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9: Processes of tectonism, magmatism and mineralization: Lessons from Europe

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Abstract

Metallogenic provinces in Europe range in age from the Archaean to the Neogene. Deposit types include porphyry copper and epithermal Cu–Au, volcanic-hosted massive sulphide (VMS), orogenic gold, Fe-oxide–Cu–Au, anorthosite Fe–Ti-oxide and sediment-hosted base-metal deposits. Most of them formed during short-lived magmatic events in a wide range of tectonic settings; many can be related to specific tectonic processes such as subduction, hinge retreat, accretion of island arcs, continental collision, lithosphere delamination or slab tear. In contrast, most sediment-hosted deposits in Europe evolved in extensional, continental settings over significant periods of time. In Europe, as elsewhere, ore formation is an integral part of the geodynamic evolution of the Earth's crust and mantle. Many tectonic settings create conditions conducive to the generation of water-rich magma, but the generation of ore deposits appears to be restricted to locations and short periods of change in temperature and stress, imposed by transitory plate motions. Crustal influence is evident in the strong structural controls on the location and morphology of many ore deposits in Europe. Crustal-scale fault–fracture systems, many involving strike-slip elements, have provided the fabric for major plumbing systems. Rapid uplift, as in metamorphic core complexes, and hydraulic fracturing can generate or focus magmatic–hydrothermal fluid flow that may be active for time spans significantly less than a million years. Once a hydrologically stable flow is established, ore formation is strongly dependent on the steep temperature and pressure gradients experienced by the fluid, particularly within the upper crust. In Europe, significant fracture porosity deep in the crystalline basement (~1%) is not only important for magmatic–hydrothermal systems, but allows brines to circulate down through sedimentary basins and then episodically upward, expelled seismically to produce sediment-hosted base-metal deposits and Kupferschiefer copper deposits. Emerging research, stimulated by GEODE, can improve the predicting power of numerical simulations of ore-forming processes and help discover the presence of orebodies beneath barren overburden.

Keywords: Geodynamic processes; Structural controls; Magmatic–hydrothermal systems; Ore formation

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1. Introduction

One of the prime aims of the European Science Foundation's GEODE programme (Geodynamics and Ore Deposit Evolution) was to identify and understand the geodynamic controls on the timing and location of major orebodies. Eight papers of this Special Issue (Neubauer et al., 2005—this volume, Paper 1; Marchev et al., 2005—this volume, Paper 2; Von Quadt et al., 2005—this volume, Paper 3; Tornos et al., 2005—this volume, Paper 4; Bouchot et al., 2005—this volume, Paper 5; Herrington et al., 2005—this volume, Paper 6; Muchez et al., 2005—this volume, Paper 7; Weihed et al., 2005—this volume, Paper 8) have addressed this issue for European mineral provinces and ore deposit types that featured in the GEODE programme, although not all European provinces are included. GEODE results on ore systems and their tectonic setting have also been presented in earlier thematic issues (Blundell et al., 2002; Heinrich and Neubauer, 2002; Von Quadt et al., 2004). The purpose of this concluding paper is to bring together the findings and ideas in the other eight papers of this Special Issue that offer new insights into the ore-forming processes and to see what lessons can be drawn from them.

2. Tectonic processes conducive to the formation of major mineral provinces

The mineral provinces described in Papers 1, 2 and 3 of the Special Issue evolved in a complex tectonic context. Progressive oblique convergence between the African and European plates over the past 100 million years, and movements and deformation of continental microplates caught between them in an evolving subduction complex, led to continental collision. Neubauer et al. (2005—this volume, Paper 1) describe the Cenozoic movements of continental blocks in the Alpine–Balkan–Carpathian region. These plates were driven mainly northward and eastward, overriding subducting oceanic lithosphere: the result was hinge retreat, or roll-back. The overall SW–NE shortening was partitioned broadly into northward thrusting and E–W strike-slip movement. Individual blocks moved at different rates, so that shear corridors developed between them; the blocks also rotated, creating further shears.

This scenario is similar to that occurring at the present time in the SW Pacific region, the focus of a supplementary GEODE project (see Blundell et al., 2005—this volume, Introduction). There, the movements of various crustal elements within an evolving subduction complex of magmatic arcs have been reconstructed by Hall (1996) for the past 50 million years, based on surface geology and palaeomagnetic measurements, supported by seismic and other geophysical information. Hall (2002) produced animations that reproduce the velocities and rotations of the various crustal elements and illustrate how most of the magmatism and ore deposits formed during three short intervals of plate reorganization, rather than during periods of steady-state subduction. King et al. (2002) demonstrated that transient plate reorganizations of this kind can be driven by localized instabilities in mantle convection (Fig. 1) in addition to the large-scale relative motions of major plates. Since 25 Ma, little or no volcanic activity occurred during hinge advance but was restricted to periods of hinge retreat (roll-back), accompanied by marginal basin formation (Macpherson and Hall, 2002). The most abundant and largest ore deposits, mainly epithermal, porphyry Cu–Au and skarn Cu–Au types (Barley et al., 2002; Macpherson and Hall, 2002), formed mainly in the last 5 million years in association with arc-related magmatism in transient tectonic settings. However, of 15 Cenozoic magmatic arcs recognized in the region, only 6 are known to

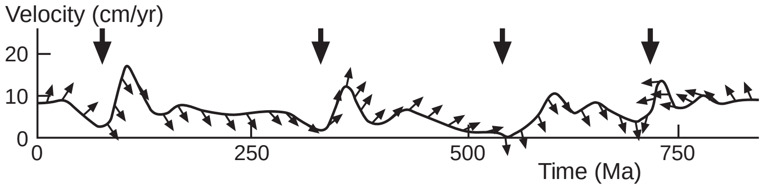

Fig. 1. Numerical model of plate motion due to instabilities in underlying convection (after King et al., 2002). Vertical arrows indicate abrupt changes in velocity; small arrows indicate direction of motion.

contain significant mineralization close to surface. Transient changes in plate configurations are insufficient alone to generate large ore deposits.

