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Paterson, J.T. and Cloos, M., 2005 - Grasberg Porohyry Cu-Au Deposit, Papua, Indonesia: 1. Magmatic History; *in Porter, T.M. (Ed.), Super Porphyry Copper & Gold Deposits: A Global Perspective*; PGC Publishing, Adelaide, v. 2, pp 313-329.

GRASBERG PORPHYRY Cu-Au DEPOSIT, PAPUA, INDONESIA: 1. MAGMATIC HISTORY

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Abstract - The Grasberg Igneous Complex, which formed at ~3 Ma, is host to one of the largest copper and gold porphyry-type ore deposits discovered on Earth. This study focuses on the magmatic characteristics of the three main phases of intrusion at the level of the open pit mine: the Dalam, subdivided into the Dalam Andesite, Dalam Volcanic and Dalam Fragmental, the Main Grasberg Intrusion (MGI), and the Kali (Early and Late). A sample suite consisting of 225 polished slabs and thin sections shows all units contain plagioclase and biotite as the dominant phenocryst phases. The Dalam Andesite, MGI and Late Kali contain(ed) hornblende as well. The Late Kali and the MGI also contained minor amounts of clinopyroxene. Apatite is ubiquitous as a trace phase. Magmatic magnetite is identifiable in the Late Kali. The magmatic groundmass in the Kali, MGI, and Dalam Andesite was potassium feldspar, albitic plagioclase, quartz and biotite. A similar groundmass assemblage probably existed in the other Dalam phase rocks, but hydrothermal alteration caused complete replacement. The phenocryst assemblages record no profound changes in magma chemistry over time, but the parent chamber was probably recharged at least twice, and possibly many times.

The porphyritic Dalam Andesite, comparatively equigranular MGI, and porphyritic Kali units are texturally distinct. The Dalam Volcanic and Dalam Fragmental units are, respectively, polymict and monomict matrix-supported breccias, typically containing 5% to 10%, but locally up to 30% clasts. Broken phenocrysts are common in the Dalam phase rocks. Dalam phase magmas only became volatile-saturated and explosive when intruded to near the surface. The monomict fragmental unit formed near the centre and the polymict volcanic unit along the edges. The geologic setting is interpreted to be a maar caldera. The MGI passively intruded as a cone shaped plug into the still hot core of the Dalam. The volumetrically minor Early Kali appears to be a small plug into the centre of the MGI whereas the Late Kali is a large wedge-shaped dyke that cuts all units.

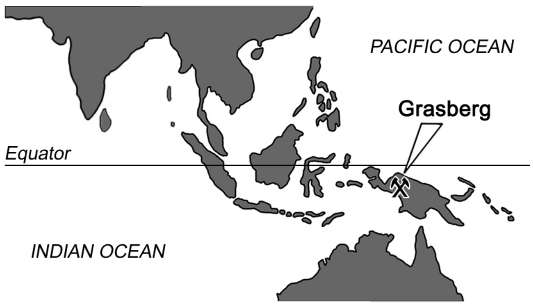
Introduction

The Grasberg Igneous Complex (GIC), located in the Ertsberg (Gunung Bijih) Mining District (Fig. 1), is situated in the western half of the island of New Guinea, the Indonesian province of Papua (formerly Irian Jaya). In both areal extent and volume the GIC is limited, with a pre-mine surficial footprint of less than 3 km^2. Ore-grade mineralisation extends to a depth of more than 2 km. Notable about the Grasberg is the quantity of hypogene ore, both disseminated and vein-hosted and a lack of significant supergene enrichment. Currently producing roughly 6% of the world's copper supply, as well as containing significant quantities of gold, this copper-gold porphyry system is one of the most extraordinary mineral systems on Earth. Production since 1989 occurs as open pit mining with underground operations by block caving to begin in 2014. The projected mine life is at least 45 years. The deposit contains more than two billion tonnes of ore grading an average 1 wt. % copper and 1 gram per tonne gold.

Regional Setting

The rocks into which the GIC and other intrusions within the Ertsberg District were intruded are Mesozoic and Cenozoic passive-margin strata deposited on the northern margin of the Australian continent (Martojojo *et al.,* 1975; Dow *et al.,* 1988). The oldest unit cropping out in the district is the Kembelangan Group (Cretaceous), a siliciclastic sequence which underlies the New Guinea Limestone Group (Quarles van Ufford, 1996). Most of the mineralisation in the district is spatially associated with the largest plutons: the Ertsberg and Grasberg intrusions.

