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PETROLOGY

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Petrology and mineralogy of the Fenghuanshan granodiorite, Anhui Province, China: implications for petrogenesis and metallogenesis implication

Aiping Zhang, Yangsong Du, Yi Cao, Zhenshan Pang[2], Gan Luo[1], Kangkang Xu[1]
1. School of the Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China
2. Development and Research Center of China Geological Survey, Beijing 100037, China
Correspondence should be addressed to Aiping Zhang, e-mail: zhangaiping_cugb@163.com

ABSTRACT

The Fenghuangshan copper deposit, in the Tongling area of Anhui Province, China, is genetically associated with the Fenghuangshan granodiorite, which contains amphiboles that can be used to determine the pressure and temperature history of the magmas that formed this intrusion. Here, we investigate the petrography and mineralogy of the Fenghuangshan granodiorite, focusing on variations in amphibole composition and determining the conditions of amphibole crystallization. The data are used to determine the petrogenetic history and metallogenic significance of the hosting granodiorite. The amphiboles within the intrusion can be divided by texture into phenocryst, matrix, and poikilocrystal amphiboles. Electro model, combined with the barometry and thermometry and the stratigraphy of the study area, indicates that the Fenghuangshan copper deposit has not undergone any significant changes since its formation, thereby indicating that both the granodiorite and the associated mineralization are well preserved. This also suggests that the final depth of emplacement of the magma (3–6 km) represents the depth of formation of the associated copper deposit. This inference, combined with the fact that the current depth of exploration and mining in the study area is <1 km, indicates the great potential for discovering significant copper mineralization by deep exploration in this area.

Key words: Fenghuangshan granodiorite, mineralogy, geothermometry–barometry, emplacement depth, denudation, Tongling, Anhui Province, China.

RESUMEN

El depósito cuprífero de Fenghuangshan, en el área de Tongling, provincia de Anhui, China, está genéticamente asociado con la granodiorita de Fenghuangshan, que contiene anfíboles que pueden ser usados para determinar la presión y la temperatura histórica de los magmas que formaron esta intrusión. En este trabajo se investigo la petrografía y la mineralogía de la granodiorita de Fenghuangshan enfocados en las variaciones de composición de anfíboles y en determinar las condiciones de cristalización de estos. Los datos se utilizaron para determinar la historia petrogenética y la significación metalogénica de la granodiorita anfitriona. Los anfíboles al interior de la intrusión pueden dividirse por texturas en fenocristales, cristales en matriz y cristales moteados. Los análisis de microsonda electrónica indican que los anfíboles son de características magnesiohornblenda y tschermakita. Las plagioclasas en la granodiorita son andesinas y oligoclasas. La barometría del aluminio en los anfíboles y la termometría de los anfíboles plagioclásticos indican que los anfíboles moteados cristalizados se fundieron a presiones entre 4,46 y 4,74 kbar y temperaturas de 1066 °C y 1071 °C, y los anfíboles en la matriz se formaron bajo condiciones de 1,00-1,91 kbar y 784-823 °C. Los datos indican que el magma que formó la granodiorita fue generado dentro del manto superior y migró a través de fracturas antes de ubicarse en la corteza media-baja a una profundidad de ~15 km, lo que formó una profunda cámara magmática donde el magma sufrió una cristalización y asimilación fraccionada. El magma migró luego a través de estructuras geológicas (como fallas y fracturas) antes de ubicarse en la corteza a poca profundidad, entre 3 y 6 km, y formando eventualmente la granodiorita Fenghuangshan. Este modelo combinado con la barimetría, la termometría y con la estratigrafía del área de estudio indica que el depósito cuprífero de Fenghuangshan no ha experimentado cambios sustanciales desde su formación, lo que indica que tanto la granodiorita como la mineralización asociada están bien preservadas. Esta condición también nos sugiere que la profundidad final de la ubicación del magma (3-6 km) representa la profundidad de formación del depósito cuprífero asociado. Esta inferencia, combinada con el hecho de que la actual exploración y explotación en el área de estudio es de <1 km, señala que el gran potencial para descubrir mineralización cuprífera con una exploración profunda en el área.

