КИЇВСЬКИЙ НАЦІОНАЛЬНИЙ УНІВЕРСИТЕТ ІМЕНІ ТАРАСА ШЕВЧЕНКА
ГЕОЛОГІЧНИЙ ФАКУЛЬТЕТ

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ДІЛОВА АНГЛІЙСЬКА МОВА

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Навчальний посібник розрахований на студентів (магістрів) та аспірантів геологічного факультету, що навчаються за напрямом 6.040103 – «Геологія». Наведені дані про сучасні уявленні щодо ранньої історію еволюції всесвіту, процесів формування та особливостей поширення хімічних елемментів сонячної системи, класифікацію та типи метеоритів як первинної речовини формування планет земної групи, ранні стадії аккреції та подальшої еволюції землі. Розгладаються відомості про структуру землі, механізми дії тектоніки плит та процеси формування глобальних структур землі – суперконтинетів. Надано інформацію про існуючі з'язки між геодинамічними плейттектонічними режимами та ассоціаціями рудних родовищ а також існуючі параметри оцінки потенціальних рудних тіл.

ЗМІСТ

ПЕРЕДМОВА

Посібник «Ділова англійська мова» до навчального курсу «Іноземна мова» розрахований на студентів (магістрів) та аспірантів геологічного факультету університету, що навчаються за напрямом 6.040103 – «Геологія», та займаються перекладом наукових статей в галузі геохімії, геології та економічної геології. Мета даного видання – розширення лексичного запасу і формування навичок ефективного використання наукових публікацій за фахом, виданих англійською мовою.

Text No 1. The early history of the Universe.

Current thinking in cosmology indicates that the history of the Universe may be described in the following stages (Fig. 1):

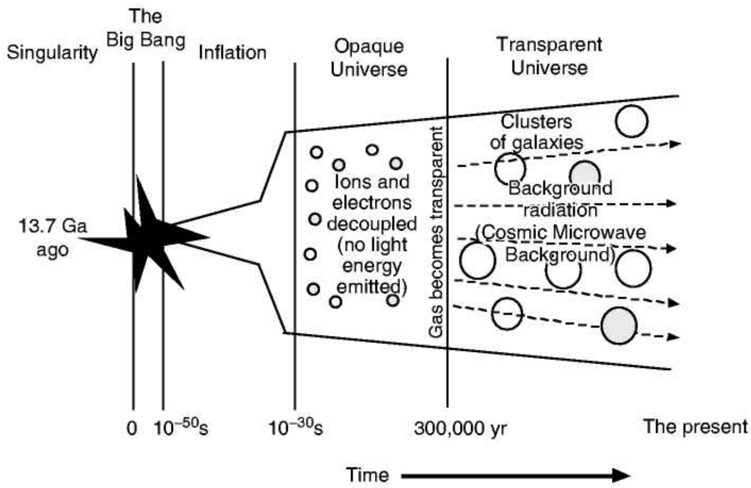

Figure 1 The origin, inflation, and expansion of the Universe from the initial singularity to the present.

An initial singularity. At the beginning of the Universe, 13.7 billion years ago, all matter was in one place at a single instant; this event in cosmological parlance is known as a «singularity». This term describes the inference that an infinitely large amount of matter is gathered at a single point in space-time.

The Big Bang. At the Big Bang there was a huge expansion of matter, an expansion that has continued ever since.

Inflation. Between 10^{-50} and 10^{-30} s after the Big Bang there was a particularly rapid expansion of the Universe. This process is known as the inflation of the Universe and represents the first burst of growth of the Universe. During inflation the part of the Universe that we see today expanded by a factor of 10^{60}. When the Universe was only one second old temperatures were of the order of 10 billion degrees. At that point the universe was permeated with radiation and subatomic particles. When the Universe was a few minutes old and temperatures were about 1 million degrees protons and neutrons formed atomic nuclei leading to the production of primordial hydrogen and helium ions.

An opaque Universe After 100,000 yr conditions in the Universe were similar to those inside the sun today. An almost uniform plasma of electrons, hydrogen, and helium ions filled the Universe. At this time the free electrons acted as a block to photons – generated from the light energy generated in the Big Bang, and prevented them escaping, rendering the early Universe opaque.

A transparent Universe. After 300,000 yr temperatures dropped to 4,500 K and gave rise to the formation of atomic matter, and atoms of hydrogen, helium, and deuterium were formed. Because electrons were removed from the plasma through the formation of atoms, radiation streamed out and the Universe became transparent. Initially the Universe contained abundant ultraviolet-and X-rays, now cooled down to microwave wavelengths. This is what is recorded as the Cosmic Background radiation.

The present Universe. As the universe continues to expand the initial radiation will appear to be derived from a much cooler body. Hence today the Cosmic Background radiation is 2.73 degrees above absolute zero.

It is a long journey from the formation of the Universe at 13.7 Ga ago to the formation of the Earth at about 4.57 Ga [4, p. 32-33].

Thought questions

- *Give a definition of the term «Big Bang» from the cosmogeochemical point of view.*
- *Give a definition of the term «inflation».* When does inflation occur in the Universe?
- *What is the difference between opaque, transparent and present Universe?*

Text No 2. The origin of the elements.

Stars shine because nuclear reactions take place in their core. When these reactions take place there is a slight lowering of the mass of the nuclei undergoing fusion which is liberated as energy. It is the fusion process which gives rise to the formation of the chemical elements.

The processes of element formation.

Our understanding of the process of element formation is based upon the elemental composition of stars, deduced from optical spectra, and from the theoretical calculations and experimental observations of nuclear physics. From these different lines of reasoning it has become clear that nucleosynthesis took place in a variety of different environments. Although the principal processes of nucleosynthesis take place in stars and supernovae, it is now also recognized that the nucleosynthesis of some light elements happened during the Big Bang, and to a lesser extent through the interactions between cosmic rays and matter in interstellar space.

Cosmological nucleosynthesis. The elements H, and its isotope D, He, and Li were created in the first few moments of the Big Bang. These are the essential ingredients of the cosmos and the starting composition for all other elements. The ratio of He/H, in terms of the number of atoms, is about 25% as a consequence of this event, and although some additional He has been created in stellar nucleosynthesis (see below) the ratio in the Universe as a whole has remained essentially unchanged since the beginning of time.

Stellar nucleosynthesis. Elements with atomic masses up to that of iron (^{56}Fe) are created in stars through a variety of different reactions, taking place over a wide range of temperatures.

Hydrogen burning and helium production. Hydrogen burns in the core of a star to form ^{4}He through either the proton-proton chain reaction, which takes place at 5×10^{6} K or at higher temperatures ($> 20 \times 10^{6}$ K) through the carbon cycle (the C-N-O cycle) in which carbon acts as a nuclear catalyst in the production of He. This process is also known as the quiescent burning phase of a star and is a slow process which takes billions of years and covers much of the life of a star. Our sun is currently in this phase.

Helium burning to form carbon and oxygen. As the hydrogen in a star is used up, the star contracts and its temperature rises to greater than 10^{8} K. At this stage nuclear reactions take place which permit the synthesis of the elements carbon, nitrogen, and oxygen, from helium. ^{12}C

forms from ^{4}He, through what is known as the triple alpha reaction, and when sufficient ^{12}C is present, further reaction leads to the formation of ^{16}O.

Carbon and oxygen burning. When the helium is almost completely consumed then the carbon and oxygen can be transformed into elements with masses up to that of silicon. This takes place after the stellar core has contracted further and increased in temperature. In detail carbon fusion reactions (^{12}C) lead to the formation of ^{24}Mg, ^{23}Na, and ^{20}Ne at about 6 x 10^{8} K. Oxygen fusion reactions lead to the formation of ^{32}S, ^{31}P, ^{31}S, and ^{28}Si at about 10^{9} K.

Silicon burning. As carbon and oxygen burning proceeds the stellar core becomes enriched in Si and is at temperatures of about 10^{9} K. At these temperatures nuclear reactions in the stellar core induced by photons lead to the formation of elements with masses up to that of iron. Elements heavier than Si cannot be formed by the process of nuclear fusion because beyond this point the nuclear reactions cease to be an energy source. The most energetic fusion reaction is hydrogen burning; a lesser amount of energy is produced by He-burning, even less from C and O, and progressively less until Fe is reached at which point no energy is released at all.

Explosive burning in a supernova. In contrast to the nuclear reactions thus far described, the formation of elements beyond the mass 56 (Fe) consumes energy. This process is that of neutron capture and involves the absorption of neutrons by the atomic nucleus. Hence heavier elements such as silver, gold, or lead can only be formed in a highly energetic environment within a star, such as found in a supernova explosion, because only in this environment is sufficient energy released to allow the energy-inefficient process of heavy-element formation to take place. Supernovae explosions are the endpoint of large stars and represent the violent collapse of a Fe-rich stellar core, during which neutrons, produced in the core collapse, are captured by other nuclei. They are built into heavy nuclei, through rapid neutron capture, up to the elements Th and U. Hence, the reason that the heavy elements are so rare is because the process by which they are formed is rare -approximately only one in a million stars is massive enough to go supernovae.

The interpretation of solar elemental abundances. Solar element abundances are plotted against increasing atomic numbers in Fig. 2. These data were obtained by the optical analysis of the solar spectrum. Abundances are measured relative to 1 million silicon atoms on a logarithmic scale.

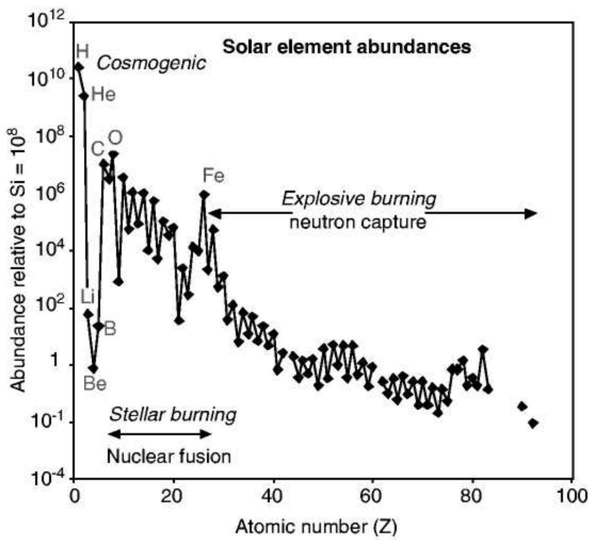

Figure 2 Abundances of elements in the sun, by atomic number, relative to solar Si = 10^{6}.

There are three important observations to be made from this graph:

First, the graph has an overall smooth trend from light to heavy elements, indicating that solar abundances are greatest for light elements and least for heavy elements. This is consistent with the discussion above, in which H and He abundances date from the Big Bang, and are the starting material from which all other elements have been built. It is also consistent with the burning of He to form C and O, and the burning of C and O to form successively heavier elements.

Second, superimposed upon the smooth trend is a smaller scale irregularity, such that elements with even atomic numbers have higher abundances than those with odd atomic numbers. This can be explained by the greater stability of atomic nuclei with paired neutrons. Thus elements with even atomic numbers have the greater nuclear stability and therefore the greater abundance.

