DEPOSITS RELATED TO METAMORPHISM.

PART-1:

METAMORPHOSED ORE DEPOSITS

OBJECTIVES

To understand:

- Features and types of metamorphism.

- Role of metamorphism in the formation of ores.

- Morphological, mineralogical and geochemical responses of ores to metamorphism.

1. INTRODUCTION

Metamorphism is the phenomenon of (essentially) solid–state reconstitution of any rock to external variables like temperature, lithostatic/hydrostatic pressure, deviatoric (i.e., non-isotropic) stress and/or the circulating fluid.

During prograde or progressive metamorphism, changes in the variables mostly occur towards an increasing intensity.

A lowering of intensities of variables after attainment of peak–metamorphism may also occur and lead to retrograde metamorphic reconstitution if sufficient internally or externally derived fluid is available to revolatilize the system and thus make good the fluid-loss during earlier prograde dehydration/devolatilization reactions. In absence of such fluid, the metamorphosed rock simply undergoes non-retrogressive cooling.

The reconstituted features are structural–textural, mineralogical and chemical– all directed towards minimization of various kinds of free energy of the system (i.e., Gibbs' free energy, lattice strain energy and grain surface energy).

The end products, the metamorphic rocks, are most often a manifestation of equilibrated interaction of the external variables with the bulk composition which constitutes the primary internal variable of rock systems. Bulk composition not only exerts a first–order control on the mineralogy of the

metamorphosed products, but can also buffer some of the external variables like temperature, redox state, pH, or the ambient fluid chemistry.

Besides the prograde and the retrograde types, metamorphism has been classified on several bases (types and sub-types) (Table 1).

If ultrametamorphism and partial-melting of rocks are excluded from the ambit of metamorphism (sensu stricto), it is obvious that the role of metamorphism as far as ordinary rocks are concerned is primarily reconstructive/redistributive, but not "creative", at least not in macroscale; some minor metamorphic (?) segregation veins and "pegmatoids" are possible exceptions.

By contrast where ore bodies are involved, the role of metamorphism may be reconstitutive, dissipatory and/or "creative". During metamorphism, sulfidic ore bodies are susceptible to translocation and/or redistribution in solid and/or liquid state by a variety of processes collectively termed mobilization and/or remobilization.

Ores in metamorphic rocks may be related to metamorphism in two principal ways. (i) Ores may be metamorphosed in the sense that metamorphism has simply changed the form and/or chemical arrangement of a pre-existing deposit, having had no or negligible effect on concentration. (ii) Ores may be metamorphogenic in the sense that the valuable constituents have been concentrated into their present positions by metamorphic processes.

Ore deposits related to regional metamorphism in association with burial and folding include those of many industrial minerals or rocks such as graphite, garnet, emery, kyanite-sillimanite, pyrophyllite, wollastonite, asbestos, talc, mica and gems –varieties of corundum (ruby, sapphire), emerald and garnet.

This lesson deals with metamorphosed ore deposits and provides data on morphological, mineralogical and geochemical modifications resulting from thermal, dynamic/cataclastic and regional metamorphism.

Table 1: Types of Metamorphism (Modified from Spear 1994)