Continued evolution of the South-east Asia subduction complex includes the arc–continent collision between Timor and the Australian NW shelf, where the continental crust has been subducted (Richardson and Blundell, 1996). Subduction has stalled there and jumped further north, reversing polarity. A parallel can be found in the Alpine–Balkan–Carpathian region, but there the evolution went further as the suture of continent–continent collision migrated eastwards from the Alps to the Carpathians, leading to all-but-complete ocean closure in the Oligocene. As Neubauer et al. (2005—this volume, paper 1) explain, eastward movement of the Alpine–Carpathian–Pannonian (ALCAPA) and Tisia–Dacia blocks in the Oligocene–Neogene filled the Carpathian arc. With continental crust apparently being subducted from the east beneath the eastern Carpathians, subduction stalled and the slab was torn. The lower part became detached, allowing hot asthenosphere to rise through the gap (Wortel and Spakman, 2000). The Baia Mare and Central Slovakia polymetallic ore districts may be related to this south-eastward-migrating slab tear At the same time the ALCAPA block rotated 60° anticlockwise and the Tisia–Dacia block rotated nearly 90° clockwise. Widespread volcanism and shallow-level plutonism in the South Apuseni Mountains accompanied these movements, creating the Transylvanian Au–Te–Au province as Europe's most important gold mining district. Short-lived magmatism here was restricted to localized extensional settings related to the larger-scale shear corridors and block rotations. The time span of associated mineralization in each district was even shorter, barely 3 million years. Although Neubauer et al. (2005—this volume, Paper 1) propose that the rise of hot asthenosphere provided additional heat to weaken the overlying crust and initiate volcanism, the style of mineralization is distinctive in each of the three ore districts and is likely to have been controlled in each case mainly by factors within the crust.

Marchev et al. (2005—this volume, Paper 2) describe how, following a long period of repeated thrust-related Alpine compressional tectonics, the Rhodope Massif of southern Bulgaria and northern Greece was affected by a relatively short-lived period of late orogenic extension. This included the rapid uplift of metamorphic core complexes, such as the Central Rhodopean Dome (Madan Dome; Kaiser-Rohrmeier et al., 2004), extensional faulting and sedimentary basin formation. Accompanying this was magmatism in the form of dyke swarms, granite emplacement and volcanism, hydrothermal activity and ore formation. Although the magmatism coincided with the extensional deformation, the composition of the igneous rocks and the metal ratios of the ore deposits correlate with crustal thickness, and the Pb and Sr isotope signatures in all ore deposits indicate a crustal source component. The implication is that whilst plate tectonic processes controlled the structural and thermal evolution of the region, and the generation of mafic to intermediate magmas in the mantle, the more acid magmatism and the related Pb–Zn-dominated mineralization were dictated by crustal contamination of mantle-derived melts.

Von Quadt et al. (2005—this volume, Paper 3) explain how the Apuseni–Banat–Timok–Srednogorie (ABTS) belt developed as a magmatic island arc in the Late Cretaceous, when oceanic lithosphere subducted obliquely northward beneath the continental Moesian platform. As shown in their Fig. 1, the overriding tectonic control was plate convergence between Africa and Europe prior to continental collision. In regions of local extension coupled with strike-slip movements, calc-alkaline magmatism created a number of large volcanic–plutonic complexes. Extensive magmatism along the ABTS belt was related to an Andean-type subduction system, but ore formation was restricted to distinct across-arc corridors in which upper-crustal magma chambers evolved to generate a large flux of magmatic–hydrothermal fluids. Von Quadt et al. (2005—this volume, Paper 3) focus on the Srednogorie segment of the arcuate ABTS belt, which is crossed by the NNW–SSE oriented Panagyurishte corridor that, together with the Rhodopes, contains all of Bulgaria's major porphyry and high-sulphidation epithermal Cu–Au deposits. Using high precision dating, they established that the magmatism along this transect occurred in short bursts of less that a million years duration, separated by 1 to 4 million years, and that the magmatism migrated progressively from north to south between 92 and 78 Ma. North-to-south variations of Sr, Nd and Hf indicate a decreasing crustal input to the magmas; together with the age progression, these changes are attributed to slab roll-back or southward retreat of the subduction front. The associated short-lived hydrothermal mineral systems, typically centred on subvolcanic intrusions, were coeval with the magmatism. Beginning in the north at 92 Ma, the mineralization migrated southwards with the magmatism; after 85.5 Ma, the magmatism was barren. Coeval and subsequent block faulting and erosion allowed some high-level, high-sulphidation epithermal deposits to survive adjacent to deeper-seated porphyry deposits. The absence of deposits in the southernmost part of the Panagyurishte profile may be due to the deeper erosion level at the transition from the Srednegorie zone to the Rhodopes, due to uplift following the accretion of continental blocks there in the lower Tertiary. This accretion prepared the ground for the next cycle of crustal orogenesis in the Rhodopes, where Pb and Zn deposits are associated with silicic, crust-dominated magmas (Marchev et al., 2005—this volume, Paper 2). Whilst the broad-scale calc-alkaline magmatism of the ABTS belt appears to have been controlled by plate tectonic processes, ore formation required additional factors, including storage of magmas in upper-crustal magma chambers and structural focusing of fluids along faults and dykes – an interpretation that is similar to the evolution of the Andes (Richards, 2003).

Major mineral provinces formed in Europe in the late Palaeozoic, including the Variscides of SW Iberia and the French Massif Central and the Uralides in Russia (see Blundell et al., 2005—this volume, Introduction, Fig. 1). Tornos et al. (2005—this volume, Paper 4) describe the oblique collision of an exotic terrane with the continental mass of Iberia between 350 and 330 Ma. They point out that the metallogenic evolution of this region differs significantly from those in other collisional plate margins, probably due to the control of the dominant strike-slip tectonics.

Large pull-apart basins formed on the lower plate passive margin of the exotic terrane that hosts the giant VMS deposits of the South Portuguese Zone. These were compartmentalized into smaller linked subbasins with half-graben geometries, filled with sedimentary and volcanic rocks. Massive sulphide mineralization formed in brine pools, where metal-rich fluids from the basin mixed with sulphide-rich seawater, or in geochemical traps within seabed muds. Hydrothermal activity lasted no more than 6 million years and in the southern sector all the major VMS deposits formed within just 2 million years. The prolific scale of the mineralization in such a short time span is attributed to the crucial role of synvolcanic tectonic processes that triggered the generation and extraction of mineralizing fluids. Basin sediments were the sources of base metals in the massive sulphide deposits. Magmatic fluids appear to be absent and the role of magmatism was limited to a heat source that drove fluid circulation (Tornos, in press).

The Ossa Morena Zone in the overriding Iberian plate is dominated by a wide magmatic arc and has a very different style of mineralization. Mineralization lasted, on and off, for more than 50 million years. Evidence of high temperatures and mantle-like geochemical characteristics are consistent with a large laminar mid-crustal mafic intrusion that has been imaged on a deep seismic reflection profile. Tornos et al. (2005—this volume, Paper 4) argue that the most likely source of hydrothermal fluids and metals in the Ossa Morena Zone is in the middle crust, associated with the laminar mafic intrusion, and that small extensional zones in a transpressional setting provided pathways for the rise of fluids to higher crustal levels where a range of mineral deposits were formed, including iron-oxide hosted Cu–Au and orthomagmatic Cu–Ni–PGE deposits.

