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GR Focus Review

A classification of mineral systems, overviews of plate tectonic margins and examples of ore deposits associated with convergent margins

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A R T I C L E I N F O

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A B S T R A C T

In this contribution I presents definitions of mineral systems, followed by a proposed classification of mineral deposits. The concept of mineral systems has been tackled by various authors within the framework of genetic models with the aim of improving the targeting of new deposits in green field areas. A mineral system has to be considered taking into account, by and large, space-time patterns or trends of mineralisation at the regional scale, their tectonic controls and related metallogenic belts. This leads to a suggested classification of mineral systems, together with a summary of previous ideas on what is, without doubt, a kind of "mine field", because if a classification is based on genetic processes, these can be extremely complex due to the fact that ore genesis usually involves a number of interactive processes. The classification presented is based on magmatic, magmatic-hydrothermal, sedimentary-hydrothermal, non-magmatic, and mechanical-residual processes.

An overview of plate tectonics (convergent and divergent margins) is discussed next. Convergent plate margins are characterised by a tectonic plate subducting beneath a lower density plate. Convergent plate margins have landward of a deep trench, a subduction–accretion complex, a magmatic arc and a foreland thrust belt. An important feature is the subduction angle: a steep angle of descent, is exemplified by the Mariana, or Tonga–Kermadec subduction systems, conducive to porphyry-high-sulphidation epithermal systems, whereas in an intra-arc rift systems with spreading centres is conducive to the generation of massive sulphide deposits of kuroko affinity. A shallower subduction zone is the domain of large porphyry Cu–Mo and epithermal deposits. The implications of this difference in terms of metallogenesis are extremely important. Continent–continent, arc–continent, arc–arc, amalgamation of drifting microcontinents, and oceanic collision events are considered to be a major factor in uplift, the inception of fold-and-thrust belts and high P metamorphism. Examples are the Alpine–Himalayan orogenic belt formed by the closure of the Tethys oceanic basins and the great Central Asian Orogenic Belt (CAOB), a giant accretionary collage of island arcs and continental fragments. The closing of oceanic basins, and the accretion of allochthonous terranes, result in the emplacement of ophiolites by the obduction process. Divergent plates include mid-ocean ridges, passive margins and various forms of continental rifting. At mid-ocean spreading centres, magma chambers are just below the spreading centre. Once the oceanic crust moves away from the ridge it is either consumed in a subduction zone, or it may be accreted to continental margins, or island arcs. Spreading centres also form in back arc marginal basins. Transform settings include transtensional with a component of tension due to oblique divergence, transform or strike–slip sensu stricto and transpressive with a component of compression due to oblique convergence. Strike–slip faults that form during extensional processes lead to the formation of pull-apart basins.

Mineral systems that form at convergent margins, the topic of this special issue, are succinctly introduced in Tables 1 to 7, as follows: principal geological features of selected mineral systems at convergent plate margins and back-arcs (Table 1); their recognition criteria (Table 2); principal geological features of selected ore deposits of back-arc basins and post-subduction rifting (Table 3) and of subduction-related magmatic arcs (Table 4), their respective recognition criteria (Table 5); accretionary and collisional tectonics and associated mineral systems (Table 6); principal geological features and associated mineral systems of transform faults (Table 7).

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1. Introduction

In this contribution, I will firstly attempt to define the concept of a mineral system then I suggest a classification of mineral systems, following which I will look at what is generally understood in the present context for convergent, transform and divergent plate margins; followed in turn by a rather systematised succinct overview of ore deposits that are formed or are associated with convergent plate margins. This overview is presented as a series of tables, in which the principal geological characteristics for the mineral deposit(s) in question are provided. Where applicable, these tables are complemented by a table giving some of the key recognition criteria (mineralogical, geochemical, alteration patterns, etc.).

2. Mineral systems

What is a mineral system? All geological and geodynamic factors at all scales that control the inception, evolution and preservation of mineral deposits, including:

- Local studies of known deposits
- Tectonic controls
- Space-time distribution
- Physico-chemical processes
- Evolution of fluids, magmas and other energy sources
- Regional context.

Alternatively a mineral system can be defined by its constituent elements (Hoatson et al., 2011):

- Energy source(s)
- Source(s) of fluids, metals and ligands
- Pathways along which fluids or melts move
- Chemical and/or physical traps
- Discharge of residual fluids
- Preservation.

The mineral system concept has been successfully used to understand and develop genetic models and also for quantitative risk analysis in mineral exploration (Wyborn et al., 1994; Hoatson et al., 2011; McCuaig and Hronsky, 2014). Similarly, we need to define what a metallogenic belt is. Metallogenic belts are characterised by a narrow age of formation, and include districts, deposits, and occurrences. More specifically (Cunningham et al., 2007):

1) Planetary-scale deposit-hosting province or planetary-scale metallogenic belt ($\geq 1000 \times 10^3$ km^2);
2) metallogenic belt (150 to 1000×10^3 km^2);
3) metallogenic system (40 to 150×10^3 km^2);
4) metallogenic province (20 to 40×10^3 km^2);
5) metallogenic subprovince (2 to 20 by 10^3 km^2);
6) ore district (0.4 to 2.0×10^3 km^2); and
7) ore cluster (concentration of deposits of similar nature over an area of about 100 km^2)

Some other important definitions are:

Ore deposit: sufficient tonnage and grade to be exploited at a profit

Mineral deposit: denotes an incompletely evaluated or sub-economic occurrence

Mineral occurrence: anomalous concentration of ore minerals

Prospect: exploration activity that has found an anomalous concentration of metals

Operating/abandoned mine: workings that are operating or on care and maintenance basis.

3. Classifications of mineral systems and models

Here, I present a classification of mineral systems that are known to form and/or occur at convergent and divergent plate margins, largely taken from Pirajno (1992, 2009 and references therein) and in the citations herein provided. Although this proposed classification is far from being comprehensive, I believe it does provide some "food for thought".

The systematic classification of ore deposits is inherently fraught with many difficulties. These stem from a large number of variables (lithological, structural, chemical and tectonic), all of which interact to make the observed data difficult to interpret. The recently recognised role of meteorite mega-impacts (e.g. Sudbury Igneous Complex in Canada) as an important geological process (Glikson, 2014) adds to an already complex scenario. Any classification scheme has to take into account that ore deposits are formed by one or more of three fundamental processes, namely: magmatic, hydrothermal, mechanical and residual, with the first two commonly interacting. Each can be further subdivided as follows:

- Magmatic

  - Layered intrusions; Cr, PGE, Fe–Ti–V, Ni–Cu
  - Alaskan zoned intrusions, PGE
  - Mafic lavas; Ni–Cu
  - Sill complexes; PGE, Ni–Cu
  - Dykes; PGE, Ni–Cu
  - Pegmatite; REE-Be–U–Li–Cs–Ta; REE-Li–Nb–Y–F, U

- Magmatic-hydrothermal

  - Porphyry; Cu, Cu–Mo, Mo–W
  - Epithermal; Au–Ag, Bi, Cu, Pb, Zn, Ba
  - Skarns; Cu, Mo, W, Pb, Zn, Fe, Sn
  - Kiruna style: Fe–P (apatite)
  - Intrusion-related; Sn–W, Au–Ag, Mo–W
  - VHMS (Volcanic hosted massive sulphides), Kuroko and Besshi types; Cu–Pb–Zn–Au, Ba
  - Sea-floor smokers at spreading centres and island arcs; Cu–Pb–Zn–Au, Ba
  - Alkaline complexes, greisens; Sn–W, Bi, U, REE, Li–Nb–Y–F
  - Carbonatites; REE, U, Ta, Th
  - Polymetallic vein deposits Ag–Sb, Sn–Ag, Ba, Hg
  - Iron oxide copper gold U and REE (IOCG); Olympic Dam style
  - Chilean manto-type Cu–Ag

Table 1
Convergent plate margins and back arc-related rifts; principal geological features of selected mineral systems.

Mineral system	Geological features
Felsic intrusive-centred F, U, Hg, Sn (NE Mexico, Rio Grande USA; Altai-Mongolia) ➔ (Price, et al. 1990; Pavlova et al., 2004)	• Igneous rocks are alkali-rich, high silica intrusives or extrusives; may contain topaz. • Sn in fissure veins. • Fluorite, U, Hg as disseminations in alkaline intrusives and/or rhyolitic volcanics (Fig. 7)
Volcanogenic Massive Sulphide (VMS) Kuroko-style Cu, Pb, Zn, Ag ± Au U (Kuroko, Japan, Buchans, Canada) ➔ (Ohmoto, 1996; Franklin et al., 2005)	• Polymetallic conformable lenses of massive sulphide, hosted by felsic volcanics. • Deposits form in clusters, with a common volcanic centre, commonly aligned along faults. Possible relationship with collapsed submarine calderas. • Sub-classified into stockwork, gypsum, barite and Au-pyrite deposits, but all have similar features. • The ore bodies are typically oval shaped, grade down into stockwork ore. Usually mantled by thin beds or small lenses of ferruginous and/or banded chert, with lenticular/irregular barite, gypsum and/or anhydrite usually present • Derived from venting of fluids at volcano-/seafloor interface. Stockwork mineralisation formed epigenetically from hydrothermal fluids moving through brecciated lava domes and tuffs.
Massive sulphides Caledonide-type Pb–Zn (Lokken, Scandinavia ➔ (Grenne and Slack, 2003)	• Deposits within strongly deformed allochthonous sheets composed of primarily metavolcanics and metasediments (Ordovician). • Have rear-arc, marginal basin affinities. The ore bodies are associated with basaltic rocks, with only a small felsic component
Volcanogenic Massive Sulphides Cu, Zn, ± Pb, Ag (Noranda/Abitibi-type, Canada) ➔ (Ayer et al., 2008)	• Distinct spatial association with felsic volcanics. Most ore bodies are close to small domes of massive rhyolite. There appears to have been contemporary faulting and the sealing of hydrothermal convective systems prior to exhalative events. Ore is derived from submarine venting of fluids during lull(s) in explosive volcanism. Such a break is indicated by the occurrence of ore bodies at horizons marked by tuff and banded chert layers. • The deposits are underlain by alteration pipes (controlled by syn-volcanic fractures) and stringer copper zones (feeders) (Fig. 8)
Stratabound W (scheelite) W, Au, Sb, Hg, Mo, Be (Eastern European Alps. E.g. Felbertal) ➔ (Höll, 1977; Thälhammer et al., 1989)	• Genetically, temporally and spatially related to submarine mafic and felsic volcanic rocks. • Common in Europe, time-bound character in relation to metavolcanic rocks. Ordovician to Silurian age. Also have been found associated with mafic metavolcanics in Archaean greenstone belts and modern geothermal systems. • Derived largely from volcano-sedimentary processes (i.e. sedimentary textures well preserved). Hosted mostly in pelitic, carbonate, calc-silicate sediments with mafic volcanics/quartz-tourmaline rocks in attendance. These are generally in a volcanic–chert–carbonate–ferrigenous sequence in rift-trough- type environment. • Geochemically enriched in F, base metals, Mo, Be, calc-silicates and chert horizons.

