Tectonic-magmatic-metallogenic system, Tongling ore cluster region, Anhui Province, China

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The Tongling ore district of the Middle-Lower Yangtze metallogenic belt is a famous Cu-Au-Fe-S polymetal region, and its tectonic deformation, magmatic evolution, and metallogenic processes have been studied for decades. In this article, we propose a comprehensive tectonic-magmatic-metallogenic model of the ore-forming mechanism constrained by magmatism and regional deformation. In the Tongling district, the tectonic regime underwent two transitions. (1) In the Middle Triassic, the tectonic regime transitioned from quiescence to intense compression. During contraction, the lithosphere thickened and a series of NE-trending folds developed in the cover sequence; because of the multi-layered structure of this caprock, bedding faults, typically cut by steeply dipping faults, developed widely. (2) From 134 to 150 Ma, the tectonic regime changed from compression to extension. During this transition, mantle–crust interaction was prominent; ore-bearing magma was generated by the mixing of crust-derived and mantle-derived melts triggered by delamination of the thickened lithosphere. Meanwhile, detachment faults developed along the interfaces, for example between the lower and upper crust, serving as emplacement sites for several magma chambers. Ore-bearing magma dikes containing large amounts of volatiles derived from a shallow chamber at about –10 km depth migrated into the cover sequence along the pre-existing steeply dipping faults. Melt injection reworked the structural framework, facilitating further development of steeply dipping faults, as well as the vertical transport of ore-bearing fluids. Hydrothermal fluids derived from the emplaced magmas not only formed a range of deposits, including skarns, porphyries, and cryptobreccias around the intrusions but also widely replaced carbonates along bedding-parallel faults and formed so-called stratabound skarn ore bodies, as well as superimposing synsedimentary orebodies developed in the quiescence stage to form several large polymetallic hydrothermal ore deposits. Various types of ore deposits at different depths are clustered in a single orefield, composing a multi-layered mineralization network. In the network, skarn deposits dominate and are characterized by fluid immiscibility processes and diverse element enrichments. The intense mineralization in the Tongling region was caused by the abundance of metals derived from the mantle, favourable ore-controlling structures, and widespread fluid boiling of magmatic hydrothermal fluids, which facilitated metal deposition during the Mesozoic, as well as the superposition of Mesozoic hydrothermal reworking of earlier Palaeozoic sedimentary ore bodies.

Keywords: ore-forming process; magmatism; structures and ore deposition; Mesozoic ore deposits; Tongling district; NE China

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Introduction

The Tongling ore cluster region is an uplifted area in the Middle-Lower Yangtze metallogenic belt located between the Lower Yangtze block and the North China block (Figure 1). During the Palaeozoic, the metallogenic belt occupied a passive continental margin. In the Mesozoic, the belt experienced intense intraplate tectono-magmatic activities, and its tectonic evolution was constrained by the collision between the Yangtze and North China blocks, the subsequent underflow of the Pacific and Izanagi plates underneath Eurasia (Sun et al. 2007; Ling et al. 2009), and later lithospheric delamination and extension in East China.

After several tectonic movements, the cover sequence in the Tongling region was deformed, and abundant Mesozoic intrusions were emplaced, inducing intense and diverse mineralizations. More than 180 ore deposits and occurrences have been discovered in the Tongling region and they are mainly clustered in five orefields: the Shizishan, Tongguanshan, Fenghuangshan, Xinqiao, and Jinlang orefields (Figure 2). On both sides of the Tongling region, abundant ore deposits are also concentrated in the Lujiang-Zongyang (abbreviated as Luzong), Fanchang, and Nanjing-Wuhu (abbreviated as Ningwu) volcanic basins of the metallogenic belt (Figure 1).

Because of the great economic value and scientific significance of the Tongling region, scientists have intensively studied its tectonic process, magmatic evolution, origin of ore-forming fluids and materials, and the metallogenic processes (Chang et al. 1991; Zhai et al. 1992; Tang et al. 1998; Mao et al. 2004, 2009; Meng et al. 2004; Hou et al. 2004, 2007; Xu et al. 2005a, 2005b, 2007a, 2007b; Yang et al. 2008b; Li et al. submitted; Yang and Lee 2011). The regional deep-seated structure has been studied using deep reflection seismic profiles (Lü et al. 2004a, 2004b). Caprock structures and their

Figure 1. Geological location of the Tongling ore cluster area, Anhui Province, China. TLF, Tancheng-Lujiang fault; XGF, Xiangfan-Guangji fault; YCF, Yangxing-Changzhou fault. Black dots are magmatic intrusion-related Cu–Fe–Au deposits (after Pan and Dong 1999).
The deformation mechanism are discussed in detail (Deng et al. 2004b, 2004c; Wu et al. 2004, 2008; Di et al. 2005; Zhand et al. 2006; Du et al. 2007b; Liu et al. 2007; Yang et al. 2007, 2008a; Wu et al. 2008; and Xie et al. 2008b). The age of Re/Os and Os/Os cited from Sun et al. 2003; Mao et al. 2004; Yang et al. 2004a; Mei et al. 2005; Xie et al. 2009a. The dating data is listed in Table 1.)

