

P-T CONDITIONS AND OXYGEN FUGACITY OF THE INTRUSION EMPLACEMENT AT THE BATU HIJAU PORPHYRY COPPER-GOLD DEPOSIT, SUMBAWA ISLAND: A CONSTRAINT FROM GEOTHERMOBAROMETRIC DATA

Arifudin Idrus*

ABSTRACT

Among the southeast Asian countries, Indonesia, nowadays, has a biggest resources and production of copper and gold. The majority of copper and gold resources and production is derived from porphyry copper-gold deposits, such as Grasberg in Irian Jaya and Batu Hijau in Sumbawa Island. To enhance an understanding on the genesis and characteristics of the porphyry deposits, it is crucial to estimate the physicochemical conditions, including temperature, pressure (depth) and oxygen fugacity (fO_2) of the ore-bearing intrusions during their emplacement and crystallisation. There are many ways to estimate the physicochemical conditions, such as isotope geochemistry, microthermometric analysis of fluid inclusion and geothermobarometric analysis. In this paper, the physicochemical conditions of the causative tonalite intrusions in the Batu Hijau deposit will be constrained from the geothermobarometric data, by applying the hornblende-plagioclase and magnetite-ilmenite thermometers and the Al-in-hornblende barometer. The thermobarometers indicate that the tonalite porphyries emplace at $764 \pm 22^\circ\text{C}$ and 1.5 ± 0.3 kbar and completely crystallised at $\sim 540^\circ\text{C}$. If the pressure is assumed to be lithostatic, it is interpreted that the hornblende and plagioclase phenocrysts crystallised at depths of about 5.5 km. Log fO_2 of the magma crystallisation ranges from -20 to -12 (between NNO and HEM-MAG buffers).

INTRODUCTION

Batu Hijau is a world-class porphyry copper-deposit as defined by its position among the top ten percent of deposits in the world in contained metal abundance. The deposit is situated in southwestern Sumbawa Island, Indonesia containing mineable reserves of 914 million metric tonnes grading 0.525 % Cu (4.80 million tonnes Cu) and 0.403 g/t Au (366.98 tonnes Au) (Clode et al., 1999). The major wall-rock units consist of andesitic volcanoclastic rocks and quartz diorite intrusions. These rock units are intruded by multiple phases of tonalite porphyries, which are subsequently referred to as "old", "intermediate" and "young" tonalites. However, current exposure in the mine pit only exhibits two tonalite porphyries, i.e. intermediate and young tonalites. The copper-gold-bearing tonalite porphyries are relatively similar in their mineralogical make up, which is characterised by coexisting phenocrysts of quartz, hornblende, plagioclase, biotite and magnetite-ilmenite. The phenocrysts are set in a fine-medium grained groundmass of quartz, plagioclase and magnetite.

The chemical compositions of the cogenetic magmatic minerals, including hornblende, plagioclase, magnetite and ilmenite have been used

for estimating the physicochemical conditions, including temperature (T), pressure (P) and oxygen fugacity (fO_2) of the tonalite intrusion emplacement. To estimate the physicochemical conditions, the hornblende-plagioclase thermometer (Holland and Blundy, 1994), the Al-in-hornblende barometer (Anderson and Smith, 1995) and the magnetite-ilmenite thermometer (Buddington and Lindsley, 1964; Spencer and Lindsley, 1981; Anderson and Lindsley, 1988), were employed and will be discussed in this paper. The physicochemical conditions of the emplacement and crystallisation of the ore-bearing intrusions are very crucial, enabling the genesis of the copper-gold deposit to be better understood.

ANALYTICAL METHODS

The chemical compositions of hornblende-plagioclase and magnetite-ilmenite were analysed using a JEOL JXA-8900R Electron Micro Probe Analyser (EMPA) at the Institute of Mineralogy and Economic Geology, RWTH Aachen University, Germany. Element determinations (Si, Al, Fe_{Total} , Mg, Ti, Mn, Na, K and Cl) were carried out using a beam size of 3 μm , an accelerating potential voltage of 15 kV, a probe current of 2.5 nA, and a counting time of

* Dr.-rer.nat. Arifudin Idrus is a lecturer and researcher at the Laboratory of Mineral Resources, Department of Geological Engineering, Gadjah Mada University.

