PGC
PUBLISHING

Rui Zongyao, Zhang Lisheng, Wu Chengyu, Wang Longsheng and Sun Xinya, 2005 - Dexing Porphyry Copper Deposits in Jiangxi, China; *in Porter, T.M. (Ed.), Super Porphyry Copper & Gold Deposits: A Global Perspective*, PGC Publishing, Adelaide, v. 2. pp 409-421.

DEXING PORPHYRY COPPER DEPOSITS IN JIANGXI, CHINA

[1]Rui Zongyao, [2]Zhang Lisheng, [3]Wu Chengyu, [1]Wang Longsheng and [4]Sun Xinya

[1]*Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing, P. R. China*
[2]*Chengdu Institute of Geology and Mineral Resources, Chengdu, Sichuan Province, P. R. China*
[3]*Rio Tinto Mining and Exploration Limited, Beijing, P. R. China*
[4]*Dexing Copper Mine, Dexing, Jiangxi Province, P. R. China*

Abstract - The Dexing porphyry copper field in Jiangxi, China, is defined by three porphyry copper deposits which are, from southeast to northwest, Fujiawu, Tongchang and Zhushahong respectively, and by the Guanmaoshan gold deposit which lies between Fujiawu and Tongchang. Tectonically, the field lies on the southeastern edge of the Jiangnan Anteclise, and is controlled by the NE-trending, deep-seated, Gandongbei fracture zone. The emplacement of the ore-bearing Fujiawu, Tongchang and Zhushahong granodiorite porphyry intrusions, dated at 184-172 Ma (Zhu *et al.*, 1983; Zhu *et al.*, 1990), was also controlled by NW-trending structures. Mineralisation and alteration continued from 172 Ma to 100 Ma, and are characterised by symmetric zoning centred on the contacts between granodiorite porphyries and the enclosing country rocks of the Mesoproterozoic Shuangqiaoshan Group phyllites.

Alteration weakens gradually away from the contact through the following stages: - (1) quartz-sericite zone (strong alteration); (2) quartz-sericite-chlorite-(epidote)-carbonate-anhydrite zone (intermediate alteration); and (3) chlorite-epidote-illite-albite-anhydrite zone (weak alteration). At Tongchang, approximately two-thirds of the ore is hosted by phyllites and one-third by granodiorite porphyry. The orebody forms a cylinder 2 500 m across with a barren core in the centre extending down plunge for over 1000 m. Chalcopyrite and molybdenite are the main ore minerals, with minor associated tennantite, tetrahedrite, bornite, chalcocite and electrum. The ore reserves at Tongchang are 1 168 Mt @ 0.446% Cu (5.2 Mt of contained Cu), 0.01% Mo and 0.19g/t Au (215 t of contained Au) supporting China's largest open-cut copper mine. Production at the Tongchang mine in 2003 amounted to about 120 000 t Cu, 5 t Au and 20 t Ag, plus by-products of Mo, Re and S. The northeast striking regional structures related to the Gandongbei deep-seated fault zone played a very important role in the generation and emplacement of granitic magma at Dexing, whereas fractures along contact zones between granodiorite porphyries and phyllite country rocks provided crucial conduits and loci for hydrothermal alteration and mineralisation. Various geochemical and isotopic data indicate that ore-forming fluids were primarily derived from volatiles fractionated from secondary boiling of magmatic hydrothermal fluids. These fluids carried metals and caused both symmetric alteration and mineral zoning along the contact zones. Circulation of heated ground water and perhaps deep-seated formation water was involved in later stages, resulting in further water-rock interactions.

Introduction

The Dexing porphyry copper field is located at 117° 44'E, 29° 01'N, in Dexing County, Jiangxi Province, and, from southeast to northwest, comprises the Fujiawu, Tongchang and Zhushahong porphyry copper deposits (Fig. 2). Fujiawu is about 4 km southeast of Tongchang, while Zhushahong is around 2 km northwest of Tongchang. The Guanmaoshan gold deposit lies between Fujiawu and Tongchang.

According to historic records, copper mining activity in the Tongchang area boomed as early as the Tang (618-907 AD) and Song Dynasties (960-1279 AD), was reactivated between 1465 and 1488 during the Ming Dynasty, then abandoned until 1862-1874 when pyrite ores were mined by local people (Geological Publishing House, 1996).

In the autumn of 1939, Xia Xiangrong and Liu Huisi completed a geological and mineral resources survey at Dexing entitled "Mineral Resources in Dexing County" which described pyrite ores at the Tongchang and Zhushahong copper occurrences.

Malachite, chalcopyrite and pyrite were found outcropping at Tongchang during a reconnaissance survey of old workings by the No. 409 Geological Brigade in 1955 and exploration of the Tongchang deposit was carried out by the No. 420 Geological Brigade and the Copper Exploration Team of the Jiangxi Geological Bureau from 1956 to 1959. The Fujiawu and Zhushahong deposits were found by the Copper Exploration Team during field reconnaissance and mapping in December 1957. In 1972, the Jiangxi Metallurgical Geological Exploration Company initiated an additional exploration program at the Fujiawu deposit and in 1975, the Jiangxi Geological Bureau carried out further exploration involving over one thousand geological workers at the Tongchang and Zhushahong deposits. These programs, which continued until 1978, delineated ore reserves as follows:

	Mt	Cu%	Mo%	Au g/t	Cu Mt	Au t
Tongchang	1168	0.446	0.01	0.19	5.20	215
Fujiawu	514	0.500	0.03		2.57	
Zhushahong	143	0.423	0.01		0.60	

These reserves make the Dexing porphyry copper field a world-class district with a total of 8.4 million tonnes of contained copper metal, plus recoverable gold, silver, molybdenum, rhenium and sulphur (Geological Publishing House, 1996).

The Tongchang Mine (Fig. 1) is owned by the Jiangxi Copper Company and has been mined since 1965 by open-cut, initially at a rate of 2500 tpd. The mining capacity was expanded to 20 000 tpd in 1990 and to 90 000 tpd in 1995 with an annual capacity of about 1 000 000 t of copper concentrates. A total of 370 000 tonnes of copper in concentrate were produced from 1965 to 1990. Production at the Tongchang mine in 2003 amounted to approximately 120 000 t copper, 5 t gold and 20 t silver, plus by products of molybdenum, rhenium and sulphur. The Fujiawu Mine is owned by Dexing County and has been in production since 1971 with a mining and processing capacity of 1250 tpd.

Regional Geological Setting

The Dexing porphyry copper field in Dexing County, Jiangxi Province, Southeastern China lies within the outer zone of the Circum-Pacific metallogenic belt (Fig. 2). Geotectonically, it is located on the southeastern edge of the Jiangnan Anteclise of the Yangtze Para-platform, associated with the Qiantang Depression of the South China Fold System and bordered by the Gandongbei deep-seated fracture zone (Fig. 2).

The Jiangnan Anteclise is composed mainly of lower greenschist facies metamorphosed, flyschoid volcanic-sedimentary formations of Mesoproterozoic age known as the Shuangqiaoshan Group. This group is divided from the base upwards into the Banqiao, Jiudu and Zhujia Formations. The main lithologies include phyllites, slates, meta-tuffs and meta-sandstones with a total thickness of over 4300 m forming a widely exposed basement in the region. The Jiangnan Anteclise was uplifted and subjected to denudation for a long period following the Mesoproterozoic before being overlain by thin marine sediments during the Carboniferous and Permian. Some northeast-trending fault controlled volcanic-clastic filled basins were subsequently developed during the Jurassic and Cretaceous. Wall rocks of the Dexing porphyry copper deposits consist mainly of phyllites, slates and meta-tuffs of the Jiudu Formation with an isotopic age of 1401 Ma. Lithogeochemistry of 1514 rock samples from the Jiudu Formation reveal relatively high Cu background (with maxima from 76 to 203 ppm) averaging 65 ppm Cu, indicating a regional, high background copper province (Rui et al, 1984).

