Halogen Geochemistry in the Ok Tedi Porphyry Copper System, Papua New Guinea

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Abstract

The Ok Tedi ore deposit is an epicontinental porphyry copper system in Papua New Guinea. The behavior of halogen elements in the mineralization was considered based on the chemical compositions of biotite and apatite.

The Si and $Mg/(Mg + Fe)$ of biotite increased, and Ti decreased with advancing hydrothermal activity. The change of chemical composition of biotite suggested a decrease of temperature and/or an increase of oxygen fugacity.

Biotite and apatite were characterized by an enrichment of F, as well as an enrichment of other incompatible elements (apatite), compared to those in the island arc regions in Papua New Guinea. The magmatism in this field might originate in the continental crust, or might be strongly contaminated with crustal materials. The f_{HF}/f_{H_2O} ratios on isothermal projection suggested further concentration of F in the residual magma during solidification of originally F-rich magma.

The f_{HCl}/f_{H_2O} ratio in magma in the Ok Tedi mining district was similar to those in island arc region. The ratio has a tendency not to concentrate in the ordinary acidic magmatism of the continental region, that is, the Ok Tedi mining district should be regarded as an abnormal Cl enriched field. The f_{HCl}/f_{H_2O} ratio on isothermal projection has increased at the veining stages. The effective transportation mechanism of base metals in the Ok Tedi mining district was suggested by HOLLAND's simulation (1972).

Key words: Ok Tedi, Halogen elements, Epicontinental, Papua New Guinea.

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Introduction

Papua New Guinea is situated on the boundary between the Australia and the Pacific Ocean plates. Porphyry copper deposits in Papua New Guinea are located in various tectonic settings ranging from a cratonic block through orogenic belts to island arcs. The Ok Tedi porphyry copper system is located in the epicontinental platform of the cratonic block.

MASON and MCDONALD (1978) pointed out that the intrusive rocks in the Ok Tedi mining district are characterized by an enrichment of incompatible elements, compared to those in the orogenic belts in the continental margin and those in the island arcs in Papua New Guinea.

NEDACHI and MALAGUN (1990) pointed out that the Ok Tedi porphyry copper mineralization is characterized by high F contents with a high $fHCl/fH_2O$ ratio. In this study, with additional data, the behavior of halogen in the Ok Tedi porphyry copper mineralization is considered again, and discussed with the results of the Panguna ore deposit (NEDACHI et al, 1990).

Outline of Geology

The Ok Tedi porphyry copper deposit is located in the Star Mountain region near the frontier with Ilian Jaya. The geology of this region has been described by many workers (e, g., ARNOLD and GRIFFIN, 1978: DAVIES et al., 1978), and Fig. 1 shows a geological map drawn by Ok Tedi Mining Ltd.

The basements in this district are Paleozoic metamorphic rocks and granites. Mesozoic to Cenozoic shelf sediments; Pnyang Formation, Ieru Formation, and Darai Limestone, unconformably cover the basements. The sediments are intruded by an Ok Tedi complex of high K suite of calc-alkaline rock series of Upper Miocene to Pleistocene (MASON and MCDONALD, 1978). The Ieru Formation is strongly contact metamorphosed, and irregular skarn masses are formed in the Darai Limestone near the contact with the Ok Tedi complex. Also silicification, argillic alteration and mineralization are observable over the entire mining district.

In the mining area, the Ok Tedi complex is mainly composed of two intrusive bodies, Sydney Monzodiorite and Fubilan Monzonite Porphyry. The earlier stock, Sydney Monzodiorite, is exposed in a $5 \times 3km$ area. The rock is porphyritic to equigranular, and is composed of plagioclase, clinopyroxene, orthoclase, and hornblende, with minor amounts of biotite, sphene, apatite and magnetite. The later two small stocks are Fubilan Monzonite Porphyry. The phenocrysts are plagioclase, orthoclase, quartz and biotite with minor amounts of apatite, rutile and magnetite. Dissemination of biotite, Cu mineralization and argillic alteration expand widely and strongly all over the stocks. Phlogopite-quartz-apatite veins are frequently observed in the Fubilan Monzonite Porphyry, especially near the center. The vein postdates the dissemination of biotite. The network of quartz vein and silicification are very strong in the center of the Fubilan Monzonite Porphyry, called "Quartz Core", which is the last stage of the hydrothermal activity.
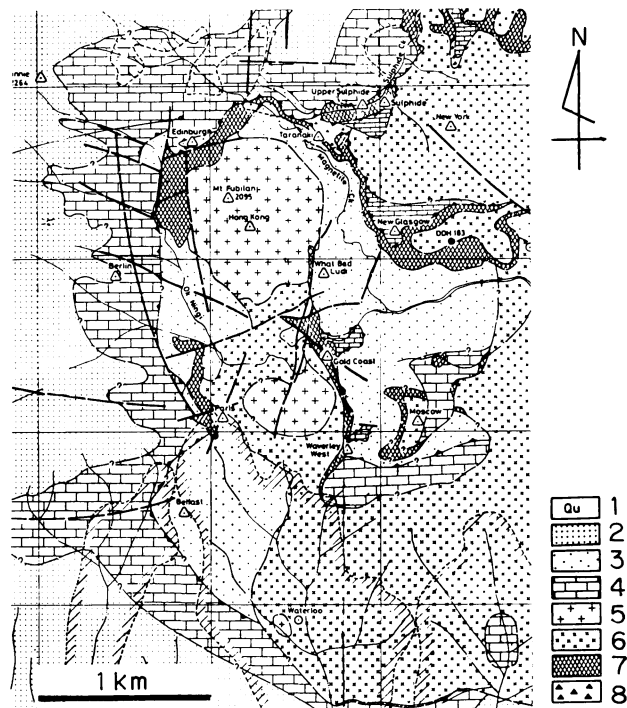
Fig. 1. Geological map of the Ok Tedi mining district, Papua New Guinea (after the Ok Tedi Mining Ltd., 1989).
1: Quaternary deposits, 2: Pnyang Formation, 3: Ieru Formation, 4: Darai Limestone, 5: Fubilan Monzonite Porphyry, 6: Sydney Monzodiorite 7: Skarn, 8: Fault breccia.

