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Geochronological framework and Pb, Sr isotope geochemistry of the Qingchengzi Pb–Zn–Ag–Au orefield, Northeastern China

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ABSTRACT

The Qingchengzi orefield in northeastern China, is a concentration of several Pb–Zn, Ag, and Au ore deposits. A combination of geochronological and Pb, Sr isotopic investigations was conducted. Zircon SHRIMP U–Pb ages of 225.3 ± 1.8 Ma and 184.5 ± 1.6 Ma were obtained for the Xinling and Yaojiagou granites, respectively. By step-dissolution Rb–Sr dating, ages of 221 ± 12 Ma and 138.7 ± 4.1 Ma were obtained for the sphalerite of the Zhenzigou Zn–Pb deposit and pyrargyrite of the Ag ore in the Gaojiabaozi Ag deposit, respectively. Pb isotopic ratios of the Ag ore at Gaojiabaozi ($^{206}Pb/^{204}Pb = 18.38$ to 18.53) are higher than those of the Pb–Zn ores ($^{206}Pb/^{204}Pb = 17.66$ to 17.96; Chen et al. [Chen, J.F., Yu, G., Xue, C.J., Qian, H., He, J.F., Xing, Z., Zhang, X., 2005. Pb isotope geochemistry of lead, zinc, gold and silver deposit clustered region, Liaodong rift zone, northeastern China. Science in China Series D 48, 467–476.]). Triassic granites show low Pb isotopic ratios ($^{206}Pb/^{204}Pb = 17.12$ to 17.41, $^{207}Pb/^{204}Pb = 15.47$ to 15.54, $^{208}Pb/^{204}Pb = 37.51$ to 37.89) and metamorphic rocks of the Liaohe Group have high ratios ($^{206}Pb/^{204}Pb = 18.20$ to 24.28 and 18.32 to 20.06, $^{207}Pb/^{204}Pb = 15.69$ to 16.44 and 15.66 to 15.98, $^{208}Pb/^{204}Pb = 37.29$ to 38.61 and 38.69 to 40.00 for the marble of the Dashiqiao Formation and schist of the Gaixian Formation, respectively).

Magmatic activities at Qingchengzi and in adjacent regions took place in three stages, and each contained several magmatic pulses: ca. 220 to 225 Ma and 211 to 216 Ma in the Triassic; 179 to 185 Ma, 163 to 168 Ma, 155 Ma and 149 Ma in the Jurassic, as well as ca. 140 to 130 Ma in the Early Cretaceous. The Triassic magmatism was part of the Triassic magmatic belt along the northern margin of the North China Craton produced in a post-collisional extensional setting, and granites in it formed by crustal melting induced by mantle magma. The Jurassic and Early Cretaceous magmatism was related to the lithospheric delamination in eastern China. The Triassic is the most important metallogenic stage at Qingchengzi. The Pb–Zn deposits, the Pb–Zn–Ag ore at Gaojiabaozi, and the gold deposits were all formed in this stage. They are temporally and spatially associated with the Triassic magmatic activity. Mineralization is very weak in the Jurassic. Ag ore at Gaojiabaozi was formed in the Early Cretaceous, which is suggested by the young Rb–Sr isochron age, field relations, and significantly different Pb isotopic ratios between the Pb–Zn–Ag and Ag ores. Pb isotopic compositions of the Pb–Zn ores suggest binary mixing for the source of the deposits. The magmatic end-member is the Triassic granites and the other metamorphic rocks of the Liaohe Group. Slightly different proportions of the two end-members, or an involvement of materials from hidden Cretaceous granites with slightly different Pb isotopic ratios, is postulated to interpret the difference of Pb isotopic compositions between the Pb–Zn–(Ag) and Ag ores. Sr isotopic ratios support this conclusion. At the western part of the Qingchengzi orefield, hydrothermal fluid driven by the heat provided by the now exposed Triassic granites deposited ore-forming materials in the low and middle horizons of the marbles of the Dashiqiao Formation near the intrusions to form mesothermal Zn–Pb deposits. In the eastern part, hydrothermal fluids associated with deep, hidden Triassic intrusions moved upward along a regional fault over a long distance and then deposited the ore-forming materials to form epithermal Au and Pb–Zn–Ag ores. Young magmatic activities are all represented by dykes across the entire orefield, suggesting that the corresponding main intrusion bodies are situated in the deep part of the crust. Among these, only intrusions with age of ca. 140 Ma might have released sufficient amounts of fluid to be responsible for the formation of the Ag ore at Gaojiabaozi.