20 second for each element analysed. Matrix effects were corrected using the ZAF software provided by JEOL. The accuracy of the reported values for the analyses is 1-5 % (1σ) depending on the abundance of the element. The structural formula was calculated on the basis of 23 oxygens using 15-NK method for hornblende, 32 oxygens for plagioclase and magnetite and 6 oxygens for ilmenite.

GEOHERMOBAMETRY AND RESULTS

Hornblende-plagioclase thermometer

The hornblende-plagioclase thermometry has been calibrated using two exchange reactions (Holland and Blundy, 1994). These are:

- (1) edenite + 4 quartz = albite + tremolite
- (2) edenite + albite = anorthite + richterite.

The first exchange reaction is applied for a quartz-bearing assemblage, whereas the second reaction can be used for both quartz-bearing and silica under-saturated assemblages. The application of the first exchange reaction is restricted to hornblendes with $Na_{(A)} > 0.02$ apfu, $Al^{VI} < 1.8$ apfu and Si 6.0-7.7 apfu as well as plagioclase with $X_{An} < 0.90$. This performs well in the temperature range of 400-900°C. The second reaction should only be used in the range of 500-900°C, and under the following compositional restrictions: the hornblendes must have $Na_{(M4)} > 0.03$ apfu, $Al^{VI} < 1.8$ apfu and Si in the range of 6.0-7.7 apfu as well as the plagioclase in the range of An_{90} - An_{10} . The precision of both thermometers is $\pm 40^\circ C$ at 1-15 kbar (Holland and Blundy, 1994). The cation abundances and the allocation of ferric and ferrous iron for the hornblendes follows the calculation of Holland and Blundy (1994).

A selected young tonalite sample from the Batu Hijau deposit contains unaltered large hornblende phenocrysts up to 8 mm in length, and texturally cogenetic with plagioclase (Figure 1), biotite, quartz, magnetite and minor ilmenite. The composition of the hornblendes meets the criteria of Holland and Blundy (1994). The hornblende grains are characterised by 0.30-0.45 apfu Na, 0.17-0.35 apfu Al^{VI} and 6.9-7.2 apfu Si. The coexisting plagioclase shows a

composition varying from An_{50} to An_{30} . A total of 14 electron microprobe analyses of the adjacent hornblende and plagioclase rims are used in this calculation (Table 1). The general lack of unaltered hornblendes in the intermediate tonalite precludes the application of the thermometer.

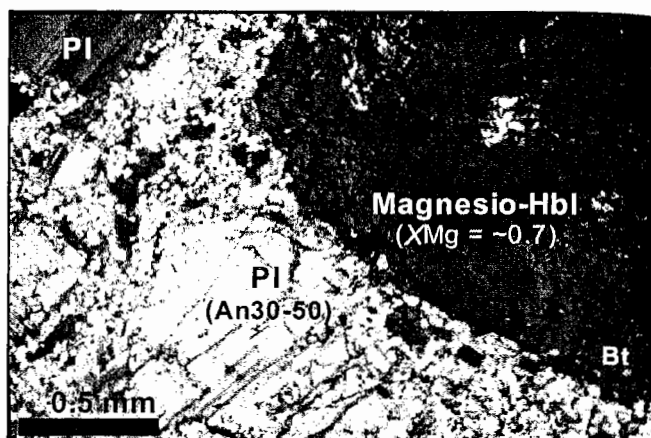


Figure 1. Photomicrograph of magnesian-hornblende (Hbl) coexisting with plagioclase (Pl) within young tonalite from the Batu Hijau deposit. Secondary biotite grains (Bt) partially replace Hbl. Mole fraction of magnesium (X_{Mg}) of hornblende is about 0.7, whereas the composition of plagioclase rims ranges from An_{30} to An_{50} .