Palabras clave:

Record

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INTRODUCTION

Amphibole is widespread in igneous rocks, can form in a number of tectonic settings, and plays an important role in the magmatic evolution of igneous systems. Many studies have indicated that Al substitution in amphibole is controlled by both temperature and pressure (e.g., Anderson, 1980; Hammarstrom et al., 1986; Johnson et al., 1989; Schmidt, 1992; Ernst, 1999; Davidson et al., 2007; Martin, 2007; Larocque et al., 2010; Ridolfi et al., 2010; Dessimoz et al., 2012; Krawczynski et al., 2012), indicating that amphiboles can accurately record the pressure and temperature evolution of a magma (Zen, 1989; Tulloch et al., 2000; Stein et al., 2001; Lu et al., 2011).

The Middle–Lower Yangtze River Polymetallic Belt (MLYRB) is one of the most economically important metallogenic belts in China, and contains more than 200 Cu, Fe, Au, Mo, Zn, Pb, and Ag deposits (Li, 1989; Chang et al., 1991; Pan and Dong, 1999). The Tongling ore district is located within Anhui Province, within the central MLYMB (Fig. 1), and hosts widespread igneous rocks that temporally and spatially related to mineralization. Dozens of metallic ore deposits have been discovered in this ore district, including the Tongguanshan, Fenghuangshan, Baocun, Chaoshan, Jiguanshan, and Dongguashan deposits, among others. The Fenghuangshan deposit is a skarn Cu deposit that is typical of such mineralization in this area (Chang et al., 1991; Zhai et al., 1992; Fig. 1). The copper mineralization within this deposit is closely related to the Fenghuangshan intrusion, with mineralization hosted by both the intrusion and the contact between the intrusion and the surrounding Triassic limestone. In addition, the mineralization in this area (141.71 ± 0.82 Ma) was formed at the same time as the Fenghuangshan intrusion (143.1 ± 1.6 Ma; Li et al., 2014). This means that research into the Fenghuangshan intrusion can provide insights into the process associated with the formation of magma and mineralization in this district. Previous geochemical and geochronological research in this area has focused on the origin of the magma that formed the Fenghuangshan intrusion, the processes involved in the emplacement of the magma, and the ages of intrusion and mineralization. However, little research has been undertaken on the crystallization conditions of minerals within the granodiorite, in turn meaning that little is known about this crucial mineralogical evidence of the magmatic conditions and ore-forming processes associated with the Fenghuangshan deposit.

Here, we describe variations in amphibole composition within the Fenghuangshan granodiorite and use these data to estimate the magmatic conditions and reveal the petrogenetic and metallogenic significance of the Fenghuangshan granodiorite. These data enable the determination of the depth of emplacement and the degree of denudation that this area has undergone, providing useful information on the preservation history of the Fenghuangshan copper deposit and the prospectivity of the surrounding region.

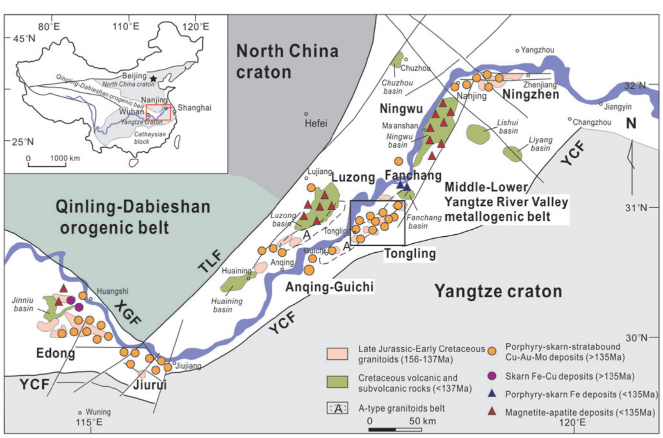

Fig.1 Sketch map of the Middle–Lower Yangtze River Polymetallic Belt, East China. The inset is a simplified structural map of China. TLF-Tancheng-Lujiang Fault, XGF-Xiangfan-Guangji Fault, YCF-Yangxing-Changzhou Fault. Modified from Chang et al. (1991), Mao et al. (2011), Tang et al. 1998), and Zhai et al. (1992).