Basis	Type & Sub-types	Characteristic features/Examples
1. Increasing or Decreasing Intensities of Variables	(a) Prograde	(a) Reconstitution in response to increasing intensities of the agencies of metamorphism.
	(b) Retrograde	(b) In response to waning metamorphic conditions, provided earlier fluid loss due to dehydration reactions is compensated by a fluid phase, internally- or externally-derived.
2. 'Closed' or 'Open' System	(a) Isochemical	(a) When no significant mass transfer has occurred during metamorphism.
	(b) Allochemical	(b) When significant mass transfer is evident in metamorphosed rocks.
3. Principal Metamorphic Agent	(a) Thermal	(a) Temperature, singularly most dominant feature. Contact metamorphism around igneous intrusives, along dyke-wall exocontact and beneath lava flows are examples.
	(b) Dynamic	(b) Either lithostatic pressure or deviatoric stress most dominant and occasionally also frictional heat; cataclastic metamorphism, along fault or shear zones producing mylonites, occurs when high strain rate impedes plastic deformation, or at shallow depths where rocks exhibit brittle failure.
	(c) Burial	(c) Result of loading in a relatively static environment on a regional scale.
	(d) Dynamothermal	(d) Temperature lithostatic pressure and directed stress are all important. Occurs on a regional scale in orogenic belts along convergent plate boundaries.
4. Geologic Setting	(a) Contact	(a) Metamorphism along contact against (usually) large intrusive bodies at some depth where thermal effects are aided by some deviatoric stress generated by the intrusion itself, as also some mass transfer and fluid flow from the intrusive. May grade into metasomatic skarns. Low-P/high-T metamorphism may occur on a regional scale where the areas of influence of several closely-spaced coeval intrusives overlap to form a gigantic thermal aureoles.
	(b) Shock	(b) Characterized by very high transient pressure and high temperature, developed locally around impact craters and diatremes. Coesite stishovite mescalinite (felspar glass) and fullerine are diagnostic minerals, and shatter cones are diagnostic structures.
	(c) High-strain (cataclastic)	(c) Restricted to orogenic belts typically along convergent collisional plate margins (see also 1 b).
	(d) Regional	(d) Any kind of metamorphism over a large terrane.
	(d_1) burial	(d_1) Due to normal stable geothermal gradient, generally unaided by any deviatoric stress and/or thermal perturbation.
	(d_2) Ocean-ridge (a la Miyashiro et al., 1971)	(d_2) Occurs at mid-oceanic ridges under conditions of high heat flow, abundant fluid circulation and low (hydrostatic) pressure.
	(d_3) Orogenic	(d_3) Occurs along convergent plate margins in island arc collisional regimes and orogenic belts. Thermal perturbation, varying lithostatic pressure and deviatoric stress are all important. Synonymous with 'regional' and dynamothermal metamorphism.
5. Plate Tectonic Setting	(a) Plate interior	(a) Contact (3a, 4a), burial (3c, $4d_1$) and regional (?) metamorphism at the base of continental crust ($4d_1$).
	(b) Divergent plate margin	(b) Ocean ridge metamorphism ($4d_2$) and contact metamorphism around intrusives in the ocean crust.
	(c) Transform plate margin	(c) Cataclastic metamorphism (3b, 4c).
	(d) Convergent plate margin	(d) Orogenic ($4d_3$); dynamothermal (3d); regional (4d); regional contact (4a); and cataclastic (3b, 4c) types of metamorphism.

2. METAMORPHOSED ORES

Metamorphic responses of three types of ores have been investigated and well documented: (a) iron formation and related iron oxide ores; (b) sedimentary manganese oxide ores; and (c) stratiform and massive sulphide ores.

2.1 *Iron oxide ores*

Thermal metamorphism of Iron Formations along contact zones with granite stocks and diabase dykes has been recorded from many localities in the Lake Superior region, North America.

In the sedimentary "Osteroder Diabaszug", Germany, conversion of hematite and siderite to magnetite and its progressive coarsening, change of pyrite to pyrrhotite, reaction of quartz+magnetite to fayalite, and separation of arsenopyrite from gel-pyrite have been documented.

Similar mineralogical changes have been reported from the Mesabi Formation along contacts with the Duluth Gabbro in Minnesota, North America; here prolific development of coarse magnetite enhanced the grade and exploitability of such ores.

Dynamic/cataclastic metamorphism of oxidic iron ores occasionally causes some thickening due to closely appressed isoclinal folding and some preferred orientation of grains.

Regional metamorphism has been reported from BIF and oolitic, limonitic, chamositic, and sideritic iron ores. James (1955) carried out pioneering studies of superposition of metamorphic facies on sedimentary facies in the Lake Superior "Iron ranges". The study involved the interaction of facies of metamorphism with facies of iron sedimentation.

