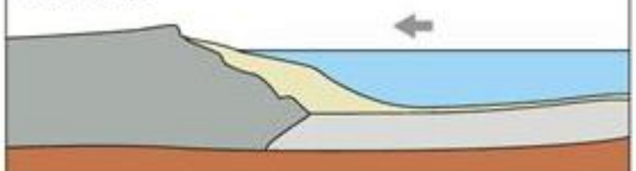
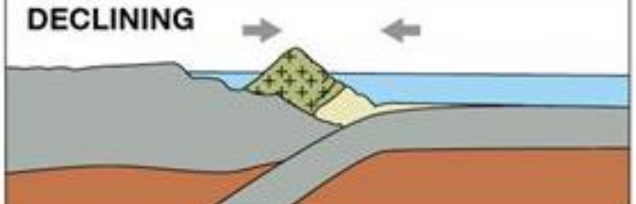
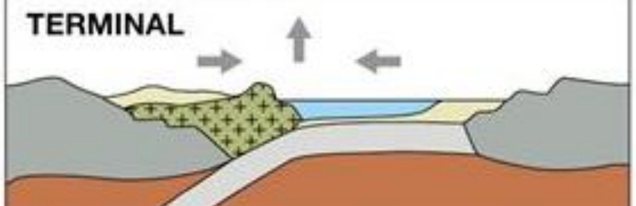
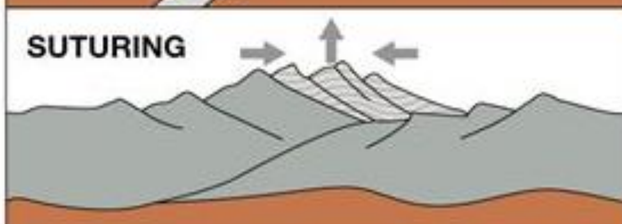
If continents rift apart to form ocean basins, other oceans must close. This may be repeated throughout Earth history. Example: the IAPETUS ocean between England & Scotland in the Lower Palaeozoic, closed in the Caledonian; later opening of the Atlantic, almost in the same place.

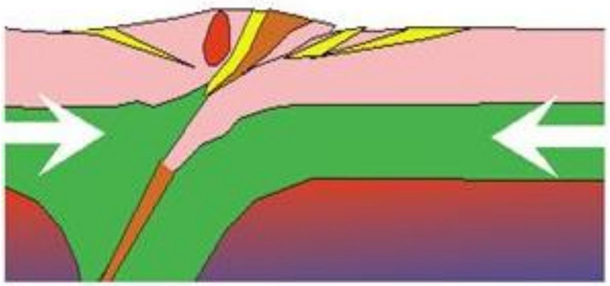
The cycle is known as the Wilson Cycle:

1. Rifting of continents by mantle diapirism;
2. Continental drift, seafloor spreading & formation of ocean basins;
3. Progressive closure of ocean basins by subduction of ocean lithosphere;
4. Continental collision and final closure of ocean basin.



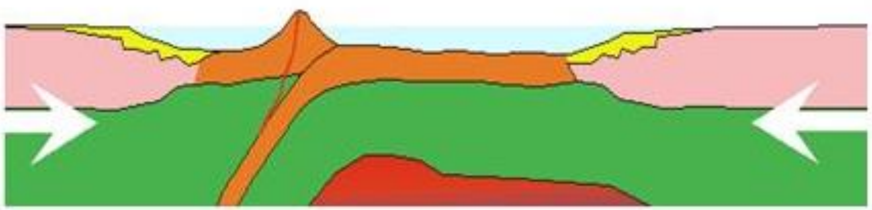
Wilson Cycle

STAGE	MOTION	PHYSIOGRAPHY	EXAMPLE
EMBRYONIC 	Uplift	Complex system of linear rift valleys on continent	East African rift valleys
JUVENILE 	Divergence (spreading)	Narrow seas with matching coasts	Red Sea
MATURE 	Divergence (spreading)	Ocean basin with continental margins	Atlantic and Arctic Oceans
DECLINING 	Convergence (subduction)	Island arcs and trenches around basin edge	Pacific Ocean
TERMINAL 	Convergence (collision) and uplift	Narrow, irregular seas with young mountains	Mediterranean Sea
SUTURING 	Convergence and uplift	Young to mature mountain belts	Himalaya Mountains



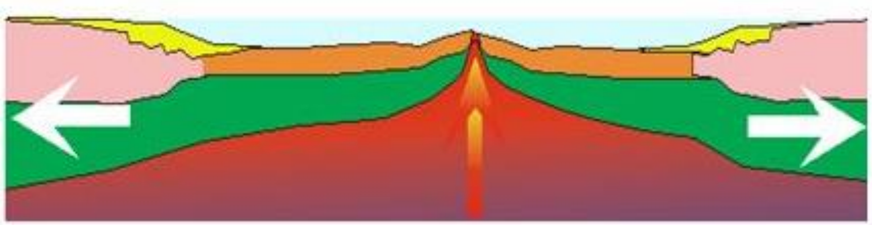
5) Remnant stage

Continental collision, suture zones, deformation and metamorphism, mountain building Extensional collapse, faulting and collapse basins



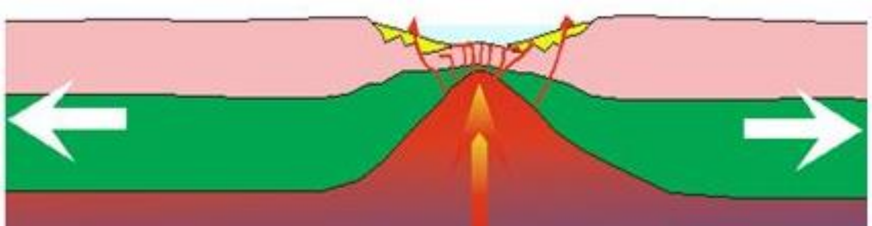
4) Terminal stage

Near closure of ocean, mature arcs and back-arc, accreationary wedges, HP-LT metamorphic complexes (Mediterranean See area)



3) Vaning stage: Intra-oceanic subduction and island arcs transition to Andean margins. (SE Asia and Western Passific)

2) Mature stage Passive margins with large shelf-areas (Atlantic Ocean)



1) Embryonic to Young stage.

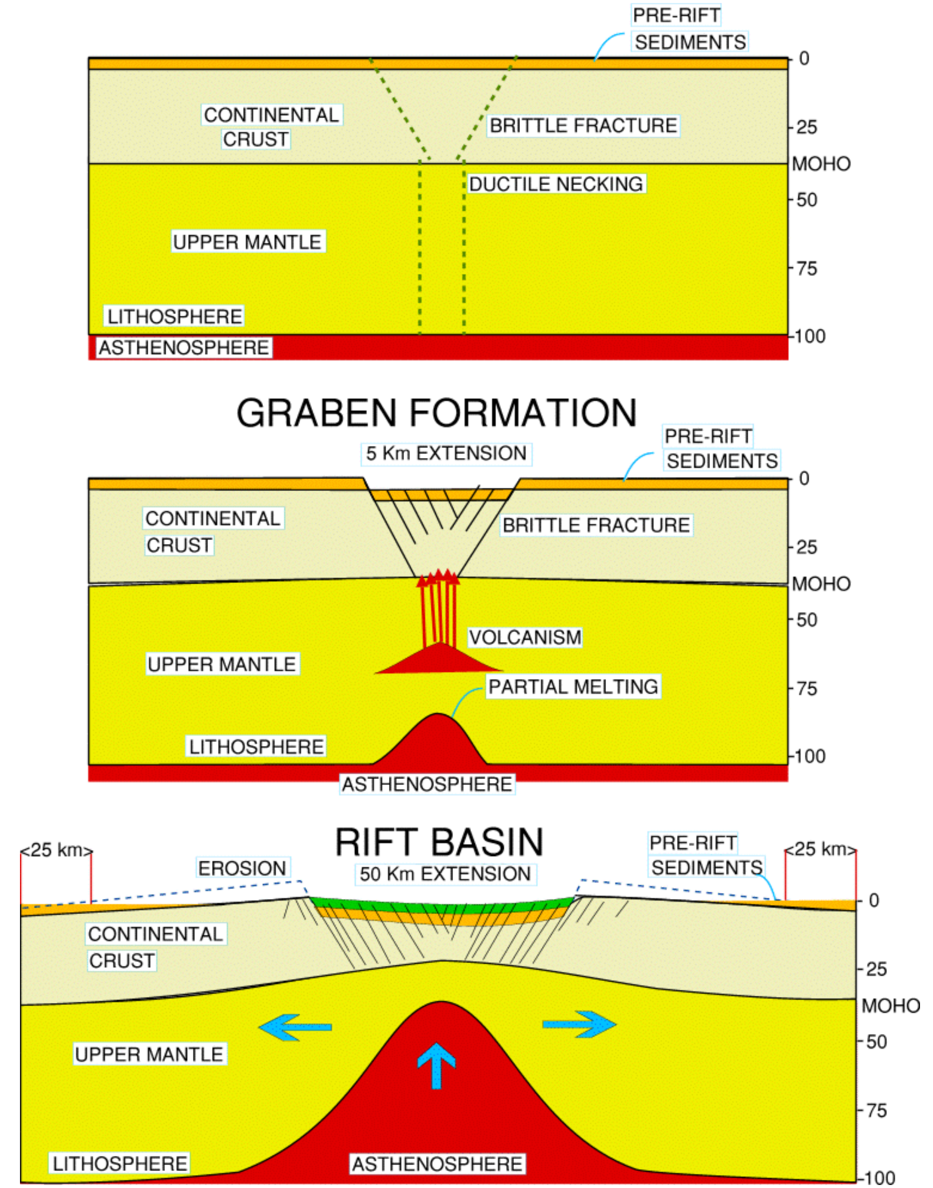
Rifts to small ocean basin with sea-floor spreading. (East African rift and Red Sea)

1. **Sediments of continental rifts include terrestrial/alluvial clastic infill that can contain uranium, placers and coal deposits.**

