The Timing and Location of Major Ore Deposits in an Evolving Orogen

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The Timing and Location of Major Ore Deposits in an Evolving Orogen

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Preface

When asked in 1996 what he thought was the major problem in geology still unresolved, Professor Rudolph Trümpy replied 'find the connection between mountain building processes and ore deposit formation'. His remark inspired the European Science Foundation to set up a five-year scientific programme in 1998 to investigate geodynamics and ore deposit evolution, GEODE, on a European scale. The GEODE programme was organised into five main projects, based on metallogenic provinces in Europe, supplemented by studies of metallogeny in the tectonically active regions of South America and the SW Pacific. A global comparison of major volcanic-hosted massive sulphide (VMS) deposits was also initiated. Metallogenesis has been related to geodynamic processes operating on a wide range of scales in space and time, involving large-scale processes conducive to the generation of magmatic and mineral fluids within the lithosphere–asthenosphere system, processes transporting and transforming those fluids through interactions with their surroundings in an ever changing thermal and pressure regime, and processes concentrating and depositing metals within the ore deposit regime progressively over time. To gain an understanding of these processes it is essential to examine them where they have been recently, or are currently, active and where information about the structure and characteristic properties of the lithosphere, and how they are evolving, can be gained from geophysical, geochemical, geochronological and other observations. As a consequence of previous European Science Foundation programmes, such as the European Geotraverse and EUROPROBE, the properties, structure and evolutionary history of the lithosphere of Europe is better known than almost anywhere else in the world. Metallogenic provinces in Europe range in time from the Archaean–Early Proterozoic to the Palaeozoic, to the Cenozoic and, in particular, in the active region of the Alpine–Balkan–Carpathian–Dinaride (ABCD) belt, to the Neogene. The latter, in comparison with the regions of South America and the SW Pacific, affords the opportunity to investigate metallogeny in a variety of modern tectonic contexts.

The contents of this book reflect these ideas. They are based on a symposium organised by GEODE and SGA (Society for Geology Applied to Mineral Deposits) held during the European Union of Geosciences Assembly in March 2001 entitled 'the timing and location of major ore deposits in an evolving orogen'. Although the majority of papers relate to Europe, their findings have a global significance for metallogenesis. Figure 1 provides a key to their locations. An introductory paper by **Blundell** to set the scene is followed by an account by **Allen & Weihed** of global comparisons of VMS districts from the first findings of a new international project. They conclude that the main VMS ore deposits take less than a few million years to form and generally occur near the top of a succession of felsic volcanic rocks within an extensional environment. A series of papers then examine various aspects of modern orogenic systems, starting with two (**Barley *et al.*** and **Macpherson & Hall**) on the SE Asia/SW Pacific region that demonstrate the speed of tectonic processes and the short duration of magmatic and mineralizing events. The latter are shown to relate to transient effects in a subduction complex, often through plate reorganization, rather than to steady state subduction. Changes in the balance between recycled fluxes of slab-derived fluid and sediment melt exert an important control on the chemical composition of arc lavas and, consequently, on their content of economically important metals. Arc-related magmatism in unusual tectonic settings produced the most abundant and largest deposits in SE Asia, the vast majority of which have formed since 5 Ma. It appears that whilst the timing of magmatic and metallogenic events can be explained in relation to tectonic changes, it is much more difficult to explain the tectonic controls on the locations of ore deposits. Papers by **Lips** and **Neubauer** identify the connections between collisional tectonics and ore deposit evolution in SE Europe and the ABCD belt, particularly relating to slab rollback in earlier stages and slab tear and detachment subsequently. **Lips** points out that roll-back of subducted lithosphere, restoration of orogenic wedge geometry and slab detachment are all scenarios that favour extension and the transfer of heat to relatively shallow lithospheric levels. Within the context of near-continuous subduction in the ABCD region over the past 100 Ma, **Neubauer** recognizes two periods of short-lived, late-stage collisional events that led to calc-alkaline magmatism and mineralization, in the Late Cretaceous and Oligocene–Neogene. In both periods, the type of mineralization and its timing changes progressively along the strike of the magmatic/metallogenic belt, which Neubauer links with the process of lithospheric slab tear observed independently in the