In striking contrast to the Jiangnan Anteclise, the Qiantang Depression underwent a long period of subsidence from the Neoproterozoic, through the Paleozoic era. Sinian to Silurian Systems are composed of marine volcanic-clastic-carbonate rocks with a thickness of about 10 000 m, while Devonian to Triassic Systems comprise marine clastic-carbonate rocks with a thickness of around 3500 m. The Jurassic-Cretaceous is similar to the Jiangnan Anteclise

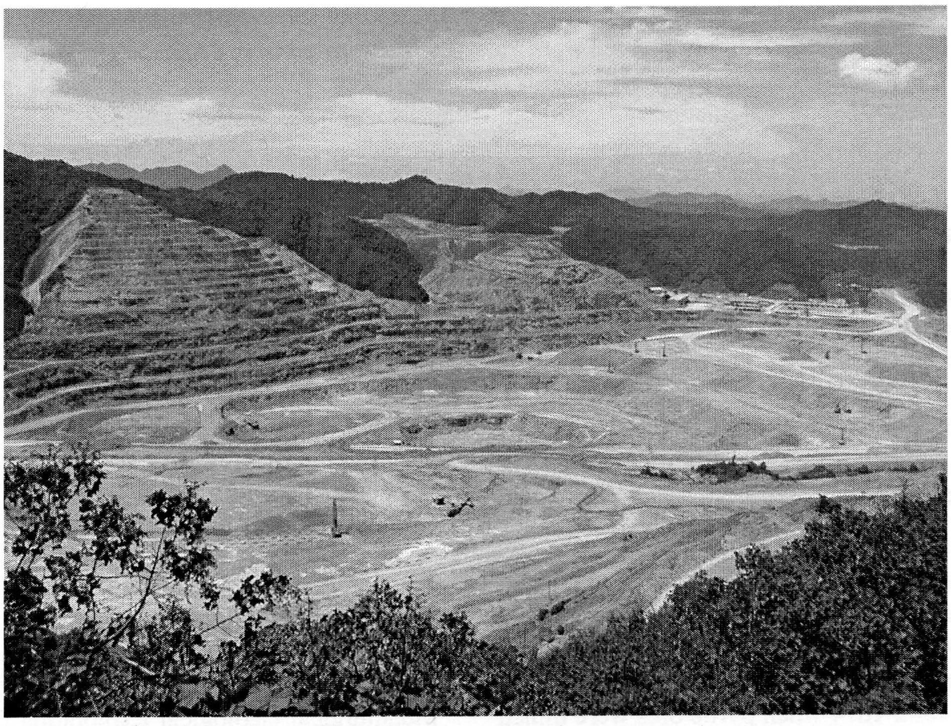

Figure 1: ***Open pit workings at the Tongchang porphyry copper mine (by Sun Xinya)***

comprising continental fault controlled basins of volcanic and clastic rocks with a thickness of 9 000 m.

Based on the differing thicknesses of sedimentary sequences, the long term subsidence of the Qiantang Depression and rise of the Jiangnan Anteclise created an amplitude of up to 18 km. These features are separated by the Gandongbei deep-seated fracture zone which is 200 km long, strikes NE (35° to 60°) and is up to 15 km wide. It is characterised by multiple stages of associated tectonic movement and magmatic activity. Strong tectonic compression resulted in schistosity and local mylonitisation of the Shuangqiaoshan Group, whereas multi-episode magmatic activity created a mineral rich province at Dexing. The area incorporates a cluster of ore deposits. The Jinshan gold deposit (Liao, 1995), lies about 5 km south of the Dexing copper field, while the Yinshan volcanic-hosted lead-zinc-silver deposit (Ye, 1987) is located 20 km southwest of Dexing.

Westward movement of the Izanqi-Pacific Plate during the Yanshanian (Jurassic-Cretaceous) period resulted in subduction of the Qiantang Depression below the Jiangnan Anteclise and triggered strong magmatic activity that formed a tectonic background for the formation of the Dexing porphyry copper deposits.

Regional Magmatic Activity

The Proterozoic Jiudu Formation in the Dexing ore field contains a large amount of dacitic pyroclastic rocks dated at 1400 Ma (Rb-Sr) and a small amount of dacite, andesite and hornblende gabbro representing intrusive activity of the Jinning Period. These rocks are metamorphosed into phyllites and meta-tuffs and serve as the main host rocks to the Dexing porphyry copper ores.

A spilite-keratophyre sequence, including lavas, volcanic breccias, tuffs and tuffaceous sandstones, associated with albite porphyry is believed to have formed in the Xuefeng Period (about 630-680 Ma) and crops out in the southwestern part of the Dexing copper field.

Pyroxene diorite dated at 503-509 Ma (K-Ar) from the Caledonian Period are found in the Jinjia area, while gabbroic dykes with a K-Ar age of 269-328 Ma occur at Huading Hill in the north of the Dexing porphyry copper field and Hercynian gabbro-dolerite (diabase) to diorite porphyry dykes are exposed at Guanmao Hill between Tongchang and Fujiawu.

Strong folding during the Indo-Sinian period was accompanied by emplacement of granitoids with a K-Ar age of 217-234 Ma.

The most important magmatic activity in the Dexing porphyry copper field is of Yanshanian age, divided into five stages as follows:

Stage 1 - Phase I of the early Yanshanian (190-193 Ma) consists of ultrabasic and basic intrusions including gabbro, pyroxenite, serpentinised peridotite and serpentinite occurring along the Gandongbei deep-seated fracture zone.