Third, some elements have anomalous abundances. Hydrogen and helium and iron have anomalously high concentrations. H and He have been discussed already. In the case of Fe this relates to the high binding energy and associated stability for Fe. The elements lithium, boron, and beryllium have anomalously low concentrations for they are not produced in stellar nucleosynthesis, as already discussed [4, p. 36-38].

Thought questions

- *List and explain the processes by which chemical elements were formed.*
- *Explain three important observations that might be made from graph of abundances of elements.*
- *What is the reason of anomalously high concentrations of hydrogen and helium and iron?*

Text No 3. Meteorites: essential clues to the beginning.

Meteorites are traditionally classified according to their composition, mineralogy, and texture. The first order division is between *Stones* and *Irons*. You can pretty well guess what this means: stones are composed mainly of silicates while irons are mainly metal. An intermediate class is the *Stony Irons*, a mixture of silicate and metal. Stones are subdivided into *chondrites* and *achondrites* depending on whether they contain *chondrules*, which are small spherical particles that were once molten and can constitute up to 80 % of the mass of chondrites (though the average is closer to perhaps 40%).

Another way of classifying meteorites is to divide them into *primitive* and *differentiated*. Chondrites constitute the primitive meteorites, while the achondrites, irons, and stony-irons constitute the differentiated meteorites. The chemical and physical properties of chondrites are primarily a result of processes that occurred in the solar nebula, the cloud of gas and dust from which the solar system formed. On the other hand, the chemical and physical properties of differentiated meteorites are largely the result of igneous processes occurring on meteorite parent bodies, namely as*teroids*. Primitive meteorites contain clues about early solar system formation whereas differentiated meteorites contain clues about early planetary differentiation.

Meteorites are also divided into *Falls* and *Finds*. Falls are meteorites recovered after observation of a fireball whose trajectory can be associated an impact site. Finds are meteorites found but not observed falling. Some Finds have been on the surface of the Earth for considerable time and consequently can be weathered. Thus the compositional information they provide is less reliable than that of falls. An exception of sorts to this is the Antarctic meteorites. Meteorites have been found in surprising numbers in the last 30 years or so in areas of low snowfall in Antarctica where ice is eroded by evaporation and wind. Meteorites are concentrated in such areas by glaciers. Because of storage in the Antarctic deep freeze, they are little weathered [7, p. 433-434].

Chondrites: the most primitive objects. There are three main classes: Carbonaceous (C), Ordinary, and Enstatite (E) chondrites. The ordinary and E chondrites are further subdivided based on their iron and nickel content and the degree of oxidation of the iron. The ordinary chondrites, which as Figure 3 shows are by far the most common, are composed primarily of olivine, orthopyroxene and lesser amounts of Ni-Fe alloy. They are subdivided into classes H (High iron or bronzite), L (Low iron or hypersthene), and LL. The name LL reflects low total iron and low metallic iron. H chondrites contain 25-31% total iron, of which 15-19% is reduced, metallic iron. L chondrites contain 20-25% iron, of which 4-10% is metallic. LL chondrites contain about the same total iron as L chondrites, but only 1-3% is metallic. The enstatite chondrites are highly reduced, with virtually all the iron is present as metal. Reduction of iron increases the Si/(Fe^{2+}+ Mg) ratio in silicates and results in enstatite, rather than olivine, being the dominant mineral in these objects, hence the name of the class. The E-chondrites can be further subdivided into EH (high iron) and EL (low iron) classes. Besides enstatite, metal and sulfides, enstatite chondrites contain a number of other exotic minerals, such as phosphides, carbides and a oxynitride of Si, that indicate they formed under highly reducing conditions. [7, p. 435]

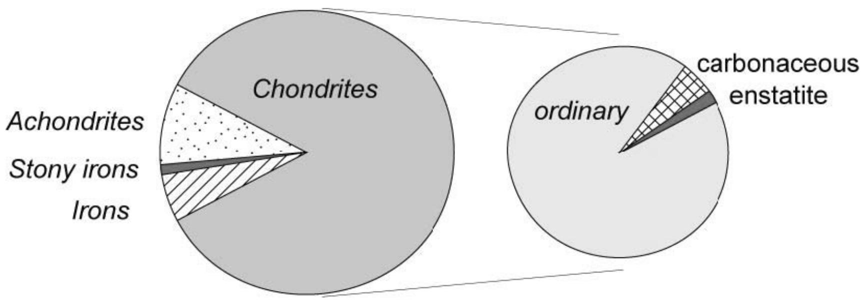

Figure 3 Relative abundance of major types of meteorites falls. Smaller pie chart on the right shows relative proportion of different chondrite classes.

*Achondrites.*While all the chondrites seem reasonably closely related, the achondrites are a more varied group. The Acapulcoites, Lodranites, Winonaites, and Urelites form a group called the primitive achondrites because they resemble chondrites in composition and mineralogy. Beyond that they are quite diverse. Meteorites of the first 3 groups are extremely rare. They represent chondritic material that has experienced extreme metamorphism and low-degree partial melting. In a few cases, relict chondrules have been identified, providing further evidence of their primitive nature. Urelites, which are both more common and more diverse than the other primitive achondrites, consist of olivine, pyroxene and a few metal grains plus a percent or so carbon, present as graphite and diamond, the latter a product of shock metamorphism produced by impacts. Their origin is problematic; it is possible they have several origins. Some are partial melting residues like other primitive achondrites; others appear to be highly fractionated igneous rocks. Brachinites are also sometimes included in the primitive achondrites. [7, p. 442-443]

Irons. Iron meteorites were originally classified based largely on phase and textural relationships. Compositionally, they all consist primarily of Fe-Ni alloys with lesser amounts of (mainly Fe-Ni) sulfides. Octahedral taenite, one of the Fe-Ni alloys, is the stable Fe-Ni metal phase at T> 900°C. At lower temperature, kamacite, a Ni-poor Fe-Ni alloy, exsolves on the crystal faces of the octahedron. If the Ni content falls below 6%, all the metal converts to kamacite at lower temperature. Thus the phases and textures of iron meteorites are related to their composition and cooling history. Iron meteorites consisting only of kamacite are named hexahedrites.

If Ni exceeds 6%, some taenite persists and the overall pattern is octahedral (= octahedrites), producing what is known as a Widmanstätten pattern. At low Ni contents, kamacite dominates and forms large crystals (coarse octahedrites). At higher Ni, kamacite and crystal size diminish (fine and medium octahedrites). Ataxites are Ni-rich (>14%) iron meteorites consisting of a fine-grained intergrowth of kamacite and taenite. The 20% or so of irons with silicate inclusions form a separate class. [7, p. 444-445]

Stony-irons. The main classes of stony-irons are the pallasites and the mesosiderites. Pallasites consist of a network of Fe-Ni metal with nodules of olivine. They probably formed at the interface between molten metal and molten silicate bodies, with olivine sinking to the bottom of the silicate magma. Mesosiderites consist of an odd pairing of metal and silicate. The silicate portion is very similar diogenites – brecciated pyroxene and plagioclase, and a genetic relationship is confirmed by oxygen isotopes. [7, p. 445]

Thought questions

- *Describe possible ways of meteorite classification.*
- *Give a definition of the term «chondrite». How many classes do chondrites include?*
- *What is the difference between irons and stony-irons?*

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Text No 4. The origin and differentiation of the Earth.

The Universe was already 9 billion years old when our solar system was born at 4.567 Ga. The compression and collapse of a gas cloud in the interstellar medium gave rise to a flattened disk of gas and dust rotating around an otherwise nondescript, medium-sized star. It was in this rotating disk of gas and dust – the primitive solar nebula – that our planetary system was formed.

The original building blocks of the Earth are thought to be preserved in a group of primitive meteorites known as the carbonaceous chondrites. These contain inclusions rich in calcium-aluminum minerals which formed at high temperature within 10^4-10^5 years of the formation of the solar system. Also present are chondrules, olivine-rich spheroidal melt droplets, a few millimeters in diameter, which formed within the first 4 Ma of Solar System history.

The formation of the Earth can be explained by the «standard model of planetary formation», in which dust fragments, including the types described above from meteorites, accumulate through the process of accretion – first, into kilometer-sized planetesimals over a timescale of 10^4 years, and then into planetary embryos – up to 4,000 km in diameter – over an interval of 10^6 years. The final stage of planetary accretion took place over 10^7-10^8 years and involved collisions between a relatively small number of large planetary bodies, giving rise to «giant impacts». These late, large-magnitude impacts are thought to have had a profound influence on the earliest history of the Earth System.

The latest of these involved an oblique collision between the proto-Earth and a body the size of Mars, at about 30 Ma after the formation of the solar system. This impact generated a huge amount of thermal energy so that a significant portion of the Earth was vaporized. This vapor coalesced around the Earth and cooled to form the Moon. A consequence of this impact is that a significant proportion of the Earth's mass would have been molten, creating what has become known as a magma ocean.

Similarly, the Earth's core is thought to have formed during the early stages of accretion, perhaps by as early as 10 Ma after the formation of the solar system. Geochemical constraints require the core to have also formed within a deep magma ocean, with liquid metal separating from a silicate melt at depths as great as 1,000 km.

Although the circumstantial evidence for the existence of a terrestrial magma ocean is strong, independent geochemical evidence has been hard to find. Recently however, the first geochemical clues of mineral fractionation with a deep molten mantle have been found, supporting the terrestrial magma ocean concept.

It was in this earliest Earth System that there was the strongest interaction between the different Earth reservoirs. There were intense, dynamic interactions between core, mantle, proto-ocean, and atmosphere. In addition there was probably an early basaltic crust, now long since lost by recycling into the mantle. [4, p. 29].

The accretion history of the Earth.

Defining the «age» of the Earth is a difficult task, for the age of the Earth may mean a number of different things. Harper and Jacobsen (1996) have shown that the age of the Earth may be defined as either the time the solar system began (T_0) or as the time at which accretion ended (T_E). However, both approaches are problematical, for the solar system began before the Earth was formed, and yet the end of accretion is very difficult to define, since the accretion process had a long tail. They suggest that a useful compromise is to define a mean accretion age for the Earth, as the time when 64% of the planetary mass had accreted. Here the main events in the accretion history of the Earth are identified.

The formation of the earliest matter in the solar system. The oldest matter of the solar system is found as refractory inclusions and chondrules in carbonaceous chondrite meteorites. The oldest refractory inclusions from the Allende meteorite have been dated at 4,567 Ma (Amelin et al., 2002) and formed over an interval of less than a million years. T_0 therefore is 4,567 Ma. The oldest chondrules formed at the same time, at 4,567 Ma but their period of formation lasted longer, until about 4,563 Ma (Amelin et al., 2004; Haack et al, 2004).

The timescale of accretion. Increasingly evidence suggests that the accretion of the Earth was rapid and was mostly formed after 10 Ma and fully formed after 30 Ma (Jacobsen, 2005).

The formation of the Earth's core. After a period of some controversy, the most recent (and self-consistent) Hf-isotope data suggest an «early» date for the formation of the core. Given that the core grew over a period of time, dating the time of formation of the core is the same problem as dating the time of formation of the Earth. Halliday (2004) suggests that the mean accretion age of the core is about 11 Ma and that core separation was complete by 30 Ma. It is possible that core formation is, on average, earlier than accretion.

