ore deposits. Symbols aim at depicting generalized genetic and morphological information, and the nature of the main metal or mineral (Figure 1.87). Metals are indicated by colour, for example yellow for gold and silver, blue for lead and zinc, red for tin and tungsten, etc. The relative size of deposits is expressed by varying the size of symbols. Usually, boundaries of metallogenetic provinces and districts are shown. Many countries have published national metallogenetic maps. Europe is covered by several sheets of the *Metallogenetic Map of Europe and Neighbouring Countries* (scale 1:1 250 000; Emberger 1984) and by one sheet of the *Mineral Atlas of the World* (scale 1:10 000 000; published by the Commission de la Carte Géologique du Monde, CGMW, Paris, and the Geological Survey of Norway, NGU, Trondhejm 1997 (Juve & Storseth 1977)). Metallogenetic maps and the supporting mineral deposit data banks serve scientific interests, but their main use is practical; they are indispensable for estimates of undiscovered mineral resources and for planning strategic exploration.

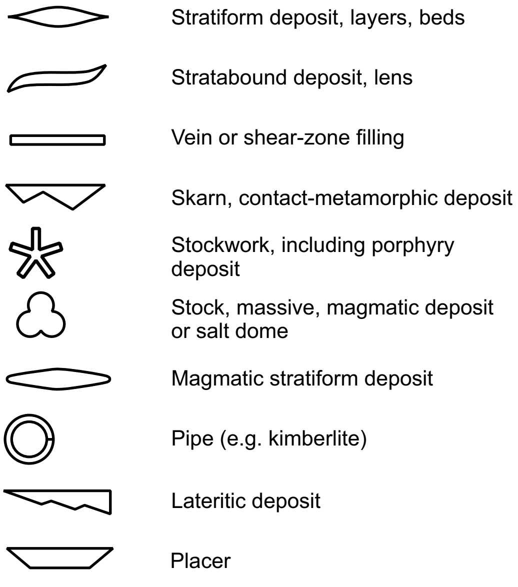

Figure 1.87 Common morphological and genetic symbols for different deposit types on metallogenetic maps.

1.7.2 Metallogeny and plate tectonics

About 60 years ago, the understanding of global tectonics experienced a revolutionary advance (Kearey *et al.* 2009). Until then, the Earth's crust was considered to move either up or down, but rarely in a horizontal direction. The new concept of plate tectonics recognized that the lithosphere is divided into a number of rigid plates, which display considerable lateral movement. The engine of plate tectonics is convective cooling of the mantle. The resulting lithosphere is in part recycled back into the mantle. Extensional and compressional interactions at plate boundaries are the cause of profusely fertile metallogenetic systems.

The Theory of Plate Tectonics was worked out only recently, but its foundations are much older. The similarity of the coastal geometry of South America, Africa and India, and their sharing Permian sediments with the striking *Glossopteris* flora made already Eduard Suess (1831–1914) speculate that continents were not fixed in time and that in the geological past, the three formed a large supercontinent that he called Gondwana (Suess 1885). Building on this, Alfred Wegener developed the hypothesis of continental drift (Wegener 1924) that is in large parts still valid. Modern understanding of plate tectonics led to great progress in many fields of the earth sciences, including metallogeny (Robb 2005, Sawkins 1990b). Several lines of evidence indicate that plate tectonics may have started to operate as early as 4.4 Ga when a stiff lithosphere had been established (Moyen *et al.* 2006, Furnes *et al.* 2007). Already in the Archaean, ore deposits are known that suggest a suprasubduction zone setting.

Main elements of plate tectonic process systems that are **"metallogenetic factories"** include:

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

Rifts originate by extensional deformation of lithospheric plates and may or may not evolve into a new plate boundary. Very often, rifting causes thinning of the crust, upflow of hot mantle and updoming of rift shoulders (Tackley 2000). Volcanic activity within the rifts is a frequent consequence, often organized into large volcanic centres ("hot spots": Foulger & Natland 2003). Hot spots can be the origin of three diverging rifts (triple junction). Two of the three rift arms may widen to form a new ocean, whereas the third remains inactive and is called a failed rift arm. Several failed rift arms display thick sediments with bimodal volcanic rock suites, which were later folded by horizontal shortening. Considerable intrusive activity may occur. Settings like this have been called aulacogens (Eriksson & Chuck 1985).

Sediments of continental rifts include early, mainly terrestrial, alluvial clastic infill that can contain uranium, placers and coal deposits. In many cases, a freshwater, saline or marine-influenced lake stage succeeds with beds of salt, gypsum, magnesite, phosphate, valuable clays or oil shale. Full marine ingression into the widening rift and inception of oceanic spreading can induce submarine metalliferous exhalation of the black smoker or brine pool type (Red Sea) and the deposition of thick marine sedimentary sequences. Later, as diagenesis is enforced by rising temperature and pressure, oil and natural gas deposits are generated.