The island of New Guinea is largely composed of passive margin strata that were "bulldozed" during continental margin-oceanic forearc collisional orogenesis into a spectacular mountain belt, the Central Range, whose maximum height is found next to the Ertsberg District at Puncak Jaya (4884 m) (Hamilton, 1979; Dow *et al.,* 1988). Quarles van Ufford (1996) proposed the Cenozoic tectonic history of the island is the product of two collisions; an earlier event, the Oligocene "Peninsular orogeny" affected only the eastern part of the island whereas the latest Miocene event, the "Central Range orogeny," created most of the mountainous topography that forms the spine of the island. Near the Ertsberg district, the southern slope of the Central Range is the northern limb of a giant fold, the Mapenduma anticline (Nash *et al.,* 1993). Owing to this structure, which is cored in outcrop by Precambrian slates, the access road from the southern portion of the district to the Ertsberg district contains a nearly continuous stratigraphic record capped by the aforementioned New Guinea Limestone Group. The Central Range orogeny in western New Guinea is bracketed in age by carbonate shelf deposition continuing until at least 15 Ma, and the change to siliciclastic deposition at approximately 12 Ma, which marks the beginning of "unroofing" related to Central Range development (Quarles van Ufford, 1996; Quarles van Ufford and Cloos, in press). Igneous activity associated with collisional tectonism dates between 7.1 and 2.5 Ma (O′Connor *et al.,* 1994).



Within this regional context, several investigators have studied the specifics of the geologic history of the greater Ertsberg District and, particularly, the Grasberg Igneous Complex.

