Geochronology and Geochemistry of Metallogenetic Porphyry Bodies from the Nongping Au-Cu Deposit in the Eastern Yanbian Area, NE China: Implications for Metallogenic Environment

REN Yunsheng[1, *], JU Nan[1], ZHAO Hualei[1], WANG Hui[1], HOU Kejun[2] and LIU Shen[3]

1 *College of Earth Sciences, Jilin University, Changchun 130061, China*
2 *MRL Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China*
3 *State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China*

Abstract: The metallogenetic porphyry bodies in the Nongping Au-Cu deposit, in the eastern Yanbian area, mainly include porphyritic granodiorite and biotite granodiorite porphyry. They are featured with high silicon and enrichment in sodium, and classified into sodic rocks of low-K tholeiitic basalt series. Except slightly low Sr content, the rock basically has the geochemical characteristics of the adakite: relatively high Al_2O_3 content, relatively low MgO content, depletion in Y and Yb; relative enrichment in large ion lithophile elements (LILEs) and light rare-earth elements (LREEs), relatively low content of high field strength elements (HFSEs); positive Eu anomaly or weak negative Eu anomaly. In situ zircon dating technology LA-MC-ICP-MS was used to conduct single-grain zircon dating of biotite granodiorite porphyry, and the results show that the age of metallogenetic porphyry body is 100.04±0.88 Ma, indicating that the porphyry bodies were emplaced in the late Cretaceous period. According to the regional tectonic setting and the comparison with the same kind of deposits, we think that the metallogenetic porphyry bodies in the Nongping Au-Cu deposit have a close genetic connection with the subduction of the Pacific plate in the late Yanshanian period. The adakitic magma generated from partial melting of the subducting plate has high formation temperature, high oxygen fugacity, and volatile constituents' enrichment, so it is helpful for enrichment of metallogenetic elements and plays an important role in the formation of porphyry Au-Cu deposits in this region.

Key words: porphyry body, zircon U-Pb dating, adakitic rock, Nongping Au-Cu deposit

1 Introduction

The Nongping Au-Cu deposit is located in the eastern Yanbian area, Jilin Province, NE China. It is currently proven that both Au and Cu resource quantities reach medium scales and it has large-scale prospecting potential for Au ore (Shi et al., 2001; Sun et al., 2010). Over years, there have been many data accumulated for such aspects of this deposit as geological conditions, geological characteristics, genetic type and prospecting direction, etc., and the understanding that "the deposit belongs to the porphyry type and has a close genetic connection with the intermediate acidic magmatism in the Yanshanian period" has basically been recognized (Shi and Li, 1998; Liu and Li, 1999; Zhang and Sun, 2001; Sun and Zhang, 2002; Zhang et al., 2007). Moreover, it was concluded in all published literatures that this deposit was formed in the Yanshanian period, on the basis of the Rb-Sr isochron age (130 Ma) and K-Ar age (120.73–157.27 Ma) of the ore-bearing porphyry bodies determined by Jilin Nonferrous Geological Institute in 1989. Due to the limitation of technical methods for test then, the above ages differed greatly and had poor precision. They could not meet the requirements for detailed studies on the metallogenetic mechanism and dynamic setting.

The Xiaoxi'nancha deposit, a well-known large-scale Au-Cu deposit in NE China, is near the Nongping deposit and they both belong to the SN-strike Au-Cu-W metallogenic belt in the eastern Yanbian area (Fig. 1a). Further, both the two deposits have comparable

* Corresponding author. E-mail: renys@jlu.edu.cn

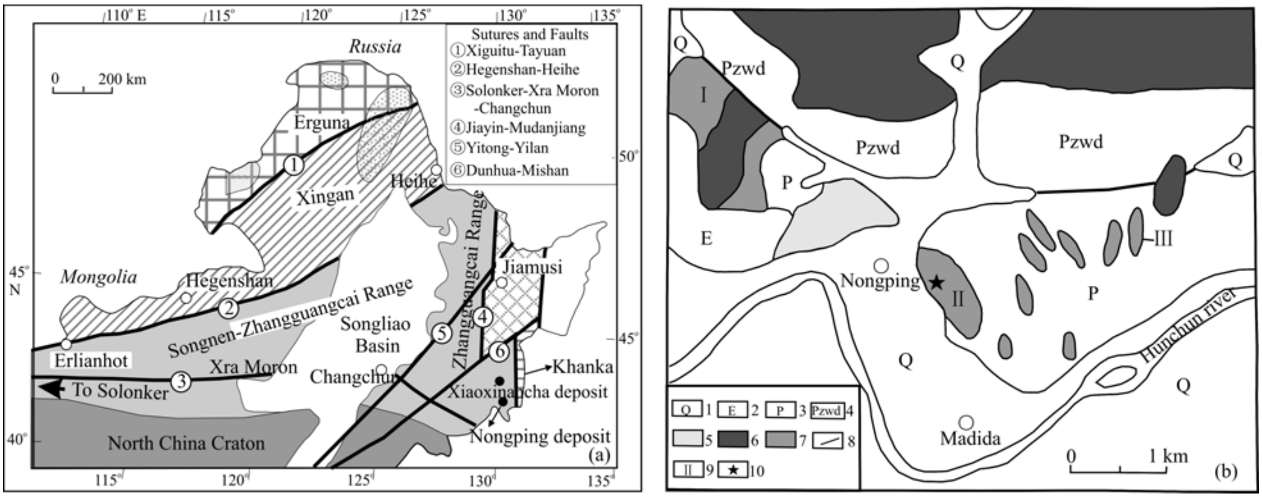

Fig. 1. Tectonic location map of the Yanbian area (after Wu et al., 2007) and simplified geological map of the Nongping deposit (after Meng et al., 2001).