The results of both thermometric calculations are shown in Table 1. The first geothermometer (T_1) calculated from the first exchange reaction indicates a temperature ranging from 722 to 796°C. The temperatures resulted from the second geothermometry (T_2) vary between 755 and 811°C. The T_2 is determined using the second exchange reaction. The consistently higher temperatures of the second geothermometer may suggest that the application of second thermometer is not suitable for the quartz-bearing Batu Hijau intrusions. Therefore, the first geothermometer most likely represents the equilibrium temperature (Holland and Blundy, 1994). The preferred mean temperature for the emplacement of the young tonalite is $764 \pm 22^\circ C$.

Table 1. Electron microprobe analyses of coexisting hornblende and plagioclase (rims) in a least-altered young tonalite from the Batu Hijau deposit. The results of both T_1 and T_2 thermometers are also shown.

Analysis	176-01a	176-01b	176-01c	176-01d	176-01e	176-01g	176-01h	176-02a	176-02b	176-02c	176-02d	176-02f	176-04c	176-04d
SiO ₂	48.64	48.90	48.68	48.63	49.41	47.70	49.12	47.97	48.03	47.95	47.75	47.30	48.41	48.39
TiO ₂	0.96	0.88	0.89	0.89	0.84	0.88	0.84	0.94	0.91	1.02	0.93	1.15	0.83	0.99
Al ₂ O ₃	6.89	6.92	6.82	7.05	6.68	7.08	6.43	7.02	7.13	7.32	7.02	7.69	6.50	6.81
Fe ₂ O ₃	6.42	6.29	6.97	5.15	4.95	6.06	4.89	6.20	6.41	6.15	6.87	6.59	5.75	5.42
FeO	7.29	7.53	6.42	7.21	7.28	6.34	7.01	6.40	6.37	6.31	5.51	6.04	5.95	6.09
MnO	0.59	0.58	0.76	0.59	0.61	0.63	0.69	0.65	0.63	0.71	0.71	0.80	0.87	1.01
MgO	15.91	15.81	16.10	15.58	15.95	15.81	16.42	16.08	16.01	15.84	16.30	15.67	16.28	16.06
CaO	10.16	10.28	10.70	10.34	10.28	10.29	10.18	9.97	10.09	10.44	10.27	10.34	10.60	10.79
Na ₂ O	1.45	1.50	1.11	1.45	1.44	1.33	1.22	1.49	1.54	1.41	1.40	1.43	1.13	1.15
K ₂ O	0.14	0.17	0.14	0.15	0.14	0.13	0.12	0.13	0.14	0.16	0.14	0.19	0.20	0.24
Total	97.83	98.23	97.88	96.53	97.05	95.63	96.42	96.23	96.62	96.70	96.20	96.55	95.93	96.40
<i>Structural formula based on 23 Oxygens, using 15-NK calculation method</i>														
Si ^{IV}	7.05	7.07	7.01	7.13	7.20	7.04	7.17	7.04	7.03	7.01	7.00	6.93	7.10	7.07
Al ^{IV}	0.95	0.94	0.99	0.87	0.81	0.96	0.84	0.96	0.97	0.99	1.00	1.07	0.91	0.93
Al ^{VI}	0.22	0.24	0.17	0.35	0.34	0.27	0.27	0.26	0.26	0.27	0.21	0.26	0.22	0.24
Fe ⁺³	0.69	0.67	0.75	0.56	0.53	0.67	0.53	0.68	0.70	0.67	0.75	0.72	0.63	0.59
Ti	0.11	0.10	0.10	0.10	0.09	0.10	0.09	0.10	0.10	0.11	0.10	0.13	0.09	0.11
Mg	3.44	3.41	3.46	3.40	3.46	3.48	3.57	3.52	3.49	3.45	3.56	3.42	3.56	3.50
Fe ⁺²	0.87	0.90	0.77	0.87	0.87	0.77	0.85	0.78	0.77	0.76	0.67	0.73	0.72	0.74
Mn	0.07	0.07	0.09	0.07	0.08	0.08	0.09	0.08	0.08	0.09	0.09	0.10	0.11	0.12
Ca	1.58	1.59	1.65	1.63	1.60	1.63	1.59	1.57	1.58	1.63	1.61	1.62	1.67	1.69
Na	0.41	0.42	0.31	0.41	0.41	0.38	0.35	0.42	0.44	0.40	0.40	0.41	0.32	0.33
K	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.04	0.04	0.04
Σ cations	15.44	15.45	15.33	15.44	15.43	15.40	15.37	15.45	15.47	15.43	15.42	15.44	15.36	15.37
XFe ⁺²	0.20	0.21	0.18	0.20	0.20	0.18	0.19	0.18	0.18	0.18	0.16	0.18	0.17	0.17
XFe ⁺³	0.44	0.43	0.49	0.39	0.38	0.47	0.38	0.47	0.48	0.47	0.53	0.50	0.47	0.44
XAb	0.57	0.55	0.55	0.58	0.57	0.57	0.56	0.57	0.61	0.56	0.56	0.61	0.57	0.59
T ₁ (°C)	782	780	780	731	722	765	735	778	772	776	796	780	750	743
T ₂ (°C)	803	806	794	757	760	779	761	799	785	791	811	783	768	755