Hot spot-related ore-forming systems include the Bushveld in South Africa, tin-fertile A-granites in Nigeria and worldwide, many alkali-carbonatite igneous complexes. When rifting reaches the stage of a deep graben with vertical displacement at marginal faults approaching kilometres (Scholz & Contreras 1998), hydrothermal convection systems may form, based on the permeable tensional structures, the heat contrast and the hydraulic head imposed by rift shoulder mountains. The ascending branch of these hydrothermal systems typically results in deposits of lead, zinc, silver, manganese, fluorine and barite, which take the form of veins and metasomatic replacement bodies in rift margin rocks, or of ore beds in the graben sediments. Good examples are many Pb-Zn and Mn occurrences in Tertiary sediments on both sides of the Red Sea, and part of the Ag-Pb-Zn-F-Ba veins along the Rhine graben in France and Germany (Figure 1.28). Carbonatites and alkali intrusions with apatite, fluorine, niobium and rare earth element ores characterize the Cretaceous-Tertiary rifts in Eastern and Central Africa. Submarine, epicontinental rifts and half-grabens are related to base metal deposits of the sedex type.

Sullivan in British Columbia, Canada (base metals in the Neoproterozoic Alberta Rift), Mt Isa in Queensland, Australia (Pb-Zn-Cu in the early Mesoproterozoic) and the large deposits of native copper in basalts and of chalcocite in fine sands of the Nonesuch Shale in the Keweenawan Rift (USA, Late Mesoproterozoic) were proposed as remarkable examples of mineralization in aulacogens. The Panafrican Damara Orogen in southern Africa has also been interpreted as an aulacogen, although with exceptionally strong tectonic shortening. Its main mineralizations are late to post-tectonic, including the giant hydrothermal karst pipe Tsumeb with polymetallic ores of Pb, Zn, Cu, Cd and Ge (Chetti & Frimmel 2000), and the uranium-deposit Rössing in alaskitic granite.

Intracontinental basins with prominent ore provinces include the European Copper Shale (Mesozoic), Witwatersrand gold (Late Archaean) and Mississippi Valley type lead-zinc-barite-fluorite deposits (Palaeozoic) in North America.

Major plate reorganizations affect both continental and oceanic systems intensely (Whittaker *et al.* 2007). Within short periods of a few million years, new subduction zones are installed, vectors of plate drift change (wander paths form "loops") and the plates are subjected to new stress fields. Oceanic and continental crust is stretched or sheared, new mantle regions experience partial melting, resulting in magma underplating, the formation of hotspots and the rise of mantle volatiles. Flood basalt volcanism may be a consequence, producing giant Cu-Ni-PGE deposits such as Noril'sk, as well as climate change and global extinction of life due to huge emissions of sulphur and chlorine such as those of the Dekkan traps at the end of the Cretaceous (Self *et al.* 2008). Enhanced heat flow and elevated permeability of the crust are favourable factors for the formation of deep convective hydrothermal systems and of mineral deposits. Mantle volatiles (mainly water and CO_2, with solutes like fluorine, arsenic, etc.) may rise, leach metals, mix with crustal fluids and form ore deposits. Examples of mineralization caused by plate reorganization include the hydrothermal "Saxonian Mineralization" of Europe north of the Alps (Walther 1983), several kimberlite provinces and unconformity uranium ore deposits in Canada and Australia.

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

The opening of new oceans passes from a high heat-flow rift stage into a marine transgression and thermal contraction phase. Relatively shallow, epicontinental seas may form. As the young ocean widens, passive continental margins develop. Sediments include salt, phosphate and hydrocarbon source rocks. Manganese ore beds of the Tertiary Black Sea province, Quaternary metalliferous marine placers and Palaeoproterozoic banded iron ores of the Superior type represent typical marine epicontinental shelf ore deposits.

The separation of continents by rifting and seafloor spreading may cut across older orogenic belts, cratons and other crustal-scale structures. With them, older ore provinces are ruptured and the fragments can be found on remote coasts across an ocean (e.g. the Atlantic borderlands of Africa and South America). In these cases, metallogenetic knowledge acquired on one coast is a valuable tool for work in its twin across the seas.