1, Quaternary sediments; 2, Paleogene sandstone and conglomerate; 3, Permian metasandstone and slate; 4, Paleozoic Wudaogou Group low-level metamorphic rocks; 5, Jurassic intermediate acidic volcanic rock; 6, Hercynian tonalite; 7, Late Yanshanian porphyritic granodiorite and biotite granodiorite porphyry; 8, fault; 9, ore-bearing porphyry bodies and numbers; 10, location of samples.

metallogenic characteristics. However, researches on the metallogenic mechanism of the Nongping deposit are not so intensive compared with those on the metallogenic mechanism of the Xiaoxi'nancha deposit, which restricts studies on the metallogenetic mechanism and regularities of the porphyry Au-Cu deposits in the Yanbian area to a large extent. Presently available data show the following facts: (1) ore-hosting rocks of the Xiaoxi'nancha deposit are adakites (Zhang et al., 2004); (2) adakitic andesitic porphyrite and dacitic porphyry dykes are associated with the metallogenetic process; and (3) the Au-Cu mineralization has a close genetic connection with the adakitic magma formed from the subduction of the Paleo-Pacific plate (Sun et al., 2007; Zhao et al., 2007). In recent years, adakite (adakitic) rocks and related Au, Cu (Mo) metallogenesis have been hot spots of research in NE China. Wang et al. (2001) pointed out that if there were adakitic rocks formed from melting of subducting plate pieces found in the Mesozoic igneous rocks in eastern China, it would be powerful evidence for direct connection of the Mesozoic igneous rocks with the subduction of the Paleo-Pacific plate or the Izanagi plate. Zhang et al. (2004) thought that the Mesozoic adakitic rocks in NE China were mainly distributed in eastern Jilin Province and they were formed in the island arc setting in the western Circum-Pacific belt. Study on the genesis of metallogenetic rock bodies in different deposits and their relationships with Au-Cu mineralization can provide important data for petrogenic and metallogenetic geological environments in the Yanbian area and even in NE China.

2 Deposit Geology and Petrographic Characteristics of Porphyry Bodies

The Nongping Au-Cu deposit lies in the east section of the Xing'an-Mongolian orogenic belt (Fig. 1a), on the western Pacific continental margin, and at the place where the deep-seated EW-strike Yanji-Tumen-Madida regional fault and the NNE-strike Sandaogou fault belt converge. The main strata occurring in the area include Paleogene sandstone and conglomerate formations, late Jurassic intermediate acidic lava and pyroclastic rock, Permian metasandstone, slate and metamorphic volcanic rocks, as well as andalusite slate, hornblende schist and plagioclase amphibolite in the Paleozoic Wudaogou group, etc. The Hercynian tonalite is distributed as batholiths in the Nongping deposit area and the northern periphery; the late Yanshanian intermediate acidic hypabyssal intrusive bodies occur in groups or belts, and invade as small stocks and veins into the Permian low-grade metamorphic rocks and the early-formed intrusive bodies (Fig. 1b).

Over ten porphyry bodies in the Nongping deposit area, as small stocks with different shapes and different sizes, compose rock groups. The outcrop area of the main metallogenetic porphyry bodies is about 0.8 km^2 and they extend in the NW direction. According to textures of rocks, there are three rock types, i.e., porphyritic granodiorite with fine-grained granitic groundmass, biotite granodiorite porphyry with micro-granitic groundmass, and biotite granodiorite porphyry with felsitic groundmass. These three types have phase change as gradual transition.

By now, 23 proved ore bodies in the mine are all blind ones, including 14 Au (Cu) ones and nine Cu (Au) ones. Both types of ore bodies are composed of altered granodiorite porphyry and altered cataclastic rock, controlled by NW-strike faulted structures. They are mostly in the forms of fine veins, stockwork veins and compound veins occurring in biotite granodiorite porphyry. Thirteen among the 23 known ore bodies are over 100 m long, from more than one to four meters thick, and extend in depth from 104 m to 380 m below the surface. All ore bodies extend persistently and mostly have gradational contact with surrounding rocks.

The ore-bearing rocks are altered strongly, and are in two forms with very weak zoning, i.e., planar and linear (Liu and Li, 1999). The former alterations, which are composed mainly of biotitization, chloritization as well as associated pyritization, have a close relationship with copper mineralization; while the latter include mainly silication, tourmalinization, hydromicazation, epidotization, sericitization and zeolitization, and usually superimpose planar wall-rock alteration. The gold grade usually has positive correlation with such linear alterations as silication, tourmalinization and hydromicatation (Sun and Zhang, 2002). Based on this study and predecessors' research data, it is indicated that the Nongping Au-Cu deposit can be listed as porphyry deposit related to the Yanshanian intermediate acidic hypabyssal intrusive bodies.

3 Zircon U-Pb Dating

3.1 Sample descriptions and analytical method

All samples for this study were collected from porphyry body II in the adit within the deposit area (Fig. 1b). Samples PD1-2-1, PD1-2-2, PD1-5-1 and PD1-5-2 were taken at locations 5-10 m from the adit opening without obvious mineralization and alteration; samples PD1-6 and PD1-7 were taken at location near the mineralized belt about 50 m from the adit opening, with apparent silication, sericitization, chloritization and sparsely disseminated pyritization. The rocks have massive structure and porphyritic texture, and the groundmass is fine grained and of felsitic texture. The grain size of phenocrysts is generally 0.5-10 mm and the phenocryst content is 30%-50%; the phenocrysts of rock are primarily andesine and oligoclase (mostly with zonal texture, An=30-45), and secondly quartz (5%-10%), biotite (3%-5%) and alkali feldspar (3%-5%). According to such petrographic characteristics that the feldspars in rocks are mainly intermediate plagioclase, the dark minerals are primarily biotite, it can be concluded that the main metallogenetic rock bodies in the Nongping deposit are biotite granodiorite porphyries.