Table 2
Convergent plate margins and back arc-related rifts: Recognition criteria for selected mineral systems (based on the references cited in Table 1).

Mineral system	Geology/alteration	Geochemistry
Volcanogenic Massive Sulphide (VMS) Kuroko-style polymetallic	Spatial relationship with felsic submarine volcanism. Clusters of deposits, along faults, lava flows, and/or in collapsed calderas Fe-chert mantle ore. Stockworks occurs beneath stratiform ores. Distinctive alteration − core of qtz-sericite; then sericite, montmorillonite, chlorite; sericite, albite, K-feldspar and qtz zone; montmor-zeolite and cristobalite	Enriched, Cu, Pb, Zn, Ag ± Au, U. Alteration haloes enriched K and Mg, depleted Na. Enriched in K, Mg − slightly depleted in Na.
Stratabound scheelite	Temporally + spatially related to submarine mafic and felsic volcanics. Hosted in turbiditic sequences.	Enrichment in W, Au, Sb, Hg, Be, Mo, F, B.

- Sedimentary-hydrothermal
  - Sedimentary exhalative (SEDEX); Cu, Pb, Zn, Ba
  - Copperbelt and Kupperschiefer types; Cu–Co
  - Metalliferous sediments; Red Sea brines; Cu–Pb–Zn, Ba, Fe–Mn; exhalative (hot springs in crater lakes); Fe–Mn–Co-REE in nodules in seafloor
  - Mississippi valley type (MVT) Zn–Pb–Cu
  - Iron formations (banded IF, granular IF) and Mn oxides

- Amagmatic/metamorphogenic/uncertain origin
  - Shear-zone hosted quartz lodes (orogenic); Au–Te
  - Black shales; Mo, PGE, Ni, U
  - High-heat producing granites
  - Unconformity-related and sandstone-hosted U (±Ni–Co–As)
  - Witwatersrand Au–U (placer-hydrothermal model)
  - Carlin-type Au
  - Meteorite impact structures; diamonds

- Mechanical/residual/weathering/regolith
  - Laterites (Au, Ni)
  - Calcrete (U, Au)
  - Placers (Au, PGE, diamonds)
  - Non-sulphide (Pb, Zn)

If geological processes are used to classify ore deposits, they necessarily rely heavily on genetic factors; however, ore genesis can be extremely complex because it usually involves a number of interactive processes. Genetic classifications lend themselves to misinterpretations. In fact, variations within the same class of ore deposits can be extreme. For instance, the "*extended family*" of Cu–Au–U-REE-Fe (IOCG) deposits includes Olympic Dam (South Australia), the Fe deposits of the Kiruna district (Sweden), Fe-REE deposits of Box Bixby and Pea Ridge (Missouri, USA) and possibly the REE-rich Bayan Obo (Inner Mongolia, China), the Palabora carbonatite-hosted Cu and the Vergenoug Fe–F deposit (South Africa). When examined in detail all of these deposits are remarkably different. Nevertheless, they all have a common theme: anorogenic mafic to alkaline magmatism in rift settings, with many, but not all, of Proterozoic age.

The alternative is to use a non-genetic classification scheme. This can be done by using host rocks and/or geological environments. However,

Table 3
Convergent plate margins: Principal geological features of selected ore deposits associated with back arc-basin; post-subduction rifting.

Mineral system	Geological features
Contact metasomatic Zn, Pb, Ag ± Cu (Northern Mexico) → (Megaw et al., 1988)	• This mineralisation is commonly related to isolated stocks intrusive into back-arc tectonic settings. The stocks range in composition from diorite to granite but are most commonly granodiorite or quartz monzonite. • The mineralisation typically forms as replacement bodies within carbonate-stable platform environments. • There are a wide variety of orebody geometries — from flat lying to manto-type, chimneys or pipes. • Alteration patterns are complex, and are typified by skarn-like assemblages (Ca–Fe–Mg–Mn silicates). • Ores are usually massive, with abundant Fe deposited as pyrite.
Polymetallic Vein Systems Ag–Pb–Zn–Cu (Peruvian Andes) → (Baumgartner et al., 2008; Witt et al., 2013)	• Develop in non-carbonate host-rocks, associated with similar plutonism as contact metasomatic deposits (above), and can be found intermixed with these ore types as well. Regional metal zonation may be apparent, with distal Ag-rich veins merging into veins typical of epithermal types nearer the intrusive source. Notably only minor Au.
Chilean manto-type Cu–Ag → (Wilson et al., 2003)	• Stratabound, epigenetic, associated with hydrocarbons and bacterial sulphate reduction; typically found in the Coastal Range (Chile), extensional back-arc basins. Framboidal pyrite is common

here too there are problems. For example, Ni and Cu deposits hosted in layered mafic–ultramafic rocks in the interior of cratons, comprise such a great variety of types and styles, ranging from primary magmatic to hydrothermal (e.g. González-Álvarez et al., 2013). Another possibility is to consider ore deposits on a combination of descriptive features, such as host rocks and dominant economic metal(s), and genetic features, such as mechanism of fluid movement, temperature of formation, alteration and extent, if any, of magmatic involvement. Some students of ore deposits adopt a descriptive classification based upon the dominant economic metals and then modify individual categories based upon compositional, tectonic, or genetic variations. An example is the classification of porphyry deposits into porphyry copper–gold, porphyry copper–molybdenum, and porphyry tin types.

In reality, none of the above schemes (genetic, non-genetic or mixed genetic–non-genetic) are adequate because they are open to all sorts of debates.

Holistic studies of ore deposits and their classification can be divided into two groups: studies done before plate-tectonics was recognised as a global geological process, and those done afterwards. In the former are the works of Lindgren (1933), Bateman (1967), Stanton (1972), Smirnov (1976) and Jensen and Bateman (1979). To the second group belong Mitchell and Garson (1981), Hutchinson (1983), Sawkins (1990), Guilbert and Park (1985), Robb (2005).

Lindgren's (1933) classification of ore deposits remains a landmark achievement. For example, his ideas of epithermal, hypothermal and telethermal are still valid concepts today. Stanton (1972) although focussing on ore petrology, which is the title of his book, did provide a useful classification by considering ore deposits in terms of lithological associations, as detailed below:

- Ores of mafic–ultramafic association
- Ores of felsic association
- Iron and manganese concentrations of sedimentary affiliation
- Stratiform sulphides of marine and volcanic association
- Stratabound ores of sedimentary affiliation
- Ores of vein association
- Ores of metamorphic affiliation.

Guilbert and Park (1985) adopted a similar approach, by considering ore deposits related to

- Mafic igneous rocks
- Oceanic crust
- Intermediate to felsic intrusions
- Subaerial volcanism
- Submarine volcanism
- Submarine volcanism and sedimentation
- Chemical sedimentation
- Clastic sedimentation
- Weathering
- Regional metamorphism
- Solution-remobilisation
- Doubtful igneous connection.

Cox and Singer (1986) preferred to classify ore deposit models by geological-tectonic environment, thereby devising a tree-like diagram such as those used in life-sciences. In this way, they consider a first division into: igneous, sedimentary, regional metamorphic and surficial. Mitchell and Garson (1981) were amongst the first to enthusiastically espouse the idea that plate tectonics offered a double solution in the difficult task of systematising ore deposits. The idea, with which we are all now familiar, is that plate tectonic processes are responsible for generating ore deposits, therefore ore deposits are effectively an expression of the tectonic setting in which they are formed, but not necessarily the tectonic setting in which they occur. Conversely, a specific type

Table 4
Convergent plate margins: Principal geological features of selected mineral systems associated with subduction related magmatic arcs.

Mineral system	Geological features
Intrusion-related (e.g. Tintina gold field; Alaska ➔ (Baker et al., 2006; Hart, 2007)	• Polymetallic veins around and within granitic intrusions • Metal assemblages vary according to distance from causative plutons • Fracture-controlled hydrothermal alteration
Porphyry-type Cu ± Pb Zn, Au, Mo (e.g. Pacific Rim) ➔ (Sillitoe, 2010) Porphyry-type Mo-dominated at continental margins (e.g. Chilean margin, Eastern China) ➔ (Pirajno and Zhou, 2015)	• Related to calc-alkaline magmatism. Low grade, large tonnage, disseminated sulphides. • Emplaced in shallow porphyritic intrusives and/or in adjacent country rocks. • Fracturing of host-rock (hydraulic; crackle breccias). • Stockwork veining and pervasive wall-rock alteration distinctive. • Copper sulphides may have associated Au in oceanic arcs, Mo in continental arcs. Ores as stockwork veins mostly in phyllic alteration shell. Contemporaneous to late intrusive breccia bodies may host mineralisation (see below). (Fig. 9) • Usually intrusives related to granodiorite parent, with sequential differentiation trends intruding at different stages. Mineralisation usually in quartz- or quartz-feldspar porphyries. The last intrusive (e.g. leucogranite) is usually unmineralised.
Breccia pipes Cu, Au, Mo ± W, Au ➔ (Baker et al., 1986)	• Minor in terms of volume, but may host high grade Cu. • Commonly related to porphyry intrusives and related mineralisation. • Occur singly or as clusters, in roofs of intermediate composition batholiths or stocks, and in their volcanic carapace. • Steeply inclined circular or elliptical pipes. Ore is associated more with fragmentals (Fig. 10). Alteration localised, including phyllic assemblages, potassic at depth.
Skarns Fe, W, Sn, Cu ± Zn, Ag, Pb, Au ➔ (Meinert et al, 2005)	• Spatially and temporally related to intermediate felsic igneous bodies (usually magnetite-I type granitoid. • Occur mainly where intrusives interact with carbonate rich country rocks (Fig. 11) • Marked by complex calc-silicate assemblages, as well as complex alteration patterns and silicate mineralogy. Metal zoning well-developed. • Some magnetite contact metasomatic deposits occur adjacent to diorite/granodiorite intrusion.
High-sulphidation epithermal deposits Cu–Au ± Ag & transitional to porphyry Cu (Agua Rica, Argentina ➔ (Simmons et al., 2005; Franchini et al., 2011) Au, Ag, Hg, As, Sb, W, S at higher structural levels (hot springs) ➔ (Renaut and Jones, 2003; Pirajno, 2009)	• Widespread in upper portions of volcanic edifices, and within the uppermost portions of stocks and batholiths. • Au and Ag occur in epithermal bonanza-type veins, as deeper seated Au-qtz lodes and base metal veins ± Au/Ag. • Epithermal deposits typically have volcanic or pyroclastic host rocks, and may occupy well defined structures. Alteration is variable, envelope of chlorite dominated propylitic alteration, with sericite and silicification. Argillic alteration and localised pyritisation of wall rocks. Advanced organic, alunite, barite, pyrophylllite, diaspore alteration. Intensive acid leaching typically results in vuggy quartz (Fig. 12) • Silica-carbonate chemical precipitates and associated deposits from hot springs (Fig. 13)
Low-sulphidation epithermal deposits ➔ (Henley and Ellis, 1983; Simmons et al., 2005)	• Au-qtz veins occur at greater depths and/or laterally in volcanic edifices, within wider and more extensive vein systems occupy pre-existing tension fractures and faults. Mineralisation more persistent laterally than vertically. Propylitisation regional, chloritisation, sericitisation and silicification, in vein envelopes. Argillic alteration adularia-sericite, clay, pyrite • Generally associated with caldera complexes.