2. Geological setting

The Fenghuangshan deposit is located in the eastern part of the Tongling ore district, 35 km southeast of Tongling. The geology of this area is dominated by the Fenghuangshan granodiorite, which intruded the core of a NE–SW-trending synclinorium (Fig. 2). The country rocks are dominantly Triassic limestones that have metamorphosed into marble, forming a 400- to 1200-m-wide thermal metamorphic aureole around the intrusion. The Fenghuangshan intrusion formed during the late Yanshanian, is high-K and calc-alkaline, and is dominated by a granodiorite phase (Qu et al., 2010; Li et al., 2014). The geochemistry of the granodiorite indicates that it formed from a deeply sourced alkaline magma that assimilated crustal material; this crustal contamination may have occurred during partial melting (i.e., contamination of the source) or during ascent and the emplacement of the magma. As such, this suggests the magma that formed the intrusion underwent typical assimilation and fractional crystallization (AFC) processes (Liu et al., 2002; Mao et al., 2004; Wang et al., 2008; Qu et al., 2010; Li et al., 2014). The Fenghuangshan granodiorite, which is the largest intrusion in the area, is circular in cross-section, and is exposed over an area of about 10 km2. It is dominated by a granodiorite phase and is cross-cut by some later trachytic, doleritic, and lamprophyre dikes. Six Cu–Fe–Au deposits are located near the contact zone of the Fenghuangshan granodiorite: the Fenghuangshan, Jiangjiachong, Qingshuitang, Xianrenchong, Tieshantou, and Baoshantao deposits (Fig. 2). The granodiorite samples analyzed in this study were collected from the –440 m level of the Fenghuangshan copper deposit.

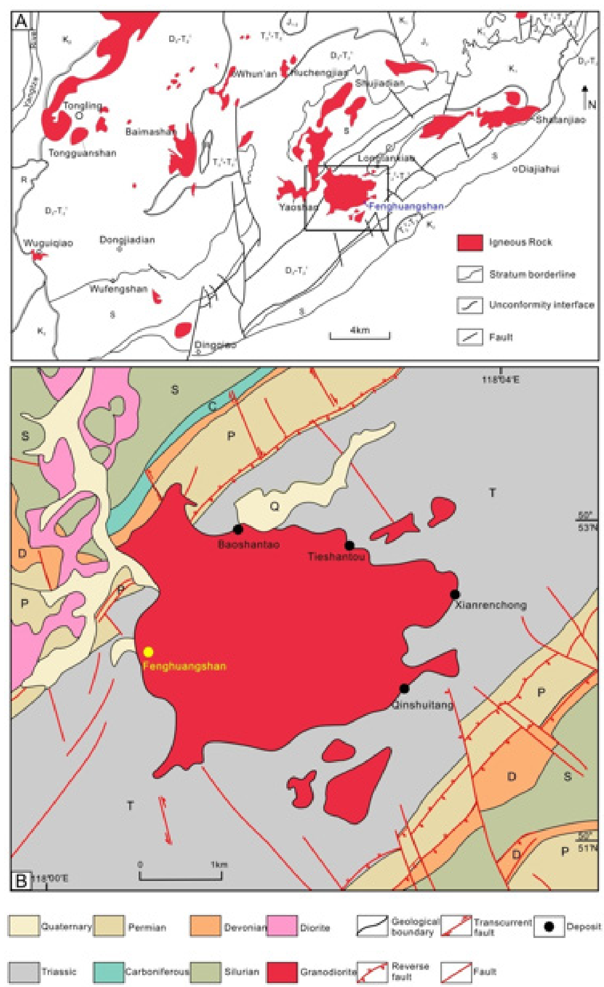

Fig.2 Location of the Fenghuangshan ore field in Tongling, Anhui Province (A) and a sketch geological map of the ore field (B). Modified from 321 Geological Team of Bureau of Geology and Mineral Exploration of Anhui Province (1989).