Sample crushing and zircon selecting were carried out by the Regional Geology and Mineral Resources Survey Institute of Hebei Province; preparation of experimental samples (target) and imaging of reflected light, transmitted light and cathode luminescence (CL) were conducted in the laboratory of the Institute of Geology, Chinese Academy of Geological Sciences. Zircon U-Pb dating was completed in MRL Key Laboratory of Metallogeny and Mineral Assessment of the Institute of Mineral Resources, Chinese Academy of Geological Sciences, and the used instruments were Finnigan Neptune MC-ICP-MS and assorted Newwave UP 213 laser ablation system. The spot beams used for laser ablation have a diameter of 25 μm, a frequency of 10 Hz, and an energy density of about 2.5 J/cm^2, with Helium as the carrier gas. Weak signals, ^{207}Pb, ^{206}Pb, ^{204}Pb(+^{204}Hg) and ^{202}Hg, were received with ion counters, while signals ^{208}Pb, ^{232}Th and ^{238}U were received with Faraday cups, so simultaneous receiving of all target isotope signals was realized. In addition, all peaks with different mass numbers were basically flat, so high precision data could be obtained.

The test precision for all zircon grains was about 2%, and the dating precision and accuracy for zircon standard were about 1%. The single spot ablation method was used for laser ablation sampling, and the instruments were tuned to optimal state with zircon GJ-1 prior to data processing. Calibration was conducted for zircon U-Pb dating with zircon GJ-1 as the external standard, U and Th contents were calibrated with zircon M127（U: 923 ppm; Th: 439 ppm; Th/U: 0.475）as the external standard (Nasdala et al., 2008). During the test, before and after every test of five to seven samples, two zircon GJ-1 standard samples were repeatedly tested for sample calibration and one zircon sample was tested for observation of instrument state so as to ensure the test accuracy. Application program ICPMSDataCal was employed for data processing (Liu et al., 2010). For most analysis points in the test process, ^{206}Pb/^{204}Pb>1000, no common Pb calibration was conducted, and ^{204}Pb was tested with an ion counter. The analysis points with extremely high content of ^{204}Pb might be influenced by common Pb in enclave etc., and they were eliminated for calculation. The zircon Concordia age diagram was obtained with application program Isoplot 3.0. For the detailed test process, see the reference by Hou et al. (2009). During sample analysis, the standard samples were assumed as unknown samples and tested; the recommended age for the standard samples was 337.13±0.37 Ma (Sláma et al, 2008), and it was completely identical to the determined age within the error range.

3.2 Analytical results

Zircon grains from the biotite granodiorite porphyries are mostly colorless and clear combined bodies in the form of tetragonal prism and tetragonal bipyramid, with general grain sizes of 50-150 μm. A few zircons are developed in prisms with a crystal aspect ratio more than 4, and most are developed in pyramids with a crystal aspect ratio less than 2.0. The cathode luminescence (CL) images show that crystal growth zoning is clear and a few grains have a regular zonal texture, and that most grains have zones with different widths or are in bands parallel to the major axis of the crystals. The Th/U ratio of zircon is generally 0.26-0.81, mostly 0.30-0.6, which indicates that the zircons are of magmatic origin (Liu et al., 2011).

The zircon U-Pb dating results are shown in Table 1, and the U-Pb Concordia diagram based on the test data is shown in Fig. 2. The tested rocks were formed in the late Mesozoic era, and the dating results were calculated as $^{206}Pb/^{238}U$ age and the age error of every single data point was 2σ. The $^{206}Pb/^{238}U$ ages from 21 test points are within 103 Ma and 95 Ma, and all data in the $^{206}Pb/^{238}U$-$^{207}Pb/^{235}U$ Concordia diagram are on or near the concordant line. Through calculation of the weighted average of the $^{206}Pb/^{238}U$ values from 21 test points, the average $^{206}Pb/^{238}U$ age was 100.04±0.88 Ma, under MSWD=6.2 and confidence level of 95%.

4 Geochemical Characteristics

Six porphyry samples from PD1 were analyzed for major, trace and rare-earth elements. These tests were conducted in the State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences. The major elements were analyzed using the Axios PW 4400 X-ray fluorescence (XRF) spectrometer with an analysis precision higher than 3%. The test flow was as follows: a representative sample was

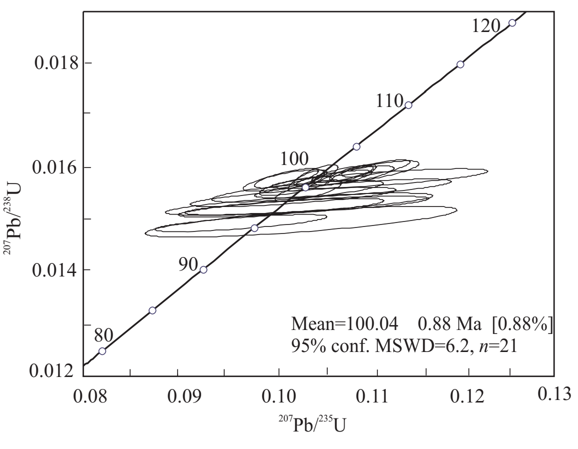

Fig. 2. U-Pb concordia plot for zircons from the biotite granodiorite porphyry in the Nongping deposit.

Table 1 LA-MC-ICP-MS analytical data of zircons from the biotite granodiorite porphyry in the Nongping deposit