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

This is the domain of ore formation at mid-ocean ridges that was presented earlier in more detail (Section 1.1 "Ore Deposits at Mid-Ocean Ridges and in Ophiolites"). After obduction, the products of these processes are ophiolite-hosted deposits. Many ophiolites, however, were not formed at mid-ocean rifts but in tensional supra-subduction settings including back-arc spreading systems, or rifts of primitive island arcs (e.g. the Cyprus ophiolite). Yet, there is no doubt that all mid-ocean rifts display segments of hydrothermal activity, including black smokers. Related ores are sulphide mounds or mud-pools in a proximate position, iron-manganese oxides (ochres and numbers) and distal manganese crusts and nodules with important contents of Cu, Ni and Co. Oceanic transform faults that offset ridges are apparently not metallotects for mid-ocean metallogenesis.

Subduction of lithospheric plates at convergent ("destructive") plate boundaries

Subduction recycles oceanic lithosphere back into the mantle (Figure 1.88). The trace of subduction on the seafloor is marked by deep oceanic trenches. Volcanic arcs develop on the overriding plate. Between trench and arc, four structural zones are typically developed: Nearest to the

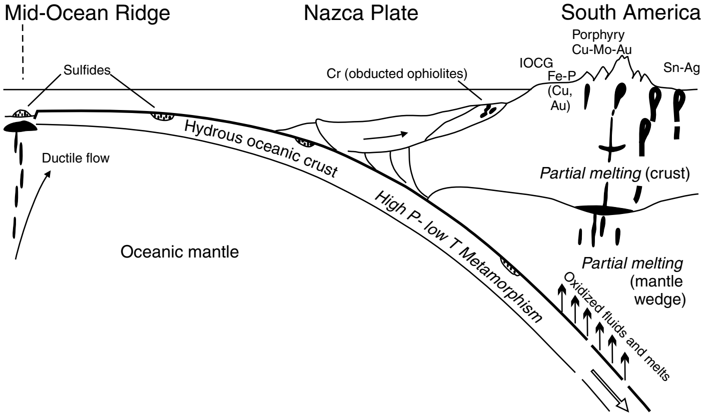

Figure 1.88 Metallogeny of active continental margins with the typical zonation, here illustrated by a schematic profile from the subducting Pacific Nazca Plate through the Central Andes (South America). Adapted from Sillitoe (1972, 2008).

trench (1) an accretionary complex of low-grade metamorphic sediments is followed by (2) a wedge of mainly continental crust with minor oceanic and hydrated mantle material of medium to high-pressure metamorphic grade. This is overlain by (3) a mega-scale melange composed of high-pressure and ultrahigh-pressure oceanic and continental crust fragments that are extruded from the subduction channel. Finally follows (4) the frontal part of the upper plate that carries the volcanic arc. Volcanic arcs in dominantly oceanic settings form island arcs, whereas active continental margins display continental or Cordilleran arcs. Recent primitive island arcs are geologically young (Tonga, Scotia), because maturation sets in quickly and produces arcs with a partially continental character (Japan, Kurile Islands). Other island arcs pass into continental collision belts (Sumatra-Malaysia-Himalaya). Andean volcanic arcs build upon older, strong upper crust that is largely of Precambrian age in both Americas. Behind the magmatic arcs appear back-arc spreading systems that include the back arc basins of island arcs, the continental "molasse" basins and broad distended regions such as the Basin and Range Province of North America.

There is a great diversity of subduction zone configurations, due to many variables including slab density, thickness and length (Schellart *et al*. 2007). Subduction zones show variously high or low trenchward plate velocities, trench retreat (or more rarely trench advance) velocities, slab dip angles and so forth. Trench retreat ("subduction rollback") is caused by the negative buoyancy of the cold, dense descending slab. This places the overriding lithosphere into a state of tension as the subduction zone moves oceanwards and facilitates movement of magmas and fluids (Hamilton 1995). Slab rollback, slab breakoff and delamination of mantle lithosphere allow asthenospheric upwelling that can provide the heat pulses required for ore forming processes, including magmatism and regional hydrothermal fluid systems. Extensive intracontinental compressional deformation migrating cratonwards is explained by flat-slab subduction. This is probably caused by the subduction of oceanic plateaus and plume tracks (Livaccari *et al*. 1981), which typically ends in delamination (foundering) of the slab from the continental lithosphere. This is the environment of Basin-and-Range type tectonic and magmatic provinces (e.g. in Mesozoic South China: Li & Li 2007). Fertile anorogenic magmatism including alkaline basalts, bimodal volcanic rocks and I- and A-type granitoids are characteristic for this setting.

It is important to stress that most of the Earth's richest ore provinces are found above subduction zones. This is conspicuously so along the margins of the Pacific Ocean, which are largely formed by long-lived destructive plate boundaries. Associated are numerous active volcanoes, accounting for the term "ring of fire". Reconstruction of similar settings for stages in the geological past is crucial for strategic exploration planning (Haeberlin *et al*. 2003, Figure 1.84).