Occurrences of Biotite and Apatite

The samples of the Sydney Monzodiorite were collected from drill hole No. 319. A small amount of magmatic biotite occurred as brownish euhedral to subhedral crystals. Some grains are included in clinopyroxene. Biotite was also observed as a pale brownish pseudomorph, which might have been changed from amphibole or other mafic minerals. Apatite was frequently observed as a rather large euhedral crystal (up to 0.1×0.5 mm).

The samples of the Fubilan Monzonite Porphyry were collected from the Fubilan open pit, and from drill holes Nos. 320, 322 and 334. Biotite was observed all over the stock except in the Quartz Core. Rather large irregular shaped relic biotite was observed in the rock near the margin of the stock. Some grains of hydrothermal biotite occurred as a pseudomorph from other mafic mineral, and others disseminate as small subhedral to anhedral crystals. A small amount of apatite occurred as a small euhedral grain.

Sometimes biotites were observed in xenoliths in the Fubilan Monzonite Porphyry. The xenolith for examination was equigranular granitic rock. Biotite occurred as a reddish brown tabular euhedral crystal. The grain size was $20 \times 100 \mu$m in average. The phosphate mineral in

the xenolith was monazite.

Hydrothermal apatites were observable in silicate skarns which were composed of garnet, clinopyroxene, actinolite and magnetite, and also in sulfide skarn (mainly pyrite). Biotite was not observed either skarn sample.

Phlogopite-quartz-apatite veins were frequently observed in the Fubilan Monzonite Porphyry, especially near the Quartz Core. The sample in this study was collected from the Fubilan open pit and at a shallow depth of drill hole No.334, near the Quartz Core. The biotite was a pale brownish euhedral crystal with a grain size of up to 2cm. Apatite coexisted with biotite as a large euhedral grain from 0.1 to 1mm in diameter.

Biotite hornfels was collected from drill hole No. 320, which originated from the siltstone of the Ieru Formation. The sample was situated very close to the contact with the Fubilan Monzonite Porphyry. The sample contained small grains of biotite from 2 to 10μm. The biotite was a pale brownish anhedral crystal. Apatite was a rare mineral in the sample, and the grain size was very fine, from 1 to 20μm in diameter.

Chemical Compositions of Biotite and Apatite

Measurements: Biotite and apatite in polished thin sections were coated with carbon and analyzed for major and trace elements on an ARL-Shimazu X-ray microanalyzer, model EMX-SM. Normally, an excitation voltage of 15kV, a sample current of 0.02μA on a biotite standard and beam of 10 μm were used. All standards were natural minerals, which have been analyzed by other methods. They were biotite for Si, Ti, Al, Fe, Mg, K and Cl measurements, apatite for Ca, P and F, monazite for Ce, La and Nd, celenite for S and Si, pyrosmalite for Mn, albite for Na, and augite for Ca, Si and Mg. After correction for dead time, the Bence-Albee correction was used for the estimation of chemical composition. α-factors of rare earth elements (REE) were calculated by the ZAF method.

The water content of hydrous minerals were calculated, based on the following assumptionrs: 1) Fe is ferrous, 2) the valences of total cation are $+44$ for biotite and $+40$ for apatite, 3) all Cl and F ions occupy the OH lattice site only, and 4) the total valences of the OH site are -4 for biotite and -2 for apatite.

Biotite composition: The chemical compositions of biotite are shown in Table 1, and Fig. 2 illustrates the major compositions in a quadrangular diagram. The magmatic biotite in the Sydney Monzodiorite had a Mg$\diagup$(Mg+Fe) of 0.63 and Si atoms of about 5.5. The Mg$\diagup$(Mg+Fe) of relic (magmatic) biotite in the Fubilan Monzonite Porphyry was similar (0.67) to that of magmatic biotite in the Sydney Monzodiorite, but the Si atoms were ranged from 5.5 to 5.8. Biotite pseudomorph after mafic minerals in the Sydney Monzodiorite was higher in Mg$\diagup$(Mg + Fe) (0.77) and richer in Si (about 6.1) than magmatic one. Hydrothermally disseminated biotite in the Fubilan Monzonite Porphyry was also high in Mg$\diagup$(Mg+Fe), 0.77, and rich in Si (6.0). The Si of phlogopite in the phlogopite-quartz-apatite vein was about 6.0, and the Mg$\diagup$(Mg + Fe) was 0.82. The biotite in hornfels is plotted near center of the diagram, and is characterized by an enrichment of octahedral Al (7 in Table 2). The biotite in the xenolith had a