2. **Freshwater, saline or marine-influenced lake stage succeeds with beds of salt, gypsum, magnesite, phosphate, valuable clays or oil shale.**

3. **Full marine ingression into the widening rift and inception of oceanic spreading can induce submarine metalliferous exhalation of the black smoker or brine pool type (Red Sea) and the deposition of thick marine sedimentary sequences.**

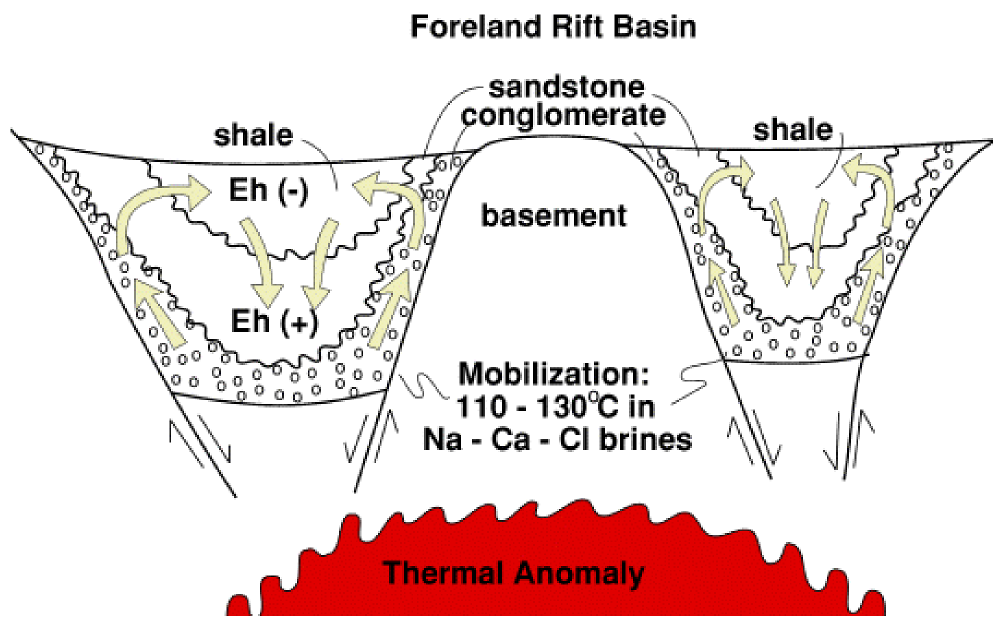
4. **Hot spot-related ore-forming systems include the Bushveld in South Africa, tin-fertile A-granites in Nigeria, many alkali carbonatite igneous complexes with apatite, fluorine, niobium and rare earth element ores.**



Progressive formation of a rift valley through extension of the lithosphere and continental crust. Uprise and decompression of the underlying asthenosphere results in magma formation. The crust responds by brittle fracture. Early rift sediments are downfaulted into the developing rift (graben). Erosion takes place on the sides of the rift valley.

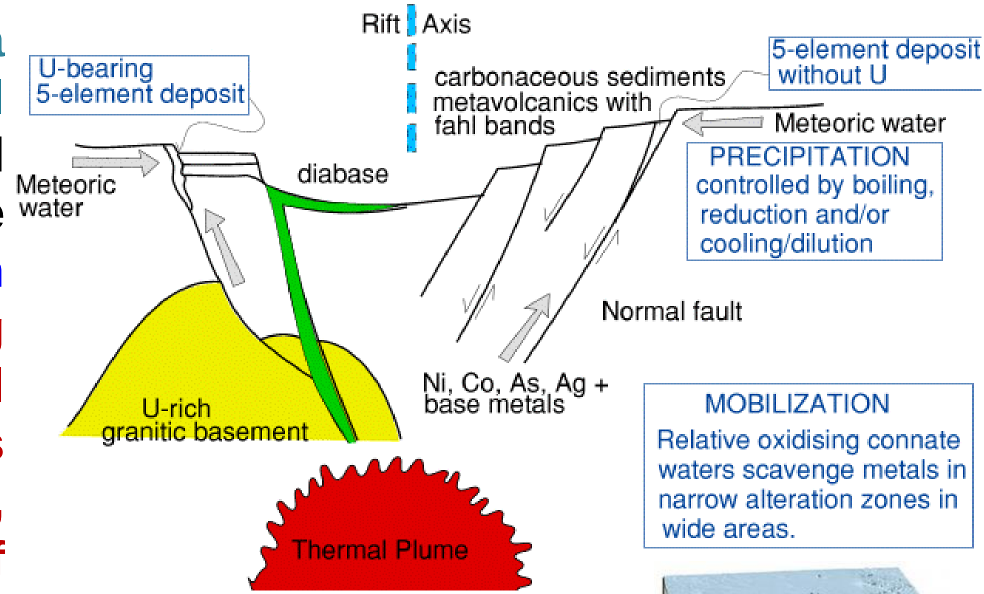
5. Rifts can be sites of thick clastic sedimentation. These sediments hold vast amounts of inter-granular salt water (brines). The brines may be in contact with reducing sediments, such as carbonaceous shales, which are also a ready supply of sulphur/sulphate. As the sediments compact, these brines are expelled and can move laterally for large distances until they move up the rift faults. Having been buried deep the brines get hot, and can be very corrosive. So en route they can dissolve considerable amounts of metals. When they rise up the rift faults, the brines cool down and allowing metals to precipitate out. This can be enhanced because oxidising meteoric water (groundwater) may also penetrate down these faults, so metals will be precipitated out when the two meet.

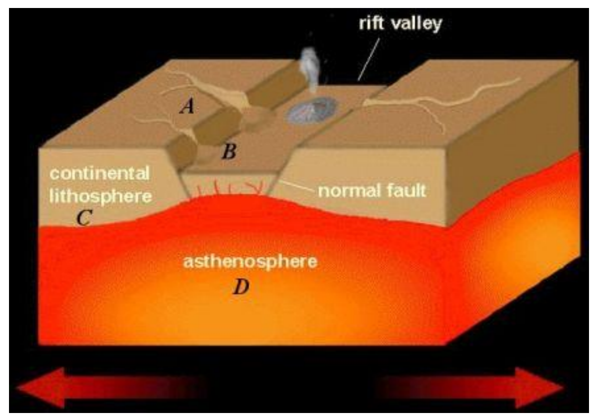
Shale-hosted Stratiform Copper Deposit

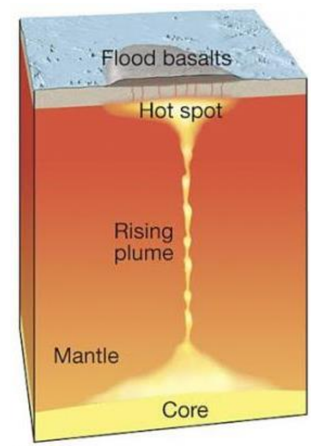


Prominent ore provinces include the European Copper Shale which is formed this way.

6. When rifting reaches the stage of a deep graben with vertical displacement at marginal faults (well into the upper mantle in some cases), hydrothermal convection systems may form. The ascending branch of these hydrothermal systems typically results in deposits of lead, zinc, silver, manganese, fluorine and barite, in the form of veins and metasomatic replacement bodies in rift margin rocks, or of ore beds in the graben sediments. Good examples are many Pb-Zn and Mn occurrences in Tertiary sediments on both sides of the Red Sea.

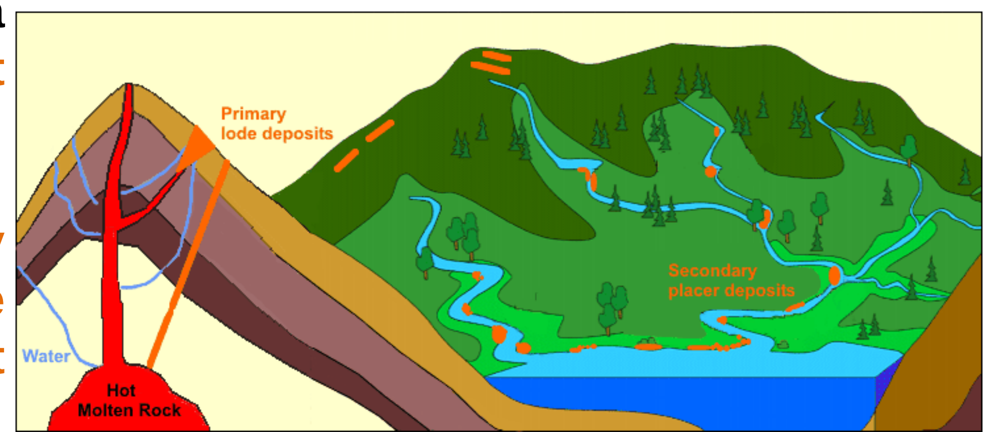






7. Flood basalt volcanism may be a result of volcanism producing giant Cu-Ni-PGE deposits.

8. Placer gold and Mississippi Valley type (MVT) lead-zinc-barite fluorite deposits are also possible in the rift environment.