James' location of the metamorphic isograd is shown Fig.1 and the mineralogical constitution of the various sedimentary facies within each metamorphic facies is given in Table 2.
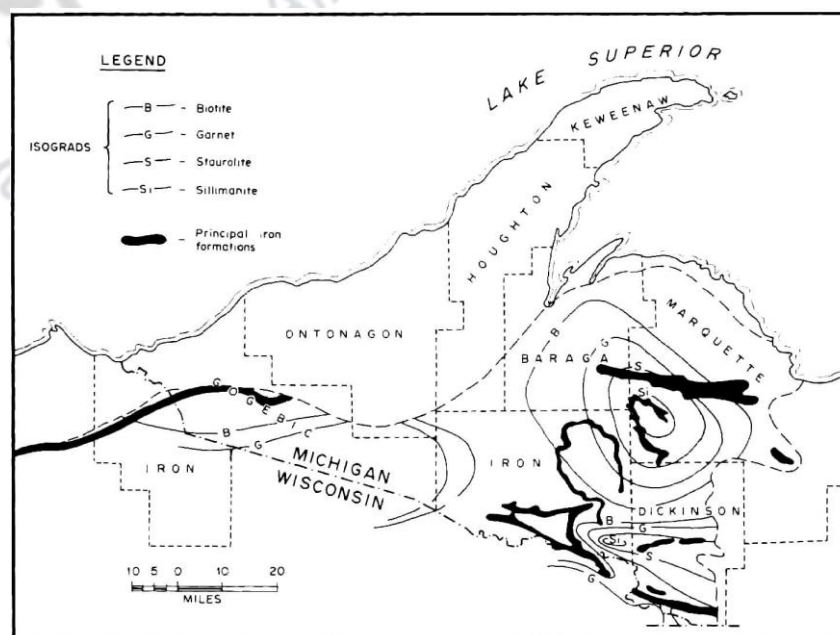

Fig.1 Regional metamorphism isograds in part of the Lake Superior iron ore district (After James, 1955).

Table 2: Interplay of sedimentary and metamorphic facies in the Lake Superior iron ore province. (After James, 1955).

Major constituents are shown in uppercase letters

		Sedimentary		Metamorphic	
	Facies	Composition†	Low grade‡	Intermediate¶	High grade§
Sulfide		Ferrous sulfide Organic carbon "Clay"	PYRITE CARBON (amorphous) QUARTZ Sericite	PYRITE GRAPHITE QUARTZ Micas Garnet (rare)	PYRITE GRAPHITE Pyrrhotite(?) Micas-garnet
Carbonate		Carbonate Chert Greenalite	CARBONATE QUARTZ Stilpnomelane Minnesotaite	GRUNERITE QUARTZ Magnetite Carbonate	GRUNERITE QUARTZ Magnetite Pyroxene
Silicate	Nonclastic	Greenalite Chert Carbonate Magnetite	MINNESOTAITE STILPNOMELANE QUARTZ CARBONATE Magnetite	GRUNERITE QUARTZ Magnetite	GRUNERITE QUARTZ Magnetite Pyroxene
Silicate	Partly clastic	Iron-rich clay Chert Carbonate Magnetite(?)	CHLORITE STILPNOMELANE QUARTZ CARBONATE MAGNETITE Biotite	GRUNERITE QUARTZ MAGNETITE EPIDOTE GARNET Carbonate Micas	GRUNERITE QUARTZ MAGNETITE Garnet Hornblende Pyroxene
Oxide	Magnetite-banded	Magnetite Carbonate Greenalite Chert	MAGNETITE STILPNOMELANE MINNESOTAITE CARBONATE QUARTZ	MAGNETITE GRUNERITE QUARTZ Garnet	MAGNETITE GRUNERITE QUARTZ Pyroxene Garnet
Oxide	Hematite-banded	Ferric oxide Chert Magnetite Calcite	HEMATITE QUARTZ Magnetite Calcite	SPECULAR HEMATITE QUARTZ Magnetite Calcite	SPECULAR HEMATITE QUARTZ Magnetite Calcite
			Less than 0.10 mm	0.1 to 0.20 mm	More than 0.20 mm
				Quartz grain size††	

† Inferred.
‡ Chlorite and biotite zones.
¶ Garnet and staurolite zones.
§ Sillimanite zone, essentially.   Inferred for some rocks.
†† Diameter of typical grains in relatively pure layers of chert.

James documented progressive coarsening of grain size (< 0.05mm size of quartz in chlorite zone to > 0.20mm size of quartz in sillimanite zone), preservation of hematite oolites up to sillimanite grade, development of hematite porphyroblasts in magnetite matrix, and preferred orientation of hematite flakes parallel to regional fold axis.

James opined that the major part of the magnetite here is not due metamorphic breakdown of sideritic carbonate but is probably essentially primary (i.e., an original component of magnetite – bearing sedimentary zones). The grunerite appears to result from carbonate – silicate reaction and hence is derived from the carbonate – silicate sedimentary facies.