Figure 2. Geological map of the Tongling ore cluster area, Anhui province, China. (The map is modified after the 1:50,000 geological map accomplished by the 321 geological team in Anhui province, 1989. The age of zircon U–Pb cited from Wang et al. 2004a, 2004b, 2004c; Xu et al. 2004, 2008; Di et al. 2005; Zhand et al. 2006; Du et al. 2007b; Liu et al. 2007; Yang et al. 2007, 2008a; Wu et al. 2008; and Xie et al. 2008b. The age of Re/Os and Os/Os cited from Sun et al. 2003; Mao et al. 2004; Yang et al. 2004a; Mei et al. 2005; Xie et al. 2009a. The dating data is listed in Table 1.)

The tectonic deformation, magmatic evolution, and ore-forming process behaved as an interconnected system. Previous studies mainly focused on one or two aspects of the system, and a comprehensive framework of the Tongling region has not yet been constructed. Based on the results obtained by different disciplines and supplemented with some new evidence, the tectonic-magmatic-metallogenic model of the Tongling region with emphasis on the interaction of the various geological processes is hereby established in this article.

**Tectonic framework and compressional deformation**

**Tectonic framework**

After multiple tectonic movements, the crust of the Tongling region shows a low thickness of about 32 km (Wu et al. 1999). The deep seismic reflection profile across the region clearly displays crustal structure (Lü et al. 2004b). In the profile, the sub-Moho reflections support the occurrence of underplating, and a weak Moho also denotes that intense magmatism happened. The lower crust shows the typical reflection characteristics of a craton, suggesting no obvious magmatism. Strong reflections between the upper and lower crust is explained as a detachment between them. In addition, a transparent zone, representing a batholith, exists underneath the folded caprock (Figure 3). According to the gravity anomaly and ETM image, it is recognized that the region is confined by deep faults and traversed by basement faults, in which the EW-trending faults in the north part is the most obvious (Wang et al. 2011).

The caprock consists of a Palaeozoic basement and a sequence of Mesozoic sedimentary rocks. The Proterozoic low-grade metamorphic basement is exposed about 30 km south of the study region (Chang et al. 1991). The stratigraphic sequence cropping out in the study region ranges from Silurian to Triassic with thickness up to 3000 m (Figure 4). The sequence includes Silurian shallow marine sandstones interbedded with shales, Devonian continental quasi-molasse formation and lacustrine sediments, Carboniferous shallow marine carbonates, Permian marine facies alternating with a marine-continental ones, Early to Middle Triassic shallow marine carbonates, and Quaternary sediments. Jurassic and Cretaceous volcanic rocks are developed in surrounding area. The first angular unconformity in the outcropped sequence lies between the Middle Triassic Dongma’anshan Formation (T2d) and the Yueshan Formation (T2y), and it divides the caprock into upper and lower structural layers. Several parallel unconformities are developed in the lower structural layer, and many angular unconformities occur in the upper layer. The lower structural layer covers most of the region and contains most ore reserves in the region.

In the lower structural layer, the strata with different lithologies and thicknesses alternate. During deformation, the Devonian thick quartz sandstone, as well as the Lower Permian and Lower Triassic thick carbonates may behave as competent layers. The thin carbonates, mudstone, shale, and silty shale in the Silurian and Upper Permian, on the other hand, act as incompetent layers. The alternation of the competent and incompetent layers facilitates the development of bedding detachment faults and non-harmonic folds.

The characteristics of the surface structures are shown in Figure 2. Three types of fundamental structures can be observed. The NE-trending folds, most of which are S-shaped, are prominent. Bedding detachment faults and the NW and NNW-trending sinistral strike-slip faults cutting the folds are widely developed. An analogous experiment was performed to reflect the formation process of caprock structural framework under overall NW compression, and several important ore-controlling structures are identified (Deng et al. 2004a). Combining the experiment results and drill sections, it is discovered that reverse faults
Figure 3. (a) Stacked section of the Tongling deep seismic reflection; (b) line drawing of stacked section and interpretative section. FCVB, Fanchang volcanic basin; TLU, Tongling uplift (modified from Lü et al. 2004b).
Figure 4. Stratigraphy and mineralization developments of the Tongling, Anhui Province, China (modified after Geological Team 321, 1989 and Lü et al. 2007).
near the fold cores and non-harmonic folds containing multi-layered void spaces are likely to be developed.

In the caprock, structures with various attitudes and in different layers compose a network, which serves as a pathway or emplacement space for magma and related hydrothermal fluids. The network is characterized by bedding-parallel faults and void spaces that are connected or cut by faults with high dip angles.