Gold mineralization in the French Massif Central is attributed by Bouchot et al. (2005—this volume, Paper 5) to a transition in the stress field controlling a brief episode of late-orogenic extension. Following a lengthy period of compressional tectonics between 400 and 330 Ma, crustal-scale thrusting thickened the continental crust of the French Massif Central. Compression gave way to synorogenic extension, resulting in the creation of a network of faults between 340 and 315 Ma and the intrusion of granites. A significant shift in the extensional stress direction, accompanied by granulite facies metamorphism at the base of the crust, then reactivated the fault network and caused rapid uplift of metamorphic core complexes and the formation of sedimentary basins. Two distinct mineralizing systems were active between 310 and 300 Ma. Au ± Sb deposits formed through circulation in large hydrothermal cells in a reactivated network of crustal-scale faults. Deposits of

W ± Sn and rare metals formed in smaller magmatic–hydrothermal cells related to the emplacement of specialized leucogranites. Lower crustal granulite-facies metamorphism was the source of both the heat that drove the hydrothermal circulation, and the ore metals. This interpretation is consistent with the origin of much younger and shallower detachment-related Au deposits such as Ada Tepe in the Eastern Rhodopes, described by Marchev et al. (2004, 2005—this volume, Paper 2).

Although slightly older, the Uralides suffered only low-grade metamorphism and its rocks and ore deposits are remarkably well preserved (Brown and Spadea, 1999). Herrington et al. (2005—this volume, Paper 6) describe how the VMS deposits of the South Urals formed in deep water environments during 1 to 2 million year intervals of intra-arc and back-arc extension that punctuated 15 to 20 million years of oceanic arc development (Herrington et al., 2002). Herrington et al. (2005—this volume, Paper 6) argue that the VMS deposits developed in distinct tectonic settings, each related to subduction-related volcanism, as the Uralide ocean progressively closed. Tectonic setting controlled the composition of the footwall volcanic rocks and in so doing influenced the chemistry of the VMS deposits. Thus tectonic setting had a major influence on their primary metal content. Most of the deposits formed as mound-type VMS systems on the sea floor but were modified and either degraded or upgraded by various sea floor processes, thus creating a wide range of orebody styles.

Weihed et al. (2005—this volume, Paper 8) focus on the early Proterozoic evolution of the Fennoscandian Shield, from 2.06 and 1.78 Ga, when rapid accretion of island arcs and microcontinent–continent collisions produced voluminous magmatism in relatively short-lived but intense orogenies. Nearly all the major ore deposits in the shield formed during this period; VMS deposits in localized extensional settings associated with arc volcanism, iron oxide–copper–gold deposits in association with calc-alkaline magmatism in continental arc settings, and Ni–Cu ± PGE deposits in rift basins, associated with mafic volcanism. Orogenic gold deposits formed during periods of crustal shortening related to syn- to post-peak metamorphism. In all cases, mineral deposit formation was confined to tectono-magmatic events of around 5 million years duration.

3. The origin of magmatic–hydrothermal ore provinces

3.1. Orthomagmatic deposits related to basaltic or picritic magmas

Orthomagmatic deposits, i.e., deposits in which silicate melts are the main agents of metal enrichment, are rare in Europe. One world-class exception is the Tellnes Fe–Ti oxide deposit in Norway, described by Weihed et al. (2005—this volume, Paper 8). This deposit, probably the second largest ilmenite resource in the world, is located in noritic rocks of the Rogaland anorthosite complex. The origin of this deposit is in many ways symptomatic of our knowledge of orthomagmatic deposits in general: the broad outlines are clear, but uncertainty surrounds the details. The anorthosite and norite host rocks probably formed through differentiation of a parental mafic magma; but the origin of this magma is problematic. Although the anorthosites are described as anorogenic, their relation to broader tectonic processes and the cause and the site of melting remain unclear. Some authors (e.g., Robinson et al., 2003) accept a plume model, while others (e.g., Duchesne, 1999; Weihed et al., 2005—this volume, Paper 8) advocate melting of delaminated lower mafic crust that sank into the underlying mantle. The ores consist mainly of ilmenite, an igneous mineral that crystallized along with the major silicate minerals. As discussed by Weihed et al. (2005—this volume, Paper 8), it is unclear whether the high concentration and tonnage of ilmenite in the deposit is due to an anomalously high Ti content in the parental magma, or to efficient concentration of ilmenite during or after its crystallization from the melt. Rather similar questions surround the origin of chromite deposits in Albania, Cyprus and in the South Urals.

Many orthomagmatic Ni–Cu–PGE sulphide deposits are known in Scandinavia, but most of these are small and low grade. The exception is the world-class deposits of the Pechenga district in the Karelia region of Russia, described by Weihed et al. (2005—this volume, Paper 8). The origin of these deposits is quite well understood. Picritic magma formed through mantle melting in a zone of long-lived continental rifting (2.5 to 1.9 Ga; Naldrett, 2004 and references therein) and ascended into the shallow crust where it encountered sedimentary rocks, before intruding as sills or erupting as lava flows. The assimilation of sulphur from these sediments led to the formation of immiscible Ni–Cu–PGE-rich sulphide liquid that segregated to the base of the host unit to form the ore deposits. The Svecofennian deposits of Finland and Sweden formed in a synorogenic accretionary margin setting, in intrusions emplaced shortly before or slightly after the peak of metamorphism. Deformation of these intrusions is believed to have played a role in ore formation, by "squeezing out" sulphide-bearing breccias from where they formed in mid-crustal chambers, to the shallower site of the ore deposits. The Aguablanca deposit in Spain, described by Martínez et al. (2005—this volume, Box 4-1), is believed to have formed in a similar manner.

3.2. Magmatic–hydrothermal deposits related to calc-alkaline magmatism

Calc-alkaline magmas provided the source of hydrothermal fluids that gave rise to Cu–Mo–Au mineralized porphyries and polymetallic vein deposits during the Alpine orogenic cycle. A persistent theme in several papers of this volume is that ore deposits formed in brief periods of time that correspond to changes in plate configurations, or to hinge retreat (roll-back), slab drop-off or delamination of the lithosphere. In such cases, normal subduction-related magmatism changed to magmatism influenced by entry of hot asthenospheric mantle into the region of mantle melting. These transitions are illustrated in Fig. 2. Under normal conditions in a subduction zone, a volatile-rich phase is released from the subducting oceanic crust, ascends into the mantle wedge and causes partial melting there. Because of forced convection, the mantle wedge is relatively cool and melts only when fluxed by subduction-derived water, assisted by corner flow from the asthenosphere of the overriding plate. The product is a relatively cool, water-rich magma. During roll-back or slab drop-off, an increased flux of hot asthenosphere rises up into the mantle wedge (Fig. 2b,c). In the first case, hot mantle enters a region overlying the slab, which continues to subduct and continues to release aqueous fluids. The product is a particularly hot, yet water-rich magma. When the slab breaks off, hot asthenosphere enters a region that is no longer subject to the fluid flux, and it should melt to give hot but water-poor magmas.