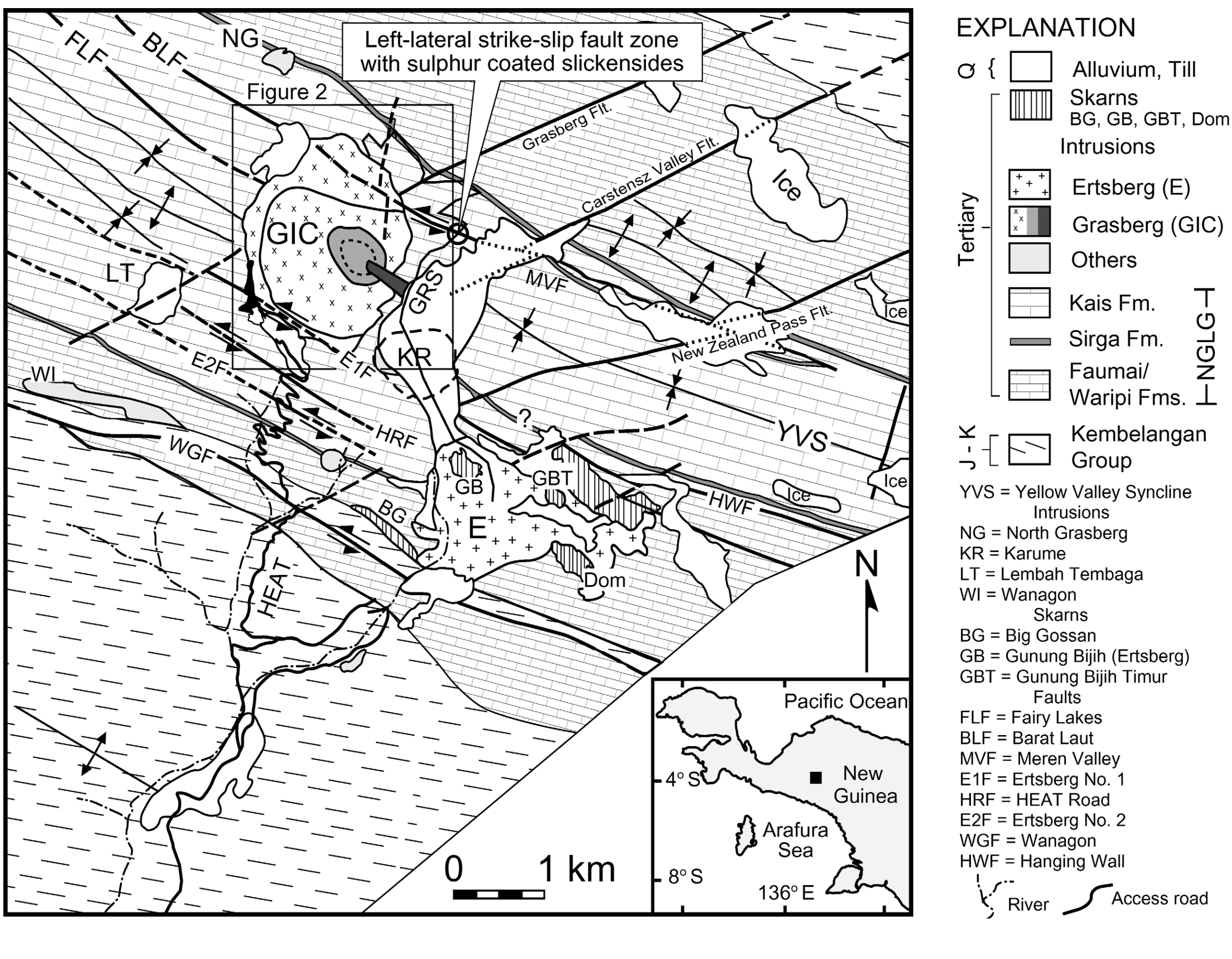
Previous Work

Geology of the Ertsberg District

The first descriptions of the geology of the area are those of Dozy (1939) who prepared them at the behest of Royal Dutch Shell, his employer. This report contained descriptions of the Ertsberg pluton and associated copper skarn mineralisation that led to the exploration and development of the district (Wilson, 1981). Work carried out by PT Freeport Indonesia (PTFI) exploration and mine geologists on the igneous rocks, ore deposits, stratigraphic and structural relationships of the district led to the 1988 discovery that a giant ore deposit underlay the Grasberg, a large grass covered rounded hill peaking at 4200 m (Mealy, 1996; Potter, 1996).

The geology of the Ertsberg district has been mapped in great detail by the PTFI geological staff (Fig. 2). Petrologic studies by McMahon (1994a) delineated 16 Pliocene intrusions. McDowell *et al.,* (1996) reported 13 K-Ar ages that indicate magmatic activity in the district ranged from

Figure 1: ***Geologic map of the Ertsberg Mining District, Papua, Indonesia.***



4.4 to 2.6 Ma. Most of the intrusions are dykes, sills or plugs with areas of outcrop ranging from a few to several hundred square metres. The Ertsberg and Grasberg are the largest plutons with areas of a few square kilometres. These intrusions have similar chemistries, but the Grasberg is largely porphyritic whereas the bulk of the Ertsberg is equigranular. The mineralogy is dominated by plagioclase, biotite and hornblende with some of the intrusions additionally containing clinopyroxene and small amounts of magnetite and sulphides (McMahon, 1994a, b, c). The potassium contents of intrusives in the district are bimodal, with one population (which includes both the Ertsberg and the Grasberg) of "high-K" latites, trachydacites and trachytes, and the other (small dykes, sills and plugs) composed of "low-K" andesites and dacites.

Pb, Nd, and Sr isotopic analysis (Housh and McMahon, 2000; James *et al.,* in prep.) indicates that the intrusions in the Ertsberg District are the product of a two-stage evolution of mantle-derived magmatism: i) intrusion and ponding in the deep crust with significant chemical modification from assimilation of Precambrian wallrock, and ii) emplacement into the shallow crust and sedimentary cover with minimal chemical modification from interaction with the wallrock. McMahon (1999) proposed that the equigranular texture of the Ertsberg pluton is the result of near-surface intrusion of an ~ 20 km^3 mass of phenocryst-poor melt. The scarcity of hornblende and presence of clinopyroxene is a manifestation that most of the crystallisation occurred at low pressure. In contrast, the GIC was emplaced as several small pulses of "crystal-rich" (20 to 40% phenocrysts) magma totalling a few cubic kilometres. Hornblende is common because deep-seated (several kb) crystallisation was substantial.

Two distinct styles of mineralisation are present in the district: i) skarn and ii) porphyry copper-type systems. The former, typified by mineralisation near the Ertsberg pluton (Dozy, 1939; Katchan, 1982; Soeparman and Budijono, 1989; Mertig *et al.,* 1994; Rubin, 1996; Meinert *et al.,* 1997; Coutts *et al.,* 1999) are Cu-Au skarn orebodies that formed as a result of extensive hydrothermal reaction of magmatic