Table 1. Chemical compositions of biotite in the Ok Tedi mining district

NUMBER	1	2	3	4	5
SAMPLE(n)	319-3(2)	319-1(3)	319-1'(2)	320-3(4)	332-9(4)
SiO2	36.98 ± 0.03	36.61 ± 0.21	41.73 ± 0.26	37.26 ± 1.23	39.44 ± 0.25
TiO2	2.85 ± 0.31	3.98 ± 0.35	1.48 ± 0.09	3.36 ± 0.32	3.38 ± 0.27
Al2O3	14.05 ± 0.07	14.28 ± 0.06	11.43 ± 0.21	13.96 ± 0.78	12.82 ± 0.43
FeO	16.83 ± 0.01	15.83 ± 0.12	10.83 ± 0.12	15.51 ± 1.16	13.79 ± 0.16
MnO	0.20 ± 0.00	0.15 ± 0.02	0.09 ± 0.00	0.11 ± 0.02	0.08 ± 0.01
MgO	15.44 ± 0.14	15.33 ± 0.24	20.01 ± 0.38	15.89 ± 1.11	17.16 ± 0.47
CaO	0.07 ± 0.01	0.04 ± 0.03	0.09 ± 0.02	0.01 ± 0.01	0.01 ± 0.01
Na2O	0.18 ± 0.01	0.20 ± 0.03	0.06 ± 0.00	0.14 ± 0.02	0.09 ± 0.01
K2O	9.71 ± 0.02	9.48 ± 0.03	8.89 ± 0.04	9.59 ± 0.13	9.47 ± 0.10
Cl	0.17 ± 0.00	0.13 ± 0.01	0.07 ± 0.00	0.14 ± 0.02	0.11 ± 0.00
F	1.03 ± 0.00	1.10 ± 0.06	1.78 ± 0.06	0.79 ± 0.20	0.61 ± 0.15
H2O	3.47	3.45	3.24	3.60	3.77
-O	-0.47	-0.49	-0.77	-0.36	-0.28
Total	100.51	100.09	98.94	100.00	100.46
Si	5.542	5.481	6.093	5.566	5.786
Al(4)	2.458 (Σ 8.000)	2.519 (Σ 8.000)	1.907 (Σ 8.000)	2.434 (Σ 8.000)	2.214 (Σ 8.000)
Al(6)	0.024	0.000	0.060	0.024	0.003
Ti	0.321	0.449	0.162	0.378	0.373
Fe	2.110 (Σ 5.583)	1.981 (Σ 5.403)	1.322 (Σ 5.737)	1.938 (Σ 5.500)	1.692 (Σ 5.448)
Mn	0.026	0.019	0.011	0.014	0.011
Mg	3.449	3.422	4.355	3.539	3.753
Ca	0.012	0.006	0.014	0.002	0.002
Na	0.052 (Σ 1.921)	0.057 (Σ 1.874)	0.018 (Σ 1.687)	0.039 (Σ 1.870)	0.025 (Σ 1.799)
K	1.857	1.810	1.655	1.828	1.773
Cl	0.043	0.033	0.018	0.035	0.026
F	0.488 (Σ 4.000)	0.522 (Σ 4.000)	0.823 (Σ 4.000)	0.373 (Σ 4.000)	0.284 (Σ 4.000)
OH	3.469	3.445	3.159	3.591	3.690

NUMBER	6	7	8	9	10
SAMPLE(n)	334-15(4)	334-4(4)	334-1(4)	003-4(5)	320-10(4)
SiO2	41.42 ± 0.50	38.21 ± 0.14	42.06 ± 0.48	41.63 ± 0.31	37.26 ± 0.94
TiO2	2.20 ± 0.08	4.35 ± 0.12	1.85 ± 0.32	2.27 ± 0.22	2.91 ± 0.11
Al2O3	11.65 ± 0.47	14.45 ± 0.29	11.83 ± 0.84	11.58 ± 0.25	18.16 ± 0.82
FeO	10.19 ± 0.36	10.46 ± 0.28	6.11 ± 0.20	8.30 ± 1.02	14.79 ± 0.79
MnO	0.10 ± 0.01	0.11 ± 0.02	0.04 ± 0.00	0.09 ± 0.01	0.14 ± 0.02
MgO	20.02 ± 0.24	18.56 ± 0.07	22.90 ± 0.35	21.55 ± 0.67	12.77 ± 0.38
CaO	0.02 ± 0.00	0.00 ± 0.00	0.01 ± 0.01	0.00 ± 0.00	0.00 ± 0.00
Na2O	0.16 ± 0.03	0.26 ± 0.02	0.21 ± 0.04	0.19 ± 0.04	0.13 ± 0.03
K2O	9.45 ± 0.20	9.92 ± 0.03	9.71 ± 0.04	10.06 ± 0.11	9.64 ± 0.07
Cl	0.05 ± 0.00	0.06 ± 0.00	0.04 ± 0.01	0.06 ± 0.01	0.20 ± 0.04
F	2.39 ± 0.08	2.38 ± 0.07	3.15 ± 0.12	3.57 ± 0.18	0.65 ± 0.04
H2O	2.98	2.99	2.68	2.46	3.70
-O	-1.02	-1.01	-1.33	-1.52	-0.32
Total	99.62	100.72	99.25	100.23	100.03
Si	6.018	5.545	6.028	5.991	5.509
Al(4)	1.982 (Σ 8.000)	2.455 (Σ 8.000)	1.972 (Σ 8.000)	1.964 (Σ 7.955)	2.491 (Σ 8.000)
Al(6)	0.014	0.016	0.027	0.000	0.674
Ti	0.241	0.475	0.199	0.245	0.324
Fe	1.238 (Σ 5.589)	1.269 (Σ 5.302)	0.732 (Σ 5.652)	0.999 (Σ 5.621)	1.828 (Σ 5.316)
Mn	0.012	0.013	0.005	0.010	0.017
Mg	4.337	4.016	4.893	4.623	2.814
Ca	0.003	0.000	0.001	0.000	0.000
Na	0.045 (Σ 1.801)	0.072 (Σ 1.910)	0.059 (Σ 1.835)	0.053 (Σ 1.901)	0.038 (Σ 1.857)
K	1.752	1.837	1.775	1.848	1.819
Cl	0.013	0.014	0.009	0.014	0.049
F	1.098 (Σ 4.000)	1.092 (Σ 4.000)	1.427 (Σ 4.000)	1.624 (Σ 4.000)	0.302 (Σ 4.000)
OH	2.890	2.894	2.564	2.362	3.648