Table 5
Convergent plate margins: Recognition criteria for selected mineral systems associated with subduction-related magmatic arcs (based on the references cited in Tables 3 and 4).

Mineral system	Geology/alteration	Geochemistry
Porphyry-Cu (Mo) Continental-margin porphyry Mo	Intermediate-felsic sub-volcanic complexes characterised by multiple igneous events. Common in Circum pacific region and related to calc-alkaline magmatism. Includes potassic core, phyllic shell (qtz-ser-pyrite), argillic (clay), and more regional propylitic (chlorite-epidote-pyrite) alteration zones. Fluorite common in continental-margin porphyry systems	Cu, Mo, Au, Pb, Zu, Au, As, Se, Sb, F Mn = peripheral Enriched in K and F mainly
Cu-breccia pipes	As above for porphyry Cu Breccia textures, interstitial sulphides. Similar alteration to above. Most pipes mineralised along margins.	Vertical zonation of metals.
Skarns	Spatially related to intermediate-felsic igneous bodies (usually I-type granitoids). Mineralisation at contact zones with carbonate rocks Base metal skarns are transitional to porphyry copper deposits (above). • Cu skarns • Pb–Zn skarns • Fe skarns • Au–W-skarns Generally sited above plutons or in the roof pendants of batholiths. Complex calc-silicate assemb. assoc. with alteration: garnet-pyrox. proximal; wollastonite-tremolite distal.	Complex mineral zonations. Well-defined metal zonation: Cu–Au–Pg → Pb–Zn–Ag.
High-sulphur epithermal Au	Strato-volcano-associated. Vuggy quartz is common; propylitic alteration; kaolinite, alunite around ore zone. Barite may be present. Sulphide: enargite-luzonite. Transitional at depth to porphyry system.	Uppermost zone enriched in Hg; passing downward to Au–Ag and Te-sulphides; at depth Ag–Cu–Pb–Zn
Low-sulphur epithermal Au (vein deposits)	Generally caldera-associated; sinter deposits are common. Adularia-sericite key alteration minerals. Downward zoning to sulphide-rich ore. Mn carbonates present.	Uppermost zone with Ag, Tl, passing downward to Au–Ag; then Pb–Zn–Cu; minor Mo–W.–Sn
Alkalic epithermal Au	Related to alkaline stock at depth. Explosion breccia or pipe spatially associated with ore zone. Silicification, stockwork veins, surrounded by propylitic alteration halo. Narrow alteration some containing adularia, carbonate, sericite, smectite	Hg–Sb–As at top (hot spring deposits) F, K, Au–Ag–Tl in ore zone. Minor Mo–Cu–Zn–Pb sulphides

of ore deposit can (and does in many cases) help in unravelling the tectonic setting of a geological terrane. Examples are ophiolite-hosted metal deposits. Some are formed in oceanic crust at a mid-ocean ridge and later tectonically transported onto a continental margin, but the same ophiolite rocks may also host hydrothermal mineralization resulting from deformation and metasomatism during a collision event.

The relationship of ore deposits first to plate tectonics and at a later stage to mantle plume dynamics and related tectonics, led to the formulation of ore deposit models. An ore deposit model describes the essential features (geological, host rocks, wall rock alteration, geochemical/metal associations, spatial distribution, grade, size, ore mineralogy, regional metallogenic framework, tectonic setting) of a group or class of deposits. Ore deposit models effectively are sets of data that best describe a deposit or family of deposits, which share similar features and which contain common geological attributes and are formed in similar tectonic environments. A model can be empirical based entirely on facts, such as field observations, geochemical and geophysical data, or theoretical based on conceptual ideas generally borne out of experience and knowledge of, and extrapolation from known mineral districts. Ore deposit models range from simplistic (very limited database) to complex (large database); in the same way as few data points define a smooth curve, whereas many points usually define a more complex curve. But, as is the case for a curve derived from many data points, this can be smoothed to obtain a fairly accurate overall picture. This is one of the keys to understanding ore deposits and their genesis: filter out the noise and home in to a general model that fits within a regional framework and that adequately explains the observations. Another important factor is that an ore deposit can be modified, perhaps more than once, by subsequent geological processes (e.g. collision tectonics, strike–slip movements, asteroid impacts).

Overall the plate and mantle plume tectonic paradigms, fostered the modelling of ore systems, which turned out to be very useful in mineral exploration because of their predictive capacity, although the difficulty of obtaining a classification of ore deposits that completely satisfies both genetic and non-genetic conditions remains. Nevertheless, building a mineral system genetic model provides insights into the geodynamic environment of ore formation and, importantly, allows a degree of predictability that can assist in exploration targeting. A thematic issue of the Australian Journal of Earth Sciences is devoted to conceptual exploration targeting (Groves, 2008), other works on the topic include McCuaig et al. (2010) and McCuaig and Hronsky (2014).

Several other books deal with various aspects of ore deposits. These include: Sawkins (1990), Pirajno (1992, 2000, 2009), Evans (1993), Barnes (1997), Misra (2000), Solomon and Groves (1994) and a comprehensive treatise by Laznicka (2010). The 100th Anniversary Volume of Economic Geology (Hedenquist et al., 2005) provides excellent and in-depth reviews of both magmatic and hydrothermal mineral systems, which include: 1) Magmatic ore deposits 2) porphyry deposits, 3) skarns, 4) granite-related ore deposits, 5) precious metal deposits in metamorphic terranes, 6) Carlin-style deposits, 7) epithermal precious and base metals, 8) sediment-hosted Pb–Zn, 7) sediment-hosted stratiform deposits, 9) iron-formations, and 10) the hydrothermal model for the Witwatersrand Au–U deposits. In addition, regional metallogeny and earth environments and processes are discussed in some detail. The Geological Association of Canada published a well-illustrated book (Goodfellow, 2007), which although focussing on the mineral deposits of Canada, does provide good reviews of ore systems that are applicable world-wide.

In the following, I attempt to embark on an overview of mineral systems that form and/occur at convergent plate margins and their key features, such as geological, alteration (where applicable), metal associations. The books and articles listed above together with my own publications have provided much of the data herein

Table 6
Accretionary and collisional terranes: Principal geological features of other types of selected mineral systems related to collision, metamorphism and associated de-volatilisation processes.

Mineral system	Geological features
Archaean greenstone belt Sb–Au (e.g. Murchison Sb Belt, S. Africa) ➔ (Anhaeusser, 1976; Viljioen et al., 1978)	• Mineralisation is associated with talc-carbonate and siliceous carbonated schist which are altered, carbonatised komatiites. There is a close association of Au mineralisation to carbonate in vein fillings, fractures and faults. • Deposit broadly zoned, with a siliceous talc-chlorite envelope around a talc carbonate core. • There are intercalated mafic volcanics (HW) and felsic volcanics (FW), with chert and carbonate facies ironstone in between. Enriched in Ni, Cr, Mg, Co, Au, Sb, As T., B, W, K, Rb, $C0_2$.
Orogenic lodes; Archaean greenstone belts; Accretionary prisms; fold-and-thrust belts (e.g. Qinling orogeny, China; Far East Russia) ➔ (Groves et al., 1998; Chen and Santosh, 2014; Goryachev and Pirajno, 2014)	• Vein type mineralisation, crosscuts volcano-sedimentary stratigraphy (Fig. 14) • Regional metamorphism is greenschist to amphibolite facies (devolatilisation processes). • Vein type probably related to regional metamorphism — structural traps in intensely altered (talc), competent rocks, and along the contacts of rocks of different competency. • Major deposits are also located near major structural breaks which may be normal, thrust, or strike-slip faults. • Alteration: Enriched in Mg, K, Rb, $C0_2$, S, Cr, Au, As. Depleted. in Sr, Na.
Granitic rocks related Sn, W, polymetallic; greisen systems) (e.g. Cordillera NW Canada, Bolivian Tin Belt, Korea, Tasmania, Australia). ➔ (Kinnaird, 1985; Wright and Kwak, 1989)	• A mixture of both I-type and S-type highly fractionated granites are associated with these ore systems. May have associated surficial ring-collapse structure. • The mineralisation occurs in greisens, vein and pipe-like bodies. • Generally there is enrichment in incompatibles, and invariably alteration haloes involving input of K, depletion in Na, possible boron and fluorine metasomatism and more complex skarn-type silicate assemblages.
Collisional granites Sn, W $\pm$ Mo, Bi, Pb, Cu, Zn (Greisens, skarns, pegmatites) (e.g. Hercynian, Europe; Tin Belt, SE Asia; Panasqueira, Portugal; Cornwall, England; Gejiu Sn province, SW China) ➔ (Kelley and Rye, 1979; Meinert et al., 2005; Neiva, 2008; Cheng et al., 2013)	• These deposits are related to the generation of anatectic S-type magmas. These produce 2-mica granites, which are associated with diffuse contact zones characterised by migmatites. • Regional metamorphism is low-pressure, and the granites have high initial Sr ratios • Metals occur with the youngest, most differentiated, granites. • Mineralised areas are usually at intrusive contacts. Mineralisation forms stockwork veins, vein complexes, or single veins with greisenisation, including tourmalinastion (Fig. 15), as well as skarns (carbonate roof-pendants) and pegmatite. • Regional metal zonation — Sn-dominated veins in central portions of district whilst base-metal sulphide dominated veins occur peripherally. The deposits generally resemble magmatic hydrothermal vein type mineralisation associated with I-type granitoid intrusions in subduction-related terranes. Main differences lie in the predominance of Sn/W mineralisation in collision terrains, and base and precious metals in subduction related deposits. • In collision granites there is a close association of Sn/W with the roof zones of differentiated plutons, which also have some post magmatic alteration • Geochemically specialised in volatiles/incompatibles. • Regional pattern of collapse/ring structures related to plutonism

Table 7
Transform faults: Principal Geological features of associated mineral systems.