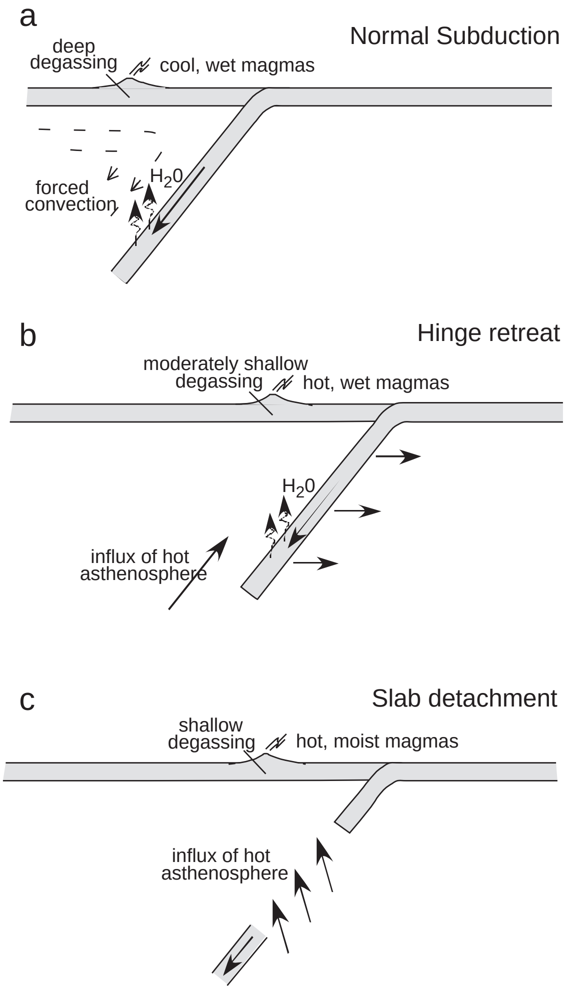

Fig. 2. Cartoons of magma generation at subduction zones (a) normal; (b) hinge retreat: (c) slab detachment.

The amount of water in a magma, and its temperature, influence how it ascends through the overlying crust, and how it releases hydrothermal fluids. Because the solubility of water in silicate melt decreases with decreasing pressure, hydrous magmas become water saturated and release hydrothermal fluids before reaching the surface. This happens deeper in the crust for a cool, water-rich magma than for a hot, water-poor magma. The hotter-than-normal magmas that form during roll-back or slab drop-off rise to shallower levels in the crust before releasing their fluids. Plate-scale interactions that generate hot and wet magmas favour the formation of magmatic–

hydrothermal ore deposits, by bringing the site of magmatic fluid generation into the upper crust.

Good evidence for hinge retreat is given in the study by Von Quadt et al. (2005—this volume, Paper 3) of the ABTS (or "banatite") belt. It is Europe's most extensive region of subduction-related, broadly calc-alkaline magmatism and also its main porphyry Cu–(Mo–Au) ore province. In the Bulgarian transect of the Panagyurishte district in the Srednegorie Zone, porphyry-style and high-sulphidation epithermal Cu–Au deposits are currently mined. At the mining-camp scale, both types of hydrothermal mineralization are closely related to coeval felsic subvolcanic intrusions (e.g., Chelopech and Elatsite). Across the entire 50-km-wide belt, however, the age of magmatic–hydrothermal centres changes from ca. 92 Ma at the northern border adjacent to the leading edge of the stable European continent to ca. 75 Ma in the southern part of the profile, possibly extending to even younger ages in the accretionary complex of the Rhodopes (Ricou et al., 1998; Von Quadt et al., 2005—this volume, Paper 3). Structural geology and zircon geochronology together indicate that migrating calc-alkaline magmatism and Cu–Au metallogeny in the Srednegorie Zone were caused by southward retreat or roll-back of a north-dipping subduction zone in the Upper Cretaceous. The evolution between 92 and 75 Ma initiated a long-lasting tectonic regime of accretion, slab retreat and extension. The geochemical characteristics of the magmas are those predicted for melts generated above a retreating slab. Despite multiple complications throughout the Tertiary, this southward migration continues to the present day, where subduction beneath Crete is associated with ongoing back-arc extension in the Aegean Sea (Von Quadt et al., 2005—this volume, Paper 3).

Slab tear and likely asthenospheric mantle rise are documented in the Miocene history of the Inner Carpathians (Lexa, 1999; Seghedi et al., 2004; Neubauer et al., 2005—this volume, Paper 1). Calc-alkaline magmatism becomes younger along the orogenic belt, from Hungary (~17 Ma) through Slovakia, southern Ukraine and northern Romania (14 to 11 Ma) to eastern Romania (nearly to the present). This progression is attributed to eastward migration of the point of slab tear, which ends near Vrancea (Wortel and Spakman, 2000) in easternmost Romania. This region, which overlies a vertically hanging slab imaged by mantle tomography (Linzer, 1996; Linzer et al., 1997), is one of Europe's most active sites of deep earthquakes. The older, already eroded western part of the calc-alkaline belt, hosts major polymetallic (Zn, Pb, Cu, Au and Ag) vein deposits such as Baia Sprie in Romania (Kouzmanov et al., 2005—this volume, Box 1-2).

An isolated region of high-K to shoshonitic and adakite-like calc-alkaline magmatism in the Apuseni Mountains of Romania is Europe's premier epithermal gold–telluride province – the "Golden Quadrangle", where intermediate-sulphidation epithermal Au–Ag ± Te deposits (e.g., Sacărîmb, Roşia Montană) are associated with medium-sized porphyry Cu–Au deposits (e.g., Roşia Poieni). This province lacks an elongate magmatic belt and, even though the products have many geochemical features of subduction-related magmas, there is no plausible coeval subduction zone that could have given rise to the magmatism (Roşu et al., 2004). Instead, distinct volcanic centres are related in time and space to progressive rotation of smaller crustal blocks, as a result of large-scale strike-slip tectonics (Neubauer et al., 2005—this volume, Paper 1). This is indicated by an amazing correlation between magmatic ages and the degree of palaeomagnetic rotation, which on the larger scale is associated with the indentation of the Adriatic microplate into the prominent S-shape of the Carpathian orogen (Roşu et al., 2004; see map and figures in Neubauer et al., 2005—this volume, Paper 1). Magma generation has been attributed to local ascent of asthenospheric mantle into disrupted, previously metasomatized mantle lithosphere, but the exact mechanism remains speculative.