The formation of the Moon. The oldest rocks on the Moon are dated at 4,562 ± 68 Ma. However, Hf isotope evidence suggests a formation age of about 30 Ma after the formation of the solar system by 4,537 Ma. This event is thought to mark the end of accretion.

The accretion of a late veneer. Whether or not a late veneer was added to the Earth towards the end of accretion is not clear. The principal evidence comes from the elevated siderophile element chemistry of the mantle. If there was a late veneer, it had to happen after core formation. At present the evidence from the trace element chemistry is ambiguous, because these data can also be explained by the formation of the core at high pressures and temperatures in a magma ocean, or by continuous core formation with decreasing metal input. Currently, the best evidence for a late veneer comes from Os-isotope evidence, where there is a clear mismatch between the composition of the PUM and chondrite. However, even this is uncertain, for there are a number of different models for the evolution of Os-isotopes in the Earth's mantle over time.

A late heavy bombardment. There is now good evidence that the Moon experienced a period of intense impacting at about 3.8-3.9 Ga, significantly after the normally accepted end of Earth accretion (Kring & Cohen, 2002). By inference the Earth must have experienced this same event, although attempts to find geochemical evidence of this event in the Earth's oldest sediments at Isua have been disappointing (Frei & Rosing, 2005).

Isotopic accretion modeling. The Earth accreted over a period of time and so defining the «age of the Earth» is not a particularly meaningful exercise. It may, however, be even more serious than this, and may be conceptually wrong, because, by its very nature, the accretion process is an open system and thereby violates one of the fundamental assumptions of geochronology (Hofmann, 2003). The recognition of this problem, that accretion is a disequilibrium process, is giving rise to a new approach to the chronology of accretion – that of isotopic accretion modeling, whereby isotopic ratios are interpreted as part of a dynamic accretion process (Kramers & Tolstikhin, 1997; Halliday, 2004). Such an approach has to make some assumptions about the nature of the unseen accreting material, its similarity or otherwise to the already formed Earth, about the degree of mixing, and about the amount of material lost in the accretion process. Although more complex, isotopic accretion modeling will become a more appropriate approach for the dynamic accretion of the Earth [4, p. 66-68].

Thought questions

- *What is the main reason of differentiation of the Earth?*
- *Describe accretion history of the Earth in general.*
- *What is the possible process and possible age of Moon formation?*

Text No 5. Structure of the Earth.

The internal structure of the Earth is revealed primarily by compressional waves (primary waves, or P-waves) and shear waves (secondary waves, or S-waves) that pass through the planet in response to earthquakes. Seismic-wave velocities vary with pressure (depth), temperature, mineralogy, chemical composition, and degree of partial melting. Although the overall features of seismic-wave velocity distributions have been known for some time, refinement of data has been possible in the last 10 years. Seismic-wave velocities and density increase rapidly in the region between 200 and 700 km deep. Three first-order seismic discontinuities divide the Earth into crust, mantle, and core (Fig. 4): the *Mohorovicic discontinuity*, or *Moho*, defining the base of the crust; the core-mantle interface at 2900 km; and the inner-core-outer-core interface around 5200 km. The core composes about 16% of the Earth's volume and 32% of its mass. These discontinuities reflect changes in composition, phase, or both. Smaller but important velocity changes at 50 to 200 km, 410 km, and 660 km provide a basis for further subdivision of the mantle.

The major regions of the Earth can be summarized as follows (Fig. 4):

1. The *crust* consists of the region above the Moho and ranges in thickness from about 3 km at some oceanic ridges to about 70 km in collisional orogens.

2. The *lithosphere* (50-300 km thick) is the strong outer layer of the Earth – including the crust, which reacts to many stresses as a brittle solid. The *asthenosphere*, extending from the base of the lithosphere to the 660-km discontinuity, is by comparison a weak layer that readily deforms by creep. A region of low seismic-wave velocity and of high attenuation of seismic-wave energy, the *low-velocity zone* (LVZ), occurs at the top of the asthenosphere and is from 50 to 100 km thick. Significant lateral variations in density and in seismic-wave velocity are common at depths of less than 400 km.

3. The *upper mantle* extends from the Moho to the 660-km discontinuity and includes the lower part of the lithosphere and the upper part of the asthenosphere. The region from the 410-km to the 660-km discontinuity is known as the *transition zone*. These two discontinuities are caused by two important solid-state transformations: from olivine to wadsleyite at 410 km and from spinel to perovskite with the addition of magnesiowustite at 660 km.

4. The *lower mantle* extends from the 660-km to the 2900-km discontinuity at the core-mantle boundary. It is characterized mostly by rather constant increases in velocity and density in response to increasing hydrostatic compression. Between 200 and 250 km above the core-mantle interface, a flattening of velocity and density gradients occurs in a region known as the

D'' layer, named after the seismic wave used to define the layer. The lower mantle is also referred to as the *mesosphere*, a region that is strong but relatively passive in terms of deformational processes.

5. The *outer core* will not transmit S-waves and is interpreted to be liquid. It extends from the 2900-km to the 5200-km discontinuity.

6. The *inner core*, which extends from the 5200-km discontinuity to the center of the Earth, transmits S-waves – although at very low velocities, suggesting that it is a solid near the melting point.

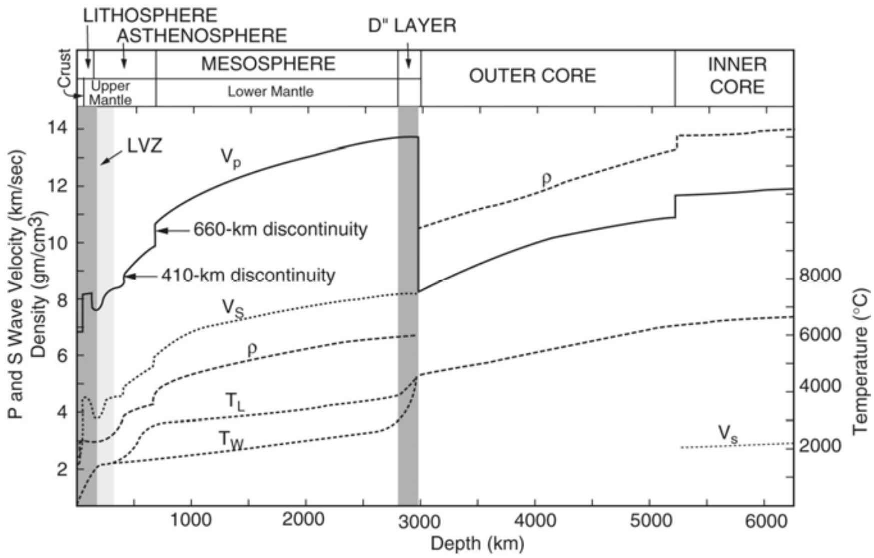

Figure 4. The distribution of average compressional-wave, or P-wave (Vp), and shear-wave, or S-wave (V_S), velocities and the average calculated density (p) in the Earth. Also shown are temperature distributions for whole-mantle convection (T_W) and layered mantle convection (T_L). LVZ, low-velocity zone.

There are only two layers in the Earth with anomalously low seismic-velocity gradients: the lithosphere and the D'' layer just above the core (Fig. 4). These layers coincide with steep temperature gradients; hence, they are thermal boundary layers in the Earth. Both layers play an important role in the cooling of the Earth. Most cooling (>90%) occurs by plate tectonics as plates are subducted deep into the mantle. The D'' layer is important in that steep thermal gradients in this layer may generate mantle plumes, many of which rise to the base of the lithosphere, thus bringing heat to the surface (<10% of the total Earth cooling).

Considerable uncertainty exists regarding the temperature distribution in the Earth. It depends on features of the Earth's history such as the initial temperature distribution in the planet, the amount of heat generated as a function of both depth and time, the nature of mantle convection, and the process of core formation. Most estimates of the temperature distribution in the Earth are based on one or a combination of two approaches: Models of the Earth's thermal history involving various mechanisms for core formation, and models involving redistribution of radioactive heat sources in the Earth by melting and convection processes.

Estimates using various models seem to converge on a temperature at the core-mantle interface of about 4500 ± 500° C and a temperature at the center of the core from 6700 to 7000° C. Two examples of calculated temperature distributions in the Earth are shown in Figure 4. Both show significant gradients in temperature in the LVZ and the D'' layer. The layered convection model also shows a large temperature change near the 660-km discontinuity, because this is the boundary between shallow and deep convection systems in this model. The temperature distribution for whole-mantle convection, preferred by most scientists, shows a rather smooth decrease from the top of the D'' layer to the LVZ.

Thoughtquestions

- *Give a definition of the term «Moho».*
- *What are the main regions of the Earth?*
- *Where is the D'' layer situated in the Earth's interior?*

*Text No 6. P*late tectonics (present and past).

Magma generation, igneous intrusions, metamorphism, volcanic action, earthquakes, faulting, and folding are usually the result of plate tectonic activity. The earth's crust is divided into six large pieces, and about twenty smaller pieces, by deep fault systems. These crustal plates include both oceanic and continental crust. Underlying convection currents in the mantle and lower crust are thought to create forces that push and pull these plates at the surface. Intense geologic activity occurs where plates move apart (divergent boundaries), collide (convergent boundaries) or slide past one another (transform boundaries). (Fig 5) About 200 million years ago, it is thought, plate tectonic forces began to break a single continental land mass into pieces that spread apart to form the continents as we know them today. [2, p. 153]

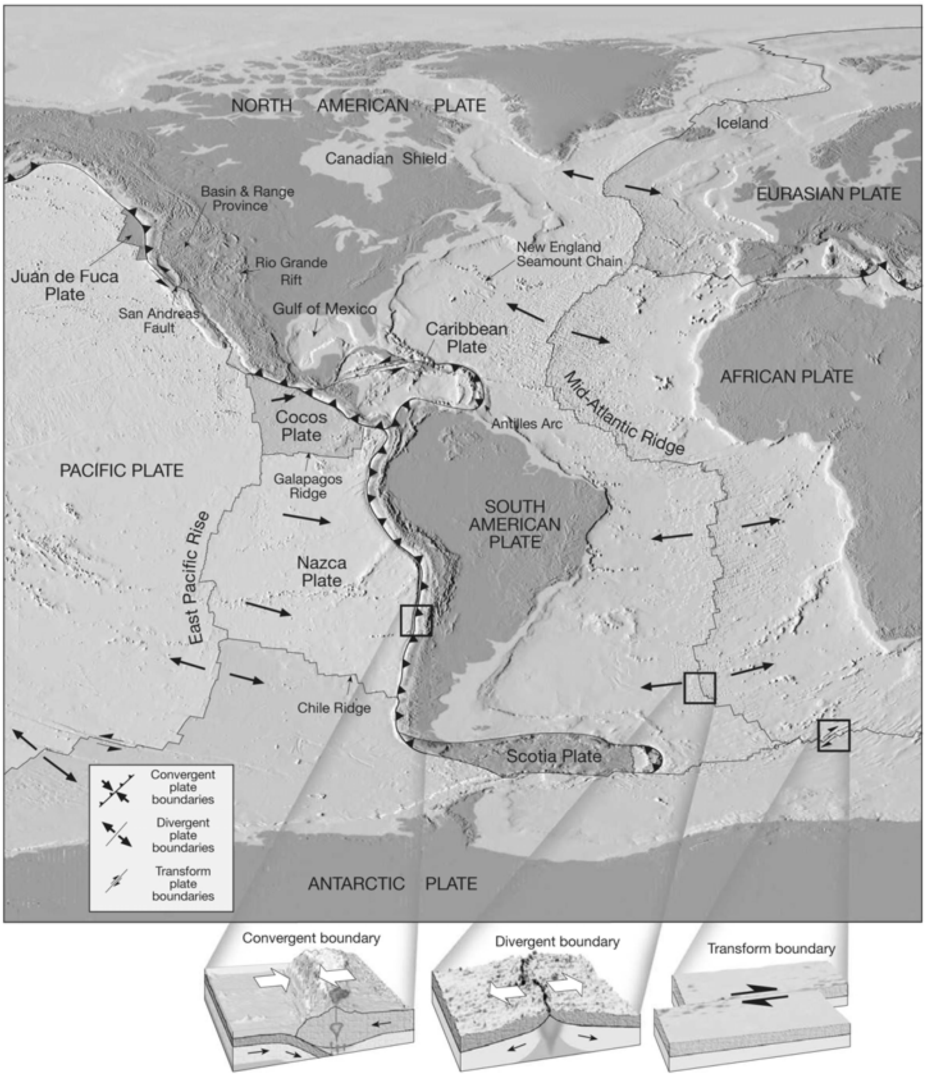

Figure 5 Map of the major lithospheric plates on Earth. Arrows are directions of plate motion. Filled barbs are convergent plate boundaries (subduction zones and collisional orogens); single lines are divergent plate boundaries (ocean ridges) and transform faults.