**Compression process**

The parallel unconformities in the lower structural layer suggest that the region remained tectonically quiescent from the Silurian to the Middle Triassic. The first angular unconformity between T2d and T2y indicates the start of intraplate horizontal compression. Because the assembly between the Yangtze and North China blocks took place during 210–240 Ma, as determined by the 40Ar/39Ar and Sm–Nd dating methods (Shen et al. 1994; Chavagnac and Jahn 1996; Rowley et al. 1997), it is deduced that this assembly triggered the horizontal deformation in the region. After the assembly ended, the active motion of the Pacific and Izanagi ocean plates underneath the Eurasian plate began to influence the tectonic and magmatic evolution in the Tongling region (Sun et al. 2007; Ling et al. 2009).

The block collision induced an overall intense NW compression, inducing the development of lithospheric and deep crustal faults. Because of the confinement of the deep faults, the Tongling region suffered a relatively independent deformation process. And some deep faults also served as concealed basement faults across the region.

The NE-trending folds and NW-trending strike–slip faults also suggest that the region mainly suffered continuous and intense NW compression. Based on the S-shaped folds, it is proposed that the region experienced progressive deformation, in which the compression was followed by a simple shear (Deng et al. 2004b; Wu et al. 2004) (Figure 2). Nevertheless, a non-coaxial and asymmetric compression model is proposed to be responsible for the formation of the S-shaped folds (Wang et al. 2011). In the deformation models, it is recognized that the caprock with multi-layered structures under an intense and complex deformation process are responsible for the development of non-harmonic folds and reverse faults.

The compressions induced by the plate collision also resulted in a thickened crust, which differs from the structure of the modern crust in the Tongling region (Wang et al. 2004c).

**Magmatic evolution and tectonic transformation**

**Geological occurrence and lithologic types**

Intrusive rocks in caprock occur mostly as stocks, dikes, and sills with 2–10 km² outcropping areas. In the Shizishan orefield, intrusions occur as stocks and dikes along faults to form a network system approximately 3 km long and 1 km wide (Deng et al. 2004a). The largest Fenghuangshan intrusive body associated with a series of skarn deposits with an area of about 10 km² is located near the southeast boundary of the region. The magma emplacement is largely controlled by the EW-trending basement fault crossing the Xinqiao, Shizishan, and Tongguanshan orefields (Figure 2) (Chang et al. 1991; Wu et al. 2003a).
The region comprises three major rock associations: (1) pyroxene diorite–pyroxene monzodiorite; (2) quartz diorite–quartz monzodiorite, which are the most important magmatic rocks in the Tongling region; and (3) granodiorite. Most magmatic bodies are virtually intrusive complexes consisting of both mafic and intermediate-acid intrusive rock types, such as the Baimangshan, Jiguanshan, Sujiadian, Caoshan, Yushan, and Shizishan magmatic bodies (Chang et al. 1991).

**Chemical compositions, emplacement age, and tectonic setting**

In the Harker variation diagrams, most intrusive rocks in the region are categorized as high-K calc-alkaline series (Wang et al. 2003a). Several models have been suggested for the formation of the intrusive rocks, including (1) the mixing of mantle- and crust-derived magmas, or assimilation and fractional crystallization of a mantle-derived magma, with major contributions from an ancient crustal component (Chen et al. 1993; Chen and Jahn 1998; Wu et al. 2000; Deng and Wu 2001); (2) the partial melting of lower crustal materials in the Yangtze continental block (Yang and Lin 1988; Du and Li 1997; Zhang et al. 2001; Wang et al. 2004c); (3) the production of rocks with SiO$_2$ ≤ 55% by the crystallization of basaltic magmas derived from an enriched mantle, with limited assimilation of lower crustal materials; and in this model, rocks with SiO$_2$ > 55% were generated by mixing of mantle-derived basaltic magmas and adakite-like magmas derived from melting of the basaltic lower crust (Wang et al. 2003a, 2003b); (4) partial melting of subducted oceanic slab and subsequent crustal contamination (Ling et al. 2009).

Despite the debates, the following opinions are well evidenced and recognized. The intrusive rocks in the Tongling region were produced by a magma mixture of at least two end-members, one mantle-derived and the other crust-derived, and the mixed magma experienced fractional crystallization during its ascent.

The mixing of the mantle-derived and crust-derived magmas is supported by the $\varepsilon_{Nd}(t)$ and ($^{87}\text{Sr}/^{86}\text{Sr}$) values of the intrusions, the geochemical and mineralogical features of enclaves, and the Fe$^{3+}/$(Fe$^{2+} + $Fe$^{3+}$) ratios of biotites in the intrusions (Wu et al. 2000; Wang et al. 2003a, 2003b; Gao et al. 2006; Lou and Du 2006; Du et al. 2007a, 2007b; Xie et al. 2009b). The fractional crystallization process is evidenced by the fact that the SiO$_2$ content is inversely proportional to that of CaO, TiO$_2$, P$_2$O$_5$, MgO, and Zr and that the REE patterns of different intrusions are generally consistent.