3. Petrology

The Fenghuangshan intrusion is granodioritic and has a porphyraceous texture (Fig. 2A) comprising phenocrysts of plagioclase (30%), amphibole (10%), quartz (15%), K-feldspar (10%), and biotite (3%) in a fine-grained matrix of the same minerals with accessory zircon, apatite, and sphene (Fig. 3A, B). The amphiboles within the intrusion can be texturally divided into phenocryst, matrix, and poikilocrystal amphiboles, and plagioclase within the intrusion is divided into phenocryst and matrix groups. Amphibole phenocrysts are 1–3 mm in size, are euhedral, have rhombus-shaped cross-sections, and are rimmed by opaque magnetite (Fig. 3C, D). These phenocrysts coexist with plagioclase phenocrysts (Fig. 3C), with the latter having oscillatory zoned overgrowths and partially resorbed textures (Fig. 3A, B). Matrix amphibole within the intrusion is present as small (<0.5 mm) subhedral–anhedral crystals (Fig. 3B, D), some of which are optically twinned. Nearly all of the matrix amphibole also coexists with matrix plagioclase (Fig. 3D). The amphibole poikilocrystals within the intrusion are small (<0.2 mm) and euhedral, and are enclosed within the cores of plagioclase phenocrysts (Fig. 3B), indicating that these poikilocrystals crystalized earlier than or at the same time as the amphibole phenocrysts. This indicates that the amphibole poikilocrystals were the first amphiboles to crystalize from the magma, whereas the matrix amphibole was the last amphibole to crystalize out, indicating that these differing amphiboles represent two different phases of the evolution of the magma that formed the Fenghuangshan intrusion.

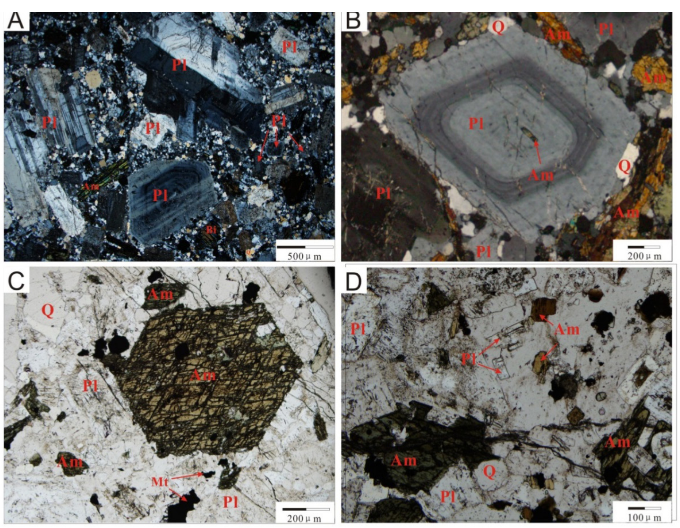

Fig. 3 Microphotographs of amphibole and plagioclase from the Fenghuangshan granodiorite. (A)-Granodiorite showing typical porphyraceous texture (crossed polarized light). (B)-Phenocryst of zoned plagioclase containing an inclusion of amphibole (crossed polarized light). (C)-Phenocryst of euhedral amphibole with a hexagonal cross-section and with nearby magnetite grains (plane polarized light); (D)-Amphibole and plagioclase in the matrix are <0.2 mm in size (plane polarized light); Pl-plagioclase, Am-amphibole, Bt-biotite, Q-Quartz; Mt-Magnetite.

4. Mineralogy

Electron microprobe analyses (EPMA) were undertaken at the Beijing Research Institute of Uranium Geology, Beijing, China, using a JXA-8100 instrument operated at a 20 kV accelerating voltage, 10 nA beam current, and using a 10 mm beam diameter, giving a detection limit of 0.002 wt%. Analyses were calibrated using albite (Na), sanidine (Si, Al, and K), diopside (Ca and Mg), almandine (Fe), rutile (Ti), fluorapatite (P), and rhodonite (Mn) standards.

