Controls of copper and gold distribution in the Kucing Liar deposit, Ertsberg Mining District, West Papua, Indonesia

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Tembagapura

The "copper town" of Tembagapura is built on glacial sediments in a deeply incised valley. The town receives 8m of rain per year on average. The smaller barracks of Hidden Valley is visible at upper right and is where drill core was housed.

Mt Zaagkham

Mt Zaagkham as viewed from the core shed where drill core samples were investigated. This very impressive mountain is generally only visible in the morning before cloud cover and accompanying rain sets in for the afternoon.

Statement of Access

I, the undersigned, the author of this thesis, understand that James Cook University will make it available for use within the university library and, by microfilm or other means, allow access to users of other approved libraries.

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"In consulting this thesis I agree not to copy or closely paraphrase it in while or in part without the written consent of the author; and to make proper public written knowledge for any assistance which I have obtained from it"

The assay data made available for every drill hole in the Kucing Liar resource delineation by PT Freeport Indonesia for this research and the results of their analysis are included. However, due to the economic sensitivity of the project, the full data set is not included in this volume.

Beyond this I do not wish to place any restriction on access to this thesis.

Brian New
November 2006

Declaration

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any other university or institution of tertiary education. Where analytical work has been completed by others they have been acknowledged. Information derived from the published or unpublished work of other has been acknowledged in the text and a list of these references is supplied.

Brian New
November 2006

Acknowledgements

This research topic was originally conceived by Roger Taylor and Peter Pollard (James Cook University) and was initiated by Chuck Brannon for PT Freeport Indonesia. Steve van Nort and George Macdonald of PT Freeport Indonesia provided continued support. The company supplied transport, accommodation and provisions for multiple field visits to the mine site in addition to funds for all analytical requirements and a living allowance for a three year period. This generous financial assistance to research is gratefully recognized. Staff at the mine site who have assisted this research by way of many discussions include Peter Manning, Nur Wiwoho and Sugeng Widodo as well as Bowo Kusnanto and Noris del bel Belluz. Detailed regional and local map material was kindly provided by Keith Parris. Uttu Mekiel and Aris Sitohang continuously provided logistical assistance for drill core examination.

The (numerous) drafts, commonly unfinished, and final manuscript were assessed by Pat Williams and his assistance in thesis compilation was much appreciated. Additional comments and suggestions for improvements were also provided by Roger Taylor and Peter Pollard. I would like to thank Roger and Peter for their invaluable teaching and friendship. I would also like to extend thanks to long-standing staff of the School, Mike Rubenach, Bob Henderson, Tim Bell and more recently Pat Williams, Nick Oliver and Tim Baker for the enjoyable education I have received over the many years I have spent at JCU. Darren Mylrea, Sharon Ness and Kevin Blake from the Advanced Analytical Centre at JCU provided much appreciated analytical support for sample preparation for geochronology and isotope analysis as well as XRD and SEM analyses and interpretations.

Finally I would like to thank my family for continued support and all the friends I have accumulated while studying at JCU from 1988-2006.

Mineral Abbreviations

Ah	Anhydrite
Bn	Bornite
Bt	Biotite
Bp	Brown phlogopite
Cc	Calcite
Cp	Chalcopyrite
Cpx	Clinopyroxene
Cspy	Coarse pyrite
Ct	Chalcocite
Cv	Covellite
Cy	Chrysotile
Dg	Digenite
Do	Dolomite
En	Enargite
Fnpy	Fine pyrite
Fo	Forsterite
Gl	Galena
Gp	Green phlogopite
Gt	Garnet
Hb	Hornblende
Hu	Humite
Kf	K-feldspar
Mo	Molybdenite
Ms	Muscovite
Mt	Magnetite
Nk	Nukundamite
Pl	Plagioclase
Po	Pyrrhotite
Py	Pyrite
Qz	Quartz
Se	Serpentine
Tl	Talc
Tr	Tremolite-actinolite
Sp	Sphalerite

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Abstract

Kucing Liar is a large sediment-hosted Cu-Au mineralized system containing some 15Moz of gold and 5Mt of copper in ~500Mt of ore. It is situated in the Ertsberg Mining District in the Central Ranges of New Guinea, in the Indonesian province of West Papua. This study demonstrates that high sulphidation ore is continuous with typical porphyry-skarn style chalcopyrite ore and that both have formed from mixing of magmatic with meteoric waters within a zone of fault offset.