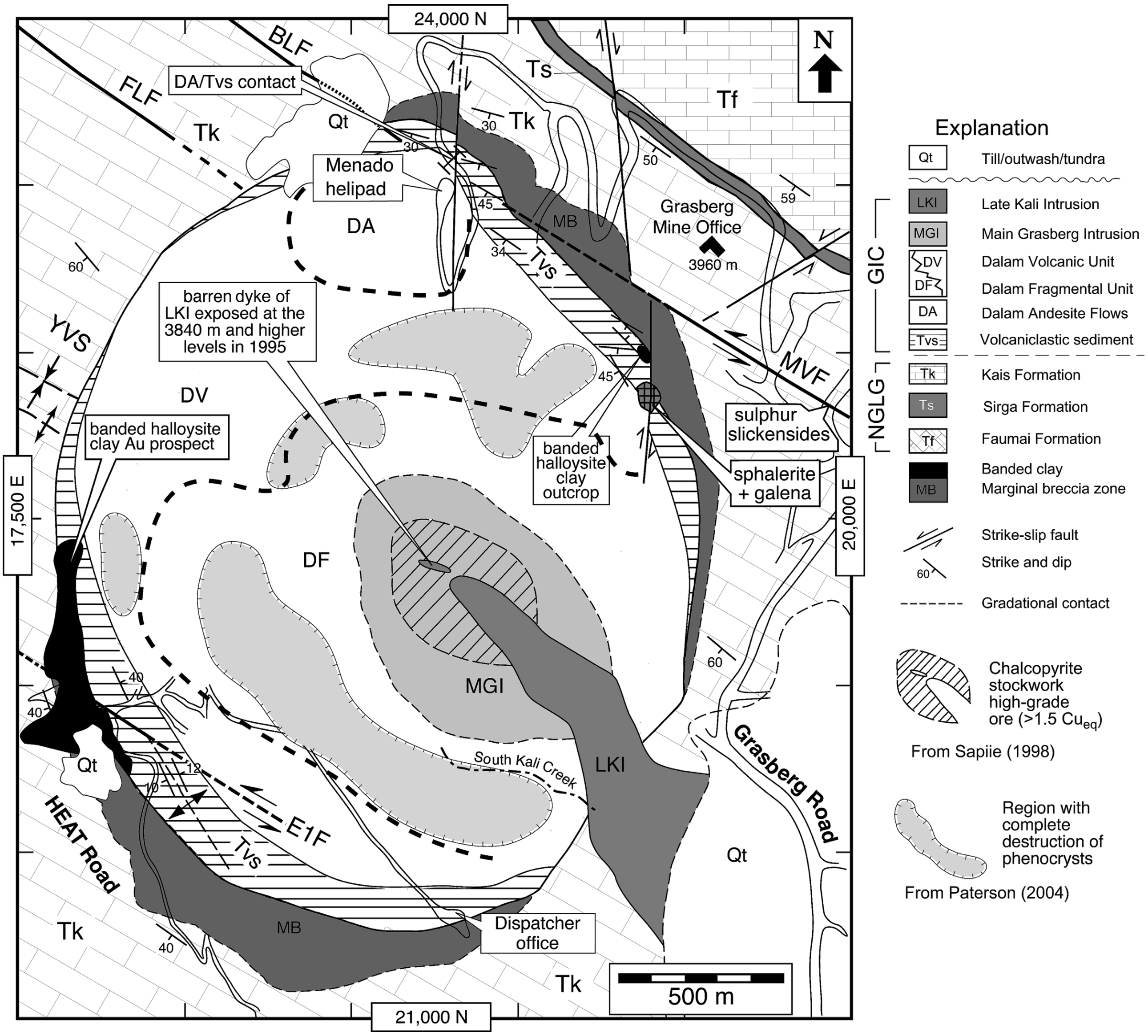


Figure 2: ***Geology of the Grasberg Igneous Complex (GIC) at the ~3900 m elevation.*** Modified from Suwardy (1995) and Sapiie (1998). The Meren Valley Fault (MVF) and Ertsberg #1 Faults (E1F) are left-lateral strike-slip faults. Sapiie (1998) concluded the GIC was emplaced into a pull-apart connecting these fault zones.

fluids with the host carbonate rock. An important Cu-Au skarn, Kucing Liar, is near the Grasberg (Widodo *et al.,* 1999). Ore mineralisation in the district is, however, dominated by the porphyry copper-type Grasberg system. The deposit, which appears to have many geologic similarities to the classical copper porphyries of the American Southwest (Beane and Titley, 1981; Titley, 1982), formed via large scale fluid invasion.