Notes:

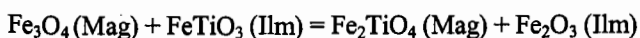
$XFe^{+3} = Fe^{+3}/(Fe^{+3} + Fe^{+2})$; $XFe^{+2} = Fe^{+2}/(Mg+Fe^{+2})$.

XAb = albite proportion of the rim of plagioclase phenocrysts in contact or in near contact with a hornblende rim.

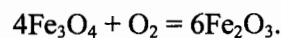
T_1 is calculated from the edenite-tremolite reaction, whereas T_2 is calculated from edenite-richterite reaction at a specified pressure. The preferred temperature values are indicated in *italic* fonts. The precision of the temperature estimates is $\pm 40^\circ\text{C}$ (Holland and Blundy, 1994).

Magnetite-ilmenite thermometer

The magnetite-ilmenite thermometer has been calibrated using the Fe-Ti exchange reaction (cf. Buddington and Lindsley, 1964; Spencer and Lindsley, 1981; Anderson and Lindsley, 1988) of the magnetite-ilmenite coexisting pair, which can be written as:



The calculation of oxygen fugacity is based on the oxidation reaction:



The least-altered young tonalite from the Batu Hijau deposit contains coexisting magnetite-ilmenite pairs. Texturally, the ilmenite lamellae are exsolved into the magnetite grains (Figure 2). Fe_2O_3 and FeO contents of the solid solution pairs are recalculated using methods of Carmichael (1967). The estimates of temperature indicate that the young tonalite crystallised at 540-590°C, with the logarithm of oxygen fugacity ($\log fO_2$) ranging from ~ -20 to -15 (Table 2).

Table 2. Representative electron microprobe analyses of coexisting magnetite-ilmenite pairs in young tonalite and the calculated temperatures and oxygen fugacity.