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Our age results support previous conclusions that sphalerite can provide a reliable Rb–Sr age as long as the fluid inclusion phase is effectively separated from the "sulfide" phase. Our work suggests that the separation can be achieved by a step-resolution technique. Moreover, we suggest that pyrargyrite is a promising mineral for Rb–Sr isochron dating.

1. Introduction

The Qingchengzi orefield, situated in eastern Liaoning Province, northeastern China (123°37' E, 40°44' N), is an important region with clusters of Pb, Zn, and precious metal deposits. The orefield contains more than ten Pb–Zn deposits and has a mining history of more than 400 years. One silver deposit and four gold deposits were recently found in the eastern part of the orefield. All these deposits are hosted by Paleoproterozoic metamorphic rocks. Orefield reserves are estimated at ca. 1.5 Mt of Pb and Zn metals, 2000 ton of Ag metal, and 100 ton of Au metal. The orefield in which the Pb, Zn, Ag, and Au deposits are concentrated is also the location of magmatism of different ages, ranging from Proterozoic, Yindosinian (Triassic) and Yanshanian (Jurassic and Cretaceous). These features have attracted attention from economic geologists.

While much work on the origin of these deposits has been carried out, discrepancies as to the ages and the metal sources of the deposits remain. Early work regarded the Qingchengzi Pb and Zn deposits as medium- to low-temperature magmatic hydrothermal deposits (103GT, 1976). Several models have been postulated since then, including a metamorphic origin model (Zhang, 1984), a Proterozoic sea floor exhalation model (Wang et al., 1994), a sedimentation–metamorphism–hydrothermal reworking model (Jiang, 1987, 1988; Jiang and Wei, 1989; Ding et al., 1992), a Mesozoic hydrothermal mineralization model (Liu and Ai, 2002; Xue et al., 2003) and many others.

Three metallogenic pulses, i.e., 190 to 160 Ma, ca. 140 Ma, and ca. 120 Ma, have been identified in northern China. Mineralization in the northern margin of the North China Craton developed in all three stages, while gold deposits in other parts of northern China mostly formed at ca. 140 Ma and ca. 120 Ma (Yang et al., 2003; Mao et al., 2005). It is unclear whether the mineralization at Qingchengzi fits into this scenario. How the mineralization at Qingchengzi relates to the geodynamic evolution of the North China Craton is also not yet known. Precise dating of the ore deposits and the country rocks, as well as study of the source(s) of the ore-forming materials, are crucial for a deeper understanding of the ore-forming process and for further prospecting.

Little geochronological work on the ores has been carried out at Qingchengzi. The ore deposits at Qingchengzi lack minerals commonly used by traditional radioactive dating methods, and the Os concentrations of the ore-forming minerals in the deposits are extremely low. Recently, Triassic and Jurassic ages for Au and Ag deposits were reported at Qingchengzi by Rb–Sr and Ar–Ar dating of fluid inclusions in the quartz and sericite (Liu and Ai, 2002; Xue et al., 2003). Further geochronological work is needed to demonstrate the mineralization ages for the Au and Ag deposits and to constrain the time of formation of the Pb and Zn deposits. Many studies have shown that Rb–Sr dating of sulfide minerals, especially sphalerite and pyrite, can be used to determine the formation age of hydrothermal sulfide mineral deposits (Nakai et al., 1990; Brannon et al., 1992; Nakai et al., 1993; Christensen et al., 1995a,b; Yang and Zhou, 2001; Wei et al., 2003; Hou et al., 2006; Han et al., 2007).