Geology of the Grasberg Igneous Complex (GIC)

Van Nort *et al.,* (1991) presented the first general description of the Grasberg system. MacDonald and Arnold (1994) published the first detailed descriptions of the three-dimensional geometry of the GIC as well as an igneous history of three distinct phases of magmatism. The GIC is an upward flaring funnel-shaped body that is about 800 m wide at 3000 m elevation and 2000 wide at 4000 m (Fig. 3). The earliest magmatic phase, the Dalam, was followed by the Main Grasberg Intrusion (MGI) and, finally, the Kali phase. K-Ar ages obtained by McDowell *et al.,* (1996) on very fresh samples from the Grasberg, range from 3.2 to 2.8 Ma. Pollard *et al.,* (2001) reported Ar-Ar ages for Grasberg samples in the range of 3.33 to 3.02 Ma. The Dalam remains undated.

MacDonald and Arnold (1994) classified the Dalam into an assemblage of rocks they called the Dalam Diatreme, including within it two principal phases, both of which are fragmental intrusive breccias: i) an upper andesitic phase, and ii) a lower dioritic phase. On the margins, they differentiated a bedded volcanic unit (Tvs) and a unit of coarse andesite porphyry flows cut by dykes and sills, the Dalam Andesite. Clasts of these units are found in the Dalam Volcanic. They concluded that a major episode of pervasive alteration and disseminated Cu-Au mineralisation occurred in the Dalam that pre-dated the intrusion of the MGI.

At pit levels, much of the MGI is intensively veined by quartz and magnetite forming a stockwork. The MGI is distinguished from the Dalam by the coarse, relatively equigranular textures and a near lack of fragments. MacDonald and Arnold (1994) and subsequent workers all agree the MGI was passively emplaced as a plug into the centre of Dalam phase rocks. MacDonald and Arnold (1994) state that a second major episode of Cu-Au mineralisation was post-MGI and pre-Kali emplacement. This event caused moderately intense alteration and ore mineralisation that was largely veinlet-hosted.

MacDonald and Arnold (1994) report that the Kali phase rocks are a nest of porphyritic dykes, with plagioclase phenocrysts and hornblende comprising 35% to 70% of the rock volume, 5% biotite phenocrysts and 1% to 2% disseminated magnetite set in a finer groundmass of quartz, feldspar and biotite. They report at least two phases of Kali magmatism: one predating or contemporaneous with limited veinlet mineralisation and a later phase, essentially barren of economic mineralisation. McMahon (1994a), in his petrographic observations on the freshest Kali samples, found clinopyroxene, partially altered to actinolite, at a maximum of 5% by volume.

A fundamental question for understanding the magmatic history of the GIC is the physical means of pluton emplacement. As the phrase Dalam Diatreme implies, MacDonald and Arnold (1994, p. 149) hypothesised that the Dalam phase of magmatism included an explosive gas-driven, space-generating eruption. Forceful ejection of sedimentary rock was invoked to explain the funnel-shaped profile of the GIC. The petrographic analysis in the present study found no pieces of sedimentary wall rock (xenoliths) in any part of the GIC. Furthermore, Pb, Sr, and Nd isotopic signatures of the host rocks and the intrusions in the district are very distinct (James *et al.,* in prep.). For the GIC in

