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大地构造与成矿学
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Relationships Between Hydrodynamics of Mineralization and Tectonic Settings

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Abstract: The formation of most mineral deposits requires circulation of large amounts of fluids, which may be driven by various geologic forces. In this paper, we demonstrate that such forces are intimately related to tectonic settings. Geologic fluid flow may be driven by topographic relief at the surface, mechanical deformation of the rocks, and thermal gradients and anomalies, all of which are related to tectonic environments and processes. The combination of fluid pressure regime, thermal regime, and topographic relief is such that upward fluid flow is dominant in compressional environments, such as the orogenic gold mineralization systems, whereas convection systems are better developed in extensional environments, e.g., VMS and SEDEX mineralization systems. Topographic relief and horizontal shortening associated with compressional stress regime in an orogen may drive fluid flow for hundreds of kilometers laterally through the foreland basin to stable platform areas, such as in the MVT mineralization systems. The detailed fluid flow patterns, however, are much more complex than this generalization, and evolve with tectonic processes. In areas that have experienced multiple tectonic cycles, such as the diwa regions, mineral deposits formed in early cycles may be overprinted by those formed in late cycles, and new fluid input from the mantle may be required for mineralization in the late stages. As metallogeny deals with the relationships between mineralization and tectonic settings, and hydrodynamics of mineralization is closely related to tectonic setting, therefore, it is important to integrate hydrodynamic studies of mineralization into metallogenic modeling.

Keywords: tectonic setting; metallogeny; hydrodynamics; fluid flow; hydrothermal deposits

成矿流体动力学与大地构造环境的关系

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摘　要：热液矿床的形成需要大量流体，而流体的运移需要包括地势差、岩石变形、热梯度及热异常等多种驱动力。这些流体驱动力与构造环境及过程有密切关系。流体压力状态和热场及地势差的组合决定了压性构造环境流体以向上运动为主，如造山型成矿系统，而张性构造环境流体以对流为主，如 VMS 和 SEDEX 成矿系统。造山作用造成的地势差及水平挤压作用所产生的超压可以驱动流体侧向迁移数百公里，如 MVT 成矿系统。但是，具体的成矿流体动力学过程比较复杂，且随构造演化而变化。在经历过多个大地构造演化阶段的地区，如地洼区，老的成矿流体动力系统不断被新的系统叠加或取代；新的构造单元需要来自地幔的流体源补充才有利于成矿。成矿学研究的是成矿作用与大地构造的关系，而流体动力学系统与大地构造环境密切相关，因此，成矿流体动力学应成为成矿学的一个重要组成部分。

关键词：大地构造环境；成矿学；流体动力学；流体流动；热液矿床

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0 Introduction

Metallogeny is a study of ore genesis in the context of tectonic settings, with emphasis on tectonic control of 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; Zhao et al., 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 (Fyfe et al., 1978; Fyfe, 1994; Deming, 1994; Sibson, 1994; Lin et al., 2003, 2006; Cathles and Adams, 2005; Cox, 2005; Zhang et al., 2006; Zhu et al., 2014). However, most metallogenic studies focus on the geochemical aspects such as ages and metal sources (Kerrich et al., 2005; Mao et al., 2013; Kaur and Chaudhri, 2014; Li and Santosh, 2014), and little attention has been paid to the systematic differences in hydrodynamics of mineralization in different tectonic settings. This paper aims to examine the relationships between the hydrodynamics of mineralization and tectonic settings, and to show that hydrodynamics is inherent in metallogenic models, which is important for understanding the genesis and distribution of various types of mineralization in space and time.

1 Fundamental relationships between tectonic settings and geologic fluid flow

Geologic fluid flow in porous media is generally governed by Darcy's law, which can be expressed as:

$$q = -\frac{k}{\mu}\frac{\mathrm{d}\Phi}{\mathrm{d}L} \tag{1}$$

where q is flow rate, k is rock permeability, μ is fluid viscosity, L is distance, and Φ is hydraulic potential (Hubbert, 1940), which is defined as:

$$\Phi = \rho g z + P \tag{2}$$

where ρ is fluid density, g is gravity, z is elevation, and P is fluid pressure. Therefore, geologic fluid flow is related to rock permeability, fluid density, viscosity, pressure, and elevation (which is closely related to topographic relief). Because fluid density and viscosity are both related to temperature, geologic fluid flow is also related to temperature. All these parameters, especially fluid pressure, temperature, and topography, are intimately related to tectonic settings. Different tectonic settings have systematically different fluid pressure regimes, thermal regimes, and topographic relieves, and are deemed to have different hydrodynamic systems.