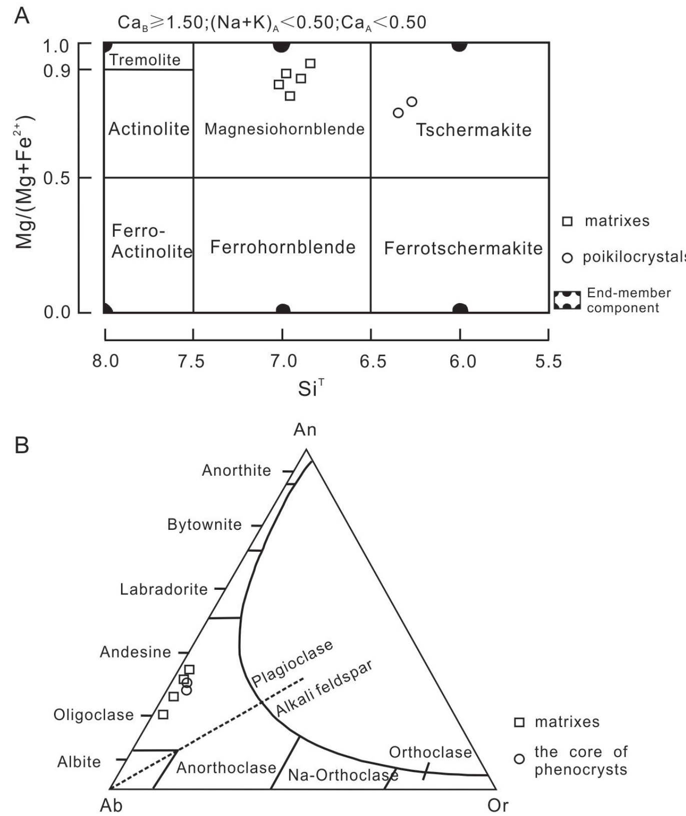

Fig.4 Classification of amphibole (A) and plagioclase (B) in the Fenghuangshan granodiorites after the International Mineralogical Association (Leake et al., 1997) and Smith (1974), respectively.

Table 1 Results of compositional analyses (wt%) of amphiboles

Sample	FH011			FH100			
Spots	1a	2a	3a	4a	5a	1b	2b
SiO_2	49.56	48.32	48.11	49.21	48.30	43.32	43.00
Al_2O_3	5.38	6.40	6.40	5.31	6.09	9.44	10.84
FeO*	12.79	12.96	13.53	14.84	15.32	19.95	17.74
MnO	0.49	0.50	0.45	0.50	0.58	0.55	0.63
MgO	16.37	15.88	16.15	15.10	14.33	11.44	11.95
CaO	11.66	11.59	11.36	11.51	11.84	11.58	11.44
Na_2O	1.26	1.59	1.60	0.91	1.15	1.61	1.83
K_2O	0.05	0.07	0.07	0.04	0.05	0.13	0.12
Total	97.56	97.31	97.67	97.42	97.66	98.02	97.55
Si^T	7.15	7.02	6.97	7.16	7.05	6.43	6.37
$Al(IV)^T$	0.85	0.98	1.03	0.84	0.95	1.57	1.63
Total T	8.00	8.00	8.00	8.00	8.00	8.00	8.00
$Al(IV)^{B+C}$	0.07	0.12	0.06	0.07	0.09	0.08	0.27
Fe^{3+B+C}	0.41	0.40	0.51	0.51	0.53	1.00	0.81
Fe^{2+B+C}	1.13	1.18	1.12	1.29	1.34	1.48	1.39
Mn^{B+C}	0.06	0.06	0.06	0.06	0.07	0.07	0.08
Mg^{B+C}	3.52	3.44	3.49	3.27	3.12	2.53	2.64
Ca^{B+C}	1.80	1.80	1.76	1.79	1.85	1.84	1.82
Total C + B	7.00	7.00	7.00	7.00	7.00	7.00	7.00
Na^A	0.35	0.45	0.45	0.26	0.33	0.46	0.53
K^A	0.01	0.01	0.01	0.01	0.01	0.02	0.02
Total A	0.36	0.46	0.46	0.26	0.33	0.49	0.55
P(kbar)	1.01	1.64	1.91	1.00	1.53	4.46	4.74
D(km)	3.35	5.42	6.31	3.32	5.05	14.72	15.63