Magnetite						
Analysis no.	175-1a	175-2a	175-3a	175-4a	175-5a	175-6a
TiO ₂	0.33	0.13	0.32	0.25	0.22	0.07
Al ₂ O ₃	0.16	0.12	0.17	0.34	0.23	0.20
Fe ₂ O ₃ ¹	67.7	67.8	67.2	66.5	68.1	68.1
FeO ¹	31.1	30.9	30.9	30.6	31.2	31
MnO	0.13	0.10	0.10	0.07	0.22	0.11
MgO	0.04	0.02	0.03	0.06	0.02	0.04
Cr ₂ O ₃	0.06	0.05	0.09	0.03	0.02	bd
V ₂ O ₃	0.29	0.43	0.24	0.37	0.45	0.48
Total	99.8	99.5	99	98.3	100.4	100
Mol.% Usp ²	0.95%	0.39%	0.93%	0.75%	0.64%	0.20%
Ilmenite						
Analysis no.	175-1b	175-2b	175-3b	175-4b	175-5b	175-6b
TiO ₂	48.46	47.30	46.46	48.08	47.99	46.57
Al ₂ O ₃	bd	bd	bd	bd	bd	bd
Fe ₂ O ₃ ¹	5.7	9.7	11.1	7.6	7.4	12.3
FeO ¹	38.4	37.3	36.8	36.9	30.6	31.5
MnO	5.04	4.99	4.74	6.18	12.29	10.12
MgO	0.05	0.14	0.13	0.05	0.05	0.09
Cr ₂ O ₃	0.09	bd	0.02	bd	bd	bd
V ₂ O ₃	bd	bd	bd	bd	bd	bd
Total	97.7	99.4	99.2	98.8	98.3	100.6
Mol.% Ilm ²	94.12%	90.09%	88.74%	92.15%	91.66%	86.76%
T(°C) ³	539	541	590	552	562	538
log fO ₂ ³	-19.92	-17.74	-16.50	-18.46	-17.47	-15.4

Notes: ^{1,2} recalculated by methods of Carmichael (1967); ³ calculated using methods of Anderson and Lindsley (1988).

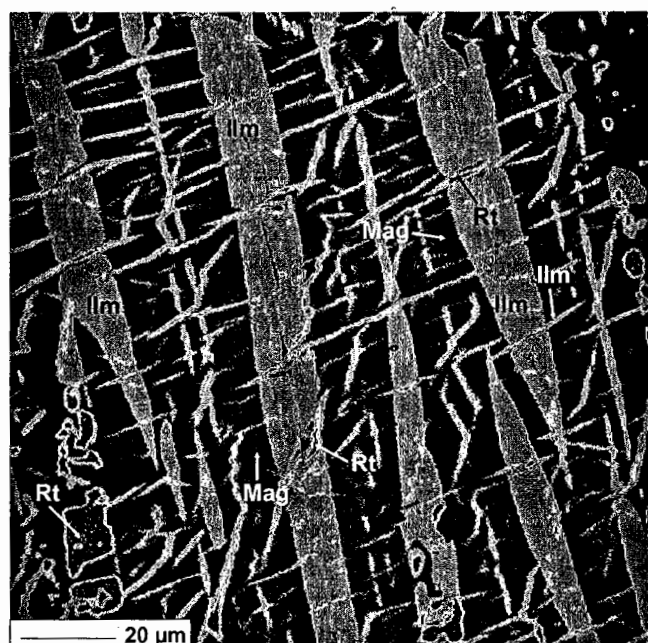


Figure 2. Electron microprobe backscatter of magnetite (Mag) coexisting with ilmenite lamellae (Ilm) within young tonalite from the Batu Hijau deposit. Rutile (Rt) replaces magnetite and ilmenite.

Al-in-hornblende geobarometer

The Al-in-hornblende barometer (cf. Anderson and Smith, 1995) potentially offers a basis for estimating the crystallisation pressure for granitic batholiths. The barometer was initially formulated on an empirical basis from the pressures determined for contact aureoles adjacent to hornblende-bearing calc-alkaline plutons (Hammarstrom and Zen, 1986; Hollister et al., 1987). The barometer has subsequently been calibrated experimentally under water-saturated conditions for the equilibrium assemblage of hornblende, biotite, plagioclase, K-feldspar, quartz, sphene, Fe-Ti-oxides, in the presence of melt and fluid from a natural tonalite (Johnson and Rutherford, 1989; Schmidt, 1992).