1.1 Fluid pressure regime

Fluid pressure regime refers to the difference between fluid pressure (P) and the hydrostatic pressure at a given depth, and can be described by fluid overpressure (OP) (Bethke, 1985; Chi and Xue, 2011), which is expressed as:

$$OP = P - \rho g d \tag{3}$$

where d is depth from the surface. A comparison between equations 2 and 3 indicates that fluid overpressure (OP) is equivalent to hydraulic potential (Φ) if the earth surface is used as the datum for elevation. The pressure regime is said to be underpressured (or subhydrostatic), hydrostatic, or overpressured (or suprahydrostatic), for OP<0, =0, and >0, respectively. In the cases of suprahydrostatic regimes, if fluid pressure is equal to lithostatic value at a given depth, the pressure regime is lithostatic, and if fluid pressure is higher than lithostatic value, it is called supralithostatic.

Suprahydrostatic fluid pressure can be caused by a reduction in pore space or an increase in fluid volume. Pore space reduction is mainly controlled by rock deformation, which are related to stress fields, strain rates, and lithologies, and fluid volume increase may be caused by fluid generation and heating (Chi and Xue, 2011). In sedimentary basins, fluid overpressure may result from disequilibrium compaction due to rapid sedimentation, thermal expansion of fluid, hydrocarbon generation, and mineral dewatering (Bethke, 1985; Swarbrick et al., 2002). In metamorphic and deformation belts as well as in the adjacent foreland basins, both rock deformation (compressive deformation or squeezing and compaction due to thrust loading) and metamorphic dewatering contribute to the development of fluid overpressure (Fyfe et al., 1978; Oliver, 1986; Ge and Garven, 1992). In subduction zones, large amounts of water and other volatiles are released from the subducting oceanic slab, contributing to magma generation and eventually to development of fluid overpressure in orogens (Fyfe, 1994; Cox, 2005). In magmatic intrusions emplaced in the upper part of the crust, fluid overpressure can be caused by the exsolution of magmatic fluids, which results in an increase in the total volume (Burnham, 1997). In all these cases, fluids are expelled from high overpressure areas to low overpressure areas (Chi and Xue, 2011); the stronger the fluid overpressure gradient, the faster the fluid flow.

Fluid pressure regime is generally close to hydrostatic near the earth surface, and gradually becomes suprahydrostatic with depth (Fig.1a), therefore fluid flow is generally upward regardless of compressional or extensional environments (Fig.1b). In particular, strong fluid overpressures tend to develop below the brittle-ductile transition zone and drive episodic, upward fluid flow along discrete deformation zones (Sibson, 2004; Cox, 2005). However, during active extensional deformation or dilation, subhydrostatic pressure may be locally developed (Oliver et al., 2006; Cui et al., 2012), and fluid may flow downward or toward the structures (Fig.1b). Even in the deep crust below the brittle-ductile transition zone, downward flow is still possible in domains of hydraulic connectivity (Connolly and Podladchikov, 2004).

Because fluid pressure regime is closely related to rock deformation, which is related to the stress fields and strain rates, which are in turn related to the tectonic settings, it is expected that different tectonic settings have different fluid pressure regimes. It has been demonstrated by Sibson (2004) that the maximum fluid overpressure that can be maintained is closely related to the differential stress (σ_1-σ_3): the smaller the differential stress, the higher the fluid overpressure. In extensional environment, fluid pressure decreases sharply from supralithostatic to subhydrostatic values with increasing differential stress, whereas in compressional environments, supralithostatic pressure can be maintained for a significant range of differential stress values and then decreases gently with increasing differential stress (Sibson, 2004). Therefore, compressional environments tend to have high fluid overpressue, and extensional environments tend to have low fluid overpressure (even hydrostatic and subhydrostatic), which has implications for the development of fluid convection systems as discussed below.

