# ECONOMIC GEOLOGY

## e – Learning Material: Unit-2

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# Process of formation of mineral deposits

# Process of formation of mineral deposits

**Mineral deposits are classified on the basis of their genesis or the processes that operates to form them.**

1. Magmatic concentration
2. Sedimentation inclusive of evaporation
3. Metamorphism
4. Contact metasomatism
5. Hydrothermal processes
6. Oxidation and supergene enrichment
7. Sublimation
8. Residual and mechanical concentration

| Type | The mechanism of ore deposition | Example |
|---|---|---|
| 1- Early magmatic | | |
| A- Dissemination | Disseminated crystallization without concentration | Diamond pipes, some corundum deposits,chromite |
| B- Segregation | Crystallization differentiation and accumulation | Bushveld chromite, Stillwater, chromite |
| 2-Late magmatic | Crystallization differentiation and residual magma accumulation. | Titanomagnetite deposits and Platinum deposits in Bushveld Complex |
| A- Gravitative liquid accumulation | | |
| 1- Residual liquid segregation<br>2. Residual Liquid Injection | | |
| B- Immiscible liquid | | |
| 1- Immiscible liquid segregation.<br>2-Immiscible liquid injection | Immiscible liquid separation .and accumulation<br>Same, with injection | Sulfide deposits |

# MAGMATIC CONCENTRATION or
# Ore Deposits Related to Magmatic Activity

Certain accessory or uncommon constituents of magmas become enriched into bodies of sufficient size and richness to constitute valuable mineral deposits eg. Chromite and platinum.

Magmatic ore deposits are characterized by their close relationship with intermediate or deep seated intrusive igneous rocks

They constitute either the whole igneous mass or a part of it

# Magmatic Deposits result from

1. Simple crystallization
2. Concentration by differentiation of intrusive igneous masses.

There are several modes of formation of magmatic deposits.

They originate during different periods of magma crystallization – in some the ore minerals crystallize early, in others late, and in still others they remained as immiscible liquids until after crystallization of the host rock

# Classification of Magmatic Deposits

I. ***Early Magmatic Deposits***: Those which resulted from straight magmatic processes (orthotectic and orthomagmatic).

These deposits have formed by:

a. Simple crystallization without concentration
b. Segregation of early formed crystals
c. Injection of material concentrated elsewhere by differentiation.

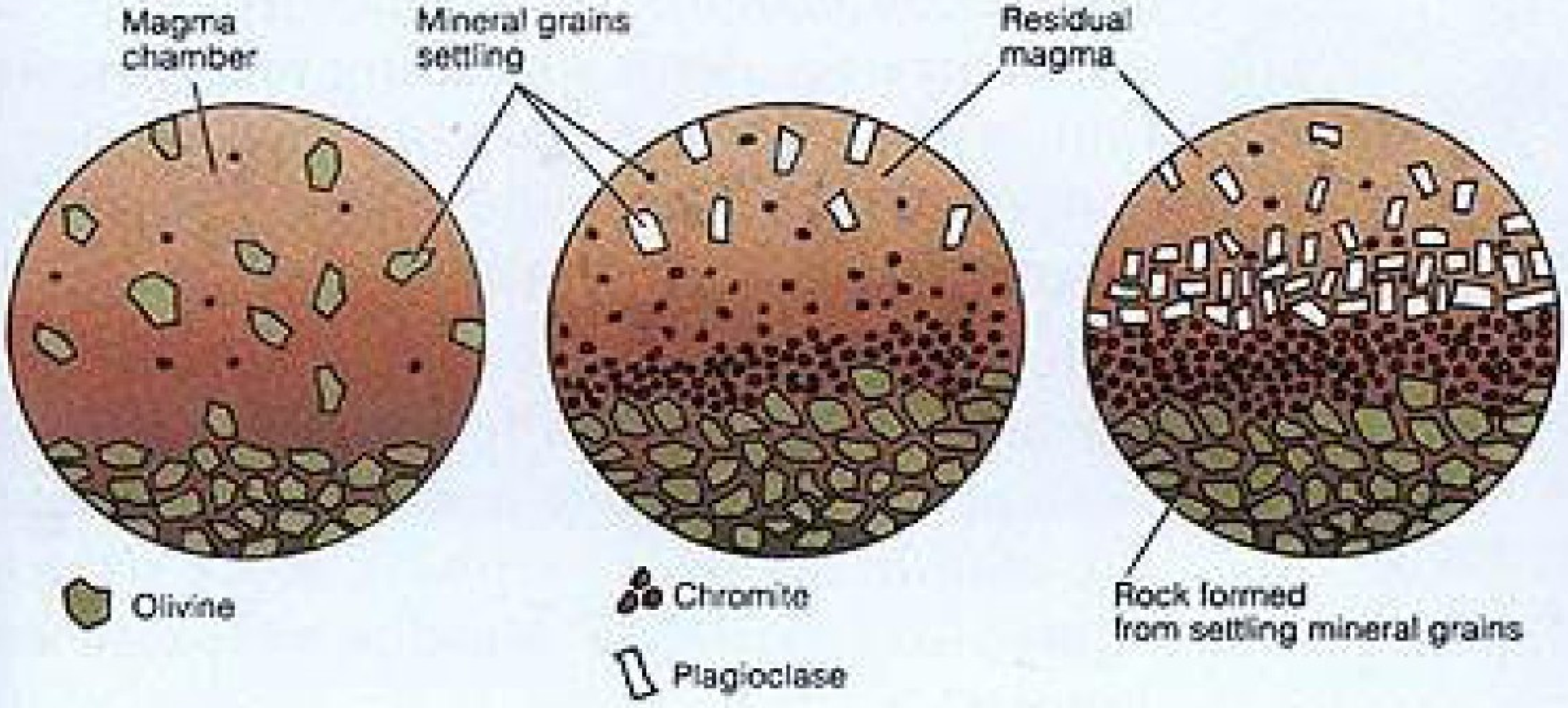
## A. *Dissemination*

Deep seated crystallization will yield a granular rock in which the early formed crystals are disseminated. If such crystals are valuable and abundant, the whole rock or a part of them becomes the orebody. The individual crystals may be phenocrysts

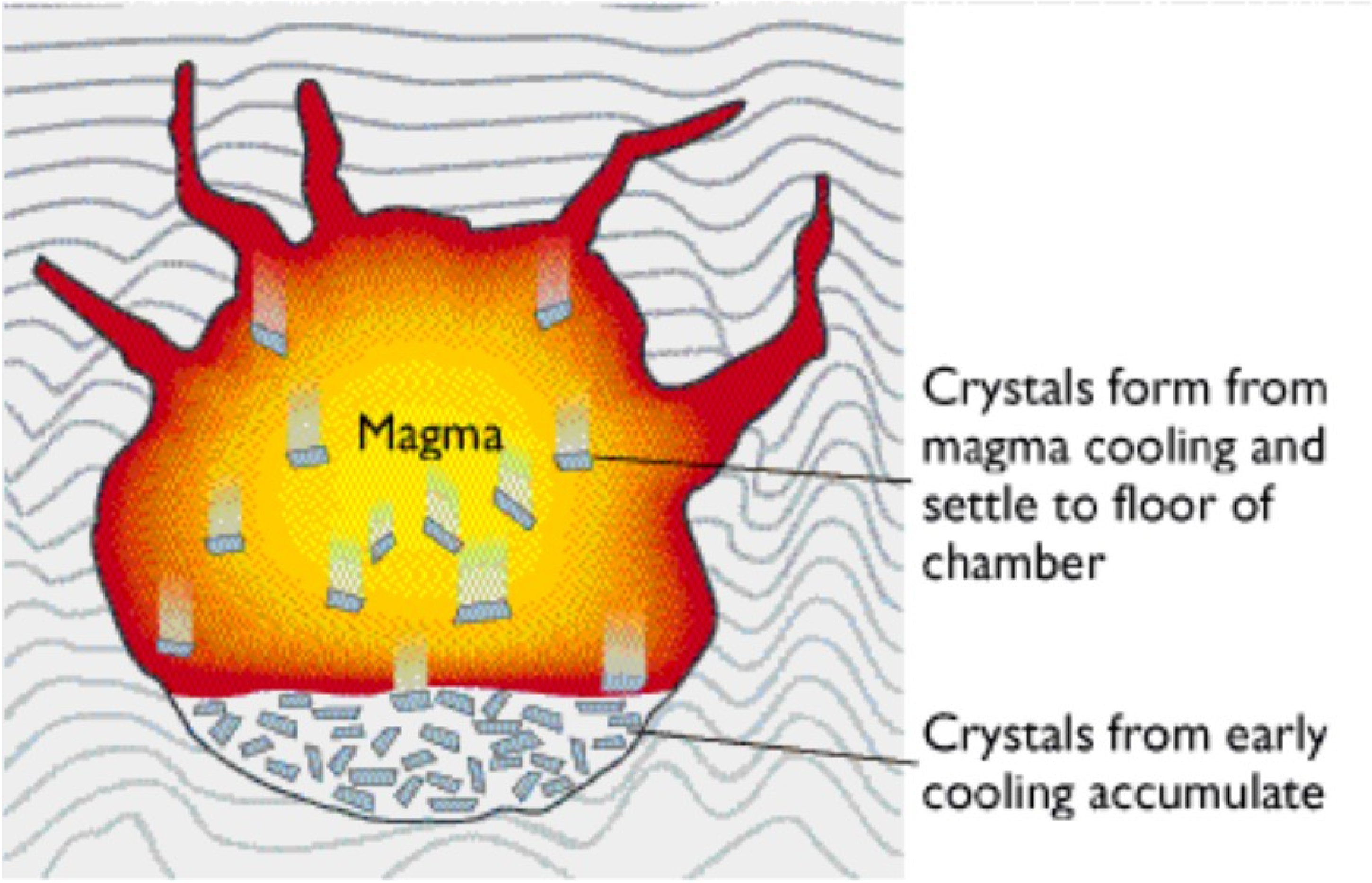
## B. *Segregation*

Concentration of early formed crystals in-situ. These are early concentrates of valuable constituents of the magma that have taken place as a result of gravitative crystallization differentiation, eg. Chromite. These orebodies are generally lenticular and small in size, commonly disconnected pod shaped lenses, stringers

# Formation of magmatic mineral deposit by crystal settling



A. Grains of three minerals settle at different rates and produce three rock types of different composition.



(a) Early crystallization

**1. Differentiation of magma**

# Early Magmatic Deposits – Indian Examples

a.) Disseminated in the enclosing rock e.g. diamond in kimberlite of Majhagawan pipe, MP and Wajrakarur pipe, AP. The diamonds might have crystallised early and were transported with the enclosing magma, and perhaps, even continued to grow before final consolidation took place in the present pipes.

b.) Segregated due to gravitational crystallization differentiation e.g. stratiform and banded graded deposits of chromite in Nausahi-Sukinda area, Orissa and other places. The early magmatic segregation may be due to sinking of heavy early formed crystals to the lower part of the magma chamber or by marginal accumulation.

# Early Magmatic Deposits – Indian Examples

c.) Injected into the host rocks or the surrounding rocks e.g. vanadiferous magmatic deposits of Dublabera, Singhbhum district in Bihar. It occurs as veins and lenses within ultrabasics and gabbro.

The early formed ore mineral, magnetite, did not remain at the site of original accumulation but have been injected into ultrabasic rocks of Iron-Ore Formation. Due to sinking of heavy early formed crystals to the lower part of the magma chamber or by marginal accumulation.

d.) Injected into the host rocks or the surrounding rocks e.g. vanadiferous magmatic deposits of Dublabera, Singhbhum district in Bihar. It occurs as veins and lenses within ultrabasics and gabbro.

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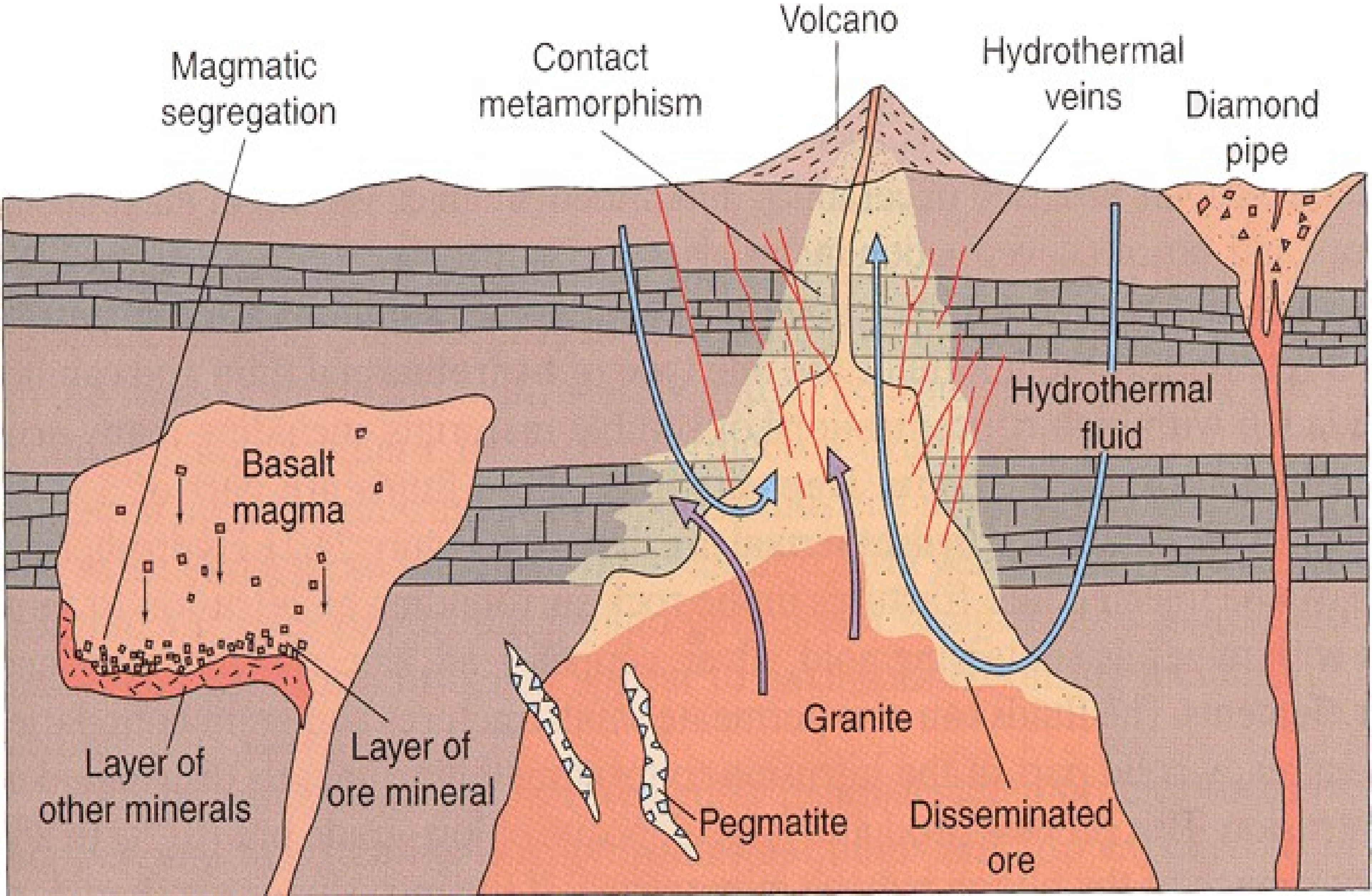
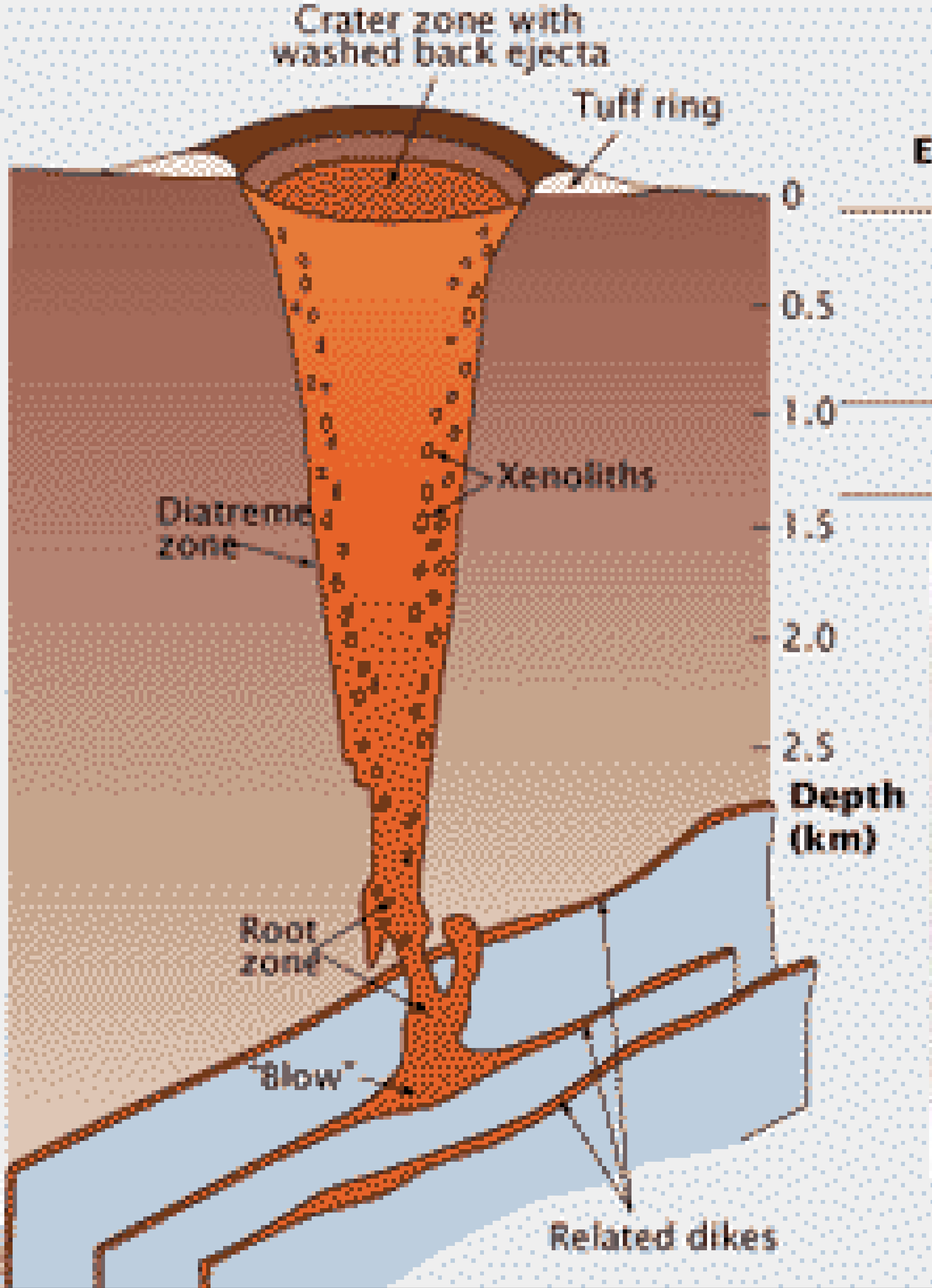
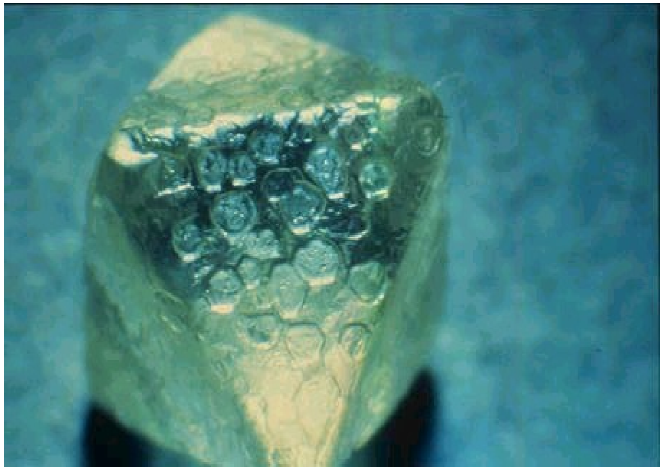

Magmatic segregation
Contact metamorphism
Volcano
Hydrothermal veins
Diamond pipe
Basalt magma
Hydrothermal fluid
Layer of other minerals
Layer of ore mineral
Granite
Pegmatite
Disseminated ore





Schematic model of a fully grown kimberlite pipe

Stratiform chromite deposit,
Bushveld Complex,
South Africa

II. ***Late Magmatic Deposits*: Those which consist of minerals crystallizing from a magma towards the close of magmatic period.**

**The ore minerals are later than the rock silicates and cut across them, embay them, and yield reaction rims around earlier minerals. They are always associated with mafic igneous rocks.**

**The late magmatic deposits have resulted from:**

**a. Variations of crystallization differentiation.**

**b. Gravitative accumulation of heavy residual liquids.**

**c. Liquid separation of sulfide droplets.**

## A. *Residual Liquid Segregation*

**In certain mafic magmas, the residual liquid becomes enriched in iron, titanium and volatiles. This liquid settles to the bottom of the magma chamber, or crystallizes in the interstices of early formed crystals. Examples: Titaniferous magnetite layers of the Bushveld Igneous Complex, S. Africa.**