The origin of the magmas reflects a complex deep process, which consists of delamination of the lower part of the thickened lithosphere, lithospheric thinning, asthenospheric upwelling, and crust–mantle interactions (Wang et al. 2003a; Xie et al. 2009b). Zircon U–Pb dating shows that the emplacement ages of the magmas varied from 132.7 ± 4.8 Ma to 151.8 ± 2.6 Ma, mainly from 134 to 142 Ma (Figure 2) (Wang et al. 2004a, 2004b, 2004c; Xu et al. 2004, 2008; Di et al. 2005; Zhang et al. 2006; Du et al. 2007a; Lu et al. 2007; Wu et al. 2008; Yang et al. 2007, 2008a; Xie et al. 2009b). The narrow age range indicates the different intrusions emplaced semi-synchronously. The emplacement duration represents the transition interval from lithospheric thickening to delamination, that is from regional compression to extension.

The zircon U–Pb ages of the Mesozoic volcanic rocks in the Luzong and Ningwu volcanic basins range from 134.8 ± 1.8 Ma to 127.1 ± 1.2 Ma (Table 1) (Fan et al. 2008; Zhou et al. 2008; Yan et al. 2009). The greatest age of the intrusions in the Tongling region is similar to the smallest age of the volcanic rocks in the volcanic basins; it is thus proposed that the onset of lithosphere thinning and extension occurred at about 134 Ma in the Tongling region and its vicinity. The zircon U–Pb ages of the A-type intrusions widely
Table 1. Dating data of magma emplacements and ore-forming events in the Tongling region, Anhui Province, China.

<table>
<thead>
<tr>
<th>Orefield</th>
<th>Ore deposit</th>
<th>Rock type</th>
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<th>Method</th>
<th>Age (Ma)</th>
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distributed in the Luzong basin range from about 126 to 124 Ma, denoting an intense lithosphere thinning (Li et al. 2011). It is inferred that the extension duration in the Tongling and adjacent regions was generally from 134 to 124 Ma.

**Magma transport process and its effect on the tectonic framework**

**Magma transport network and migration process at deep and shallow levels**

Based on the pressure calculation for the enclaves in intrusions and the crustal structure detected by deep seismic reflection, three magma chambers are proposed to exist in the crust (Wu et al. 2000; Du et al. 2007a). The deep and middle magma chambers developed around the Moho and the interface between the upper and lower crust, respectively. A concealed magma chamber existed at about –10 km, from which the ore-forming magma transported into the caprock.

In regional extension, the tectonic framework may be changed to some extent, and detachment faults along the interfaces formed. Meanwhile the steeply dipping compression fault displayed dilational characteristics: vertical weakness zones in the middle and lower crust may be developed. These steeply dipping structures can connect the multilayered detachments in the crust, as is similar to the spatial assembly of different structures in the caprock. The magma stemming from the deep magma chamber was transported upwards along the vertical structures and aggregated in the detachments, forming the middle and shallow chambers (Du 1999). Because the lower crust shows little evidence of magmatic activity, mesoscale pervasive flow, rather than diapirism, is supposed to be the transport pattern between the chambers, in which magma moves upwards through an extensive network developed in hot, low-viscosity country rocks where diking is inhibited (Leitch and Weinberg 2002; Weinberg 1998; Wu et al. 2004).

In the upper crust, the basement faults and the above NE-trending high-angle reverse faults served as the main magma pathways, and the magma emplaced in the pathways and the saddle void spaces within the folds.

In addition, the zircon U–Pb age and the K–Ar, Rb–Sr, and $^{40}\text{Ar}/^{39}\text{Ar}$ ages are almost identical for the same intrusive, even though the closure temperatures of these isotopic systems are very different (Xie et al. 2009b). It is thus suggested that the felsic magmas experienced fast transport and cooling. Based on the fast transport of the magmas, the wide development of cryptobreccias denoting a high abundance of volatiles, and the geological occurrences of the intrusions, it is deduced that the magma transported into caprock from the shallow magma chamber rapidly via a diking pattern. The diking pattern indicates that magma with volatiles at its top migrated rapidly upwards along pre-existing weak structural planes in an elastic medium (Emerman and Marrett 1990; Petford et al. 1993, 1994). Pulse generations of the dikes because of continuous fractional in the shallow magma chamber may be partly responsible for the concentrated emplacement of magmas and the multiple lithological components in one intrusion (Deng et al. 2006; Petford and Koenders 1998).