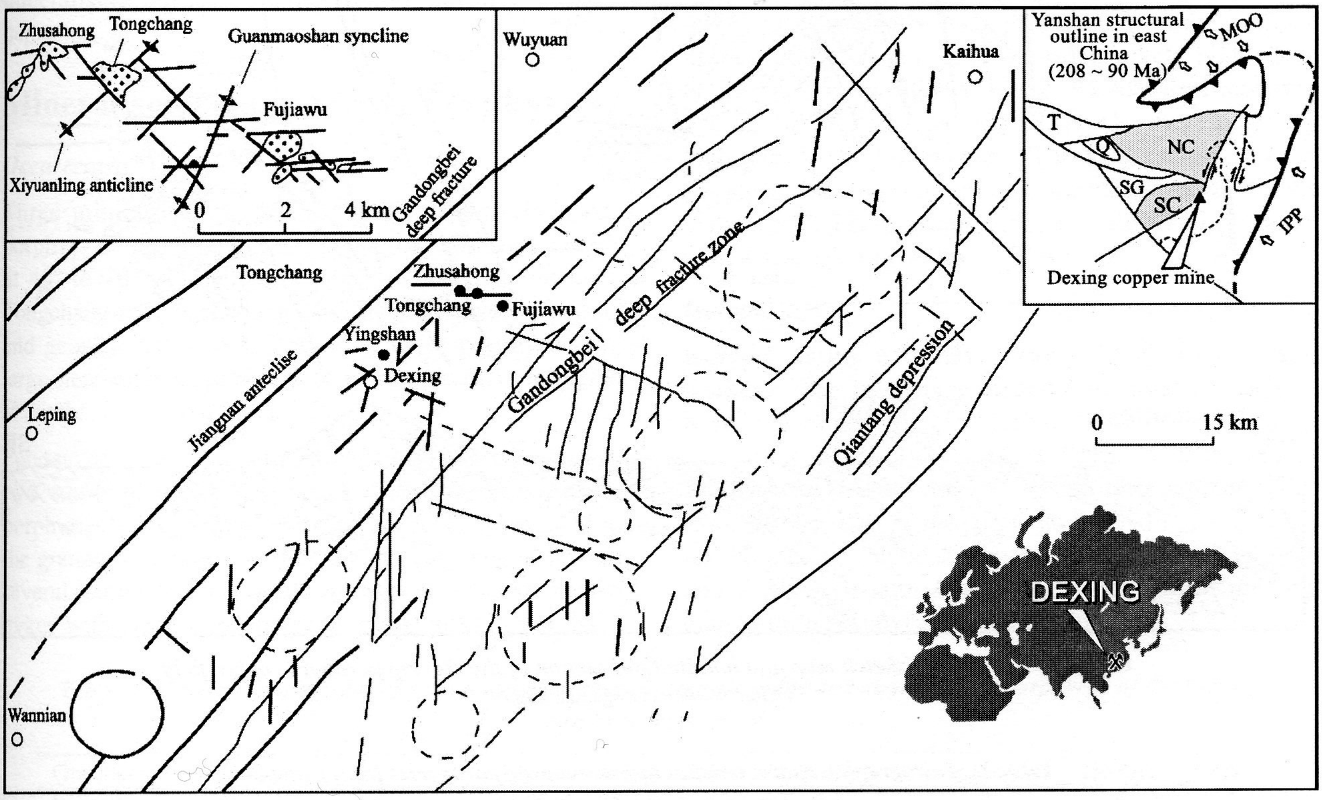

Figure 2: ***Regional geological setting of the Dexing porphyry copper field compiled from satellite image interpretation*** *(Modified after Zhu et al., 1983).*
The upper left inset shows the tectonic setting of the three ore-bearing granodiorite porphyries in the Dexing ore field. The upper right inset is after Zhou *et al.*, (2002). IPP = Izanqi-Pacific Plate; NC = North China platform; SC = Yangtze Para platform; MOO = Mongolia-Ohotsk Oceanic basin; SG = Songpan-Garzê basin; Q = Qaidam basin; T = Tarim basin; Black triangle = Dexing porphyry copper field; Dashed line = coast of China and Korea.

Table 1: ***Shape and occurrence of the granodiorite porphyry intrusions of Fujiawu, Tongchang and Zhushahong***

Intrusions	Fujiawu	Tongchang	Zhushahong
Shape on surface	Irregular polygon	Rounded triangle	Several apophyses
Length (m)	650	1300	n - 450
Width (m)	300	300 - 800	0.n - 80
Area (km^2)	0.2	0.7	0.06
Plunge direction	310°	320°	340°
Dip angle	40°	45°- 50°	60° - 70°

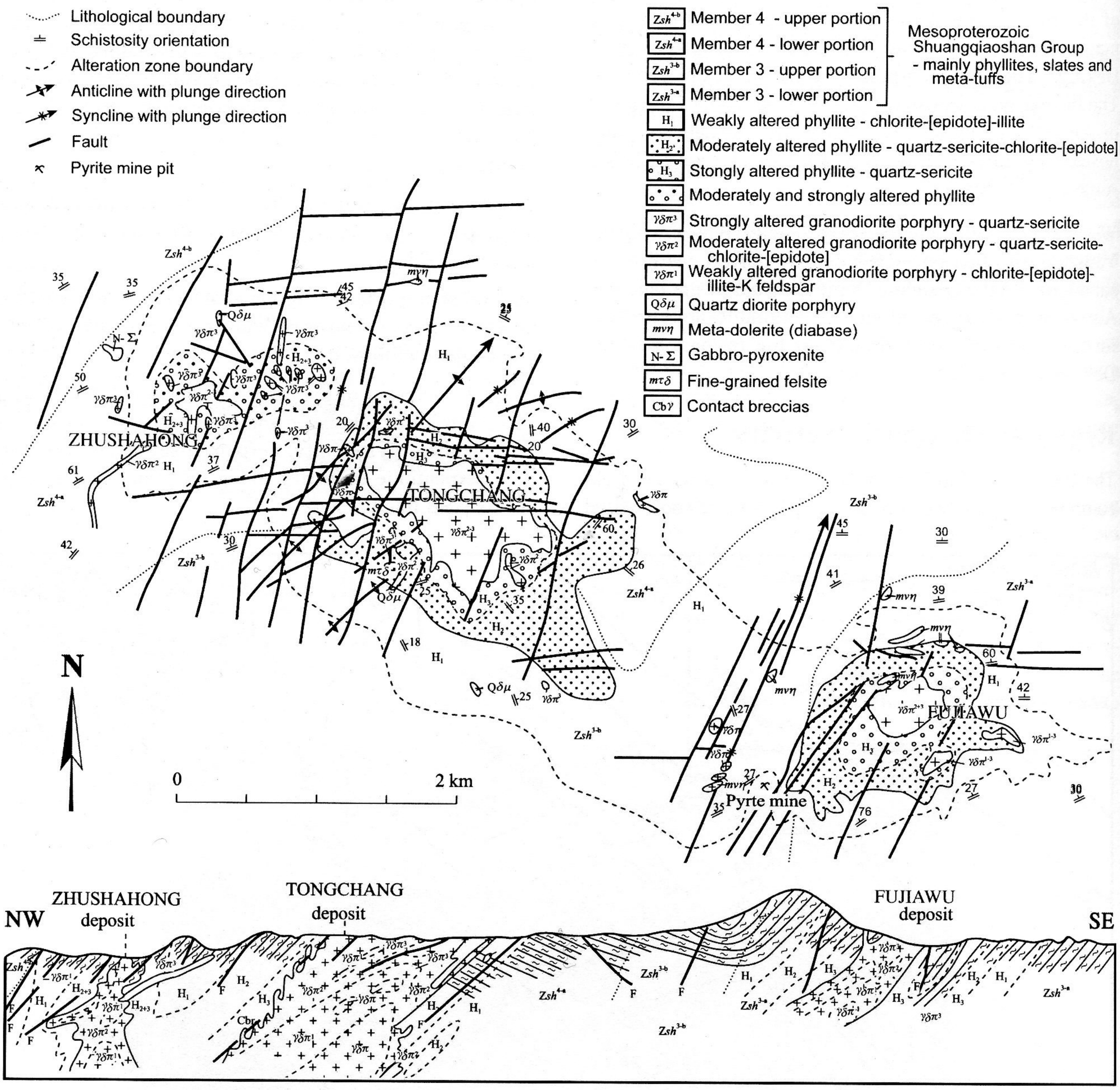

Figure 3: ***Geological sketch map and longitudinal section of the Dexing porphyry copper field.***
(After Yan Meizhong et al, 1980)

Table 2: ***Petrographic characteristics of granodiorite porphyries from Fujiawu, Tongchang and Zhushahong***

Intrusions	Fujiawu	Tongchang	Zhushahong
Colour	Pinkish grey	Pale grey	Grey
Phenocryst content (%)	50 - 60	35 - 60	20 - 45
Phenocryst grain size (mm)	2 - 5	0.5 - 40	0.5 - 3
Groundmass grain size (mm)	0.1 - 0.3	0.05 - 0.3	0.05 - 0.1

Stage 2 - Phase II of the early Yanshanian (172-186 Ma) was characterised by Cu-Mo mineralisation related to granodiorite porphyries, diorite porphyry, quartz diorite porphyry and granite porphyry. The granodiorite porphyries were emplaced into Proterozoic phyllites and slates and serve as the major source of copper mineralisation.