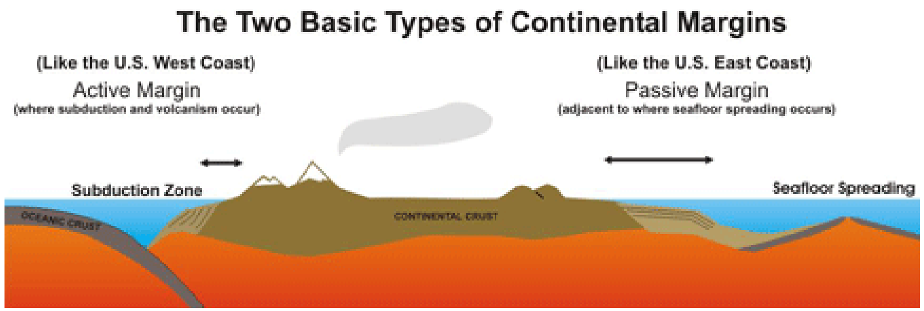


2- The evolution of passive continental margins and the disruption of older ore provinces (divergent plate boundaries - Extensional setting)

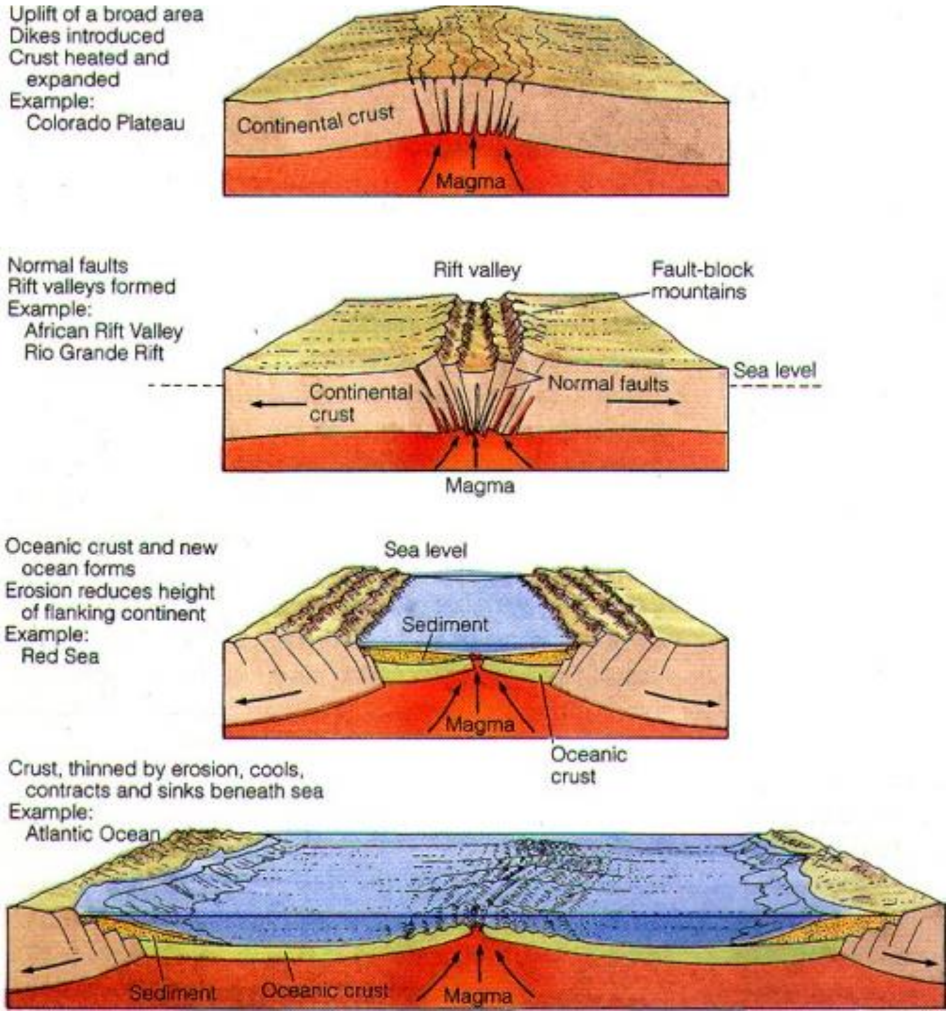
The opening of new oceans passes from a high heat-flow rift stage into a marine transgression and thermal contraction phase. Relatively shallow, epicontinental seas may form. As the young ocean widens, passive continental margins develop.

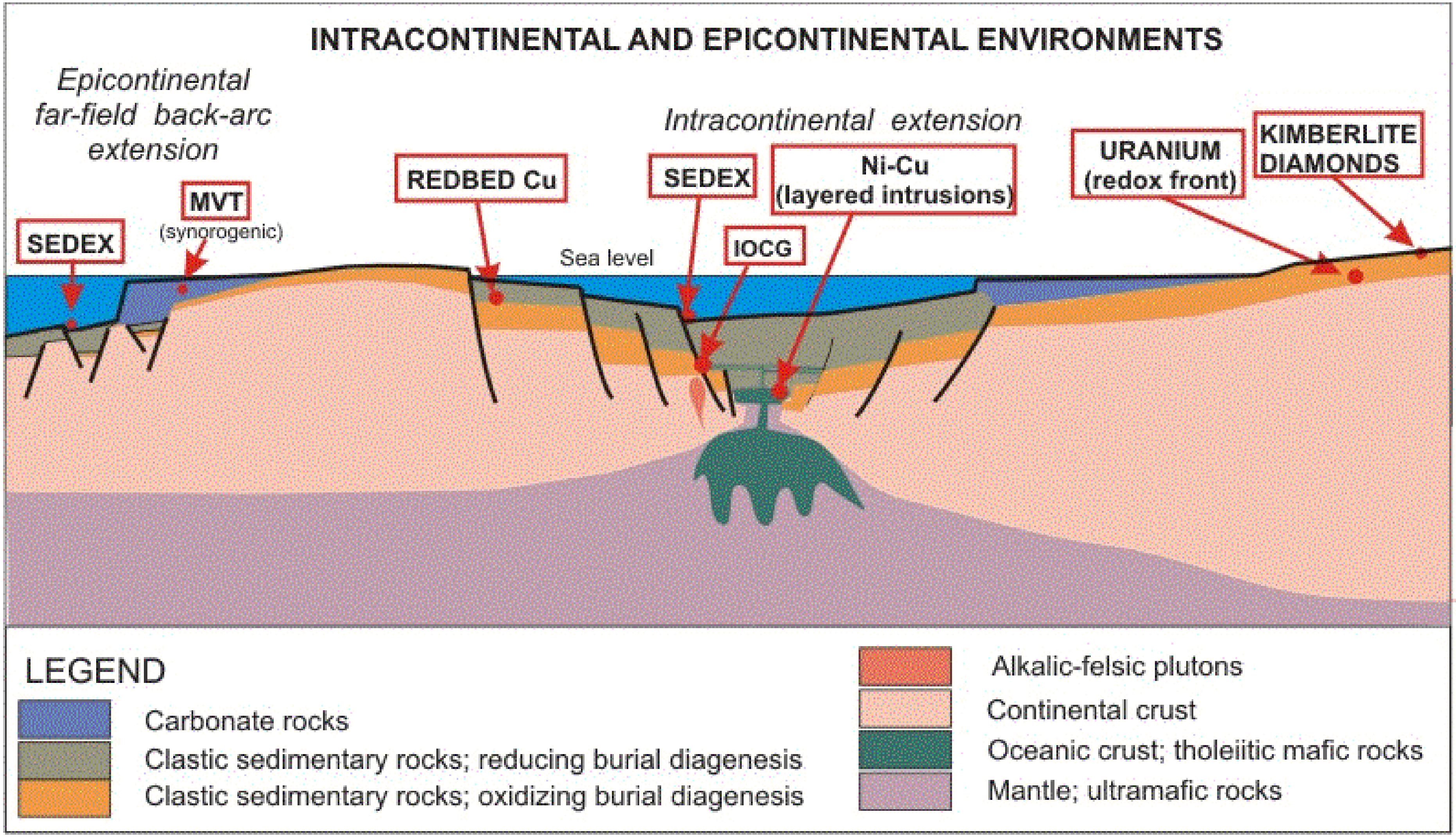
Typical marine epicontinental shelf ore deposits include:

1. **salt, phosphate and hydrocarbon source rocks;**
2. **manganese ore beds;**
3. **metalliferous marine placers; and**
4. **banded iron ores of the Superior type.**



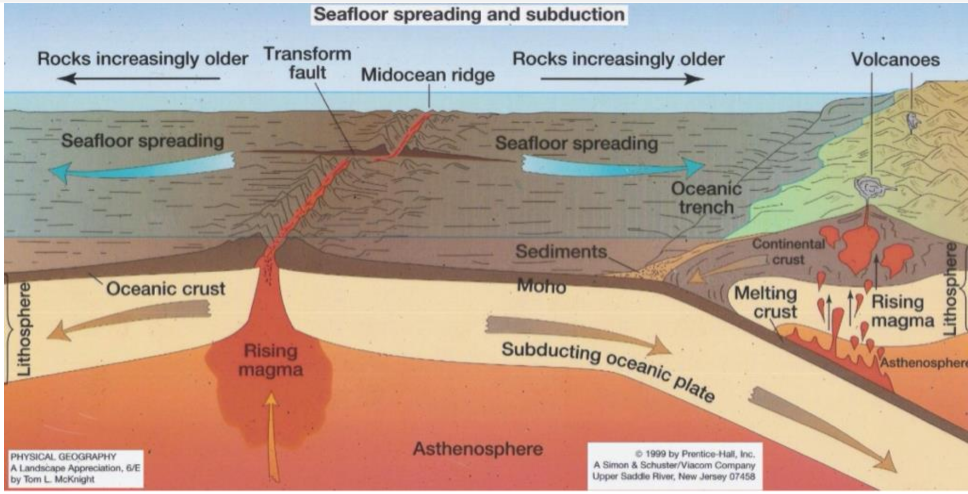
Epicontinental sea "inland/epriric sea" is a shallow sea that covers central areas of continents (e.g., Caspian Sea – the largest lake on the Earth).