**Influence of the magma emplacement on the caprock structures**

To further study the strata deformation after several tectonic movements, trend surface analysis of the S–D, D–C, C–P, P$_2$–P$_3$, and P–T boundaries is performed based on their elevations sampled evenly in a composite 1:50,000 geological and topographic map (Deng...
Trend surface analysis has been used consistently by geologists to separate map data into a regional component and one with local fluctuations (Davis 1986). After superposing trend surfaces of adjacent boundaries (such as superposing the S–D boundary on the D–C boundary), it is discovered that the lower trend surface always pierces the upper one. Moreover, the position and orientation of the pierced part of the different superposed trend surfaces are similar and in accordance with the regional EW-trending magmatic-metallogenic belt comprising the Shizishan, Tongguanshan, and Xinqiao orefields (Figure 1). This indicates that the caprock on the EW-trending basement fault is subject to bending resulting from magmatic emplacement.

In the Fenghuangshan intrusion, the foliation and lineation defined by the dark minerals and enclaves in the intrusion margin (Figure 1), the strike of the fold hinge, as well as the flow cleavage of the ductile shear zone in the contact, are parallel to the intrusion boundary, indicating a final ballooning emplacement of the intrusion and a corresponding compression to the nearby strata (Zhang and Li 1999; Wu et al. 2004). The ballooning emplacement can be explained as a result of the rapid supply speed, that is the fast transport, of the magma, as is consistent with its diking pattern.

The stratal trend surface simulations and the internal and contact deformation of the large intrusion both indicate the great kinetic energy of the magmas as they ascended, further supporting the diking pattern and its influence on the caprock deformation.

The major ore-controlling structures in the caprock, which experienced regional compression and later extension, were further reworked by the bending resulting from magma emplacements. The bending can activate the vertical and bedding structures around the intrusions, providing suitable physical conditions for multi-layered emplacement and long migration of ore-forming fluids (Deng et al. 2007).

Ore-forming process

Metallogenic diversity and superposition of ore-forming processes

Ore deposit types in the Tongling region mainly include skarn, stratabound hydrothermal, porphyry, and cryptobreccia. The Fenghuangshan orefield consists of contact skarn and porphyry deposits, whereas the Tongguanshan, Xinqiao, and Shizishan orefields are composed of more types, such as stratabound skarn and hydrothermal deposits, as illustrated in Figure 5, which shows an overall distribution of the ore deposits in the Tongling region.

The skarn deposits, characterized by Cu and Au mineralization, are dominant in the region. Skarn ores are composed of chalcopyrite, pyrrhotite, pyrite, garnet, diopside, quartz, calcite, epidote, chlorite, and wollastonite, with a few containing sphalerite, galena, and native gold. Mineralization of the skarn deposits can be generally divided into five stages. Stage 1 is characterized by anhydrous skarn minerals (garnet, diopside, and wollastonite) and calcite. Stage 2 is represented by an assemblage of actinolite, tremolite, epidote, and chlorite. Stage 3 is characterized by the formation of magnetite as the main mineral. Stage 4 is the main ore stage and is characterized by the formation of chalcopyrite and bornite, together with quartz, pyrite, siderite, and calcite. Stage 5 is represented by the calcite and sulphides, such as pyrite, sphalerite, and galena (Pan and Dong 1999; Lai et al. submitted).

Some skarn orebodies with jagged and sharp boundaries developed along the intrusion contact zone. Ore minerals are deposited in tensional spaces distributed unevenly along the contact zone, and some of the tensional spaces are genetically related to the activities of the magmatic hydrothermal (Liu et al. 2008). For example, in the open pit of the Jinniudong
deposit located in the Fenghuangshan orefield, orebodies are contained in the tensional fractures in the skarns and cryptoexplosive breccias (Figure 6). Moreover, replacement skarns of both calcic and magnesium types within sedimentary strata along the bedding faults are widely developed and host so-called stratabound skarn orebodies (Figure 7). In the stratabound skarn orebodies, cryptoexplosive breccias are barely observed, because the bedding-parallel fault could keep the pressure balance between the intrusions and
surrounding skarns. An ore deposit can comprise several stratabound skarn orebodies, which are controlled by the multi-layered ore-controlling bedding-parallel faults (Figure 7).

The polymetallic stratabound hydrothermal orebodies, such as those in the Huangshilao deposit in the Tongguanshan orefield and the Xinqiao deposit, are developed mostly on the D–C boundary. The Xinqiao deposit, situated 24 km east of Tongling city, is a large-scale Cu–S–Fe–Au polymetallic deposit (Figure 1). In the deposit, there are two different types of sulphide mineralization. One is the stratabound orebody restricted to the D–C boundary and the other is the skarn mineralization restricted to the intrusion contact. However, significant economic reserves have only been explored in the stratabound orebody. A horizontal extension of 2550 m and a vertical extension of 1810 m with an average thickness of 21 m have been confirmed for the stratabound orebody by drilling (Figure 8). The stratabound mineralization is dominated by pyrite with minor amounts of chalcopyrite, magnetite, pyrrhotite, galena, sphalerite, quartz, and dolomite (Xu and Zhou 2001). In the Xinqiao ore deposit, 300 groups of Au–S–Fe–Cu–Zn concentrations of ores were collected for performing a cluster analysis, as shown in Figure 9. The cluster analysis shows that the Fe and S are highly correlated, indicating that pyrite is dominant in the ores. In addition, numerous occurrences characterized by pyrite mineralization around the D–C boundary are widely developed in the region (Figure 5). The mineral compositions of the stratabound hydrothermal ores are very different to those in the skarn ores, indicating that the origins of the two types of deposits are possibly distinct.