Stage 3 - Phase III of the early Yanshanian (125-145 Ma) was the peak of magmatic activity in the region. Dacitic volcanic and pyroclastic rocks form a sequence with a thickness of 400-1600 m, associated with a variety of subvolcanic rocks including hornblende-andesite porphyry, dacite porphyry, quartz diorite porphyry, trachy-andesite porphyry, quartz porphyry, granite porphyry and quartz syenite porphyry. This sequence was well developed within the Yinshan area. The dacite porphyry is the main host of Pb-Zn-Ag-Cu-Au mineralisation at the Yinshan deposit.

Stage 4 - Phase I of the late Yanshanian (103-127 Ma) was marked by intermediate to acid volcanics, locally with basalt and associated olivine pyroxenite, gabbro, diorite porphyry and quartz diorite porphyry. These rocks occur in areas neighbouring the Dexing porphyry copper field.

Stage 5 - Phase II of the late Yanshanian (96-100 Ma) as represented in the Dexing porphyry copper field included post-mineralisation granite, granite porphyry, quartz porphyry and quartz diorite porphyry.

Granodiorite porphyries of Stage 2 served as the main mineralising intrusive of the Dexing porphyry copper deposits.

Mineralised Granodiorite Porphyries

Occurrences

Three mineralised, pipe-like bodies of granodiorite porphyry of varying size, each plunging north-westwards at 40° to 70° (Table 1 and Fig. 3), host the Fujiawu, Tongchang and Zhushahong deposits respectively. Drilling and geophysical data indicate that these porphyries are large, near-surface apophyses of a more extensive intrusion at depth.

Potassic aplite and quartz diorite porphyry are present as two common dyke sets intersecting the granodiorite porphyries. Potassic aplite dykes are mainly confined to the granodiorite porphyry bodies and vary in width from several centimetres to tens of centimetres, either as sheeted dykes with sharp contacts or as stockworks which have obscure boundaries with the host. In the latter case, K feldspar rich aplite grades into pervasive potassic (K feldspar) alteration indicating its pre-ore nature and a close genetic affinity between stockwork veining and potassic alteration. Dykes of quartz diorite porphyry (or diorite porphyry with less quartz) are generally several metres in width, occurring both within mineralised granodiorite porphyry intrusions and extending into the country rocks as post-ore dykes.

Petrology and Mineralogy

The three mineralised granodiorite porphyries of Fujiawu, Tongchang and Zhushahong share very similar petrographic features. They are porphyritic in texture and massive in structure with varied colour, grain size and phenocryst/ ground mass ratio (Table 2).

Phenocrysts are mainly euhedral tabular andesine, with lesser amounts of euhedral and subhedral bladed hornblende, biotite, tabular K feldspar and a small amount of corroded quartz. The groundmass is composed of fine-grained to micro-grained, rounded to granular oligoclase, quartz, K feldspar and minor hornblende and biotite. Accessory minerals include magnetite, apatite, sphene, ilmenite and zircon. A comparison of the mineral compositions of the three granodiorite porphyries and associated potassic aplite and quartz diorite dykes are shown in Table 3.

Petrochemistry

Chemical compositions of granodiorite porphyries and associated dykes are listed in Table 4. Although the effects of alteration cannot be fully precluded from the analysed samples, they are characterised by relatively high silica: 64.21- 66.13% for Fujiawu, 62.32 - 63.70% for Tongchang and 62.82% for Zhushahong. They also have relatively high (Na_2O + K_2O) contents. The K_2O content is about 1% higher than the average value of similar rocks elsewhere in the world. These granodiorites are calc-alkalic in nature with a calc-alkaline index of 57.4.

Isotopic ages

Isotopic dating data have been published by several workers. The Tongchang granodiorite porphyry yields a K-Ar age of 186 Ma (Institute of Geology and Mineral Resources, MMI, 1984) and an Rb-Sr isochron age of 172 Ma with an initial Sr^{76}/Sr^{86} isotopic ratio of 0.7043 (Zhu *et al.*, 1983). Zhu *et al.* reported a Sm-Nd age of 184 Ma for the Dexing granodiorite porphyries (Zhu *et al.*, 1990), and a Rb-Sr isochron age of 165 Ma for Tongchang granodiorite porphyry (Zhu *et al.*, 2002).

Table 3: ***Mineral compositions of granodiorite porphyries, potassic aplite and quartz diorite porphyrite of the Dexing porphyry copper field***

Ore district	Lithology	Quartz	Plagioclase	K feldspar	Hornblende	Biotite	Others
Fujiawu	Granodiorite (4)	21	49	15	8	5	2
Tongchang	Granodiorite (5)	20	49	15	9	5	1
Zhushahong	Granodiorite (1)	20	49	14	9	6	2
Tongchang	Potassic aplite (1)	34	21	43		1	1
Dawutou	Potassic aplite (1)	36	18	44		1	1
Tongchang	Quartz diorite porphyry	8	64	6	11	8	3

All minerals in % by area/lithology. Numbers in brackets are numbers of samples studied under microscope.

Table 4: ***Chemical compositions of the ore-bearing granodiorite porphyries from Fujiawu, Tongchang and Zhushahong ore districts (wt %)***