Mineral system	Geological features
"Leaky" transforms Ba, Fe, Mn — oxides → (Hein et al., 2013)	• There is no generation or destruction of lithosphere at these plate boundaries. • The faults may transect seafloor and continental areas. • Only limited mineralised occurrences, which include Ba, Fe–Mn oxides and hydroxides in sediments with associated high Ba basalts localised along a transform (Fig. 16)
McLaughlin type Au, Hg, Sb. (Western USA) → (Sherlock, 2005) Alpine Fault (New Zealand); Ailao Shan-Red River and Irtysh faults; orogenic lode Au deposits, Ni–Cu in mafic intrusions, porphyry Cu–Mo, REE in carbonatites (SW and NW China) → (Pirajno, 2010; Craw et al., 2013; Deng et al., 2015)	• Mineralisation is typical hot spring type — disseminated gold in veins and veinlets, sinters. There is a close spatial relationship between transform faulting, ore deposits, and volcanism (basalt and rhyolite). Spatial relationship, in particular, with San Andreas transform and associated faults to the east. Volcanics are essentially calc-alkaline, exhibit complex Sr-isotope variations multiple magma sources in the upper mantle and lower crust. • Fluids from which metals deposited likely to be derived from geothermal system related to volcanism, and remobilised from within crustal pile. • Fault jogs and flower structures that form in strike-slip faults are particularly efficient in the channelling of fluids, because these structures promote vertical flow and can tap metal-rich reservoirs. Hot springs are common. • Dominantly clastic sediments. Strong deformation, argillic, propylitic, silica, chloritic alteration widespread. Carbonatites and alkaline intrusions may be present

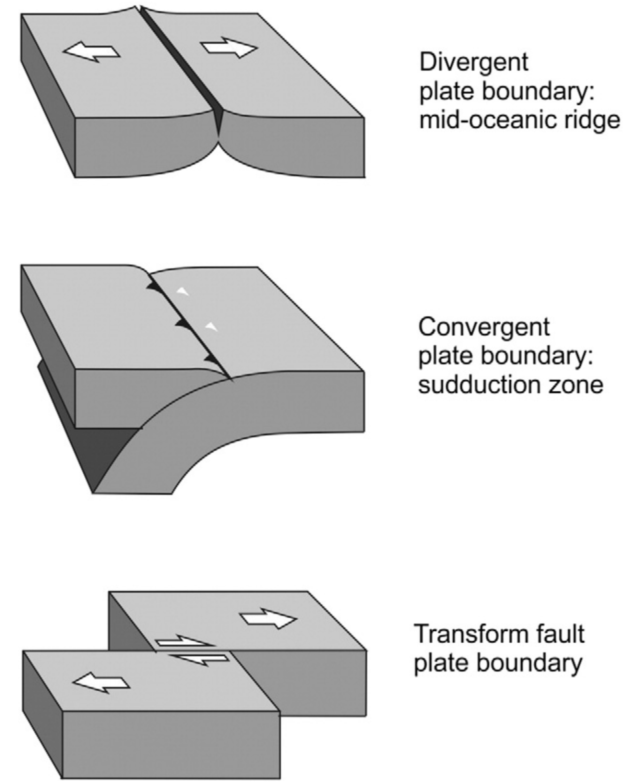

Fig. 1. Simplified diagrams of the three main plate margins discussed in this paper. Modified after Frisch et al. (2011).

presented, in addition to more specific citations. Tables 1 to 7 display the range of mineral systems for each tectonic setting under consideration, where applicable, in the first column of each table a selection of type localities is provided.

4. Plate margins

The geology of plate margins has been dealt with in several books and articles, such as Le Pichon et al. (1973), Wessel (1986), Condie (1989, 1997, 2005), Howell (1995), Windley (1995), Kearey and Vine (1996), Frisch et al. (2011), just to name a few. The three principal elements of plate boundaries (convergent, transform and divergent) are shown in Fig. 1, whilst an idealised plate setting in the outer shell of our planet is shown in Fig. 2. Wessel (1986) provided a comprehensive and very useful chart depicting practically all types of convergent and divergent plate tectonic settings. This author considered intra-oceanic, continental and intracontinental margins. Intra-oceanic margins were subdivided into "migratory" (e.g. Tonga-Kermadec, Scotia arcs), "detached" (continental sliver within the arc, e.g. Japan) and "stationary" with respect to back-arc, as exemplified by the Aleutians arc. Continental margins were divided into "contracted" (e.g. Peru, western USA) and "non-contracted" with back-arc spreading (e.g. Java-Sumatra island arcs). Intracontinental margins or continent–continent collisions (island arc-continent also included), as represented by the Himalayan orogens and the Appalachian fold belt. For divergent margins, Wessel (1986) considered the following scenarios: oceanic spreading centres, passive margins, intracontinental rifting, and back-arc spreading (e.g. Basin-and-Range of the western USA). Lastly are the transform settings (intraoceanic, continental margins and intracontinental) associated with strike–slip faulting and comprising transtensional, transform and transpressional. These are not strictly speaking plate margins, but can

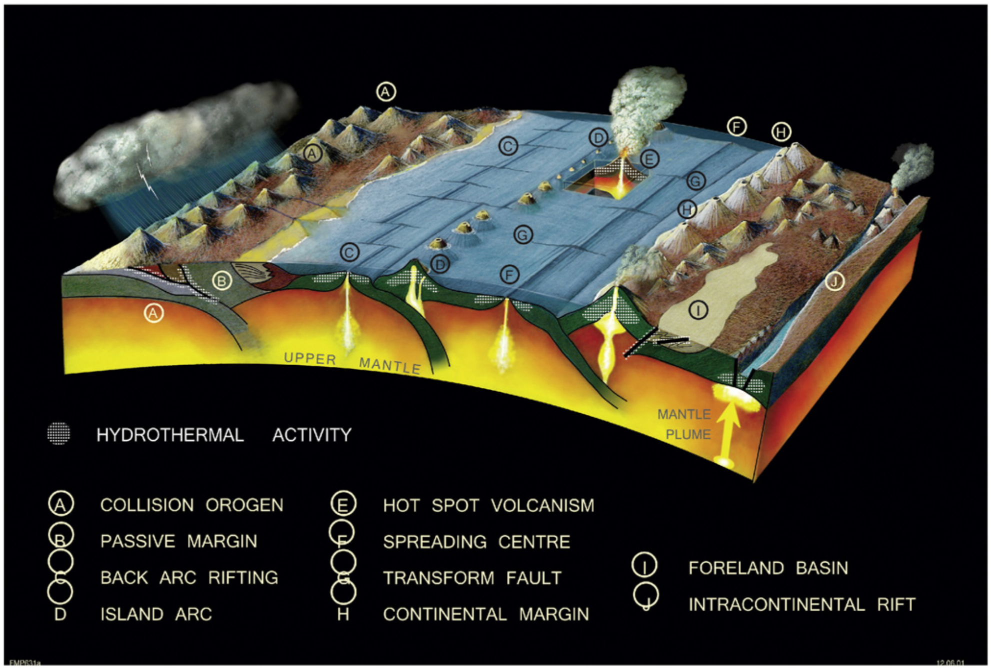

Fig. 2. Cartoon (not-to-scale) of principal convergent and divergent plate boundaries and associated upwelling magmatic systems and types of hydrothermal activity. After Pirajno (2009).

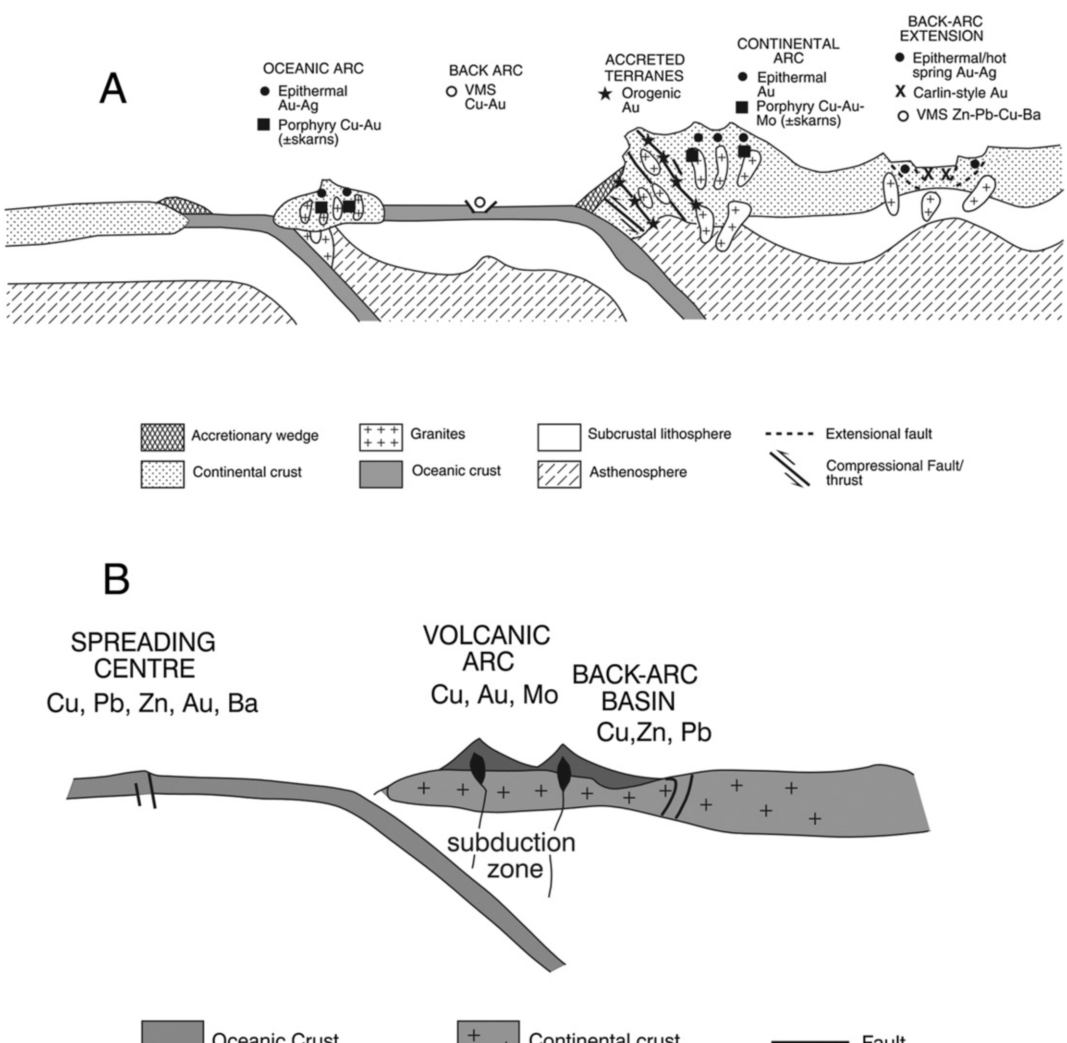

Fig. 3. Subduction-related tectonic settings and related mineral systems. Based on and modified from Groves et al. (1998).