The Al content of the hornblende increases with pressure, following the Tschermak exchange vector, $Si^{IV} + (Mg, Fe)^{2+} = Al^{IV} + Al^{VI}$ (Johnson and Rutherford, 1989; Schmidt, 1992). The barometer is temperature-dependent. In order to determine the pressure, the temperatures obtained by the application of the hornblende-plagioclase thermometer (cf. Holland and Blundy, 1994) were used (Table 1). Anderson and Smith (1995) noted that the barometer is also sensitive

to oxygen fugacity, with low fO_2 conditions leading to an increase in Al^{VI} and a decrease in Fe^{+3} of hornblendes and anomalously high estimates of pressure. Hence, in order to avoid incorrect results, they recommended that the iron-rich hornblendes containing XFe^{+2} ($Fe^{+2}/[Fe^{+2}+Mg]$) > 0.65 and XFe^{+3} ($Fe^{+3}/[Fe^{+2}+Fe^{+3}]$) < 0.25 should be excluded in the calculation. The composition of the hornblendes in the tonalite is consistent with the criteria of Anderson and Smith (1995). The hornblendes are typically characterised by XFe^{+2} and XFe^{+3} in the range of 0.16-0.21 and 0.38-0.53, respectively (Table 1). The barometer is applicable over a range of conditions, 600 to 850°C and 1 to 10 kbar. The precision of the barometer is ± 0.6 kbar (2σ) and the temperature-dependence is about 1 kbar per 75°C at 2 kbar (Anderson and Smith, 1995). The Al-in-hornblende geobarometer equation (Anderson and Smith, 1995) is defined by the formula as follows:

$$P \text{ (kbar)} = 4.76Al_T - 3.01 - \{[T-675]/85\} \times \{0.530Al_T + 0.005294[T-675]\},$$

where T is the temperature (°C), estimated from Hbl-Pl geothermometer, and Al_T is the total number of Al-cations in the hornblende.

The barometric calculations from the first thermometer (T_1) of Holland and Blundy (1994) indicate that the pressures vary between 0.9 and 2.2 kbar (Table 3). The preferred mean pressure for the crystallisation of the Batu Hijau tonalite porphyry is about 1.5 ± 0.3 kbar. The pressure is slightly lower, compared to that of the tonalite porphyries near the Batu Hijau deposit, i.e. the Arung Ara tonalite porphyry (1.8 ± 0.3 kbar) and the Katala tonalite porphyry (2.3 ± 0.3 kbar; Garwin, 2000).

If the pressure is assumed to be lithostatic, then the depth of emplacement can be estimated. The hydrostatic pressure component is not considered to be significant during the crystallisation of the hornblende and plagioclase phenocrysts analysed. Hence, the hornblende and plagioclase phenocrysts are inferred to be crystallised at depths of about 5.5

km with, assuming 1 kbar = 3.6 km (density = 2.8 g/cm³).

DISCUSSION

P-T conditions and depth of emplacement

As described in the preceding section, the temperature and pressure estimates using the plagioclase-hornblende thermometer and Al-in-hornblende barometer indicate that the shallow crustal-level young tonalite porphyry was emplaced at $764 \pm 22^\circ\text{C}$ and 1.5 ± 0.3 kbar. The analysed young tonalite sample was taken from drill core at depth of about 1 km below current mine surface. The crystallisation depth of ~5.5 km may represent the lower level of the tonalite intrusions, which may directly contact with the tonalitic magma chamber. The estimated uplift rate for the Batu Hijau area since the time of 3.7 Ma is about 1.2 mm/yr.