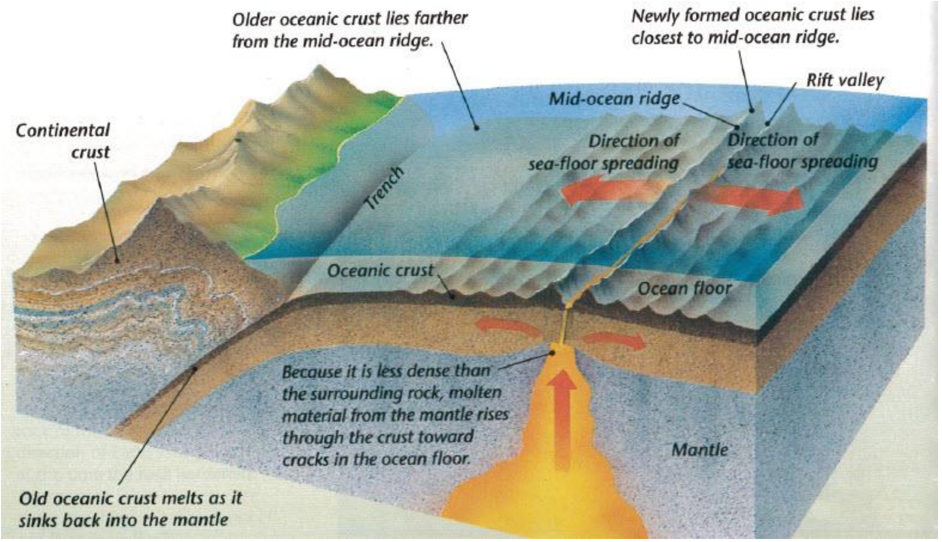


Schematic illustration of the major geological characteristics of mineral deposit types that typically occur in ore-forming environments within the interior regions of continents. (IOCG: iron oxide-copper-gold)

3- Seafloor spreading and the production of new lithosphere at mid-ocean ridges (oceanic divergent, or "constructive" plate boundaries - Extensional setting)



This concerns ore formation at mid-ocean ridges and in Ophiolites. After obduction, the products of these processes are ophiolite-hosted deposits. Many ophiolites, however, were not formed at mid-ocean rifts but in tensional settings including back-arc spreading systems, or rifts of primitive island arcs (e.g. the Cyprus ophiolite).



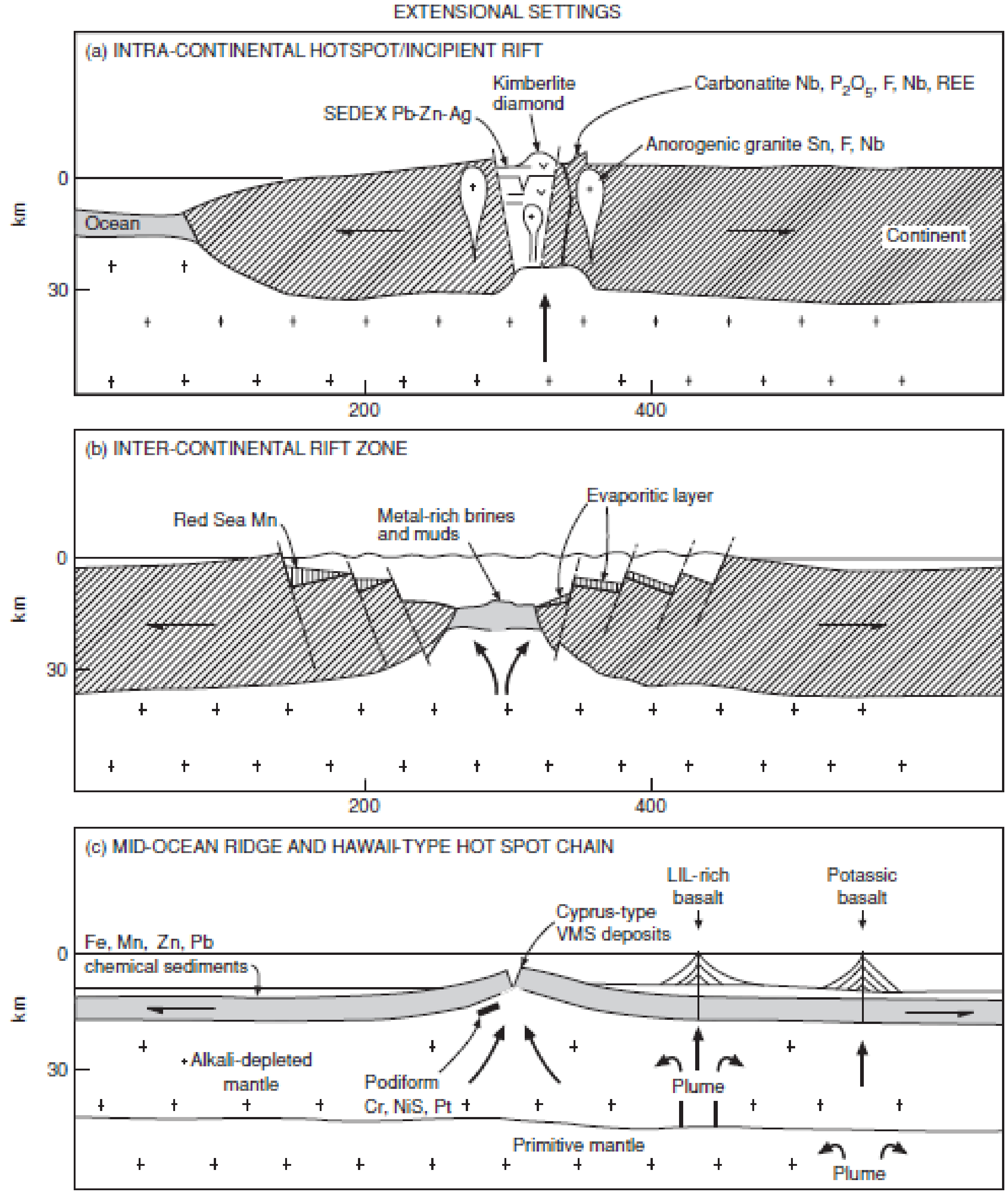
Related ores are:

1. sulphide mounds or mud pools;
2. iron-manganese oxides (ochres and numbers); and
3. distal manganese crusts and nodules with important contents of Cu, Ni and Co.

Incipient rifting of stable continental crust where thinning and extension may be related to hotspot activity. Magmatism is often localized along old sutures and is alkaline or ultrapotassic (kimberlites and lamproites) in character. Anorogenic granites such as those of the Bushveld Complex (Sn, W, Mo, Cu, F, etc.), pyroxenite–carbonatite intrusions such as Phalaborwa (Cu–Fe–P–U–REE etc.), and kimberlites (diamonds) represent ore deposits formed in this setting. Intracontinental rifts can host SEDEX-type Pb–Zn–Ba–Ag deposits (Fig. a).

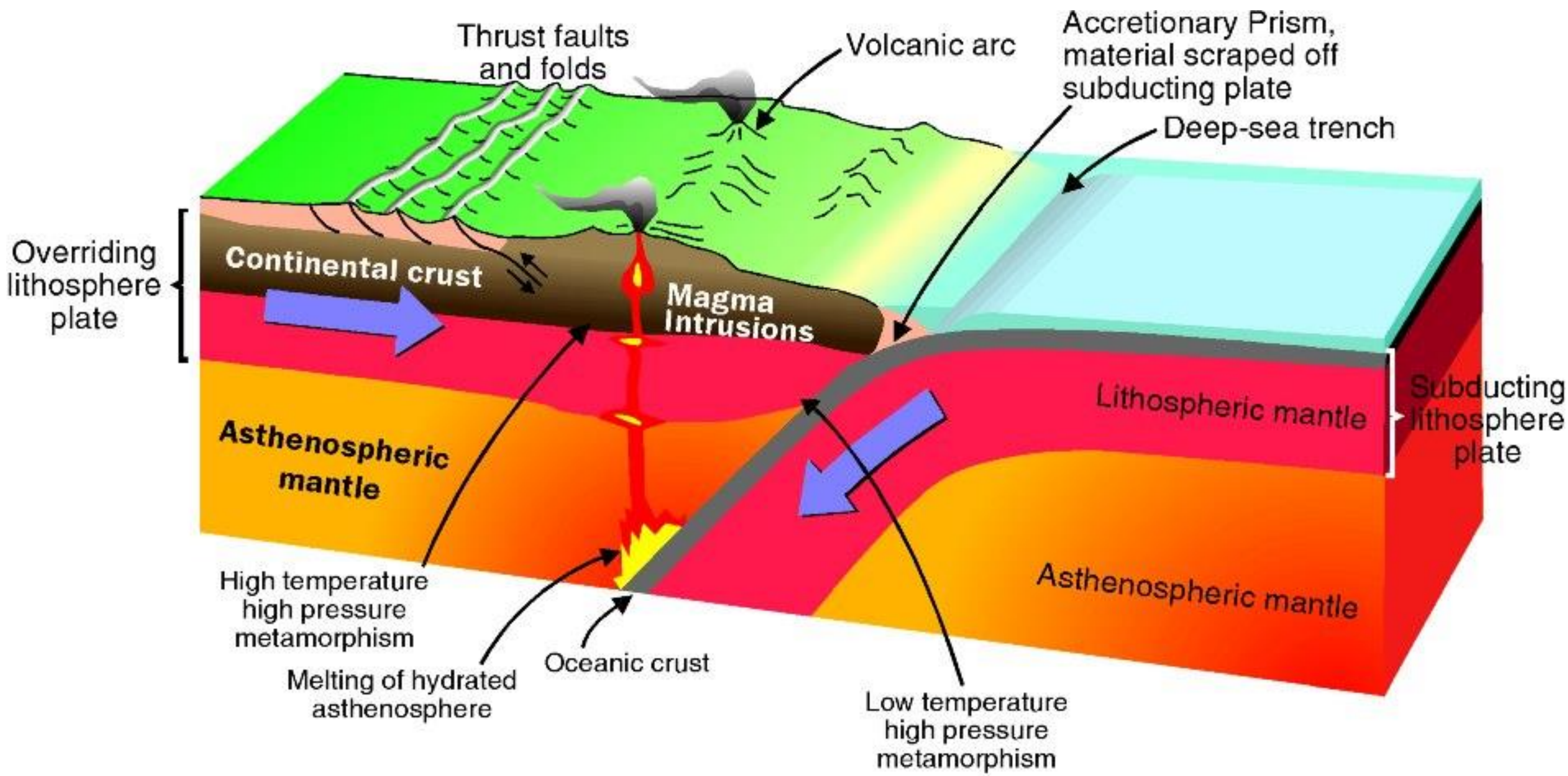
As continental rifting extends to the point that incipient oceans begin to open (such as the Red Sea; Fig. b), basaltic volcanism marks the site of a mid-ocean ridge and this site is also accompanied by exhalative hydrothermal activity and plentiful VMS deposit formation. Such settings also provide the environments for chemical sedimentation and precipitation of banded iron-formations and manganiferous sediments. Continental platforms host organic accumulations that on catagenesis give rise to oil deposits. Carbonate sedimentation ultimately provides the rocks which host MVT deposits, although the hydrothermal processes that give rise to these epigenetic Pb–Zn ores are typically associated with circulation during compressional stages of orogeny.