Alteration and mineralization were localised within calcareous shale and thinly bedded limestone adjacent to the Grasberg Igneous Complex where they are zoned around fault offsets. Early phases of alteration are stratiform and are juxtaposed against the Idenberg Fault Zone, which has displaced host stratigraphy at least 600m vertically and possibly up to ~1,500m laterally. Four principal hydrothermal mineral associations are (1) calcic and magnesian skarn, (2) potassic assemblages including magnetite, (3) quartz-muscovite plus anhydrite and (4) locally massive pyrite. Cu and Au are associated with pyrite and occur discretely either as chalcopyrite ± bornite with an association of Cu-Au-Co (Zn-Pb) or as covellite ± enargite associated with Cu-Au (As-Sb-Hg). $^{40}Ar/^{39}Ar$ geochronology shows muscovite (3.18 ± 0.02Ma) was coeval with potassic-biotite assemblages (3.18 ± 0.02Ma and 3.20 ± 0.04Ma). Calcic and magnesian skarn were derived from magmatic fluids ($\delta^{18}O_{FLUID}$ = 9-6‰), while potassic and magnetite alteration were derived from high temperature (>650°C), high salinity (>50wt%$NaCl_{EQUIV.}$) magmatic fluids ($\delta^{18}O_{FLUID}$ = 6-12‰). Quartz infill crystals associated with voluminous silicification contain a variety of fluid inclusions that range from moderate temperature (T_H<420°C) high and moderate salinity brines (35-55 and 15-30wt%$NaCl_{EQUIV.}$), to low density - low salinity vapour-rich fluid inclusions. Fluorite-hosted inclusions with lower T_H (<300°C) and salinity (~5wt%$NaCl_{EQUIV.}$) are also related to quartz alteration. Quartz alteration, muscovite and anhydrite have estimated $\delta^{18}O_{FLUID}$ ranging from 0-6‰. δD data from magnesian skarn suggest that the magma source was strongly but variably degassed during skarn formation while clustering of biotite and tremolite δD data may indicate ponding of fluids prior to exsolution, which was preceded by monzonite dyke emplacement that were emplaced during skarn and potassic stage alteration.

Fluid infiltration was controlled by an active fault system characterised by strike-slip deformation overprinting a pre-existing reverse-slip fault. Periodic slip allowed infiltration of the magmatic fluids while a complex structural offset controlled the mixing of magmatic and meteoric fluids. Fluid mixing was augmented by phase separation which gave rise to brine and vapour-rich phases that migrated differently due to density contrasts. Ore deposition was related to mixing of magmatic and meteoric fluids, which resulted in an increase in H_2S relative to SO_2, causing intense sulphidation of magnetite and precipitation of sulphides, beginning with gold-rich chalcopyrite-dominant mineralization. High sulphidation covellite-style mineralization occurred by contraction of the vapour phase that had separated from quartz-forming brines. Au, As and Sb were partitioned away from the high sulphidation copper mineralization due to higher solubilities of these metals as bisulphide complexes and deposited in distal pyrite along with chloride-complexed Pb and Zn.

Correction Notes (PhD) – Brian New

Page numbers as they appear here refer to the original review copies rather than the current edition of the thesis. This was followed as it was thought to be easier for review. Page numbers have changed through editing making the numbers presented below obsolete.