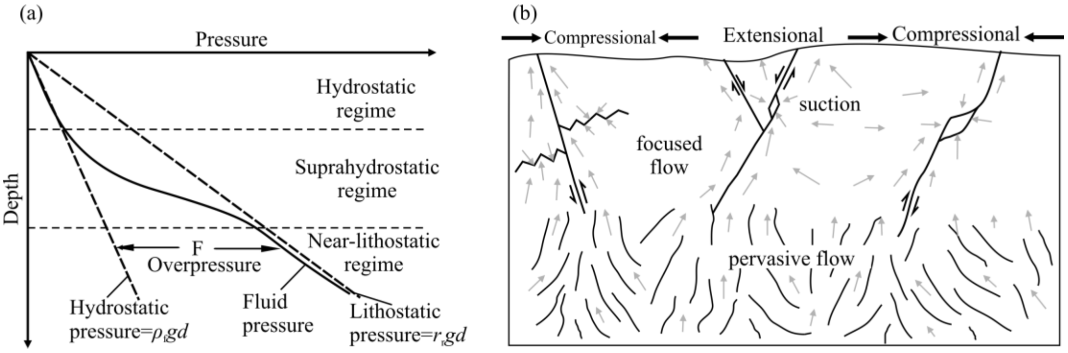
1.2 Thermal regime

Equation 2 shows that hydraulic potential is related to fluid density, which means that fluid flow can be caused by variation of fluid density, i.e., buoyancy-driven flow. Fluid density is related to temperature and pressure as follows:

$$\rho(T,P)=\rho_o+(\frac{\mathrm{d}\rho}{\mathrm{d}T})_P\Delta T+(\frac{\mathrm{d}\rho}{\mathrm{d}P})_T\Delta P \tag{4}$$

Because the effect of temperature on fluid density is more important than that of pressure, buoyancy-driven flow is mainly related to thermal regime, which may be described by vertical and lateral thermal gradients, both having impact on fluid flow patterns.

As fluid density decreases with increasing depth due to vertical thermal gradient, fluid at depth tends to move upward and fluid in the upper part tends to move downward because of buoyancy (Turcotte and Schubert, 2002). However, because of friction, this fluid circulation will not happen unless the combination of geothermal gradient, rock permeability,



(a) A fluid pressure-depth profile showing the hydrostatic, suprahydrostatic, and near-lithostatic fluid pressure regimes with increasing depths; (b) A sketch showing pervasive flow in the deep crust and focused flow at shallow depths; note the flow is overall upward regardless of compressional or extensional environments except in dilation areas, consistent with fluid overpressure as the main driving force of fluid flow.

Fig.1 Fluid pressure regimes and associated fluid flow patterns

thickness of the rock unit in consideration and other thermodynamic parameters is such that the Rayleigh number of the system exceeds a critical value (Turcotte and Schubert, 2002; Zhao et al., 2008). While high vertical thermal gradient is the most critical factor for development of fluid convection systems, the initial and ambient fluid pressure regime before the onset of the convection is also very important. Under hydrostatic pressure regime (i.e., no fluid overpressure gradient), the only driving force for fluid flow is buoyancy, which is favorable for development of fluid convection. In contrast, if there is fluid overpressure gradient, as depicted in Figure 1, then the buoyancy force will have to overcome the force from fluid overpressure (either positive or negative) in order to establish the convection system. As a result, fluid convection is generally better developed in extensional environments, where fluid overpressure is relatively weak, compared to compressional environments, which favors development of fluid overpressure, as discussed above. However, it should be pointed out that subhydrostatic fluid pressure regime due to strong extension may also suppress development of fluid convection (Oliver et al., 2006).