Mid-ocean ridges are the culmination of extensional processes (Fig. c). Exhalative activity at these sites gives rise to "black-smoker" vents that provide the environments for the formation of Cyprus type VMS deposits. The basalts which form at mid-ocean ridges also undergo fractional crystallization at sub-volcanic depths to form podiform chromite deposits as well as Cu–Ni–PGE sulfide segregations.



4- Subduction of lithospheric plates at convergent ("destructive") plate boundaries (Compressional settings)

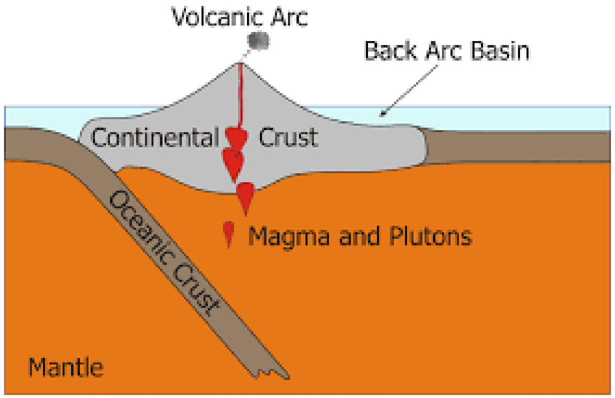
Subduction recycles oceanic lithosphere back into the mantle. The trace of subduction on the seafloor is marked by deep oceanic trenches. Volcanic/Island arcs develop on the overriding plate.

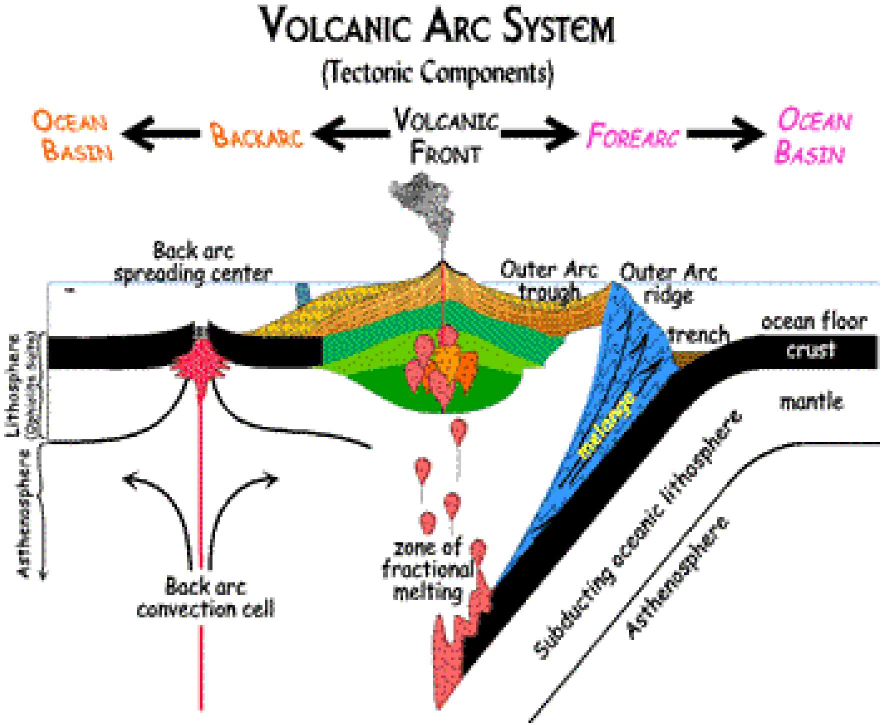


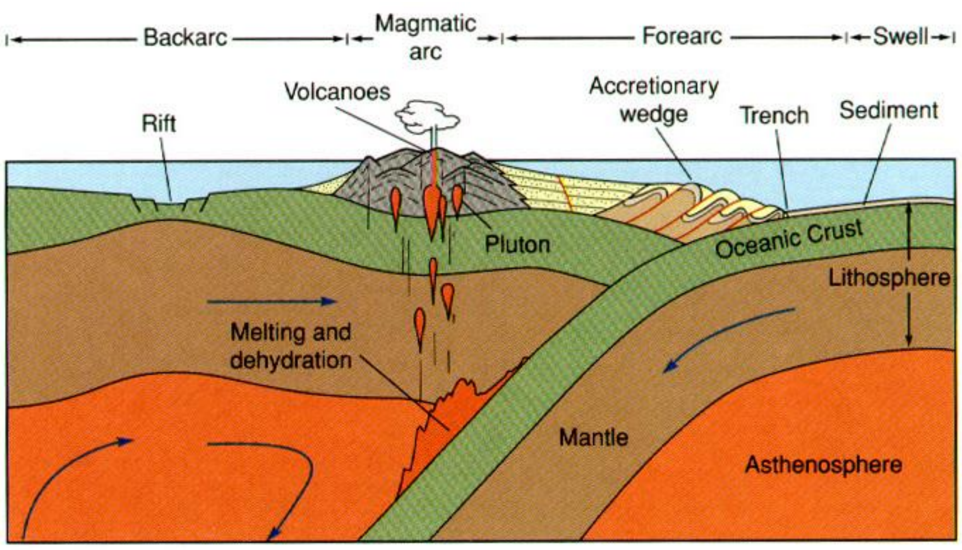
Volcanic arcs in dominantly oceanic settings form **island arcs**, whereas active continental margins display **continental or Cordilleran arcs.**

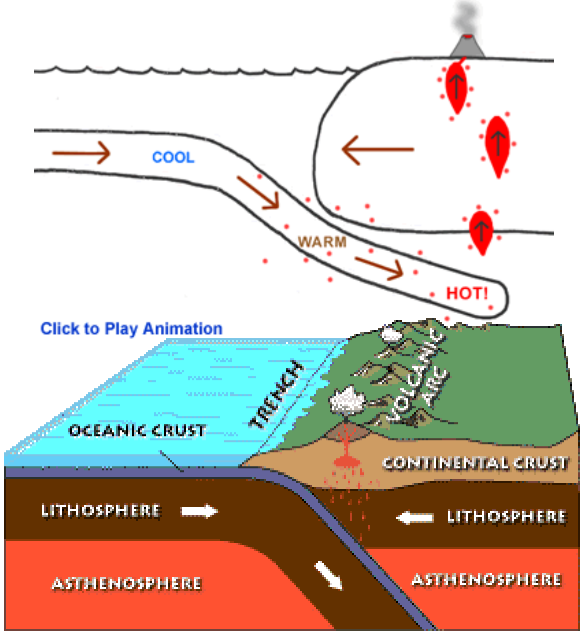
There is a great diversity of subduction zone configurations, due to many variables including slab density, thickness and length. Subduction zones show variously:

1. **high or low trench ward plate velocities;**
2. **trench retreat (or more rarely trench advance) velocities;**
3. **slab dip angles and so forth.**

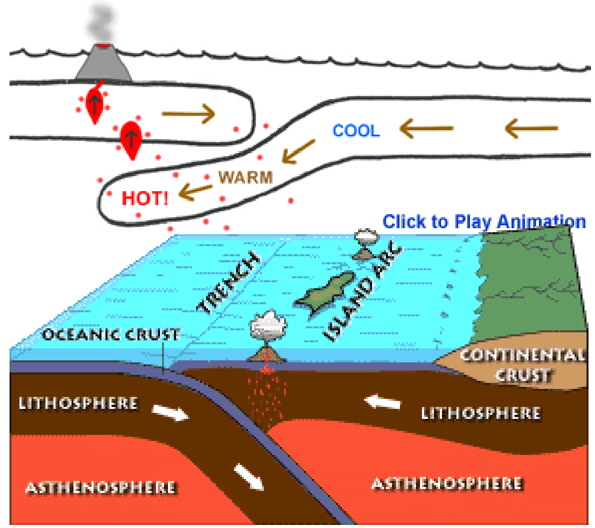




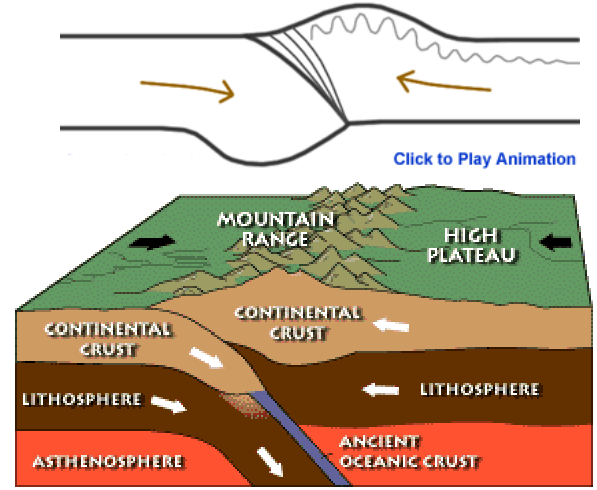




The dense, leading edge of the oceanic plate *pulls* the rest of the plate into the flowing asthenosphere and a subduction zone is born!