Giant porphyry copper deposits form at times of tectonic compression of the crust, which may be caused by relatively flat slab subduction (e.g., Andes) or the collision of an ocean plateau (e.g., Solomon Islands) or a continent (e.g., eastern Indonesia to Papua New Guinea) with the overriding plate. The latter events are commonly marked by changes in the polarity of subduction (Solomon, 1990). In the magmatic provinces of Miocene age in the Carpathians, there is extensive field evidence for a combination of extension and strike-slip tectonics when magmas intruded the upper crust, with the development of copious volcanic rather than intrusive products. An extensional regime of this type favours the formation of low-sulphidation epithermal deposits in large open-space veins (Sillitoe and Hedenquist, 2003), which indeed predominate over the comparatively small, but locally quite high grade, porphyry-style or high-sulphidation deposits in the South Apuseni Mountains.

Although plate-scale extension due to slab roll-back may have prevented the formation of giant porphyry deposits such as those in the Chilean Andes, it generated the right hydrous magmas in the large Cretaceous andesite belt of Europe to form deposits with all the essential characteristics of their Chilean counterparts, and may have contributed to the preservation of the medium-sized European deposits. Extension during and shortly after magmatism and ore formation, again related to slab roll-back, may have prevented the rapid orogenic uplift and major erosion that characterizes most of the much younger giant porphyries around the Pacific. These deposits would be completely removed by erosion during the next million years. An extensional setting due to slab retreat may have preserved small but rich epithermal Cu–Au deposits like Chelopech, which formed within a km of the Cretaceous land surface and whose altitude may never have exceeded 1000 m.

4. Structural controls at the scale of an ore-forming system

Structures in the crust–faults, stratification and other heterogeneities–guide the passage of ore-bearing fluids or magmas, condition the interaction between fluid and host rock, and influence the precipitation of ore minerals.

By far the most important structures in this respect are fractures and faults. Open fractures provide ready pathways for fluids and space for vein-forming minerals. In the brittle upper crust, fractures tend to open in directions perpendicular to the least principal stress, especially if they are newly formed, rather than inherited. A necessary condition for them to open widely is that they fill with a supporting fluid under pressure. Hydraulic fracturing (or hydrofracturing) is the process by which they form and propagate through the rock (Hubbert and Willis, 1957). There is good evidence that most epithermal veins form in this way, as do magmatic dykes and sills. Once consolidated, the infilling material preserves the veins. Otherwise, the fluids would at some stage escape, allowing the fractures to collapse and become less visible (Cosgrove, 1995). Most veins and dykes that have formed by hydraulic fracturing are vertical, indicating that the least principal stress was horizontal. This may have happened, either in a purely extensional context, where the greatest stress was vertical, or in a strike-slip context, where it was horizontal. Hydraulic fracturing under an external stress field produces a regular pattern of veins or dykes.

Parallel veins indicate that the external stress field was regionally uniform at the time of formation, whereas radiating ones indicate a central maximum. The source may have been a magmatic conduit, chimney or volcanic neck, where the fluid pressure was highest. Both types of pattern are present in the European ore provinces described in this volume. Three papers describe regions of late orogenic collapse, where deformation resulted from a combination of crustal thinning and strike-slip faulting. In the eastern Carpathians (Neubauer et al., 2005—this volume, Paper 1), most veins strike NW–SE to NE–SW and they are compatible with regional extension marked by larger-scale graben structures containing coeval volcanics; in the Rhodopes (Kaiser-Rohrmeier et al., 2004; Marchev et al., 2005—this volume, Paper 2), they strike mainly E–W to SE–NW, compatible with N–S extension; and in the Massif Central (Bouchot et al., 2005—this volume, Paper 5), they strike nearly N–S, compatible with E–W extension. These correlations between vein orientations and tectonic context are convincing, because the data are numerous and of good quality, the deformation is relatively recent, the rocks are brittle, and the veins have escaped later erosion or alteration. It is much more difficult to draw conclusions of this kind where the rocks are old and the tectonic context is less well understood, as in the Fennoscandian Shield (Weihed et al., 2005—this volume, paper 8); or where they have been through several orogenic cycles, as in the south Urals (Herrington et al., 2005—this volume, Paper 6).

Marchev et al. (2005—this volume, Paper 2) describe radial swarms of dykes and veins around Borovitsa and Madjarovo volcanoes in the Rhodopes of Bulgaria; both types of structure probably exploited the radial stress field generated by the intrusion of the central magmatic conduit or chimney. On a more regional scale, Marchev et al. (2005—this volume, Paper 2) also describe Oligocene dyke swarms that strike E–W, parallel to coeval veins containing precious metals.

The horizontal orientation of many sheet-like orebodies results directly or indirectly from the force of gravity. In near-surface settings, flat-lying intrusions or veins are common. When magma ponds at a density discontinuity, it forms a sill in which sheet-like orthomagmatic deposits develop as a result of crystal settling. In undeformed sedimentary piles, horizontal strata guide the development of orebodies, either by influencing the passage of ore-forming magmas or fluids, or by providing chemically reactive layers that are susceptible to replacement by circulating fluids. Chemical sedimentation from hydrothermal vents, at or just below the sea floor, results in flat-lying lensoid orebodies, as during the formation of VMS deposits. Less obviously, perhaps, some horizontally extensive orebodies may form by hydraulic fracturing (Hubbert and Willis, 1957) in a compressional context, where the least principal stress is vertical (Galland et al., 2003), or in other contexts, if bedding surfaces are less cohesive than surfaces in other orientations (Cosgrove, 1995). For a given sheet-like orebody, it may be difficult to decide which of these factors has provided the main structural control.

Almost all of the papers in this volume describe examples of sheet-like orebodies. Weihed et al. (2005—this volume, Paper 8) describe mineralized intrusions in the Fennoscandian Shield, which formed when heavy minerals such as ilmenite or sulphide settled out of melts. Papers by Tornos et al. (2005—this volume, Paper 4), Herrington et al. (2005—this volume, Paper 6) and Weihed et al. (2005—this volume, Paper 8) refer to orebodies that resulted from hydrothermal processes at or near the free surface, good examples being the VMS deposits of the Urals (Herrington et al., this volume, Paper 6) and the South Portuguese Zone (Tornos et al., 2005—this volume, Paper 4). Papers by Marchev et al. (2005—this volume, Paper 2), Von Quadt et al. (2005—this volume, Paper 3), Tornos et al. (2005—this volume, Paper 4) and Bouchot et al. (2005—this volume, Paper 5) refer to orebodies in skarns that formed by chemical replacement of beds.

The most obvious manifestation of control by pre-existing structure on the distribution and orientation of orebodies lies in the association between ores and faults. In the brittle upper crust, shear faulting is the norm, if the effective stresses are compressive and relatively large. This generally implies that fluid pressures are closer to hydrostatic than lithostatic. Otherwise, at each point the vertical gradient of overpressure induces a seepage force that contributes to the overall balance of forces and results in small effective stresses (Mourgues and Cobbold, 2003). In a brittle rock, as in a granular material, shear failure is typically dilatant. The porosity increases as a result of microfracturing and the opening of new voids. Where hydrothermal fluids are present, the voids may fill with ore minerals or gangue. Episodic slip on the fault may lead to brecciation of the infill, as well as of the country rock. Eventually, there may be multiple phases of brecciation and infill.