Chapter 1 – Introduction (pp1-22)

- Wilkins:
  - Sources added for figures 1-1, 1-3 and 1-4.
  - Figures 1-5, 1-7, 1-8, 1-9 and 1-10 made larger. Figures 1-8 and 1-9 clarity reduced due to printing hardware quality
- Friehauf:
  - Orientation comment added to figure 1-8
  - Names of faults added on page12
  - Legend of figure 1-9 made larger for better legibility
  - Position of Lembah Tembagah described in figure 1-9 caption
  - Clear indication of what drill holes logged in this study for figures 1-12 and 1-13
- Richards:
  - Sources added/clarified for figures 1-1, 1-3, 1-4, 1-6, 1-7, 1-9
  - Details from caption of figure 1-9 added to text on page 13
  - Typos page 1, 3, 5, 7
  - References page 1 added to list

Chapter 2 – Host Rocks (pp23-46)

- Wilkins:
  - Annotations changed in Table 2-1
  - Stratigraphic names capitalized as suggested
  - Incorrect cross reference page 37
  - Included references to plates 2-9 and 2-10
  - Removed reference to hornfels on page 44
  - Included reference to plate 2-12 in text on page 44
- Friehauf
  - Grammar page 24
  - Standard abbreviations added to table 2-1
  - Clarification page 29
  - Hatch symbols explained for figure 2-2
  - Limestone-dolostone reference in plate 2-4a
- Richards
  - Typo table 2-1
  - Clarification figure 2-1

Chapter 3 – Paragenesis (pp47-81)

- Wilkins:
    - Grammar page 47
    - Missing labels is a computer translation error (*.doc to *.pdf), labels are present in final version
    - Pyrrhotite formula page 66
    - Terminology of hornfels-alteration and prograde-retrograde addressed in section 3-2
    - The paragenesis table required by Wilkins is embedded in Chapter 7 as it did not seem logical to place the conclusions before the evidence. The paragenetic sequence is an interpretation rather than a fact and the organization in the thesis reflects this.
- Friehauf
    - Grammar and clarification page 47
    - Grammar and clarification page 48
    - Wrapping figure 3-1
    - Grammer page 54
    - Grammar and clarification page 61
    - Grammar page 67
    - Clarification page 69
- Richards
    - Missing labels is a computer translation error and are present in final version
    - Grammar page 67
    - Grammar page 78
    - Clarification page 81

Chapter 4 – Structure (pp82-109)

- Wilkins:
    - Caption added for Figure 4-2
    - Caption for Figure 4-3, 4-4 and 4-5
    - Improved Legend for Figure 4-6
- Friehauf
    - Clarification figure 4-1
    - Clarification figure 4-6
    - Clarification figure 4-9
    - Clarification figure 4-10
    - Clarification figure 4-11
    - Grammar page 108
    - Grammar page 109
    - Clarification page 109
    - References

    - Clarification page 110
    -
- Richards
    - Clarification of authors work page 83
    - Spelling Figure 4-3
    - Spelling figure 4-8
    - Clarification page 109
    - Paragraph break page 111

Chapter 5 – Mineralisation (pp110-147)

- Wilkins
    - Figure 5-17, 5-22 placement corrected
    - Last sentence page 150 removed, speculative and unsupported
- Friehauf
    - Grammar page 112, paragraph 1 and 2
    - Expanded description page 113 para 3 (middle Waripi sandstone)
    - Caption spelling figure 5-3
    - Placement figure 5-17
    - Placement figure 5-22
    - Speculative statement removed page 146 "However, data in this…."
    - Spelling caption figure 5-23
    - Note on scientific clarity page 149 "cloride-complexed" not chlorine
    - Reference Crerar and Barnes, 1976
- Richards
    - Figure labels 5-1, cross references in text pp 113-114
    - Deformation control sentence page 114
    - Grammar paragraph 2 page 114
    - Legends figure 5-2, 5-3 and 5-4
    - Annotation figure 5-2 to 5-11
    - Improved Legend Figure 5-1
    - Cross reference page 129 (figure 5-12)
    - Comment of tilting of deposit post formation page 129
    - Grammar figure 5-13 caption
    - Grammar figure 5-14 caption
    - Caption order figure 5-18
    - Cross reference page 140 (figure 5-21)
    - Cross reference figure 5-20 caption (table 5-2)
    - Grammar 1st paragraph section 5.2
    - Grammar 3rd paragraph page 145
    - Cross reference page 146 (fig 5-13 and 5-14)
    - Missing word page 146
    - Note on microgeochemical study of sulphides and gold page 146
    - Section 5.2 has been reorganized by removing paragraphs concerning other deposits in district