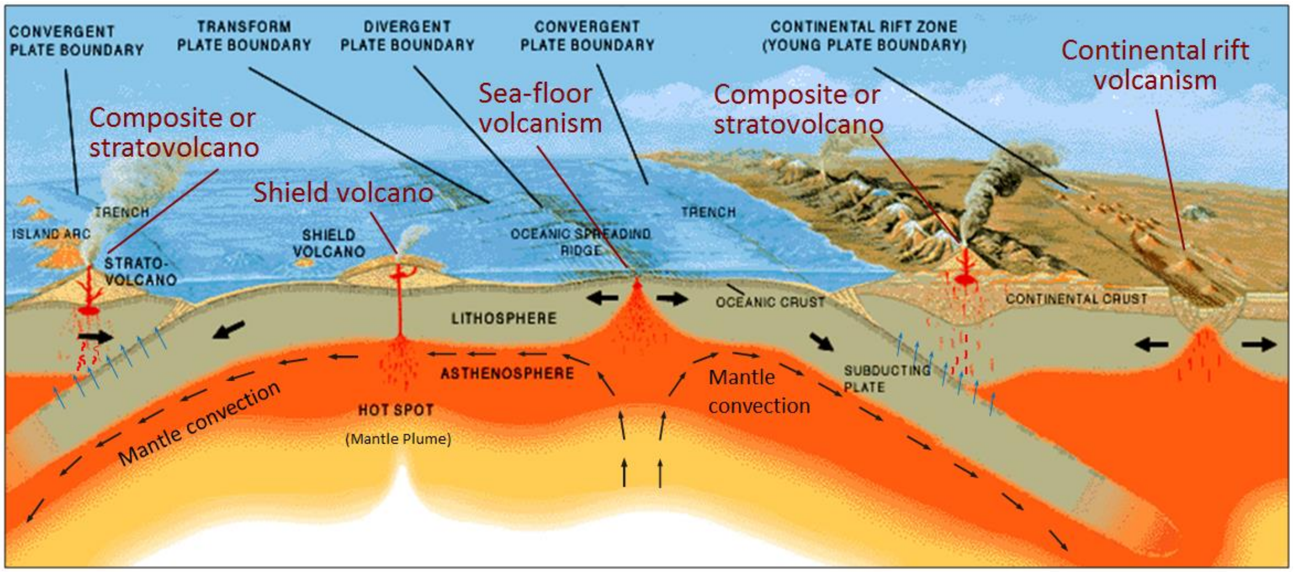


When two oceanic plates collide, the plate that is older, therefore colder and denser, is the one that will sink.

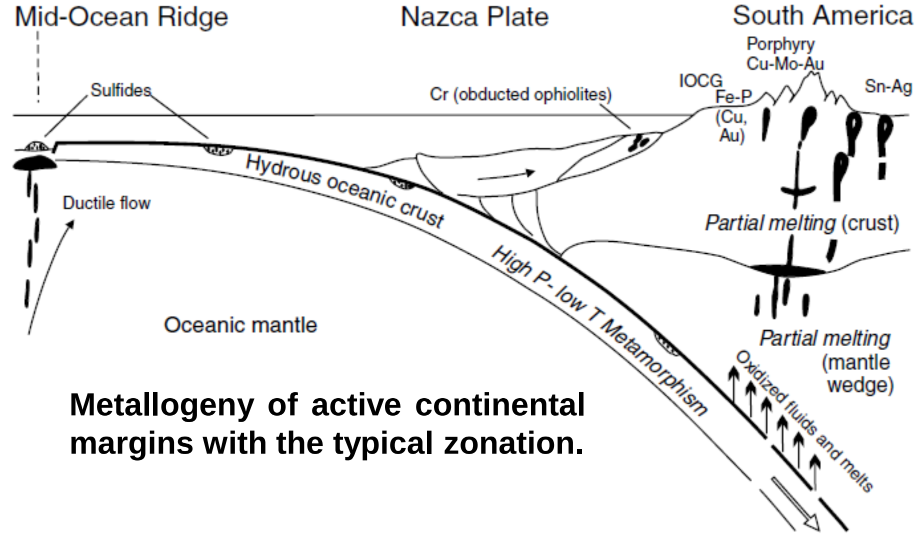


When two huge masses of continental lithosphere meet head-on, neither one can sink because both plates are too buoyant.

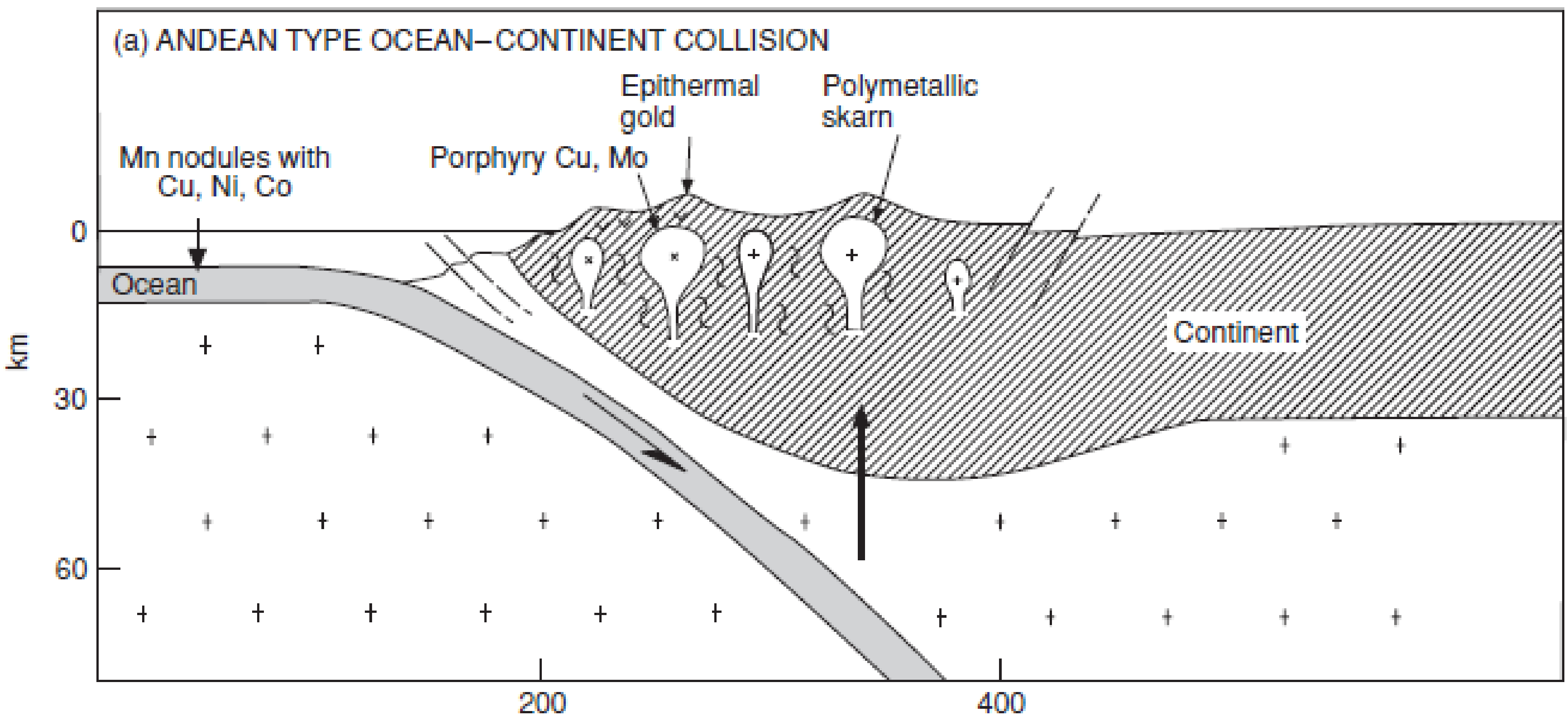
It is important to stress that most of the Earth's richest ore provinces are found **above subduction zones.**



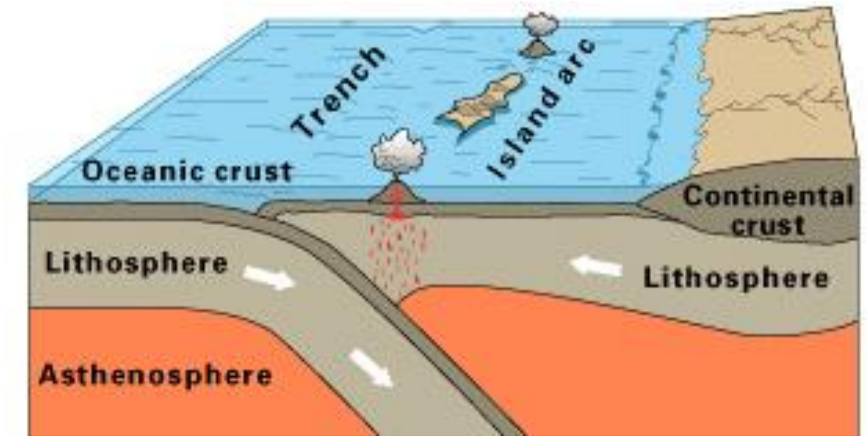
A- The highly significant Andean type (ocean-continent) collisional margins are the sites of the great porphyry Cu–Mo provinces of the world, while inboard of the arc significant Sn–W granitoid-hosted mineralization also occurs. The volcanic regions above the porphyry systems are also the sites of epithermal precious metal mineralization (gold).