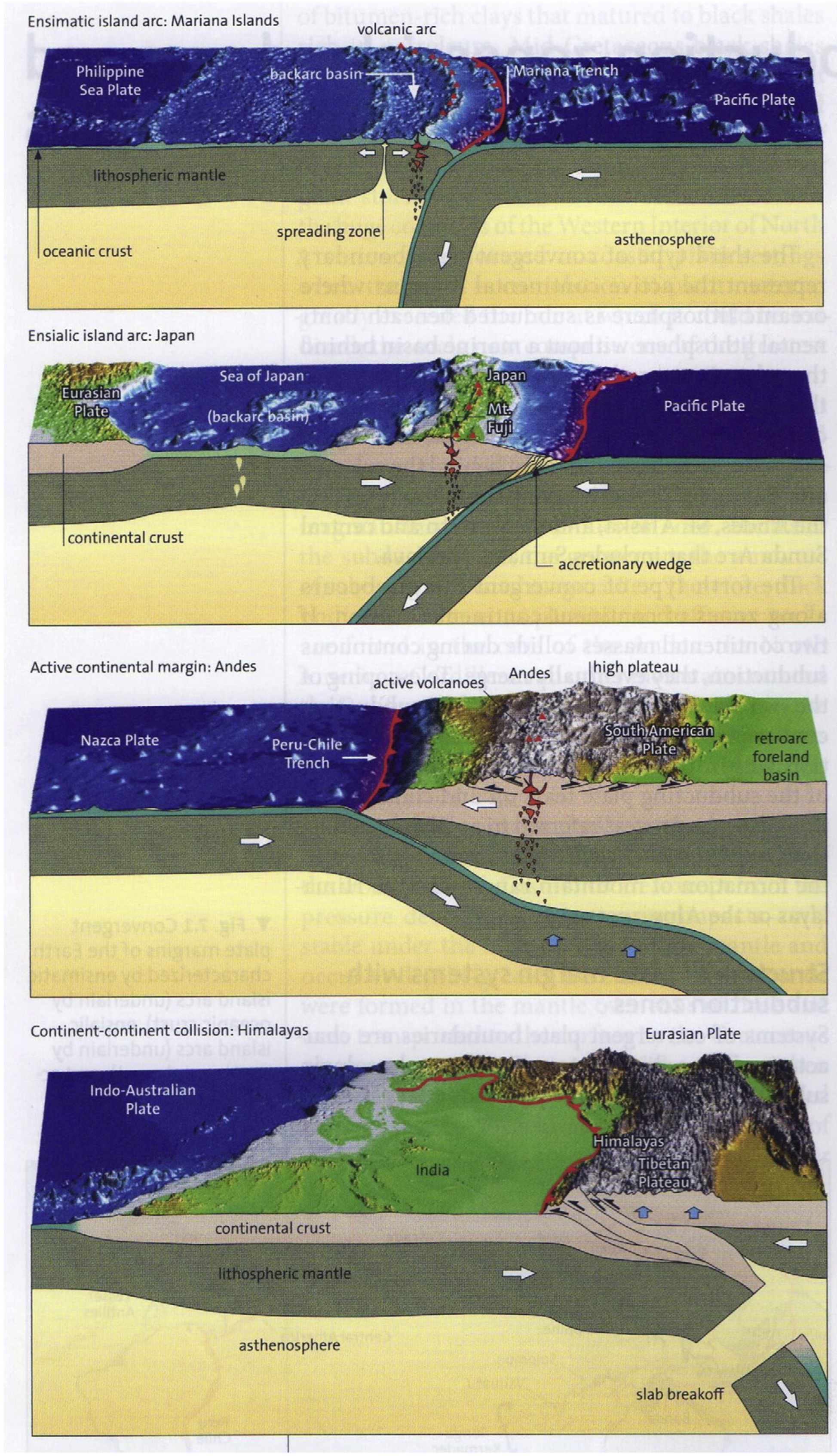

Fig. 4. Types of subduction-related plate margins, based on angle of subduction, from steep to moderately dipping (A and B), to shallow (C) and flat (D). Figure courtesy of Wolfgang Frisch, Martin Meschede and Ronald Blakey (Frisch et al., 2011).

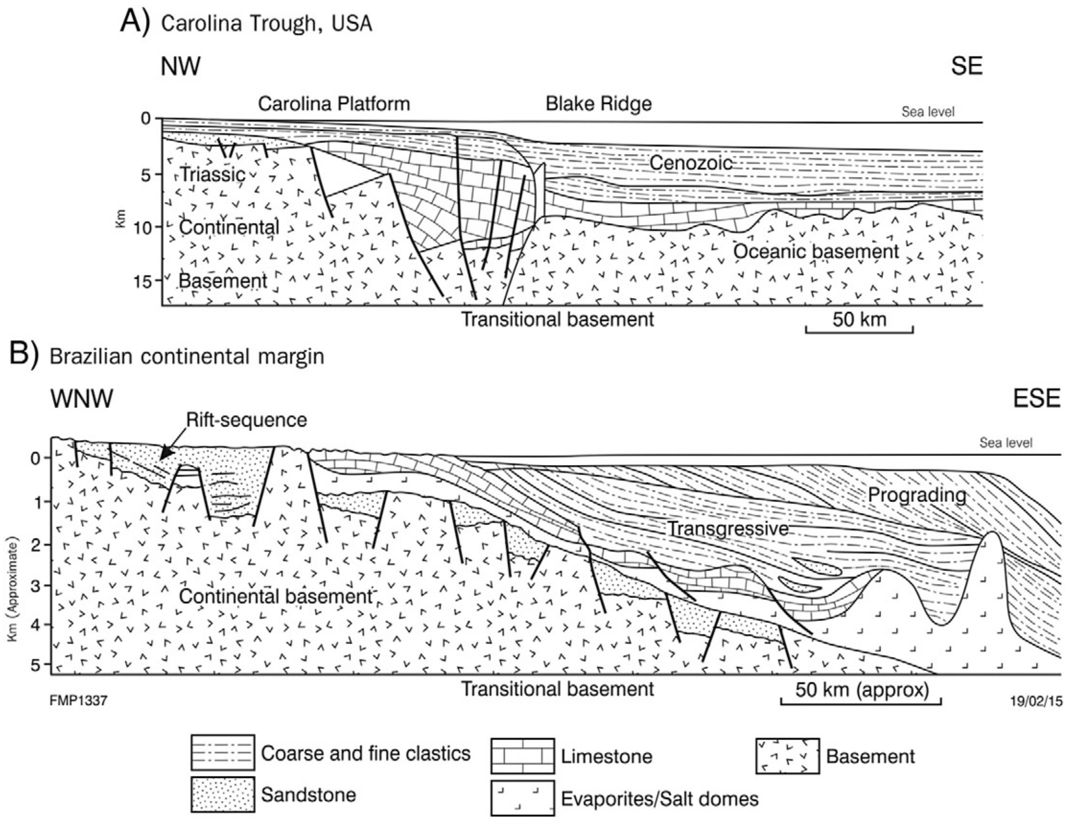

Fig. 5. Key examples of passive margins; (A) passive margin of the eastern seaboard of the USA, Carolina Trough, extending onto oceanic basement and (B) Brazilian type passive margins and associated salt diapirs. Original figure courtesy of Philip Allen (in Allen and Allen, 2005).

and do generally develop from convergent margins that are laterally pushed, as beautifully exemplified by the Alpine Fault in New Zealand's South Island (Campbell et al., 2012), or during extensional processes that lead to the formation of pull-apart basins (Nilsen and Sylvester, 1999).

4.1. Convergent plate margins

Convergent plate margins are characterised by a higher density tectonic plate subducting beneath a lower density plate. Convergence generates a continental magmatic arc where oceanic lithosphere subducts a continental margin (e.g. Andean arc), or an island arc where older oceanic crust subducts younger and less dense oceanic crust. Convergent plate margins have landward of a deep trench, a subduction–accretion complex, a magmatic arc and a foreland thrust belt. Configurations of subduction–trench–arc–back–arc systems and associated ore systems are shown in Fig. 3. A steep angle of descent, as is the case for the modern-day Mariana, or Tonga-Kermadec subduction systems, is conducive to creating an extensional stress field which would promote the formation of a mafic-dominated volcanic arc, in which porphyry-high-sulphidation epithermal systems develop, an intra-arc rift system with spreading centres (e.g. the Lau Basin), in which massive sulphide deposits of kuroko affinity may form. By contrast, a shallower subduction zone, such as that occurring under the South American active margin (Andean-type), would result in the development of a shallower trench and a compressive regime behind the intermediate to felsic magmatic arc. Here is the domain of large porphyry Cu–Mo and epithermal deposits. Furthermore, it is important to note that in Andean-type subduction systems, accretionary sedimentary prisms in the trench area are well developed, whereas they may be absent in the Mariana-type trench. Some of these convergent margins features are illustrated in Fig. 4. The implications of this difference in terms of metallogenesis are extremely important, because the presence of a sedimentary accretionary prism is relevant to the formation of epigenetic Au-bearing quartz vein lodes. Intraoceanic island arcs develop on the overriding plate, parallel to the plate boundary, and those of Phanerozoic to recent ages may range from hundreds to thousands of kilometres long, and up to 100 km wide. Magma generation occurs in the asthenospheric wedge above the dehydrating subducting slab, producing plutonic rocks ranging in composition from dioritic to granodioritic (I-type magmas). These magmas vent at the surface producing a series of volcanic products ranging from basaltic to rhyolitic. The igneous rocks tend to become more enriched in alkalies and incompatible elements away from the trench, forming a sequence from tholeiites, low-K andesites, dacites (calc-alkaline series) to shoshonites. Andean-type subduction settings form huge magmatic arcs thousands of kilometres long. Here, too, volcanic rocks are of calc-alkaline affinity, but are more silicic and intermediate in composition, with basaltic rocks being less abundant than in island arcs. The Andean magmatic arcs are characterised by tall stratovolcanoes, whereas the corresponding plutonic rocks comprise a range from tonalites, granodiorite, to quartz-monzonite. The source and petrogenesis of magmas of subduction zones have great importance not only for the evolution of the magmatic arc in space and time, but also for its metallogenesis. Details on subduction geodynamics and magmatism can be found in Prichard et al. (1993), Tatsumi and Eggins (1995), Leat and Larter (2003) and Frisch et al. (2011).

Continent–continent, arc–continent, arc–arc, amalgamation of drifting microcontinents, oceanic plateaux, ridges and seamounts and their accretion on to continental margins have all been recognised in the Phanerozoic geological record. Collision events are considered to be a major factor in uplift and mountain building. Young collision belts are characterised by mountains, fold and thrust belts, zones of intense deformation and metamorphism, obducted ophiolites, and intrusion of post-collision crustal-derived granitoids. The entire Alpine-

