Skarn formation and ore deposition at the Gunung Bijih Timur (Ertsberg East) complex, Irian Jaya, Indonesia

by

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Dissertation

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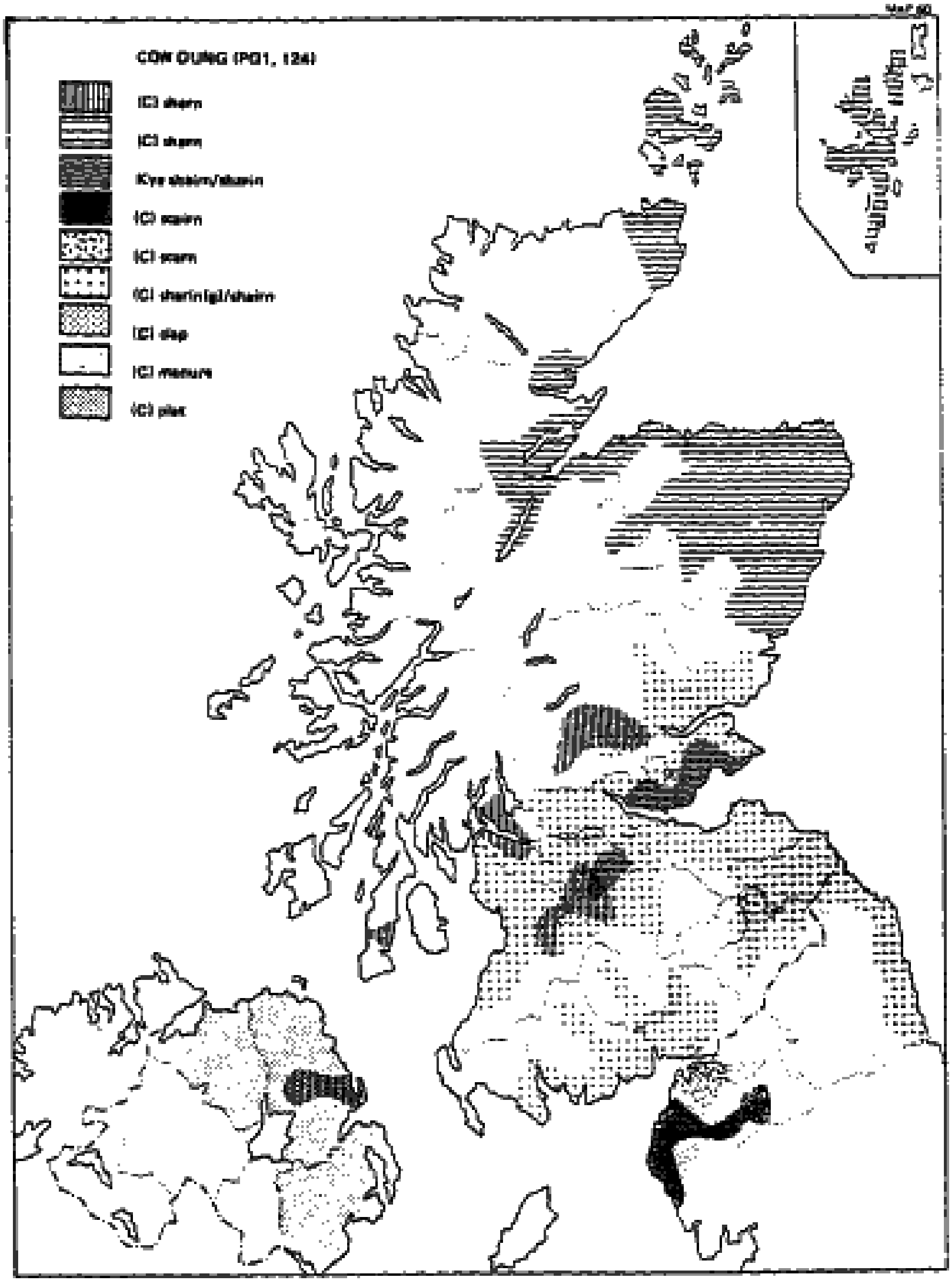

Linguistic map of Scotland showing partial speciation of the word "skarn" (Mather, 1975).

Acknowledgments

Even misery begets gratitude. It became apparent to me (and presumably to those around me) early on that this might not have been such a good idea after all. Although I unequivocally (and at great length) proved that graduate school really wasn't where I wanted to be (again), many people made life easier and/or more pleasant during this experience. Obviously this project couldn't have happened without the largess of Freeport McMoRan and its subsidiaries. CEO (and UT Geology grad) Jim Bob Moffett made this experiment his personal project and backed it with all of his considerable will. Although Jim Bob made the decision, Steve Van Nort allowed it to happen. I couldn't come close to counting the number of times that Steve helped us out (including some rather tight spots). He possesses all of the important characteristics of a fine leader: integrity, intelligence, compassion, decisiveness, and apparent imperturbability. Nice guy, too. I can't say that I feel I owe anything to UT, but I'll always feel indebted to Steve. Many of the Freeport staff in New Orleans, Cairns, and Indonesia, offered their services and support - too many to list, actually. There were several who stood out. Kris Hefton, Dave Potter, Tom Collinson, Larry Johnson, and Alan Schappert (and their families) invited us into their homes on several occasions and definitely made us