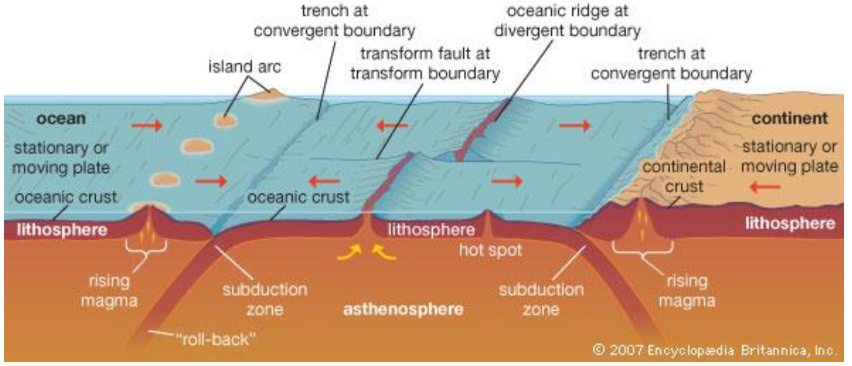


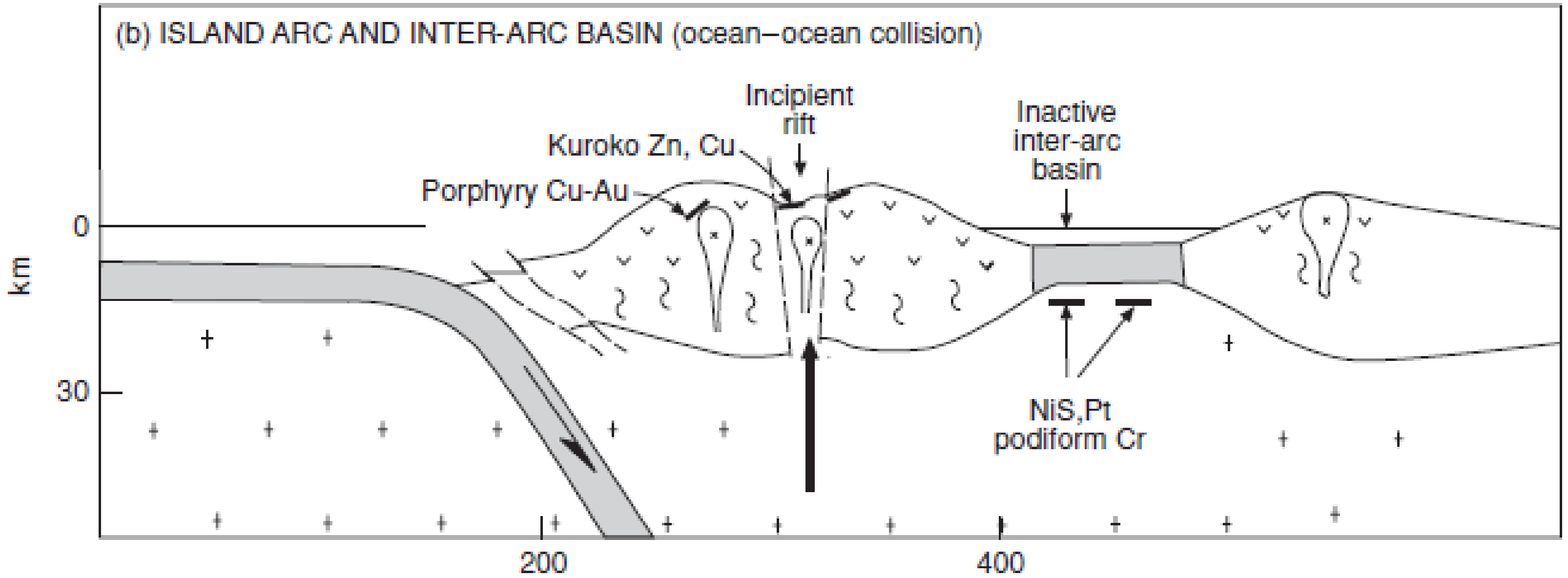
Metallogeny of active continental margins with the typical zonation.



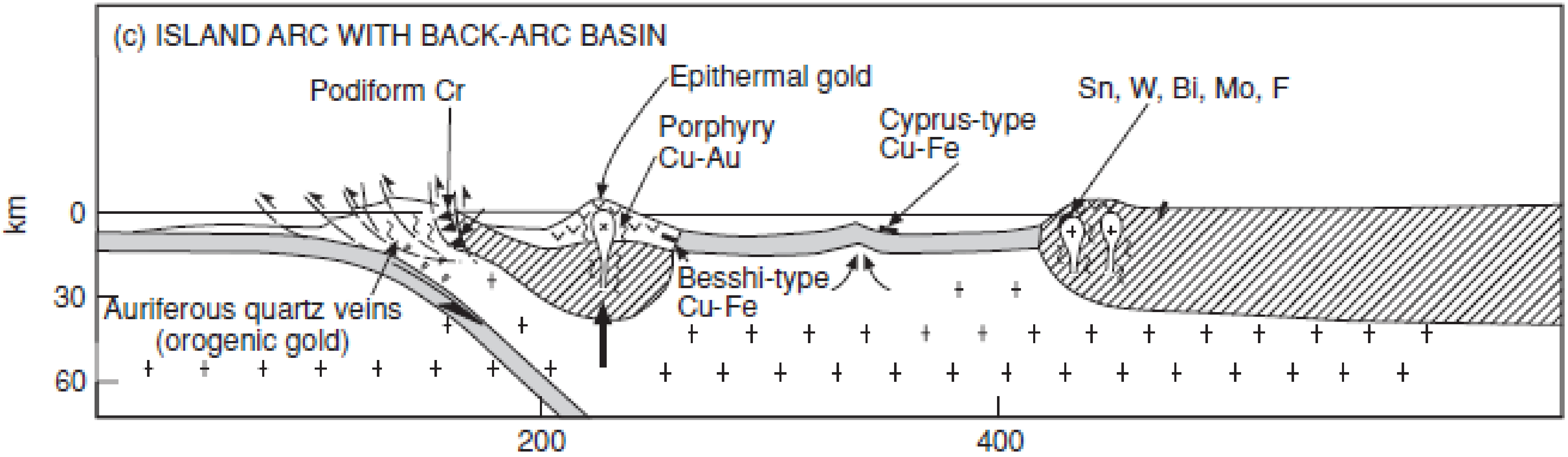
B- A similar tectonic setting can exist between two slabs of oceanic crust **(ocean-ocean collision).** In this environment, **porphyry Cu–Au deposits** occasionally occur associated with the early stages of magmatism in these settings, whereas the later, more evolved **calc–alkaline magmatism gives rise to Kuroko-type VMS deposits.** The back-arc basins represent the sites of Besshi type VMS deposition.





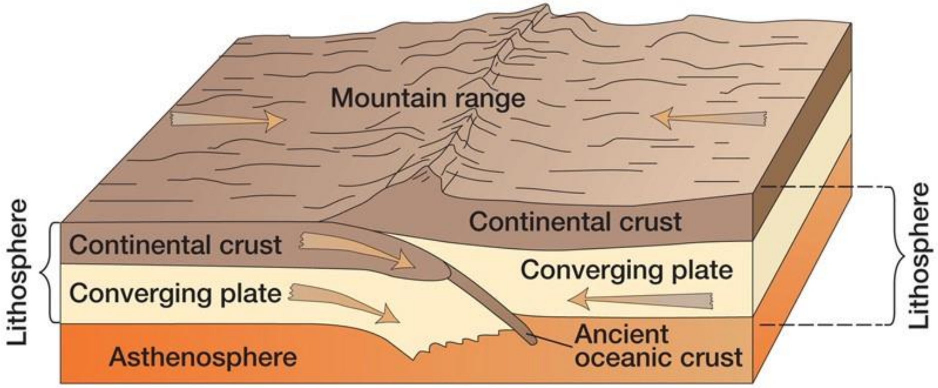


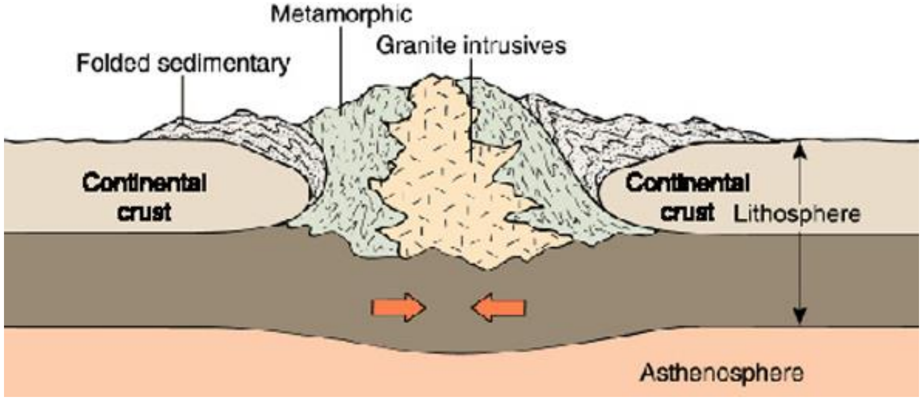
C- Arc–arc collision in the back-arc environment can also result in the preservation of obducted oceanic crust within which podiform Cr and sulfide segregations might be preserved.