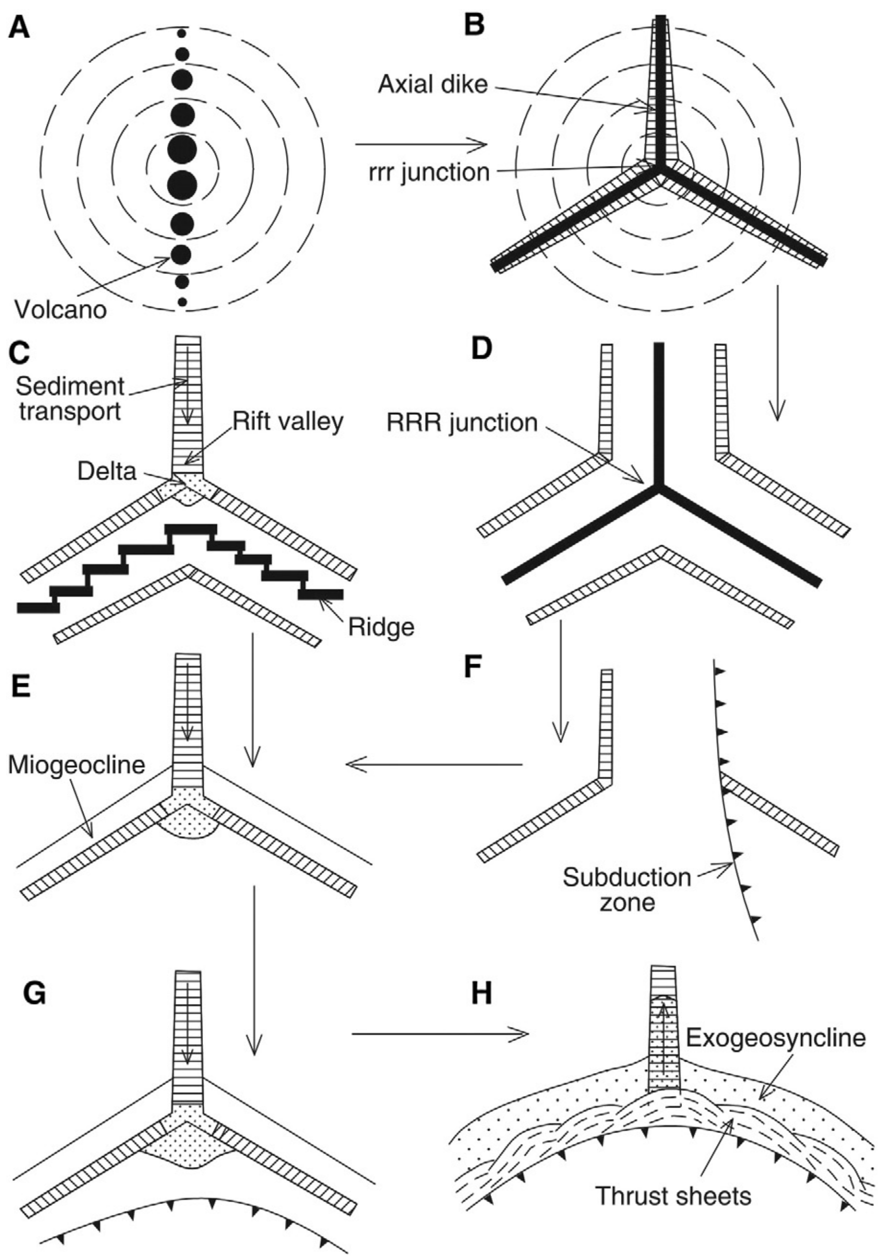

Fig. 6. Typical plate margins associated with rifting and mantle upwellings, resulting in a series of evolving and diverging rift systems (A to F), which may develop into passive and convergent margins (G and H). From Burke and Dewey (1973; see also Pirajno, 2009).

Himalayan orogenic belt was largely formed by the closure of the Tethys oceanic basins, and the collision of a number of microcontinental fragments from the northern edge of the Gondwana continent with the Laurasian continent (Sengör and Natal'in, 1996; Hou and Zhang, 2014; Richards, 2014). Similarly, the great Central Asian Orogenic Belt (CAOB) represents a giant accretionary collage of island arcs and continental fragments (Windley et al., 2007). Also, most of the North American cordilleras formed by the collision and accretion of a number of terranes that may have originated from the eastern margin of Gondwana (Nance et al., 2014). Allochthonous fragments of oceanic and continental material are regarded as important additions to the growth of continents. Allochthonous terranes originate by rifting and dispersion from a larger landmass, during drifting the fragments may "amalgamate" before accretion on to a continental margin. From here, however, they can be dispersed and moved along major strike-slip faults (Storti et al., 2003). The closing of oceanic basins, and the accretion of allochthonous terranes, may result in the emplacement of ophiolites by the obduction process (Dewey and Casey, 2011; Dilek and Furnes, 2014). In many old terranes, all that remains of a former "suture" is either a line of small slivers of mafic–ultramafic bodies, or, in extreme cases, only a zone of shearing.

Windley (1995) proposed two types of convergent margin orogens: collisional (continent–continent) and accretionary (or Cordilleran type). Collision of two continental plates is typically marked by ophiolitic suture zones, resulting from the closure of an intervening ocean and develop magmatic arcs on the active margin and passive margin sequences on the trailing side. Accretionary or Cordilleran orogens develop from the assembly and accretion of tectonostratigraphic terranes, mostly fragments of island arcs, oceanic plateaux and microcontinental fragments, all of which assemble to form accretionary prisms. For

Fig. 7. Fluorite veins associated with alkaline granite intrusion; from the Donggoumen fluorite mine in northern Hebei province (China).

accretionary orogens, Condie (2005) considered two end-members: simple orogen and complex orogen. The former is characterised by accretion of juvenile terranes, whereas the latter, in addition to juvenile terranes, includes exotic microcontinents. Commonly in accretionary orogens, collision is oblique and not orthogonal and characterised by extensive lateral and vertical accretion above a subducting slab. The degree and nature of the oblique collision also results in the suture zones developing major thrust and/or strike-slip faults, which tend to become sites of orogenic Au lodes, due to extensive fluid flow resulting from seismic pumping (Sibson et al., 1988, Sibson, 2001; Goldfarb et al., 2005).

Other important features to note are the retro-arc, fore-arc basins and subduction complex, or accretionary prism of highly deformed sediments interleaved with slivers of oceanic crust. On collision, the sedimentary packages of these basins will form thrust belts, with severely deformed and metamorphosed rocks. These geodynamic effects are of great importance because many orogenic lode deposits originate through the deformation and metamorphism of these sedimentary piles, whereas thrust faults often act as major avenues for mineralising fluids (Chen et al., 2004; Chen and Santosh, 2014).

4.2. Divergent plate margins

These include mid-ocean ridges, passive margins and various forms of continental rifting. At mid-ocean spreading centres, new lithosphere is formed which consists of mafic material welled up from partially molten asthenosphere, and which forms magma chambers just below the spreading centre. This part of the lithosphere, or oceanic crust, consists of an uppermost layer of basaltic pillow lavas and associated pelagic sediments, underlain and intruded by sheeted dyke systems, passing downward into gabbroic, peridotitic, dunitic and harzburgitic rocks. Once the oceanic crust moves away from the ridge it is either consumed in a subduction zone, or it may be accreted to continental margins, or island arcs. Accreted oceanic crust is known as ophiolite.

Spreading centres also form in back arc marginal basins (a modern-day example being the Sea of Japan). Although geochemical discrimination has been attempted to differentiate between mid-ocean centres and marginal basin spreading centres, the distinction in ancient systems

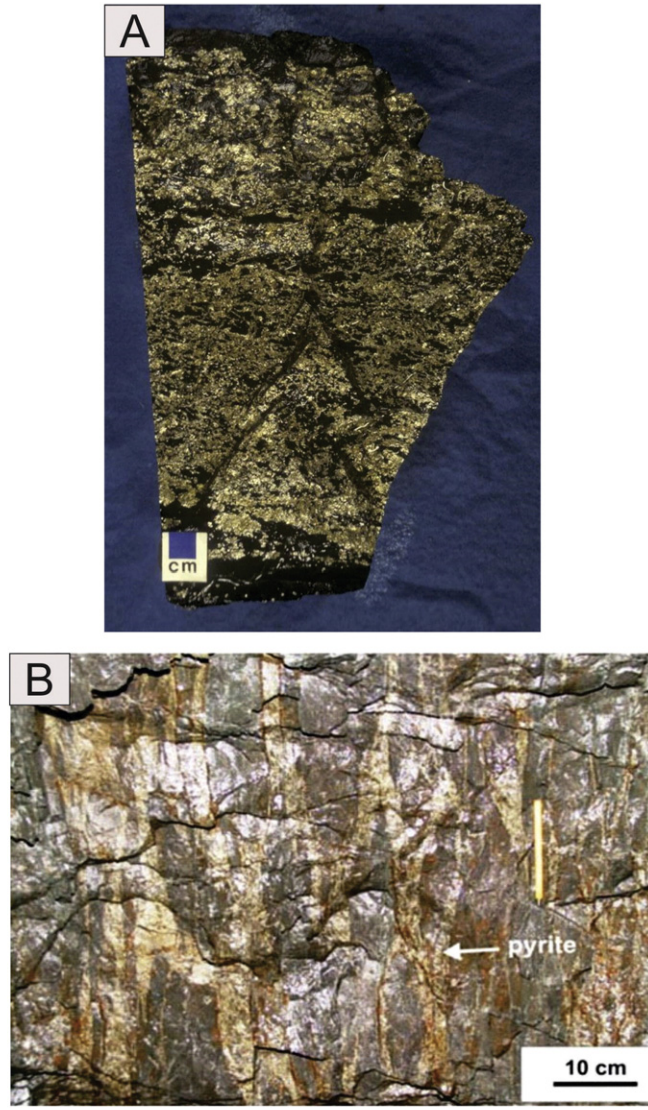

Fig. 8. Some features of Abitibi-type VMS, A) Massive sulphide lens, Agnico Eagle, Quebec; B) Pyrite-rich stockwork subjacent to massive sulphide lenses, LaRonde Penna. Images taken from a power point presentation by Robert Kerrich (deceased).

Fig. 9. Porphyry Mo stockwork veining; at Leimengou, Qinling orogenic belt; China.

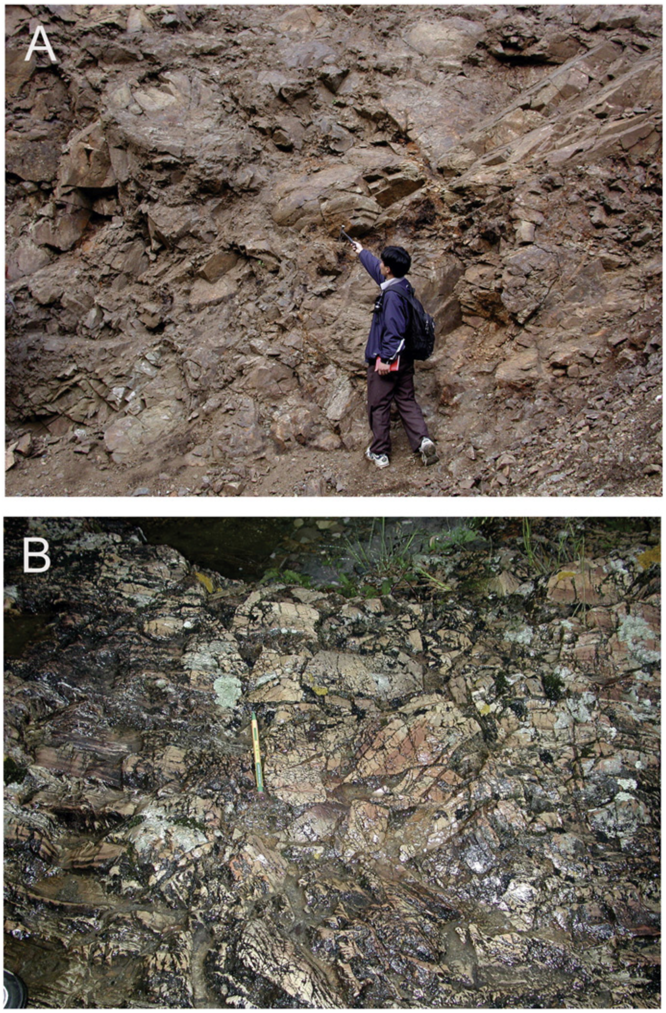

Fig. 10. Field photographs of two contrasting aspects of porphyry-related breccia pipes; A) large rounded clasts in a typical fluidisation breccia, the rounding is due to gas streaming resulting in repeated milling of rock fragments; B) jigsaw-style breccia characterised by angular rock fragments. Both breccias are from the Leimenggou and Qiyuggou porphyry Mo and auriferous breccia pipes in the Qinling orogeny of central China (Pirajno, 2009).