Sample No.	Composition (ppm)		Th/U	U-Th-Pb isotopic ratio						Age (Ma)					
	Th	U		$^{207}Pb/^{206}Pb$	σ	$^{207}Pb/^{235}U$	σ	$^{206}Pb/^{238}U$	σ	$^{207}Pb/^{206}Pb$	σ	$^{207}Pb/^{235}U$	σ	$^{206}Pb/^{238}U$	σ
a3do-2	91.13	289.93	0.3143	0.0478	0.0012	0.1025	0.0026	0.0157	0.0001	100.09	61.11	99.11	2.35	100.15	0.76
a3do-3	169.02	427.68	0.3952	0.0505	0.0012	0.1110	0.0030	0.0159	0.0001	216.74	53.69	106.88	2.77	101.94	0.84
a3do-4	97.17	370.36	0.2624	0.0501	0.0022	0.1114	0.0076	0.0158	0.0001	211.185	100.91	107.26	6.91	101.04	0.80
a3do-6	150.85	381.48	0.3954	0.0468	0.0010	0.1015	0.0022	0.0158	0.0001	35.28	51.85	98.19	2.06	101.10	0.79
a3do-8	214.99	460.66	0.4667	0.0496	0.0007	0.1086	0.0016	0.0159	0.0001	188.97	35.18	104.66	1.51	101.74	0.67
a3do-9	282.70	433.28	0.6525	0.0504	0.0010	0.1110	0.0024	0.0160	0.0001	213.035	46.29	106.88	2.19	102.29	0.68
a3do-10	137.76	350.48	0.3930	0.0484	0.0010	0.1038	0.0023	0.0156	0.0001	116.755	43.52	100.32	2.16	99.56	0.88
a3do-11	536.13	782.46	0.6852	0.0478	0.0005	0.1036	0.0013	0.0158	0.0001	100.09	28.70	100.13	1.17	100.78	0.84
a3do-12	113.31	309.36	0.3663	0.0491	0.0010	0.1075	0.0022	0.0159	0.0001	153.79	44.44	103.66	1.98	101.60	0.68
a3do-13	487.50	603.54	0.8077	0.0496	0.0010	0.1087	0.0028	0.0159	0.0001	176.01	52.77	104.75	2.60	101.44	0.76
a3do-14	221.21	600.26	0.3685	0.0480	0.0006	0.1047	0.0015	0.0159	0.0001	98.24	31.48	101.07	1.42	101.46	0.84
a3do-15	112.62	291.33	0.3866	0.0496	0.0022	0.1086	0.0069	0.0156	0.0001	188.97	101.84	104.67	6.33	99.85	0.76
a3do-19	106.45	238.05	0.4472	0.0489	0.0012	0.1066	0.0027	0.0158	0.0001	146.38	62.03	102.81	2.47	101.05	0.67
a3do-20	76.14	202.89	0.3753	0.0470	0.0013	0.1014	0.0029	0.0158	0.0001	55.65	66.66	98.07	2.71	100.83	0.87
KYS1-1	212.21	513.17	0.4135	0.0462	0.0033	0.1029	0.0094	0.0153	0.0001	9.36	162.95	99.43	8.62	97.95	0.89
KYS1-3	106.48	279.70	0.3807	0.0483	0.0033	0.1037	0.0085	0.0153	0.0001	122.31	149.98	100.20	7.87	97.75	0.76
KYS1-7	385.93	742.35	0.5199	0.0463	0.0026	0.0967	0.0060	0.0149	0.0001	9.36	133.32	93.74	5.59	95.63	0.68
KYS1-10	250.61	655.25	0.3825	0.0470	0.0031	0.1010	0.0072	0.0152	0.0001	50.095	148.14	97.69	6.65	97.49	0.76
KYS1-16	168.64	391.66	0.4306	0.0463	0.0026	0.1022	0.0072	0.0154	0.0001	13.06	129.62	98.83	6.65	98.80	0.78
KYS1-17	69.79	262.33	0.2660	0.0463	0.0038	0.1031	0.0109	0.0150	0.0002	13.06	185.17	99.62	10.06	95.80	1.25
KYS1-19	167.34	365.30	0.4581	0.0473	0.0024	0.1027	0.0060	0.0156	0.0001	64.91	118.51	99.29	5.54	99.50	0.87

taken and then crushed to 200-mesh; then 0.7 g of crushed sample and 7 g of solvent dedicated for XRF analysis (composite solvent: $Li_2B_4O_7$, $LiBO_2$ and LiF) were weighed separately, mixed together evenly, and then poured to a platinum crucible; the crucible with sample was put into a sample melting machine for high temperature melting to form fused bead. The prepared fused bead was put into an XRF instrument for test. The trace and rare-earth elements were analyzed using an inductively coupled plasma mass spectrometer (ELAN DRC-e ICP-MS) with an analysis precision higher than 5%. The specific test flow was the same as that described by Qi and Zhou (2008). The analysis results are listed in Table 2.

4.1 Major elements

Table 2 shows that the SiO_2 contents in the biotite granodiorite porphyry samples have a small variation range, from 68.58 wt% to 70.69 wt%; the MgO contents 0.99 wt% to 1.60 wt%. The $A1_2O_3$ contents of four samples are over 15 wt%, and those of the other two altered porphyry samples are approximate to 15 wt%. The total alkali content is high (from 5.67 wt% to 6.24 wt%) and sodium is obviously rich, with a Rittmann index of 1.15-1.61. All the porphyry samples fall in the granodiorite area in the TAS diagram (Fig. 3a), in the sub alkaline series in the SiO_2-(K_2O+Na_2O) diagram (Fig. 3b), in the low-potassium tholeiitic basalt series in the SiO_2-K_2O rock series classification diagram (Fig. 3c), and in the sodic rock area in the Na_2O-K_2O classification diagram (Fig. 3d). The major element composition fully reveals that the porphyry bodies in the Nongping deposit belong to sodic rock formation of low-potassium tholeiitic basalt series.

4.2 Trace elements

The porphyry bodies have relative enrichment in LILEs (Rb, Sr, Ba, etc) and depletion in HFSEs (Nb, Ta, Hf, etc) (Table 2). All of the six samples tested are featured with obvious depletion in Y and Yb, and 4 unaltered porphyry samples have Sr contents within 400-460 ppm. The normalized diagram of trace elements versus primitive mantle shows evident enrichment in LILEs, and relative Th enrichment and obvious negative anomaly of Nb and Ta in HFSEs (Fig. 4a). The above characteristics indicate that the porphyry bodies have the geochemical characteristics similar to those of the rocks in the subduction belt (Wilson, 1989).