Ore deposits with various types located at different depths are clustered in one single orefield. From a cross-section view, the main orebodies exist as multiple floors from the top to the bottom of the orefield, composing a multi-layered mineralization network. For example, in the Shizishan orefield, the Dongguashan porphyry and stratabound skarn deposit exist in the deep part, Huashupo and Datuanshan stratabound skarn deposits are in
the middle, Laoyaling and Xishizishan stratabound skarn deposits are in the upper part, and Dongshizhishan cryptobreccia deposit and Baocun, Baimongshan, and Jiguanshan skarn deposits are developed in the shallow (Figure 5).
Most ore deposits in the Tongling region are genetically related to the magmatic rocks. The molybdenite samples were collected from the different skarn orebodies for precise Re–Os dating. The determined mineralization ages are identical to formation ages of intrusive rocks within errors (Sun et al. 2003; Meng et al. 2004; Mei et al. 2005) (Figure 2). In addition, sulphur and lead isotopes of sulphides both suggest that most ore-forming materials come from magmatic rocks, and REE distribution patterns of most ores are also similar to the adjacent intrusions (Tian et al. 2005, 2007; Xie et al. 2008a; Yang et al. 2011; Yang and Lee 2011). The hydrogen and oxygen isotope compositions of the fluid inclusions in vein quartz of different mineralization stages in the skarn deposits show that the ore-forming fluids mainly originated from magmatic fluid with a minor mixture of meteoric water (Zhou et al. 2000; Ren et al. 2006; Qiu et al. 2007). Qin et al. (2003, 2004) discovered sulphides in amphibole cumulate xenoliths and amphibole megacrysts in Mesozoic magmatic rocks, verifying that the magma brought metals from the deep.

However, several mineralizations, including the Laoyaling molybdenite mineralization in black shale of the Upper Permian Dalong Formation and the polymetallic ore deposit at the D–C boundary, are shown to be synsedimentary via geological phenomena, dating, and isotopic data (Zhou et al. 2000; Yang et al. 2004b) (Figures 4 and 5). The black shale from the Laoyaling Mo orebody has been dated to 234.2 ± 7.3 Ma by the Re–Os technique, which is much earlier than the regional Mesozoic intrusions, and younger than the Later Permian deposition age, denoting that the Mo ore is sedimentary in origin and possibly suffered a later hydrothermal disturbance (Yang et al. 2004a). In terms of the ore compositions, and the isotopic and dating evidence, the Xinqiao and Huangshilao deposits were inferred to be first formed via pyrite accumulation in synsedimentary mineralization during the Hercynian period, then superimposed by the Yanshanian magmatic hydrothermal fluids, during which they became enriched in Au, Cu, and Zn elements (Chang et al. 1991; Hou et al. 2004). The superposition of the different ore processes is prominent in the Tongling region, increasing the deposit tonnage and facilitating polymetallic mineralization. The superposition mineralization on the D–C boundary makes it host the greatest ore reserve in the caprock.

Magmatic hydrothermal ore-forming processes

Ore-controlling structures

The ore-controlling structures are composed of those related to the intrusive boundary and those in the strata. The structures in the strata were first formed under intense compression and later reactivated by regional extension and magma intrusion. The previous compressional structures became dilational and facilitated fluid migration and element deposition. Several types of structures are considered to control migrations of magmatic hydrothermal fluids. The most important is the multi-layered bedding-parallel fault, which controls stratabound orebodies. The great length of the stratabound orebodies, such as the orebody up to several kilometres long in the Huangshilao deposit, means that the fluids can migrate far along the detachment fault. The widespread non-harmonic folds are emplacement localities for fluids; for example, an excellent non-harmonic fold was developed in the Xinqiao deposit and partly controls the emplacements of magmatic bodies and orebodies (Figure 8). High-angle reverse faults can behave as pathways for hydrothermal fluids. The ore-controlling structural network in the strata is also characterized by interconnected bedding faults and steeply dipping ones. For instance, in an ore hand specimen of the Caoshan deposit in the Shizishan orefield, the ore-forming hydrothermal is observed to transport
first along the reverse fault, which shows dilational characteristics, and then to migrate along the bedding-parallel faults as the hydrothermal ascends (Figure 10).