Island arc ore deposits may be either allochthonous, which implies tectonic transport, for example of slivers of oceanic lithosphere, or autochthonous, formed within the arc. Allochthonous are first of all the ophiolite-related ores, including chromite (Cuba, Luzon) and platinum placers; Cyprus type sulphide deposits are infrequent. Lateritic nickel ore deposits (New Caledonia) are autochthonous formations. Major autochthonous deposits are associated with the large mass of calc-alkaline to potassic intrusive and volcanic rocks. Of outstanding economic prominence are porphyry and skarn copper-gold deposits, epithermal gold deposits and volcanogenic massive sulphides. Similar to continental margin arcs, sources of the metals may be subducted oceanic crust or the mantle wedge above the subduction zone. The latter was confirmed for Lihir, Papua New Guinea (McInnes *et al*. 1999), which is a giant epithermal gold deposit of very recent geological age (ca. 690 ka). It is significant that some metals such as tin and mercury appear only in older, more complex island arcs with a partially continental character.

Active continental margin ore deposits are often more clearly zoned compared with island arcs, as a function of increasing distance from the subduction zone. In the apparently simple geotectonic setting of Central South America, the results are long and narrow ore provinces (Sillitoe 1972).

Prominent along the western coast within Precambrian basement and Cretaceous plutons are iron-apatite and iron oxide-copper-gold (IOCG) deposits associated with hydrous intermediate magmatism (Sillitoe 2003, Oyarzun *et al.* 2003). A belt of giant porphyry Cu-Mo-Au deposits follows towards the east, roughly along the Neogene-Recent volcanic arc. These mines currently dominate world copper production. Near the eastern margin of the Cordillera, a Sn-Ag belt is developed (Figure 1.88). However, neither this zonation nor all deposits in single belts are synchronous, but are the product of several regional metallogenetic episodes that range from Late Triassic (earliest tin deposits) to Cretaceous (iron and part of copper) and Tertiary ages (most of the copper and tin-silver). Subduction configurations during this time changed considerably (James & Sacks 1999).

The structure of the North American Cordillera is even more complex. One example is the subducting East Pacific Ridge, which is a factor that enhances metallogenetic processes. Partial melting of young, hot subducting oceanic plates favours the formation of oxidized adakitic magmas and of important gold and copper-gold deposits (Cooke *et al.* 2005, Mungall 2002). South Alaskan gold deposits are thought to be related to ridge subduction (Haeussler *et al.* 1995). Another difference is the collage-like nature of the North American Cordillera that consists of many "suspect" or "exotic" terranes, which preserved distinct but interrelated geological records (Colpron & Nelson 2006). This complicates metallogenetic interpretation.

Ore deposit formation above subduction zones is causally tied to the fate of the subducting lithospheric slab of oceanic crust and mantle. At mid-ocean ridges, the crust is largely hydrated and oxidized. When the oceanic slab bends before entering the subduction zone, additional hydration appears to take place (Faccenda *et al.* 2009). Altered basalts, gabbros and depleted mantle peridotites enter the subduction zone as a "cold" slab at geothermal gradients of 15°C/km or less. Along the subduction plane, continental material can be scraped off ("subduction erosion") and taken down to the zone of dehydration and melting. The high-pressure/low-temperature metamorphism of subduction zones converts the rocks to the typical blueschist and eclogite lithologies. Mantle rocks, oceanic crust and its sedimentary cover incur devolatilization and possibly, partial anatexis. Dehydration processes control the structure of slabs from ca. 40 to 150 km depth (Rondenay *et al.* 2008). As a function of T and P, hydrous fluids, anatectic melts or supercritical liquids may be set free (Kessel *et al.* 2005). The latter are characterized by high trace element solubilities and consist of H_2O, Cl, S, CO_2, etc., including large ion lithophile elements (LILE: Ba, K, Rb, Cs, Ca, Sr) and other incompatible elements (U and Pb). This transfer "metasomatizes" the mantle wedge above the subduction zone and triggers widespread melting. Because of relatively high fO_2 (roughly from fayalite-magnetite-quartz [FMQ] to FMQ + 2) sulphide (S_{2^-}) and sulphate (S_{6^+}) coexist and combine to high total sulphur contents in melts, which favours sulphur saturation and mineralization in the upper crust (Jugo 2009). Extensive formation of sulphide melt during metasomatism and partial melting of the hot mantle wedge would be detrimental, because sulphide melts scavenge chalcophile and siderophile elements such as copper and gold from silicate melt and being heavy, tend to remain trapped in the deep crust (Mungall 2002).