Sample locality 1: Magmatic biotite in Sydney Monzodiorite from 346.5m depth of drill hole No. 319. 2: Ditto from 39.0m. 3: Pseudomorphous biotite in the same sample with 2. 4: Relic biotite in Fubilan Monzonite Porphyry from 265.0m of drill hole No. 320. 5: Ditto from 334.9m of drill hole No. 332. 6: Disseminated biotite in Fubilan Monzonite Porphyry from 508.3m of drill hole No. 334. 7: Biotite in xenolith from 261.3m of drill hole No. 334. 8: Phlogopite in phlogopite-quartz-apatite vein from 182.1m of drill hole No. 334. 9: Ditto from Fubilan open pit (315210mE, 424240mN, 1840mL). 10: Biotite in hornfels from 385.9m of drill hole No. 320.
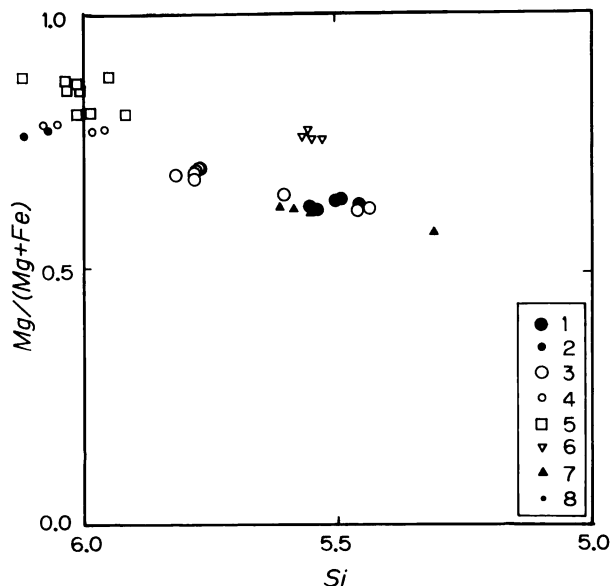
Fig. 2. Mg/(Mg+Fe) versus Si of biotite in the Ok Tedi mining district.
1: Magmatic biotite in Sydney Monzodiorite. 2: Pseudomorphous biotite in Sydney Monzodiorie. 3: Relic biotite in Fubilan Monzonite Porphyry. 4: Disseminated biotite in Fubilan Monzonite Porphyry. 5: Phlogopite in phlogopite-quartz-apatite vein. 6: Biotite in xenolith. 7: Biotite in hornfels. 8: Biotite from the Panguna mining district.

higher $Mg/(Mg+Fe)$ (about 0.8), and moderate Si atoms (about 5.5).

Fig. 3 shows the Ti atoms against $Mg/(Mg+Fe)$ of biotite. The magmatic biotite in the Sydney Monzodiorte and relic biotite in the Fubilan Monzonite Porphyry had rather high Ti (0.32 to 0.45). The pseudomorphous biotite in the Sydney Monzodiorite and hydrothermally disseminated biotite in the Fubilan Monzonite Porphyry were poorer in Ti (0.32 to 0.16) than the magmatic one. The vein phlogopite was also poor in Ti (about 0.2).

The chemical features of biotite might reflect the host rock compositions and the environment of biotitization, as are observed elsewhere (MOORE and CZAMANSKE, 1973; FORD, 1978). Magnetite and/or hematite was common in all samples, the fresh Sydney Monzodiorite and Fubilan Monzonite Porphyry, and the skarn zone, hence the increase of $Mg/(Mg+Fe)$ suggested the decrease of temperature and/or the increase of oxygen fugacity at the hydrothermal stage.