**Fluid evolution process in skarn deposits**

When magma with a large number of volatiles is rapidly emplaced in the caprock and encounters void spaces, fluid boiling can be caused because of the sudden pressure drop. The fluid boiling is evidenced by the cryptobreccia ores, in which the breccias are sealed by quartz (or calcite) and sulphide veins or by felsic materials, and also revealed by fluid inclusions formed in the metallogenic stages 4 and 5 in skarn deposits (Table 2). For instance, in the open pit of the Jinniudong deposit in the Fenghuangshan orefield, the cryptobreccia ores, in which the marble breccias are sealed by the calcite and sulphide veins, are widely developed around the intrusive (Figure 6). The skarn deposits in the different orefields experienced similar fluid evolutions with decreasing temperatures and salinities from early to late stages, as manifested by fluid inclusions (Table 2). From the early to late stages, $\delta^{18}$O$_{H_2O}$ usually declines, suggesting a greater involvement of meteoric water, as is exemplified by the Dongguashan deposit (Xu et al. 2005a, 2005b; 2007a, 2007b). Thus, it is concluded that the fluid evolution is characterized by immiscibility in the early stage and by fluid mixing in the late stage.

**Element-enrichment features during skarn mineralization**

Because of the ore-forming process in a relatively complex structural network, the spatial distributions of ore-forming elements should show much irregularity. Five drillcores that are nearly 1000 m in length, located in the Dongguashan, Changlongshan, Huashupo,
Table 2. Fluid inclusions in skarn deposits of the Tongling region, Anhui Province, China.

<table>
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<tr>
<th>Orefield</th>
<th>Ore deposit</th>
<th>Ore-forming stage</th>
<th>Host mineral</th>
<th>FI type</th>
<th>Th°C</th>
<th>Salinity (%NaCl, equ.)</th>
<th>Geological significance</th>
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<td>Quartz-sulphide- (or) carbonate stage</td>
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(Continued)
Table 2. (Continued).

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I, Gas-rich fluid inclusions; II, liquid-rich fluid inclusions; IIa, liquid-rich inclusions without daughter minerals; IIb, liquid-rich inclusions with daughter minerals; III, gas-liquid inclusions; IV, multi-phase fluid inclusions.
Hucun, and Datuanshan skarn deposits in the Shizishan orefield, were chosen for analysing the characteristics of element enrichment. The Datuanshan drillcore is dominated by marble and the other four by skarns.

The five drillcores were sampled from top to bottom with an interval of 10 m, and the ore-forming elements in the samples were analysed (Wang et al. 2008). The concentration curves of the ore-forming elements in the typical drillcores are irregular, as shown in Figure 11, and thus analysed by the fractal models (Wang et al. 2010a).

The Hurst exponent in the self-affine fractal and multifractal spectrum was utilized to analyse the distributions and assemblages of ore-forming elements to better understand the element transport during the formation of the skarn deposit (Deng et al. 2008; Wang et al. 2008). The Hurst exponent was proposed by Hurst et al. (1965) to discriminate random and persistent distributions. Via the Hurst exponent, it is reflected that the elemental distributions in the marble-dominated drillcore, where the original characteristics of the sedimentary rocks generally remain, show approximately random distributions. The elemental distributions in the skarn-dominated drillcores are generally persistent, and the persistence indicates that the mineralized segments developed repeatedly along the drillcores, as is according to the multi-layered structures of the ore-controlling bedding faults and orebodies (Deng et al. 2008; Wang et al. 2010b).

The multifractal spectrum is powerful in characterizing singular measures arising in a variety of physical situations, including the spatial element distribution during ore-forming processes. The multifractal spectrum is a reverse bell shape, with a width $\Delta \alpha$ and a height

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**Figure 11.** Element concentration curves along the drillcores located in the Dongguashan, Huashupo, and Datuanshan ore deposits respectively, Shizishan orefield, Tongling ore cluster area (modified from Wang et al. 2010b).
difference $\Delta f(\alpha)$ between the two ends of the spectrum. An increase in $\Delta \alpha$ means a transition from a homogeneous (random, space filling) to a heterogeneous (ordered, complex, clustered) pattern. A positive $\Delta f(\alpha)$ means the spectrum is right hooked, indicating that there are more small values within the dataset than large ones; otherwise, they are dominated by larger ones (Zeleke and Si 2006; García Moreno et al. 2008). Wang et al. (2008) studied the multifractal parameters of the ore-forming element distributions in the drillcores, discovered that the $\Delta f(\alpha)$ of most elements between two drillcores show proportional relationships, and thus proposed that different deposits show similarities in the element enrichments. In this article, the multifractal parameters are analysed further. The $\Delta f(\alpha)$ and $\Delta \alpha$ of various elements in the Changlongshan drillcore against those in the Dongguashan drillcore and those in the Hucun drillcore were plotted in Figure 12. In Figures 12(a) and (b), the $\Delta f(\alpha)$ of most ore-forming elements are positive, indicating that the elements are locally enriched in the drillcores. Although generally proportional relationships among the elements in Figures 12(a) and (b) are easily observed, most plots in Figure 12(a) and part plots in Figure 12(b) are away from the diagonal line. It is revealed that the elemental enrichment characteristics in one drillcore still show much variance compared to those in another drillcore. The $\Delta \alpha$ plots, as illustrated in Figure 12(c) and (d), still show inconsistent element-enrichment characteristics between the drillcores. It is