The average permeability of a fractured rock tends to be greater, by several orders of magnitude, than the permeability of its non-fractured equivalent (de Dreuzy et al., 2002). In particular, a single, relatively long fracture will short-circuit the carrying capacity of all shorter fractures around it. For these reasons, orebodies tend to lie along major faults or at their intersections. This is especially true if faults are steep, so that they tap efficiently into the lower crust, the source of many ore-bearing fluids. In this volume, almost all papers refer to an association of mineral occurrences and faults. Bouchot et al. (2005—this volume, Paper 5) make a compelling case for such an association in the Massif Central.

A non-compressional tectonic context and a high fluid pressure may conspire to form arrays of vertical open fractures. As long as the fractures contain fluids, and not solids, they provide efficient and direct drains to the surface. If they fill with solid material, as during the precipitation of ore minerals, the permeability is reduced. For the flow to persist, in order to form an orebody, the process of opening and filling may proceed episodically, perhaps by the mechanism of crack seal (Ramsay, 1980). Earthquake activity, which is characteristically episodic, may provide the main driving forces. A periodic intake and expulsion of fluids by seismic pumping (Sibson et al., 1975; Sibson, 2001) may keep the fractures open and help to circulate large quantities of fluid over geological time. Muchez et al. (2005—this volume, Paper 7) draw on this mechanism to explain sediment-hosted deposits in Europe, including the Kupferschiefer copper deposits of SW Poland.

Pipes, vents or chimneys are steep axisymmetric structures whose form and orientation are only moderately influenced by the stress state or structure of the crust. Pipes form by fluidization (Davidson, 1995), a process that sets in when fluids at depth become so overpressured that they first counteract and then surpass the weight of the overburden, causing it to fracture and disaggregate. The rapidly ascending fluid carries the resulting fragments to the free surface and beyond. If the fluid is a gas, which dilates as the pressure drops, the process may become explosive, as in a Plinian volcanic eruption. Fluidization is a strongly dynamic process in which inertial forces are significant. Typically, it sets in at a point where the overburden is anomalously weak or light, to form a vent that flares outwards towards the surface. Once the pressure drops at depth, the fluid stops flowing and any fragments remaining in the vent coalesce to form a pipe breccia. The overall structure is sometimes known as a diatreme. If there is coeval horizontal extension, fluidization may result in a tabular vent that consolidates as a breccia-filled dyke. Like fault breccias, pipe breccias and dyke breccias have large porosities and may become mineralized as a result of late hydrothermal activity. Magmas that contain large quantities of dissolved gases may fluidize explosively. When a gas-rich magma reaches shallow levels, the pressure drops and the magma degasses violently, to produce a magmatic breccia (Cashman et al., 2000). Another possibility is phreatomagmatic fragmentation, when ascending magma encounters groundwater (Morrisey et al., 2000).

Mineral deposits in porphyry pipes and breccias are relatively common in south-eastern Europe. Neubauer et al. (2005—this volume, Paper 1) describe a diatreme, containing a mixture of tree logs with brecciated and subsequently altered and gold-mineralized dacite porphyry clasts, in the Roşia Montană deposit of the southern Apuseni Mountains of Romania. Other examples from the same region are the Deva porphyry Cu–Au deposit, an igneous to hydrothermal pipe breccia, and breccia dykes in the Baia Mare district. Von Quadt et al. (2005—this volume, Paper 3) describe distinctly pipe-shaped pyrite–enargite–Cu–Au orebodies of high-sulphidation epithermal character at Chelopech (Moritz et al., 2001, 2005—this volume, Box 3-2). Marchev et al. (2005—this volume, Paper 2) refer to small porphyry copper–molybdenum necks of Palaeogene age around Borovitsa caldera in the Rhodopes of Bulgaria.

5. Timescales and driving forces of hydrothermal fluid flow

Bouchot et al. (2005—this volume, Paper 5) describe the scale of the plumbing system for the late orogenic 310 to 300 Ma gold mineralization of the French Massif Central. Arsenic anomalies, directly related to the gold occurrences, have been mapped across an extensive area within the Massif Central and are associated with a network of major faults. The faults had initially developed some 10 to 15 million years before the mineralization during a period of Variscan syncollisional extension. Normal and strike-slip faults in the interior of the Massif were active at the same time as thrust faults around the exterior. The faults have been imaged on deep seismic reflection profiles to depths of around 15 km where they root into the ductile shear zones of the so-called “layered” lower crust. The As anomalies (Fig. 3 in Bouchot et al., 2005—this volume, Paper 5) indicate that the hydrothermal plumbing system was up to 100 × 10 km in areal extent and the seismic profiles show that it could have been 30 km deep. Reactivated during a short period of rapid uplift and exhumation that was accompanied by the creation of migmatite–granite domes, the faults provided pathways for upward flow of mineralizing fluids. Bouchot et al. (2005—this volume, Paper 5) present evidence indicating (a) rapid upward flow of hot fluid at near-lithostatic pressure from at least 15 km depth, (b) a rapid drop in pressure to hydrostatic around 6 km depth and (c) an accompanying decrease in temperature from 450 to 200 °C. A second hydrothermal stage of Au deposition, at around 5 km depth and under hydrostatic pressure, was not accompanied by uplift and erosion. It probably resulted from pressure drops associated with seismic rupture. At the same time, but on a smaller scale, mineralizing fluids at hydrostatic pressure and carrying As–W ± Sn and rare metals were centred on small bodies of specialized leucogranites that intruded at depths of less than 5 km. Bouchot et al. (2005—this volume, Paper 5) show in this case that the scale of the plumbing system was closer to 10 × 10 km in areal extent. The forces driving fluid flow were thermally derived from a short episode of localized extension and rapid uplift, reinforced by erosional offloading and exhumation, that created high fluid pressure in the lower crust. The scale of the main hydrothermal plumbing system suggests that a large volume of fluid was involved, some 30 km^3 with a porosity of 0.1%.