On the basis of the (U-Th)/He apatite geochronometry and the geological setting, the upper part of the young tonalite was emplaced at depths of $\leq 2 \pm 0.5$ km beneath the Batu Hijau paleosurface (Garwin, 2000). The emplacement level of the top of the tonalite porphyry is relatively similar to the depth of emplacement estimated for the felsic porphyry intrusions in the Bajo de la Alumbrera, Argentina (~2.5 km; Proffett, 2003). The lower part of the young tonalite intrusion may directly contact with the corresponding magma chamber(s). It means that the paleodepth of the top of the tonalitic magma chamber(s) is inferred to be ~5.5 km. This is relatively similar or slightly shallower compared to that estimated by Garwin (2000) with a paleodepth of the top of the magma chamber(s) at about 6 km. The combined range for depths of intrusion and the magma chamber(s) is similar to that determined for the Yerington batholith in Nevada (1 to > 8 km; Dilles, 1987), the Wasatch Mountains in Utah (0.5 to 9 km; John, 1989) and Far Southeast (FSE) porphyry intrusions in Philippines (~6 km; Hedenquist et al., 1998).

Table 3 Pressures of the crystallisation of the Batu Hijau tonalite porphyries.

Analysis no.	176-01a	176-01b	176-01c	176-01d	176-01e	176-01g	176-01h	176-02a	176-02b	176-02c	176-02d	176-02f	176-04c	176-04d
T1	782	780	780	731	722	765	735	778	772	776	796	780	750	743
P1	1.1	1.1	1.1	2.2	2.0	1.6	1.6	1.3	1.5	1.6	0.9	1.8	1.5	1.8

Notes:

The pressures (P_1) are determined by the iterative application of the Al-in-hornblende barometer of Anderson and Smith (1995) and the edenite-tremolite thermometer (T_1) of Holland and Blundy (1994).

Oxygen fugacity (fO_2) of magma crystallisation

As outlined before, the magnetite-ilmenite thermometric data indicate that the oxygen fugacity (fO_2) and temperature of magma crystallisation range from -20 to -15, and 540 to 590°C, respectively (Table 2 and Figure 3).

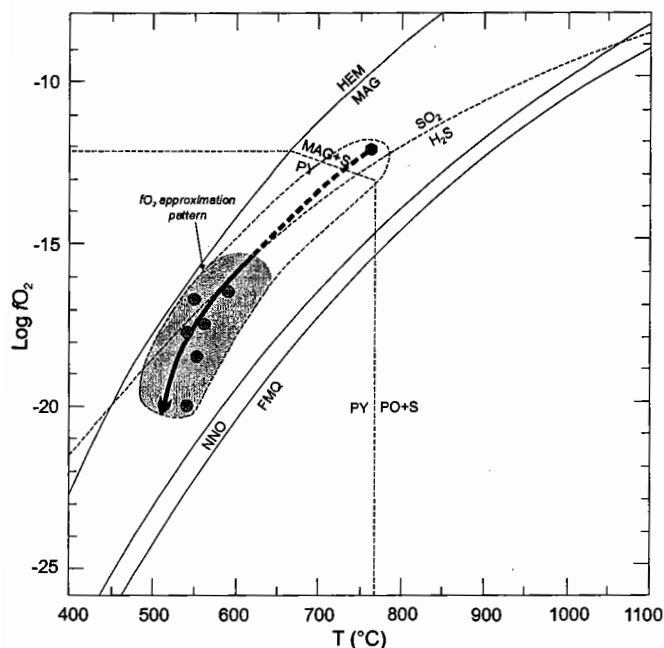


Figure 3. T-log fO_2 diagram showing the inferred magma crystallisation and cooling path of the Batu Hijau tonalite porphyries. For reference, the oxygen buffers hematite-magnetite (HEM-MAG; Chou, 1978), Ni-NiO (NNO; Huebner and Sato, 1970) and quartz-fayalite-magnetite (FQM; Hewitt, 1978) are shown. The stability fields of pyrite (PY) and pyrrhotite (PO), as defined by the reactions (not balanced with O_2) $PY = PO + S$ and $PY = MAG + S$, respectively, and the boundary between H_2S - and SO_2 -dominant fields are derived from Barton and Skinner (1967), and Ohmoto (1986).