Most plates consist of both continental and oceanic crust. Plates move away from each other at spreading centers (divergent boundaries). A convergent plate boundary separates plates that are moving toward each other. A transform plate boundary is a fault zone along which two plates slide in opposite directions. Oceanic crust is subducted underneath continents or in oceanic trenches. Continental crust is less dense than oceanic crust and therefore will not subduct because it is lighter. Compared to its edges, a plate's interior is relatively stable, with few earthquakes and little igneous activity or structural deformation. Flood basalts and mantle plume «hot spots» have been known to occur in the interior, but the majority of seismic, volcanic, and mountain building activity occurs along a plate's boundaries, including frequent earthquakes.

Convergent boundaries. Plates may converge directly or at an angle. Three types of convergent boundaries are recognized: continent-continent, ocean-continent, and ocean-ocean.

Continent-continent convergence results when two continents collide. The continents were separated at one time by oceanic crust that was progressively subducted under one of the continents. The continent overlying the subduction zone will develop a magmatic arc until the ocean floor becomes so narrow that the continents collide. Because the continents are less dense than the oceanic crust, they will not be pulled down the subduction zone. One continent may override the other for a short distance, but the two continents eventually become welded together along a geologically complex suture zone that represents the original line of collision. The crust is thickened along the suture zone, resulting in isostatic uplift, mountain-building, and thrust faulting.

Ocean-continent convergence occurs when oceanic crust is subducted under continental crust. This forms an active continental margin between the subduction zone and the edge of the continent. The leading edge of the continental plate is usually studded with steep andesitic mountain ranges . Earthquakes occur in the Benioff zones that dip underneath the continental edge. *Magmatic arc* is a general term for belts of andesitic island arcs and inland andesitic mountain ranges that develop along continental edges. These mountain ranges (also called volcanic arcs) are under lain by crust that has been thickened by intrusive batholiths that were generated by partial melting along the underlying subduction zone. Volcanic arcs result from isostatic processes, compressional forces along the leading edge of the continent, and thrust faults that move slices of mountain-belt rocks inward over the continental interior, creating *backarc thrust* belts. The additional weight of these rocks downwarps the inland area, forming a *foreland basin*. The foreland basin fills with eroded material from the mountain ranges or occasionally with marine sediments if it becomes submerged.

Ocean-ocean convergence occurs when two plates carrying ocean crust meet. One edge of ocean crust is subducted beneath the other at an ocean trench. The ocean trench curves outward toward the subducting plate over the subduction zone. Data from earthquakes along the subducting plate show that the angle of subduction increases with depth. Subduction probably occurs to a depth of at least 670 kilometers (400 miles), at which point the plate probably becomes plastic.

Andesitic volcanism often forms a curved chain of islands, or *island arc*, that develops between the oceanic trench and the continental landmass. Modern-day examples of island arcs are the Philippines and the Alaska Peninsula. Geologists think that at a depth of about 100 kilometers (60 miles) the asthenosphere just above the subduction zone partially melts. This mafic magma may then assimilate silicious rocks as it moves up through the overlying plate, forming a final andesitic composition that vents to form the island arc. The distance the island arc forms from the oceanic trench is dependent on the steepness of the subduction zone – the steeper the angle of subduction, the more quickly the subducted material reaches the magma – forming depth of 100 kilometers, and the closer the arc will be to the oceanic trench.

The trench becomes filled with folded marine sediments that slide off the descending plate and pile up against the wall of the trench. This accumulation is called the *accretionary* *wedge*. The accretionary wedge is continuously pushed up to form a ridge along the surface of the trench over the subducted crust. The *forearc basin* is the relatively undisturbed expanse of ocean floor between the accretionary wedge and island arc; the area on the continental side of the arc is called the *backarc***.**

The backarc basin, the basin that occurs between the island arc and the continental mass, is occasionally split by new extensional forces into two parts that migrate in different directions *(backarc rifting)***.** In other words, a «mini» spreading center develops as an equilibrium response to changes in the way the plate is being subducted. This backarc spreading can push the island arc away from the continent toward the subduction zone. If it develops along the continental edge, it can also split off a strip of the continent and push it seaward toward the subduction zone. The rifting may be caused by a mantle plume that has come near to the surface and is spreading out, creating convection currents that stretch the crust to the point of breakage. [4, p. 162-164]

Divergent boundaries. A divergent plate boundary is formed where tensional tectonic forces result in the crustal rocks being stretched and finally split apart, or rifted. The central block drops to form a *graben*, and basaltic volcanism is abundant along the rift's faults. The rise of hot mantle material beneath the rift zone pushes the rift valley farther apart (Figure 60). Today's active divergent boundaries are midoceanic ridges (sea floor spreading centers). Divergent boundaries can also develop on land, as did those that broke up Pangaea about 200 million years ago. Continental rifting can end before the crustal mass has been fully separated. These failed rifts then become seas or large basins that fill with sedimentary material.

Geologists have debated for years whether uplift causes rifting or whether rifting causes uplift. Some scientists feel that rifling thins the crust, reducing the amount of pressure it can exert; the reduced pressure allows deeper, more pressurized rocks to ascend, causing uplift (similar to unloading and dome structures).

Eventually the crust is totally split by continued divergence along the rift, and the two parts are separated by a new sea that floods the rift valley. New, basaltic oceanic crust continues to build up along the rift, causing high heat flows and shallow *earthquakes***.** Rivers do not discharge into the new ocean because the continental edges have been uplifted by the rising mantle material and slope away from the ocean. As divergence continues, the sea widens and the midoceanic ridge continues to grow. Eventually the continental edges subside as the underlying rocks cool and are further lowered by erosion. Rivers begin to flow into the sea forming deltas, and marine sedimentation begins to form the continental margin, shelf, and rise. [4, p. 164-166]

Transform boundaries. A transform boundary is a fault or a series of parallel faults (fault zone) along which plates slide past each other via strike-slip movements. As previously discussed, transform faults connect offset midoceanic ridges (including the rift valleys). The motion between the two ridge segments is in opposite directions; beyond the transform fault, crustal movement is strike-slip in the same direction. Thus, the transform fault «transforms» into a fault that has different motions along the same fault plane. Transform faults can connect diverging and converging boundaries or two converging boundaries (such as two oceanic trenches). Transform faults are thought to form because the original line of divergence is slightly curved. As an adjustment to mechanical constraints, the tectonic forces break the curved or irregular plate boundary into a series of pieces. The segments are separated by transform faults that are parallel to the spreading direction, allowing the ridge crest to be perpendicular to the spreading direction, which is the easiest way for two plates to diverge. Transform faults allow the divergent boundary to be in a structural equilibrium. [4, p. 167]

Mantle plumes. Hot mantle rock that rises toward the earth's surface in a narrow column is called a mantle plume**.** Plumes can be located beneath continental or oceanic crust or along plate boundaries. Plumes are thought to spread out laterally at the base of a continent, creating increased pressure that stretches the crust and results in uplift, fracturing, rifting, or flood basalts. Mantle plumes are thought to be strong enough to induce rifling and the formation of plates. The pressure creates a domed region that eventually splits in a three-pronged pattern (*triple junction or triple point*). If rifting continues, two of the three faults become active, forming the continental margins of two new continents. The two faults join to form an active divergent boundary that dissipates the tectonic forces. The third «arm» becomes a failed rift, or *aulacogen***,** that rapidly fills with sediment. [4, p. 168]

Plate tectonics with time.

As data continue to accumulate, it becomes more certain that plate tectonics in some form is the principal mechanism by which the Earth has cooled for the last 4 Gy. One way of tracking plate tectonics with time is with the petrotectonic assemblages summarized in this chapter. How far back in time do we see modern petrotectonic assemblages, and are their time–space relationships, tectonic histories, and chemical compositions similar to modern assemblages? Except for ophiolites, the greenstone and TTG assemblages are recognized throughout the geologic record from the oldest known rocks between 4.0 and 3.6 Ga to the present (Fig. 3.33). The oldest well-preserved cratonic-passive margin sediments are in the Moodies Group in South Africa, deposited at 3.2 Ga, and such sediments are minor yet widespread in the rock record by 3.0 Ga. Thus, it would appear that cratons, although probably small, were in existence by 3.2 to 3.0 Ga. Although the oldest isotopically dated mafic dyke swarm is the Ameralik swarm in southwestern Greenland, intruded around 3.25 Ga, deformed remnants of dykes in TTG complexes indicate earlier swarms, perhaps as early as 4.0 Ga in the Acasta gneisses. The oldest dated anorogenic granite is the Gaborone granite in Botswana emplaced at 2875 Ma. However, clasts of granite with anorogenic characters in conglomerates of the Moodies Group have igneous zircons with U-Pb isotopic ages of 3.6 Ga, indicating that highly fractionated granites formed in some early Archean crust. The oldest known continental rift assemblages are in parts of the Dominion and Pongola Supergroups in South Africa, which were deposited on the Kaapvaal craton around 3.0 Ga. The oldest accretionary orogens are the Acasta gneisses (4.0 Ga) and the Amitsoq gneisses (3.9 Ga) in northwestern Canada and southwestern Greenland, respectively. Although the oldest well-documented collisional orogens are Paleoproterozoic in age (such as the Wopmay orogen in northwestern Canada and the Capricorn orogen in Western Australia), it is likely that late Archean collisional orogens with reworked older crust exist in the granulite terranes of east Antarctica and southern India.