Intrusion	Number	Lithology	Si_2O	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^+	CO_2	LOI	Total
Fujiawu	Fu-1	Granodiorite porphyry	64.64	0.40	15.34	1.44	2.91	0.08	1.88	3.38	3.93	3.00	0.25	1.34		1.38	99.97
	Fu-2	Granodiorite porphyry	64.76	0.42	15.38	1.88	3.10	0.75	1.83	3.86	4.00	3.00	0.21			1.02	100.21
	Fu-3	Granodiorite porphyry	65.80	0.42	15.56	1.71	2.04	0.09	1.37	2.99	3.91	3.45	0.20			1.90	99.44
	Fu-4	Granodiorite porphyry	64.74	0.45	15.90	1.85	2.87	0.11	2.09	4.66	3.22	3.15	0.28	1.40			100.72
	Fu-5	Granodiorite porphyry	64.21	0.41	16.67	1.45	2.10	0.06	1.36	3.63	4.30	3.35	0.15	1.12			98.81
	Fu-6	Granodiorite porphyry	66.13	0.36	15.60	1.83	2.05	0.06	1.62	2.89	3.84	3.28	0.16	1.72		1.50	101.04
	Average	Granodiorite porphyry	65.05	0.41	15.74	1.69	2.51	0.11	1.69	3.57	3.87	3.21	0.21	1.40	0.58		100.04
Tongchang	Tong-1	Adamellite-diorite porphyrite	62.32	0.45	15.79	2.52	2.88	0.08	2.55	4.10	4.23	2.90	0.25	1.82	0.50		100.39
	Tong-2	Granodiorite porphyry	63.70	0.40	14.88	1.77	2.64	0.05	2.07	4.32	3.71	3.19	0.25			3.41	100.39
	Tong-3	Granodiorite porphyry	63.54	0.45	15.46	2.93	1.97	0.05	2.52	3.84	3.39	3.24	0.23	1.29	0.61		99.52
	Tong-4	Granodiorite porphyry	63.22	0.45	15.07	2.55	2.89	0.05	2.55	3.83	3.78	3.38	0.25	1.12	0.21	1.09	100.44
	Tong-5	Granodiorite porphyry	63.25	0.43	15.65	3.21	1.56	0.04	2.77	4.42	3.68	3.63	0.23	1.17	0.41		100.45
	Tong-6	Granodiorite porphyry	62.60	0.45	15.58	2.73	2.59	0.08	2.55	4.50	4.00	3.33	0.25	1.64	0.12		100.42
	Tong-7	Granodiorite porphyry	62.82	0.45	15.11	2.06	2.80	0.08	2.31	4.33	3.89	3.20	0.30	1.04	0.87	1.75	101.01
	Tong-8	Granodiorite porphyry	62.81	0.44	15.29	3.00	1.98	0.08	2.83	3.80	3.37	3.55	0.24	1.34	1.06		99.79
	Tong-9	Granodiorite porphyry	62.88	0.41	15.60	1.26	4.34	0.31	2.04	4.08	3.63	2.88	0.24	1.69			99.36
	Tong-10	Granodiorite porphyry	62.89	0.41	15.47	1.56	3.56	0.24	2.10	4.31	3.61	2.74	0.24	1.69	0.59		99.41
	Average	Granodiorite porphyry	63.00	0.43	15.39	2.36	2.69	0.06	2.43	4.15	3.73	3.20	0.25	1.49	0.49		99.67
Zhushahong	Zhu-1	Granodiorite porphyry	62.82	0.40	15.24	0.72	2.52	0.03	2.41	3.17	3.84	3.34	0.25	2.46	0.75	3.58	101.53
Tongchang	Tong-11	Potassic aplite	73.18	0.10	11.43	0.74	2.40	0.02	0.50	1.26	2.88	5.25	0.03	0.82	0.61		99.22
	Tong-12	Quartz diorite porphyry	59.90	0.45	15.02	2.06	3.70	0.03	3.45	4.70	3.30	2.95	0.33	1.68			97.57
	Tong-13	Quartz diorite porphyry	60.66	0.50	15.64	2.02	3.51	0.08	3.60	4.72	3.50	3.15	0.30	1.48			99.16
Dawutou	Da-1	Potassic aplite	76.04	0.10	12.02	0.47	0.74	0.01	0.20	0.80	3.09	5.50	0.03	0.44	0.05		99.49

Table 5: ***Mineral compositions of granodiorite porphyry, phyllite and their altered varieties from Fujiawu and Tongchang (%)***

	Tongchang								Fujiawu							
	Granodiorite porphyry _ Contact zone _ Phyllite								Granodiorite porphyry _ Contact zone _ Phyllite							
Alteration intensity	Fresh rock	Weakly	Moderately	Strongly	Strongly	Moderately	Weakly	Fresh rock	Fresh rock	Weakly	Moderately	Strongly	Strongly	Moderately	Weakly	Fresh rock
Rock type	$\gamma\delta\pi$	$\gamma\delta\pi^1$	$\gamma\delta\pi^2$	$\gamma\delta\pi^3$	H^3	H^2	H^1	H	$\gamma\delta\pi$	$\gamma\delta\pi^1$	$\gamma\delta\pi^2$	$\gamma\delta\pi^3$	H^3	H^2	H^1	H
Plagioclase	49.4	18							48.8	14						
K-feldspar	15.1	7							15.5	8						
Hornblende	0.5								8.3							
Biotite	5	1							4.8	2						
Quartz	19.5	22	28	33	28	17	7	1	20.5	23	32	36	31	23	9	1
Illite (Hydro-muscovite)		28	38	58	63	59	15	86		28	34	56	61	52	70	81
Chlorites		15	24			15	13	12		14	21			17	15	14
Epidote		2								4	5				1	
Albite		1								1						
Carbonates		3	4	5	6	6	3			2	3	3	4	5	3	
Anhydrite		2	2	1	1	1	1	1		2	2	2	1	1	1	
Magnetite*	8,763	3,742	5	35	n	n	n	N/A	5,261	2,950	125	73	150	291	112	24
Apatite*	2,546	1,730	969	147				N/A	351	87	13	5				
Zircon*	124	131	49	106	n	n		N/A	194	100	130	153	Trace	Minor	Minor	Minor
Sphene*	1,192	192		1	n	n		N/A	145	19	13					
Ilmenite*	196	14						N/A								

After: Zhu Xianjia (1980, unpublished) and Rui, et al. (1984). Minerals in % studied under microscope except for those marked with * in g/t in mineral separates; N/A- No data available; n-Several grains.

Alteration Zonation

Zonation of alteration and mineralisation within the Dexing porphyry copper deposits is well documented by Zhu *et al.*, (1983) and Rui *et al.*, (1984). The country rocks underwent heating during the emplacement of the granodiorites, converting phyllites and slates into biotite and andalusite-biotite hornfels in a 100-400 m wide hornfelsed halo surrounding the intrusions.

Early stage high-temperature potassic alteration was not well developed. Secondary K feldspar and biotite are observable in the Fujiawu granodiorite porphyry, but are rarely recognised at Tongchang and Zhushahong. Subsequent hydrothermal alteration was then focused along the contact zones between the granodiorite porphyries and hornfelsed country rocks, resulting in a symmetric alteration zoning from the contact zone, both inwards and outwards (Fig. 3 and Table 5) as follows:

Quartz-sericite zone (strong alteration zone, $\gamma\delta\pi^3$ and H^3) - composed of 80% secondary quartz and sericite which replaced primary feldspars and mafic minerals and destroyed the original textures of phyllites and granodiorite porphyries.

Chlorite-(epidote)-sericite zone (intermediate alteration zone, $\gamma\delta\pi^2$ and H^2) - consists of 60-80% alteration minerals of chlorite, sericite, quartz, epidote, carbonate and anhydrite. The original texture was partially destroyed and secondary minerals grew around the edges and along cleavages of primary feldspars. This zone may extend for hundreds of metres into granodiorite ($\gamma\delta\pi^2$) and outwards into country rocks (H^2).

Chlorite-epidote-illite zone (weak alteration zone, $\gamma\delta\pi^1$ and H^1) - has variable amounts of (10-60%) illite, chlorite, epidote, albite, carbonate and anhydrite replacing primary feldspars and mafic minerals. The original textures are generally preserved.

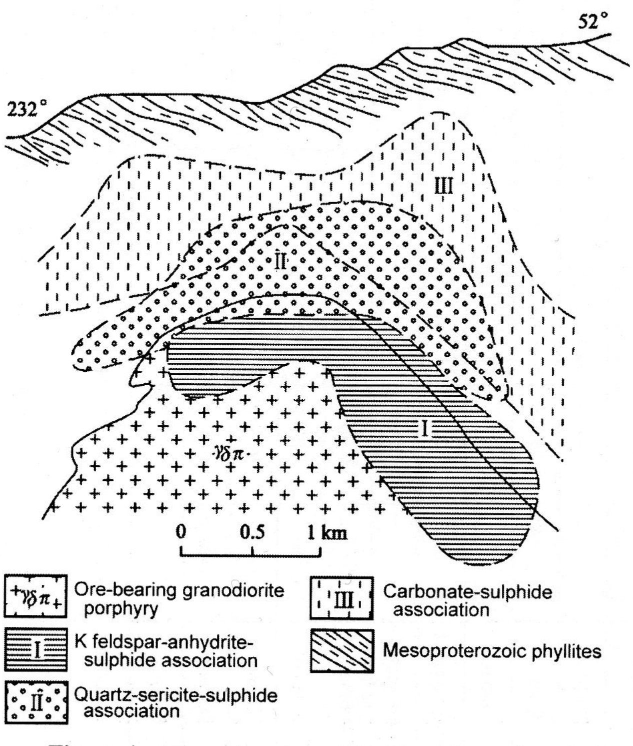

Figure 4: ***Mineral zoning of the Tongchang deposit***

Vertical alteration zoning is also described at Tongchang. A K-feldspar-anhydrite-sulphide association is recognised in the upper portion of the granodiorite porphyry, while a quartz-sericite (illite)-sulphide assemblage occurs in the contact zone and a sulphate-sulphide association in the outer contact zone (Fig. 4).