As shown in Table 1, most biotites were rich in F and poor in Cl. Fig. 4 shows the F/OH ratio against the $Mg/(Mg+Fe)$ of biotie. The F/OH was correlative with the $Mg/(Mg+Fe)$ as interpreted by MUNOZ and LUDINGTON (1974). The biotites in the Panguna porphyry copper deposit, island arc region (NEDACHI *et al*, 1990), are also plotted in the figure for comparison. Almost all biotites in the Ok Tedi deposit had higher F/OH ratios than those in the
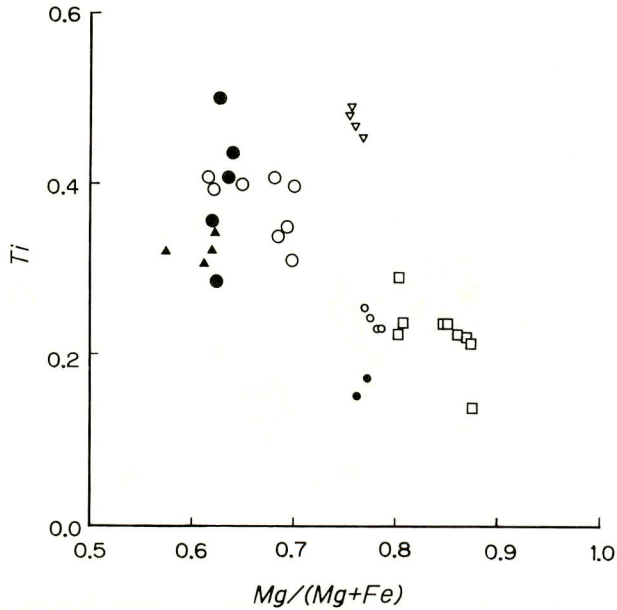
Fig. 3. Ti versus Mg/(Mg+Fe) of biotite in the Ok Tedi mining district.
Symbols are the same as those in Fig. 2.

Panguna deposit. Fig. 5 shows the Cl/OH ratio against the Mg/(Mg+Fe) of biotite. In contrasting to the F/OH ratio, the Cl/OH ratio decreases with an increase of the Mg/(Mg+Fe) as interpreted by NEDACHI (1980), and MUNOZ and SWENSON (1981). The distribution of Cl/OH ratio of the biotite in Ok Tedi deposit roughly overlapped those of the Panguna deposit. The halogen contents will be discussed again after the description of apatite.
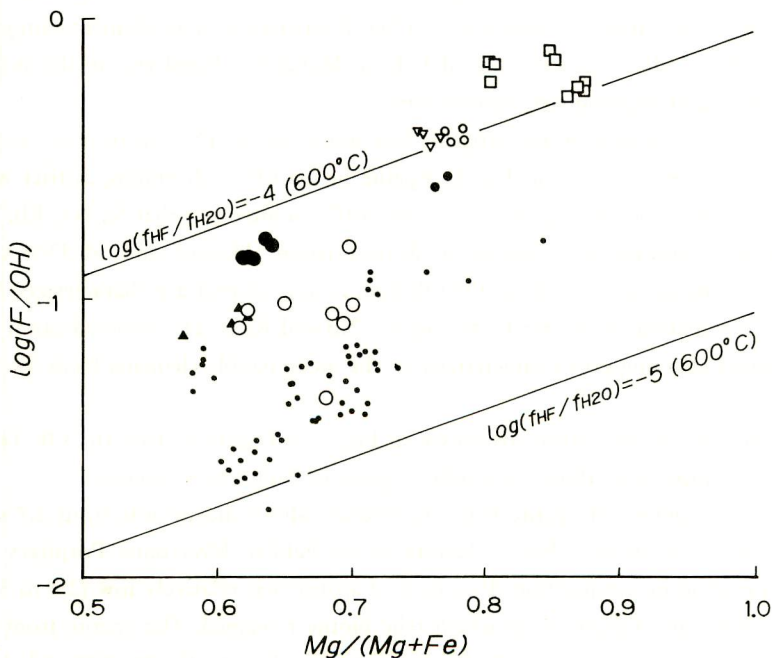

Fig. 4. log (F/OH) versus Mg/(Mg+Fe) of biotite in the Ok Tedi mining district.
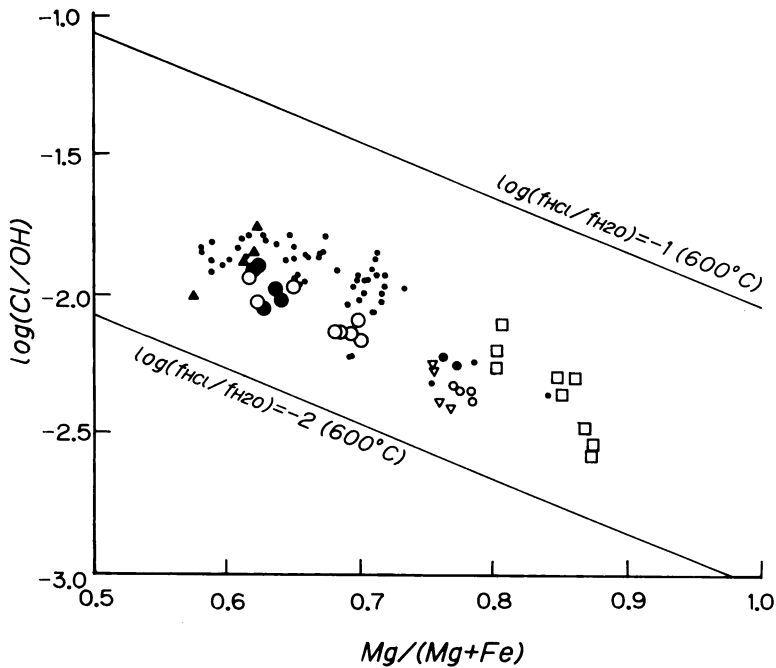Symbols are the same as those in Fig. 2.

Fig. 5. log (Cl/OH) versus Mg/(Mg+Fe) of biotite in the Ok Tedi mining district. Symbols are the same as those in Fig. 2.

Apatite composition: The chemical compositions of apatite are shown in Table 2. Almost all apatites were near fluorapatite. There were no big differences in trace elements among apatites in the Sydney Monzodiorite, in the altered Fubilan Monzonite Porphyry, in the skarn, and in the hydrothermal phlogopite-quartz-apatite vein.