Fig. 12. Vuggy quartz, due to intensive acid leaching (advanced argillic alteration) from the El Indio high-sulphidation epithermal system. Image courtesy of Brian Townley.

is by no means clear (Gerya, 2011). The overall structural configuration of a mid-ocean ridge system depends on the rates of spreading. Present-day mid-ocean ridges have fracture-controlled black and white smokers, and surrounding metalliferous aprons, with metal association of Fe–Cu–Zn–Pb–Ba–Au–Ag (Herzig and Hannington, 1995; Kelley et al., 2002; Hannington et al., 2005). In the geological record these are represented by ophiolite-hosted stratiform massive sulphide and epigenetic stockwork feeder zone (Cyprus-type) (Hadjistavrinou and Constantinou, 1982). In the Guaymas basin (Gulf of California) smoker vents and metalliferous aprons are buried in terrigenous sediments with a metal association of Cu–Zn–Co–Ag. (Goodfellow and Zierenberg, 1999). In the geological record these are represented by Besshi-type massive sulphide deposits, exemplified by the Sambagawa belt (Japan) and the DeGrussa deposits in Western Australia (Pirajno et al., 2015).

Passive continental margins develop from continental rifts that evolve into oceanic basins (Fig. 5). Typical examples are the North American Atlantic margin in its advanced evolutionary state with a continental shelf, slope and rise and the incipient Red Sea margins and the Atlantic margin of Iberia (Allen and Allen, 2005). Between 2.5 and 1.8 Ga, banded iron formations and granular iron formations developed on passive margins resulting from continental break ups (Trendall and Morris, 1983; Beukes and Gutzmer, 2008; Bekker et al., 2010). For more details on tectonic and depositional processes of passive margins, the reader is referred to Roberts and Kusznir (1997), Allen and Allen (2005) and Bradley (2008). Passive margins can be a major source of halogens (e.g. Cl, F), derived from evaporitic sequence and salt diapirs, which are very important for the transport of metals in hydrothermal systems (Warren, 2010).

Rift basins are an important repository of a wide range of mineral systems from magmatic to hydtothermal. More than a century of geological studies has focused on basin tectonics and rifting, such as Allen and Allen (2005), Einsele (2000), and Olsen (1995 and references therein). Burke and Dewey (1973) proposed an evolutionary scheme of plume-generated triple junctions from a three-arm rifting stage (rrr

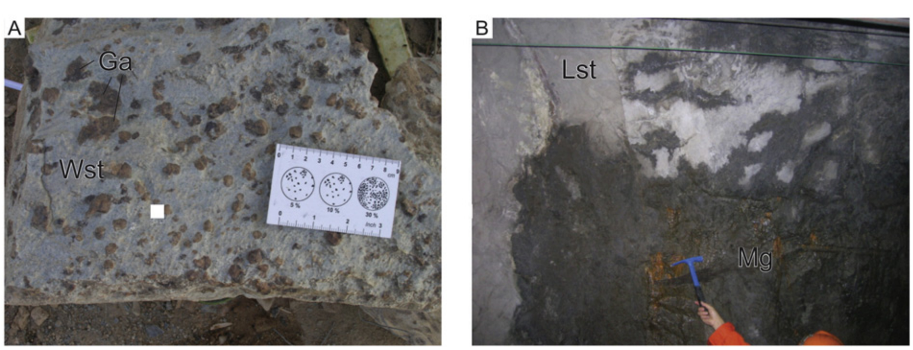

Fig. 11. Field photographs of some typical skarns; A) outcrop of wollastonite-garnet skarn from eastern Tianshan (Xinjiang Province, NW China); B) magnetite skarn replacing limestone, Longgiao Fe Mine, in Yangtze River Valley, China. From Pirajno (2013).

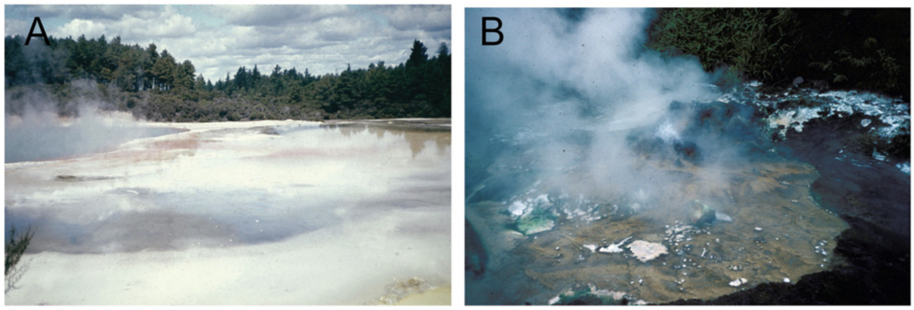

Fig. 13. Hot springs in the Taupo Volcanic Zone, New Zealand, A) Champagne pool hot spring, where orange-coloured precipitates contain anomalous Au and Sb. B) Waimangu hot spring with algal mats (pink and greenish colour) with anomalous abundances of W (Pirajno, 2009).

junction), to the opening and spreading of two arms, with one arm remaining inactive (or failed arm, termed aulacogen), their closure and eventually collision to form a fold-and-thrust belt. These authors proposed an evolutionary sequence shown in Fig. 6. In this sequence, rifts evolve into basins, in which sedimentary accumulations can reach thicknesses of more than 10 km. Sedimentary successions in rift basins commonly host base metal deposits and hydrocarbon reservoirs. A continental rift, or tectonic basin has been defined as a "*fault-bounded basin produced by extension of continental crust*" (Condie, 1997) and a rift system as a "*tectonically interconnected series of rifts*" (Olsen and Morgan, 1995). More precise definitions of rifts present some difficulties, but for a good review of terminology and classification the reader is referred to Olsen and Morgan (1995). Sengör and Natal'in (2001) defined rifts as fault-bounded elongate troughs, identified some 290 rifts and provided a comprehensive list of rifts of the world.

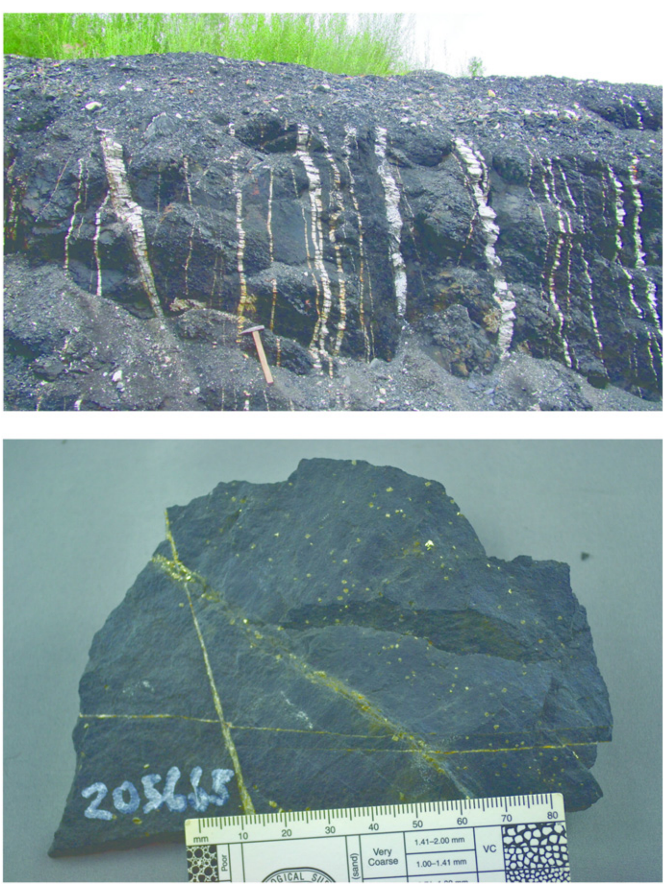

Fig. 14. Field photographs from the Dedgekan orogenic Au deposits in Far East Russia (Goryachev and Pirajno, 2014), top photo shows sheeted auriferous quartz veins in carbonaceous siltstone, the photo below shows a hand specimen of the carbonaceous siltstone with disseminated sulphides and three generations of sulphide veinlets.

Continental rifting has been a major geological process on planet Earth at least since the Late Archaean. Some examples of these early rift structures which led to basins infilled with thick volcano-sedimentary successions include, the Witwatersrand, Ventersdorp and Transvaal intracratonic rift basins in South Africa, the Capricorn Orogen rift basins in Western Australia, the Athapuscow, Bathurst, Belt-Purcell and Mid-continent Rift System in North America, the rift structures developed between the Anabar and the Aldan shields in the Siberian craton (e.g. Udzh, Iagor-Norilsky, Kjuntigdin, Viliuy and Ygatinsky aulacogens; Zonenshain et al., 1990). Most modern continental rifts contain lakes and are in fact lacustrine rift basins, the best modern-day examples being the East African lakes (e.g. Tanganyika, Malawi, Turkana) and Lake Baikal in Siberia (Mats and Perepelova, 2011). A continental rift, can evolve into a proto-oceanic basin and eventually, by advanced seafloor spreading, to an oceanic basin. Thick successions of sediments and/or volcanic products accumulate in rift basins, regardless of whether or not the rifting process evolves to form oceanic crust. The lacustrine rift systems of East Africa contain up to 5 km of syn-rift sedimentary fill; whereas Lake Baikal contains up to 8 km of syn-rift sediments (Pirajno, 2009 and references therein; Mats and Perepelova, 2011).

The origin of stratabound and/or stratiform sedimentary-rock hosted mineral deposits is intimately associated with the evolution of the host basin for which, in turn, a link with mantle plumes and rifting processes is assumed. There are cases, in which lithosphere thinning and rifting occur in response to crustal thickening and delamination processes of the lithospheric mantle. These processes result in a style of basin structure and topography referred to as basin-and-range, from the prime example in western USA, where this style was first documented in the Great Basin, which is a major repository for epithermal and Carlin-type deposits. Basin-and-range style tectonics are now recognised in other parts of the world, most notably in northeastern China, where Mesozoic to Cenozoic volcanic products fill basin-and-range style depressions (Pirajno, 2013).

4.3. Transform settings and strike-slip faults

As mentioned above, these include transtensional with a component of tension due to oblique divergence (e.g. Dead Sea, Salton Sea in California), transform or strike–slip sensu stricto (e.g. Alpine Fault) and transpressive with a component of compression due to oblique convergence (e.g. Transverse Range, California) (Wessel, 1986).