Within the Dexing porphyry copper deposits hydrothermal micas (sericite and illite) are distributed over a 2 km belt and are related to the contact zones between granodiorite porphyries and wall-rocks (Fig. 3). They were also mentioned as hydromuscovite and hydromica in earlier publications (Zhu *et al.*, 1983; Rui *et al.*, 1984). They occur as fine-grained, muscovite-like clay minerals with variable contents of potassium and H_2O, and are difficult to distinguish by naked eye in the field from each other and from those of metamorphic origin. X-ray diffraction analyses (Zhu *et al.*, 2002) indicate that the Kübler indices of illites from altered granodiorite porphyry and altered phyllite are 0.45°-1.37°ΔZQ and 0.40°-0.84°ΔZQ respectively, with an average values of 0.79°ΔZQ and 0.55°ΔZQ, respectively. For a comparison, Kübler indices measured for illites from phyllite two km away from the contact zone, representing non- or less-altered rocks, are apparently much lower, varying from 0.11° to 0.18°ΔZQ with an average value of 0.16°ΔZQ. X-ray diffraction spectral comparison also indicated that illites from altered rocks are 1M type with Ir values >1, suggesting the presence of an expansion layer and of alteration genesis, while illites from non-altered phyllites are 2M1 type with Ir values of 1 indicating absence of an expansion layer and a metamorphic genesis.

Mineralisation

Orebodies

In general, orebodies are confined to contact zones between granodiorite porphyries and wall-rocks. Shells of 0.4% Cu broadly coincide with the strong alteration zone forming ring-shaped orebodies in plan and, in three dimensions, north-westerly plunging cylinders with barren central cores (Fig. 5). Two-thirds of the ores are hosted by altered phyllites, and one-third by altered granodiorite porphyries. The Tongchang orebody is the largest of the three deposits. It is oval-shaped at surface, with a northwest-southeast trending long axis of 2.54 km and an inner barren core measuring 400 by 700 m. The Fujiawu orebody is a rounded square with a diameter of 1000 m and inner barren core diameter of 800 m. The down plunge extent of both the Tongchang and Fujiawu orebodies is more than 1000 m. In profile, Zhushahong comprises several smaller *en echelon* orebodies (Fig. 5).

Ores from the Fujiawu, Tongchang and Zhushahong deposits are very similar and of typical porphyry copper style. Orebodies are characterised by stockwork and disseminated mineralisation, varying from predominantly disseminated at Fujiawu, to stockwork-dominated at Tongchang and Zhushahong. Millimetre to centimetre wide cross-cutting quartz veins and veinlets form a framework in a strongly quartz-sericite altered background. Disseminated pyrite, chalcopyrite, specularite and

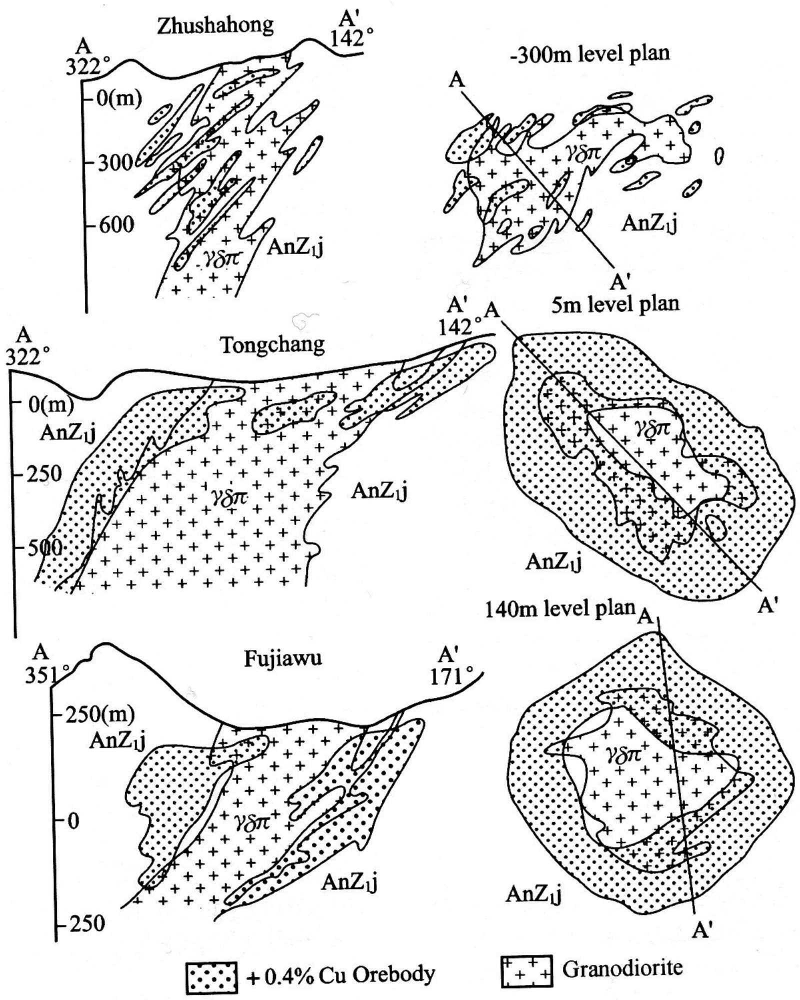

Figure 5: ***Shape and occurrence of orebodies in profile (left) and in plan (right) of the Fujiawu, Tongchang and Zhushahong deposits***

molybdenite are found either in veins or in the altered host rock. Ore grade and metal ratios are controlled by both the density of veining and the abundance of ore-forming minerals. Average Cu:Mo ratios are 15:1 for Fujiawu, 45:1 for Tongchang and 43:1 for Zhushahong. Other associated metals include Au, Ag, S, Re, Te, Se, Co and Os.

Primary sulphide ores account for between 85 and 90% of the total ore reserves at all three deposits, whereas secondary copper sulphides account for about 5 to 12% and oxide ores make up less than 5%. Oxidation and leaching are very weak in this region of mountainous relief and no supergene enrichment zone was developed.

Mineralogy

As detailed previously, pyrite, chalcopyrite and molybdenite are the main ore minerals. According to Hu Zongsheng (1981, unpublished), molybdenite:chalcopyrite:pyrite ratios in the Tongchang deposit vary from 1:30:57 in the lower part, through 1:85:205 in the middle part to 1:150:879 in the upper part.

Chalcopyrite contributes about 90% of the copper grade in primary ores, while minor tennantite, bornite, tetrahedrite and chalcocite account for the remainder. Molybdenite contains 244 ppm Re at Fujiawu and 1419 ppm Re at Tongchang (Rui, *et al.,* 1984), and rhenium is recoverable from molybdenite concentrates. Other minor metallic minerals include galena, sphalerite, magnetite, digenite, covellite, goethite, lepidocrocite, maghemite, tenorite, pyrolusite, malachite and azurite. A complicated ore mineral paragenesis was observed (Rui *et al.,* 1984).