Von Quadt et al. (2005—this volume, Paper 3) describe porphyry copper and Au–Cu epithermal mineralization in Bulgaria that was associated with Late Cretaceous volcano-plutonic complexes. Hydrothermal fluid flow was limited to the individual intrusions and their immediate surroundings, driven by the fluid pressure gradient between a crystallizing hydrous magma chamber and the hydrostatically pressured near-surface environment (e.g., Fournier, 1999). Von Quadt et al. (2005—this volume, Paper 3) established that the hydrothermal circulation that formed an individual ore deposit lasted less than 1 million years, in line with observations on porphyry copper deposits in Chile, such as Chuquicamata (Ballard et al., 2001) and Potrerillos (Marsh et al., 1997), and with the numerical models of Cathles et al. (1997) for the maximum thermal lifetime of upper-crustal magmatic–hydrothermal systems. The intimate association of porphyry-type and high-sulphidation epithermal deposits in the ABTS belt (Von Quadt et al., 2005—this volume, Paper 3) requires both a common source of magmatic and hydrothermal fluids, and hydrological conditions that permitted fluid cooling under elevated pressure in a confined crustal stress regime (Tosdal and Richards, 2001). In contrast, in low-sulphidation epithermal systems such as those in the Rhodopes, a large-scale extensional regime of core complex uplift favoured deep circulation of meteoric water along major open fractures (Marchev et al., 2005—this volume, Paper 2). A particularly efficient mechanism for the transfer of gold from a magmatic fluid source to an epithermal deposit involves initial separation of buoyant Au–S-rich vapour from a Fe-rich brine (typically observed in porphyry deposits) and subsequent ascent and contraction of the vapour phase at elevated pressures in the single-phase fluid stability field, allowing it to contract to a very gold-rich epithermal liquid (Heinrich et al., 2004).

In the geotectonic regime of the Carpathian belt, indentation of the Adriatic microplate led to rotational strike-slip deformation, which created more local extensional and compressional environments. Examples include the horsts and basins in the Miocene magmatic–hydrothermal provinces of the Apuseni Mountains and large extensional jogs along major strike-slip faults, such the giant Baja Sprie vein in the Inner Carpathians. Typically, both ore provinces contain major low to intermediate-sulphidation epithermal gold deposits together with minor to significant, but not world-class porphyry Cu–Au deposits (Neubauer et al., 2005—this volume, Paper 1). However, even the epithermal deposits probably have an essential component of low-salinity magmatic fluid input, as indicated by current fluid inclusion work at the Roşia Montană Au–Ag deposit (Wallier, Rey and Kouzmanov, unpublished data). Similarly, Tornos et al. (2005—this volume, Paper 4) propose that crystallization of highly contaminated magmas emplaced as large mid-crustal sills can liberate a vast amount of fluid, greater than 1200 km^3, sufficient to form large ore deposits. Examples include some of the hydrothermal deposits of the Iberia belt (Tornos et al., 2005—this volume, Paper 4), the genetically enigmatic iron oxide-hosted Cu–Au deposits (Weihed et al., 2005—this volume, Paper 8) and perhaps the gold-bearing mesothermal quartz veins of the Massif Central (Bouchot et al., 2005—this volume, Paper 5), all of which have no obvious connection with mantle-derived magmas.

In contrast, the fluid circulation systems associated with basin-hosted Zn–Pb deposits in Europe appear to have operated episodically for tens of millions of years. Muchez et al. (2005—this volume, Paper 7) argue that metal-bearing brine originated as seawater (or as evaporated seawater) and not only circulated within the sedimentary basin but also migrated down through the basin into fracture networks within the underlying basement. The hot brine scavenged metals from the basement rock, and was then expelled during periods of active extension at times of seismic fault rupture. Blundell et al. (2003) use this mechanism to account for the volume of brine needed to form the copper deposits of the Kupferschiefer in the Lower Silesia basin of SW Poland, based on estimates by Muir-Wood and King (1993) of the amount and duration of water expelled to surface by recent normal faulting in the Basin and Range Province, USA. Their model demonstrates the capacity of fluid flow in basement rocks with very low fracture porosity to provide large volumes of hot, metal-bearing brine by upward expulsion during repeated seismic fault rupture over a period of time. The driving forces are heat, which produced fluid pressures close to lithostatic in the basement fractures, and the mechanical forces that expelled the fluids and drove them through the sediment pile.

6. Source, transport and deposition: the conspiracy of chemical and physical processes forming major hydrothermal orebodies

The papers of this volume illustrate, with examples from Europe and elsewhere, that ore formation is an integral part of the geodynamic evolution of the Earth's crust and mantle. Ore formation does not require exceptional processes. This conclusion is emphasized by the global observation that similar types of mineral deposits form repeatedly in different times and places in similar geotectonic environments through much of Earth's history. There are, to be sure, some notable exceptions such as the impact-related Sudbury complex that hosts the world's biggest nickel deposits, komatiite-hosted Ni deposits that are restricted to the Archaean and early to mid Proterozoic, and the major iron deposits of the early Proterozoic, which are related to the evolution of Earth's atmosphere. What is remarkable, however, is the similarity of most ore deposits in Archaean and more recent terrains, despite differences in the overall geodynamic regime.

Mineral deposit types are consistently related to the major magma-generating processes on our planet – subduction, oceanic crust generation, mantle plumes – and to recurrent processes of large-scale fluid motion triggered by basin evolution, continental orogenesis and metamorphism. The recurrence of similar deposits in similar tectonic environments shows that ore-forming magmatic and hydrothermal processes are not "anomalous" as such, but rather widespread in a particular geodynamic environment. Indeed, the large size of individual ore deposits provides fundamental constraints on the scale and duration of these lithospheric mass transport processes, notably the large scale of hydrothermal fluid flow and the quantities of fluid flowing through crustal rocks well after initial diagenesis. For example, the thousand-fold copper enrichment in a spatially restricted (< 1 km^3) major porphyry-Cu orebody requires the existence of a pluton that is at least 3 orders of magnitude larger (10 to 100 km^3) than the deposit, acting as an essential source of metal, fluid and sulphur. The giant sediment-hosted copper deposits in the Kupferschiefer require (based on the model of Blundell et al., 2003) the permeation of some 6000 km^3 of metalliferous brine not only through a major part of the Lower Silesian basin but through the underlying basement as well (Oszczepalski and Blundell, 2005—this volume, Box 7-4; Muchez et al., 2005—this volume, paper 7). A third example is the accumulation of large amounts of high-tenor Ni–Cu–PGE sulphide ore in the lower parts of small intrusions, such as those of the Pechenga region of Russia. Because the solubility of sulphur in silicate liquid, and the capacity of sulphide to extract metals from silicate liquid, are both low, to explain the quantity and the richness of the ore requires that a large volume of magma, many times that now present in the intrusions, flowed through the magmatic conduit system.

Although many lines of evidence show that the formation of ore deposits is a natural consequence of common and widespread geodynamic processes, really large and rich orebodies are rare. This is true even taking account of the fact that only a small part of the accessible crust is adequately explored and allowing for the possibility that many more large deposits remain to be found. Exceptionally large and rich, and therefore particularly valuable and economically important, ore deposits are rare because they require a particular combination of physical and chemical processes. Three groups of factors must work in conjunction to produce a major ore deposit.