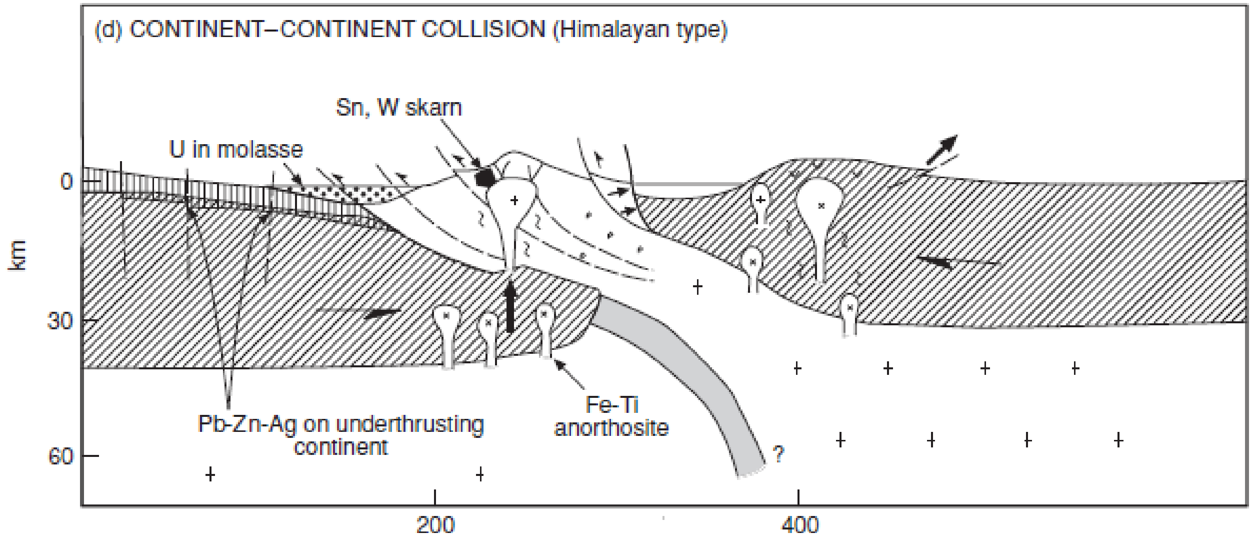
4- Continental collision

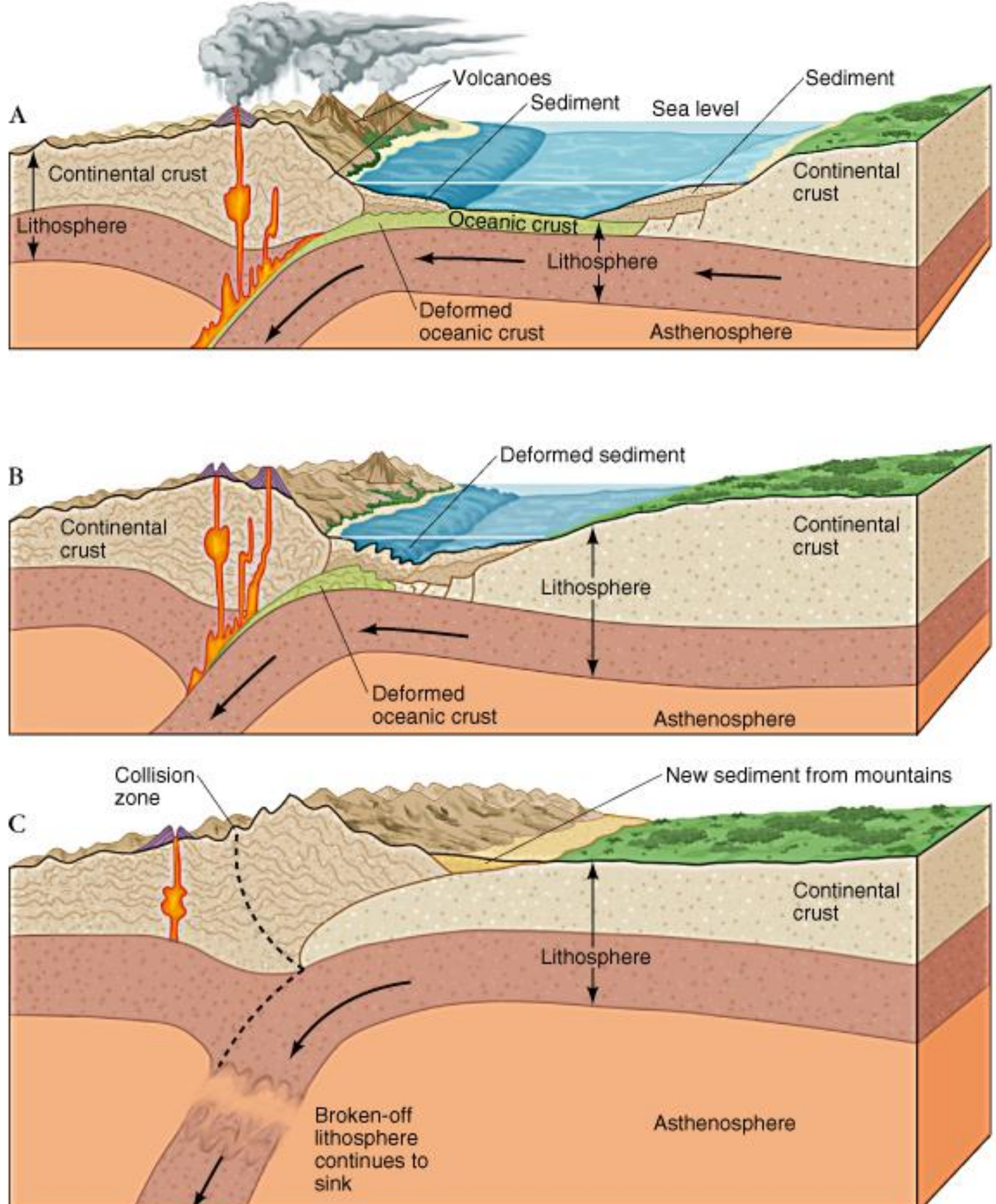
D- As the arc and continent accrete (become closer), ophiolite obduction can occur, and felsic magmatism may give rise to large-ion lithophile element mineralization (LILE: Ba, K, Rb, Cs, Ca, Sr). Ultimately, the oceanic crust is totally consumed to form a zone of continent–continent collision. The process results in thickened crust below collisional belts and the formation of anatectic S-type granitoid melts.





From these melts, Sn–W–U mineralization could occur. In addition, orogeny-driven fluids give rise to orogenic vein-related Au systems (orogenic gold deposits) which could be associated with MVT Pb–Zn deposits.




A
Volcanoes
Sediment
Sea level
Sediment
Continental crust
Lithosphere
Continental crust
Oceanic crust
Lithosphere
Deformed oceanic crust
Asthenosphere
B
Deformed sediment
Continental crust
Continental crust
Lithosphere
Deformed oceanic crust
Asthenosphere
C
Collision zone
New sediment from mountains
Continental crust
Lithosphere
Broken-off lithosphere continues to sink
Asthenosphere

Genetic Classification of Ore Deposits

Various geological aspects are employed to classify ore deposits, including:

1. **the presence of certain metals or minerals (e.g. silver, haematite);**
2. **the form of the orebody (vein, bed, etc.);**
3. **the local geological environment (submarine or terrestrial volcanism);**
4. **the plate tectonic setting (island arc, continental margin) and**
5. **other genetic characteristics such as formation temperatures and fluid chemistry.**

However, a stringent genetic classification of mineral deposits is very difficult. One reason for this is that many ore deposits represent a position in a complex multi-dimensional space of well defined end members:

1. **The formation of Kuroko ore deposits, for example, is an interplay of volcanic, intrusive, sedimentary and diagenetic processes;**
2. **The origin of high-grade BIF-haematite ore seems to comprise sedimentation induced by proliferating marine life, later passage of saline basinal brines and supergene components.**

Table 1.6 A simple genetic classification of ore deposits

I. Magmatogenic Ore Deposits

1. Orthomagmatic Deposits:
   Sulphide Fe-Ni-(Cu-PGE) ore hosted by Archaean komatiites and subvolcanic ultramafic intrusions; Alpine type Cr-PGM in ophiolites, and seams in layered mafic intrusions; Cu-Ni-PGM "reefs" in layered mafic intrusions; complex mafic-ultramafic intrusions with, for example, conduit-hosted Cu-Ni-PGM; impact magma bodies with Ni-Cu-PGM; Ural-Alaska type ultramafic ring intrusions with Cr-PGM; Ti-Fe in Mesoproterozoic anorthosite-ferrodiorite complexes; orthomagmatic iron ore deposits of iron oxides and apatite in intermediate to felsic igneous rocks (Kiruna type); apatite-Fe-Nb-Zr, or REE-U-F in carbonatite plugs and nephelinite intrusions
2. Pegmatites with ore of Be, Li, Rb, Cs, Ta (Nb), U, Th, REE, Mo, Bi, Sn and W, industrial minerals, gemstones
3. Magmatic-Hydrothermal Deposits:
   Skarn ore, with magnetite-Cu-Co-Au, W, Zn-Pb-Ag, Mo-Bi-Au and Sn-As-Pb-Zn-W-Mo; contact-metasomatic ore (Pb, Ag, Zn); Fe-oxide-Cu-Au (U-REE) deposits (IOCG); porphyry deposits (Cu-Mo-Au, Sn-W); submarine volcanogenic (Kuroko) and volcanic-hosted massive sulphide deposits (VMS); vein deposits (Sn, W, Cu); terrestrial epithermal Ag-base metal deposits; epithermal Au-Ag deposits

II. Supergene Ore Deposits

1. Residual (Eluvial) Deposits:
   Residual placers (e.g. W, Sn); bauxite; lateritic Au, Fe and Mn ore deposits
2. Supergene Enrichment Deposits:
   Enriched sulphide ore (Cu, Ag); lateritic Ni
3. Infiltration Deposits
   U in sandstone; Pb-Zn-F-Ba and Mn in karst cave systems

III. Sedimentary Ore Deposits

1. Allochthonous:
   Colluvial, alluvial (gold, columbite, cassiterite, wolframite, platinum) and coastal (rutile, ilmenite, zircon, monazite) placers
2. Autochthonous:
   Sulphide deposits, mainly in black shales; polymetallic deposits of Cu-Sb-Zn-Pb-Ag (-Au), mostly of sedex type; Palaeoproterozoic banded Fe ore (BIF) of Algoma and Superior type, and banded Mn ore; oolitic Fe and Mn ore; deep sea manganese nodules and crusts (Mn-Cu-Ni-Co-PGM)

IV. Diagenetic-Hydrothermal Ore Deposits

1. Stratabound and/or stratiform sediment-hosted Cu deposits:
   European Copper Shale (Cu); Central African Copper Belt (Cu, Co, Pb, Zn, U)
2. Mississippi Valley type (MVT) Pb-Zn-F-Ba deposits (hosted in marine carbonates)
3. Saline brine-related deposits
   Pb-Zn-F-Ba, metasomatic siderite, preconcentration of high-grade hematite

V. Metamorphosed and Metamorphic Ore Deposits

Metamorphism of pre-existing ore generally improves processing characteristics of ore, but is rarely a factor of metal accumulation and ore formation; metamorphic examples include ± *in situ* redistribution, concentration and recrystallization of gold

VI. Metamorphogenic-Hydrothermal Ore Deposits

Prograde and retrograde metamorphogenic-hydrothermal ore deposits (e.g. orogenic Au deposits in accretion-subduction-collision complexes; part of the Central African Cu-Co ore deposits; Cu in Mt Isa, Australia).

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For Further detailed classification please read:

The "chessboard" classification scheme of mineral deposits: Mineralogy and geology from aluminum to zirconium. Review Article *Earth-Science Reviews, Volume 100, Issues 1–4, June 2010, Pages 1-420*

Harald G. Dill

End of Lecture