The calculated temperatures, however, are 150°C lower than that estimated from the plagioclase-hornblende thermometer (cf. Holland and Blundy, 1994). This may be attributed to re-equilibration of magma, which led to slight change in compositions, particularly magnetite upon cooling of the crystallising magma (Candela, 1989). A single calculation of fO_2 using coexisting biotite-ilmenite-(alkali feldspar) assemblage (cf. Ague and Brimhall, 1988) has also been undertaken and yields log fO_2 of

about -12. Based on the results of the two calculation methods, it is interpreted that the log fO_2 of the magma crystallisation ranges from -20 to -12 (between NNO and HEM-MAG buffers), with a cooling path following the arrow in Figure 3. The log fO_2 of -12 is interpreted to be the oxidation state of the tonalite crystallisation at a temperature of ~764°C. The temperature of 764°C was calculated from the hornblende-plagioclase thermometer, which petrographically indicates that the biotite and ilmenite are cogenetic with hornblende and plagioclase. Hence, the estimated temperatures of crystallisation and of cooling occurred from 764 to 540°C. Garwin (2000) inferred that the average cooling rate from the solidus to ~90°C for the Batu Hijau tonalite complex is about 450°C/m.y.

The Batu Hijau magma crystallisation occurred at relatively high fO_2 condition. This is consistent with the conditions estimated for the porphyry intrusions elsewhere, e.g. Yerington, Nevada (Dilles, 1987) and Alumbrera, Argentina (Proffett, 2003). The inferred crystallisation path lies at high oxidation state, crosses from the SO_2 - to H_2S -dominant fields during cooling, and lies in the pyrite field at temperature less than about 770°C (Figure 3). Copper-iron sulphides are also stable in the pyrite field, if sufficient copper is present (Dilles, 1987). The estimated oxygen fugacity for the Batu Hijau magma crystallisation agrees well with log fO_2 for the formation of copper and copper-molybdenum in the related magmas (ranging from -20 to -12; Lang and Baker, 2001).

CONCLUSION

The application of the hornblende-plagioclase thermometer (cf. Holland and Blundy, 1994), magnetite-ilmenite thermometry (cf. Anderson and Lindsley, 1988) and Al-in-hornblende barometry (cf. Anderson and Smith, 1995) performs well in the estimates of the temperature and pressure conditions for the Batu Hijau tonalite emplacement. The thermobarometer indicates that the young tonalite porphyry emplaces at $764 \pm 22^\circ\text{C}$ and 1.5 ± 0.3 kbar and completely crystallised at temperature of ~540°C. The temperature and pressure lie above the wet tonalite solidus (Anderson and Smith, 1995; Schmidt and Thompson, 1996). If the pressure is assumed to be lithostatic, it is interpreted that the hornblende and plagioclase phenocrysts crystallised at depths of about 5.5 km, with a uplift rate of 1.2 mm/yr. On the basis of the (U-Th)/He apatite geochronometry and the geological setting, the upper part (solidus conditions) of the young tonalite was emplaced at depths of $\leq 2 \pm 0.5$ km beneath the paleosurface (Garwin, 2000).

In addition, the hornblendes in the young tonalite porphyry are typically Mg-rich with $X_{\text{Fe}^{+3}} > 0.2$. The relatively high Mg and Fe^{+3} of the hornblende compositions may reflect the high oxygen fugacity ($f\text{O}_2$) conditions, which are commonly associated with magnetite-bearing, calc alkaline igneous suites (Czamanske and Wones, 1973; Ishihara, 1981). This interpretation coincides with the estimate of oxygen fugacity using magnetite-ilmenite pairs, which indicates the $f\text{O}_2$ ranging from 10^{-20} to 10^{-15} . The high levels of the emplacement ($\leq 2 \pm 0.5$ km) and oxidising conditions (high $f\text{O}_2$) inferred for the young tonalite are supported by the presence of primary biotite and magnetite in the aplitic feldspatic groundmass.

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