4.3 Rare-earth elements

The analysis results of rare-earth elements (REEs) show that the porphyry bodies have low total content of rare-earth elements, obvious enrichment in LREEs and weak negative Ce anomaly (Table 2). Three of the four unaltered biotite granodiorite porphyry samples are characterized by obvious positive Eu anomalies and another sample by weak positive Eu anomaly. Two altered samples have weak negative Eu anomaly (δEu are 0.67 and 0.96, respectively). Some researches indicated that Eu depletion or enrichment was usually caused by hydrothermal alteration (Campbell et al., 1984; Sverjensky et al., 1984; Bence and Taylor, 1985; Oreskes and Einaudi, 1990). When the plagioclase in the porphyry

Table 2 Contents of major elements (wt%) and trace elements (ppm) from the porphyry bodies in the Nongping Au-Cu deposit

Sample	PD1-2-1	PD1-2-2	PD1-5-1	PD1-5-2	PD1-6	PD1-7
SiO_2	69.08	68.58	70.34	70.45	68.91	70.69
Al_2O_3	15.75	15.71	15.47	15.21	14.47	14.70
Fe_2O_3	2.30	2.22	2.02	2.01	3.33	2.04
MgO	1.40	1.35	1.19	1.20	1.60	0.99
CaO	3.34	3.39	2.78	2.81	2.01	2.26
Na_2O	4.78	4.68	5.15	5.12	4.74	5.01
K_2O	0.97	0.99	1.09	1.06	1.27	1.08
MnO	0.03	0.03	0.03	0.03	0.04	0.02
P_2O_5	0.11	0.11	0.10	0.10	0.12	0.09
TiO_2	0.41	0.42	0.40	0.39	0.40	0.37
LOI	1.73	2.32	1.33	1.49	2.98	2.69
Total	99.90	99.81	99.89	99.86	99.86	99.95
Sc	8.77	8.39	8.31	8.24	9.37	8.45
V	42.8	45.5	40.1	40.9	53.9	33.9
Cr	10.9	10.5	9.04	8.05	14.1	8.38
Co	2.57	2.34	2.21	2.11	4.06	2.13
Ni	8.83	8.52	7.46	7.23	9.83	6.48
Cu	27.2	23.2	19.9	19.2	94.7	53.1
Zn	115.0	90.8	90.9	74.3	94.1	40.2
Ga	14.8	15.6	15.4	14.6	18.5	15.2
Rb	44.8	49.0	48.9	47.6	69.7	48.8
Sr	417	460	415	400	359	388
Y	8.79	8.46	7.63	7.62	10.3	10.6
Zr	113	116	129	148	112	133
Nb	6.23	6.41	8.71	8.01	7.24	8.07
Ba	191	212	236	216	131	172
La	4.99	5.20	6.01	12.60	7.88	20.2
Ce	8.92	9.17	10.6	22.7	15.6	38.3
Pr	1.03	1.01	1.24	2.35	1.82	4.20
Nd	4.35	4.26	5.00	8.33	7.60	15.9
Sm	1.03	1.04	1.10	1.52	1.83	2.85
Eu	0.56	0.56	0.55	0.51	0.57	0.58
Gd	1.06	1.07	1.10	1.33	1.73	2.30
Tb	0.20	0.20	0.19	0.21	0.29	0.35
Dy	1.19	1.15	1.03	1.01	1.52	1.60
Ho	0.27	0.26	0.22	0.23	0.32	0.32
Er	0.73	0.72	0.62	0.60	0.89	0.90
Tm	0.11	0.11	0.09	0.09	0.13	0.12
Yb	0.73	0.75	0.59	0.61	0.84	0.84
Lu	0.12	0.11	0.10	0.09	0.13	0.12
Hf	2.68	2.81	3.26	3.66	2.67	3.17
Ta	0.54	0.58	0.88	0.82	0.62	0.77
Pb	36.1	29.9	25.4	23.3	35.8	15.4
Th	4.24	4.35	6.08	8.09	5.21	6.87
U	1.59	1.61	2.16	2.20	1.55	2.08
LREE	20.88	21.24	24.50	48.01	35.30	82.03
HREE	4.41	4.36	3.93	4.16	5.84	6.55
LREE/HREE	4.73	4.87	6.24	11.53	6.04	12.53
$(La/Yb)_N$	4.88	4.98	7.37	14.77	6.72	17.31
δEu	1.62	1.61	1.52	1.07	0.96	0.67
δCe	0.91	0.92	0.90	0.95	0.97	0.97
Sr/Y	47.44	54.37	54.39	52.49	34.85	36.60
La/ Y	12.04	11.28	12.93	12.49	12.26	12.62