That greenstones, TTG, anorogenic granites, mafic dyke swarms, and accretionary orogens all appear in the earliest vestiges of our preserved geologic record from 4.0 to 3.5 Ga strongly supports some sort of plate tectonics operating on the Earth by this time. By 3.2 to 3.0 Ga, cratonic-passive margin sediments and continental rifts appeared, recording the development of the earliest continental cratons. Although plate tectonics appears to have been with us since at least 4.0 Ga, there are differences between some Archean and some post-Archean rocks that indicate Archean tectonic regimes must have differed in some respects from modern ones. These differences have led to the concept that plate tectonics operated in the Archean but differed in some ways from modern plate tectonics. Scientists are now faced with the question of how and to what degree Archean plate tectonics differed from modern plate tectonics and what these differences mean in terms of the evolution of the Earth. [1, p. 112-114]

Thought questions

- *What is the difference between convergent and divergent plate boundaries?*
- *Give a definition of the term «Mantle plume».*
- *When did plate tectonics begin?*

Text No 7. Supercontinents (assembly and dispersal).

Supercontinents are large continents that include several or all of the existing continents. Matching of continental borders, stratigraphic sections, and assemblages are some of the earliest methods used to reconstruct supercontinents. Wegener (1912) pointed out the close match of opposite coastlines of continents and the regional extent of the Permo- glaciation in the Southern Hemisphere, and DuToit (1937) was first to propose an accurate fit for continents based on geological evidence. Today, in addition to these methods, we have polar-wandering paths, seafloor-spreading directions, hotspot tracks, and correlation of crustal provinces. The use of computers in matching continental borders has resulted in more accurate and objective fits. One of the most definitive matching tools in reconstructing plate positions in a former supercontinent is a piercing point. A piercing point is a distinct geologic feature such as a fault or a terrane that strikes at a steep angle to a rifted continental margin, the continuation of which should be found on the continental fragment rifted away.

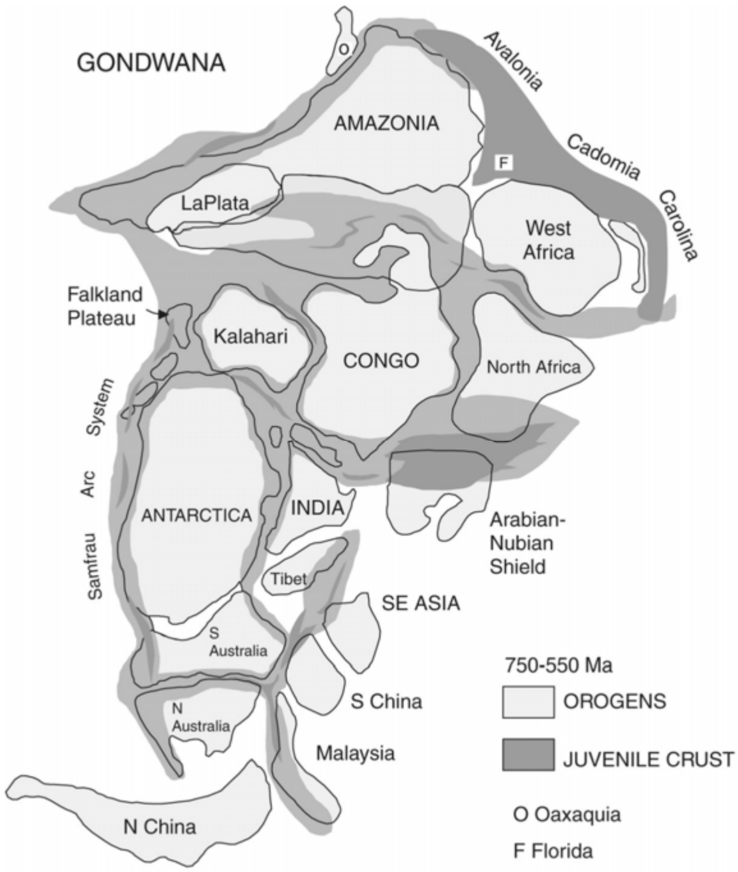

Figure 6 Gondwana, a supercontinent formed between 750 and 550 Ma, which became part of Pangea in the late Paleozoic. Also shown are major orogens formed as blocks collided to make the supercontinent and the distribution of juvenile crust extracted from the mantle as the supercontinent formed.

The youngest supercontinent is *Pangea***,** which formed between 450 and 320 Ma and includes most of the existing continents. Pangea began to fragment about 160 Ma and is still dispersing today. *Gondwana* is a Southern Hemisphere supercontinent composed principally of South America, Africa, Arabia, Madagascar, India, Antarctica, and Australia (Fig. 6). It formed in the latest Neoproterozoic and was largely completed by the Early Cambrian (750-550 Ma) (Unrug, 1993). Later it became incorporated in Pangea.**,** which is also part of Pangea, includes most of North America, Scotland and Ireland north of the Caledonian suture, Greenland, Spitzbergen, and the Chukotsk Peninsula of eastern Siberia. The oldest well-documented supercontinent is *Rodinia***,** which formed from 1.3 to 1.0 Ga, fragmented from 750 to 600 Ma, and appears to have included many cratons in a configuration quite different from Pangea (Pisarevsky et al., 2003) (Fig. 7). Although the existence of older supercontinents is likely, their configurations are not known. Geologic data strongly suggest the existence of supercontinents in the Early Proterozoic and in the Late Archean (Aspler and Chiarenzelli, 1998; Pesonen et al., 2003). Current thinking is that supercontinents have been episodic, giving rise to the idea of a supercontinent cycle (Nance et al., 1986; Hoffman, 1991). A supercontinent cycle consists of the rifting and breakup of one supercontinent, followed by a stage of reassembly in which dispersed cratons collide to form a new supercontinent with most or all fragments in configurations different from the older supercontinent (Hartnady, 1991). [1, p. 54-57]

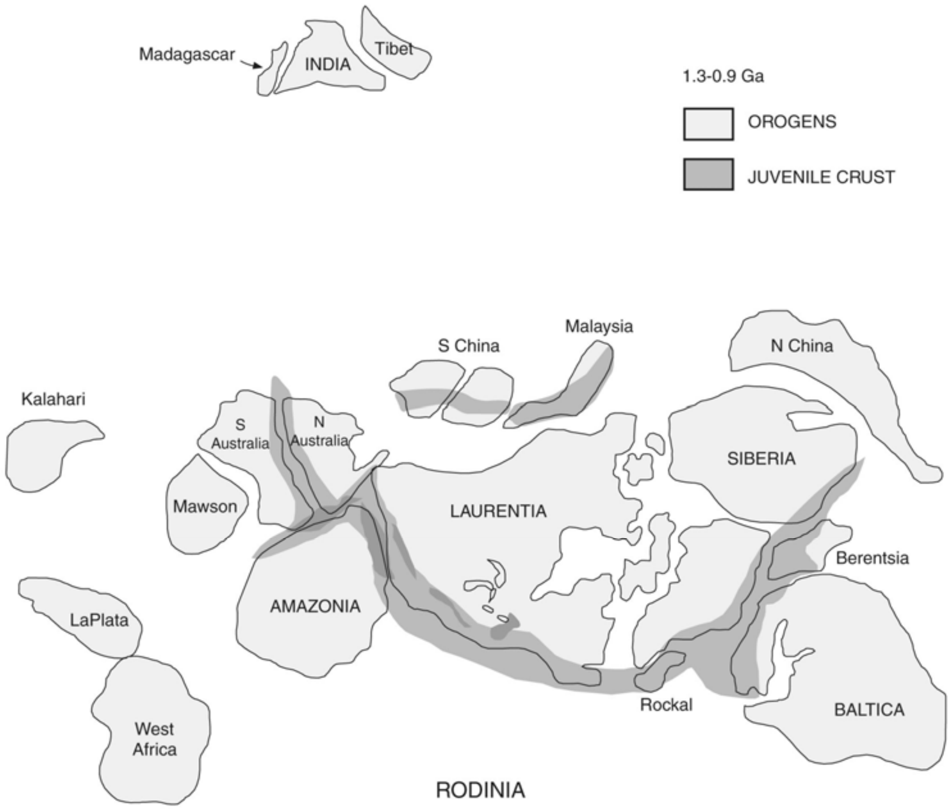

Figure 7 Rodinia, a supercontinent formed between 1.3 and 1.0 Ga and fragmented from 750 to 600 Ma.

Causes of supercontinent assembly. There is a relationships among plumes, superplumes, and slab avalanches in the mantle and crustal processes such as the rate of production of continental crust and the times of supercontinent assembly.

A fundamental seismic discontinuity in the mantle at a depth of 660 km is caused by downward phase change to denser material. Mantle processes associated with plate tectonic movements normally occur above this discontinuity, which forms the base for convection cells that rise at spreading centers and also the lowest depth reached by subducting slabs (hence the deepest earthquakes). Mantle below the discontinuity affects surface processes largely through plumes that may be generated as deep as the base of the mantle, which is seismically designated the D” layer.

At various occasions in earth history, the 660-km discontinuity seems to have been disrupted. Subducted slabs of oceanic lithosphere tend to accumulate at the discontinuity because they are denser than the mantle above and around them. Their low temperature and lack of LIL elements, removed during subduction-zone magmatism, also make them slightly denser than the mantle beneath the discontinuity. Thus, places where numerous slabs have accumulated can become unstable, with the slabs dropping into the lower mantle as a «slab avalanche» (Condie, 2001). This avalanche displaces material in the lower mantle, causing it to rise elsewhere on the earth as a plume or, if large enough, as a «superplume».

Material rising from the lower mantle has important effects on the composition of the upper mantle. Because continental crust is derived solely by extraction of material from the upper mantle, that part of the mantle becomes rapidly depleted in LIL elements, including those important in analysis of isotopic systems (Rb, Nd, Re). The upper mantle may not contain enough of these LIL elements to generate all of the continental crust in the earth and to account for isotopic changes. Consequently, many earth scientists propose that compositional evolution of the upper parts of the earth can be explained only if plumes, superplumes, or other infusions from the lower mantle periodically replenish the upper mantle in LIL elements.

In addition to compositional effects, plumes cause plate movements on the surface (Gurnis, 1988). Both the geoidal low created by a slab avalanche and the high created by rising large plumes/ superplumes should move surface plates toward the area of the avalanche. Plates that are purely oceanic lithosphere would presumably disappear into the mantle, but plates that contain continents would be too light to subduct. Thus, where this process continues for a few hundred million years, it is likely that virtually all continental blocks would accumulate in one area to form a supercontinent.

Because the breakup of one supercontinent overlaps the assembly of the next one, it is possible that mantle movements that cause breakup automatically begin the accretion process elsewhere. Rising mantle beneath a supercontinent sends continental blocks toward areas of accretion above a geoid low. Presumably this was a continuing process during most of earth history. [6, p. 93-94]

Causes of dispersal of supercontinents. Supercontinents break up because they are subjected to lateral extension throughout most of their area. This requires uplift that can be caused only by an accumulation of heat under the supercontinent. Part of this accumulation results from the comparatively low conductivity of continental crust, which prevents escape of heat across the earth's surface as rapidly as it does across oceanic lithosphere. Some of the increase in temperature may also result from the inability of subducting slabs to reach the interior of the supercontinent and cool the upper mantle beneath it.

It is unclear whether uplift of a supercontinent is related to the development of plumes and superplumes (Condie, 2001). The problem is complicated by the uncertain relationship between plumes/superplumes and basalt plateaus. Many geologists assume that large areas of basaltic eruption are the «heads» of plume (hotspot) tracks, although this assumption has been challenged by examination of sequences of ages along the tracks.