A comparison with apatites in the orogenic belt and island arc (NEDACHI *et al*., unpublished) in Papua New Guinea is shown in Fig. 6. Apatite in the Ok Tedi mining district was rich in Ce, La, Si and S, but poor in Mg and Fe. NASH (1972) pointed out that Si, Na, Rb, F increase and Fe and Mg decrease with advancing differentiation. MASON and MCDONALD (1978) pointed out that the intrusive rocks in the Ok Tedi mining district are characterized by the enrichment of incompatible elements; K, Ba, Sr, Zr, Nb and REE. The mineralization in the Ok Tedi ore deposits also might be characterized by the incompatible elements from the thick continental materials.

The halogen contents of apatite are shown in Fig. 7. All apatites from the Ok Tedi deposit were rich in F, compared to those from other regions in Papua New Guinea.

In detail, the F content of apatite from the Sydney Monzodiorite was from 2.7 to 3.4wt% and the Cl content is about 0.2wt%. Apatite in the Fubilan Monzonite Porphyry showed a rather wide variation in composition. F content of apatite was relatively low (2.4 to 3.0wt%) in the Fubilan Monzonite Porphyry, in which relic biotite remained. The apatite from the stock, in which disseminated biotite is predominant, was very close to fluorapatite end member. In

Table 2. Chemical compositions of apatite in Ok Tedi mining district

NUMBER SAMPLE	1 31911	2 31912	3 33291	4 33292	5 32081	6 32082	7 334151	8 334152	9 00341	10 00342
Al2O3	0.00	0.01	0.03	0.00	0.01	0.02	0.02	0.01	0.00	0.02
Y2O3	0.03	0.04	0.07	0.10	0.05	0.02	0.06	0.08	0.12	0.14
La2O3	0.15	0.11	0.12	0.16	0.10	0.04	0.11	0.12	0.05	0.09
Ce2O3	0.33	0.31	0.24	0.07	0.31	0.18	0.22	0.31	0.12	0.12
Nd2O3	0.07	0.09	0.00	0.00	0.12	0.05	0.05	0.07	0.11	0.13
FeO	0.06	0.07	0.29	0.26	0.24	0.24	0.03	0.07	0.14	0.10
MnO	0.09	0.08	0.11	0.09	0.02	0.02	0.05	0.09	0.14	0.14
MgO	0.03	0.03	0.02	0.01	0.02	0.02	0.00	0.02	0.05	0.04
CaO	55.33	55.52	54.43	54.41	55.31	55.20	55.17	55.07	55.01	55.25
SrO	0.13	0.07	0.16	0.10	0.03	0.02	0.10	0.12	0.03	0.03
Na2O	0.06	0.09	0.13	0.09	0.03	0.08	0.11	0.09	0.15	0.30
P2O5	41.53	41.67	41.44	41.56	41.18	41.51	41.76	41.40	42.39	41.45
SiO2	0.36	0.28	0.42	0.39	0.64	0.25	0.32	0.29	0.11	0.17
SO3	0.33	0.30	0.26	0.16	0.55	0.19	0.33	0.27	0.17	0.35
Cl	0.17	0.15	0.44	0.36	0.06	0.03	0.07	0.06	0.06	0.06
F	2.71	2.83	2.91	2.94	2.94	3.43	3.46	3.27	3.39	3.50
H2O	0.87	0.78	0.55	0.55	0.73	0.28	0.25	0.40	0.33	0.21
-O	-1.18	-1.22	-1.32	-1.32	-1.25	-1.45	-1.47	-1.39	-1.44	-1.49
Total	101.06	101.20	100.28	99.93	101.09	100.13	100.65	100.37	100.93	100.61
Al	0.000	0.003	0.005	0.000	0.003	0.005	0.003	0.002	0.000	0.003
Y	0.003	0.003	0.006	0.009	0.004	0.002	0.005	0.007	0.010	0.012
La	0.009	0.007	0.008	0.010	0.006	0.002	0.007	0.008	0.003	0.005
Ce	0.020	0.019	0.015	0.004	0.019	0.011	0.014	0.019	0.007	0.007
Nd	0.004	0.005	0.000	0.000	0.007	0.003	0.003	0.004	0.007	0.008
Fe	0.008	0.010	0.041	0.037	0.034	0.034	0.005	0.010	0.019	0.014
Mn	0.012	0.012	0.015	0.014	0.003	0.003	0.007	0.013	0.020	0.020
Mg	0.007	0.007	0.005	0.003	0.004	0.005	0.000	0.005	0.013	0.011
Ca	9.930	9.945	9.830	9.844	9.905	9.959	9.892	9.934	9.824	9.935
Sr	0.012	0.007	0.015	0.010	0.003	0.002	0.010	0.012	0.003	0.003
Na	0.020	0.030	0.042	0.029	0.009	0.027	0.035	0.030	0.048	0.097
P	5.888	5.897	5.914	5.940	5.826	5.917	5.916	5.901	5.982	5.889
Si	0.061	0.046	0.070	0.066	0.108	0.042	0.053	0.049	0.019	0.029
S	0.041	0.038	0.033	0.020	0.069	0.025	0.042	0.034	0.021	0.044
Cl	0.048	0.043	0.126	0.104	0.016	0.007	0.019	0.018	0.017	0.018
F	1.437	1.494	1.549	1.571	1.554	1.827	1.833	1.743	1.787	1.858
OH	0.516	0.463	0.326	0.326	0.430	0.165	0.149	0.239	0.197	0.124

