CHI Guoxiang and LIN Ge, 2014. Relationships between Hydrodynamics of Mineralization and Tectonic Settings. *Acta Geologica Sinica* (English Edition), 88(supp. 2): 1597-1599.

Relationships between Hydrodynamics of Mineralization and Tectonic Settings

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1 Introduction

Metallogeny is a study of ore genesis in the context of tectonic settings, with emphasis on tectonic control on regional and global distribution of mineral deposits (Chen, 1978; 1982; Mitchell and Garson, 1981; Sawkins, 1990). Most mineral deposits formed from circulation of large amounts of geologic fluids over extended periods of time, driven by various geologic forces, and hydrodynamics is an important part of mineralization models (Chi and Xue, 2011; Ingebritsen and Appold, 2012). The flow direction, velocity and pathway of ore-forming fluids as well as the dissolution and precipitation of minerals are closely related to tectonomagmatic and structural processes in different tectonic environments (e.g., Lin et al., 2003; 2006; Zhu et al., 2013). However, most metallogenic studies focus on the geochemical aspects, and no systematic studies of the hydrodynamics of mineralization in different tectonic settings seem to have been carried out. This paper aims to examine the relationships between the hydrodynamics of mineralization and tectonic settings, adding a new component to metallogenic studies.

2 Fundamental Relationships between Tectonic Settings and Geologic Fluid Flow

The driving forces of geologic fluid flow include topographic relief, rock deformation (including sediment compaction), and fluid density variation (especially those related to geothermal gradients, thermal anomalies, and salinity anomalies) (Chi and Xue, 2011). These factors, as well as rock permeabilities that affect fluid flow velocities, are intimately related to tectonic settings. For example, topographic relief is unavoidably associated with orogenies, and geothermal gradients are closely related to the depth of the asthenosphere. Therefore, geologic fluid flow systems in different tectonic settings are deemed to be systematically different.

3 Fluid Flow in Tectonically Active versus Stable Environments

The driving forces for geologic fluid flow are relatively weak in tectonically stable environments. Such environments are characterized by low topographic relief, and low geothermal gradients, thus weak topography-driven and thermally driven fluid flow systems. The sedimentation rates in this kind of setting (e.g. intracratonic basins) are also typically slow, leading to very minor fluid overpressure and slow fluid flow related to sediment compaction.

In contrast, tectonically active environments are characterized by high topographic relief, high geothermal gradients, abundance of heat anomalies (e.g., magmatic intrusions), various rock deformations (e.g., folding and faulting), and high sedimentation rates in the basins. Consequently, geologic fluid flow systems are generally stronger and more diversified in tectonically active regions. This may be one of the fundamental reasons why mineral deposits (especially hydrothermal deposits) are much better developed in tectonically active environments than stable ones.

4 Fluid Flow in Convergent versus Extensional Tectonic Environments

The tectonically active environments can be broadly divided into convergent and extensional ones, the former being exemplified by orogens including subduction zones and overlying magmatic arcs as well as inter-continental or inter-terrane collision zones, and the latter by rifts, mid-ocean ridges, and back-arc spreading centers. Each of these environments is endowed with different combinations of mineral deposits, in part due to different hydrodynamic regimes.

The convergent tectonic settings are generally

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characterized by high topographic relief on the surface, high fluid overpressures (lithostatic or supralithostatic pressures) at depths, and abundance of magmatic intrusions. Both the compressional stress regime and the fluid production process (including fluid released from the subducting plate and from metamorphism of crustal rocks) contributed to the building up of fluid overpressure, which drives an overall upward fluid flow. The fluid flow can be channeled along shear zones and faults, which may be responsible for mineralization at great depths, such as orogenic gold deposits. Fluid flow associated with magmatic intrusions include those driven by the fluid pressure contrast between the interior of intrusions (lithostatic and supralithostatic) and the country rocks (hydrostatic and suprahydrostatic), and those driven by forced convection due to the heat imposed by the intrusions, both contributing to the formation of mineral deposits such as porphyry copper. The topographic relief is important for the involvement of meteoric water in the formation of epithermal deposits, the supergene enrichment of porphyry copper deposits, as well as in driving continent -scale basinal fluid flow responsible for the formation of Mississippi Valley-type Zn-Pb deposits.