feel at home. Many others on the geology staff were there to answer questions, give tours, help locate core (no small feat). Chuck and Mary Jane Lowman, and Gene and Claudia Strouss also opened their homes to us (and they're not even geologists!). Boedijono and Rachmat Wirawan enabled me to get through DOZ in one piece (and Boedijono generously parted with some rare botryoidal bornite (gold-bearing at that) for my studies when no one else would), Uttu Mekel seemed to remember where everything was, and Ramli "Bubba" Rantung seemed to be able to smile through anything. Leo Wowiling and his crew of draftsmen patiently responded to my numerous requests for maps, sections, and diamond drill data. Yvette Gingler of Independent Mining Consultants was able to provide me with assay data and maps that no one else could. Finally, Gerry Chatham and Elizabeth Mancuso handled all sorts of details stateside and over at "Jobsite". *Terima kasih banyak.*

My dissertation committee may have been the most surprised group among anyone associated with my research when, after more than two years of near inactivity, I decided to finish (and then, five months after my defense, I finally did). Rich Kyle, my supervisor, may be the hardest working member of the UT Geology faculty. It's a lot easier for a supervisor to expect some sign of activity from his students when he's working as hard or harder than they are. With pressure on to "show results" from the Irian Jaya research, he probably was less than thrilled with my general lack of motivation (and the fact that I had a full-time job that inevitably would delay completion of my studies). Still, he provided encouragement, support (moral and logistical), and advice.

Dan Barker offered his usual blend of sagacity, dry humor (he provided the reference for the frontispiece), and practical outlook. I asked Mark Cloos to be on my committee because I had little interest in structure or tectonics, and figured that he would force me to think about some concepts that I'd otherwise avoid. Mark and I have different philosophies about the importance of geology in the life of a geologist. On the other hand, I've always been impressed by his willingness to ask questions that many would consider embarrassingly basic (how many questions have gone unasked for that reason?).

Jon Price has been a friend and mentor for more than ten years. He was my first (and best) boss at the Bureau, and one of the Bureau's few true scientists before his escape to Nevada. In the short time we spent together in my field area, he provided considerable insight and helped me formulate some basic features of my model (blame him). In fact, Jon probably prompted me more than anyone to pursue a Ph. D. (blame him for that, too). Larry Meinert came on board a bit after the rest, but brought with him a worldwide skarn perspective, a slew of references that came in handy, and good wine. Larry was the first to impart to me the true meaning of "skarn" (see Frontispiece) - I'm proud to be a skarn geologist.

Further thanks go to Jeff Horowitz, who provided invaluable assistance when I desperately needed it. Greg Thompson became a pretty fair craftsman when it came to making thin sections - the doublets he cranked out on short notice were superb. Dennis Trombatore and his able staff made the Geology Library a nice place to drop into, even when I wasn't looking for any literature. I have a hunch that if they let Geology librarians run UT, it would be a nicer (and certainly more customer-friendly) place.

My friends, although wondering why someone who voiced such an aversion to school always seemed to be *in* school, were pretty tolerant of the effects that my dissertation had on my normally sunny disposition. Phil Bennett, whom I never thought of as a faculty member (that's not an insult, Phil), allowed me to have someone to talk to about the Fire Department while I was at school, and school while I was with the Fire Department (is that good?). Phil's wife, Liz, should have been awarded her Ph. D. in listening - she does that well. Rachel Eustice and Linda Davis were two of the nicer people in the Department, and Tim McMahon, the other survivor of the original "Gang of Four", was/is one of the most intelligent people associated with the project. The quality of Tim's work guaranteed success in Phase I (and certainly made my life easier). Best of luck, Tim and Spike.

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Last but not least, my family bore the brunt of my moods, but remained supportive ("Finish it!"). My wife, Kathleen, was there when I needed her - i.e., always (even coloring a figure and pasting numbers). Suffice it to say that she will be luxuriating in Godiva chocolate for some time to come.

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The Gunung Bijih Timur (GBT - "Ertsberg East") skarn complex, Gunung Bijih (Ertsberg) mining district, was formed within the Tertiary New Guinea Limestone Group and is adjacent to the 2.9-Ma Ertsberg intrusion. The complex consists of three vertically stacked orebodies (in descending order: GBT, Intermediate Ore Zone - IOZ, Deep Ore Zone - DOZ) which total ~ 122 Mt of ore averaging 2.0 wt% Cu, 0.8 g/t Au, and 10.6 g/t Ag.