First, high-grade ore formation requires not only efficient metal scavenging and transport by a large volume of chemically suitable fluid or melt, but also an efficient chemical trap; i.e., a mineral precipitation mechanism available at the same time and in the right location. Metal accumulation by mineral precipitation in any hydrothermal orebody is generally limited by mass balance, because it involves chemical reaction of a focused interaction of a large quantity of fluid with a relatively small mass of rock. Thus, according to the model of Blundell et al. (2003), saline and oxidized brines in and beneath the Lower Silesian basin, SW Poland, were capable of dissolving and transporting large amounts of chloride-complexed Cu, together with S in the form of sulphate, from the basement and into the microseismically active part of the basin.

The generation of the rich Lubin deposit within the much larger area of subeconomic Kupferschiefer additionally required an adequate availability of a reductant. This not only included in-situ organic material and pyrite in the thin Kupferschiefer bed, but probably also mobile liquid and/or gaseous hydrocarbons that accumulated in the dune and lagoon environment along the southern coastline of the basin (Karnkowski, 1999). A contrasting example is the Salton Sea geothermal field, in which a vast volume of Cu and Zn-rich brines are in convective motion and contain enough metal to generate a major ore deposit (McKibben et al., 1988). These fluids are compositionally very similar to those that formed the giant Mount Isa copper deposit, but will never precipitate their ore metals in an economic orebody unless they are focused into a chemically reactive trap, such as the pyritic and organic-rich carbonate sediments that determined the precipitation site for the Mount Isa copper orebody (Heinrich et al., 1995). A third example is the Ni–Cu–PGE deposits of the Noril'sk–Talnakh region in Russia, which formed when picritic magmas with compositions like those in volcanic plateaus worldwide encountered a series of evaporitic sediments. The result was the formation of some of the world's most valuable ores. The hot picritic magma assimilated anhydrite, a source of sulphur and coal, a reductant, leading to the segregation of sulphides that scavenged ore metals from the magma (Naldrett, 2004).

Second, the formation of a large and rich orebody requires a subtle balance of competing non-equilibrium processes, which must interact in such a way that ore metals not only precipitate in large quantity, but also concentrate in one location. Broadly speaking, porphyry copper deposits form as a result of the steep temperature and pressure gradients between a crustal plutonic source of hot fluids (typically at ~900 °C and ~5 km depth) and the cool land surface. More precisely, recent fluid inclusion microanalysis has indicated that Cu–Fe–sulphide precipitates in response to fluid cooling over a relatively small temperature interval between ca. 425 and 350 °C (Ulrich et al., 2001; Kehayov et al., 2003; Landtwing et al., 2005). Even given a large volume of metal-rich magmatic–hydrothermal ore fluid, high-grade ore will only accumulate if a hydrologically stable fluid flow environment is established for some time (Heinrich et al., 2005). Stabilizing factors conducive to ore formation at sites of overall thermal and chemical disequilibrium include self-sealing by mineral precipitation alternating with renewed hydraulic fracturing, heat exchange between convecting meteoric fluids around a major channelway of hot ascending magmatic fluid and the self-organization of convection cells in hydrostatically pressured submarine environments.

A third critical parameter controlling the distribution of large and rich ore deposits is their depth below the present land surface. For a variety of geological reasons, discussed below, many ore forming processes operate much more efficiently within a few kilometres from the surface. An accumulation of ore minerals that forms, and remains, tens of kilometres below the surface will never constitute an orebody. Arndt et al. (2003, in press) have argued that picritic magmas at Noril'sk initially assimilated granitic wall rocks at mid-crustal depths to form a sulphide body well below, and inaccessible from the mining operations that exploit the near-surface, sediment-derived orebodies.

Most hydrothermal ore formation occurs as a result of chemical and thermal gradients, and these are generally most extreme close to the Earth's surface. Extreme redox contrasts exist between the Earth's interior and its surface environment in contact with an oxygenated atmosphere, but also within the crust at contacts between oxidized sediments and more reduced environments containing organic materials derived from biota. Temperature gradients are steepest near the Earth's surface, where fluids and magmas expelled upward along focused conduits cool rapidly by thermal interaction with the open ocean bottom or the groundwater-saturated land surface. Thus most major deposit types form within a few kilometres of the Earth's surface, including all the base metal and most gold deposits discussed in this volume. However, near-surface conditions favourable for ore formation can be in areas with active surface uplift and erosion that are liable to destroy their own precious product shortly after its formation. Thus, rapid uplift and erosion in magmatic arcs overlying Andean-type subduction zones explains why the richest and largest epithermal gold and porphyry copper deposits are of Tertiary or even younger age. Special geological conditions must provide a mechanism for the protection and longer-term preservation of older deposits. The likelihood of preservation explains, at least in part, why the most productive ore deposits in any one area commonly relate to the last event of major thermal disturbance, although large deposits due to earlier ore-forming cycles can be reworked and even upgraded under special circumstances (e.g., metamorphosed sedimentary-exhalative Pb–Zn–Ag deposits of Broken Hill style, currently searched for in the Fennoscandian Shield). Rich high-sulphidation epithermal deposits in the ABTS belt (e.g., Chelopech; Moritz et al., 2005—this volume, Box 3-2) are among the geologically older examples of their type, and their preservation probably depended on the block-faulting due to extension attending subduction roll-back, shortly after ore formation in the Late Cretaceous.

In summary, the formation and present-day distribution of economic ore deposits reflects the history of the lithosphere, which is particularly long and complex in Europe, extending from the Archaean events of the Fennoscandian shield through to the presently active plate margin between Eurasia and Africa. Although ore deposits appear to be anomalous in their composition and degree of geochemical element enrichment, their formation and preservation are systematic and therefore predictable. Future research will focus on clarifying the large-scale lithospheric and sublithospheric processes underlying ore formation, such as the relationships between mantle melting, the passage of magma through the crust and the formation of magmatic ore deposits. Another major thrust of long-term significance for the supply of essential resources, which are increasingly difficult to find as exposed deposits become depleted, is to improve the predictive power of numerical simulations of ore-forming processes to find undiscovered orebodies beneath barren overburden. The aim is to combine increasingly sophisticated 4-D observational data (3D geophysical observations, geochronology, palaeofluid compositions derived from micro-inclusions) with numerical models for magma emplacement, structural evolution in a deforming rock mass and fluid flow, as well as chemical fluid–rock reaction. A new era of ore-genesis research is emerging, in which a quantitative understanding of fundamental processes will be used to predict the most likely location of as yet undiscovered, but increasingly essential mineral resources. The understanding of these processes and the development of numerical simulation tools will also contribute to improve the methods of extracting these increasingly deep-seated resources with less deleterious impact on our living environment. GEODE research in Europe has helped to pave the way for these exciting new developments.

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