a-amphibole in the matrix, b-amphibole poikilocrystals

Table 2 Results of compositional analyses (wt%) of plagioclase

Sample	FH011			FH100			
Spots	1c	2c	3c	4c	5c	1d	2d
SiO_2	58.73	58.26	58.49	61.68	60.37	59.15	60.60
TiO_2	0.07	0.08	0.08	0.00	0.00	0.00	0.00
Al_2O_3	25.08	25.31	25.48	23.38	24.51	25.78	25.31
FeO	0.19	0.33	0.24	0.27	0.24	0.20	0.24
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.02
CaO	7.15	7.11	7.48	4.98	6.07	6.61	6.16
Na_2O	7.39	7.90	7.28	9.19	8.49	7.49	7.63
K_2O	0.06	0.04	0.03	0.02	0.02	0.27	0.42
Total	98.67	99.06	99.08	99.52	98.28	99.52	100.39
Si	2.66	2.63	2.64	2.75	2.70	2.65	2.69
Ti	0.00	0.00	0.00	0.00	0.00		
Al	1.34	1.35	1.35	1.23	1.29	1.36	1.32
Fe^{2+}	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.35	0.34	0.36	0.24	0.29	0.32	0.29
Na	0.65	0.69	0.64	0.80	0.74	0.65	0.66
K	0.00	0.00	0.00	0.00	0.00	0.02	0.02
Cr	0.00	0.00	0.00	0.00	0.00		
Ab	64.94	66.64	63.67	76.87	71.60	66.15	67.42
An	34.72	33.14	36.15	23.02	28.29	32.26	30.12
Or	0.35	0.22	0.17	0.11	0.11	1.59	2.47
P(kbar)	1.01	1.64	1.91	1.00	1.53	4.46	4.74
T(°C)	798.50	812.29	822.73	784.26	803.41	1066.39	1070.55

c-plagioclase in the matrix; d-core of plagioclase phenocrysts coexisting with amphibole poikilocrystals

The classification of amphiboles is based on the composition of the standard amphibole formula $AB_2\ ^{IV}C_5{}^{IV}T_8O_{22}(OH)_2$. The composition and stoichiometrically calculated chemical formulae of representative amphiboles from the Fenghuangshan granodiorite are given in Table 1, with mineral formula calculations based on 23 oxygens and standardized on 13 cations. The calculation method of Droop GTR (1987) was used to adjust Fe^2+ and Fe^3+ concentrations, and the electrovalency balance principle was used to calculate crystal formulae. Amphibole stoichiometry and nomenclature followed the International Mineralogical Association (IMA; Leake et al., 1997; Fig. 4). All of the amphiboles analyzed during this study are calcic amphiboles, defined by $(Ca + Na)^B$ values of ≥1.00, with Na values of <0.50 and Ca^B values of ≥1.50 (Leake et al., 1997). Consequently, they are classified as magnesiohornblende and tschermakite amphiboles, with the matrix amphiboles being classified as magnesiohornblende and the lower-Si amphibole poikilocrystals being classified as tschermakite.

Magnesiohornblende within the intrusion has Si values of 6.97–7.16, $Al(IV)^T$ contents of 0.84–1.03, Ca^B values of 1.96–1.85, (Na + K)^ values of 0.27–0.46, and Ca^ values of <0.5. In comparison, tschermakite within the intrusion has Si values of 6.37–6.43, $Al(IV)^T$ values of 1.57–1.63, CaB values of 1.82–1.84, (Na + K)^ values of 0.48–0.55, Ca^ values of <0.5, and $Mg/(Fe^{2+} + Mg)$ values of 0.63–0.66 (Table 1).

The compositions and calculated formulae of the plagioclase analyzed during this study are given in Table 2, with structural plagioclase formulae calculated on the basis of 8 oxygens and 5 cations. These data indicate that the plagioclase has An values of 23.02–36.15 and that the granodiorite contains oligoclase (An = 23–28) and andesine (An = 30–36) plagioclase (Fig. 4). Both matrix and phenocryst plagioclase have similar compositions, with Na_2O and CaO concentrations increasing from 7.49 to 8.49 wt% and decreasing from 6.61 to 6.07 wt%, respectively, from core to rim in zoned plagioclase.

5. Barometry and thermometry

Amphibole is stable over a wide range of pressure (P) and temperature (T), making it useful for determining the geothermometry and geobarometry of calc-alkaline intrusive magmatic systems (Blundy et al., 1990).