The contact between the calcareous Faumai and dolomitic Waripi Formations separates Ca±Mg skarn (GBT and much of IOZ: together the upper skarn - US) from Mg±Ca skarn (DOZ and lowermost IOZ: lower skarn - LS). The US is typified by monticellite and diopside ± forsterite. Garnet replaced earlier-formed calc-silicate minerals. The LS consists of forsterite ± diopside. Retrograde phases include tremolite-actinolite, phlogopite, talc, serpentine, and chlorite. Anhydrite increases with depth.

Minor quartz fills space. Bornite and subordinate chalcopyrite are the principal ore minerals, filling interstices in magnetite, particularly in the LS. Bornite and chalcopyrite occur in highly brecciated ore in the US. Native Au occurs as inclusions in bornite and less commonly in quartz veinlets.

Fluid-inclusion and sulfur-isotope analyses indicate that the skarn and associated orebodies were formed from predominantly magmatic waters. Hot, prograde skarn-forming fluids cooled progressively. Salinities may have increased during skarn formation. Latest assemblages formed from substantially cooler and more dilute fluids.

Sulfur isotopes yield magmatic signatures for sulfides. Anhydrite displays a bimodal distribution of $\delta^{34}S$-values, indicating igneous and sedimentary sources. Shallow emplacement and crystallization of the Ertsberg intrusion created contact-metamorphic skarn and marble. Metasomatic calc-silicate - magnetite skarn, along with Cu-Au-Ag ore, were formed by hot, saline, hydrothermal fluids from a cupola of an underlying magma chamber. Volume loss resulting from lower skarn formation led to failure of overlying rocks and dip-slip motion along a pre-existing fault, brecciating the orebodies.

GB-district Au displays generally high fineness typical of Au in porphyry/skarn systems. Native Au from the GBT complex has a wide fineness range: 920-990 and 340-820. Native Au (± Pd) from Grasberg is ≥ 930 fine, averaging half as much Cu as GBT-complex Au. Fineness of Big Gossan Au ranges from 540 to 960, and is Cu-poor. Bornite contains most of the Ag and native Au in the GBT complex. Copper and silver correlate positively throughout the GBT complex, Grasberg, and Dom.

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Abstract

The Gunung Bijih Timur (GBT - "Ertsberg East") skarn complex was formed within the Tertiary New Guinea Limestone Group and lies adjacent to the 2.9-Ma Ertsberg intrusion. The GBT complex consists of three contemporaneous, vertically stacked orebodies on the northern contact (in descending order: GBT proper, Intermediate Ore Zone - IOZ, Deep Ore Zone - DOZ), which make it one of the richest magnesian skarns in the world. At approximately 122 Mt of ore, averaging 2.0 wt% Cu, 0.8 g/t Au, and 10.6 g/t Ag, it also is the largest of several economic Cu-Au(-Ag) skarn deposits associated with the Ertsberg intrusion.

Skarn composition in the GBT complex displays strong stratigraphic control, with Ca±Mg skarn (GBT and much of IOZ - together the upper skarn) overlying Mg±Ca skarn (DOZ and lowermost IOZ - the lower skarn). The boundary between the two corresponds to the stratigraphic boundary between the mostly calcareous Faumai Formation and the dolomitic Waripi Formation. The upper skarn (US) is typified by diopsidic clinopyroxene ± forsterite, with subordinate grandite garnet and monticellite. Monticellite is most abundant at the highest elevations in the complex. Garnet replaced earlier-formed calc-silicates, and garnet skarn hosts much of the high-grade ore. Other phases include wollastonite, tremolite-actinolite, clintonite, idocrase, epidote, chlorite, and serpentine. The US is characterized by intense brecciation. The lower skarn (LS)

characterized by forsterite and diopside with rare spinel. Common retrograde phases include tremolite-actinolite, phlogopite, talc, serpentine, and chlorite. Magnetite postdates most prograde phases but predates anhydrite, forming large-scale, dense bodies of subhedral grains. Anhydrite is ubiquitous in the LS. Grayish-white, nodular anhydrite bears close textural likeness to sedimentary anhydrite in the Waripi Formation, and purple space-filling anhydrite appears hydrothermal in origin. The anhydrite:carbonate ratio increases markedly with depth throughout the complex, and the Ca:Mg ratio in silicates and carbonates decreases with depth. Minor quartz fills veins and lines vugs.

Bornite and subordinate chalcopyrite are the principal ore minerals in the complex, commonly filling interstices in large-scale magnetite deposits, particularly in the LS. Chalcopyrite is more abundant, relative to bornite, in the US, where both minerals occur in highly brecciated ore. Native gold (average composition $Cu_{01}Au_{85}Ag_{14}$ by weight) occurs mainly as < 10-µm inclusions in bornite and less commonly as space-fill in quartz veinlets. Molybdenite and several Bi minerals form < 5-µm inclusions in bornite and other phases. Digenite and chalcocite/djurleite are common alteration products; covellite and idaite are most common in and near breccia and fault zones.

Vertical zonation is better-developed than horizontal zonation. The ratios Ca:Mg and carbonate:sulfate decrease with increasing depth, and Cu:Fe increases with increasing depth, as do grades for Cu, Au, and Ag.