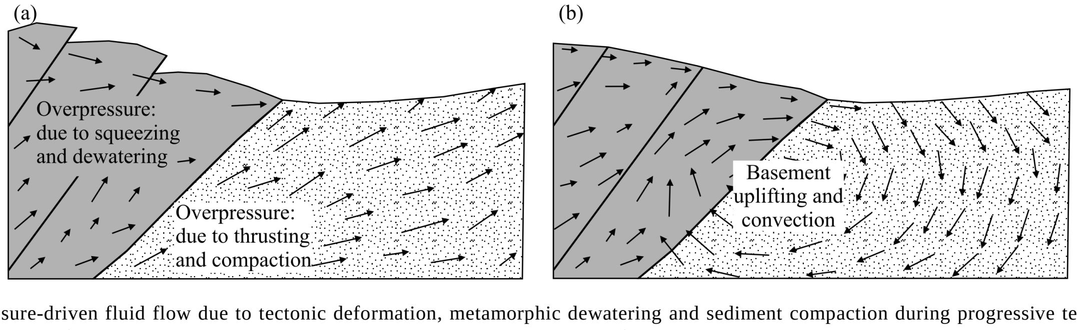
It has been demonstrated that when there is a lateral thermal gradient (i.e., presence of heat anomaly), fluid convection is inevitable if the ambient fluid pressure is hydrostatic (Norton and Cathles, 1979). It is shown that fluid tends to flow upward above a heat anomaly in the vertical direction and toward the heat anomaly in the horizontal direction, as exemplified by fluid convection systems around magmatic intrusions (Norton and Cathles, 1979). It is important to note that if the ambient fluid pressure is not hydrostatic, or if the heat anomaly is associated with strong fluid overpressure, buoyancy-driven flow may be still be suppressed by other driving forces. For example, outward fluid flow will be dominant if a magmatic intrusion is overpressured due to exsolution of magmatic fluids from the magmas (Burnham, 1997).

As an analog to magmatic intrusions, fluid flow in an orogen undergoing regional metamorphism and deformation is dominantly outgoing and upward (Fig.2a), due to fluid overpressure caused by rock deformation and fluid production (Oliver, 1986; Hanson, 1997). However, with the dissipation of fluid overpressure, the lateral thermal gradients induced by rapidly uplifting basement rocks can lead to large-scale fluid convection, in a direction opposite to the overpressure-driven flow (Fig.2b), as demonstrated by Hanson (1997) and Matthai et al. (2004). Large-scale heat anomalies are also commonly associated with extensional environments, such as hot spots, rifts, and mid-ocean ridges. For example the average heat flow near mid-ocean ridges is over 300 mW/m^2, compared to 50 mW/m^2 near the ocean margins (Ingebritsen et al., 2006). Such lateral variation of temperature also contributes to the development of fluid convection in extensional environments, in addition to high vertical thermal gradient and low fluid overpressure as discussed above. Even topographic relief of the seafloor may induce lateral thermal gradient and invoke fluid convection (Ingebritsen et al., 2006).

1.3 Topographic relief

It can be seen that hydraulic potential is related to elevation from Equation (2). Variation of elevation on the surface, or topographic relief, is the major driving force of modern groundwater flow systems, with water generally flowing downward in recharge areas, and upward in discharge areas (Hubbert, 1940; Freeze and Cherry, 1979; Domenico and Schwartz, 1998). It has been shown that topographic relief can drive fluid flow several kilometers deep into the crust and for hundreds of kilometers in lateral direction (Bethke and Marshak, 1990; Garven, 1995).

The highest topographic features are generally found in orogens in compressional tectonic settings, such as the Andes and Himalayas. However, this does not necessarily mean that topography-driven fluid flow systems are best developed in compressional environments. As discussed above, fluid overpressure



(a) overpressure-driven fluid flow due to tectonic deformation, metamorphic dewatering and sediment compaction during progressive tectonism and metamorphism; (b) fluid convection driven by heat anomaly caused by basement uplifting during the post-tectonic period.

Fig.2 Fluid flow patterns associated with an orogen

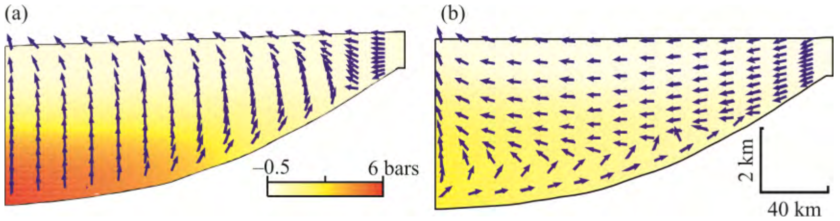
is generally better developed in compressional environments than in extensional ones, and consequently the forces driving fluid to flow upward is generally stronger in compressional areas than in extensional areas. Furthermore, high topographic relief is generally associated with rapid erosion, which leads to rapid sedimentation in the foreland basins, which in turn causes strong fluid overpressure in the basin. Therefore, topography-driven fluid flow system is limited to shallow depths during active compressional deformation, metamorphism, and sedimentation, as demonstrated by numerical modeling of competing compaction-driven and topography-driven fluid flow systems (Fig.3a) (Chi and Xue, 2014). However, with the dissipation of fluid overpressures after the peak deformation, metamorphism and sedimentation, the interface between the overpressure-driven, upward fluid flow system and the topography-driven, downward fluid flow system can penetrate deep into the crust, as shown by the competing compaction-driven and topography-driven analog (Fig.3b) (Chi and Xue, 2014).