  - Grammar page 149
  - Reference to Seward
  - From the reading it is deduced that Richards' is actually suggesting a multivariate analysis be undertaken of element correlations. This is unnecessary as the element associations referred to are clearly evident in Figs. 5.5-5.11 and a more quantitative assessment is not required to support later discussion in the thesis

Chapter 6 – Fluid inclusions (pp148-174)

- Wilkins
  - Value changed 650 to 550, section 6.2.1
- Friehauf
  - Grammar tense, second sentence page 151
  - Clarification mineral species figure 6-3 and 6-4
  - Second image added to figure 6-6, inclusions represented by fluid inclusion type
- Richards
  - Section headings altered to properly define content
  - Issue of format translation (.doc to .pdf) for missing labels, labels are present in final version
  - Classification of inclusions, plate 6-4, 6-5 and 6-6
  - Clarity page 162 "some deeper …."
  - Page 163, clarify SLV inclusions form high relief phases
  - Figure 6-2, note on bin ranges added to caption
  - Figure 6-3, note on bin ranges added to caption
  - Ice melting by inclusion type graph added to figure 6-4
  - Salt melting graph made to individual figure 6-5
  - Notes on high temperatures page 168.
  - Sentence removed p169 "All the high….."
  - Grammar page 169 (comma inserted)
  - Alterations to opening statements section 6.2
  - Section 6.2.1 final statements removed
  - Paragraph on fluid inclusions on page 173 merged with paragenesis section, as to whether inclusions are primary, pseudosecondary or secondary
  - Rewrite of final section to consider models of fluid development from magma depth of emplacement, fluid separation and different magma sources
  - The fluid inclusions presented in the chapter have been reevaluated in terms of primary, secondary and pseudosecondary where possible and a note has been added that was not always possible to definitively assign a timing criteria to each. In addition, the definitive statements that a boiling assemblage is supported by the evidence is removed and reappraised to indicate that the observed inclusions plus homogenization temperature

data <u>may</u> support a boiling assemblage and that the weight of evidence points to a boiling assemblage.
    - In his skepticism of the high temperatures assumed for quartz deposition Richards has ignored previous data in foundation papers (Wilkins, 1974) on fluid inclusion studies that indicated temperatures of formation >700°C as well as data collected locally at Grasberg from another researcher (Harrison, 2000).
    - Standard phase change symbols have been used throughout the thesis and where they are impractical an explanation has been added to the figure caption. For examples, where all fluid inclusion data are presented in a graph relating to sample number it is not possible to identify which inclusions have homogenized vapour to liquid, liquid to vapour, or to salt. In these instances the symbol Th_{FINAL} has been used.

Chapter 7 – Stable Isotopes (pp175-193)

- Wilkins
    - Figure 7-1 and 7-3, missing labels due to *.doc to *.pdf translation
    - Figure 7-2 increased in size to fill 2 pages
- Friehauf
    - Clarified who did anlyses on opening page Chapter 7
    - Grammar section 7.1 page 176
    - Legend figure 7-1 problem with format translation
- Richards
    - Analytical people specified opening page chapter 7
    - Calcite instead of limestone opening page chapter 7
    - Grammar paragraph 1 section 7.1.1
    - Clarification of anhydrite values (del18O) page 177 para 3 section 7.1.1
    - Temperature justification figure 7-2 added end of paragraph 2 section 7.1.2
    - Correction "due to preferential fractionation…." Section 7.2 opening paragraph. Sentence removed
    - Grammar paragraph 1 section 7.2
    - Incorrect reference (Campbell and Larson, 1998) paragraph 2 section 7.2
    - Note of high water-rock ratio added to sentence 3 paragraph 3 section 7.2
    - Possibility of mixing added paragraph 3 section 7.2
    - Figure 7-4 and 7-5 labelling
    - Note "at high temperature" added to sentence 3 on section titled "magmatic exsolution processes"
    - The suggestion by Richards for reorganization of the chapter along lines of isotope rather than data and analysis seems to be a matter of personal preference as the other two examiners were quite happy with approach taken
    - Assessment of possible errors in fractionation is present in the thesis as graphs of fractionation curves showing the position of the assumed