Trace amounts of native gold and electrum are the main gold minerals, producing an average grade of 0.19g/t Au at Tongchang. Other trace metallic minerals are bismuthinite, cubanite, pyrrhotite, arsenopyrite, aikinite, emplectite, carrollite, millerite, gersdorffite, tetradymite, hessite, petzite, calaverite, melanite, merenskyite, ilmenite, anatase, wolframite, cassiterite, manganosiderite, siderite, mushketovite, chromite, native copper, native silver, marcasite, wulfenite, cerussite and anglesite.

Quartz is the dominant gangue mineral, and as a result, ores contain generally high silica. Other gangue minerals include sericite, illite, chlorite, epidote, K feldspar, ankerite, dolomite and anhydrite.

Minor gangue minerals are biotite, muscovite, albite, andesine, oligoclase, hornblende, laumontite, zoisite, clinozoisite, tourmaline, gypsum, apatite, barite, rutile, fluorite, kaolinite, montmorillonite, hydrobiotite and chalcanthite. Trace amounts of andalusite, sphene, zircon, pyroxene, allanite, garnet, monazite, xenotime and spinel are recorded (Rui *et al.,* 1984).

Age of Mineralisation

As detailed above, the granodiorite porphyry at Tongchang was isotopically dated by different methods at 172-186 Ma (Zhu *et al.*, 1983; Institute of Geology and Mineral Resources, MMI, 1984; Zhu *et al.*, 1990). Re-Os isotopic dating on two molybdenite concentrate samples from Tongchang yielded 173±9 Ma (Wu Chengyu, Huang Dianhao and Du Andao, 1997, unpublished). Ye (1987) indicated a range of isotopic ages of 157 Ma to 170 Ma for a variety of rocks from Tongchang. Zhu *et al.*, (1983) reported K-Ar ages of 157 Ma and 152 Ma for quartz-K feldspar veins from the Fujiawu granodiorite porphyry and from country rocks, respectively. K-Ar ages for sericite from the Tongchang granodiorite porphyry and for biotite from the Tongchang post-ore quartz diorite porphyry dyke are 112 Ma and 100 Ma, respectively. It is concluded that the Dexing granodiorite intrusions were emplaced at 186-172 Ma, immediately followed the early molybdenum mineralisation at 173 Ma. The subsequent alteration and mineralisation continued from 157 to 112 Ma, followed by emplacement of post-ore quartz diorite porphyry dykes at 100 Ma.

Ore Genesis and Discussion

Hydrothermal Fluids

Fluid inclusions from the Fujiawu porphyry copper deposit have three homogenisation temperature ranges, 540-595°C, 255-471°C and 151-218°C, corresponding to magmatic pneumatolytic, hypo-mesothermal and meso-epithermal stages, respectively (Institute of Geology and Mineral Resources, MMI, 1984). Zhu Xun *et al.*, (1983) reported similar homogenisation temperature ranges for fluid inclusions from the Tongchang porphyry copper deposit, namely:

- 425-745°C high volatile and high salinity inclusions related to biotite-K feldspar alteration,
- 275-425°C gaseous-liquid and high salinity inclusions associated with quartz-sericite and quartz-chlorite-anhydrite alteration, closely related to chalcopyrite, molybdenite, bornite and pyrite mineralisation,
- 100-275°C low salinity fluid inclusions associated with quartz-illite alteration.

Recent studies by Zhu Jinchu *et al.*, (2002) indicated that fluid inclusions with a temperature of 570-520°C are high salinity (31.0-63.3 wt% NaCl), representing an immiscible phase, exsolved from granitic magma in equilibrium with residual silicate melt. Decreasing temperature and pressure during ascent resulted in boiling at 480-360°C, forming three immiscible phases, as follows:

- a highly saline (43.0-52.2 wt % NaCl) phase,
- a low salinity (0.05-3.9 wt% NaCl) and gas-rich phase,
- a moderate salinity (11.6-17.5 wt % NaCl) and CO_2-rich phase, respectively.

Based on geological evidence and fluid inclusion studies, Zhu Jinchu *et al.*, (2002) concluded that the Tongchang granodiorite porphyry was emplaced under pressures of 65 to 15 Mpa, corresponding to a depth of about 1.5 to 2.5 km depth below the surface.

Source of Ore Metals

$\delta^{34}S$ values for 136 pyrite and chalcopyrite samples from the Tongchang deposit vary from –2.8‰ to +3.1‰ (Zhu *et al.*, 1983). This suggests that sulphide sulphur at Tongchang originated from a mantle-derived magma. This is supported by the low initial $^{87}Sr/^{86}Sr$ ratio (0.7043) of the Tongchang granodiorite (Zhu *et al.*, 1983). According to Zhu *et al.*, (1990), $\varepsilon_{Nd\,(t)}$ and $\varepsilon_{Sr\,(t)}$ values for the Tongchang granodiorite porphyry are –1.9 and 0.1, respectively and calculated component weight ratios between average mantle-derived end-member and average crustal end-member are 0.719 and 0.281, respectively. From this it could be deducted that granitic magma generated by partial melting of the underplate during subduction of the Izanqi-Pacific plate below the China continental crust was dominated by mantle-derived materials (72%) and contaminated by crustal materials (21%).

Zhu *et al.*, (2002) demonstrated that water-rock interaction and isotopic exchange reaction resulted in increases in ε_{Sr} from 10.7 to 79.1 and $(^{87}Sr/^{86}Sr)_i$ from 0.70508 to 0.71092 from the central part to the margin of the Tongchang intrusion respectively. This suggests that input of high $^{87}Sr/^{86}Sr$ values (0.71123 to 0.71151) from wall-rock phyllites played an important role. Similarly ε_{Nd} values of Tongchang granodiorite porphyry decrease from - 0.76 to -3.6 from its centre to the margin.

Oxygen isotopes of primary quartz from the Tongchang granodiorite yield $\delta^{18}O_{H_2O}$ values of +8.0 to +6.2‰ for water in equilibrium with the mineral. These typically magmatic signature values decrease to +6.0 to +1.4 ‰ for early stage quartz-K feldspar veins and down to +4.6 to -2.6‰ for later stage quartz-sulphide and chlorite-sericite veins, indicating involvement of meteoric water in the progress of alteration and mineralisation (Rui, *et al.*, 1984). Hydrogen isotopes provide similar support as δD varies from –79 to -82‰ for magmatic water in equilibrium with biotite phenocrysts and early stage alteration rocks, to –54 to -62‰ for fluid inclusions from copper sulphide-quartz veining and post-ore quartz veins (Zhang *et al.*, 1996; Zhu *et al.*, 2002).

Experimental studies (Candela *et al.*, 1984 and Williams *et al.*, 1995) indicated that in a granitic magma-water system, Cu in fluid/melt preferentially enters into a fluid phase with a Cu partition coefficient of more than 10 to 50. In the presence of Cl^- in the fluid phase in particular, Cu will more readily enter the fluid phase and migrate as complexes.

Granitic magmatic systems generally possess high oxygen fugacities with fO_2 varying from 10^{-14} to 10^{-8}. The fO_2 values of Cu-Mo-Au mineralisation systems observed in China range from 10^{-24} to 10^{-11} (Rui *et al.*, 2002). This prevents Cu, Mo and Au from entering into Fe-bearing mineral phases during crystallisation of magma and favours these elements entering into a hydrothermal phase with abundant SO_2. This process will be enhanced by the hydrolysis of SO_2 and precipitation of anhydrite and gypsum. A reducing environment will further concentrate Cu, Mo and Au in a hydrothermal system by forming complexes with H_2S. With a further decrease in temperature, pressure, pH values and degassing of CO_2, mineralisation occurs by precipitating molybdenite, chalcopyrite and pyrite.