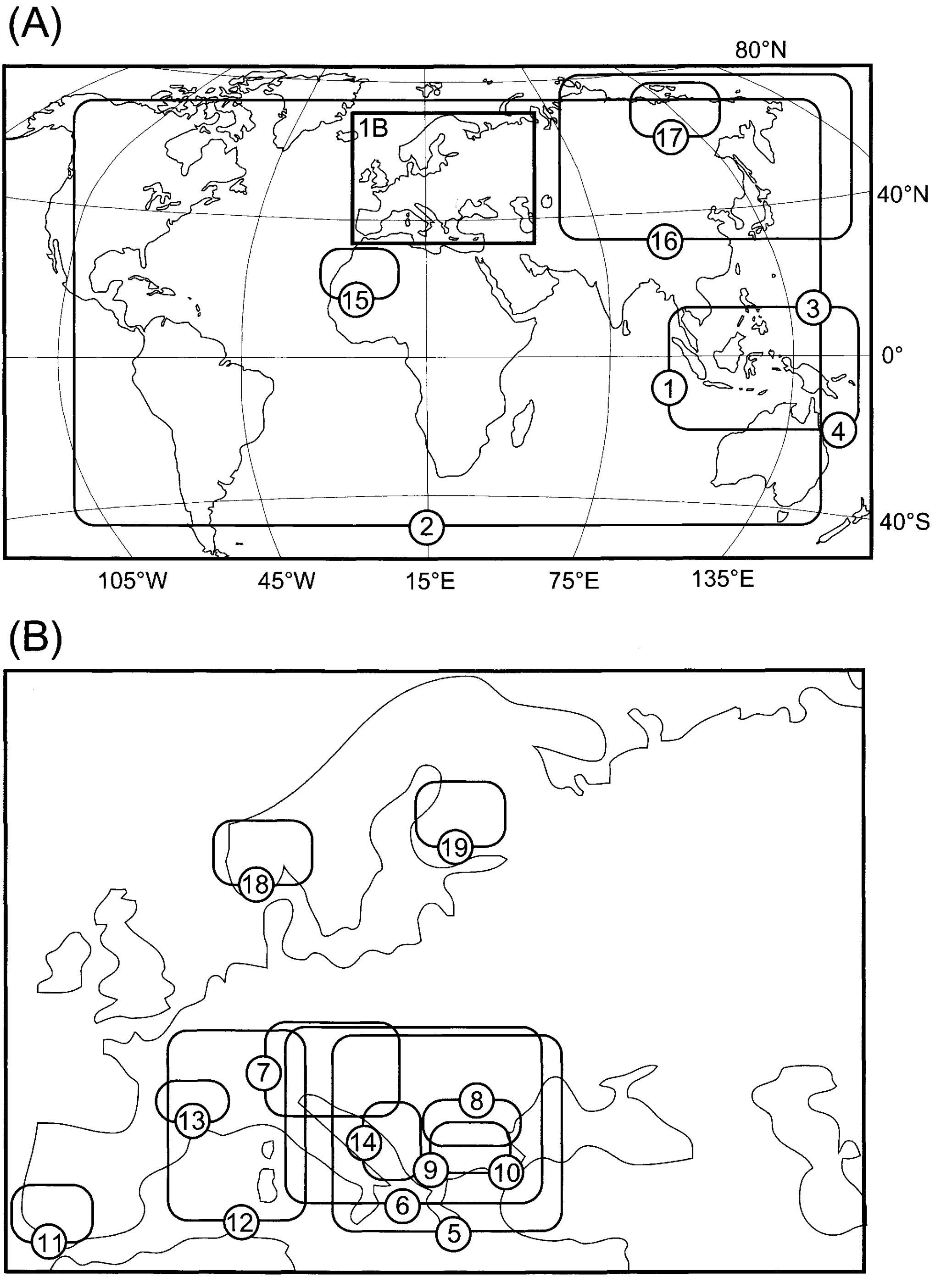

Fig. 1. Key maps showing general locations relating to the papers. (**a**) World map: 1, Blundell; 2, Allen & Weihed; 3, Barley *et al.;* 4, Macpherson & Hall; 15, Chauvet *et al.*; 16, Yakubchuk; 17, Fridovsky & Prokopiev. (**b**) Map of Europe: 5, Lips; 6, Neubauer; 7, Amann *et al.;* 8, von Quadt *et al.;* 9, Marchev & Singer; 10, Krohe & Mposkos; 11, Tornos *et al.;* 12, Boni *et al.* 13, Cuney *et al.;* 14, Jurković & Palinkaš; 18, Stein & Bingen; 19, Rajavuori & Kriegsman.

area from seismic tomography and other evidence. Papers by **Amann *et al.*** and **von Quadt *et al.*** explain the timing and genesis of specific ore deposits in the Eastern Alps and the Bulgarian Srednogorie zone of the Carpathians, respectively. **Amann *et al.*** examine late-tectonic gold mineralization of Oligocene–Miocene age related to a complex transtensional shear regime of conjugate strike-slip faults. **Von Quadt *et al.*** use high precision U–Pb dating of individual zircons from dykes bracketing the time of formation of the Elatsite porphyry Cu–Au deposit to demonstrate that the high-temperature ore forming process was constrained to a very short period within the Late Cretaceous collisional event, between 92.1 ± 0.3 and 91.84 ± 0.31 Ma ago. A paper by **Marchev & Singer** looking at the timing and nature of magmatism and hydrothermal activity in the eastern Rhodope region is complemented by an analysis of the structural evolution of the Rhodope mountains by **Krohe & Mposkos**. **Marchev & Singer** show how short the duration of volcanism and hydrothermal activity can be in a single ore district. They find that volcanism in the Madjarovo volcanic complex and ore district in Bulgaria began at 32.7 Ma and finished by 32.2 Ma, at which time the hydrothermal activity and fault-controlled base/precious metal mineralization occurred. This happened during a period, shown by **Krohe & Mposokos**, when the Rhodope region suffered pervasive deformation and granitoid intrusion, being uplifted, extended and exhumed through a series of inter-linked detachment faults.