2 Hydrodynamics of mineralization in different tectonic settings

Most hydrothermal deposits which were formed in tectonically active environments, can be broadly divided into convergent and divergent ones, the former being exemplified by orogens including subduction zones and overlying magmatic arcs as well as inter-continental or inter-terrain collision zones, and the latter by rifts, mid-ocean ridges, and back-arc spreading centers (Fig.4a). Each of these environments is endowed with different combinations of mineral deposits (Mitchell and Garson, 1981; Sawkins, 1990), associated with different hydrodynamic regimes. Volcanic rocks-hosted massive sulfide (VMS) Cu-Zn-Pb±Au deposits are best developed in mid-ocean ridges and back-arc basins (Franklin et al., 2005), and sedimentary exhalative (SEDEX) Zn-Pb±Ag deposits and sediment-hosted stratiform (SSC) Cu±Co deposits mainly occur in rifts or other extensional basins (Leach et al., 2005). Porphyry-type Cu-Mo±Au and epithermal Cu-Au-Ag-As-Sb-Hg deposits are mainly associated with magmatic arcs above subduction zones, and so are some granite-related W-Sn-Bi-Mo deposits as well as orogenic Au deposits, which are also developed in continental collision belts (Cerny et al., 2005; Goldfarb et al., 2005; Seedorff et al., 2005). Mississippi Valley-type (MVT) Zn-Pb deposits are mainly found in platform areas adjacent to orogenic belts (Leach et al., 2005), and Carlin-type Au deposits are located in back-arc extensional environments (Cline et al., 2005).