Some basalt plateaus are clearly related to the breakup of Pangea. Hawkesworth et al. (1999) and Storey et al. (2001) discussed the possibility that a broad region of Gondwana was underlain by hot mantle (superplume?) that generated basalt provinces during different ages of fragmentation in at least three locations. Courtillot et al. (1999) also suggested that much of the breakup of Pangea was caused by plumes that developed at different times. Broad uplift of Pangea before rupturing is also shown now by a geoidal high in most of the Atlantic Ocean, which is almost certainly the remains of an axis of uplift beneath Pangea.

The relationship of plumes (and basalt plateaus) to fragmentation of supercontinents, however, is not always clear (Storey and Kyle, 1997; Condie, 2001). Some parts of Pangea seem to have rifted apart without any associated magmatism, either of basalts or other magmatic rocks. Furthermore, some basalt plateaus clearly have no relationship to supercontinents. Examples include the ~15 Ma Columbia River basalts in western North America and, less clearly, a possible superplume in the Pacific Ocean from about 120 Ma to 80 Ma (Larson, 1991). This superplume apparently caused so much reorganization of the earth's interior that no magnetic reversals occurred for 40 million years, referred to as the Cretaceous «magnetic quiet zone». The plume also formed numerous oceanic plateaus that are still preserved in the ocean and may have initiated some of the Pacific hotspot tracks. [6, p. 98-99]

Summary. Models for the formation of supercontinents depend highly on interpretation of the history of orogenic belts within the continents. Intercontinental belts formed by closure of oceans within the belts demonstrate assembly of terranes on either side. Intracontinental belts that formed by reworking of older crust within the belt, however, probably developed within a large continental block that accreted intact to the supercontinent. Some confined orogens opened briefly and closed without dispersing the continental blocks that contain them, thus permitting those blocks to accrete intact to a supercontinent.

Supercontinents probably accrete where mantle processes bring most of the earth's terranes into one area, probably above the downgoing limbs of very large convection cells. Different interpretations of the nature of orogenic belts lead to different models for the assembly of supercontinents. If most belts are intercontinental, then supercontinents have been formed by accretion of numerous small terranes. If many belts are intracontinental or confined, however, then supercontinents formed by accretion of a few large blocks and accumulation of smaller terranes around their margins.

Dispersal of supercontinents is probably caused by accumulation of heat under the supercontinent, possibly above rising convection cells. The dispersal of Pangea can be traced by patterns of ocean opening, but the breakup of older supercontinents must be inferred from evidence of widespread continental extension. Indicators of extension include rift systems, granite-rhyolite terranes, anorthosite complexes, and dike swarms. [6, p. 100]

Thought questions

- *What does the term «Supercontinent» mean?*
- *List and explain causes of possible assembly of supercontinent?*
- *List and explain causes of possible dispersal of supercontinent?*

Text No 8. Plate tectonics and ore deposits.

Extensional settings. Incipient rifting of stable continental crust is represented in Figure 8,a, where thinning and extension may be related to hotspot activity. Magmatism is often localized along old sutures and is alkaline or ultrapotassic (kimberlites and lamproites) in character. Anorogenic granites such as those of the Bushveld Complex (Sn, W, Mo, Cu, F, etc.), pyroxenite-carbonatite intrusions such as Phalabora (Cu-Fe-P-U-REE etc.), and kimberlites (diamonds) represent ore deposit types formed in this setting. Intracontinental rifts can host SEDEX-type Pb-Zn-Ba-Ag deposits. As continental rifting extends to the point that incipient oceans begin to open (such as the Red Sea, – Figure 8,b), basaltic volcanism marks the site of a mid-ocean ridge and this site is also accompanied by exhalative hydrothermal activity and plentiful VMS deposit formation. Such settings also provide the environments for chemical sedimentation and precipitation of banded iron-formations and manganiferous sediments. Continental platforms commonly host organic accumulations that on catagenesis give rise to oil deposits. Carbonate sedimentation ultimately provides the rocks which host MVT deposits, although the hydrothermal processes that give rise to these epigenetic Pb-Zn ores are typically associated with circulation during compressional stages of orogeny. Mid-ocean ridges are the culmination of extensional processes (Figure 8,c). Exhalative activity at these sites gives rise to «black-smoker» vents (such as those at 21° N on the East Pacific Rise) that provide the environments for the fomation of Cyprus type VMS deposits. The basalts which form at mid-ocean ridges also undergo fractional crystallization at sub-volcanic depths to form podiform chromite deposits as well as Cu-Ni-PGE sulfide segregations. [5, p. 339-341]

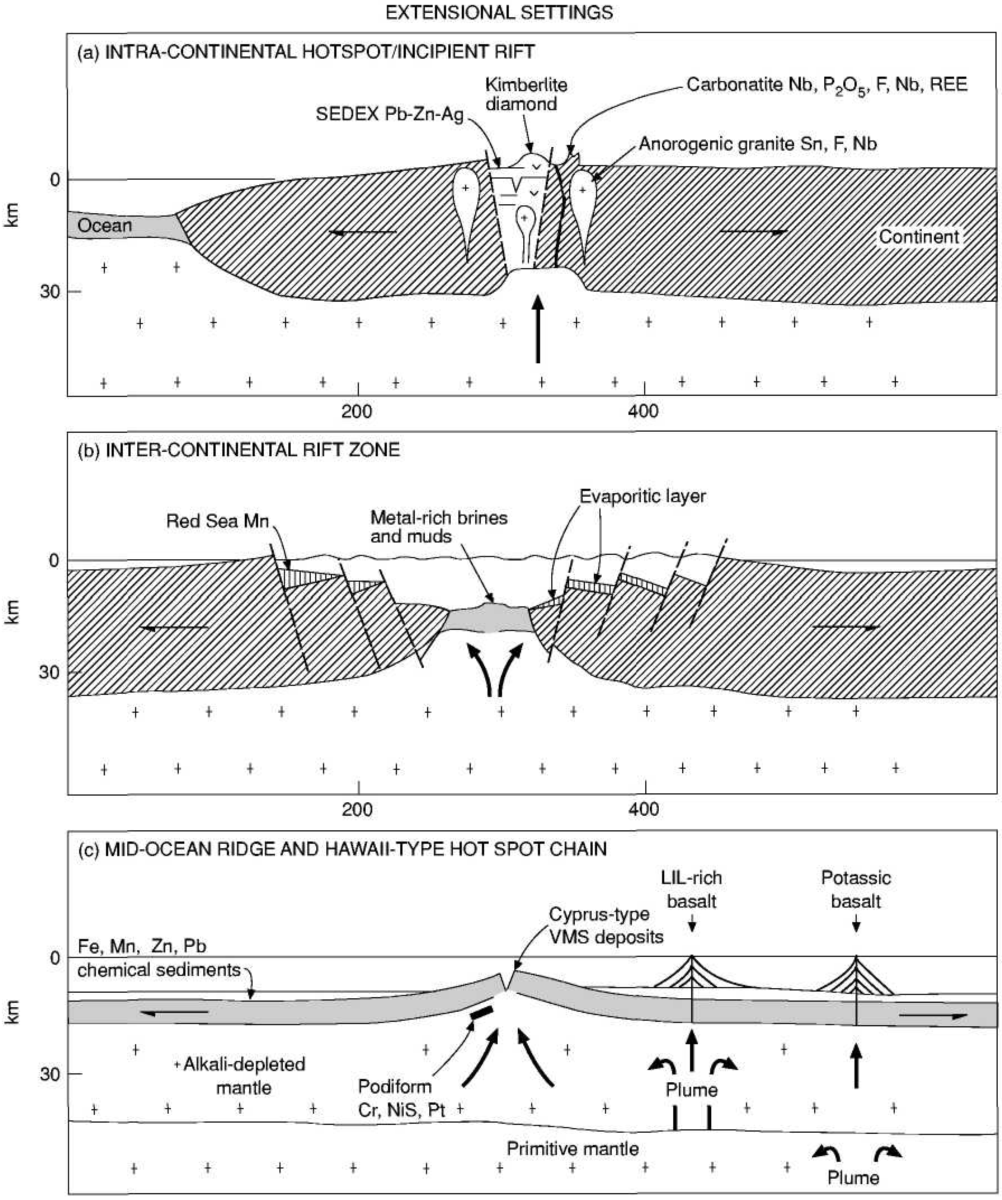

Figure 8 Simplified illustrations of the major extensional tectonic settings and the ore deposit types associated with each.

Compressional settings. The highly significant Andean type collisional margins are represented in Figure 9,a. These are the sites of the great porphyry Cu-Mo provinces of the world, while inboard of the arc significant Sn-W granitoid-hosted mineralization also occurs. The volcanic regions above the porphyry systems are also the sites of epithermal precious metal mineralization. A similar tectonic setting can exist between two slabs of oceanic crust, as represented by the island arc environment in Figure 9,b. Porphyry Cu-Au deposits occasionally occur associated with the early stages of magmatism in these settings, whereas the later, more evolved calc-alkaline magmatism gives rise to Kuroko-type VMS deposits. The back-arc basins represent the sites of Besshi type VMS deposition. Arc-arc collision in the back-arc environment can also result in the preservation of obducted oceanic spreading centers within which podiform Cr and sulfide segregations might be preserved. In the Japanese setting, where the island arc develops fairly close to a continent (Figure 9,c), marginal sedimentary basins floored by oceanic crust occur.