2.2 Manganese oxides ores

Thermal metamorphism of Mn-oxide ores has been reported from Goldongri Hill, Gujarat, India. Here lower oxides such as hausmanite, bixbyite and hollandite and Mn-silicates have been found along contact of apophyses of porphyritic granite with gonditic ore/rocks (spessartite- and quartz- bearing rocks).

Regional metamorphism of Mn-ores and Mn-rich sediments was first investigated in India by Fermor (1909) and subsequently in the Minas Gerais area of Brazil (Dorr et al. 1956). Fermor (1909) established that the mineralogy of metamorphically reconstituted Mn ores primarily depended on the presence and the nature of impurities in the primary Mn-oxides. Pure Mn-oxide sediments recrystallized into pure (lower) oxide ores; siliceous ($\pm$ ferruginous) impurities produced braunite, while Al_2O_3, Fe_2O_3, and SiO_2 produced spessartite garnet and other Mn-alumino-silicates. Roy (1966) recognised specific assemblages of Mn-oxide minerals in different metamorphic zones from Indian gonditic ores on the basis of comparison with the grades of metamorphism (from chlorite zone to sillimanite zone) of the enclosing metapelites.

In gonditic ores, textural evidence of deformation and metamorphism has been registered by: (a) development of braunite and/or bixbyite porphyroblasts; (b) preferred orientation of hollandite and hausmanite, and (c) development of translation twinning, undulose extinction and grain elongation of several Mn-oxide minerals.

In regionally metamorphosed manganiferous terrains, five distinct mineralogical types have been recognised: (I) Mn-oxide+quartz, (II) Mn-silicates (+ minor oxides), (III) interbanded Mn-oxides and Mn-silicates, (IV) Mn-silicates-Mn-carbonates ($\pm$ Mn-oxides) and (V) interbanded Mn-oxide layers and Mn silicate- Mn carbonate layers. Types (I) and (III) are inferred to have originated from higher – oxide precursor manganiferous sediments ($\pm$ impurities) through prograde deoxidation reactions, while types (IV) and (V) originated from precursor Mn-carbonate sediments through prograde decarbonation ($\pm$ oxidation) reactions.

2.3 Sulfide ores (stratiform and massive sulfide ores)

2.3.1 Thermal metamorphism

Thermal metamorphism of sulphide ores along dyke contacts has been recognised by several investigators from the observed (i) dissociation of pyrite to magnetite in the ores; (ii) complementary sulfurization of the glassy, crackled margin of dykes to skeletal pyrite; (iii) increased "nonclinicity" of pyrrhotite due to desulfurization in the ores towards the contact plane; (iv) ultrafine-grained rheomorphic sulfide veins emanating from the massive ore body into the younger intrusive; and (v) sulfide xenoliths. All such features are, however confined within a few cm on either side of contact plane.

2.3.2 Dynamic/cataclastic metamorphism

Dynamic metamorphism unattended by appreciable thermal effects has been registered by ore breccias, "steel-galena", mylonitized sphalerite, polished "ore mirrors," and strung-out trails of hard porphyroclasts - features that grossly indicate brittle deformation of minerals like pyrite, arsenopyrite and sphalerite, and ductile deformation of softer sulfides like chalcopyrite, galena and pyrrhotite which however recrystallized with foam texture quite often.

2.3.3 Regional Metamorphism

Studies carried out during last 70 years on (a) pyritic ore bodies scattered along the 1500km length of the Scandinavian Coledonide belt, (b) the North American massive sulfide deposits, (c) the Mt Isa, the Broken hills and other deposits in Australia, (d) the cupriferous deposits in Sambagwa district and the central Abukuma metamorphic terrain in Japan brought to light that some of these areas clearly suffered regional polyphase metamorphism including retrograde metamorphism and/or multiple phase deformation.

Details on the response of sulfide deposits to regional metamorphism can be listed on the basis of features of successively finer scales from (a) structural–morphological to (b) meso- and micro-structural to (c) mineralogical to (d) chemical reconstitution/modification.

(a) *Structural and morphological changes*

The most obvious features noticeable in volcanogenic massive sulfide (VMS) and sediment–hosted stratiform (SHS) ore bodies are due to buckling, stretching and/or shearing on regional scale. The resultant modifications are many and varied due to sharp contrast in rheological properties of sulfide and non-sulfide materials.