Sample locality 1-2: Sydney Monzodiorite from 39.0m of drill hole No. 319, 34: Fubilan Monzonite Porphyry from 334.9m of drill hole No. 322. 5-6: Skarn from 366.3m of drill hole No. 320. 7-8 Fubilan Monzonite Porphyry disseminated by biotite from 508.3m of drill No. 334. 9-10: Phlogopite-quartz-apatite vein from Fubilan open pit (315210mE, 424240mN, 1840mL).

spite of the variation in individual elements, the Cl/OH ratios of the apatites were all roughly the same which was similar to those in the island arc region. The apatites in skarn and hydrothermal veins were also near fluorapatite. On the other hand, the halogen contents of apatite in hornfels varies widely; F was from 2 to 3wt% and Cl was up to 0.5wt%.

Halogen Behavior in the Ok Tedi Mineralization

An apatite-biotite geothermometer assuming equilibrium of partition of F and OH was applied to the assemblage. The estimated temperatures varies widely, 720°C and 770°C for the fresh Sydney Monzodiorite, 580°C and 720°C for the altered Fubilan Monzonite Porphyry, 500°C for the hydrothermal phlogopitequartz-apatite vein, and 1120°C for the hornfels. The
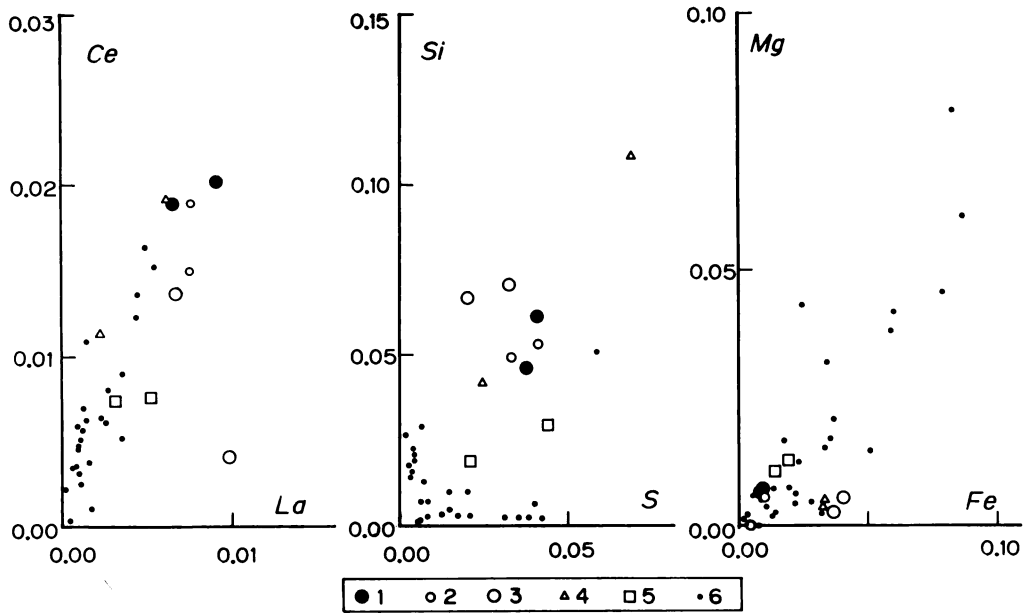
Fig. 6. Trace elements in apatite in the Ok Tedi mining district.
    1: Sydney Monzodiorite. 2: Fubilan Monzonite Porphyry, in which hydrothemal biotite dissemi-
    nates. 3: Fubilan Monzonite Porphyry, in which relic biotite remained. 4: Skarn.5: Phlogopite-
    quartz-apatite vein. 6: Plutonic rocks from the orogenic belt (Frieda, Kainantu, and Wau regions)
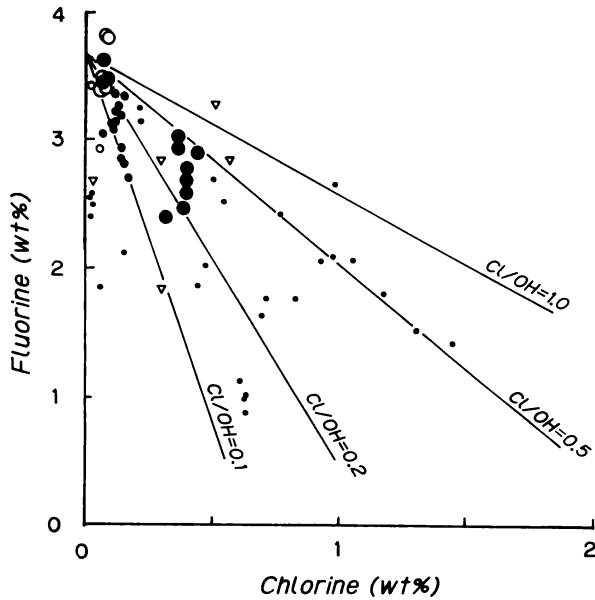   and the island arc (Panguna region) in Papua New Guinea (NEDACHI *et al.*, unpublished).