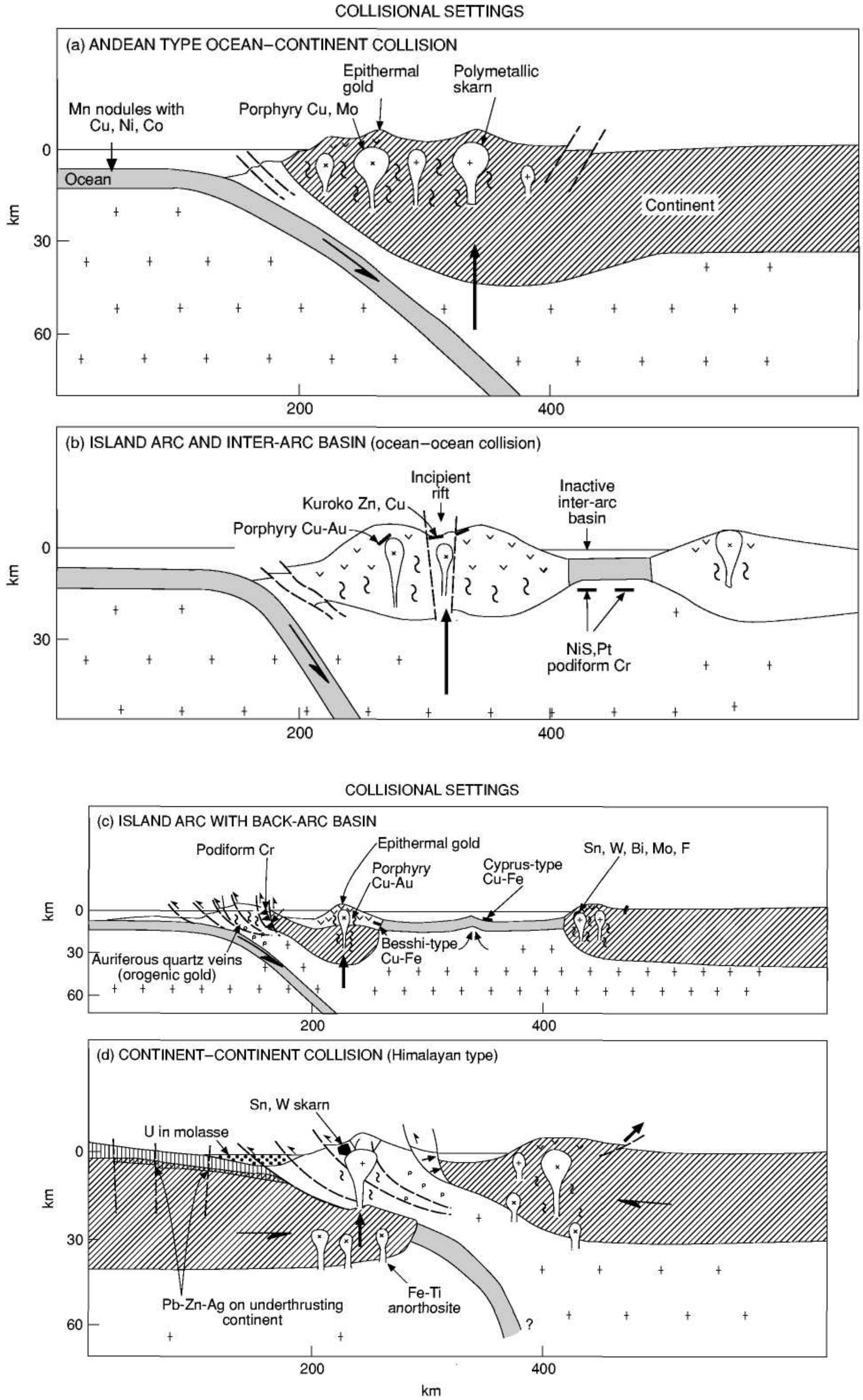

Figure 9 Simplified illustrations of the major compressional tectonic settings and the ore deposit types associated with each.

This setting typically hosts Besshi- and Cyprus-type VMS deposits. As the arc and continent accrete, ophiolite obduction can occur, and felsic magmatism may give rise to large-ion lithophile element mineralization. Ultimately, the oceanic crust is totally consumed to form a zone of continent-continent collision (Figure 9,d). Modern examples such as the Himalayas and Alps do not appear to be significantly mineralized, but this may be an expression of insufficient exhumation of mineralized zones. Older examples preserve Sn-W-U mineralization in S-type granites, whereas orogeny-driven fluids give rise to orogenic vein-related lode Au systems and MVT Pb-Zn deposits in suitably preserved platformal sediments. [5, p. 342-343]

Metallogeny in time. Broad trends emerge when relating ore deposit types to geological time and global tectonic setting. The mechanisms by which the crust has evolved, and the amalgamation and dispersal of continents over time, have played an overriding role in the formation of all deposit types. Although the processes are obscure in the early periods of Earth history, it appears that primitive continents started to form after the late heavy meteorite bombardment, from about 4000 Ma. Only a limited range of ore deposit types, mainly related to ocean floor hydrothermal processes, appears to have developed at this stage. As more evolved continents formed in the Mesoarchean and conventional plate tectonic processes were entrenched, the range of ore deposit types broadened, although many of the near-surface variants may not be preserved due to erosion. The Neoarchean Era was a period of intense global orogenesis and ore deposits formed at this time tend to be arc-related and magmatic-hydrothermal to hydrothermal in nature, not unlike those typifying the latter part of the Phanerozoic Eon. Although global tectonic processes continued unabated in the Proterozoic Eon, and a number of major crust-forming orogenies occurred, this extensive period of time appears to have been characterized by longer periods of tectonic quiescence and continental stability. Consequently, deposits reflect hydrothermal and sedimentary ore-forming processes in intracratonic settings or passive margins. Likewise, magmatism is more commonly anorogenic or post-tectonic in nature and is associated with an entirely different suite of metal deposits than those found in arc-related provinces. Global tectonic processes are much better understood in the Phanerozoic Eon and the distribution of continental land masses is well documented in terms of Wilson cycles. Certain deposit types (such as VMS Cu-Zn ores) are preferentially associated with break-up and dispersal stages of the cycle, such as Gondwana in the early Paleozoic and Pangea in the Mesozoic. Other ores (such as SEDEX Pb-Zn and red-bed Cu deposit types) exhibit a complementary association in terms of the Wilson cycle and are linked with peak continental amalgamation and stasis. The biggest concentration of metals on the Earth's surface is, however, linked to subduction along the western margins of Pangea, commencing in the Mesozoic and extending through the Cenozoic Era. The present day Pacific Ocean has been, and still is being, consumed beneath North and South America and has given rise to a large variety of world-class deposit types, of which the porphyry and epithermal ores are the most prolific. The skew in the distribution of these and other deposit types is, however, also related to the enhanced preservation of young ore bodies that have not yet been eroded or consumed at a plate margin. [5, p. 344]

Thought questions

- *Extensional settings and associated ore deposits*
- *Compressional settings and associated ore deposits*
- *What is the trend of metallogeny in time?*

Text No 9. Factors in the evaluation of a potential orebody.

Ore grade. The concentration of a metal in an orebody is called its grade, usually expressed as a percentage or in parts per million (ppm). The process of determining these concentrations is called assaying. Various economic and sometimes political considerations will determine the lowest grade of ore that can be produced from an orebody; this is termed the cut-off grade. In order to delineate the boundaries of an orebody in which the level of mineralization gradually decreases to a background value many samples will have to be collected and assayed. The boundaries thus established are called assay limits. Being entirely economically determined, they may not be marked by any particular geological feature. If the price received for the product increases, then it may be possible to lower the value of the cut-off grade and thus increase the tonnage of the ore reserves; this will have the effect of lowering the overall grade of the orebody, but for the same daily production, it will increase the life of the mine.

Grades vary from orebody to orebody and, clearly, the lower the grade, the greater the tonnage of ore required to provide an economic deposit. [3, p. 16-17]

The grade of an industrial mineral deposit is not always as critical as that for a metal deposit. The important criteria for assessing the usefulness of non-metallic deposits include both chemical and physical properties, and many types of deposit are used *en masse.* This means that deposit homogeneity is important; patches with different properties must either be discarded or blended to form a uniform product. For example, in an aggregate to be used for roadstone the properties that matter are the aggregate crushing, impact and abrasion values (ACV, AIV and AAV), the 10% fines value, the polished stone value (PSV), the size grading possible from the plant, and the petrography of the pebbles. As another example, limestone has a wide variety of uses, depending on such properties as the chemical purity (for making soda ash or sea water magnesia), the colour, grain-size distribution and brightness of a powder (paper and other filler applications) or its oil absorption (putty manufacture).

For a new industrial mineral deposit to be worked at a profit, it is essential firstly that the properties of the material either before or after processing match the specification for intended use, and secondly that there are adequate reserves to meet the expected demand. From many deposits a number of products with different properties can be made; a variety of different markets may therefore be required to achieve the most economical exploitation of the deposit. [3, p. 17]

By-products. In some ores several metals are present and the sale of one may help finance the mining of another. For example, silver and cadmium can be by-products of the mining of lead-zinc ores and uranium is an important by-product of many South African gold ores. Among industrial minerals the recovery of by-product baryte and lead from fluorspar operations can be cited.

Commodity prices. The price of the product to be marketed is a vital factor. The mineral economists of a mining company must try to forecast the future demand for, and hence the price of, the mine product(s), well in advance of mine development.

Mineralogical form. The properties of a mineral govern the ease with which existing technology can extract and refine certain metals and this may affect the cut-off grade. Thus nickel is recovered far more readily from sulphide than from silicate ores, and sulphide ores can be worked down to about 0.5% whereas silicate ores must assay about 1.5% in order to be economic.

Tin may occur in a variety of silicate minerals, such as andradite and axinite, from which it is not recoverable, as well as in its main ore mineral form, cassiterite. Aluminium is of course abundant in many silicate rocks, but normally it must be in the form of hydrated aluminium oxides, the rock called bauxite, for economic recovery. The mineralogical nature of the ore will also place limits on the maximum possible grade of the concentrate. For example, in an ore containing native copper it is theoretically possible to produce a concentrate containing 100% Cu but, if the ore mineral was chalcopyrite ($CuFeS_2$), the principal source of copper, then the best concentrate would contain only 34.5% Cu.

Industrial mineral deposits present different problems. For example, for a silica sand deposit to be utilized for high quality glass making the Fe_2O_3 content should be less than 0.035%. Some brown-looking sands with much more Fe_2O_3 can be upgraded if most of the iron is present as a coating on the grains, which can be removed either by scrubbing or by acid-leaching. If the iron is present as inclusions within the quartz grains then upgrading may be impossible. [3, p. 17-18]

Grain size and shape. The recovery is the percentage of the total metal or industrial mineral contained in the ore that is recovered in the concentrate; a recovery of 90% means that 90% of the metal in the ore is recovered in the concentrate and 10% is lost in the tailings. It might be thought that if one were to grind ores to a sufficiently fine grain size then complete separation of mineral phases might occur and make 100% recovery possible. With present technology this is not the case, as most mineral processing techniques fail in the ultra-fine size range. Small mineral grains and grains finely intergrown with other minerals are difficult or impossible to recover in the processing plant, and recovery may be poor. Recoveries from primary (bedrock) tin deposits are traditionally poor, ranging over 40-80% with an average around 65%, whereas recoveries from copper ores usually lie in the range 80-90%. Sometimes fine grain size and/or complex intergrowths may preclude a mining operation. [3, p. 18]

Undesirable substances. Deleterious substances may be present in both ore and gangue minerals. For example, tennantite ($Cu_{12}As_4S_{13}$) in copper ores can introduce unwanted arsenic and sometimes mercury into copper concentrates. These, like phosphorus in iron concentrates and arsenic in nickel concentrates, will lead to custom smelters imposing financial penalties. The ways in which gangue minerals may lower the value of an ore are very varied. For example, an acid leach is normally used to extract uranium from the crushed ore, but if calcite is present, there will be excessive acid consumption and the less effective alkali leach method may have to be used. Some primary tin deposits contain appreciable amounts of topaz which, because of its hardness, increases the abrasion of crushing and grinding equipment, thus raising the operating costs.

Size and shape of deposits. The size, shape and nature of ore deposits also affects the workable grade. Large, low grade deposits that occur at, or near, the surface can be worked by cheap open pit methods whilst thin tabular vein deposits will necessitate more expensive underground methods of extraction, although generally they can be worked in much smaller volumes so that a relatively small initial capital outlay is required. Although the initial capital outlay for larger deposits may be higher, open pitting, aided by the savings from bulk handling of large daily tonnages of ore (say > 30 kt), has led to a trend towards the large scale mining of low grade ore-bodies. As far as shape is concerned, orebodies of regular shape can generally be mined more cheaply than those of irregular shape particularly when they include barren zones. For an open pit mine the shape and attitude of the orebody will also determine how much waste has to be removed during mining, which is quoted as the waste-to-ore or stripping ratio. The waste will often include not only overburden (waste rock above the orebody) but waste rock around and in the orebody, which has to be cut back to maintain a safe overall slope to the sides of the pit. [3, p. 19-20]

Ore character. A loose unconsolidated beach sand deposit can be mined cheaply by dredging and does not require crushing. Hard compact ore must be drilled, blasted and crushed. In hard-rock mining operations a related aspect is the strength of the country rocks. If these are badly sheared or fractured they will be weak and require roof supports in underground working, and in open pitting a gentler slope to the pit sides will be required, which in turn will affect the waste-to-ore ratio adversely.