Repetition of ore horizons due to folding and faulting are commonest features. Thickening of ore width at the hinge zones and its complimentary attenuation in the limbs with differential physical and/or chemical migration of select ore constituents have been documented at many places. Elongation of ore bodies along the direction of regional stretching, lineation in country rocks constitutes another manifestation of such responses.

(b) *Meso- and micro- structural changes*

Changes in ore fabric are a complex function of interactive processes like brittle/ductile deformation, recrystallization/neocrystallization and (metamorphic) fluid-aided dissolution/precipitation/replacement(metasomatic).

Evolution of the resultant fabric is also dependent on the sequence of operations of these processes, the pressure and temperature at which each operation occurs, and the bulk rheology of the ore masses.

Experimental deformation of dry sulfides reveals that the most common sulfide minerals, barring pyrite, undergo brittle-ductile transformation even prior to the onset of regional metamorphism. Relative strengths of the common sulfides remain dynamically variable until all undergo steady-state flow. Physical manifestation of brittle deformation is a variety of cataclastic textures such as pervasive microfracturing, porphyroclasts of harder minerals with "matching" pulled–apart fragments separated by in filled fibrous or massive sulfide or non-sulfide minerals, and cataclastic flowage along discrete (micro-) shear zones.

Ductile deformation imposes preferred orientation, kinking, twinning, slip and elongation in individual minerals.

Rotational movement of "clasts" (silicate minerals or harder sulfides) in a matrix undergoing ductile-flowage sometimes result in "rock ball" structure.

Recrystallization/neocrystallization promotes coarsening of grain size, "foam" texture and porphyroblastic growth of minerals like pyrite, arsenopyrite, magnetite etc. Pyrite in ores may preserve records of pre-, syn-, and post- metamorphic features in much the same way as garnet does in metamorphic rocks.

During prograde metamorphism, earlier idioblasts of pyrite would be corroded and converted peripherally and internally to pyrrhotite, resulting in subhedral relic idioblasts of pyrite in pyrrhotite matrix. By contrast, retrograde metamorphism would trigger growth of sharply euhedral pyrite grains from phyrrhotite with concomitant depletion of sulphur in pyrrhotite.

Reaction rims of pyrrhotite (± magnetite) around silicate "islands" in sulfide matrix, caused by desulfurization of Fe-Mg silicate and extraction of iron there from, constitutes another textural manifestation of metamorphism of sulfide ores.

(c) *Mineralogical changes*

Several imprints of mineralogical changes in micro- to macro scales have been observed in metamorphosed sulfide ores. They include (a) conversion of non-stoichiometric metal–deficient sulfides (djurleite, anilite) to stoichiometric equivalents (chalcocite, tetragonal Cu_2S) due to desulfurization; (b) decay of X-bornite to tetragonal bornite + chalcopyrite; (c) formation of intermediate compounds at the expense of metastable assemblages like digenite+chalcopyrite or diginite+pyrite, (d) appearance of relatively high temperature minerals like tetragonal Cu_2S, S-deficient chalcopyrite and pyrrhotite.

Zincian Spinel [$(Zn, Fe, Mg) Al_2O_4$] is a common mineral in many metamorphosed sulfide and oxide-silicate deposits where it is considered to be a product of desulfidation of sphalerite during metamorphism.

(d) *Chemical reconstitution / redistribution*

Redistribution of metals (some non metallic constituents) within the ore deposits in response to metamorphism takes place through the processes of solid–state migration of minerals (e.g., plastically–mobilized galena) and fluid–assisted physical transport of ore minerals and fluid–state chemical remobilization.

Evidences of fluid–state chemical redistribution of metallic constituents are: (a) coarse - grained "ore pegmatites" occurring as discordant bodies within the ores; (b) late, fibrous ore ± silicate ± carbonate veins and veinlets along tension cracks and in pull apart, intragranular microfractures (resulting from syntectonic vein filling); (c) rotated porphyroblasts of Mo-rich scheelite with pressure–shadows occupied by Mo-poor, recrystallized scheelite; (d) multiple-pulse "crack-seal" veins along openings between boundaries of fractured veins; (e) occurrence of thin rim of chalcopyrite along boundaries of foam-textured, recrystallized pyrite polygons; (f) "regenerated" axial plane-parallel sulfide (± quartz) veins in banded sulfide-silicate rhythmites (e.g., Rajpura-Dariba polymetallic deposit, Rajasthan, India); and (g) pressure shadow "tail" of chalcopyrite and pyrrhotite at one end of deformed pyrite metablasts.