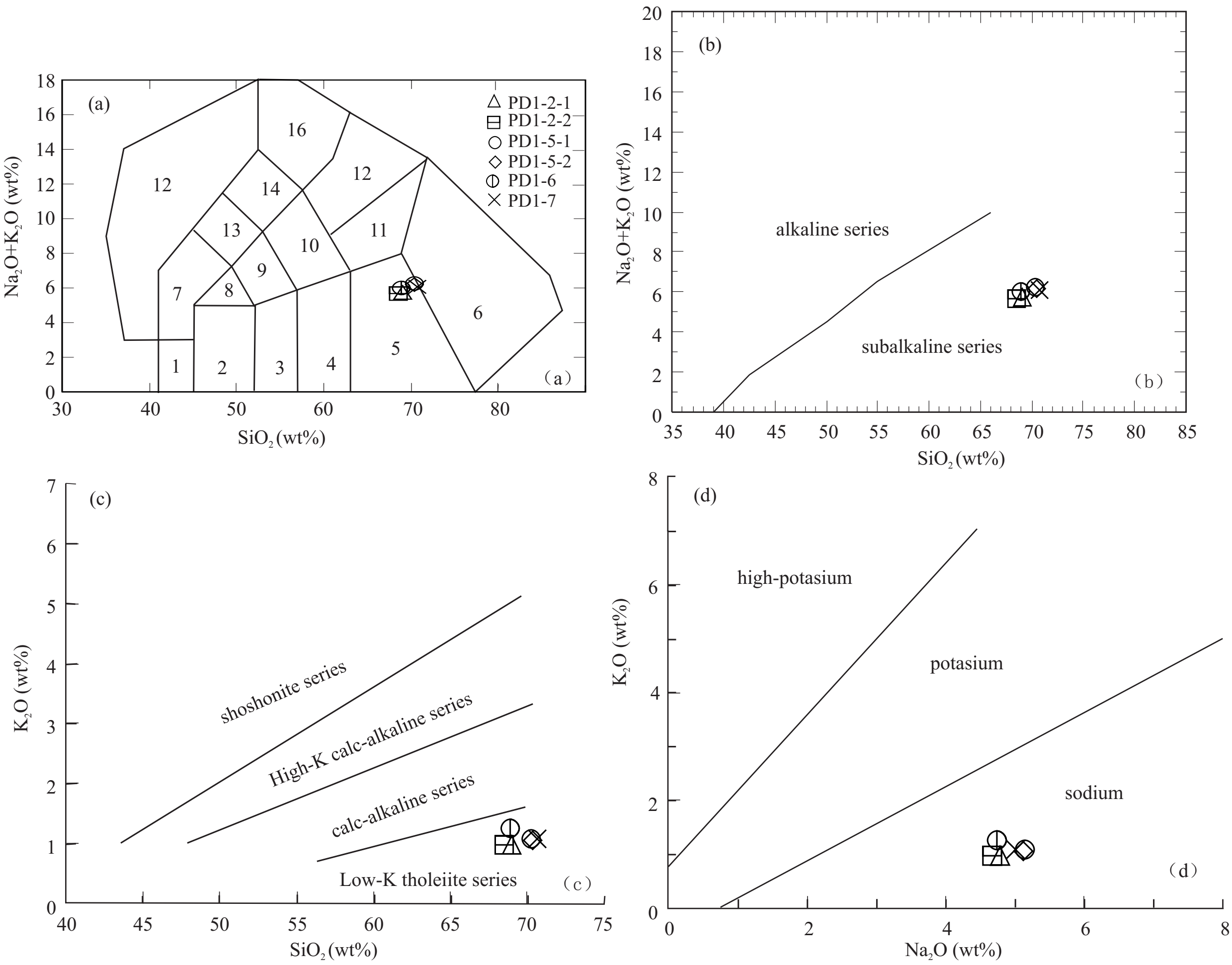

Fig. 3. Petrochemical diagrams of the porphyry rocks in the Nongping Au-Cu deposit.

(a), TAS classification (after Middlemost (1994)); (b), K_2O+Na_2O-SiO_2 (after Irvine and Baragar (1971)); (c), K_2O-SiO_2 (after Le Maitre (1989)); (d), K_2O-Na_2O (after Middlemost (1994)). Note: Diagram (a): 1. peridot gabbro; 2. gabbro; 3. gabbroic diorite; 4. diorite; 5. granodiorite; 6. granite; 7. foid gabbro; 8. monzogabbro; 9. monzodiorite; 10. monzonite; 11. quartz monzonite; 12. foidolite; 13. foid monzodiorite; 14. foid monzosyenite; 15. syenite; 16. foid syenite.

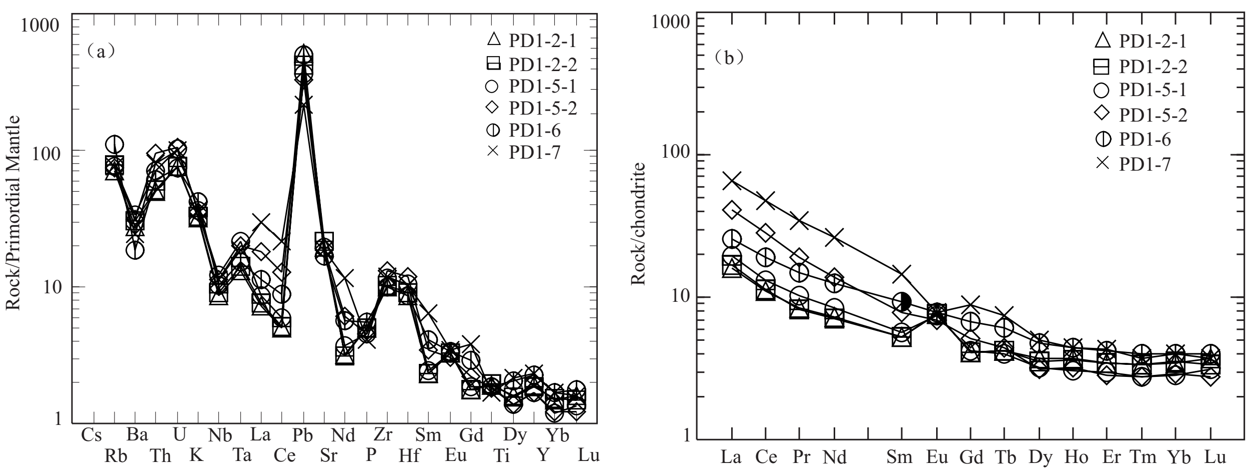

Fig. 4. The primitive mantle-normalized multi-element plots (a) (normalized data from Sun and Mcdonough (1989)) and the chondrite-normalized REE patterns (b) of the porphyry rocks (normalized data from Boynton (1984)).

bodies with positive Eu anomaly was altered in such manners as sericitization, the Na^+ ions and some Ca^{2+} ions would be separated out, and meanwhile carbonate minerals and quartz were formed. Due to the ion radius of REE^{3+} is approximate to that of Ca^{2+}, Eu^{3+} ions easily react with Ca^{2+} ions in the manner of isomorphous replacement and enter into the carbonate minerals, so that the altered porphyries manifest as negative Eu anomalies (Xiong et al., 2006).

The chondrite-normalized rare-earth element diagram demonstrates that all six samples have right oblique graphs with enrichment in LREEs and depletion in heavy rare earth elements (HREEs). The unaltered porphyry samples are featured with low total content of rare-earth elements and positive Eu anomaly as a whole, while the altered porphyry samples are featured with weaker negative Eu anomaly and total content of rare-earth elements slightly higher than those in unaltered samples (Fig. 4b).