## B. *Residual Liquid Injection*

**The iron-rich residual liquid accumulated in the above manner may be subjected to movement because of:**

**a. Gentle tilting (causing lateral movement).**
**b. Pressure and be squirted out to places of lesser pressure.**

**In both cases it may be injected into adjacent rocks and even in the earlier consolidated parent silicate mass. Examples: Titanomagnetite Deposits, Adirondack Region, New York; Allard Lake Deposits; Magnetite Deposits of Kiruna, Sweden.**

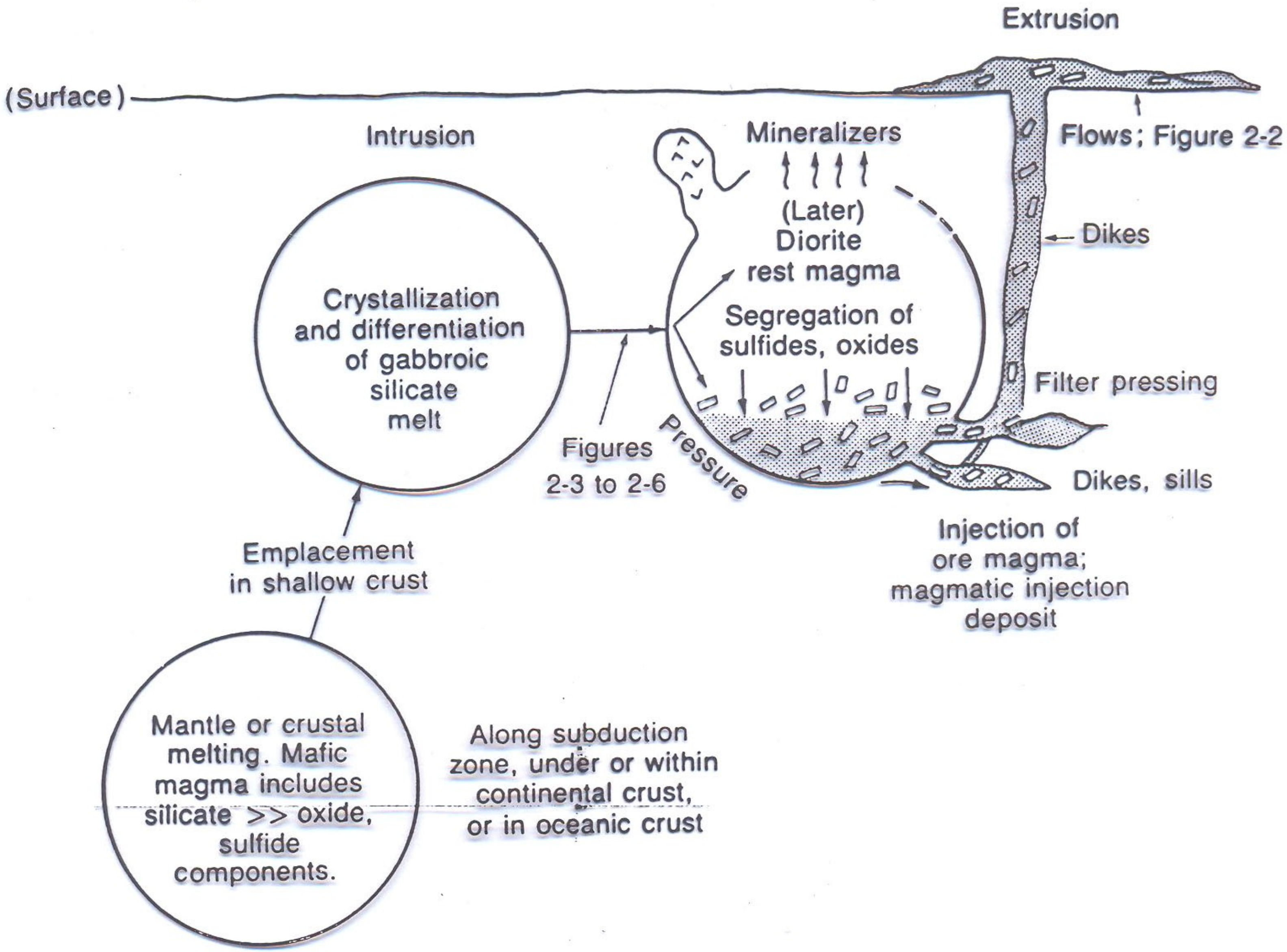


**Figure 2-1.** Schematic of a sequence of early magmatic events leading to ore magmas and their emplacement. The diagram generally extends to perhaps diorite stages of differentiation in the magma portion at the right. See also Figures 2-3 to 2-7. (*Adapted from diagrams by* A. J. Naldrett.)

## C. *Immiscible Liquid Segregation*

*Immiscible liquid* - Typical example is oil and water. In ore deposits we deal with silicate and sulfide magmas. As a magma cools, sulfides coalesce as droplets and due to higher density settle out. Most common sulfides are iron sulfides, but nickel, copper and platinum also occur.

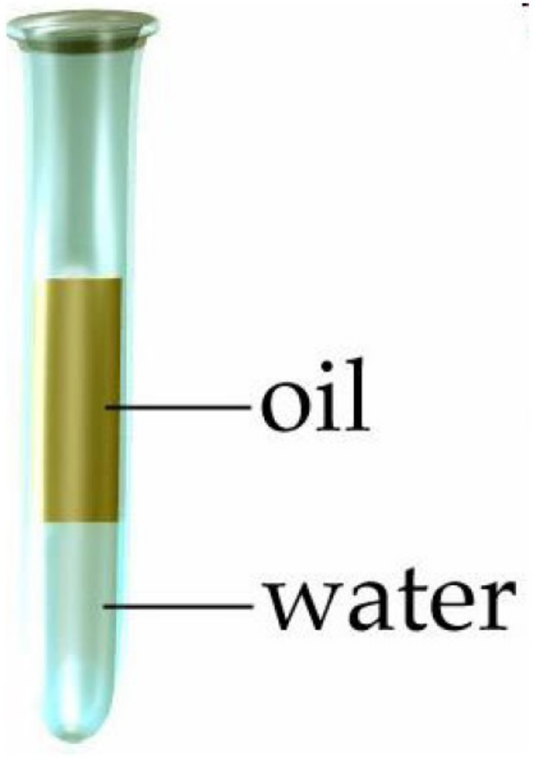
Sulfide-rich magmas are immiscible in silicate rich magmas. This gives rise to separation even before crystallization. The accumulated sulfide may not necessarily be pure – in fact it quite often is an enrichment of sulfides in the lower parts of the magma.

Deposits formed in this manner are pyrrhotite-chalcopyrite-pentlandite nickel-copper ores confined to rocks of the gabbro family. Examples: Ni-Cu Deposits of Insizwa, S. Africa; Nickeliferous Sulfide Deposits of Bushveld, S. Africa & Norway; Nickel Sulfide Deposits of Sudbury, Ontario.

## D. *Immiscible Liquid Injection*

Examples: Vlackfontein Mine of S. Africa; Nickel Deposits of Norway.

# *immiscible separations*



Oil and water don’t mix …

. As magmas cool, they can split into two liquids of different composition and density.

. One of these liquids is the silica-rich melt. It has the most volume

. The other, typically much smaller in volume, can be rich in metal oxides, sulfides or carbonates.

# Late Magmatic Deposits – Indian Example

a.) Residual liquid segregation wherein the residual magma with crystallization becomes progressively richer in silica, alkali and water. It sometimes contains titanium and iron which on crystallization segregated to form titaniferous magmatic deposit e.g. titaniferous magmatite of Hassan District, Karnataka, which occurs as comformable bands in amphibolites and basic schists. Vanadiferous magnetite deposits of Mayurbhanj, Orissa is another example. Here, it occurs associated with gabbro-anorthosite suite of rocks.

b.) Residual liquid injection which takes place due to earth's disturbance like igneous intrusion. E.g. on dated 23 August, 2007, Igneous intrusions took place in 8km from Kimin, in Arunachal Pradesh; the residual liquid rich in iron when injected crystallised to form magnetite deposits, e.g. magnetite dyke rock of Kasipatanam, Visakhapatanam district, AP, where it occurs as cutting across the NE-SW foliation of charnockite-gneiss and also metamorphoses the wall rocks.

# Late Magmatic Deposits – Indian Example

**c.) Immiscible liquid segregation in which certain salts in magma under certain conditions separate out an unmixed solutions like oil and water, and segregate to form important mineral deposits. It has been observed that sulphur and silica form two hot immiscible liquids wherein a molten mass consists of various metals. The examples of this category are lead-zinc-copper-sulphide deposits of Hesatu-Belbathan Belt, Bihar where they occurs associated with altered basic-schists in disconnected bodies.**

**d.) Immiscible liquid injection when the unmixed sulphide rich fraction accumulated in the magma chamber, as described above, is squirted out before consolidation towards the places of less pressure, such as shear zones. They intrude the older rocks and enclose brecciated fragments of host and foreign rocks. The nickeliferous chalcopyrite pockets associated with altered basic-schists (chlorite-biotite schist) of Singhbhum Copper Belt may be cited as an example. This type of deposits shows transition to hydrothermal type with enrichment of volatile matters.**

**Pegmatitic Deposits**: Pegmatites are very coarse grained igneous rocks. Commonly form dike-like masses a few meters to occasionally 1-2 km in length. Economic ore deposits are associated with granitic pegmatites since felsic magmas carry more water. Residual elements such as Li, Be Nb, Ta, Sn and U that are not readily accommodated in crystallizing silicate phases end up in the volatile fraction. When this fraction is injected into the country rock a pegmatite is formed. Temperatures of deposition vary from 250-750°C*.* Pegmatites are divided into simple and complex. Simple pegmatites consist of plagioclase, quartz and mica and are not zoned.

Complex have a more varied mineralogy and are strongly zoned. Crystals in pegmatites can be large, exceeding several meters. Three hypotheses to explain their formation:

- fractional crystallization
- deposition along open channels from fluids of changing composition
- crystallization of a simple pegmatite and partial to complete hydrothermal replacement

Pegmatite dyke in a granodiorite body

# Association of Rocks and Mineral Products:

**Definite associations exist between specific magmatic ores and certain kinds of rocks:**

1. Platinum occurs only with mafic to ultramafic rocks such as varieties of norite, peridotite or their alteration products.
2. Chromite (with rare exceptions) is formed only in peridotites, anorthosites and similar mafic rocks.
3. Titaniferous magnetite and ilmenite are found with gabbros and anorthosites.
4. Magnetite deposits occur with syenites.
5. Ni-Cu deposits are associated with norite.
6. Corundum occurs with nepheline syenite.
7. Diamond occurs only in kimberlite, a variety of peridotite.
8. Pegmatite minerals, such as beryl, cassiterite, lepidolite, scheelite, and niobium-bearing minerals occur chiefly with granitic rocks.

# Characteristics of different rock types:

*Peridotite*: A coarse grained mafic igneous rock composed of olivine with small amounts of pyroxene and amphibole.

*Anorthosite*: A plutonic rock composed mainly of Ca-rich plagioclase feldspars.
*Gabbro*: A black, coarse grained intrusive igneous rock, composed of calcic plagioclases and pyroxenes. The intrusive equivalent of basalt.

*Syenite*: A group of plutonic rocks containing alkali feldspars, a small amount of plagioclase, one or more mafic minerals, and quartz only as an accessory, if at all. The intrusive equivalent of trachyte.

*Kimberlite*: A peridotite that contains garnet and olivine and is found in volcanic pipes.

*Pegmatite*: An igneous rock with extremely large grains (> 1 cm in dia). It may be of any composition, but is most frequently granitic.

# HYDROTHERMAL DEPOSITS

Hydrothermal mineral deposits are those in which hot, mineral laden water (hydrothermal solution) serves as a concentrating, transporting, and depositing agent. They are the most numerous of all classes of deposit.

The term hydrothermal means hot water with possible temperature of $500^0$ to $50^0$C. The fluid resulting as an end product of magmatic differentiation, constitutes hydrothermal solution which carries metals originally present in the magma to the site of deposition.

The process is responsible for formation of epigenetic mineral deposits i.e. those formed later than the rocks that enclose them. The hydrothermal solution in its journey through the rocks loses heat and metal contents with increased distance.

The deposition may have taken place at high temperature (hypothermal deposit), intermediate temperature (mesothermal deposit) or low temperature (epithermal deposit).

## Origins of the Solutions

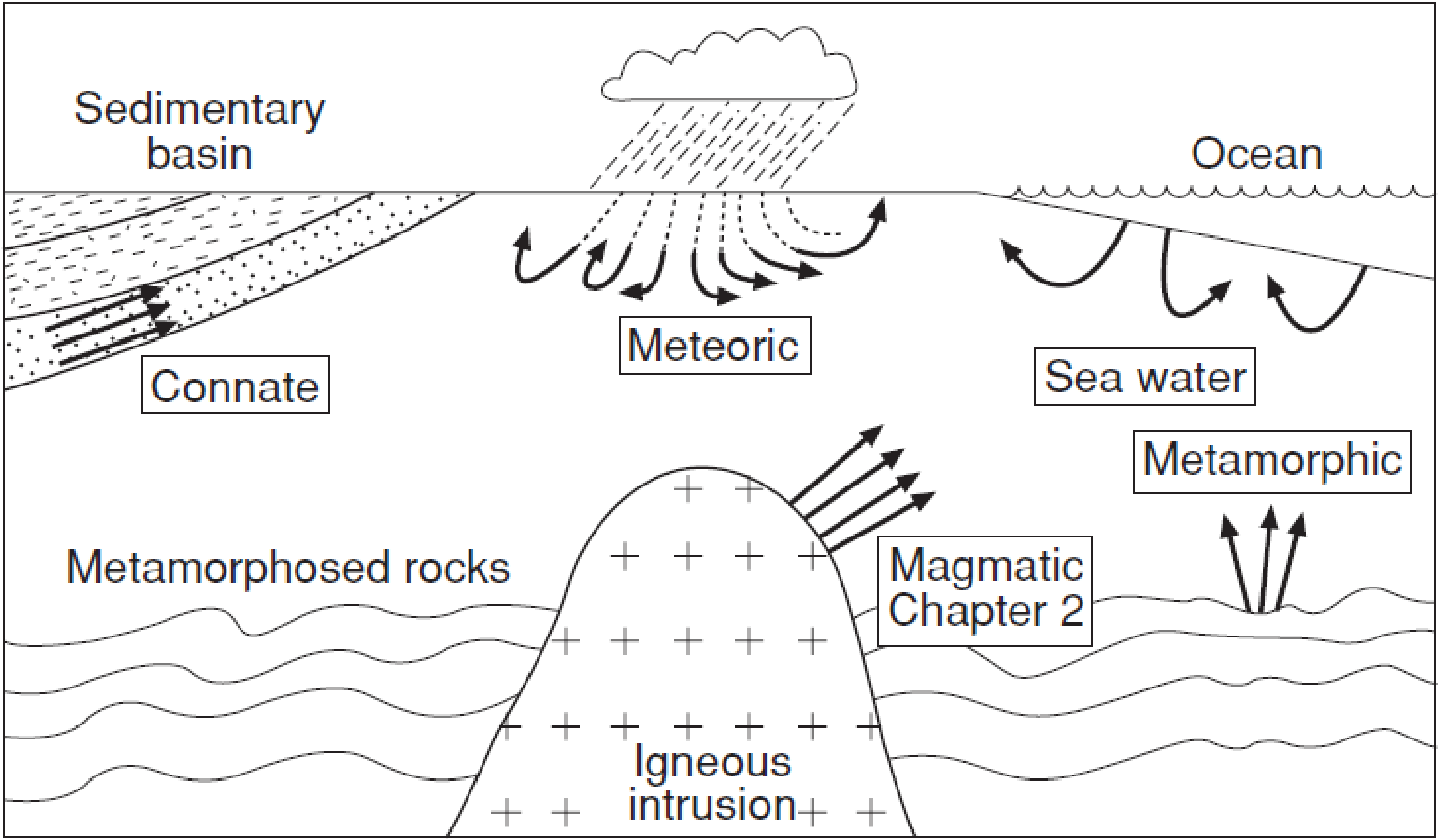
**The water in a hydrothermal solution can come from any of several sources.**

**It may be released by a crystallizing magma;**

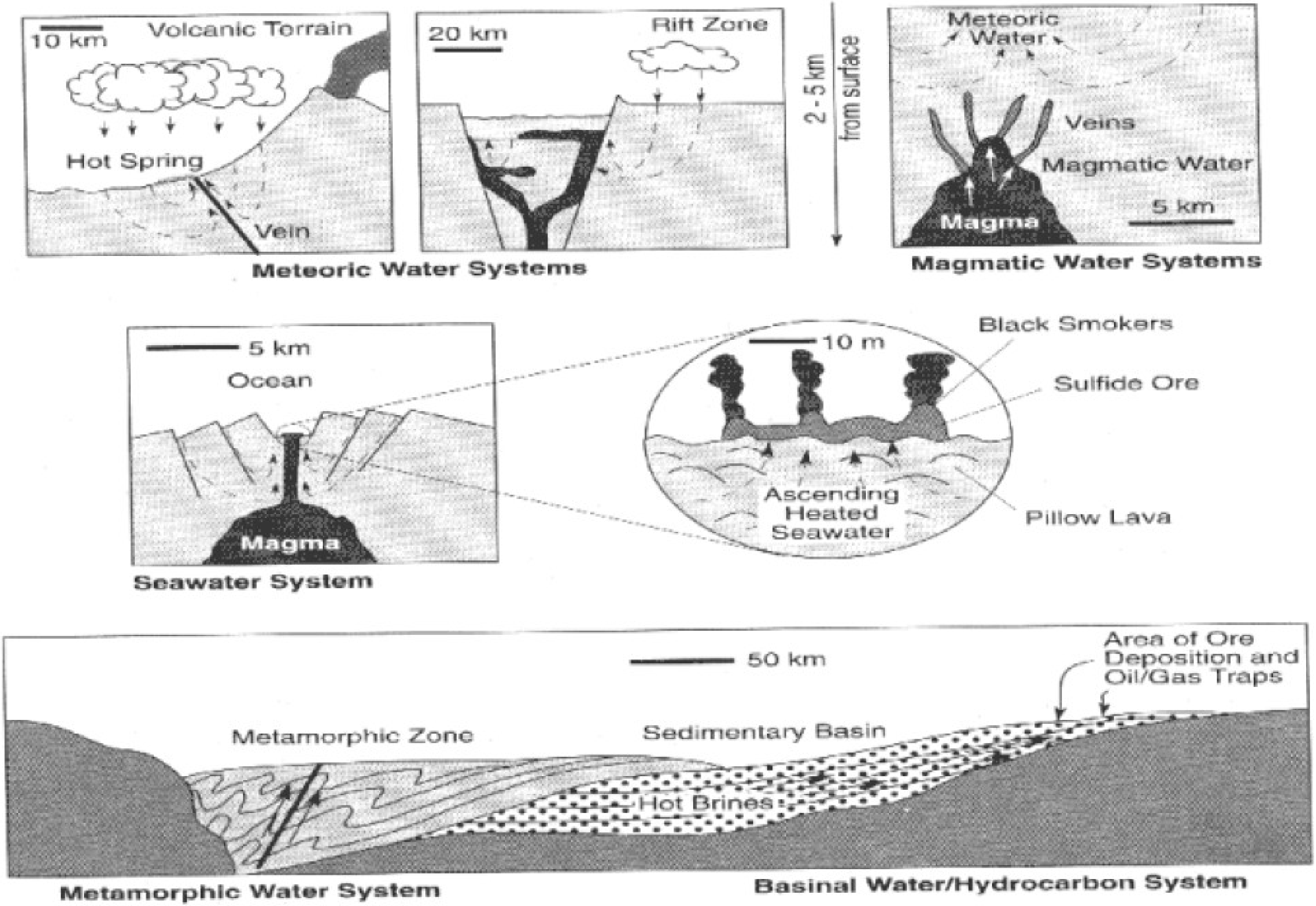
**it can be expelled from a mass of rock undergoing metamorphism; or**

**it may originate at the Earth's surface as rainwater or seawater and then trickle down to great depths through fractures and porous rocks, where it will be heated, react with adjacent rocks, and become a hydrothermal solution.**

**Connate waters, when set into motion by tectonic activity, may also constitute hydrothermal fluids.**


Sedimentary basin
Ocean
Connate
Meteoric
Sea water
Metamorphic
Metamorphosed rocks
Magmatic
Chapter 2
Igneous intrusion