Besides solid-state (with or without fluid assisted) and solution-transport, melting of ores may also take place, at least in local scale. On a regional scale, metamorphically–generated sulfide–melt inclusions in healed fractures of quartz in metamorphogenic segregation veins have been documented in the Lengenbach deposit, Swiss Alps (Hofmann, 1994).

SUMMARY

1. Metamorphism is the phenomenon of (essentially) solid-state reconstitution of any rock to external variables like temperature, lithostatic/hydrostatic pressure, non-isotropic stress and/or circulating fluid.

2. Ores in metamorphic rocks may be related to metamorphism in two principal ways. (1) They may be metamorphic in the sense that the valuable constituents have been concentrated in their present positions by metamorphic processes (2) On the other hand the ores may be metamorphosed in the sense that metamorphism has simply changed the form and/or chemical arrangement of a pre-existing deposit, having had no or negligible effect on concentration. Thus in relation to metamorphism, ores may be (1) metamorphogenic or (2) metamorphosed (or metamorphic).

3. In published literature, metamorphic responses of iron, manganese and sulfide ores have been well documented. James (1955) carried out studies on the interaction of facies of metamorphism (viz., chlorite and biotite grade, garnet and staurolite grade and sillimanite

grade) with facies of iron sedimentation (viz., oxide facies, carbonate facies, silicate facies and sulfide facies) and reported mineral assemblages belonging to each facies of iron sedimentation. According to him, oxide and carbonate facies BIF contain the following progressive mineral assemblages in low, intermediate and high grade metamorphic zones:

Oxide facies: (Magnetite + Carbonate + Greenalite + Chert) → (Magnetite + Stilpnomelane + Minnesotaite + Carbonate + Quartz) → (Magnetite + Grunerite + Quartz + Garnet) → (Magnetite + Grunerite + Quartz + Pyroxene + Garnet).

Carbonate facies: Carbonate + Chert + Greenalite → (Carbonate + Quartz + Stilpnomelane + Minnesotaite) → (Grunerite + Quartz + Magnetite +Carbonate) → Grunerite + Quartz +Magnetite + Pyroxene).

4. Regional metamorphism of higher-oxide precursor manganiferous sediments (± impurities) generates Mn ores with Mn-oxide minerals + quartz and/or inter-banded Mn oxide and silicate minerals as a consequence of prograde deoxidation reactions. Regional metamorphism of Mn-carbonate sediments yields Mn ores with Mn silicate minerals, Mn carbonate minerals (± Mn oxide minerals) and/or inter-banded layers of minerals of Mn oxide, Mn silicate and Mn carbonate as a sequence of prograde decarbonation (± oxidation) reactions.

5. Thermal metamorphism of massive sulfide deposits (1) may generate ultrafine grained rheomorphic sulfide veins emanating from the massive ore body into the overlying younger intrusive and (2) may cause desulfurization of pyrrhotite and dissociation of pyrite to magnetite.

6. During dynamic/cataclastic metamorphism of sulfide deposits, minerals like pyrite, arsenopyrite and sphalerite are subjected to brittle deformation whereas minerals like chalcopyrite, galena and pyrrhotite are subjected to ductile deformation. Occurrence of ore breccias, steel galena, "mylonitized sphalerite and polished "ore mirrors" in sulfide ores are attributed to dynamic/cataclastic metamorphism.

7. Response of sulfide deposits to regional metamorphism includes (1) structural and morphological changes, (2) mineralogical changes and (3) chemical reconstitution and redistribution. The resulting features may include: buckling and shearing on a regional scale, elongation of ore bodies along the direction of regional stretching lineation in the country rocks (deformation-induced change in ore body morphology). Conservation of non-stoichiometric metal-deficient sulfides (djurleite, anilite) to stoichiometric equivalents (chalcocite, tetragonal Cu_2S) due to desulfurization, decay of X-bornite to tetragonal bornite + chalcopyrite, replacement of chalcocite by chalcopyrite-bornite, desulfidization of

sphalerite and development of zincian spinel [(Zn, Fe, Mg) $Al_2 O_4$], plastically-mobilized solid-state migration of minerals (e.g., galena) and physical transport of ore minerals development of coarse grained "ore pegmatites", development of pressure shadow "tail" of chalcopyrite and pyrrhotite at one end of deformed pyrite metablasts).