Fig. 7. Cl and F contents of apatite in the Ok Tedi mining district.
    Symbols are the same as those in Fig. 2, without the small soild circle, which is the same as that in
    Fig. 6.

reasons for the variation might be that the effect of octahedral composition of biotite was different from the evaluation by MUNOZ and LUDINGTON (1974) (e. g., hornfels), and most probably that the measurement error was too large to estimate the accurate temperature. The apatites were near the F end member, of which the error of F/OH might be very large. The biotite-apatite pair in this field might not be useful to estimate the accurate temperature. Nevertheless, the estimated temperatures suggest that the chemical compositions of these minerals have remained unchanged within its error range.

Halogen behavior in the magmatic stage: Because of the uncertainty of temperature, the f_{HF}/f_{H_2O} and f_{HCl}/f_{H_2O} ratios of liquid coexisting biotite will be discussed on the isothermal projection, 600°C. In Figs. 4 and 5, the constant fugacity ratios are also drawn, using the formulae by MUNOZ and LUDINGTON (1974), and MUNOZ and SWENSON (1981).

The magmatic biotite in the Sydney Monzodiorite and relic biotite in the Fubilan Monzonite Porphyry suggested values from $10^{-4.8}$ to $10^{-4.1}$ for f_{HF}/f_{H_2O} and from $10^{-1.7}$ to $10^{-1.6}$ for f_{HCl}/f_{H_2O} ratios. The f_{HF}/f_{H_2O} ratios were higher than those in the island arc region. The high ratio might be explained by a concentrated F through acidic magma strongly contaminated by crustal materials, as well as the incompatible elements in apatite (Fig. 6) and those in whole rocks (MASON and MCDONALD, 1978). The f_{HCl}/f_{H_2O} ratio was similar to that in the island arc region. Cl has a tendency not to concentrate in ordinary differentiated magma. Hence, the f_{HCl}/f_{H_2O} ratio in the Ok Tedi mining district might be abnormal.

Halogen behavior in the mineralization stage: The f_{HF}/f_{H_2O} ratio of hydrothermal fluid might be similar to that of magmatic stage in the Sydney Monzodiorite, but the ratio might have increased from the disseminated stage to the veining stage in the Fubilan Monzonite Porphyry. The excess F might have concentrated in the residual magma and in the emanated fluid during solidification of the magma originally rich in F. The Ok Tedi porphyry copper mineralization was also characterized by high F contents, in contrast to other porphyry copper deposits in the island arc region. The F content of rocks might be a good indicator for exploration of porphyry copper deposits in the epicontinental platform.

The f_{HCl}/f_{H_2O} ratios in the disseminated stage might be nearly the same as those in the magmatic stage of both stocks. Phlogopite in the phlogopite-quartz-apatite vein suggested a slightly higher f_{HCl}/f_{H_2O} ratios of fluid. The ratio of emanated fluid from magma had increased from dissemination to veining stages. HOLLAND (1972) simulates the removing of Cl and base metals to emanated fluid during the solidification of magma. The simulation suggests that the fluid, of which f_{HCl}/f_{H_2O} ratio increased, transports base metal effectively. The high value and its increase of the f_{HCl}/f_{H_2O} ratio might be an essential feature of the Ok Tedi porphyry copper mineralization, as is recognized elsewhere.

Biotite and apatite in hornfels suggested a low f_{HF}/f_{H_2O} ratio, but a slightly high f_{HCl}/f_{H_2O} ratio. Biotite in the xenolith in the Fubilan Monzonite Porphyry suggesed the same fugacity ratios as those of hydrothermal biotite in Fubilan Monzonite Porphyry and Sydney Monzodiorite.

Conclusion and Summary

The Ok Tedi ore deposit is an epicontinental porphyry copper system in Papua New Guinea. Biotite and apatite chemistry were examined in the study.

Magmatic biotite in the Sydney Monzodiorite had moderate $Mg/(Mg+Fe)$ of about 0.6, Si of about 5.5, and Ti of 0.4. The relic biotite in the Fubilan Monzonite Porphyry had similar $Mg/(Mg+Fe)$ and Ti to those in the Sydney Monzodiorite, with slightly increased Si from 5.5 to 5.8. The disseminated biotite near the central part of the Fubilan stock showed high $Mg/(Mg+Fe)$ (about 0.8), high Si (about 6.0) and low Ti (0.1), which is similar to the pseudomorphous hydrothermal biotite in the Sydney Monzodiorite. These data can be interpreted by differences of the temperature and/or fo_2. The temperature estimated from F-OH partitioning between apatite and biotite suggest that the halogen contents of biotite and apatite might have remained unchanged.

The f_{HCl}/f_{H_2O} and f_{HF}/f_{H_2O} ratios on isothermal projection suggest the following process of mineralization.

(1) The magma in the Ok Tedi mining district had a higher f_{HF}/f_{H_2O} ratio than those of island arc region. The contents of incompatible elements in the apatite were higher than those in the orogenic belt and island arc region. F and other incompatible elements might have been derived from the magma originated in the continental crust, or might have concentrated through acidic magmatism contaminated with crustal materials. The f_{HF}/f_{H_2O} ratio increased from the magmatic stage, through the dissemination stage to the veining stage. F was concentrated in the residual magma and in the emanated fluid, during solidification of the originally F-rich magma.

(2) The f_{HCl}/f_{H_2O} ratio is quite similar to those in the island arc region. Generally Cl has a tendency not to concentrate in highly differentiated magma or in the magma of continental origin, that is, the Cl content should be regarded as an abnormal enrichment in the Ok Tedi mining district. The f_{HCl}/f_{H_2O} had increased in the veining stages.

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