Hydrothermal Systems



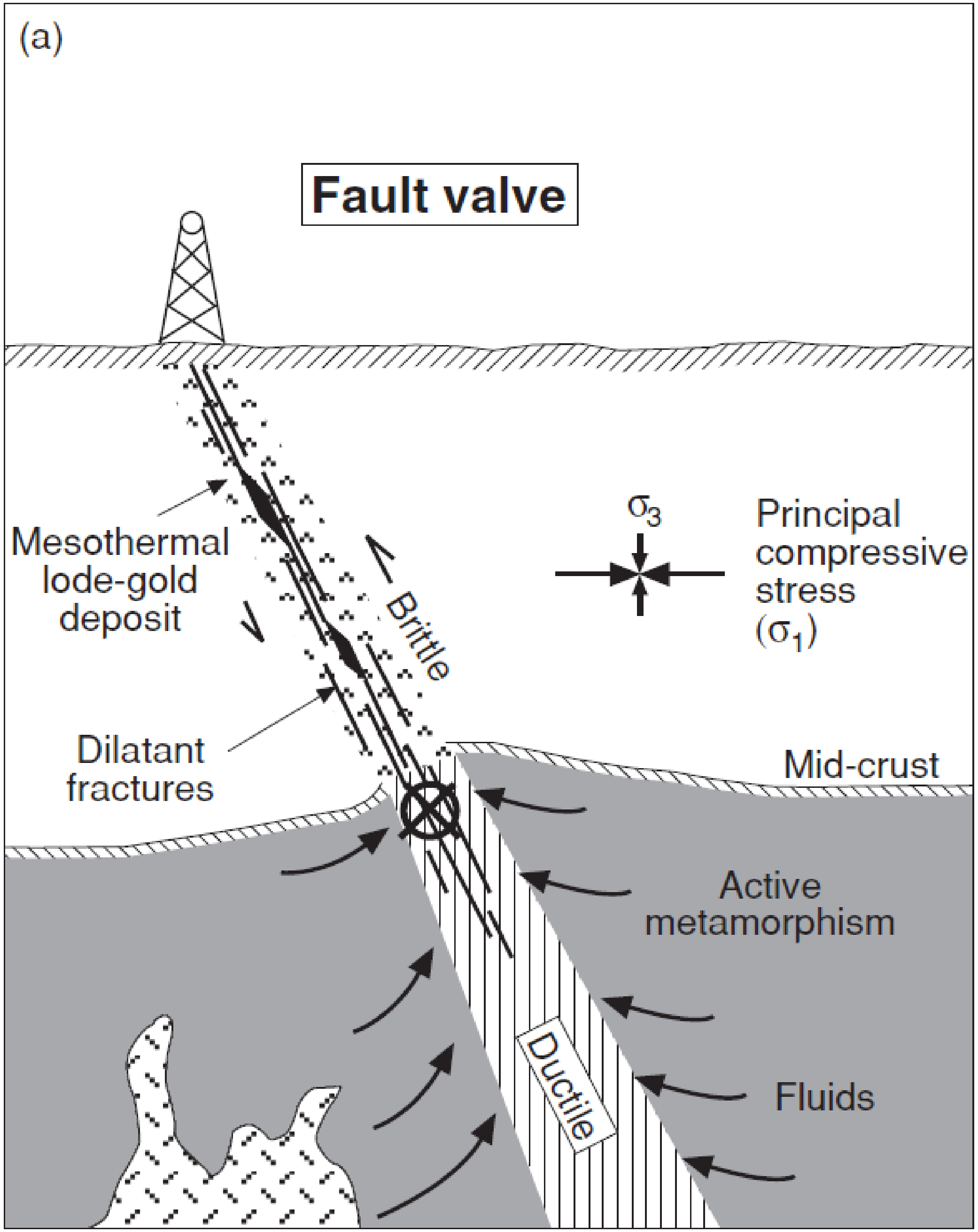
## Composition of the Solutions

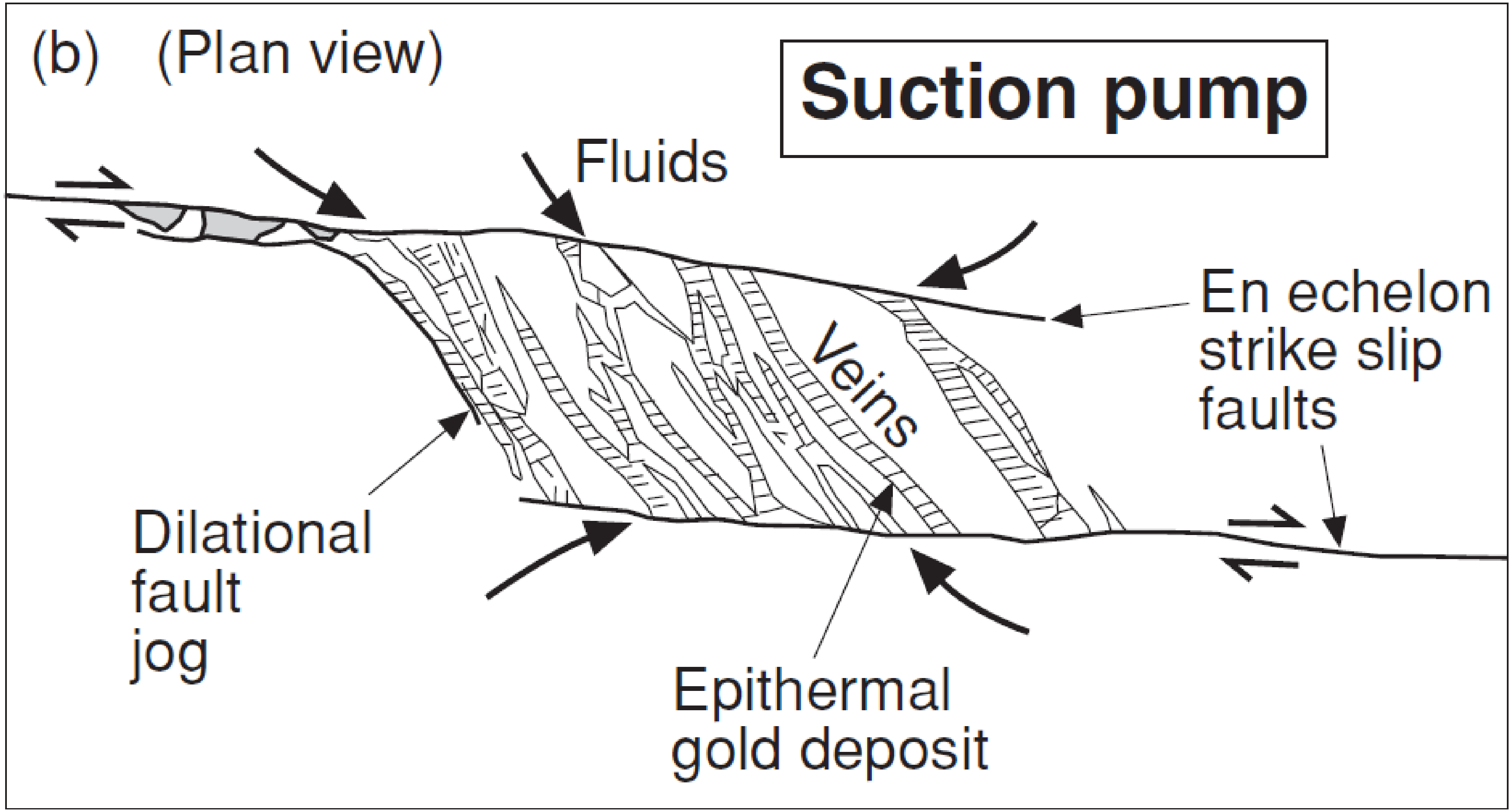
The principle ingredient of hydrothermal solutions is water. Pure water, however, can not dissolve metals.

Hydrothermal solutions are always brines, containing dissolved salts such as NaCl, KCl, $CaSO_4$ and $CaCl_2$.

The range in salinity varies from that of seawater (around 3.5 wt %) to about ten times the salinity of seawater.

Such brines are capable of dissolving small amounts of elements such as Au, Ag, Cu, Pb and Zn. High temperatures increase the effectiveness of the brines to dissolve metals


(a)
Fault valve
Mesothermal lode-gold deposit
Brittle
σ3
Principal compressive stress (σ1)
Dilatant fractures
Mid-crust
Active metamorphism
Ductile
Fluids


(b) (Plan view)
Suction pump
Fluids
En echelon strike slip faults
Veins
Dilational fault jog
Epithermal gold deposit

# Conditions necessary for the formation of hydrothermal ore deposits

- Presence of hot water to dissolve and transport minerals
- Presence of interconnected openings in the rock to allow the solutions to move
- Availability of sites for the deposits, and
- Chemical reaction that will result in deposition

## Openings

Pore spaces, crystal lattices, bedding planes, vesicles, cooling cracks, breccias, fissures, shear zones, folding and warping, volcanic pipes, solution and rock alteration etc. are the various types of openings in the rocks permitting movement of solution or deposition of ore-minerals.

For large deposits vast quantities of solution and fairly large confined channel ways are needed. The flow of solution must be confined to avoid dispersal of mineral matter.

Fissures, shears and permeable beds may provide confined channel-ways. Volcanic breccias, on the other hand, exhibit widespread permeability and the mineralizing solution is spread over a large area which results in dispersed ore. Crystal lattices permit diffusion which is a slow process and may not generate large deposits.

The deposition from hydrothermal solutions is influenced due to chemical changes in solution, reactions between solution and wall rocks or veins matter and changes in temperature and pressure. The loses temperature and pressure which decreases solubility and promotes precipitation.

The heat loss is also influenced by nature of openings. Open fissures with straight wall would cause less heat loss than the intricate openings of breccia with large exposed area.

Although hydrothermal ore deposits may form in any host rock, deposition is influenced or localized by certain kinds of rock.

For example, lead-zinc-silver ores in some parts of Mexico occur in dolomitic rather than pure limestone

## Wall rock alteration

The wall-rock alteration is quite common in case of hydrothermal deposits.

The nature of mineralizing solution like its chemical character, temperature and pressure as well as character and kind of wall rock decide about the nature and intensity of alteration. Sericitization, kaolinisation and silicification are the common forms of alteration in the wall rock.

High temperature minerals like tourmaline, topaz and amphibole may develop. Basic and ultrabasic igneous rocks are serpentinized accompanied by the production of epidote and chlorite.

**Advanced argillic** - characterized by the clays dickite, kaolinite and pyrophyllite (all hydrated aluminum silicates) and quartz. Sericite may be present as well as alunite and tourmaline. Alteration involves the extreme leaching of cations, especially the difficult to leach alkalis and calcium, and the concentration of H+. This type of alteration is characteristic of many epithermal precious metal deposits and a smaller number of mesothermal deposits such as Butte, Montana.

**Potassic alteration** - characterized by secondary *kspar* + *biotite*. Anhydrite may be present, but its susceptibility to solution generally results in its dissolution in near surface environments. Because it is characterized by common silicates, potassic alteration is often difficult to detect. Pyrite and minor chalcopyrite and molybdenite are the only ore minerals associated with this alteration.

**Sericitization (Phyllic)** - characterized by the assemblage *quartz* + *sericite* + *pyrite*. Generally the most common form of alteration. Sulfides present, in addition to pyrite, include chalcopyrite, bomite and a variety of less common copper sulfides.
rock. Generally the result of oxidation of Fe.

**Argillic** - characterized by *kaolinite* + *montmorillonite*. Somewhat similar to advanced argillic alteration, but with a lesser degree of leaching of cations. Also unlike advanced argillic alteration which is associated with vein type deposits, argillic alteration is more closely associated with disseminated deposits, porphyry coppers in particular. Sulfides are less common in association with this alteration type.

**Propylitic** - characterized by the assemblage *chlorite* + *epidote* + *calcite*. Albite as well as other carbonates may be present. Due to presence of the green minerals chlorite and epidote this zone is usually easily recognizable by its color. Associated sulfides include pyrite, copper sulfides, galena, sphalerite and a host of complex arsenides. Often this zone can be quite large and is useful during mineral exploration. Unlike the previous types above which are characterized by leaching of cations this zone seems to represent the addition of cations.

**Silicification** - characterized by quartz or chert. Can be added by solutions as is the case in many low temperature deposits or the result of complete leaching of all cations plus aluminum.

**Dolomitization** - addition of magnesium to limestone to form dolomite. Common in Mississippi Valley type deposits.

## Other alteration types:

Feldspathization - *kspar* + *albite*, forms in the deep zones of some porphyry copper deposits.

Greisenization - *tourmaline* + *topaz* + *cassiterite* + *various tungsten-bearing minerals*. Common form of alteration on association with porphyry tin deposits.

Fenitization - characterized by *nepheline, alkali feldspar and Na-bearing amphiboles*. Hematization - characterized by secondary *hematite*.

Bleaching - not characterized by any specific mineral assemblage, but rather a color change between altered and unaltered rock. Generally the result of oxidation of Fe.

# Types of Deposits

The hydrothermal deposits are formed within a temperature range of 500 to 50°C.

The modes of formation are replacement and cavity filling.

Lindgren divided this class into three subclasses viz. (a) hypothermal, (b) mesothermal and (c) epithermal, according to the temperature of formation of the minerals

The replacement deposits are formed at the higher end of the temperature range and close to the intrusive. Most deposits of gold, silver, copper, lead and zinc, mercury, antimony and molybdenum come under this class.

Most deposits of minor metals and many non-metallic minerals are formed by this process. Cr, Ti, V, Zr, U, Ce, Ta and Pt are absent in deposits of this class.

The replacement deposits have always an alteration zone surrounding the ore-bodies. The nature of the alteration varies with the kind of enclosing rocks. The different types of wall rock alteration characteristic of different sub-classes of hydrothermal deposits may be summarised as follows :

1. Hypothermal : Greisenization, Serpentinization
2. Mesothermal : Sericitization, silioification. and argillic alteration
3. Epithermal : Silicification, argillic alteration & alunitization.

The wall rock alterations have often been used as a guide to ore-finding for where weathering has removed the top of the ore-body, these alteration haloes serve as indicator of hidden ore-bodies.

# Hydrothermal Deposits Forming Today

## 1.Imperial Valley, southern California

In 1962, oil/gas drilling struck a 350°C brine at 1.5 km depth. As the brine flowed upwards and cooled, it deposited a siliceous scale. Over a period of 3 months, some 8 tons were precipitated, containing 20 wt % Cu and 8 wt % Ag. This was the first unambiguous evidence that mineral deposits can be formed from hydrothermal fluids.

## 2.Red Sea

In 1964, oceanographers discovered a sries of hot, dense brines at the bottom of the Red Sea. The higher density of the brines (i.e. increased sanility) means that they remain at the bottom of the sea, despite being hot. The sediments at the bottom of these pools contain ore minerals such as chalcopyrite, sphalerite and galena. The Red Sea is a stratabound mineral deposit in the making.

## 3.East Pacific Rise

In 1978, deep-sea submarines on the East Pacific Rise, at 21°N, found 300°C hot springs emerging in plumes along the oceanic ridge, 2500 m below sea level. Minerals precipitated out of the solution as soon as it emerged, and around the vents was a blanket of sulphide minerals. This is the modern analogue of volcanogenic massive sulphide (VMS) deposits.

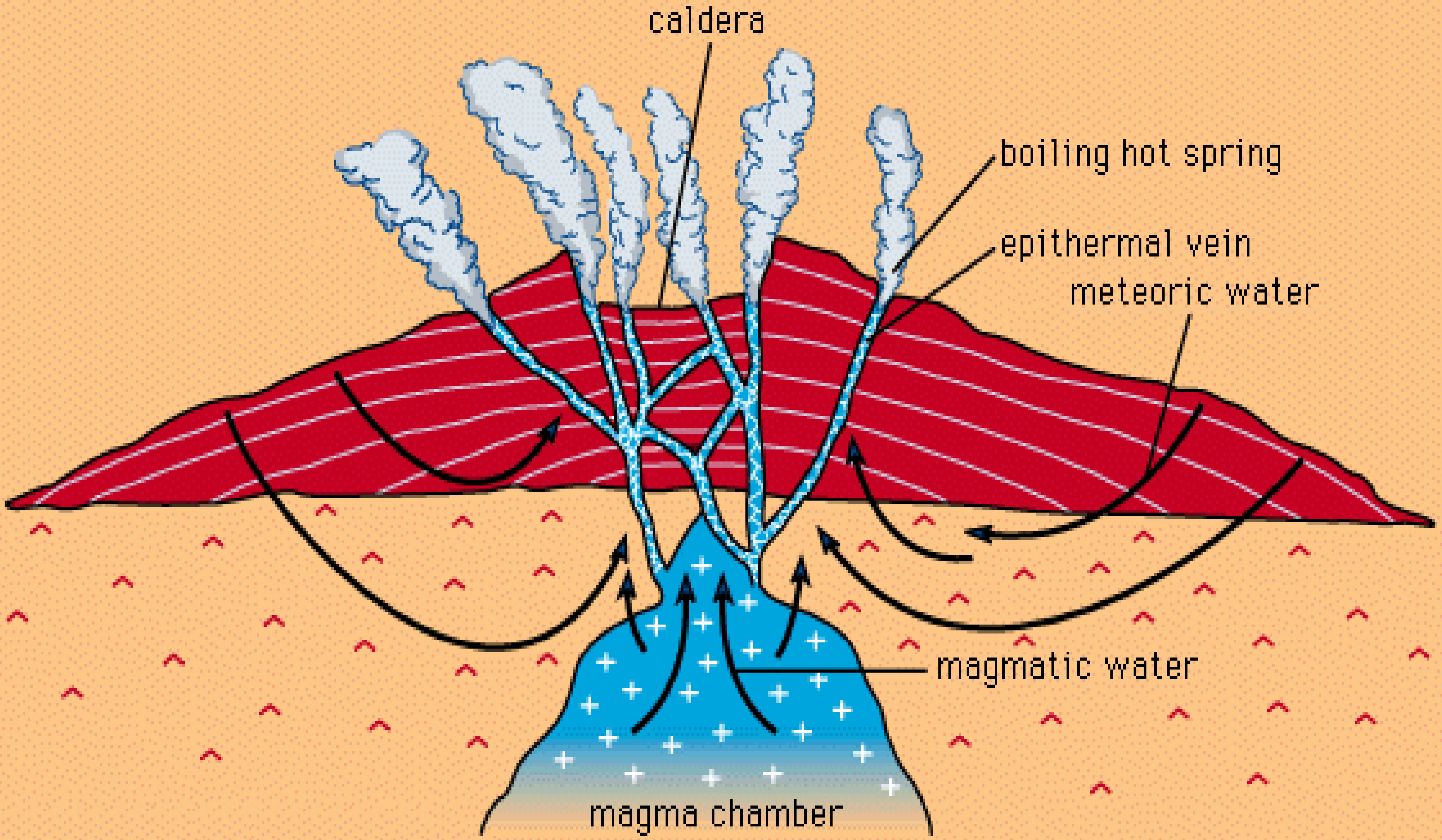
# Control of ore localisation

The ore localisation is controlled by the following factors:

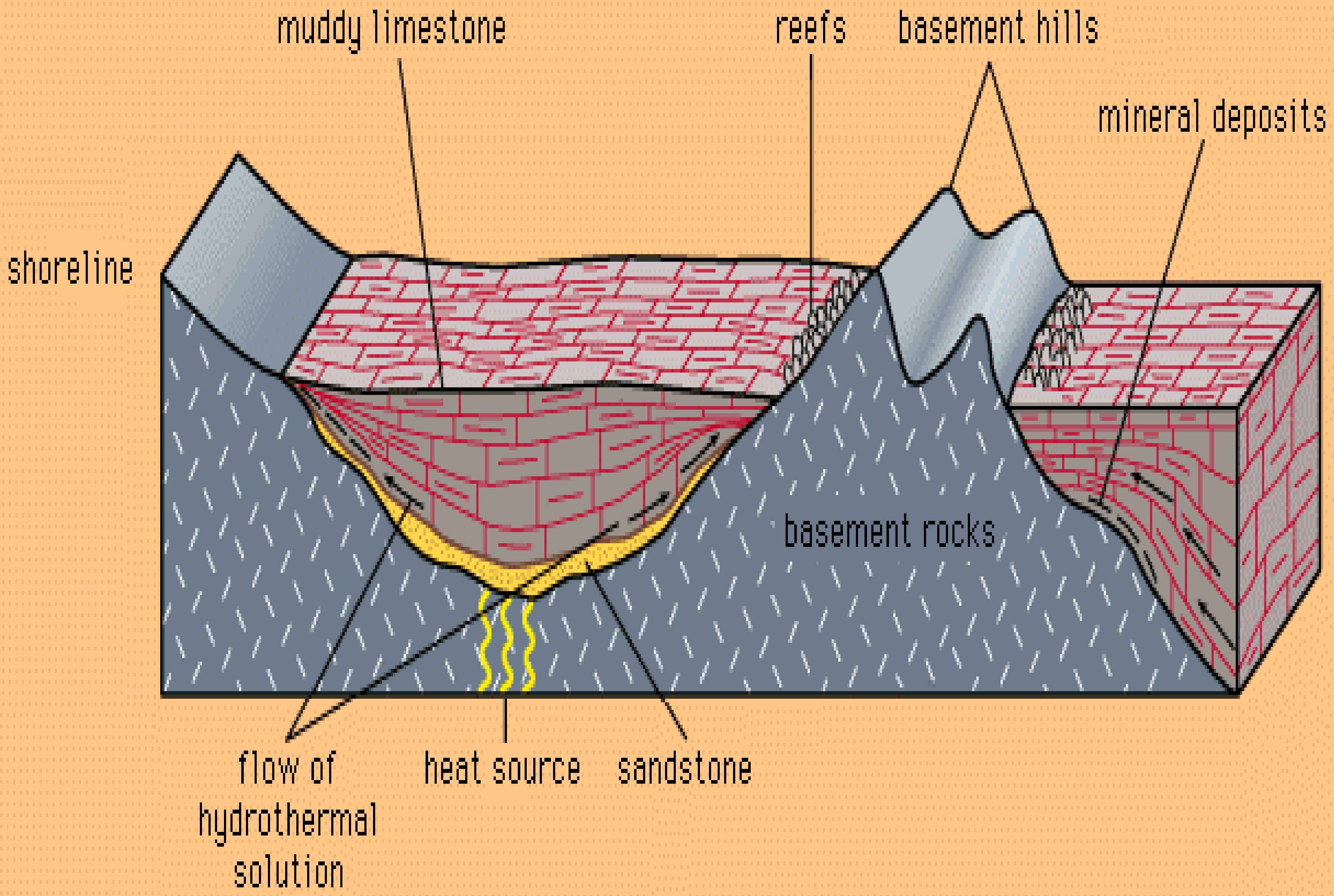
*Chemical and physical characters of host rock*: this determines the location, shape and size of opening. For example, carbonate rocks permits solution openings and brittle rocks shatter more readily to localize fractures or breccia. Permeability which is necessary in rock for passage of solution and ore localisation is caused due to pore spaces, fissibility, cleavage planes, brecciation, joints, fractures etc.