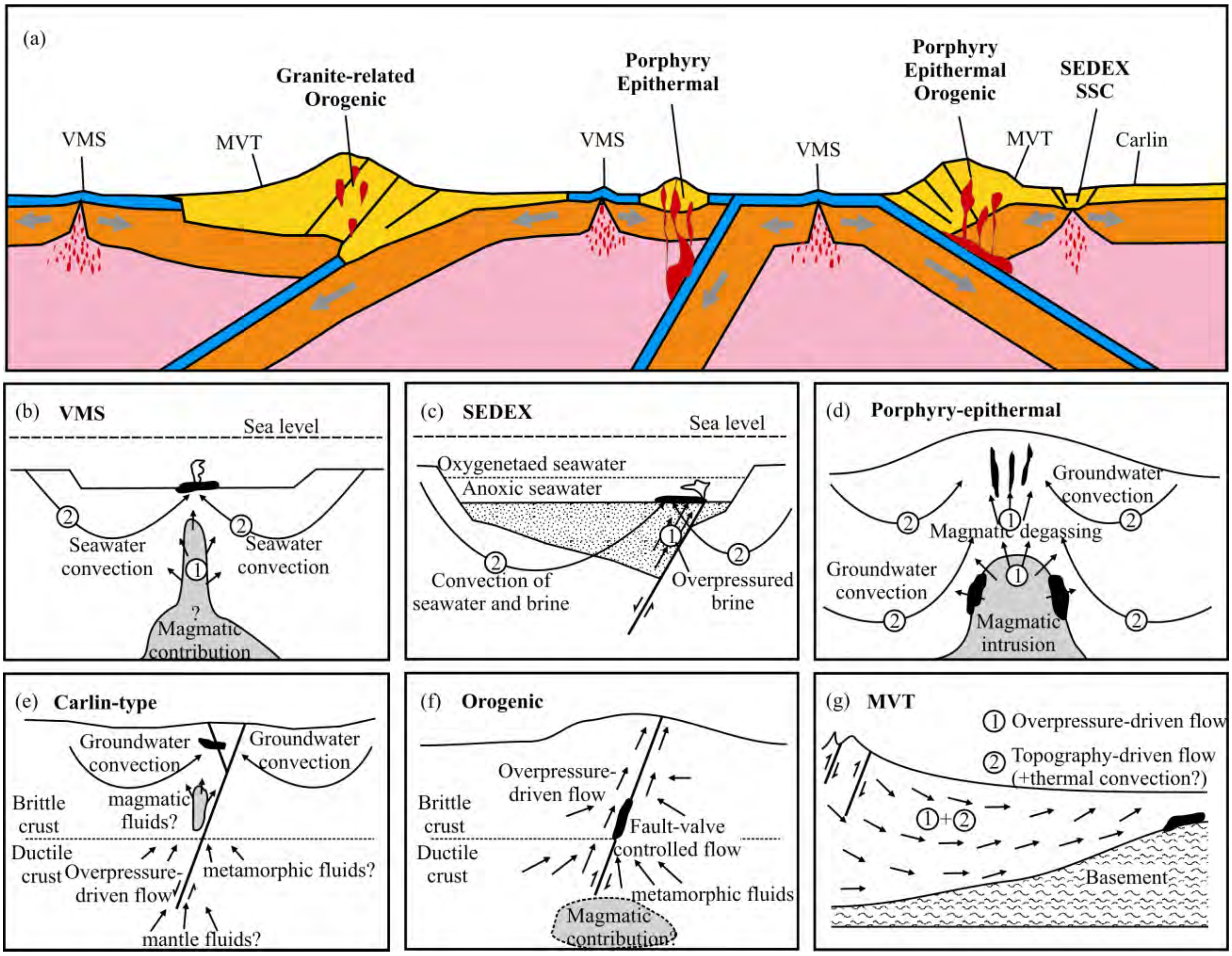
It is generally agreed that VMS deposits formed from convection of seawater, which extracted metals and sulfur from the ocean crust and deposited them on the sea floor when the hydrothermal fluids were vented (Fig.4b). Both the high heat flux (high vertical thermal gradient) and lateral thermal gradient (heat anomaly) associated with the spreading centers in mid-ocean ridges or back-arc environments may have contributed to the development of the convection cells (Ribando et al., 1976; Parmentier and Spooner, 1978; Cathles, 1981; Franklin et al., 2005). This is also facilitated by the relatively low fluid overpressures due to the extensional stress field. However, it has been noted that magmatic fluids may have contributed to the mineralization system (Yang and Scott, 1996), and therefore some overpressure-driven flow may have been in operation during the early stage of the mineralization system (Fig.4b), as for the porphyry-epithermal systems to be discussed below.

The SEDEX deposits are similar to VMS in that both of them were formed from venting of hydrothermal fluid on the sea floor. As for VMS, thermally-driven fluid convection is also believed to be the main mechanism for SEDEX mineralization (Cathles, 1981; Oliver et al., 2006; Yang et al., 2006; Fig.4c). However, a major difference is that SEDEX deposits were formed in rift environments, and may be underlain by thick sediments. Consequently, at the early stage of mineralization, the fluid may have been



(a) the interface of the two systems is located at a shallow depth in the overpressure-dominated stage of the basin (or orogen); (b) the interface of the two systems is pushed to a great depth when fluid overpressure is dissipated in a later stage of the basin (or orogen), even if the topographic relief has been reduced.

Fig.3 Numerical modeling results showing evolution of the interface between the topography-driven, downward fluid flow system and the overpressure-driven, upward fluid flow system in a sedimentary basin, as an analog to that in an orogen



(a) locations of major types of mineral deposits in a plate tectonic framework; (b) fluid flow model related to VMS mineralization; (c) fluid flow model related to SEDEX mineralization; (d) fluid flow model related to porphyry-epithermal mineralization; (e) fluid flow model related to Carlin-type gold mineralization; (f) fluid flow model related to orogenic gold mineralization, and (g) fluid flow model related to MVT mineralization. Numbers in the fluid flow models refer to relative stages in the evolution of the hydrothermal system.

Fig.4 Major types of mineral deposits found in different tectonic settings and schematic fluid flow models related to mineralization

strongly overpressured, driving upward fluid flow, and fluid convection will be developed after the fluid overpressure was dissipated (Oliver et al., 2006).