Strike–slip faults are characterised by horizontal maximum (σ_1) and minimum (σ_3) compressive stresses. Many strike–slip structures have splays that are discontinuous or breakup into several branches. Structural patterns caused by strike–slip movements in time and space can be very complex, because of continuing tectonic movements. An interesting feature of transpressive settings is the flower-structure, a geometry related to the uplift of the fault system, well exemplified in the

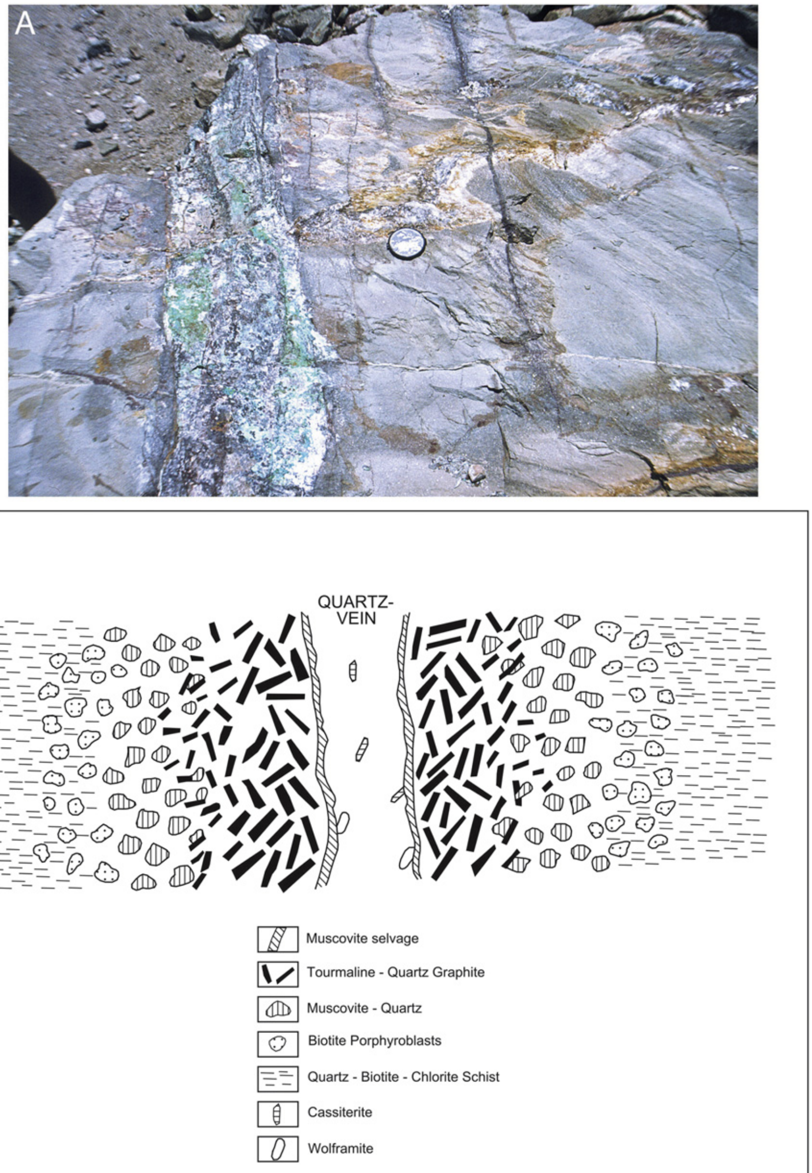

Fig. 15. A) Quartz vein and associated greisen-tourmaline alteration at Brandberg West (Namibia), cutting through an earlier deformed quartz vein, green is supergene malachite staining, to the right of the camera lens is a monomineralic tourmaline vein; B) schematic diagram showing the quartz vein and wall rock greisen (quartz + muscovite, tourmaline) alteration, the biotite porphyroblasts represent an earlier stage of potassium metasomatism along the original fracture (after Pirajno, 2009).

Salton Trough (southwest USA), where high-heat flow and magmatism are spatially linked to major strike-slip faults (Allen and Allen, 2005).

Strike–slip faults that form during extensional processes lead to the formation of pull-apart basins. These are generally narrow and of small size, commonly rhomb-shaped and fault-bounded, ranging from small sags to larger basins up to 50 km wide (Nilsen and Sylvester, 1999). Nilsen and Sylvester (1999) proposed a 6-fold classification of strike-slip basins, namely: 1) fault-bend; 2) stepover; 3) transrotational; 4) transpressional; 5) polygenetic and 6) polyhystory. The first four are perhaps more common. Fault-bend basins develop, as the name implies, at bends along the main fault, a classic example of which is the San Andreas fault system in California. Stepover basins develop between the ends of two parallel strike-slip faults), which may merge at depth into a single fault. Stepovers between two offset faults result in either pull-apart basins in the case of releasing stepovers, or uplifts in the case of restraining stepovers (McClay and Bonora, 2001). Basins related to strike-slip faults can form in transtensional settings, which can become inverted in transpressional settings, with shortening along the strike-slip faults (Nilsen and Sylvester, 1999). Strike-slip basins evolve through time and space, and if they encounter a change in strike of the principal fault (releasing bends), transtension and subsidence will occur, whereas at restraining bends transpression occurs, resulting in uplift (Nilsen and Sylvester, 1999). An example of these time-space evolutionary changes is provided by the Alpine Fault of New Zealand.

Examples of stepover strike-slip faults and associated basins can be found in the Dead Sea and the Jordan Valley, at the northern end of the Red Sea (Smit et al., 2008). Transpressional basins are narrow depressions subparallel to the general strike of faults in zones of oblique convergence. Thus, transcurrent movements that characterise strike-slip faults can create either pull-apart basins or uplifts, depending on how the movement is transferred.

Allen and Allen (2005) considered two types of strike-slip basins, "hot" and "cold". Hot strike-slip basins are characterised by volcanism and geothermal activity, whereas cold strike-slip basins are characterised by shallow fault systems. This brings on the important point that if there is continuing extension in the strike-slip fault geometry, ruptures may extend deep into the crust, the subcontinental lithospheric mantle (SCLM) and perhaps in some instances reaching the

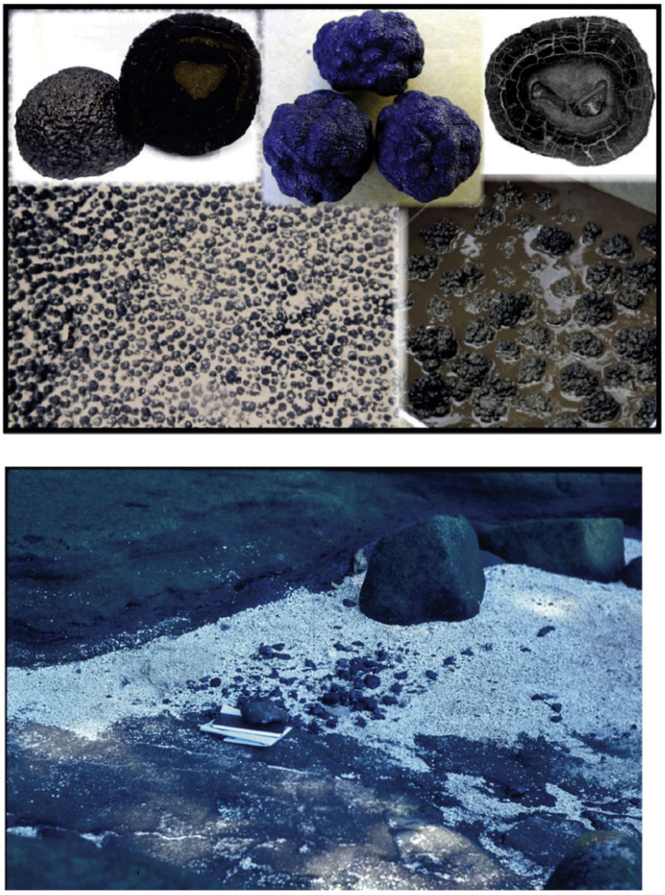

Fig. 16. Mn nodules on sea floor; A) cross-section of large 13.6 cm diameter seamount nodule from Lomilik seamount, Marshall Islands EEZ; B) three abyssal plain nodules each 3 cm in diameter showing a botryoidal surface, from the CCZ; C) cross-section of nodule collected from the Blake Plateau; D) diagenetic nodules collected in a box core from the Peru Basin; E) a dense concentration of nodules in the Johnston Island EEZ, with a field of view of about 4 m by 3 m (images courtesy of James Hein, Hein et al., 2013). Bottom photograph shows Mn nodules washed up on shore on the island of Eua (Tongan archipelago; Pirajno, unpublished).

asthenospheric mantle, resulting in magmatic activity and high heat flow (hot type). However, transpressional fault system with associated uplifts can also be "hot". This is exemplified by the Alpine Fault of New Zealand, which is associated with numerous hot springs and localised magmatic activity along its length. The hot springs are likely the result of exhumation of deep-seated hot rocks (Craw et al., 2013). During the extensional stage of its evolutionary history swarms of alkaline mafic (lamprophyre) dykes of Cretaceous age and 24 Ma carbonatites were emplaced on both sides of the Fault. Some of these dykes are known to contain Pb, Zn, REE and Th mineralisation (Brathwaite and Pirajno, 1993; Cooper and Paterson, 2008). Splays of the Alpine Fault in the north (Awatere and Clarence Faults) are spatially associated with layered alkaline mafic–ultramafic complexes, with minor Ni–Cu sulphide mineralisation (Brathwaite and Pirajno, 1993). In western Europe, intraplate anorogenic, dominantly alkaline, magmatism is widespread and associated with rifting and a complex array of strike–slip faults (Wilson and Downes, 2006), accompanied by extensive polymetallic mineral systems (Seifert, 2008).

5. Convergent plate margins and associated mineral systems

In this section the mineral systems that form in convergent tectonic settings are summarised in Tables 1 to 6. I have included a table for transform faults (Table 7). Type localities and key references are inserted for each mineral system(s), whereas for selected deposit type, examples either of outcrops or type models are provided in figures. These tables are by no means comprehensive, the intention here is to provide an outline of the more significant features of mineral systems of convergent margins.

6. Concluding remarks

In this short and perhaps somewhat debatable as well as arduous journey through the concept(s) of mineral systems, their classification and their formation at convergent plate margins (the topic of this special issue), I have endeavoured to deliver a relatively simple classification of mineral systems based on genetic models. This is followed by an overview of plate margins, convergent, divergent and transform, I set out to provide brief descriptions of mineral systems in convergent and transform margin settings by way of Tables 1 to 7). Using the published works cited in the text, including parts of my own works, I have included some of the key recognition criteria (e.g. geochemical enrichments or depletions) in separate tables. Much remains to be done and for that matter understood, particularly since more and more detailed studies of mineral deposits become available, leading to further subdivisions of mineral systems and the recognition of new ones which, although they may have been previously described, their uniqueness has not been realised. One of the more complex mineral systems is the IOCG which, depending on different views, may include carbonatites and even Kiruna-type Fe–P deposits, hence my labelling of IOCG "extended family". The future of classifying mineral system remains, if I may use the expression, a mine field, as testified by the abundance of books and papers dealing with this subject matter, each providing different ideas and models. The use of accurate geochronology (e.g. Re–Os, previously confined to molybdenite, but now also extended to pyrite, pyrrhotite and chalcopyrite), is giving the geological community a powerful weapon, because mineral deposits can now be temporally correlated with major tectono-thermal events, thereby facilitating a new or renewed understanding of the concept of mineral systems in a larger time and space framework.

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