*Structural features*: structural features like fissures, shears, folds, faults, bedding planes, lamination and unconformity serve important localisers of hydrothermal deposits.

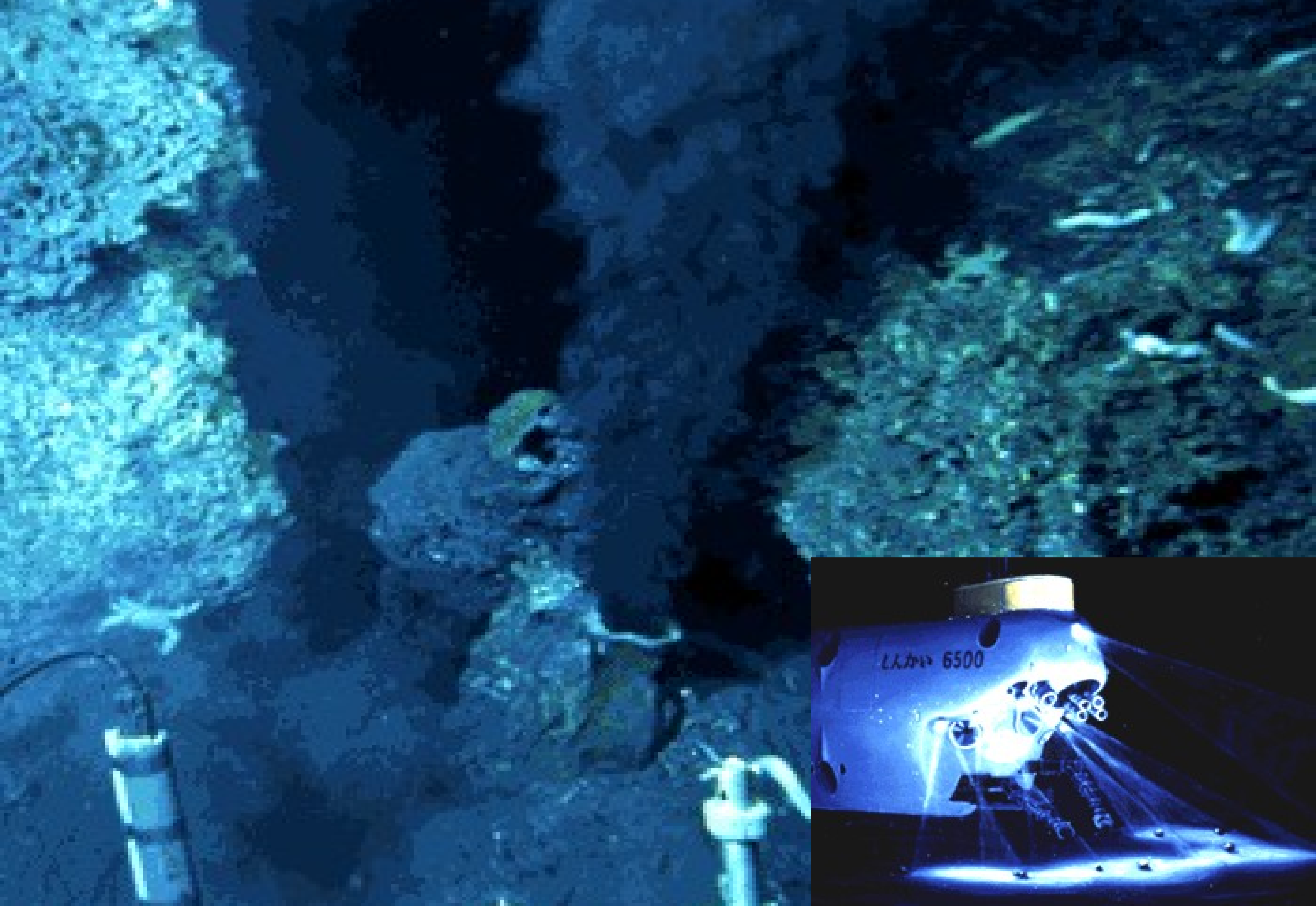
*Intrusives*: intrusive being source of ore-bearing fluid, constitute ore loci on a regional scale.



The magma chamber is the heat source for the hydrothermal solutions, which contain both magmatic and meteoric matter.


muddy limestone
reefs
basement hills
mineral deposits
shoreline
basement rocks
flow of hydrothermal solution
heat source
sandstone

# Submarine hydrothermal vent or “Black Smoker”



Cavity filling and replacements are the two types of deposits formed due to hydrothermal processes.

- Cavity filing is due to deposition of minerals in various types of openings

- Metasomatic replacement or replacement deposit the earlier formed minerals is replaced by the new mineral.

- In general, replacement deposits are formed at higher temperature and pressure, and cavity filling deposits at lower temperature and pressures.

- However, both types of deposits may also form at the same time and at all temperature.

## (a) CAVITY FILLING

The precipitation of minerals forms mineralizing solution in the cavities or the open spaces in rock forms cavity filling deposits.

The walls of the cavity are lined first by the first mineral to be deposited. The minerals usually grow inward with development of crystal faces pointed towards the supplying solution in the form of comb structure.

Successive crust of different minerals may be precipitation and if the cavity is a fissure, a crustified vein is formed.

Symmetrical crust may result with similar precipitation on both the walls of the vein, and asymmetrical with unlike crustification on each side. In case of breccia, the crusts surround the breccia and cockade ore is formed.

The cavity filling may also give rise to ribbon structure with narrow layers of quartz separated by thin dark seams of altered wall rock. The following types of deposits may result due to cavity filling -

## Fissure vein:

It is a tabular type of deposit, involving formation of fissure itself by stresses operating within earth's crust, and ore forming processes, e.g. fissure filling deposit of magnesite in Salal area, Jammu.

These fissure veins may be massive or crustified. They may be simple, composite, linked, sheeted, dilated and chambered.

They may be vertical or inclined. Pinches and swells produced by movement along irregular fissures may occur. Several minerals, both ore and gangue, may fill in the fissure.

Fissures may occur in groups, and may have formed at the same time or may be different ages. The depth of fissure vein is quite variable. Some of them continue to depth of several thousand metres like those at Kolar Gold Mine.

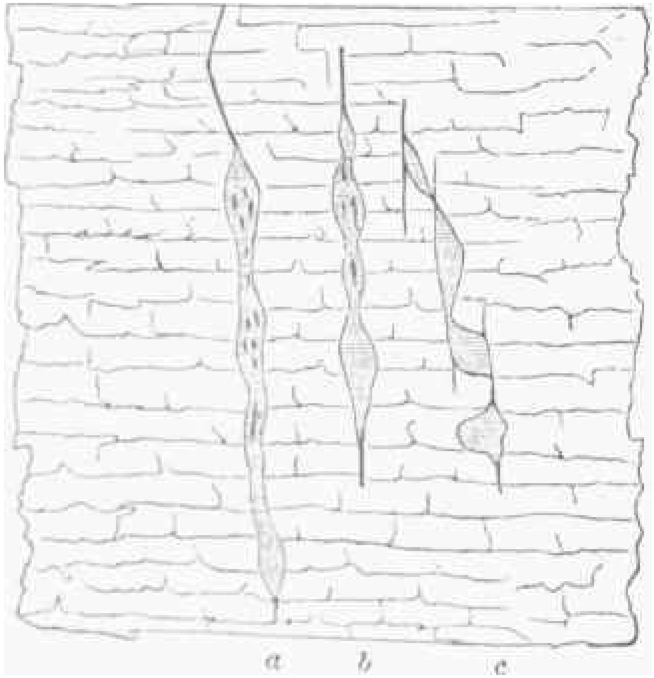


**Fig. 1. - Gash Viens filled with Lead Ore Galena Lime stone. a.Crevie opening.b, c. Crevices with pocket openings.**

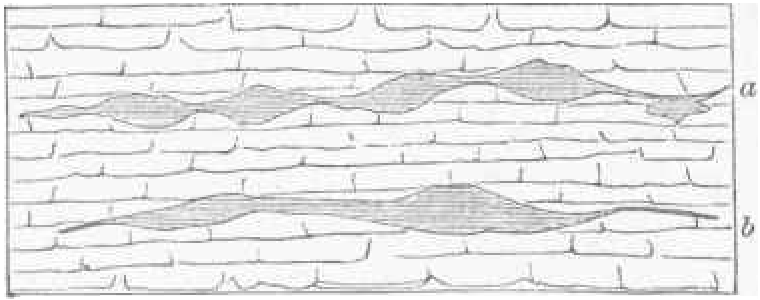
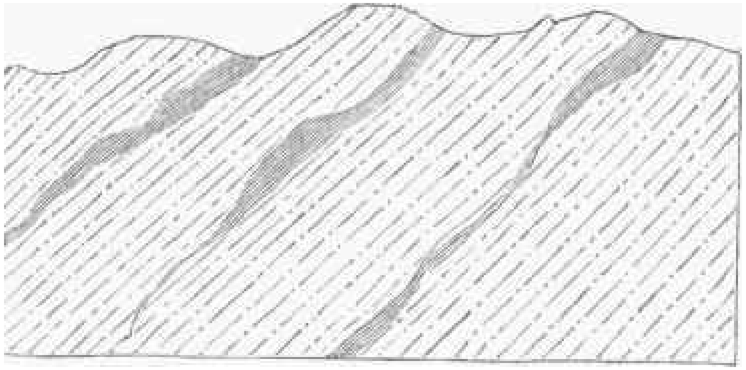


**Fig. 2. - Horizontal Gash Veins or Floors of Lead in Galena Limestone, a. Crvice with pocket opening, b. Crevice opening.**



Segregated Veins of Auriferous Quartz in Gneiss

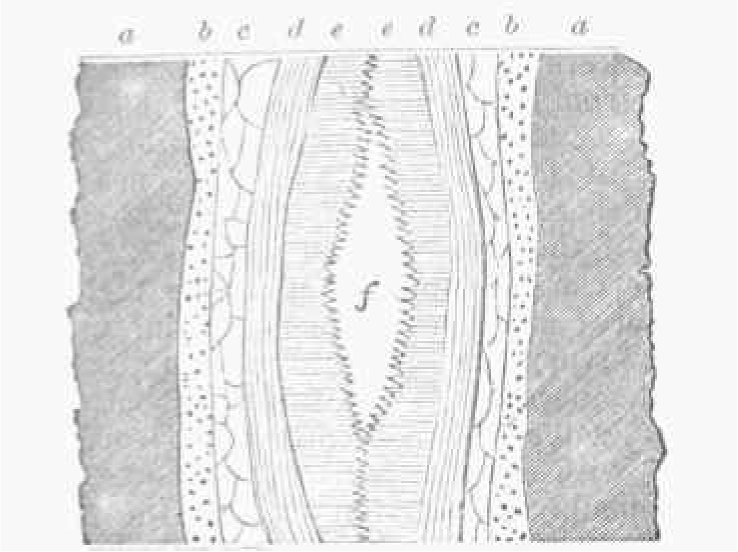
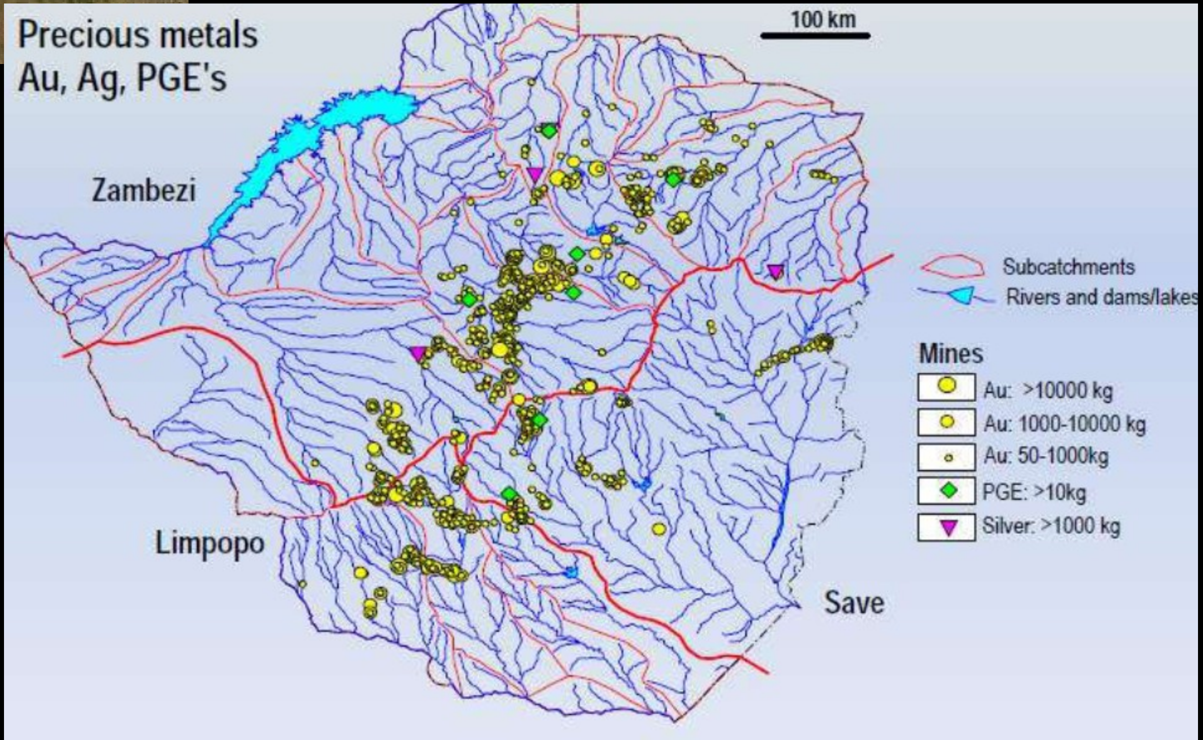


Fig. 6. - Fissure Vein with Cavity of "Tug" at Centre. aa Country rock, bb. Heavy spar, c c. Calc spar. dd. Blende, e e. Coinby quartz. f. Vug.

Fig. 4 Mineralization zone in Banik area N- thrust zone

Fig. 5 Vein of barite in Aqra Formation  Lfan areaN-thrust zone


Precious metals
Au, Ag, PGE's
100 km
Zambezi
Limpopo
Save
Subcatchments
Rivers and dams/lakes
Mines
Au: >10000 kg
Au: 1000-10000 kg
Au: 50-1000kg
PGE: >10kg
Silver: >1000 kg

# Crustiform banding

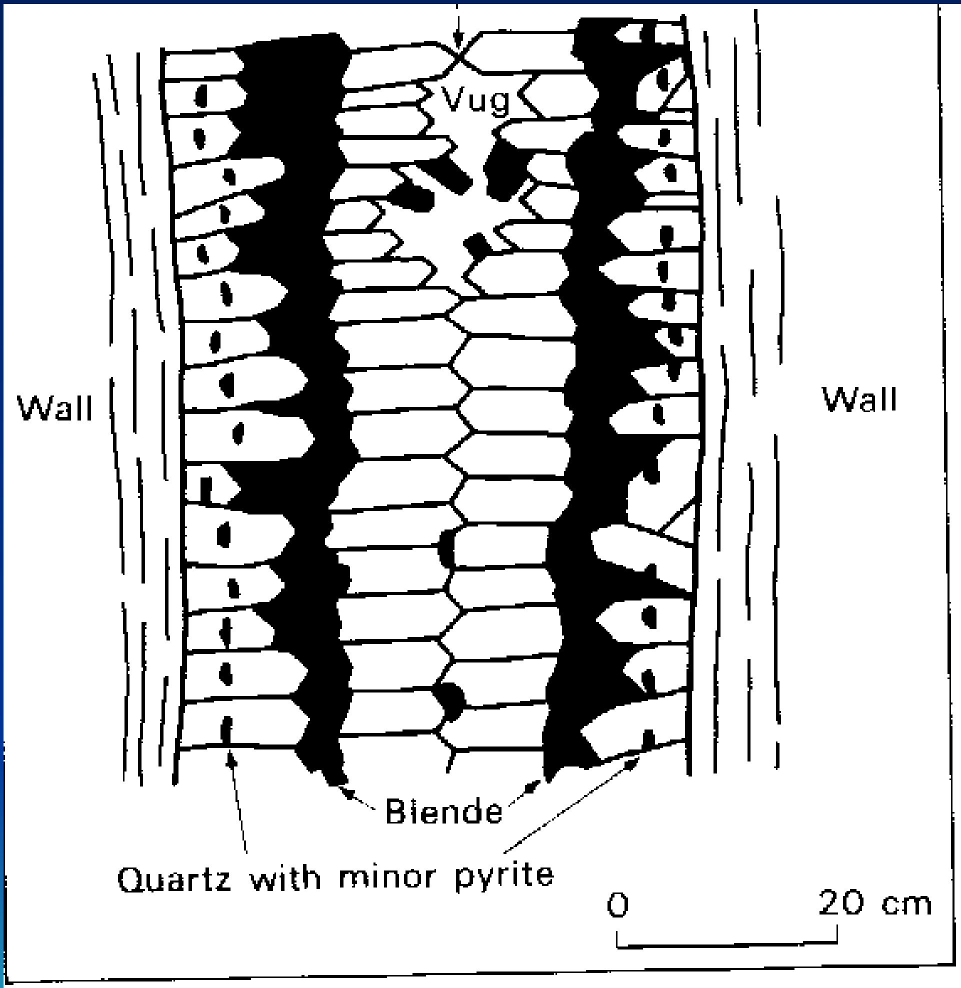


**Fig. 5.2** Section across a vein showing crustiform banding.

**Shear zone deposits:** a shear zone with sheet like connected openings, and large exposed surfaces serves as excellent channel ways for mineralizing solutions and precipitation takes places as thin plates of minerals or in the form of fine grains, e.g. Singhbhum shear zone deposits.

**Stockwork:** it signifies a network of small ore bearing veinlets and stringers traversing a mass of rock. The veinlets show crustification, comb-structure and druses, and represent open space fillings. For example, in Zawar area, Rajasthan, veins and stringers of galena and sphelerite traverse dolomite mass and form lenticular bodies. Stockworks of asbestos occur in the Archeaen terrain of Barabana area, Singhbhum, Bihar.

**Saddle reef:** it results when alternating competent and incompetent rocks are closely folded. This gives rise to openings in the crest part of the arch, which latter on filled with ore minerals. The quartz reefs of Hutti gold deposit, Karnataka, and those of Wynad gold deposit, Tamil Nadu are the best illustrations.

Anticlinal fold in sandstones and shales, United Kingdom. The white material in the hinge of the fold at the center of the photograph is quartz, and fills a void that opened up during folding. Such filled-in features are called saddle reefs.