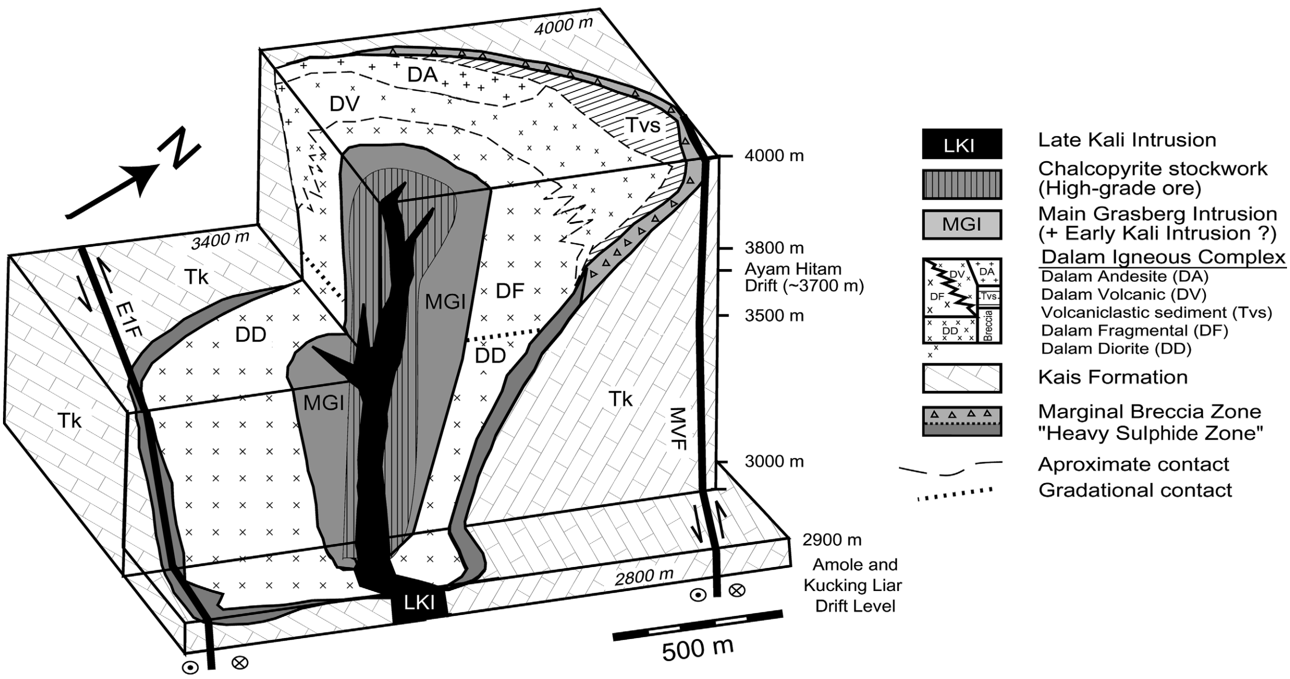


Figure 3: ***Schematic block diagram of the Grasberg Igneous Complex (GIC).*** Modified from MacDonald and Arnold (1994) and Sapiie (1998).

particular, and across the district in general, remarkably little isotopic evidence has been detected that indicate the magmas chemically interacted with the sedimentary wall rock column that extends to depths of 10 to 15 km. Emplacement models which invoke any phase of magma generating space by assimilating near-surface wall rock are not plausible.

McMahon (1994a) was the first to speculate that the emplacement of the GIC was fundamentally controlled by space-generating tectonic movements rather than the pressure of intruding magma. The critical study was that of Sapiie (1998), who discovered abundant evidence for strike-slip faulting near and in the GIC. He concluded the fundamental control for Grasberg intrusion and mineralisation involved a dilatational jog, or pull-apart, between two 300° trending, left-lateral strike slip faults (E1F and MVF on Figs. 2 and 3) (Sapiie and Cloos, 2004, in review).

Sapiie (1998) also concluded the marginal breccia that encircles the GIC at outcrop levels was the product of a large amount of solution/collapse of carbonate wall rock by acidic magmatic fluids. With this realisation, it became apparent that the origin of the funnel shape of the GIC has another explanation. The University of Texas investigators replaced the general term Dalam Diatreme with purely descriptive names: the Dalam Andesite (DA), a sequence of thick, massive porphyritic flows, perhaps once forming an extrusive dome, the Dalam Volcanic (DV), a polymict breccia, and the Dalam Fragmental (DF), a monomict breccia. The sub-surface part of the Dalam (not part of this study), which is more equigranular and has few clasts, is the Dalam Diorite. This nomenclature is used in this study.

The abundance and diversity of clasts in the Dalam Volcanic and Dalam Fragmental units is highly variable. At the ten metre scale, clasts commonly form 5% to 10% of the rock volume, but locally occur in abundance up to about 30%. Most clasts are rounded to subrounded indicating significant movement after fragmentation. The inner boundary of the DV is mapped based upon the last occurrence of polymict breccia (Fig. 4). The inner boundary of the DF with the MGI is mapped based upon the last occurrence of monomict breccia. The contacts are gradational, in that parts of the DV are monomict, and parts of the DF lack clasts. Despite intensely pervasive alteration, outlines of replaced clasts are commonly quite distinct. In the open pit mine benches, the boundaries between these map units were typically localised within distances of several tens of metres. Indistinct contacts are explainable as the result of magma intruding still hot rock.