Magma batches rising through the crust continue to change by complex assimilation and contamination processes, until they reach the surface as calc-alkaline melts of andesitic-dioritic nature. These magmas have only ~50% material from the mantle, the other half is derived from the crust. Intrusive and extrusive activity of continental arcs is concentrated in short pulses of 10–15 My ("flare-ups") that occur during and after tectonic shortening (Ducea & Barton 2007). Porphyry copper-molybdenum-gold deposits are direct products of these processes within and above the subduction zone (Richards 2003, 2009). Among many other arguments, this can be substantiated by the observation that localization and metal contents of porphyries are largely independent of their specific setting (e.g. primitive or evolved island arcs, diverse types of active margins). The precise source of the chalcophile metals and gold – oceanic crust or mantle wedge – remains obscure (Dreher *et al.* 2005). A continental source, however, is implied for the metals tin, tungsten and tantalum, because deposits appear only in regions with thick and old crust.

Continental collision

Oceans that were consumed by subduction leave a suture in the newly welded continent, which is marked by ophiolites. One of the most remarkable and metal-endowed sutures worldwide is the Palaeozoic accretionary orogenic collage of the Altaids in Central Asia, with a length of 3000 km (Xiao *et al*. 2009). Usually, continental collision results in the subduction of continental crust (Ampferer or A-subduction), although this is limited by the buoyancy of crustal rocks. The process results in thickened crust below collisional belts and the formation of anatectic S-type granitoid melts. Less frequent are post-subduction Cu-Au porphyries and related epithermal gold deposits, which are formed where former magmatic arcs are involved in the collision (Richards 2009). Continental crust of the lower plate can be subducted to depths of more than 100 km and exhumed after ultrahigh-pressure metamorphism. Also, collision causes giant systems of hydrothermal fluid flow involving metamorphic, basinal and meteoric fluids (Mark *et al*. 2007, Craw *et al*. 2002, Oliver 1986). Similar features are reported from intracontinental mountain belts involving very narrow oceans (Alps, European Variscan Belt) and from purely intracontinental orogens (Kibarides in Central Africa: Pohl 1994). Typically, collisional orogens exhibit: i) granitoid-related deposits of tin, tungsten, gold and rare metals; and ii) deposits formed by migrating metamorphic fluids. Gold is especially common in this setting (orogenic gold deposits: Groves *et al*. 2003). Mineralization in orogenic belts is favoured by phases of extension, because melts and fluids can more easily rise to shallow depths. Extension may be related to orogenic collapse and other post-collisional processes.

Assemblage and break-up of supercontinents

The plate-tectonic evolution of the Earth's crust follows not only the relatively short Wilson cycles (opening and closure of oceans) but also a trend of large-scale cycles of amalgamation of all continental plates into supercontinents and the following break-up. The Phanerozoic supercontinent Pangaea is well-known, existing from the Permian into the Jurassic (~300–175 Ma). Mesoproterozoic Rodinia (~1100–800 Ma) is generally accepted but its assemblage is more contentious because data are insufficient for a unique solution (Torsvik 2003). Older supercontinents are even less well-defined. Supercontinents can be related to specific characteristics of the metallogenetic evolution, including the incidence of anorogenic ore formation (e.g. titaniferous anorthosite-ferrodiorite complexes) and the prevalence of continental, sediment-hosted deposits (Kupferschiefer: Robb 2005). When Gondwana and Laurasia finally fused into the supercontinent Pangaea, the Variscan belt in Europe experienced a short-lived metallogenetic peak of unique fertility. Deep processes inducing initial crustal distension and break-up of Pangaea, at about the Triassic/Jurassic boundary, again produced an ore-forming heat and fluid pulse across much of Europe (Box 1.14).

Apart from the relatively simple plate tectonic model situations described above, many quite complex interaction fields are known today. One recent example is the Gulf of California, where a subducted oceanic ridge passes along strike into a continental rift and ultimately into an intra-continental transform structure (San Andreas Fault). Only rarely, connections such as these can be reconstructed for the geological past so that the precise plate-tectonic setting of some ore deposits may never be fully understood. Yet, the quest for solving a given plate-tectonic puzzle is always scientifically fascinating and results benefit applications of economic geology.

1.8 GENETIC CLASSIFICATION OF ORE AND MINERAL DEPOSITS

> *We can get so wrapped up in debating terms that we forget entirely about the subjects of our original interest: minerals, rocks, geology, and such…*
>
> Stephen A. Langford in *GSA Today*,
> February 2002