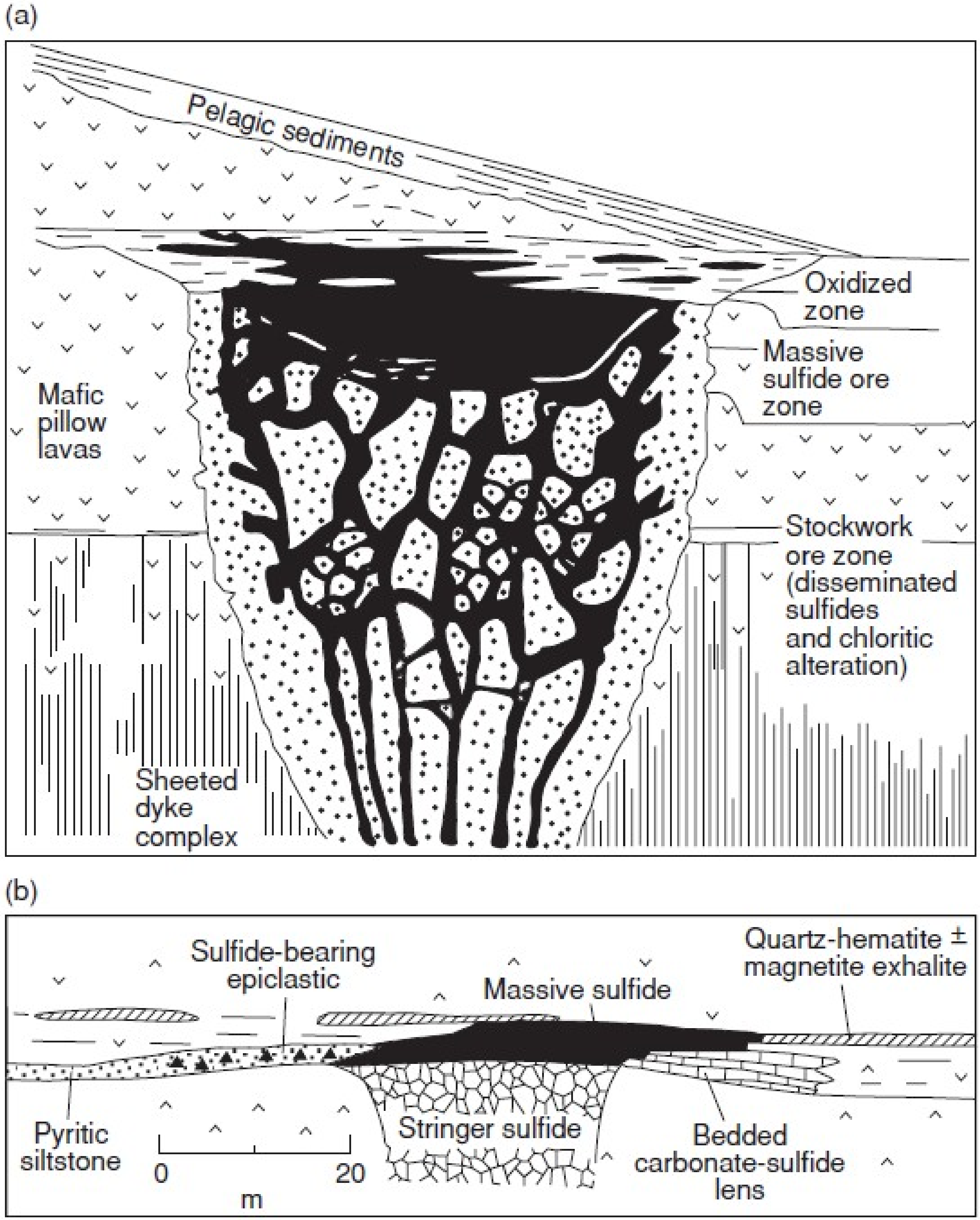
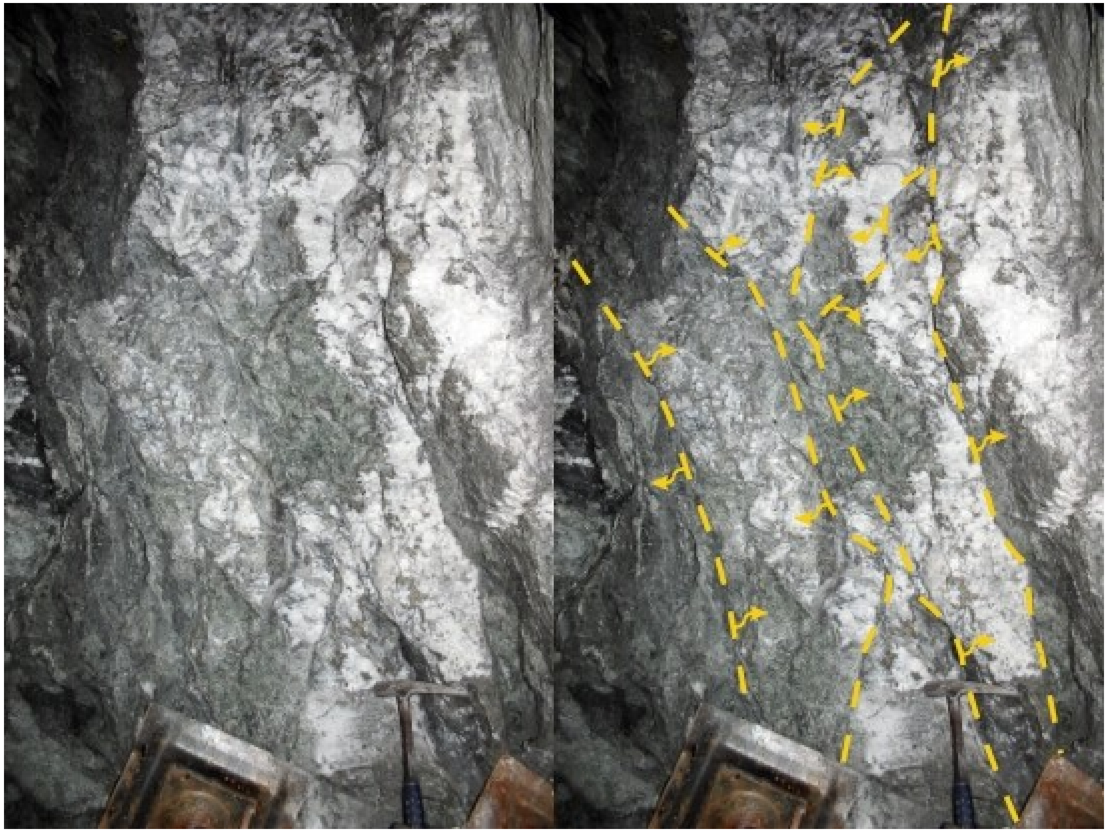


**Figure 3.21** (a) Section through a typical ophiolite-hosted, Cyprus-type VMS deposit. Footwall rocks may consist of a sheeted dyke complex and the associated volcanics are often pillowed and have a tholeiitic composition. After Hutchinson and Searle (1971). (b) Section showing the characteristics of VMS deposits other than the ophiolite-hosted type. Associated volcanics may be intermediate or felsic in composition and a closer lateral link to chemical and epiclastic sediments is often apparent. The lens of massive sulfide ore formed on the ocean floor, underlain by a stockwork zone of disseminated sulfides and intensely altered volcanic rock, is typical of VMS deposits in general (after Large, 1992).



Gold-bearing quartz vein of an orogenic gold deposit, which has been sheared several times. Fluids migrated along the shear bands (dashed) and mineralized the quartz with sulfides and gold.

**Ladder veins:** this type of deposit forms due to transverse veins or fracture, e.g. magnesite deposit of Mysore, Karnataka, and asbestos deposits of Cuddapah district, AP.

**Pitches and flats:** these are formed due to folding of brittle sedimentary beds which gives rise to a series of disconnected deposits. Iron-ore deposits of Bailadila and Chotadongar, Baster district, MP, lead – zinc deposits of Baghmari (Katuria), Banka district, Bihar, and talc deposits of Cannore and Kalicut district, Kerela are the several examples.

**Breccia filling deposits:** the breccias offer openings spaces in between the angular fragments for deposition by the mineralizing solutions traversing through them. These may be volcanic breccia, tectonic breccia or collapse breccia deposits. Wajrakarur kimberlite pipe, AP, and fault breccia in Singhbhum Shear Zone, Bihar with copper, lead, uranium and apatite mineralization may be cited as examples.

**Solution cavity filling:** certain solution forming rocks like limestone, gives rise to this type of deposit e.g. barytes deposits in Krol limestone of Sirmur district, Himachal Pradesh.

**Pore cavity filling:** many mineral deposits occur as pore space fillings, say in sandstone. Oil, gas and water are the most important among all. Disseminated lead-zinc deposit in gritty conglomerate dolomite and quartzite of Zawar, Rajasthan is an example of pore space filling.

**Vesicular filling:** the vesicular lava flows being permeable form channel ways for mineralizing solution and sites of mineral deposits. Copper occurrence is Dras volcanics, Kargil area, Jammu and Kashmir and in Deccan trap of Maharastra and Gujarat, and agate, chalcedony, amethyst and opal occurrences in the Deccan trap is the examples of vesicular fillings.

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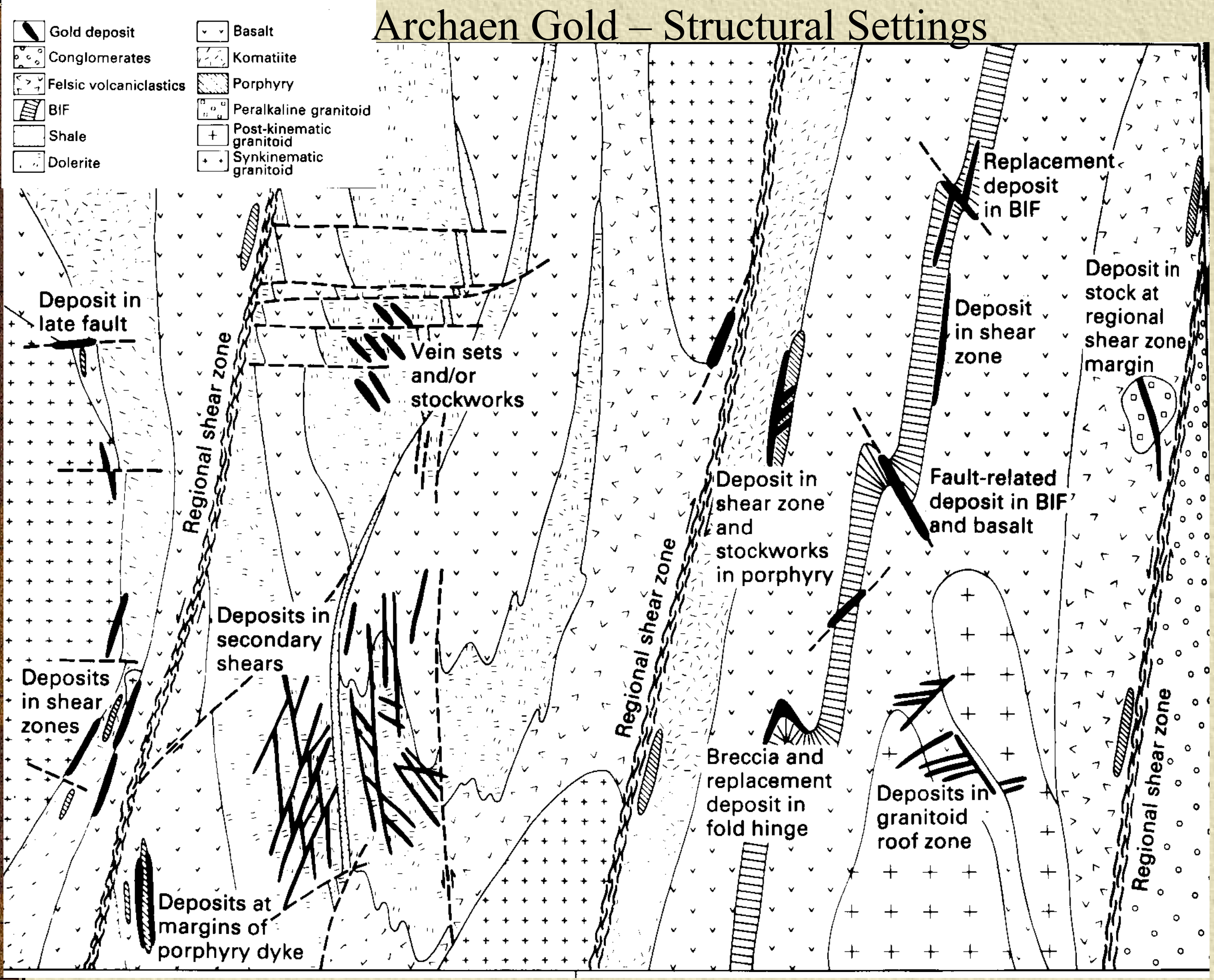
# Archaen Gold – Structural Settings



Quartz veins formed in this rock.

When minerals are deposited in open spaces, large crystals form

Amygdules (mineral deposits filling extrusive vesicles) in the Neoproterozoic-aged Catoctin Formation meta-basalt, Shenandoah National Park, Virginia.

| **Vein** | **Metal** | **Ore Mineralogy** and related *alteration assemblages* |
|---|---|---|
| Surface (epthermal) | Barren | Chalcedony, qtz, barite, fluorite, carbonate minerals |
| | Hg | **Cinnabar**, chalcedony, qtz, bar, fluor, carbonates |
| | Sb | **Stibnite**, qtz |
| | Au-Ag | **Gold, electrum, acanthite**, qtz, chalcedony, adularia, alunite, carbonates, *silicification, some potassic, phyllic and propylitic alteration* |
| | Barren | Qtz and carbonate minerals |
| | Ag-Mn | **Acanthite, rhodochrosite**, qtz, carbonates, some *phyllic, argillic, propylitic alteration* |
| Intermediate (mesothermal) | Pb | **Galena**, qtz w/ minor carbonate minerals |
| | Zn | **Sphalerite**, qtz w/ occasional carbonates, *advanced argillic* |
| | Cu-As-Sb | **Chalcopyrite, tennantite-tetrahedrite,** qtz, *phyllic, propylitic, argillic alteration* |
| | Cu | **Chalcopyrite,** qtz, *phyllic alteration* |
| | Mo-W-Sn | **Molybdenite, huebnerite, scheelite, cassiterite,** qtz, *potassic alteration* |
| Deep (hypothermal) | Barren | *Potassic alteration,* anhydrite, carbonate minerals |

Metasomatic replacement is defined as a process of simultaneous solution and deposition by which earlier formed mineral is replaced by a new one

Metasomatic replacement deposits form, when the hydro- thermal solutions react with some mineral or substances in the crust, dissolving one substance and replacing it with the ore condition Mostly these deposits are formed under hypothermal condition

The chemical composition and physical characteristics of the host rocks or minerals and the composition, temperature and pressure of the invading mineralising solutions determine the Metasomatic replacement deposits are characterised by:

(a)Presence of remnants of the country-rock.

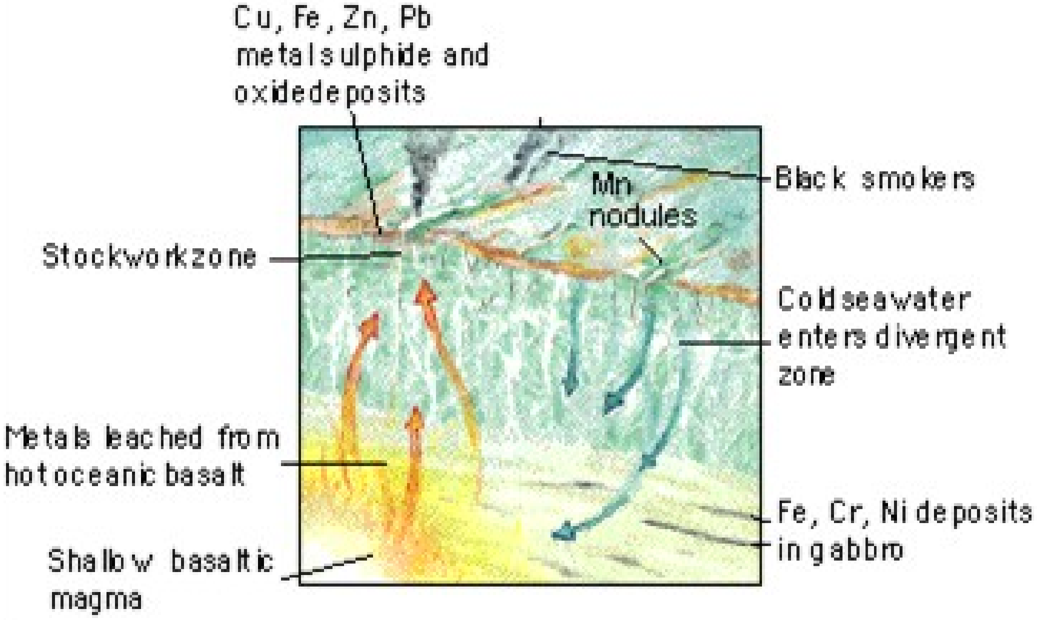
(b)Presence of pseudomorphs of replacing minerals after the replaced ones.

(c) Absence of crustification etc.

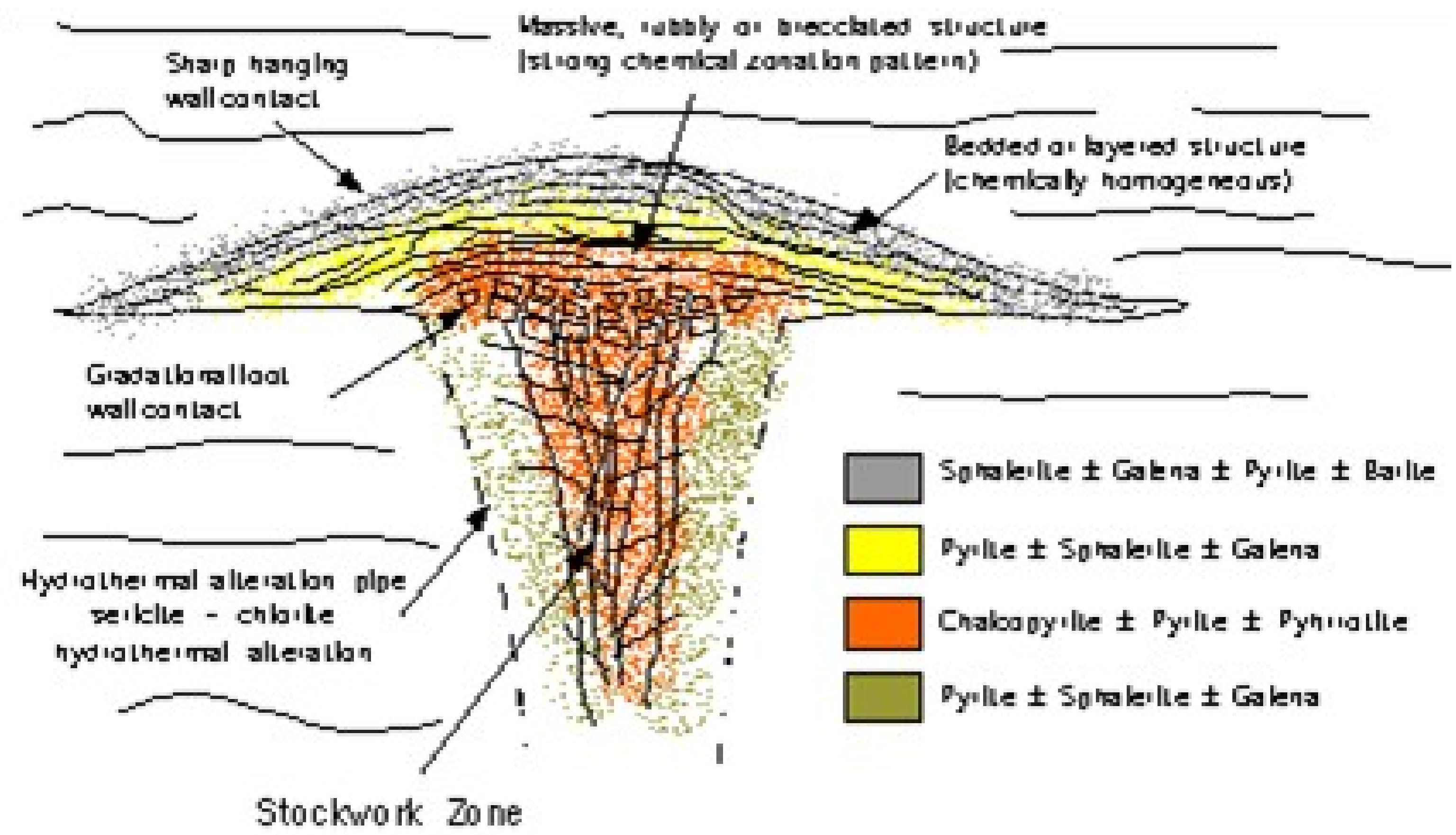
## Volcanogenic Massive Sulphide (VMS) Deposits

**At divergent boundaries, water from the ocean floor flows through fractures in the oceanic crust. The waters are heated by the nearby magma source, producing a seawater convection cell which reacts with neighbouring rocks to leach out metals.**

**These dissolved metals are transported to the ocean floor where they mix with cold bottom waters. The sudden decrease in temperature causes the minerals to precipitate from solution and they are incorporated into sediments deposited along the ocean ridge system.**



**Circulation of fluids and precipitation of mineral deposits at divergent boundaries**


Massive, rubbly or brecciated structure
(strong chemical zonation pattern)
Sharp hanging
wall contact
Bedded or layered structure
(chemically homogeneous)
Gradational foot
wall contact
Hydrothermal alteration pipe
sericite – chlorite
hydrothermal alteration
Stockwork Zone
Sphalerite ± Galena ± Pyrite ± Barite
Pyrite ± Sphalerite ± Galena
Chalcopyrite ± Pyrite ± Pyrrhotite
Pyrite ± Sphalerite ± Galena

# Ore Deposits Formed by Metamorphism

- Metamorphic processes profoundly alter pre-existing mineral deposits and form new ones.
- The chief agencies involved are heat, pressure, time, and various solutions.
- The materials acted upon are either earlier formed mineral deposits or rocks.
- Valuable nonmetallic mineral deposits are formed from rocks chiefly by the crystallization and the combination of rock making minerals.