Sapiie (1998) concluded the Dalam phase magmas intruded to less than ~1 km depth prior to water saturation and explosive auto-fragmentation. He concurred with MacDonald and Arnold (1994) who concluded that the Dalam was emplaced in a setting of low relief, a maar volcano. The DF, which formed in the centre, is probably largely an intrusive unit, whereas the DV is probably largely extrusive. For explosive fragmentation to have only

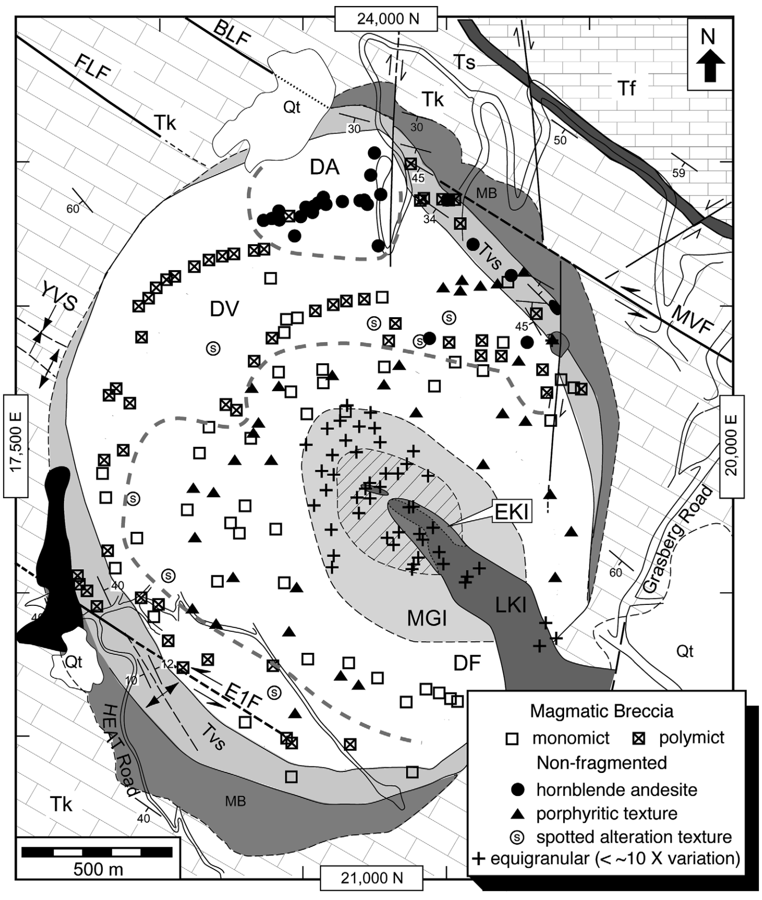


Figure 4: ***Brecciated and non-fragmented hand specimens.*** See Figure 2 for explanation of map abbreviations.

occurred at shallow depths, the volatile content of the magma must have been modest, about 2 wt.%. In this interpretation, the rise of the Dalam-phase magma was also relatively passive, except very near the surface.

Porphyry copper deposits, of which the GIC is a supergiant example, have a distinctive mineralogic zonation of alteration that results from pervasive fluid flow. This pattern is most easily explained as alteration by magmatic fluids emanating from a point source - a fluid-charged cupola at the top of a solidifying stock (see Cloos, 2001). This paper concerns the magmatic mineralogy of the GIC based upon the analysis of a suite of 225 hand specimens that were prepared into polished slabs and thin sections. The Grasberg was a hill and the samples were collected in the open pit mine between 1994 and 2002 and at elevations between 3700 m and 4200 m. Most samples are from the elevation interval of 3800 m to 4100 m. The sample suite is the basis for constructing a set of maps that depict mineralogic and textural variations in the GIC at the ~3900 m level. An accompanying paper (Paterson and Cloos, this volume) concerns the effects of pervasive alteration in the sample suite by diffuse fluid flow.

No volcanic deposits extend beyond the mapped limits of the GIC (Fig. 1) as would be expected if the Grasberg deposit were to underlay a 2 or 3 km tall composite volcano. A small part of the GIC consists of bedded, water-lain volcaniclastic sediments (the Tvs) along the northeast and southwest edges (Fig. 2). The most diagnostic evidence of only shallow burial comes from the presence of small areas of contorted, gold-bearing halloysite clay, the "banded clay unit," on the southwest and northeast sides of the GIC (Fig. 2). These deposits are remnants of a once extensive field of boiling mudpots. It is believed that the sample suite in this investigation was located at positions that were less than 1 km, most probably several hundred metres, from the surface at the time of mineralisation.