5 Discussions

5.1 Age of metallogenetic porphyry bodies

In recent years, with the development of geochronological technology, a set of precise age data have been obtained in the Yanbian region (Zhang, 2002a, 2002b; Wu et al., 2004; Zhang et al., 2004; Sun et al., 2008a; 2008b; Fu et al., 2010). Based on the single point age data of the zircon from granitic bodies, the Phanerozoic granitoids in this region can be categorized into late Hercynian tonalite-granodiorite, Indosinian monzonitic granite-quartz diorite, early Yanshanian alkali feldspar granite-monzonitic granite-granodiorite, and late Yanshanian tonalite (porphyry)-granodiorite (porphyry).

All the twenty one pieces of single-grain zircons from the biotite granodiorite porphyry in the Nongping deposit, tested for this paper, show the characteristics of magma zircon in terms of the crystal form, internal structure, and composition, and no elder zircon (i.e., zircon with an age more than 120 Ma) was captured. Most zircon grains have Th/U ratios within 0.30-0.60 and all data are located on or near the concordant line. It is evident that the age of the tested zircons can fully represent the magma emplacement age of the metallogenetic porphyry bodies in the Nongping deposit, that is, the magma emplaced in the late session of the Early Cretaceous period.

The Xiaoxi'nancha deposit, another porphyry Au-Cu deposit in the eastern Yanbian area, belongs to the SN-strike Au-Cu-W metallogenetic belt, together with the Nongping deposit. Both have obvious similarity on metallogenetic setting and mineralization characteristics, etc. In the Xiaoxi'nancha deposit, the emplacement ages of the late Yanshanian granite complexes related to mineralization are 112–104 Ma (Sun et al., 2008a), and the Re-Os isochron age of molybdenite in the newly found vein-type molybdenum ore bodies was 111.1±3.1 Ma (Ren, et al., 2011). Due to these data, together with the dating results obtained in this paper, it can be concluded that there happened a large scale of porphyry Au-Cu mineralization related to granitic epizonal magmatism, occurring in this region in the late session of Early Cretaceous period.

5.2 Rock types and tectonic setting

The major, trace and rare-earth elements in rocks show that, except slightly low Sr content (259–460 ppm), the porphyry bodies in the Nongping deposit basically have such geochemical characteristics of adakitic rocks as listed by Defant and Drummond (1990) and Wang et al. (2000). These geochemical characteristics include high SiO_2 (68.58 wt%–70.69 wt%), enrichment in sodium (Na_2O: 4.68 wt%–5.15 wt%; Na_2O/K_2O=3.69–5.31), relatively high $A1_2O_3$ content (14.47 wt%–15.75 wt%), relatively low MgO content (0.99 wt%–1.60 wt%), depletion in Y and Yb, relative enrichment in LILEs and LREEs, relatively low content of HFSEs, positive Eu anomaly or weak negative Eu anomaly and high Sr/Y ratio (34.85–54.39), and being located in the adakite area in the Sr-Y discrimination diagram (Fig. 5). The above characteristics are basically identical to the geochemical characteristics of the adakites in NE China (Zhang, et al., 2004).

According to the tectonic setting, the adakitic rock was divided into two types by Zhang et al. (2001): O-type and C-type. The O-type adakitic rock is enriched in Na and related to plate consumption, while the C-type adakitic rock is enriched in K and might result from partial melting of granulite in the lower crust due to underplating of basalt magma to the bottom of the thickened continental crust. The porphyry bodies in the Nongping deposit area are evidently enriched in Na, and distributed in the western Pacific epicontinental setting in the Yanshanian period, and are typical O-type adakitic rocks, that is, they were derived from partial melting of oceanic crust during the

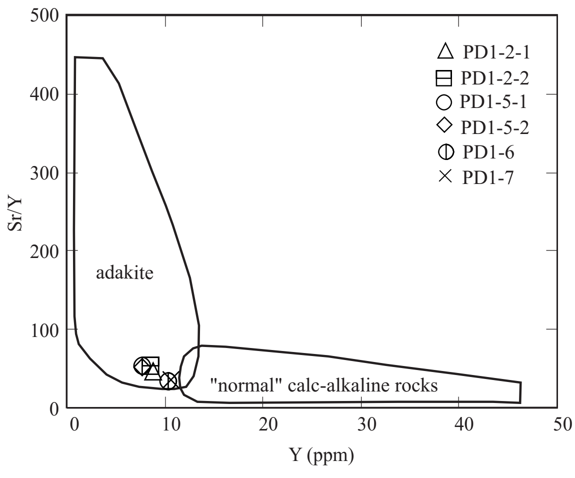

Fig. 5. Sr/Y-Y diagram of the porphyry rocks in the Nongping Au-Cu deposit (after Defant and Drummond (1990)).

subduction of the Paleo-Pacific plate. The tectonic setting and material source area discrimination diagrams of igneous rock, including Nb-Y, Ta-Yb, Rb-(Y+Nb), Rb-(Yb+Ta), Th/Yb-Tb/Yb and Th/Yb-Sr/Nd, show that the porphyry bodies in the Nongping deposit belong to volcanic arc granites and were related to plate fluid (Fig. 6), which further demonstrates that the diagenesis and metallogenesis of the porphyry bodies have a close relationship with the subduction of the ocean plate. Men et al. (2011) also drew a similar conclusion on the Xiaoxi'nancha deposit, which indicates that the two deposits formed in the common tectonic setting.