The total Al content of amphibole can be used to estimate the crystallization pressure of a magma (Hammarstrom et al., 1986; Hollister et al., 1987; Johnson et al., 1989; Ghent et al., 1991; Vyhnal et al., 1991; Ague et al., 1992; Schmidt, 1992). The first empirical Al-in-amphibole barometer was proposed by Hammarstrom (1986; Eq. 1), who used this barometer with hornblende compositions to estimate the pressure of formation of intermediate calc-alkaline plutons. Hollister (1987) reduced the error of this barometer by using a larger dataset for calibration (Eq. 2) with a similar correlation. Johnson and Rutherford's (1989) calibra tion (Eq. 3) was obtained by performing experiments on natural samples under set $CO^2 + H_2O$ volatile pressures, with further experimental calibration of this barometer under water-saturated conditions (Eq. 4) by Schmidt (1992).

$$P\ (+3\ kbar) = -3.92 + 5.03\ Al^T \quad (1)$$

$$P\ (+1\ kbar) = -4.76 + 5.64\ Al^T \quad (2)$$

$$P\ (\pm 0.5\ kbar) = -3.46 + 4.23\ Al^T \quad (3)$$

$$P\ (\pm 0.6\ kbar) = -3.01 + 4.76\ Al^T \quad (4)$$

The last two calibrations are more commonly used because they are experimentally rather than empirically derived and have lower uncertainties that the first two calibrations. Here, we use the calibration of Schmidt (1992; Eq. 4) to calculate the pressures obtained from amphibole analyses. The present amphiboles yield pressures of 1.00–4.76 kbar, with the highest values (4.46–4.74 kbar) being derived from the amphibole poikilocrystals.

Blundy (1990) published an empirical thermometer based on the edenite–tremolite reaction that can only be used on quartz-bearing, intermediate to felsic igneous rocks containing plagioclase with compositions of An ≤92% and amphibole with Si values of ≤7.8, as follows:

$$T = \frac{0.677P - 48.98}{-0.0429 - 0.008314\ \ln K}$$

where $K = \left(\frac{Si - 4}{8 - Si}\right)$ Xab, Xab = the composition of plagioclase co-existing with amphibole, and using the pressure values derived from the Al-in-amphibole barometry described above.

The Fenghuangshan granodiorite has SiO2 concentrations that vary between 60.82 wt% and 65.97 wt% (Shao et al., 2003; Li et al., 2014), contains plagioclase with An values between 23.02 and 36.15, and contains amphibole with Si values of 6.37–7.16. All of these features mean that these samples are suitable for amphibole–plagioclase thermometry (Blundy et al., 1990), yielding crystallization temperatures of 784°C–1071°C, with amphibole poikilocrystals yielding both higher pressures (as detailed above) and temperatures (1066°C–1071°C).

6. Discussion

6.1 Crystallization conditions

The fact that poikilocrystals and matrix amphiboles within the Fenghuangshan granodiorite have different compositions suggests that they formed in two different magmatic environments. The poikilocrystals most likely formed in a deeper and hotter setting, in a deep magma chamber, whereas the matrix amphiboles probably formed within a shallow magma chamber under the conditions of the final emplacement of the magma, and these amphiboles therefore record the depth and temperature of emplacement. The barometry and thermometry undertaken during this study indicate that the amphibole poikilocrystals crystallized from the melt at pressures of 4.46–4.74 kbar and temperatures of 1066°C–1071°C, whereas matrix amphiboles formed at 1.00–1.91 kbar and 784°C–823°C. The pressures are probably equivalent to the depth of emplacement of the magma, which, when combined with the fact that the average crustal density of the MLYRB is 3.3 g/cm3, yields a depth of 14.72–15.63 km (average of 15.16 km) and a temperature of 1066°C–1071°C (average of 1068°C) for the deep magma chamber, and an emplacement depth and temperature for the shallow magmatic chamber of 3.32–6.32 km (average of 4.7 km) and 784°C–823°C (average of 804°C), respectively.