# Role of Temperature and Pressure

- Metamorphic processes occur to make adjustments between the chemical potential of any system and the changes in temperature and pressure.

- A particular chemical reaction that cannot occur in one environment may readily do so under different temperature and pressure conditions.

- An increase in pressure will cause a reaction to move in a direction in which the total volume of the system decreases, for example increasing pressure results in the following changes with a reduction in the total molar volume:

Olivine + anorthite → garnet
augite +anorthite → garnet + quartz
ilmenite + anorthite → sphene + hornblende
nephelene + albite → glaucophane or jadeite
anorthite + gehlenite + wollastonite → grossularite
andalusite → sillimanite → kyanite

- An increase in temperature normally results in endothermic reactions. A possible example is the conversion of pyroxene to hornblende during the metamorphism of diabase to amphibolite.

- In short, metamorphic reactions result from the tendency of mineral systems to adjust to their physicochemical environment of high temperatures and pressures in contrast to the low temperatures of weathering processes, both of which processes generally occur in the presence of water.

# Metamorphism of Earlier Deposits

- When rocks are metamorphosed, enclosed mineral deposits may also be metamorphosed.
- Unlike rocks that undergo both textual and mineralogical changes, Ores undergo less mineral re-combinations.
- Textual changes, however, are pronounced. Schistose or gneissic textures are induced, particularly with sectile minerals, and flow structure is not uncommon.
- Galena, for example, becomes gneissic. It may also be rendered so fine grained that individual cleavage surfaces cannot be discerned with a hand lens.
- It "flows" around hard minerals, such as pyrite. Other minerals, such as chalcopyrite, bornite, covellite, or stibnite, behave similarly.
- The result is that ores may exhibit streaked, banded, smeared appearances with indistinct boundaries between minerals of different color.
- The original textures and structures may be so obscured that it is difficult to determine to which class the originally deposits belonged. Such deposits are then classified as "metamorphosed".

## Formation of Mineral Deposits by Metamorphism

- Several kinds of nonmetallic mineral deposits are formed as a result of regional metamorphism.
- The source materials are rock constitutions that have undergone recrystallization or re-combination, or both.
- Rarely, water or carbon dioxide has been added, but other new constitutions are not introduced as they are in contact metasomatism deposits.
- The enclosing rocks are wholly or in part metamorphosed; it is the rock metamorphism that has given rise to the deposits.
- The chief deposits thus formed are asbestos, graphite, talc, soapstone, andalusite-kyanite-sillimanite, dumortieritea, garnet, and possibly some emery.

- Asbestos forms by the metamorphism (hydration) of ultrabasic igneous rocks – peridotites and dunites.
- Graphite forms by regional metamorphism of organic matter, crystallization from igneous rocks, contact metamorphism and hydrothermal solutions.
- Talc, soapstone and pyrophyllite form by a mild hydrothermal metamorphism of magnesian minerals eg tremolite, actinolite, olivine, epidote and mica. Talc also occurs in regionally metamorphosed limestones, altered ultrabasic igneous rocks, and contact metamorphic zones.
- Andalusite-kyanite-sillimanite – these minerals are high grade refractories. Kyanite is formed by the dynamothermal metamorphism of aluminous silicate minerals. Andalusite is formed by the pneumatolytic action on aluminous silicates. Sillimanite results from high temperature metamorphism of aluminous crystalline rocks.
- Garnet forms during the regional and contact metamorphism and is consequently found in schists and gneisses. It is also found as a constituent of igneous rocks.
- Emery is a mixture of corundum and magnetite with hematite or spinel and is a product of contact metamorphism.

**Bedded manganese deposits in parts of Madhya Pradesh and Maharashtra, primarily of sedimentary origin, have been subsequently effected by metamorphism. Braunite, a manganese silicate, is the important ore mineral besides several other oxide minerals.**

# Ore Deposits Formed by Sedimentation

**The process of sedimentation results in the formation of some important mineral deposits viz., iron, manganese, copper, phosphate, coal, oil shale, carbonates, cement rock, diatomaceous earths, bentonite, fuller's earth magnesite, sulfur and uranium-vanadium deposits.**

**The essential conditions for the formation of sedimentary deposits are:**

1) **an adequate source of material**
2) **gathering of the solution by solution or other processes**
3) **transportation of the material to the site of deposition, and**
4) **deposition of material in sedimentary basins.**
5) **Compaction, alteration or other chemical changes may follow deposition.**

# Source of Material:

Materials of sedimentary deposits have been derived chiefly from:

1) weathering of rocks

2) weathering and oxidation of former mineral deposits viz., iron, manganese, copper.

The earth's crust contains on average 5.6% Fe. This means that beneath the surface, upto a depth of 30 km, the earth's crust contains about 30 million tons/km2 of iron.

Of this, only 0.0001% is concentrated in commercial deposits. Iron in sedimentary rocks comes from the iron bearing minerals of igneous rocks such as hornblende, pyroxene and mica, from the iron-bearing minerals of sedimentary and metamorphic rocks, and from the red coloring matter of sedimentary rocks.

Manganese of sedimentary deposits hs been derived from the weathering of Mn-bearing minerals in rocks, former sedimentary concentrations and lode deposits of manganese. Mn makes up about 0.095% of the earth's crust, there being 50 times as much iron as manganese. There are over 200 minerals containing manganese as an essential constituent.

The source of sedimentary phosphate is phosphorous bearing minerals , among which apatite is the most common.

Some phosphorous is also derives from the weathering of collophanite and dahllite in sedimentary rocks. Constituents of sedimentary carbonates viz., industrial limestone, dolomite and magnesite are derived from the sea or saline waters to which they are largely supplied by rock weathering.

Constituents of clay deposits, bentonite and fuller’s earth originate in rock weathering.

## Solution & Transportation:

Solution of material constituting sedimentary deposits goes on during weathering. This is true of Fe, Mg, P, CO3, Cu, and some rare metals, but not of clays. The chief solvents are carbonated waters, humic and other organic acids and sulfate solutions.

## Carbonated Waters:

These are very effective solvents of limestones, iron, Manganese and phosphorous. Vast quantities of metals are transported as carbonates by carbonated waters. Ferrous iron is soluble whereas ferric iron offers resistance.

To undergo solution, ferric iron must first b converted to the ferrous state. Organic matter aids such a conversion. The Precambrian iron ores were probably transported as ferrous bicarbonate solutions or in the colloidal state.

## Humic and other Organic Acids:

These are the decomposition products of vegetation and are considered excellent solvents. Weak organic acids dissolve large quantities and are the most effective of all solvents. It has been noticed that iron is not carried as bicarbonate in surface waters rich in organic matter.

## Sulfate Solutions:

These are excellent solvents of Fe and Mn but rarely abundant enough to effect large scale solution and transportation.

$FeS_2 + 7O + H_2O \rightarrow FeSO_4 + H_2SO_4$

Most of the materials (except coal) are transported by rivers and subsurface waters.

Most often these substances reach the sea, but some are arrested en route and are deposited in inland water bodies or basins. The dissolved substance remain in solution so long as the solution does not undergo any appreciable physical or chemical change. Some or all of the iron and manganese may be lost if the solution traverses limestone country.

If Fe and Mn escape these hazards, they may be transported to bogs, lakes, playas or the sea, where their concentration and deposition takes place.

Five important processes are associated with the sedimentary mineralisation, viz.

1. Residual concentration.

2. Mechanical concentration.

3. Oxidation and Supergene Enrichment.

4. Remobilisation by meteoric circulating water.

5. Sedimentation.

   The manner of deposition depends upon:

   a) The nature of solvent
   b) The place of deposition
   c) The pH and Eh (redox) conditions, eg. in the sea or swampy basins.

   Deposition from solutions depends upon the environmental relations of chemical sediments in normal sea water.

# Depositional Separation of Manganese & Iron:

## Depositional Separation of Manganese & Iron:

Separation of manganese and iron occurs if precipitation is taking place from carbonate solutions. This happens because manganese carbonate is more stable in carbonate solutions than iron carbonates, and is hence carried further than the latter.

The separation of iron and manganese in an oxidizing environment takes place because the iron oxides precipitate at a lower oxidation potential than the comparable manganese compounds at any given pH.

Similarly under fixed Eh, iron starts precipitating as an oxide at a lower pH than manganese. In a neutral environment both iron and manganese may precipitate together as carbonates.

# Residual concentration:

The term 'residual concentration indicates the concentration of ores as residue. Residue left as insitu after weathering, followed by transportation sometimes give rise to valuable ore deposits.

These are the insoluble products of rock weathering, the process which removes the undesired constituents of rocks or minerals. The residue may continue to accumulate until their purity and volume make them commercially important.

Of the three modes of weathering, the chemical mode of weathering is of paramount significance for the formation of residual deposits

The effects of weathering usually do not extend deeper than a couple of meters but occasionally reach 30 to 60 meters. It is most active in tropical and sub-tropical climates.

In such climates, rock decay is carried further; leaching is more complete; the silicates are thoroughly broken down and surface water readily removes the silica, thus bringing about the concentration of the residual material which, when useful, forms valuable mineral deposits.

## Process of Formation of Residual Deposits:

- The first condition is the availability of rocks or lodes containing valuable minerals, of which the undesired substances are soluble and the desired ones insoluble under surface conditions.
- The climatic conditions should favour chemical decay. Tropical & sub-tropical climatic conditions are most favourable.
- The relief must not be too great, or the valuable minerals will be washed away as soon as they are in the least concentrated.
- Long continued crustal stability is essential for residues to accumulate in quantity, and the deposits may not be destroyed by erosion.
- Important deposits include: Iron ores, manganese, bauxite, clays, nickel, phosphate, kyanite, barite, ochers, tin, gold, etc.
- Given these conditions, a limestone formation with minor iron oxides will slowly be dissolved leaving the insoluble iron oxides as a residue. As bed after bed of limestone disappears, an overlying mantle of iron ores of sufficient thickness, and grade accumulates to make a workable deposit.

**Residual deposits therefore form in two ways:**

**1)the residue is simply an accumulation of a mineral that has not changed during the process e.g. iron oxides in banded iron formations, and**

**2)the valuable mineral first comes into existence as a result of weathering processes, and then persists and accumulates e.g. the feldspars of a syenite decomposes upon weathering to form bauxite, which persists at the surface while other constituents are removed in solution.**

**Valuable deposits of iron ore, manganese, bauxite, clays, nickel, phosphate, kyanite, barite, ochre, tin, gold and other substances occur as residual concentrations.**

## Residual Deposits and their Source Materials:

### Iron Concentrations:

1)Lode deposits of siderite or iron sulfides - these residues are rarely used as iron ores.

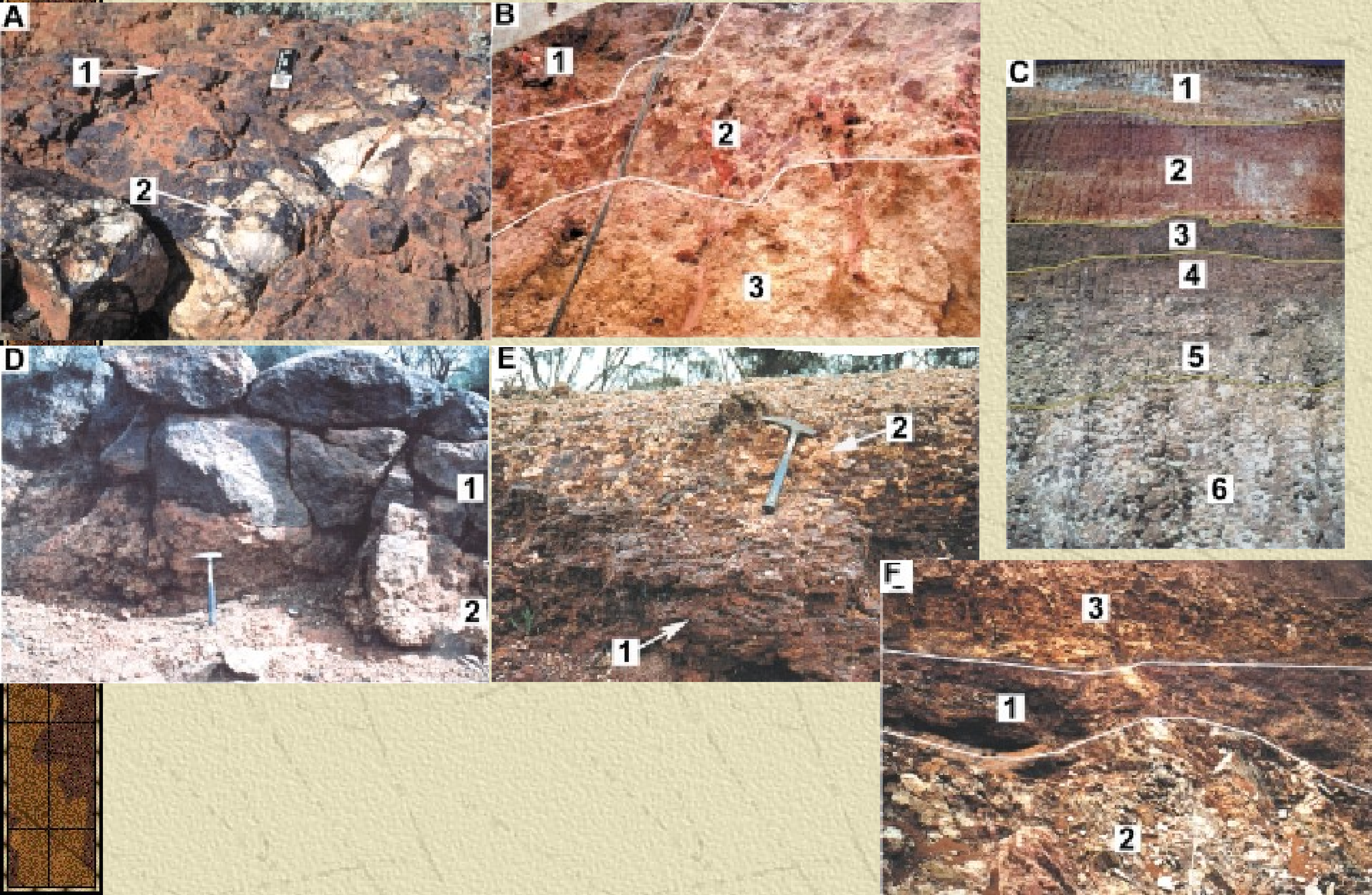
2)Disseminated iron minerals in non-aluminous limestones.

3)Limestones that have been partly replaced by iron minerals, either before or during the period of weathering.

4)Basic igneous rocks.

5) Ferruginous siliceous sediments.

# Lateritic Residuum (a-c) and



## Manganese Concentrations:

1) Limestones or dolomites low in alumina but containing disseminated syngenetic manganese carbonates and oxides.

2) Limestones containing disseminated introduced manganese. Carbonate rocks precipitate manganese under certain conditions.

3) Manganiferous silicate rocks such as crystalline schists or altered igneous rocks.

4) Lode deposits of manganese minerals or ores high in manganese e.g. veins, replacement deposits or contact metasomatic deposits (containing rhodochrosite, rhodonite, manganiferous siderite and calcite, spessartite, tephroite, alleghenite, piedmontite, hausmannite, manganosite, etc.).

## Bauxite Formation:

**Rocks relatively high in aluminum silicates and low in iron and free quartz e.g.**

1) nephline syenite.
2) Limestones or clays in limestones
3) Clastic sediments derived from Archaean rocks
4) Basalts
5) Clay alluvium
6) Feldspathic sandstones

## Clay Formation:

**The source rocks are crystalline rocks and silicic granular rocks rich in feldspars and low in iron minerals such as:**

1) Granites and gneisses
2) Basic ignous rocks
3) Feldspar rich pegmatites
4) Syenites
5) Limestones
6) Shales
7) Sericitized igneous rocks

# Formation of Mineral Deposit by Mechanical Concentration:

**When mineral grains of different density are moved by flowing water, the less dense grains will be most rapidly moved, and a separation of high-density and low-density grains can be effected. Mineral deposits formed as a result of gravity separation based on density are called placer deposits.**

**For effective concentration, placer minerals must not only have a high density (greater than about 3.3 grams per cubic centimetre), they must also possess a high degree of chemical resistance to dissolution or reaction with surface water and be mechanically durable.**

**The common sulfide ore minerals do not form placers, because they rapidly oxidize and break down.**

**Ore minerals having suitable properties for forming placers are the oxides cassiterite (tin), chromite (chromium), columbite (niobium), ilmenite and rutile (titanium), magnetite (iron), monazite and xenotime (rare-earth metals), and zircon (zirconium). In addition, native gold and platinum have been mined from placers, and several gemstone minerals--in particular, diamond, ruby, and sapphire--also concentrate in placers.**

## Requirements for mechanical concentration:

(a) The valuable minerals should be of high specific gravity.

(b) They should be chemically resistant to weathering.

(c) They should be of adequate durability.

(d) There should be a continuous supply of placer minerals for concentration.

## Factors Affecting Formation of Placer Deposits:

(i) Specific gravity of minerals.

(ii) Specific surface of the particles.

(iii) Shape of the particles.

(iv) The ability of a body of flowing water to transport the particles and the viscosity of the transporting medium.

These are essentially four factors which have much significance in the formation of placer deposits, they are:

(i) Geomorphological factors.

(ii) Climatic factors.

(iii) Hydrographic factors which is associated with the river action and the deposits at the meandering of the river and the junction between the tributaries.

(iv) Tectonic factors, which is associated with the rejuvenation of the base level of local and general erosion, creating conditions for recurrent cycles of erosional activity for development of alluvial placers.

## Types of placer deposits:

(a) **Eluvial placers:** Placer deposits along hill slopes are formed due to weathering and erosion of the country rocks containing low-grade deposits of the desired materials and are known as eluvial placers.

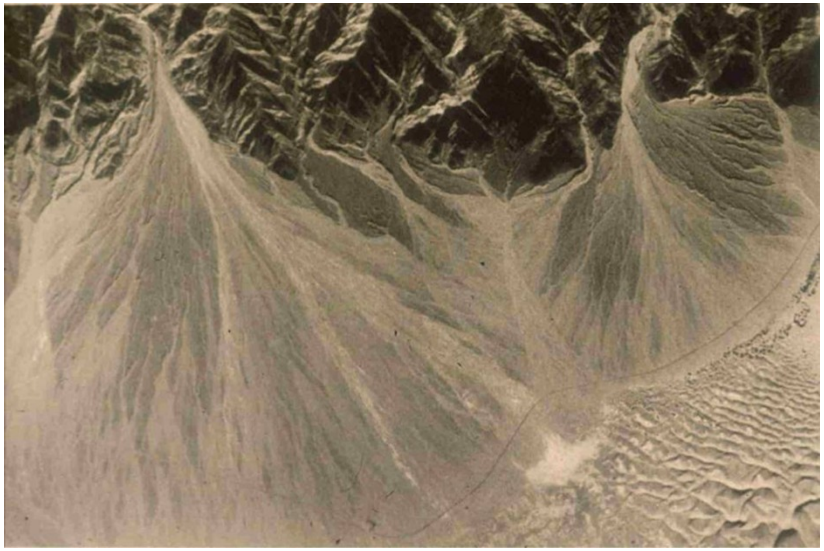
(b) **Deluvial placers**: When the weathered and disintegrated material is shifted down hills deluvial (scree or talus) placers are formed.

(c) **Proluvial (colluvial) placers**: Accumulation of the material at the foot of a slope can lead to the development of proluvial placers.

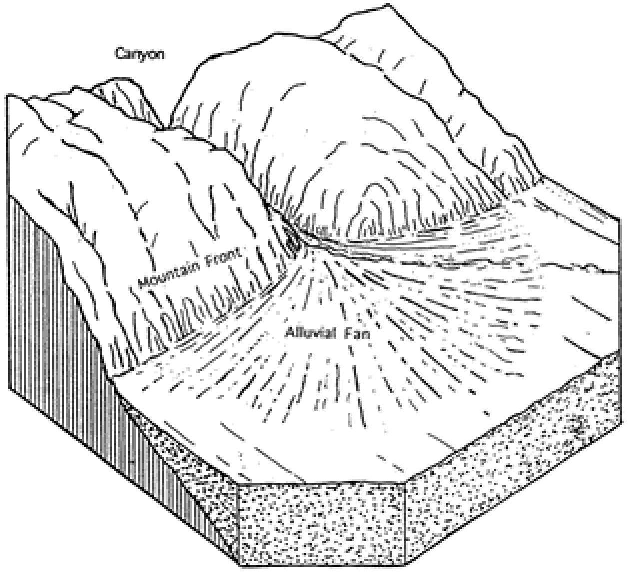
(d) **Alluvial placers:** Running water is the most important agency in the formation of alluvial placers. Irregularities on the floor of the channel in the form of natural barriers or riffles encourage deposition of placer deposits. Besides, at the meander¬ing of the river and at the confluence of tributaries, alluvial placers are formed.