As a major component of the Pb and Zn deposits, Pb isotopes can be used to directly trace the source of the ore-forming material and to delineate the evolutionary history and the origin of Pb and Zn deposits. On the other hand, as a chalcophile element, Pb isotopes can be used to indirectly infer the source of the ore-forming material and the origin of other sulfide deposits (Zhang, 1995; Bouse et al., 1999; Chu et al., 2001; Marcoux et al., 2002). Extensive Pb isotopic studies have been carried out on the deposits at the Qingchengzi orefield (Chen et al., 1980; Jiang, 1987; Ding et al., 1992; Fang et al., 1994). However, the data produced in the 1960's and 1970's were not precise enough (Ding et al., 1992), necessitating a new Pb isotopic study (Chen et al., 2005).

In this paper, we report the results of zircon U–Pb dating of the granitic intrusions and on step-dissolution Rb–Sr dating of sulfide minerals carried out with the aim of constructing a geochronological framework for the orefield. We also present the results of Pb and Sr isotopic studies of the ores and country rocks in order to constrain the possible source(s) of the ore-forming materials and determine the origin of various ore deposits at the Qingchengzi orefield.

2. Geologic setting

The Qingchengzi orefield is situated in the Paleoproterozoic Liaodong rift zone in the eastern part of Liaoning Province (Fig. 1). This intracontinental rift developed on the Archaean North China Craton and formed through the processes of crust extension, rapid subsidence, and compression folding in the Paleoproterozoic (Fang et al., 1994). The rift zone trends NEE with a total length of ca. 700 km, is truncated by the Tanlu fault in the west, and runs into the Sea of Japan to the east. The rift zone can be divided into three tectono-lithofacies belts: the northern marginal slop, the central depression and the southern marginal slop. The orefield is located in the central depression (Fig. 1). The metamorphic rocks of the Archaean Anshan Group comprise the basement of the rift zone. The thick Paleoproterozoic Liaohe Group was deposited on the basement and is disconformably overlain by the Paleoproterozoic quartzite of the Yushulazi Group. The lower Liaohe Group, consisting of the Yujiabaozi and Langzishan Formations, comprises volcanoclastic rocks, while the upper Liaohe Group, including the Dashiqiao and Gaixian Formations, includes carbonate and clastic rocks with some volcanic interdeds. The rocks in the Liaohe Group experienced metamorphism from greenschist to amphibolite facies at ca. 1800 Ma, forming amphibolite, granulite, schist, and marble (Jiang, 1987; Fang et al., 1994; Chen et al., 2005). Recently, Faure et al. (2004) and Lu et al. (2006) postulated a hypothesis that the region studied was a Paleoproterozoic orogenic belt, probably developed at approximately 1.93 to 1.90 Ga.

Mesoproterozoic magmatism in this rift region is represented by gabbro–diabase dykes and granitic stocks (Liu, 1998). Many Triassic igneous rocks, including syenite and granite, occur in the eastern part of the Triassic magmatic belt along the northern margin of the North China Craton (Liu, 1998; Yan et al., 1999; Wu et al., 2005c). Jurassic and Early Cretaceous igneous activities are widespread in the whole rift region, as in the entire eastern China (Liu, 1998; Wu et al., 2005a,b).

The Qingchengzi orefield is covered by the Dashiqiao and Gaixian Formations of the Upper Liaohe Group. The Dashiqiao Formation can be divided into several horizons. They are, from the base to the top: D1, consisting of graphite-bearing marble; D2 garnet mica schist; D31 interbeded granulite and banded marble with tremolite marble; D32 mica schist and mica sillimanite schist; D33 dolomite marble and tremolite marble; D34 leucoleptite and schist; and D35 dolomite marble and calcite marble. They were metamorphosed from limestone and interbeded sandstone and minor volcanic rocks. The Gaixian Formation is comprised of schist with thin interbeds of marble at the base, which were metamorphosed from sandstone, volcanic rocks, and limestone interbeds (Fang et al., 1994).