The geochemistry of the Fenghuangshan granodiorite suggests that the intrusion has an adakitic affinity similar to that of other intrusions in the Tongling area (Du et al., 2004, 2007; Cao et al., 2008, 2010 ; Wang et al., 2008; Mao et al., 2009; Zhai et al., 2010; Wu et al., 2014), which have initial 87Sr/86Sr ratios of 0.709074 – 0.709965 and eNd(t) values of –9.26 to –16.25 (Xing et al., 1996). This suggests that the magma that formed the Fenghuangshan granodiorite originated from the upper mantle, and assimilated crustal material during its evolution.

These data have allowed the development of the following model for the Fenghuangshan granodiorite: an upper-mantle-derived magma migrated along faults and was emplaced within the middle–lower crust (at a depth of ~15 km), forming a deep magma chamber where the magma underwent assimilation and fractionation crystallization processes. The region then underwent tectonic deformation, causing the magma within the deep magma chamber to migrate along tectonic fractures to the shallow crust (depths of 3–6 km), forming the Fenghuangshan granodiorite.

6.2 Estimate of denudation amount

Ore deposits undergo significant changes after formation, and post-formational changes and preservation of orebodies provide vital information for targeting during mineral exploration (Harrison, 1994; Kesler et al., 2006; Uchida et al., 2007; Wilkinson et al., 2007; Wang et al., 2008; Kirstein, 2011; Lu et al., 2011; Zheng et al., 2011). The degree of denudation of an ore deposit is an important factor in determining the preservation potential of orebodies and hence the prospectivity of an area. The copper mineralization in the present study area is closely related to the Fenghuangshan granodiorite, indicating that the denudation of the deposit can be inferred from the emplacement depth of the intrusion, the timing of mineralization in the area, and the thickness of overlying sediments.

The samples analyzed in this study were obtained from the –440 m level of the Fenghuangshan deposit. This, combined with the shallowest emplacement depth obtained during this study (3.23 km), suggests that this area has experienced at least ~2.8 km of uplift since 141 Ma. The intrusion in the study area was emplaced into sediments at 141 Ma; the total thickness of all of the sediments overlying the intrusion is >2.6 km (321 Geological Team, 1989). This indicates that all of these sediments must have been eroded away, although the intrusion itself has not undergone significant erosion. As such, the Fenghuangshan copper ore deposit, which is closely related to the Fenghuangshan granodiorite, is well preserved and has undergone few post-mineralization changes. This suggests that the emplacement depth (3.32–6.32 km) of the intrusion could also represent the depth of exhumation of the copper mineralization in this area. Therefore, exploration for copper mineralization at depths of <1 km, which is the current limit of exploration and mining in this area, may identify significant amounts of previously unknown mineralization

.

7. Conclusions

Analyses of minerals from the Fenghuangshan granodiorite yielded the following conclusions.

Amphibole poikilocrystals contain lower amounts of Si than other amphiboles in the intrusion and are classified as tschermakite, whereas matrix amphibole in the intrusion is magnesiohornblende. Plagioclase within the deposit has oligoclase and andesine compositions.

Amphibole poikilocrystals crystallized from the melt at pressures of 4.46–4.74 kbar and temperatures of 1066°C–1071°C, whereas matrix amphibole formed at pressures of 1.00–1.91 kbar and 784°C–823°C, representing conditions within deep and shallow magma chambers, respectively.

The Fenghuangshan granodiorite formed from upper-mantle-derived magmas that initially migrated along fault zones before being emplaced in the middle–lower crust (at a depth of ~15 km), forming a deep magma chamber where these magmas underwent fractionation crystallization and assimilation. Tectonism then caused the magma within the deep magma chamber to migrate along faults to the shallow crust (depths of 3–6 km), forming the Fenghuangshan granodiorite.

The barometry and thermometry undertaken during this study, combined with the stratigraphy of this region, indicates that the Fenghuangshan copper deposit is well preserved and has undergone few changes since formation. This indicates that the emplacement depth of the intrusion (3.32–6.32 km) also represents the initial burial depth of the copper deposit. The current depth of exploration and mining in this area is <1 km, meaning that this area is highly prospective for deeper exploration for copper mineralization similar to that within the Fenghuangshan copper deposit.

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