For porphyry and epithermal systems, it is generally agreed that the mineralizing fluids and ore-forming components were mainly derived from magmatic intrusions (Seedorff et al., 2005). The driving forces of the fluid flow include fluid overpressure caused by fluid volume increase due to exsolution of magmatic fluids, either through first boiling or second boiling, and heat anomaly imposed by the intrusions (Norton and Cathles, 1979; Cathles, 1981; Burnham, 1997; Fournier, 1998). Because the magma derived from the subduction zone and overlying mantle wedge is enriched in volatiles, fluid exsolution takes place before or immediately following emplacement of the intrusions, and the heat anomaly persists after the solidification of the intrusions, overpressure-driven flow generally precedes fluid convection (Fig.4d). Furthermore, with the disappearance of the heat anomaly, topographic driven fluid flow may eventually take over, controlling the supergene processes.

Compared to the mineralization systems described above, the driving forces and fluid flow patterns of Carlin-type gold deposits are much less understood. Because of the inconsistencies in geochemical data, the mineralization has been related to convection of meteoric water, epizonal intrusions, and deep metamorphic and/or magmatic fluids, as summarized by Cline et al. (2005). Fluid flow may have been driven by overpressure imposed by magmatic intrusions, metamorphism, and mantle degassing, as well as fluid convection driven by local heat anomaly (Fig.4e). It is possible that all these mechanisms have played a role in mineralization at different times, but the sequence of fluid flow events remains to be investigated.

The orogenic gold deposits also have the problem of uncertainty with regard to metal and fluid sources (Goldfarb et al., 2005), but it is generally agreed that the fluid flow was driven by fluid overpressure gradient in conjunction with episodic fracturing and hydrothermal sealing along shear zones, as described by the fault-valve model (Sibson et al., 1988; Sibson, 1994; Cox, 2005). The overall compressional stress regime favors the development of fluid overpressure. In such a model, fluid flow is unidirectional, i.e., from the strongly overpressured (near-lithostatic) ductile part of the crust (upstream) toward the brittle and shallow part (downstream) (Fig.4f). However, it is possible that downward fluid flow may take place during stress relaxing periods, when the stress regime becomes temporarily extensional (Liu et al., 2011).

The MVT deposits are among the most studied in terms of fluid flow mechanisms (Cathles and Smith, 1983; Bethke and Marshak, 1990; Garven et al., 1993; Garven, 1995; Cathles and Adams, 2005; Cathles, 2007), but the driving forces of fluid flow remain controversial. Many of these deposits are spatially and temporally associated with orogens (Sangster et al., 1994), and the mineralization temperature appears to decrease away from the orogens (Leach and Rowan, 1986), suggesting a fluid flow system driven by forces related to the orogeny (Fig.4f). Topographic relief has been suggested as the main driving force (Bethke and Marshak, 1990; Garven et al., 1993; Garven, 1995), although additional heat from the basement may be required to satisfy the thermal conditions (Deming and Dunn, 1991). Fluid overpressue related to deformation in the orogenic belt (Oliver, 1986) or due to sedimentation and hydrocarbon generation within the foreland basin (Cathles and Smith, 1983; Cathles, 2007) has also been invoked to explain the fluid flow pattern. It is possible that all these driving forces may have played a role, with the overpressure-driven flow preceding the topography-driven one, but the relative importance of these forces is unclear. In basins unassociated with orogens, such as the Maritimes basin in eastern Canada, where no systematic spatial change in mineralization temperature was observed (Chi et al., 1998), fluid flow was more likely to be driven by fluid overpressure from within the basin rather than by topographic relief (Chi and Savard, 1998).

3 Discussion

3.1 Evolution and superposition of different hydrodynamic systems

The hydrothermal mineralization systems discussed above are only snapshots in the tectonic evolution history of a region. The hydrodynamics, including fluid flow driving forces and rock permeabilities, evolves with the tectonic setting, and mineral deposits formed in one hydrodynamic regime may be overprinted by mineralization in a completely different hydrodynamic environment, forming the so-called polygenetic compound ore deposits (Chen, 1982).