Cost of capital. Big mining operations have now reached the stage, thanks to inflation, where they require enormous initial capital investments. For example, to develop the 450+ Mt Cu-U-Au Roxby Downs Project in South Australia, Western Mining Corporation and British Petroleum have estimated that a capital investment of A$ 1200 million will be necessary, and for the 77 Mt Ag-Pb-Zn deposit of Red Dog, in northern Alaska, US$ 300-500 million will be required; grades there are 17% Zn, 5% Pb, 61.7 g/t Ag. This means that the stage has been reached where few companies can afford to develop a mine with their own financial resources. They must borrow the capital from banks and elsewhere, capital which has to be repaid with interest. Thus the revenue from the mining operation must cover the running costs, the payment of taxes, royalties, the repayment of capital plus interest on it, and provide a profit to shareholders who have risked their capital to set up or invest in the company. [3, p. 21]

Location. Geographical factors may determine whether or not an orebody is economically viable. In a remote location there may be no electric power supply, roads, railways, houses, schools, hospitals, etc. All or some of these infrastructural elements will have to be built, the cost of transporting the mine product to its markets may be very high and wages will have to be high to attract skilled workers.

Environmental considerations. New mines bring prosperity to the areas in which they are established but they are bound to have an environmental impact. The new mine at Neves-Corvo in southern Portugal will raise that country's copper output by 93 000% and tin production by 9900%! The total labour force will be about 900. When it is remembered that one mine job creates about three indirect jobs in the community in service and construction industries, the impact clearly is considerable. Impacts of this and even much smaller size have led to conflicts over land use and opposition to the exploitation of mineral deposits by environmentalists, particularly in the more populous of the developed countries.

Pollution hazards owing to heavy metals or acid waters are low or non-existent and atmospheric pollution, caused by the burning of coal or the smelting of metallic ores, is much less serious or absent. The excavations created by industrial mineral operations are often close to conurbations, in which case these holes in the ground may be of great value as landfill sites for city waste. [3, p. 22]

Taxation. Greedy governments may demand so much tax that mining companies cannot make a reasonable profit. On the other hand, some governments have encouraged mineral development with taxation incentives, such as a waiver on tax during the early years of a mining operation.

When a company only operates one mine, then it is particularly true that dividends to shareholders should represent in part a return of capital, for once an orebody is under exploitation it has become a wasting asset and one day there will be no ore, no mine and no further cash flow. The company will be wound up and its shares will have no value. In other words, all mines have a limited life and for this reason should not be taxed in the same manner as other commercial undertakings. When this fact is allowed for in the taxation structure of a country, it can be seen to be an important incentive to investment in mining in that country.

Political factors. Many large mining houses will not now invest in politically unstable countries. Fear of nationalization with perhaps very inadequate or even no compensation is perhaps the main factor. Nations with a history of nationalization generally have poorly developed mining industries. Possible political turmoil, civil strife and currency controls may all combine to increase greatly the financial risks of investing in certain countries. [3, p. 22-23]

Thought questions

- *List the factors used in the evaluation of a potential orebody.*
- *Which problems do industrial mineral deposits present?*
- *What does the term «undesirable substances» mean?*

GLOSSARY

A

abundance – поширеність
accretion – аккреція
accretionary wedge – аккреційний клин
acid-leaching – кислотне вилуговування
andesitic – андезитовий
andradite – андрадит
anorogenic – андрогенний
anorthosite – анортозит
Archean – Архейський період
assay – опробувати, проводити тестування
assaying – опробування
asteroid – астероїд; мала планета
asthenosphere – астеносфера
ataxite – атаксит
aulacogen – авлакоген
axinite – аксиніт
achondrite – ахондрит

B

backarc – задуговий
banded iron-formations – джеспіліти, залізисті кварцити
barren – пустий; той що не містить корисної копалини
bauxite – боксит
bedrock – корінна порода
Benioff zone – зона Беньйофа
binding energy – енергія зв'язку
bulk handling – безтарне перевезення
by-product – супутній продукт

C

calc-alkaline – вапняно-лужний
Caledonian – Каледонська епоха складчастості
Cambrian – Кембрійський період
capital investment – капіталовкладення
capital outlay – капітальні витрати
carbonatite – карбонатит
Carboniferous – Карбоновий період
carbonaceous – вуглець-вміщуючий
catagenesis – катагенез
chain reaction – ланцюгова реакція
chondrite (*meteorite*) – хондрит
chondrules (*meteorite*) – хондри (*sing*. chondrule)
coating – облямівка
collision – колізія, зіткнення
collisional – колізійний
commodity prices – товарні ціни
concentrate – концентрат, продукт збагачення
convection – конвекція, конвективний
convection cell – конвекційна ячейка
convergent – конвергентний, той що сходиться
cosmic background radiation – фонове космічне випромінювання
cosmology – космологія
cost of capital – капітальна вартість
crushing – дроблення
crust – земна кора
crystal face – грань кристалу
cut-off grade – бортовий вміст

D

deleterious – шкідливий
dike swarm – дайковий комплекс
dip – спадати, занурюватися
discontinuity – границя; перерва
divergent – дивергентний, той що розходиться
dividend – дивіденд
dome – купольний
dredging – драгування
drilling – буріння
dyke – дайка, дайковий

E

earthquake – землетрус
en masse (фр.) – разом, у цілому
enstatite – енстатит
epigenetic – епігенетичний
epithermal – епітермальний
exhalative – ексгалятивний
exhumation – ексгумація
extraction – вилучення

F

fault – розлом
faulting – розломна тектоніка
felsic – фельзичний, кислий
fine grain – дрібнозернистий
flood basalts – плато-базальти
fluorspar – плавиковий шпат
fold – складка
folding – складчастість
forearc – перед дуговий
foreland – форланд; передгірський басейн
fossil – викопна рештка
fusion – плавлення

G

gangue mineral – жильний мінерал
geoid – геоїд
Gondwana – Гондвана
graben – грабен
greenstones – зеленокам'яні утворення
grinding – розтирання

H

hardness – твердість
hexahedrite – гексаедрит
hotspot – гаряча крапка (вулканічний прояв)
hypersthenes – гіперстен

I

incentives – засоби заохочення
inflation – швидке розростання (розширення)
interest – процент
intrusion – інтрузія
iron (*meteorite*) – залізистий метеорит
island arc – острівна дуга
isostatic – ізостатичний

K

kamacite – камасит
kimberlite – кімберліт

L

labour force – робітнича сила
lamproite – лампроїт
land use – землекористування
landfill – звалище мусора
late veneer – «піздня оболонка» (зовнішня оболонки землі, що була додана вже після стадії первинної акреції землі)
Laurentia – Лаврентія
LIL (large ion lithophile) elements – літотофільні елементи з великим радіусом іонів
limestone – вапняк
lithosphere – літосфера
lode – рудний поклад
logarithmic scale – логарифмічна шкала (масштаб)

M

mafic – мафічний
magmatic arc – магматична дуга
magnesiowustite – магензіовюстит
manganiferous – марганець вміщуючий
mantle plume – мантійний плюм
mesosiderite – мезосидерит
metamorphism – метаморфізм
Mohorovicic (Moho) discontinuity – границя Мохоровичича (Мохо)
MVT (Mississippi valley type) deposit – стратиформне родовище (типу долини Місисипі)

N

Neoarchean – Неоархей
nuclei – ядра (*sing.* nucleus)
nucleosynthesis – ядерний синтез

O

obduction – обдукція
octahedral – октаедричний
octahedrite – октаедрит
olivine – олівін
open pit – кар'єр
ophiolite – офіоліт
ore grade – сорт руди
orogen – ороген
orogenic – орогенний
orogeny – орогенія
orthopyroxene – ортопіроксен
overburden – вскриша
oxynitride – оксинітрид

P

Paleozoic – Палеозой
pallasite – палласит
Pangea – Пангея
partial melting – часткове плавління, анатексис
pebble – галька, гравій
Permian – Пермський період
perovskite – перовскіт
Phanerozoic – Фанерозой
phosphide – фосфід
planetesimal – планетозималь
plateau – плато
podiform – линзоподібний
pollution – забруднення
porphyry – порфіровий
primordial – первинний
processing – обробка, переробка
processing plant – збагачувальна фабрика
Proterozoic – Протерозойський період
PUM (primitive upper mantle) – примітивна верхня мантія
P-waves – повздовжні (первинні) хвилі

R

pyroxenite – піроксеніт
recovery – вихід корисного компонента
reducing conditions – відновні умови
revenue – дохід
rhyolite – ріоліт
rift valley – рифтова долина
rifted – рифтовий, відокремлений рифтом
road stone – дорожний щебінь
Rodinia – Родинія
roof support – креплення гірської виробки
royalty – арендна плата

S

section – розріз
SEDEX (sedimentary exhalative) – осадово-екгалятивний
sedimentation – осадконакопичення, седиментація
setting – обстановка (геодинамічна)
shareholder – акціонер
sheared – розсланцьований
shock metamorphism – ударний метаморфізм
siderophile – сидерофільний
silicious – кислий; що вміщує кремнезем
singularity – сингулярність
skilled worker – кваліфікований робітник
slab – слеб (плита), що занурюється у зону субдукції
slab avalanche – лавиноподібне занурення слебу
smelter – плавильна піч
soda ash – кальцинована сода
solar nebula – сонячна небула (туманність)
spectra – стектри (*sing.* spectrum)
spinel – шпінель
spreading – спредінг (розтяг)
stellar – зірковий
stone (*meteorite*) – кам'яний метеорит
stony iron (*meteorite*)– залізо-кам'яний метеорит
stratigraphic – стратиграфічний
strike – простягатися, простягання
strike-slip – зі зсувом по простяганню
stripping – вскришні роботи

subatomic – субатомний

subduct – занурюватися, піддаватися субдукції

subduction – субдукція, субдукційний

supercontinent – суперконтинент

supernova – наднова зірка

superplume – суперплюм

S-waves – поперечні хвилі

T

taenite – теніт

tailings – хвости, відходи

taxation – обкладання податком

tensional – той, що піддається розтягу

terrane – террейн

terrestrial – земний

thrust – насув

transform – трансформний

trench – жолоб

triple junction – потрійне зчленування

TTG (tonalite-trondhjemite-granodiorite) – ТТГ (тоналіт-тронд'єміт-гранодіорит)

U

ultrapotassic – ультракалієвий

V

VMS (volcanic massive sulphide) – колчеданні родовища

W

wadsleyite – вадслеїт

wages – заробітня плата

waste – відходи

workable grade – рентабельна сортність руди

X

X-ray – рентгенівський

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