Ore Forming Controls and Models

Studies of porphyry copper deposits throughout the world has resulted in the establishment of various models and theories (Lowell and Guilbert, 1970; Sillitoe, 1990; Sillitoe, 1997). A porphyry model has been widely accepted for the Dexing copper deposits, although opinions differ on the interpretation of details relating to the source of ore forming materials and the nature of hydrothermal fluids. As shown above, Zhu Xun *et al.,* (1983) believed on the one hand that primary volatiles resulting from fractionation of the second boiling of magmatic fluids were responsible for alteration and copper-molybdenum mineralisation and that ore-forming materials were primarily derived from magmatic hydrothermal solution, although a mixture of heated meteoric water played a role in the later stage. Ji Kejian *et al.,* (1989) on the other hand emphasised the importance of heated ground water circulating throughout the surrounding country rocks resulting in wall-rock alteration and mineralisation. Their interpretation favoured the main ore-forming materials being derived from country rocks as evidenced by a depletion halo of copper and other metals around the Dexing copper deposits. Based on recent studies, Zhu Jinchu *et al.,* (2002) supported a magmatic source of hydrothermal fluids which brought dominant ore-forming materials and indicated a contribution from meteoric water and deeply-buried formation water through a water-rock interaction process.

Fig. 6 illustrates a generalised zonation pattern of geology, alteration mineral assemblages, ore mineralogy, ore- and rock-forming element geochemistry, mineralisation styles, temperature and sulphur isotopes of the Dexing porphyry copper deposits. From the inner core to outer zone of the deposit, mineral components change from molybdenite, through chalcopyrite to sphalerite and galena; element associations change from W-Bi through Mo-Cu, Ni-Co, Pb-Zn to Mn; while ore textures evolve from disseminated through veinlet-stockwork to veins. It may serve as a comparison to help porphyry copper-gold exploration in the region.

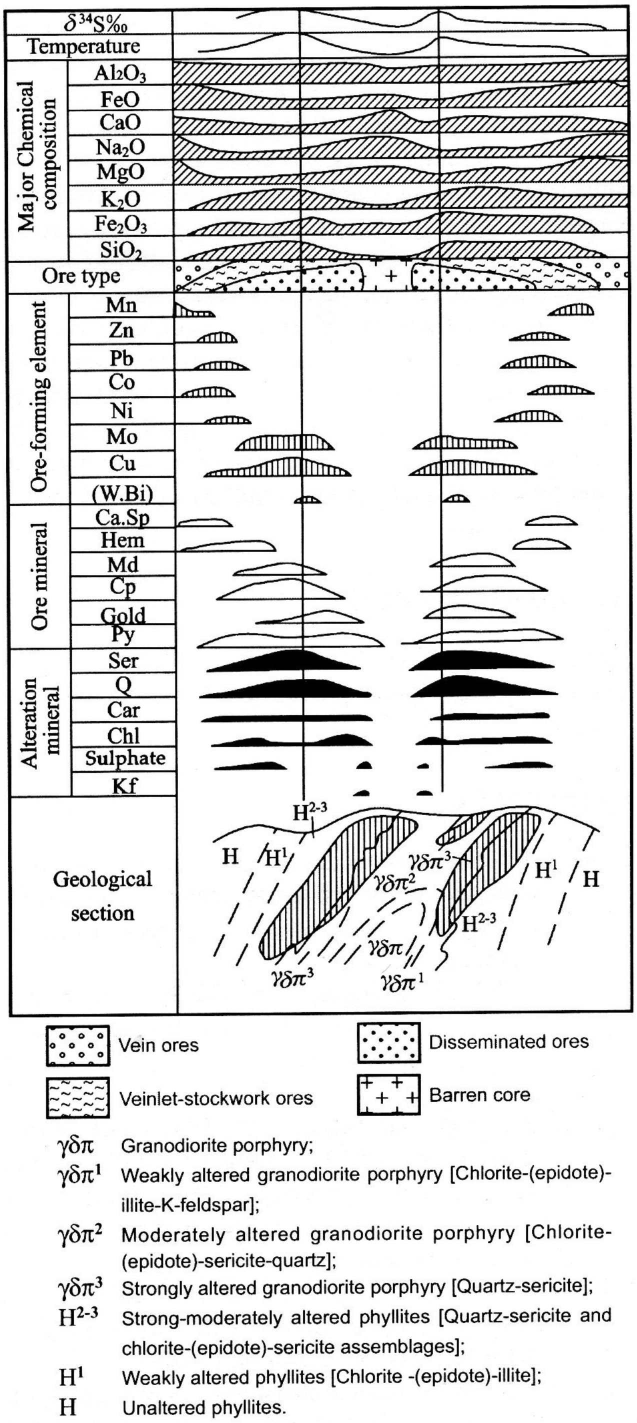

Figure 6: ***A generalised zonation pattern for the Dexing porphyry copper deposits***

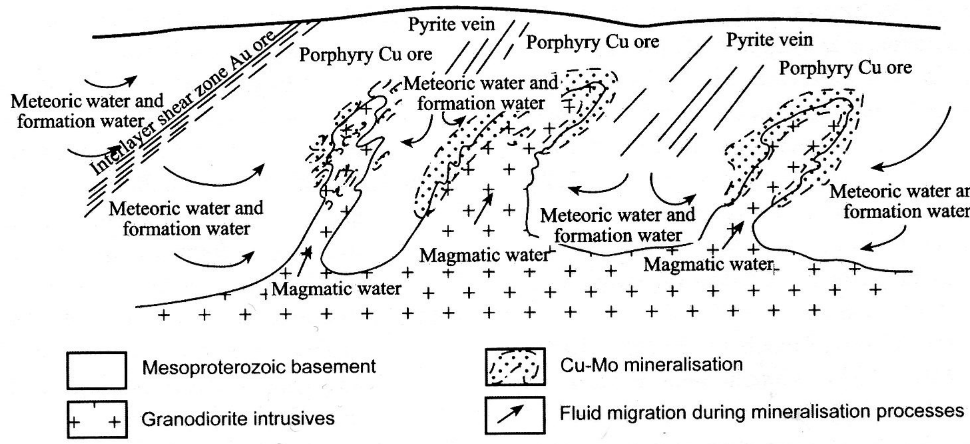

Figure 7: ***A genetic model for the Dexing porphyry copper deposits, Jiangxi, China.***

To conclude, a genetic model for the Dexing porphyry copper deposits is illustrated in Fig. 7. Cross structures, in the form of northwest striking regional faults related to the Gandongbei deep-seated fault zone played a very important role in the generation and emplacement of granitic magma, while fractures along contact zones between granodiorite porphyries and phyllite country rocks provided crucial conduits and loci for hydrothermal alteration and mineralisation. Ore-forming fluids were primarily derived from volatiles fractionated from a second boiling of magmatic hydrothermal fluids which brought metals and caused symmetric zoning of alteration and mineralisation along the contact zones. Circulation of heated ground water and possibly deep-seated formation water, were involved in the process at a later stage, resulting in further water-rock interactions.

Acknowledgement

Sincere thanks to Dr Ross Andrew who thoroughly reviewed the paper and improved both content and English language.

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