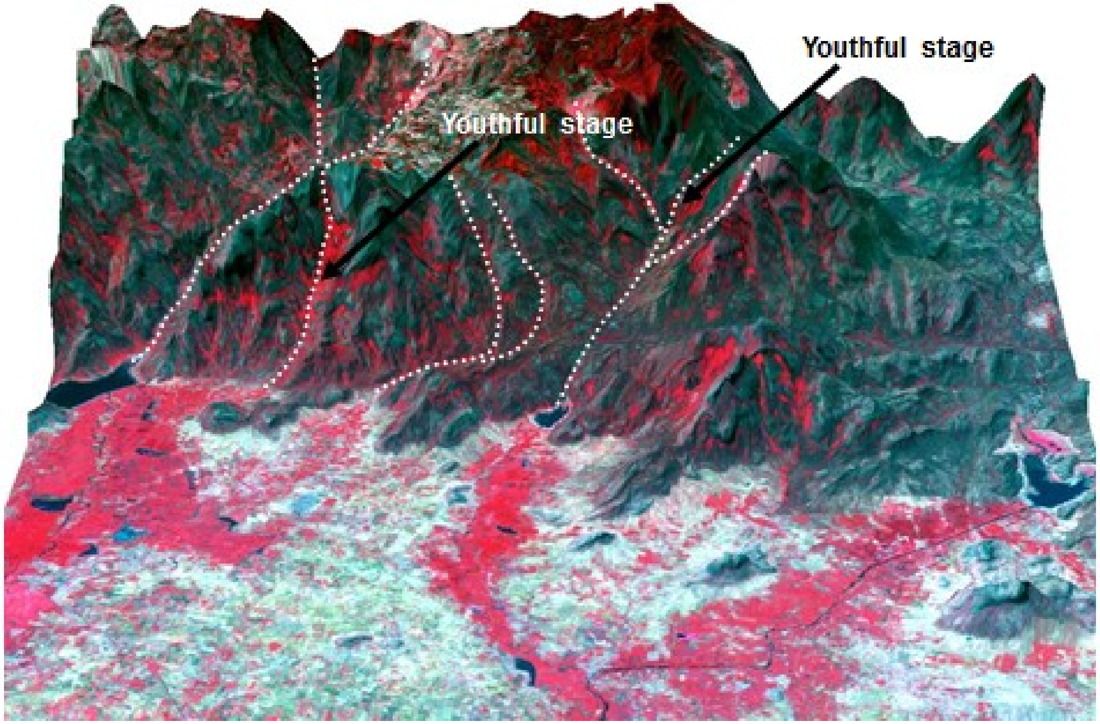
(e) **Aeolian placers:** These are because of wind action, by which the lighter sand particles are blown away leaving behind a mass of coarser detritus containing valuable minerals.

(f) **Beach placers**: These are formed along the shores of lakes seas and oceans, mainly by the wave action.



## Youthful stage of River





# Elluvial and Residual Deposits

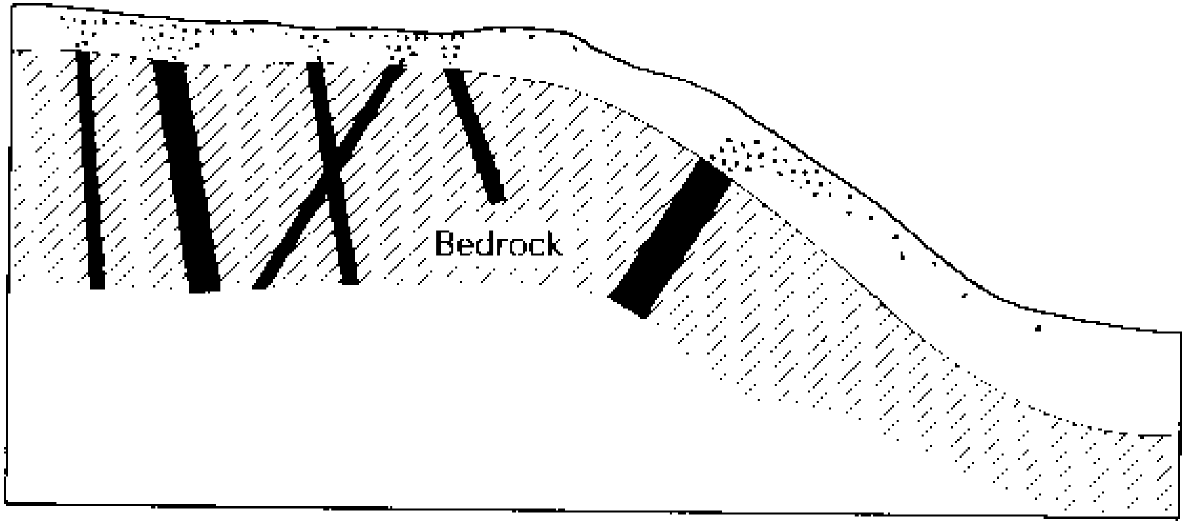


**Fig. 19.1** The formation of residual (left) and eluvial (right) placer deposits by the weathering of cassiterite veins.

# Alluvial Deposits

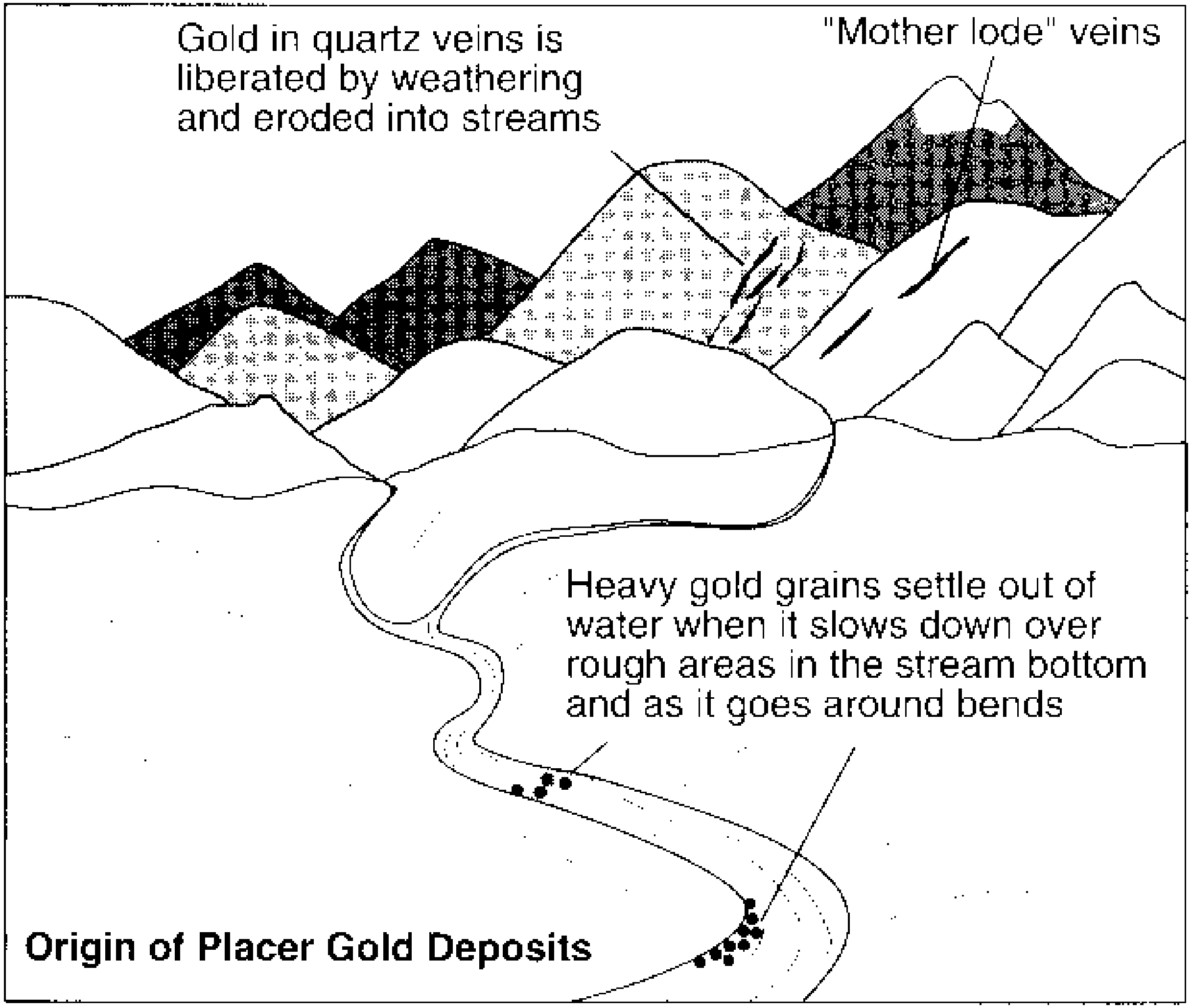
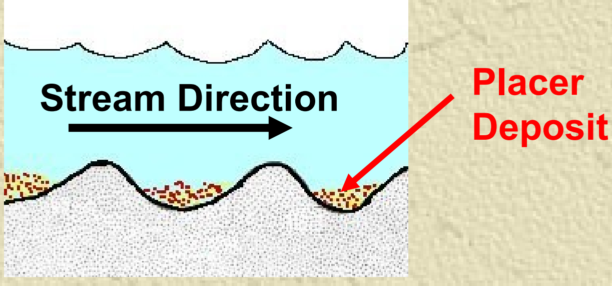


**FIGURE 2-6**

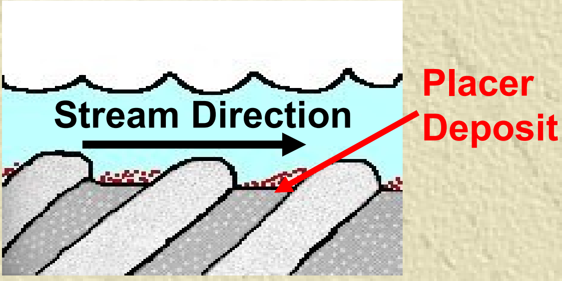
Origin of placer deposits, which are concentrations of heavy clastic grains in stream, lake, or ocean sediment. As shown here, minerals liberated from quartz veins by weathering and erosion are carried downstream and deposited where the water slows.

**Placer deposits occur in any area where current velocity is low, such as;**

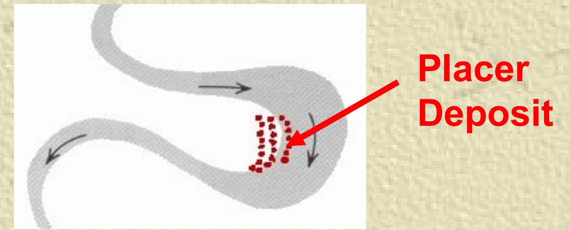
1) **between ripple marks**



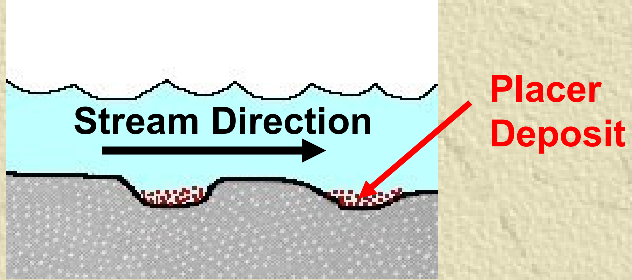
2) **behind rock bars**



3) **on the inside of meandering streams**



4) **in holes on the bottom of a stream**



# Alluvial Deposits

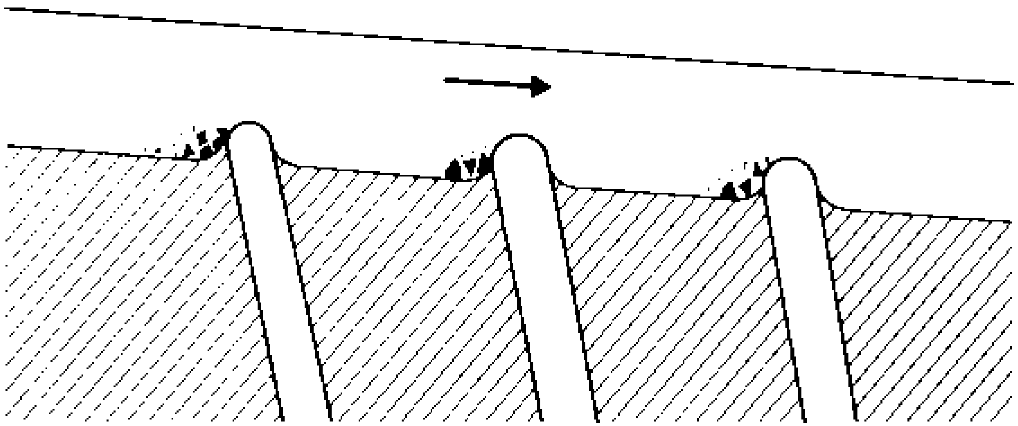


**Fig. 19.2** Quartz ribs interbedded with slate serving as natural riffles for the collection of placer gold.

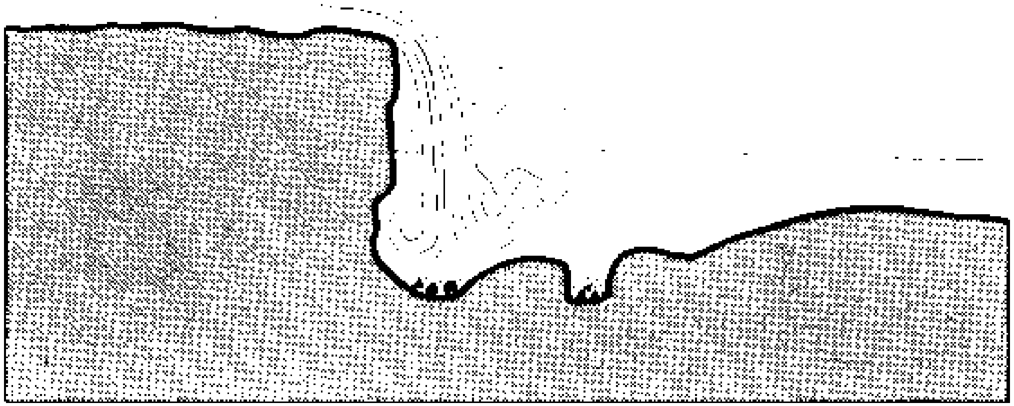


**Fig. 19.3** Plunge pools at the foot of a waterfall and potholes can be sites of heavy mineral accumulations.

# Alluvial Deposits

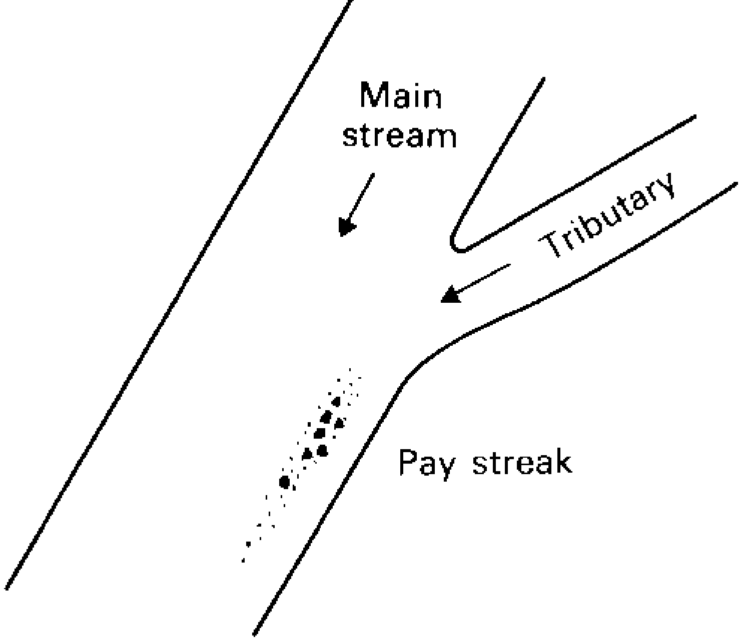


**Fig. 19.4** A pay streak may be formed where a fast-flowing tributary enters a master stream.

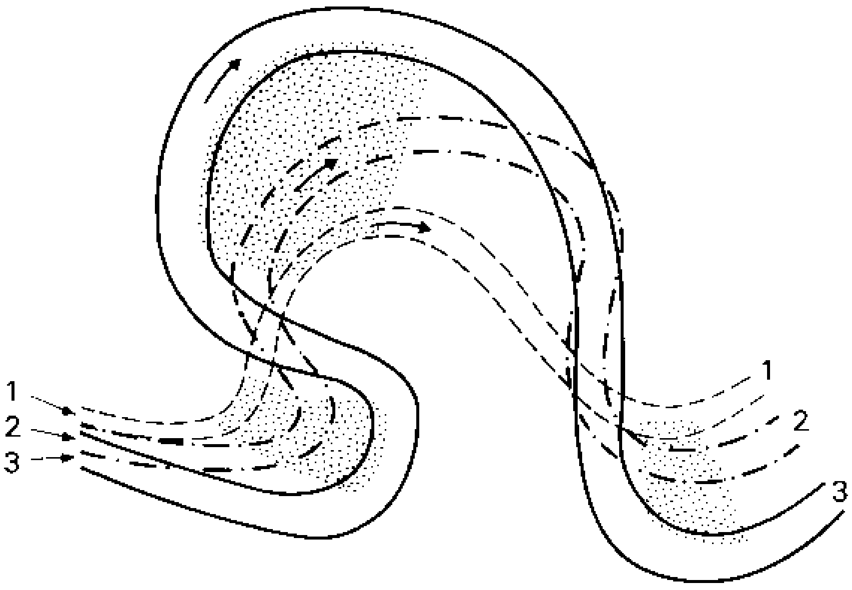


**Fig. 19.5** Formation of pay streaks (dotted) in a rapidly flowing meandering stream with migrating meanders. 1, Original position of stream; 2, intermediate position; 3, present position. Note that pay streaks are extended laterally and downstream. Arrows indicate direction of water flow.

# Beach Placers

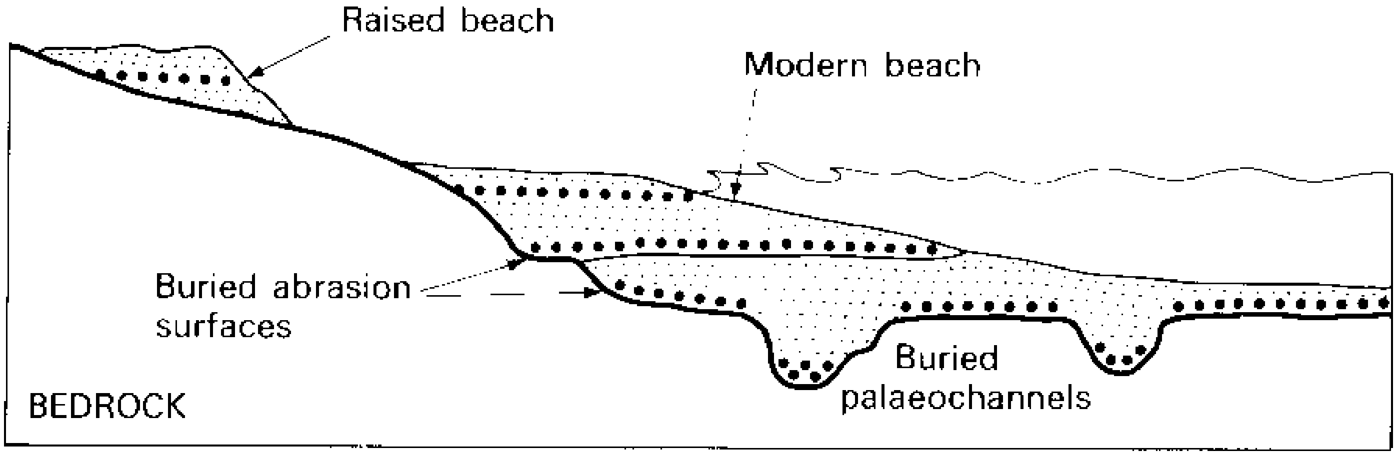


**Fig. 19.6** Sketch section to illustrate some sites of beach placer deposits. Placers shown by heavy stipple.

# Ore Deposits Formed by Oxidation and Supergene Enrichment

- ❑ **The portion of the ore-body lying above the water-table is described as the zone of oxidation, since within this zone the ore- minerals forming the deposit may be oxidised readily in presence of air and water.**

- ❑ **By the reaction of the surface water containing free oxygen with the ore a solvent is formed. This solvent is very reactive and is helpful to oxidise the whole of the rock up to the water-table.**

- ❑ **An orebody thus becomes oxidized and generally leached of many of its valuable materials down to the groundwater table, or to depth where oxidation cannot take place.**