Turning to older orogenic systems, one of the world's major metallogenic provinces is the Iberian Pyrite Belt of Southwest Iberia, set within the larger province of the western Variscides. **Tornos *et al.*** show how mineralization evolved as a consequence of oblique collisional plate tectonic processes. They find that most of the mineralization is related to localized extension in shear zones, pull-apart basins and escape structures within a regional transpressional regime in which deep, crustal-scale structures developed. Based on a detailed study of Sardinia, **Boni *et al.*** demonstrate the importance of large-scale, and persistent, fluid flow systems in the continental crust as a mechanism for ore deposit formation. They envisage a 'crustal-scale hydrothermal palaeofield' as applicable to much of the post-orogenic (Variscan) mineralization across western and southern Europe. **Cuney *et al.*** investigate the causes and effects of orogenic gold mineralization in the Massif Central, France. They distinguish two short-lived metallogenic episodes, related to emplacement of leucogranites. The first, *c.* 325 Ma, related to syn-collisional extension and the second, *c.* 310 Ma, related to general extension and rapid exhumation of the Variscan belt, possibly due to lithosphere delamination. **Jurković & Palinkaš** tackle the task of discriminating between Variscide or Alpide (Triassic) origins of ore deposits in the Dinarides, in Palaeozoic and Permo–Triassic allochthonous units thrust over Mesozoic–Palaeogene rocks during Alpine deformation. With radiometric dating not possible, they successfully developed a package of discriminatory criteria, involving (^{34}S isotope values, $SrSO_4$ content and fluid inclusion properties. **Chauvet *et al.*** explain the structural controls on copper mineralization in the High Atlas of Morocco, a southerly extension of the Variscides to north Africa. They relate the mineralization to a ductile tectonic event associated with granite emplacement some 20 Ma earlier. To the east, and on a grand scale, the formation of very large ore deposits in relation to the evolution of orogenic collages across eastern Asia through the Mesozoic and Cenozoic is explained by **Yakubchuk**. He is able to demonstrate that the timing of mineralization is related to plate reorganization and oroclinal bending of magmatic arcs. Interestingly, the location of major gold deposits is correlated with marine shelf and platform sequences containing black shales. Complementing this work is a paper by **Fridovsky & Prokopiev** describing gold mineralization on the eastern margin of the north Asia craton, an area rich in black shales.

Stein & Bingen demonstrate the immense value of Re–Os dating techniques for obtaining direct information about the ages of mineral occurrences in southern Norway, which enable them to pinpoint the timing of deformation and metamorphic change associated with the mineral occurrences to a duration of just 30 Ma, between 1047 and 1017 Ma. The strength of their approach, as they say, is that 'small ore occurrences in molybdenum-endowed regions of the Earth's crust are capable of unleashing important age information that bears on the metamorphic history and tectonic assembly of major orogens'. Finally, **Rajavuori & Kriegsman** point out the role of fluorine as a pathfinder in metamorphic hydrothermal volcanogenic massive sulphides. Their study of F in Zn–Cu–Pb deposits in Finland and Australia examines the role of F in the fluid transport system of magmatic–hydrothermal ore formation.

The overall conclusion to be drawn from this collection of papers is that ore formation in magmatic–hydrothermal systems occurs over a short period of time, probably less than a million years, usually at or close to the end of a magmatic event. The timing relates to a transient effect of plate reorganization, which creates heat and a particular style of magmatism conducive to the generation of mineralizing fluids. Specific scenarios have been proposed. The location of ore deposits is difficult to pinpoint but is often controlled by localized extensional structures developed within a regional transpressional regime. But what controls the amount of mineralization produced and what determines where it is concentrated into very large ore deposits remain obscure.

All the papers in this book have benefited greatly from the critical assessments and helpful comments given by referees, who have given freely of their time and expertise. We would like to thank the referees, D. Alderton, M. Anderton, S. Cuthbert, T. Berza, A.-V. Bojar, H. de Boorder, K. Clark, R. Clayton, N. Cook, L. Diamond, M. Economou-Eliopoulos, M. Faure, H. Fritz, Ch. Gauert, J. Glodny, R. Hall, R. Handler, W. Halter, Y. Kostitsyn, D. Kozelj, W. Kurz, R. Large, J. Lexa, E. Marcoux, K. McClay, S. McCutcheon, A. Mogessier, R. Moritz, L. Nakov, W. Nokleberg, S. Petersen, T. Pettke, J. Raith, J. Relvas, J. Ridley, J. Schneider, S. Sengör, C. Spöttl, M. Tichimorova, F. Tornos, P. Tropper, N. White, E. Willingshofer and M. Wortel.

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