The divergent or extensional tectonic settings are generally characterized by extensional stresses and therefore the hydrostatic fluid pressure regime may extend to greater depths than in convergent environments. The extensional settings are also commonly associated with upwelling of the asthenosphere or thinning of the lithosphere. The combination of these two factors favors the development of thermally-driven fluid convection systems, such as in the formation of VMS deposits. In continental environments, the extensional stress regime also favors the penetration of meteoric water into great depths of the crust and mixing with fluids of other origins, as was suggested for the formation of Carlin-type gold deposits. In extensional sedimentary basins where the SEDEX type deposits were typically formed, the fluid flow patterns may vary from overpressure-driven, upward-dominated flow systems to thermally-driven or salinity-driven convection systems, depending on the sedimentation rate. Overall, however, the extensional stress regime tends to make the basin "leaky", thus unfavorable for development of strong fluid overpressure as in foreland basins (convergent setting).

5 Evolution of Fluid Flow Mechanisms

The metallogeny evolves with the tectonic settings, and so does the hydrodynamics of mineralization. Mineral deposits formed in the early stages are potentially subjected to reworking by the later stages, under very different fluid flow regimes.

Thermal convection-dominated mineralization systems are best developed in the early stages of the Wilson cycle. These are succeeded by the various fluid flow systems related to the subduction zones and magmatic arcs, and then by those in the orogens and collision zones.

The various vigorous fluid flow and mineralization systems in the geosyncline stage (including all those in a Wilson cycle) are followed by relatively quiet fluid flow regimes in the platform stage. However, strong fluid flow and mineralization activities are renewed in the diwa stage with relationship with post-platform tectonomagmatic reactivation, such as that typically developed in eastern China.

Fluid flow regimes also evolve with geological time. The overall high thermal gradients in the Archean and Proterozoic, which is favorable for thermally-driven fluid convection, may be partly responsible for the better development of VMS and SEDEX in the Precambrian than in the Phanerozoic. On the other hand, the abundance of orogenic gold deposits in the Precambrian may be related to the erosion required to expose these deeply formed deposits.

6 Conclusions

Metallogeny generally deals with the relationships between the genesis and distribution of mineral deposits and tectonic settings. In this paper, we demonstrate that the hydrodynamics of mineralization is also closely related to tectonic settings, and is an integral part of metallogeny. Geologic fluid flow is relatively strong and diverse in tectonically active environments than in stable ones. Convergent tectonic settings are characterized by strong fluid overpressures due to compressional stress regimes and fluid generation in metamorphic and subduction processes, as exemplified by orogenic type gold deposits and various deposits formed in the magmatic arcs. Whereas extensional environments are favorable for the development of thermally driven fluid convection due to extensional stress regimes and elevated thermal gradients, as in the formation of VMS and SEDEX deposits. The hydrodynamics of mineralization evolves with tectonic cycles, with mineralization systems related to fluid convection better developed in the early stages of a Wilson cycle, and overpressure-driven systems dominating in the late stages. Fluid flow systems are stronger and more diversified in the geosyncline and diwa stages than in the platform stage. Thermally driven fluid convection systems appear to have been better developed in the Precambrian than in the Phanerozoic, probably due to elevated geothermal gradients.

Acknowledgements

This study is in part supported by an NSERC-Discovery grant (to Chi). We devote this paper to late professor CHEN Guoda in memory of the 10th anniversary of his death. Professor CHEN made important contributions to the tectonics and metallogeny of China, and was a mentor to many geoscientists in China. We greatly benefited from his teaching when we were graduate students in the Changsha Institute of Geotectonics, Chinese Academy of Sciences.

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