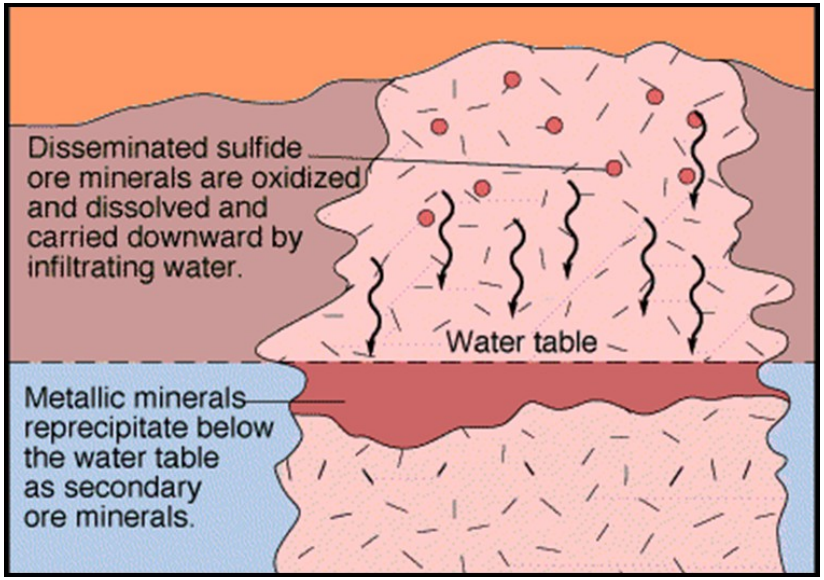
- ❑ **This process is called as 'Infiltration' deposits also. This involves weathering and leaching of the upper parts of a mineral deposit (zone of oxidation) and re-deposition of the ore-minerals at lower levels (zone of secondary or supergene enrichment).**

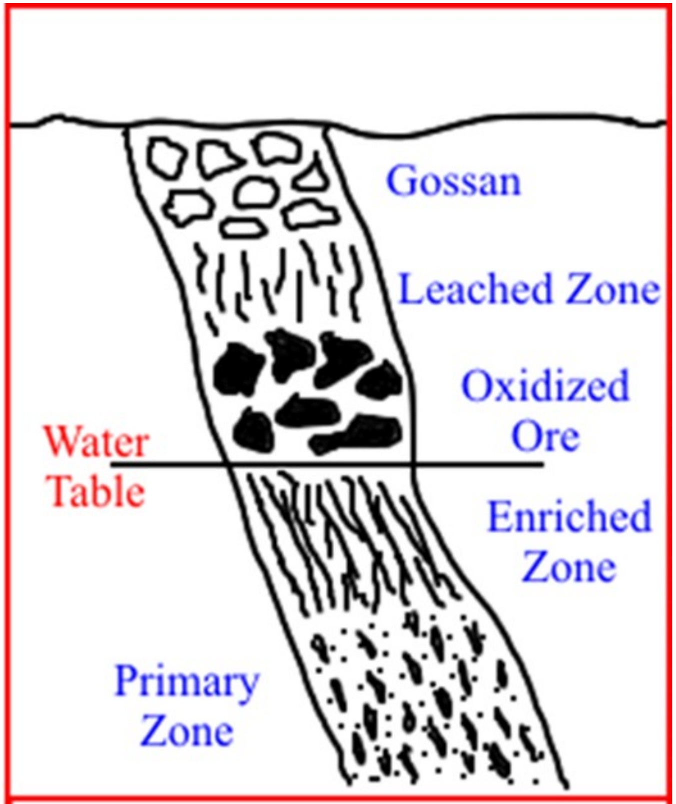
**As the cold, dilute, leaching solutions trickle downwards, they may lose a part or all of their metallic content within the zone of oxidation to give rise to oxidized ore deposits**

**The oxidized or near-surface part of an orebody is made colorful due to the oxidation of sulfides to oxides and sulfates.**

**As the down trickling solutions penetrate the water table, their metallic content may be precipitated in the form of secondary sulfides to give rise to a zone of secondary or supergene sulfide enrichment.**

**The lower, unaffected part of the orebody is called the hypogene zone.**





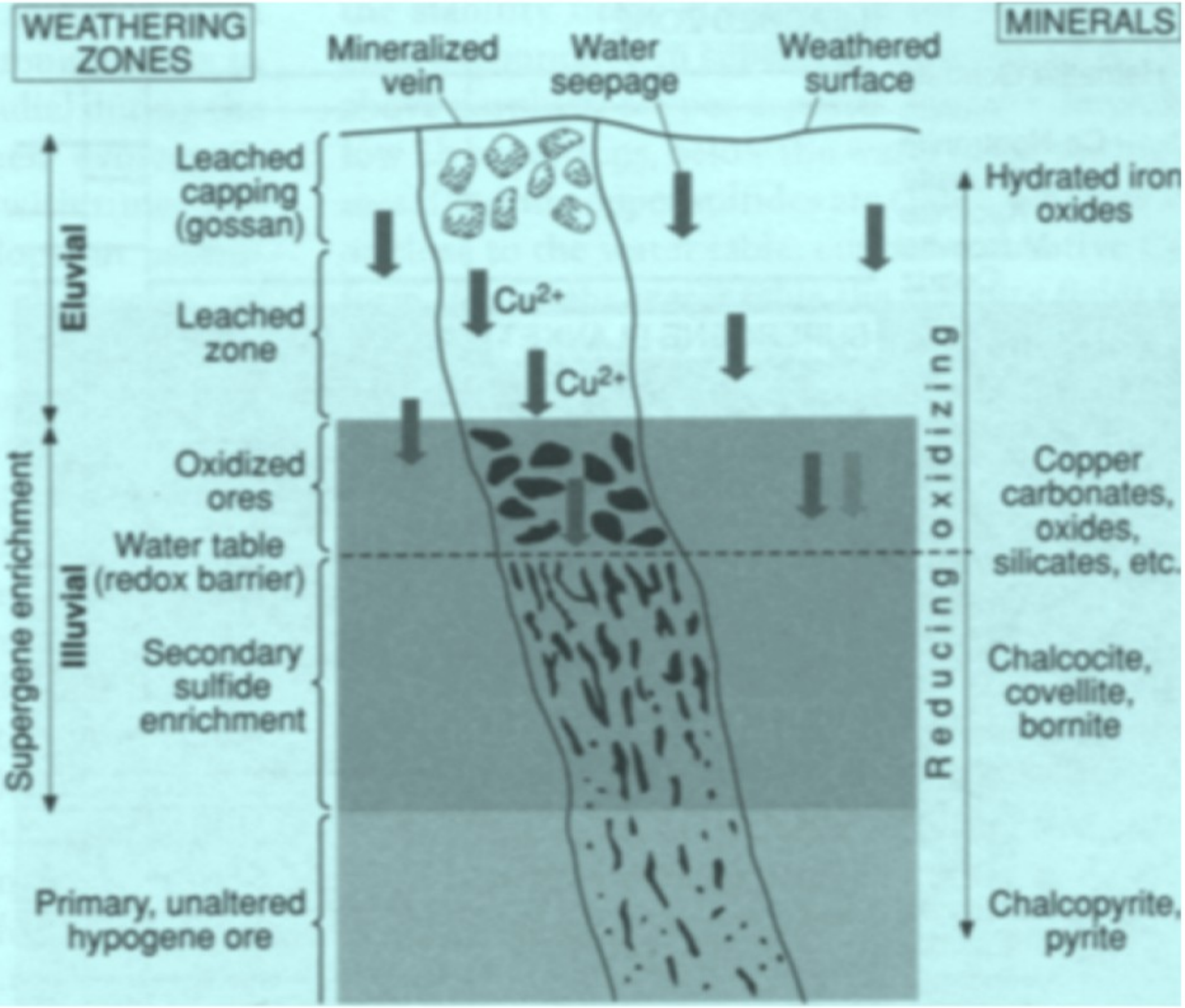


**Figure 4.13** Schematic section through a copper deposit showing the typical pattern of an upper, oxidized horizon (the leached or eluvial zone) overlying a more reduced zone of metal accumulation (the supergene blanket or illuvial zone). The uppermost zone of ferruginous material, often containing the skeletal outlines of original sulfide minerals, is known as gossan. The redox barrier may be the water table or simply a rock buffer (after Webb, 1995).

## Secondary enrichment

**An especially important class of residual deposit is formed by both the removal of valueless material in solution and and redeposition of valuable ore minerals.**

**Because solution and redeposition can produce highly enriched deposits, the process is known as a secondary enrichment.**

## Different circumstance of Secondary enrichment

**1) The first circumstance arises when gold-bearing rocks--even rocks containing only traces of gold--are subjected to lateritic weathering. Under such circumstances, the gold can be secondarily enriched into nuggets near the base of the laterite.**

**The importance of secondary enrichment of gold in lateritic regions was realized only during the gold boom of the 1980s, especially in Australia.**

**2.)** The second circumstance involves mineral deposits containing sulfide minerals, especially copper sulfides, that are subjected to weathering under desert or tropical conditions.

Sulfide minerals are oxidized at the surface and produce sulfuric acid, and acidified rainwater then carries the copper, as copper sulfate, down to the water table.

Below the water table, where sulfide minerals remain unoxidized, any iron sulfide grains present will react with the copper sulfate solution, putting iron into solution and precipitating a copper mineral.

The net result is that copper is transferred from the oxidizing upper portion of the deposit to that portion at and just below the water table.

Secondary enrichment of porphyry copper deposits in the southwestern United States, Mexico, Peru, and Chile is an important factor in making those deposits ores. Lead, zinc, and silver deposits are also subject to secondary enrichment under conditions of desert weathering.

3.) The third circumstance in which secondary enrichment is important involves Banded Iron Formations and sedimentary manganese deposits.

A primary BIF may contain only 25 to 30 percent iron by weight, but, when subjected to intense weathering and secondary enrichment, portions of the deposit can be enriched to as high as 65 percent iron.

Sedimentary manganese deposits, especially those formed as a result of submarine volcanism, must also be secondarily enriched before they become ores.

# Chemical Changes:

There are two main chemical changes within the zone of oxidation:

a) Oxidation, solution and removal of the valuable material.
b) Transformation, in situ, of metallic minerals into oxidized compounds.

Most metallic minerals contain pyrite, which rapidly yields sulfur to form iron sulfate and sulfuric acid:

$$FeS2 + 7O + H2O \rightarrow FeSO4 + H2SO4$$
$$2FeSO4 + H2SO4 + O \rightarrow Fe2(SO4)3 + H2O$$

The ferrous sulfate readily oxidizes to ferric sulfate and ferric hydroxide:

$$6FeSO_4 + 3O + 3H_2O \rightarrow Fe_2(SO_4)_3 + 2Fe(OH)_3$$

The ferric sulfate hydrolizes to ferric hydroxide and sulfuric acid:

$$Fe2(SO4)3 + 6H2O \rightarrow 2Fe(OH)3 + 3H2SO4$$

Ferric sulfate is also a strong oxidizing agent and attacks pyrite and other sulfides to yield more ferrous sulfate:

$$\mathrm{Fe2(SO4)3 + FeS2 \rightarrow 3FeSO4 + 2S}$$

The ferric hydroxide changes over to hematite and goethite and forms the ever present “limonite” that characterizes all oxidized zones;

The part played by ferric sulfate as a solvent can be seen by the following reactions:

| | |
|---|---|
| Pyrite | $\mathrm{FeS2 + Fe2(SO4)3 \rightarrow 3FeSO4 + 2S}$ |
| Chalcopyrite | $\mathrm{CuFeS2 + 2Fe2(SO4)3 \rightarrow CuSO4 + 5FeSO4 + 2S}$ |
| Chalcocite | $\mathrm{Cu2S + Fe2(SO4)3 \rightarrow CuSO4 + 2FeSO4 + CuS}$ |
| Covellite | $\mathrm{CuS + Fe2(SO4)3 \rightarrow 2FeSO4 + S}$ |
| Sphalerite | $\mathrm{ZnS + 4Fe2(SO4)3 + H2O \rightarrow ZnSO4 + 8FeSO4 + 4H2SO4}$ |
| Galena | $\mathrm{PbS + Fe2(SO4)3 + H2O + 3O \rightarrow PbSO4 + 2FeSO4 + H2SO4}$ |
| Silver | $\mathrm{2Ag + Fe2(SO4)3 \rightarrow Ag2SO4 + 2FeSO4}$ |

Most of the sulfates formed are readily soluble, and these cold dilute solutions slowly trickle downwards through the deposit till the proper Eh-pH conditions are met to cause deposition of their metallic content.

If pyrite is absent in deposits undergoing oxidation, only minor mounts of solvents are formed, and the effects are mild.  This is illustrated in the New Cornelia Mine, Ajo, Arizona.

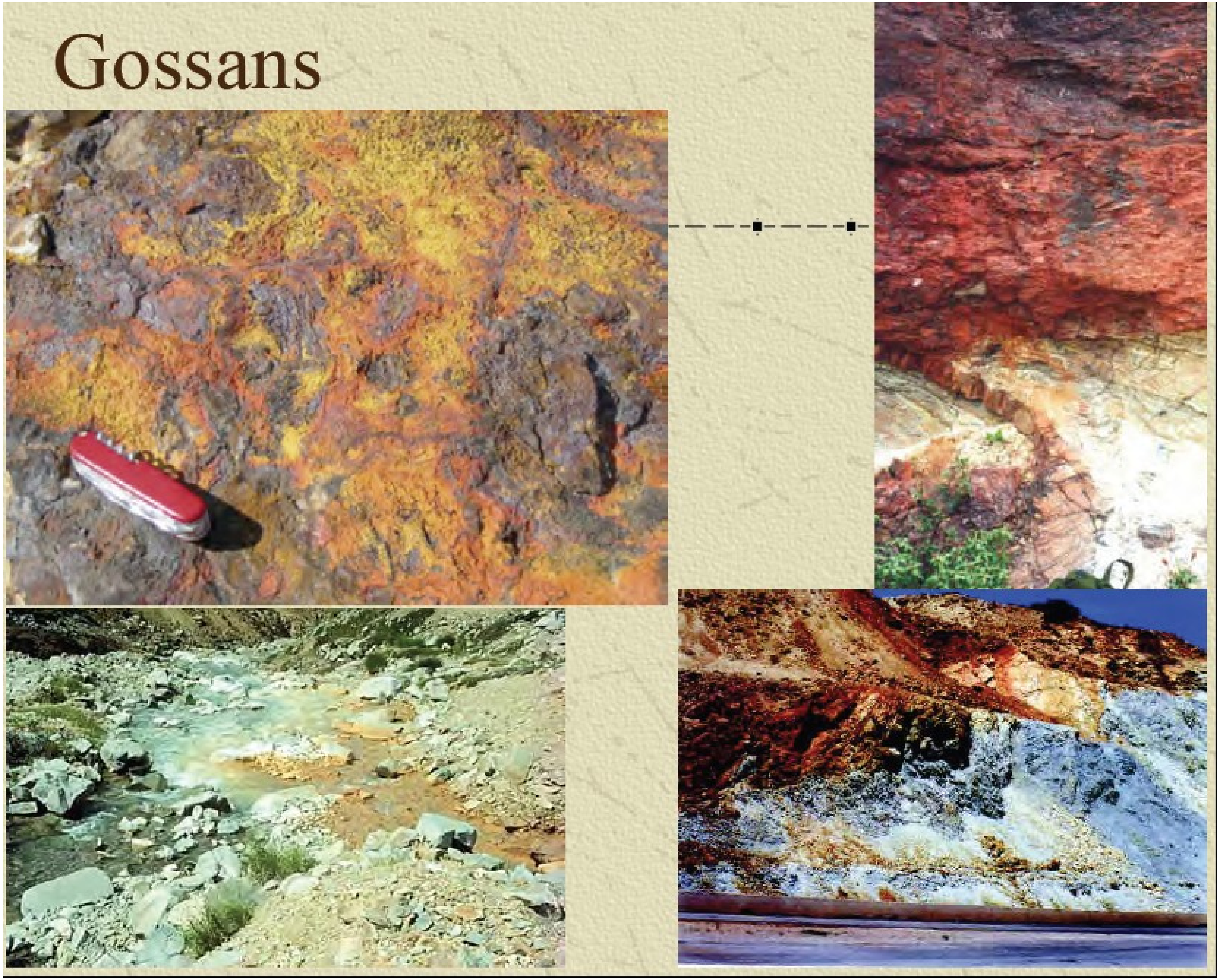
## Gossan:

Oxidation, solution and consequent downward move¬ment of the valuable minerals lead to the concentration of useless residual materials and some of the desiccated products of oxidation upon the surface, where the ore-body had its outcrop and these together form a hard mantle known as gossan or cap-rock.

The gossan is made up principally of limonite, gangue minerals and some of the oxidised products of the ore minerals. Sometimes, false gossans are, however, produced as a result of precipitation of extraneous ferruginous solutions upon the exposed surfaces of the country-rocks.

But in the majority of cases, gossans supply many decipherable inferences as to the size, character and mineral contents, of the hidden ore deposits. Therefore gossans are considered as sign boards of oxidised as well as enriched zones beneath the surface.

# Gossans



# Ore Deposits Formed by Evaporation

- ☐ Evaporation is an important mineral forming process, which supplies valuable materials used by the housewife, farmer, builder, chemist, engineer, manufacturer and even birds, beasts and plants.
- ☐ Great sections of the oceans may be cut off during slow oscillations of land and sea and be gradually evaporated to yield deposits of gypsum, common salt and potash.
- ☐ Ground waters reaching arid surfaces leave behind valuable minerals upon evaporation.
- ☐ Lakes may disappear under arid conditions to form playas

# Conditions of Formation:

Evaporation proceeds most rapidly in warm humid climates. Evaporation o bodies of saline water leads to concentration of soluble salts, and when supersaturation is reached, the salts are precipitated.

Deposition of minerals by evaporation depends on supersaturation, which in turn depends upon other factors, chief of which are:

a) temperature

b) pressure

c) depositional environment, and

d) seasonal & climatic changes

Sea water is the prime source of minerals formed by evaporation. About 3.45% of which consists of dissolved salts of which 99.7% by wt. Is made up of only seven ions:

Na+ (30.61), Mg2+ (3.69), Ca2+ (1.16), K+ (1.10), Cl- (55.04), SO42- (7.68) and HCO3- (0.41).

About 45 other elements whose concentration is known in sea water occur as trace minerals in evaporites.

Few carbonates occur in marine evaporites as compared to terrestrial evaporites. Calcite, dolomite and magnesite are the chief carbonates of marine evaporites.

# Deposition from Oceanic Waters:

- The salts of oceanic waters are mainly obtained from the weathering of terrestrial rocks. Rain water carries soluble salts from continental areas to the oceans, evaporates, leaving behind the salts, to return to the continents as more rain.
- Small mounts are contributed by submarine volcanism, and by solution from oceanic rocks.
- The total amount of salts in the ocean is estimated to be 21.8 million km3, enough to form 60 m thick layer over the ocean bottom. Of this common salt would constitute 47.5 m, MgCl2 5.8 m, MgSO4 3.9 m, CaSO4 2.3 m and the remaining salts 0.6 m.
- The rivers of the world are estimated to contribute 4 billion tons of salt to the ocean annually.
- Ocean water also contains gold, silver, base metals, manganese, aluminum, vanadium, nickel, cobalt as well as iodine, fluorine, phosphorous, uranium, arsenic, lithium, rubidium, cesium, barium and strontium.

**Of these, iodine concentrates in sea weeds, copper in shellfish, manganese, copper, nickel and other metals in nodules which alone have become concentrated into potentially commercial deposits.**

**To attain the necessary conditions to induce precipitation, bodies of sea water must become isolated from the ocean in places where evaporation exceeds inflow. Such isolation may be effected by:**

**a) formation of barrier reefs**

**b) cutoffs near coasts where sills or reefs isolate sinking inland basins**

**c) formation of sand bars**

- **If the original body of water contained 100 km3 of water and this were to be concentrated to 50 km3, the iron oxide and calcium carbonate present would be precipitated. The water would still contain 3500 million tons of salt of which 2700 million tons would be common salt.**
- **If evaporated to 20 km3, gypsum would be precipitated. When the volume reaches about 10 km3, common salt would be deposited.**
- **Subsequent evaporation would bring about deposition of magnesium sulfate and chloride followed by the bittern salts.**

## Deposition from Salt Lakes:

- The deposits formed from the evaporation of salt lakes are similar to those obtained from ocean water because salt lakes contain the same salts as the ocean, but generally in greater proportions.
- The relatively small size of lakes makes them more responsive to climatic changes resulting in greater fluctuations of deposition.
- Evaporites formed during periods of dessication may be redissolved during periods of subsequent expansion.
- Since lakes constantly receive new supplies of fresh water, salts and sediments, their deposits are generally thin bedded alternations of impure salts and clays.
- On salt playas, desert winds distribute sands and silt upon which later salts may be deposited during subsequent lake periods.

## Deposition from Groundwater:

- Evaporation of groundwater is universal and in arid regions the evaporites may accumulate as long as the climate remains dry.
- Groundwater contains salts similar to those of the ocean and salt lakes but their concentration is low and the proportion of individual salts may vary according to the character of the soil, bedrock, topography and climate.
- Calcium carbonate is almost always present; magnesium, sodium, potassium, iron and manganese compounds are common. Silica, phosphorous and locally boron and iodine are relatively abundant.
- Deposition ensues when evaporation occurs at or near the surface, or in caves. If the site of evaporation is fed by fresh supplies of groundwater, extensive deposits may eventually result.
- Evaporation of groundwater will proceed most rapidly where it is supplied relatively close to the surface viz., valley bottoms, slopes where hills and valleys merge, and long hill slopes interrupted by gentler or reverse grades.

## Deposits of economic importance are:

a) nitrate salts with iodine
b) boron
c) calcium and sodium carbonate
d) common salt
e) Gauber’s salt
f) soda
g) epsom salts
h) borax