![Figure 12](image-url)

Figure 12. Plots of the multifractal parameters of the element distributions in skarn deposits in the Shizishan orefield, Tongling ore cluster area. (a) $\Delta f(\alpha)$ plots between Changlongshan and Hucun deposits; (b) $\Delta f(\alpha)$ plots between Changlongshan and Dongguashan deposits; (c) $\Delta \alpha$ plots between Changlongshan and Hucun deposits; (d) $\Delta \alpha$ plots between Changlongshan and Dongguashan deposits.
demonstrated by further analysis of multifractal parameters that the skarn deposits in the same orefield show diverse element-enrichment characteristics.

**Evolution of the Tongling tectonic-magmatic-metallogenic system**

The evolution of the tectonic-magmatic-metallogenic system of the Tongling ore cluster region is outlined in this article. The regional evolution is divided into three stages (Figure 4). The first stage ranging from S to T₂ is a relative tectonic quiescence period, during which several parallel unconformities and multi-layered synsedimentary orebodies formed. In the second and third stages ranging from T₂ to K₁, the Tongling region suffered intense intraplate tectono-magmatic activations in a tectonic environment evolving from compressional to extensional.

Stage 2 from the Middle Triassic (T₂) to the Late Jurassic (J₃) is the tectonic compressional stage; the region suffered NW compression resulting from the collision between the North China block and the Yangtze block. Continuous and intense compression resulted in a thickened lithosphere. The NE-trending folds and bedding-parallel faults induced by compression were dominant in the caprock. The bedding faults containing void spaces between various strata are commonly connected by various types of nearly vertical faults.

Stage 3 lasted roughly from 150 to 134 Ma, defined by the emplacement age of the regional intrusions. The magmatic activity was triggered by the delamination of the thickened lithosphere, and this stage is considered as a transition from a compressional to extensional environment. The lithospheric delamination and asthenosphere upwelling caused crust–mantle interactions and the mixing of mantle- and crust-derived magmas. The mixed magma experienced fractional crystallization during its ascent. The structural framework formed by the previous compression was reworked and shows more tensional characteristics to facilitate the magma ascent.

In the crust, the magma ascended along the deep faults or structural weakness zones probably as mesoscale pervasive flow at depth and aggregated at the detachment faults to form multi-layered magma chambers. The magma generated from the shallow magma chamber at about 10 km migrated into the caprock in a diking model. Because of the inherent kinetic energy of dikes, the magma emplacement caused the bending of the strata and further reactivation of the existing structural network. Magma emplacement further enhanced the vertical transport of ore-bearing fluid, promoting the formation of a multi-layered mineralization network.

The magma emplacements and the following magmatic hydrothermal activities induced the formation of deposits with various types, in which skarn deposits are dominant. Some orefields were composed of multi-layered orebodies, constrained by the spatial features of ore-controlling structures. The different skarn deposits generally show diverse element-enrichment characteristics and similar fluid evolution. In the early stage, ore-forming fluid activity was influenced by a rapid decrease of the magma external pressure and characterized by fluid immiscibility in skarn deposits. Superpositions of the Mesozoic hydrothermal fluids on the synsedimentary orebodies formed in the first evolution stage are outstanding in the region.

**Conclusions**

The tectonic-magmatic-metallogenic system of the Tongling ore district is characterized by the following features:
(1) The system experienced two major tectonic transitions. In the Middle Triassic, the tectonic regime changed from quiescence to intense compression. The second tectonic transition, from compression to extension, occurred during the interval from 134 to 150 Ma. The main ore deposits formed during the second transition.

(2) Because of the transition of the tectonic regime, superposition of Mesozoic magmatic hydrothermal deposition on the previously formed Palaeozoic sedimentary ore bodies occurred throughout the region during the quiescence stage.

(3) Intense Mesozoic mineralization in the Tongling region was due to the abundant metals derived from mantle, favourable ore-controlling structures, and widespread fluid boiling attending hydrothermal fluid evolution, which facilitated metal deposition.

(4) The ore-controlling structure system in the cover sequence formed during strong tectonic compression and was reworked by the deformation that resulted from magma emplacement, and is reflected in the multi-layered bedding faults cut by steeply dipping faults. This structural assemblage resulted in the spatial multi-layered distribution of bedding-parallel ore bodies in a number of deposits.

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