temperature. From these graphs it is possible to guage the difference if a temperature of ±50, 100 or 150 degrees is assumed.

Chapter 8 – Geochronology (pp194-212)

- Wilkins
  - References for Mathur et al. (2000) and Mathur et al. (2005)
- Friehauf
  - Details of analytical personnel opening page Chapter 8
  - Note on word choice page 208 (indicates replaced by suggests)
- Richards
  - Repetition third sentence opening page removed
  - Analytical person clearly stated opening page chapter 8
  - Word choice page 194 (constituted replaced by consisted)
  - Figure labels page 197 file format translation (*.doc to *.pdf)
  - Grammar, section 8.1.2 (now 8.2) paragraph 1
  - Correction of age dates, section 8.1.2 (now 8.2) paragraph 2
  - Grammar, section 8.1.2 (now 8.2) paragraph 2
  - Discussion of age graphs copied from appendix to figure captions
  - Increased data on table 8-1 to include plateau and isochron ages
  -
  - Removed last sentence section 8.2 paragraph 2 to opening page chapter 8
  - Cross reference to figure 8-11 changed to table 8-3 in 1st paragraph "geochronology of the ertsberg mining district"
  - Grammar page 209

Chapter 9 – Discussion

- Wilkins
  - 1st note means as in text
  - Figure labels and cross references for figure 9-2, 9-3, 9-4 and 9-5
  - Figure 9-5 label
  - Cross reference figure 9-8 in 1st sentence-paragraph of section 9.3.2
- Richards
  - Grammar opening page Chapter 9
  - Grammar 1st paragraph section 9.1
  - Figure 9-1 caption reference and description of figure
  - Labels on Figure 4-5
  - Rearrangement paragraph 3 section 9.2.2 "the origin of…."
  - Reorder figure 9-6 and 9-7 to reflect sequence of cross references
  - Clarity paragraph 3 section 9.3.1 (economic interest and fO_2)
  - Reference and spelling Figure 9-6 (now figure 9-7)
  - Reference Figure 9-7 (now figure 9-6)

- 2nd paragraph section 9.1.2, “Fluid flow….*probably* produced”, “fluid infiltration *most likely* occurred”
- 1st paragraph 9.2.1, “Quartz alteration also…..*probably* not related….and *could be* interpreted…”
- 2nd paragraph 9.2.1 “Quartz alteration is closely….and this association *may* indicate…”
- 2nd paragraph 9.2.1 “Fluid dilution…may *also* have….”
- 2nd paragraph 9.2.1 “~~However~~, *If phase separation of hydrothermal fluids did occur* at Kucing Liar…”
- 1st paragraph 9.2.2 “Higher degrees of local water…..” is now “A higher degree of local water interaction is believed to have promoted….”
- 1st paragraph 9.2.2 “The effect of reduced temperatures in the system was *probably*…”
- 3rd paragraph 9.2.2 ” Low salinity magmatic fluids related to covellite mineralization were *circulating* at temperatures…”
- 3rd paragraph 9.2.2 “Phase separation ~~appears to have been~~ *was probably* limited…”
- Discussion and Conclusions have been rewritten taking into account uncertainties and changed interpretations as required by Richards. In many instances this relates to the interpretation of the fluid inclusion assemblage where Richards believes that not enough information has been collected to support a boiling assemblage. Discussion with others at JCU and perusal of existing literature suggests that there is a weight of evidence that supports a boiling assemblage, however, the thesis has been revised to reflect the opinion of Richards.