The VMS and SEDEX deposits formed in extensional environments, typically in the early stage of a tectonic cycle, are commonly deformed and reworked during orogenies, with the fluid flow systems changing from a convection-dominated regime to an overpressure-dominated one. For example, the Bousquet Au-Ag-Zn-Pb deposit in Canada is a VMS deposited overprinted by orogenic gold mineralization (Groves et al., 2003). However, with further evolution of an orogen into the post-tectonic period, fluid overpressure may gradually dissipate, and thermally-driven convection may be developed again (Fig.2b). For example, the SEDEX Zn-Pb-Ag deposits in the Mount Isa basin in northern Australia were formed from fluid convection in an extensional environment (Oliver et al., 2006; Yang et al., 2006), with cyclic interruption by extension-induced downward flow (Oliver et al., 2006), in the early stage of the tectonic cycle, but the Mount Isa Cu deposit was formed from basement uplifting-induced fluid convection in a later stage of the tectonic cycle (Matthai et al., 2004).

Porphyry-epithermal deposits formed in the magmatic arcs, relatively early in a tectonic cycle, may also be overprinted by orogenic mineralization in orogenies, with the fluid flow models changing from magmatic overpressure-driven flow and thermally- driven convection (Fig.4d) to overpressure-driven flow channeled along major faults (Fig.4f). Examples of this kind of overprinted mineralization include the Hemlo Au deposit in Canada and the Boddington Au deposit in Australia (Groves et al., 2003).

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. It has been noted that orogenic and anorogenic mineralization concentrations may be linked to supercontinent formation and breaking up cycles (Kerrich et al., 2005), which can also be linked to hydrodynamic regimes. For example, the concentration of SEDEX deposits in Paleoproterozoic is probably related to the prolonged existence of supercontinents, which favors the development of thermally driven fluid convection systems.

3.2 Hydrodynamic considerations of mineralization related to tectonomagmatic reactivation in diwa regions

In many parts of the world, exemplified by eastern China, the crust has experienced tectonic evolution from the geosyncline through the platform to the diwa stage (Chen, 1956, 1978, 1982). In recent years, much attention has been given to the geodynamic mechanisms of platform reactivation, or destruction of cratons, and related metallogeny (Mao et al., 2013; Li and Santosh, 2014). However, little is known about the hydrodynamic regimes related to mineralization in these reactivated or diwa regions.

There is no doubt that all the fluid flow-driving forces, including fluid overpressure, buoyancy, and topographic relief, are in operation in diwa regions, as in other tectonic regions. However, the fact that the diwa regions have already experienced one or multiple deformation and metamorphism events, followed by a stable period (in many cases prolonged, such as the North China craton), before entering a new period of active tectonic regime, has significant implications for the hydrodynamic regimes in the diwa stage. Fluid overpressure developed in the geosyncline stage may have dissipated after the platform stage, and therefore, orogenic type mineralization driven by fluid overpressure is generally more difficult. Furthermore, the basement units, which have experienced multiple deformation and metamorphism events, are likely of low permeability and poor in volatiles. In order to initial a new round of mineralization, new fluid input, such as from the mantle or from the surface (i.e., marine or meteoric water), is required. Indeed, many recent studies of Meso-Cenozoic metallogeny in eastern China invoked fluids from the mantle (Hu et al., 2008; Mao et al., 2013; Li and Santosh, 2014) or from basinal fluids infiltrating into the basement (Chi and Zhou, 2012). In some cases, even if basinal fluids were available, mantle fluid input is still required for fluid overpressure development in the formation of mineral deposits in the diwa stage, for example the Jinding Zn-Pb deposit in Yunnan, China (Chi et al., 2006, 2007).

4 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. 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 within a tectonic cycle, with mineralization systems related to fluid convection better developed in the pre-tectonic stage, overpressure-driven systems dominating in the syn-tectonic stage, and topographic relief-driven fluid flow best developed in the post-tectonic stage. In areas that have experienced multiple tectonic cycles, such as the diwa regions, mineral deposits formed in early cycles may be overprinted by those formed in late cycles, and new fluid input from the mantle may be required for mineralization in the late stages.

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We dedicate this paper to late professor CHEN Guoda in memory of the 102th anniversary of his birthday. Professor CHEN made important contributions to the tectonics and metallogeny of China, and he 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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