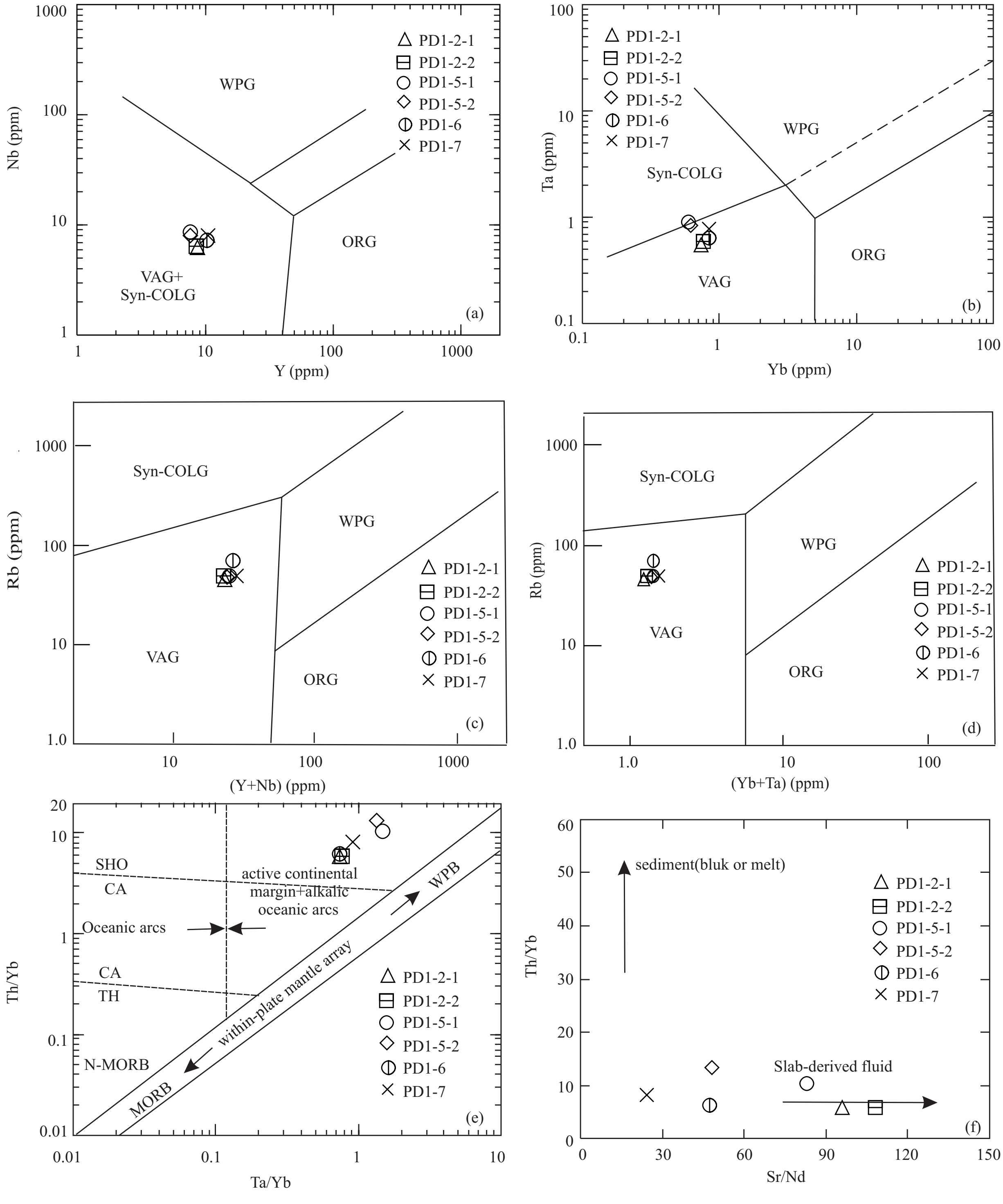

Fig. 6. Discrimination diagrams of tectonic setting of the porphyry rocks in Nongping Au-Cu deposit.
(a), Nb-Y; (b), Ta-Yb; (c), Rb-Y+Nb; (d), Rb-Yb+Ta; (e), Th/Yb-Ta/Yb; (f), Th/Yb-Sr/Nd; from (a) to (d) after Pearce et al.(1984); (e) modified from Pearce (1982); (f) after Woodhead (1998).

5.3 Metallogenetic significance

According to statistical data by Zhang et al. (2004), 38 out of 43 Au, Ag, Cu, Mo epithermal and porphyry deposits all over the world, and 12 out of 14 porphyry Cu deposits, as well as epithermal deposits in Philippines are related to adakitic rocks. Moreover, some large porphyry and epithermal deposits in the eastern regions of Jilin and Heilongjiang Province are also related to adakitic rocks, for example, the Xiaoxi'nancha Au-Cu deposit, Daheishan Mo deposit, Wulaga Au deposit as well as Duobaoshan Cu deposit. It can be concluded that the porphyry and epithermal deposits have close genetic relationship with the adakite (adakitic) rocks.

Some researches have confirmed that the key factor restricting metallogenesis of adakitic rocks is the dehydration during the transition from amphibolite facies to eclogite facies, which usually caused metallogenetic elements extraction from the mantle into the magma. Adakite (adakitic) rocks and adakite-like rocks are the host rocks of most porphyry Cu deposits and the metallogenetic parent rocks of many epithermal mineralization systems. The genetic connections might lie in fact that the adakitic magma is rich in fluid, high oxygen fugacity, and basic source-rock, which is favorable to extraction, enrichment and metallogenesis of deep source metal elements such as Cu and Au (Wang et al., 2007).

The porphyries in the Nongping deposit have obviously higher contents of metallogenetic elements (Au and Cu) than the Clark value of these metallogenetic elements and have larger coefficients of variation (Zhang and Sun, 2001). They provided material sources for metallogenesis and became metallogenetic parent rocks. Therefore, the Nongping Au-Cu deposit has a close relationship with adakitic porphyry bodies in both space and genesis.

6 Conclusions

Firstly, the single-grain zircon LA-MC-ICP-MS dating results show that the emplacement age of the metallogenetic porphyry bodies of the Nongping Au-Cu mineralization is the late session of the Early Cretaceous period, namely the late Yanshanian period.

Secondly, the geochemical characteristics in major, trace and rare-earth elements indicate that the porphyry bodies belong to the O-type adakitic rocks and related to plate consumption. Moreover, they have a close genetic connection with partial melting of oceanic crust under the subduction of the Pacific plate.

In addition, the large-scale porphyry Cu and Au mineralization related to adakitic magmatism ever occurred in the eastern Yanbian area in the late Yanshanian period. The adakitic magma had high formation temperature, high oxygen fugacity, and enrichment in volatile constituents, which is favorable to enrichment of metallogenetic elements and important ore-controlling function on the formation of porphyry Au-Cu deposits in this region.

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