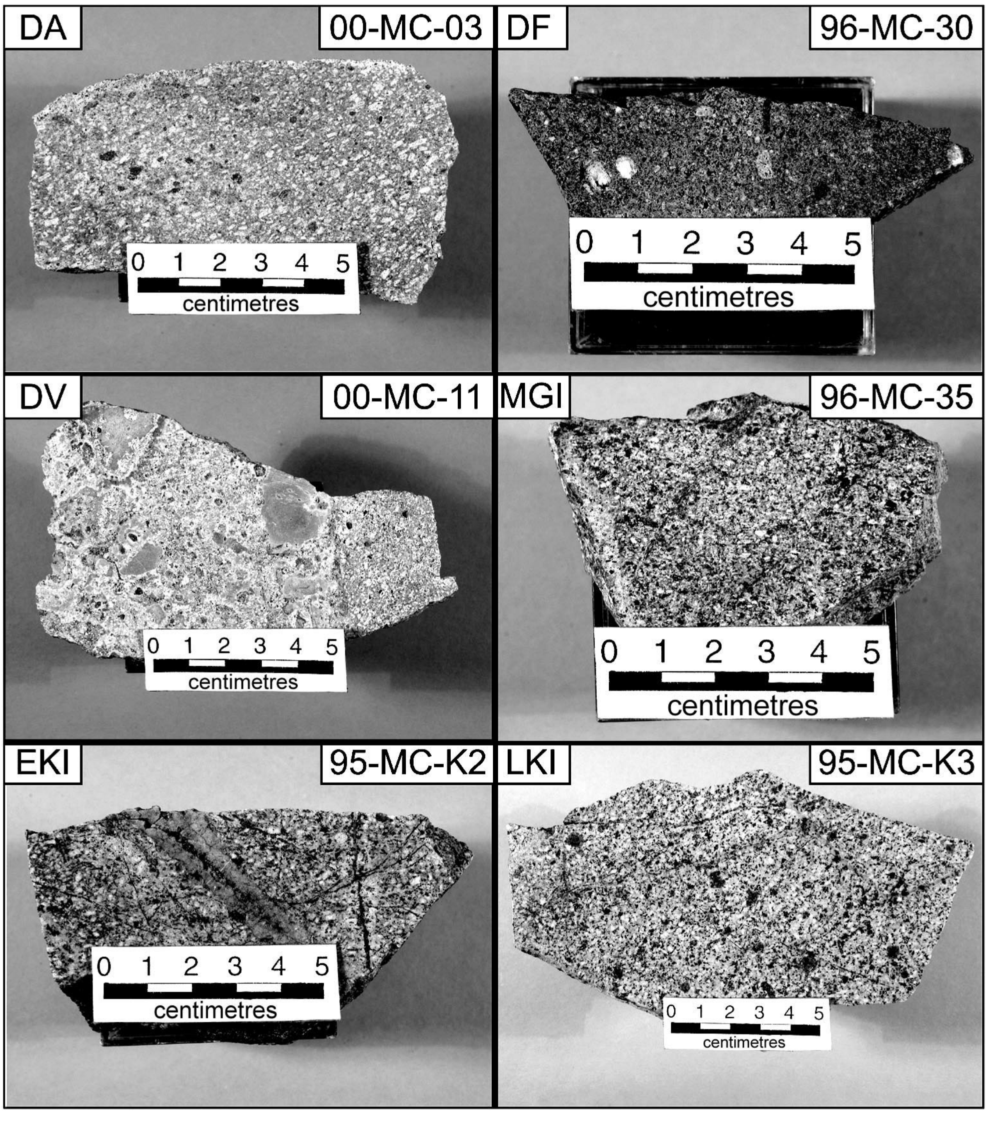


Figure 5: ***Representative polished slabs of igneous units in the Grasberg Igneous complex.*** DA = Dalam Andesite. DF = Dalam Fragmental. DV = Dalam Volcanic. MGI = Main Grasberg Intrusion. EKI = Early Kali Intrusion. LKI = Late Kali Intrusion.

Magmatic Mineralogy of the GIC

The magmatic mineralogy of each igneous unit must be characterised to gain insight into the evolution of the parent magma chamber and to fully recognise the effects of fluid infiltration and pervasive alteration. Samples from across the GIC vary greatly in their degree of textural reconstitution. In some parts of the deposit, all igneous minerals and textures are destroyed. This report centres on the analysis of the freshest examples of each igneous unit. One point is evident from even casual hand-specimen observations; most of the Kali phase rocks, even from the centre of the GIC, are relatively unaltered when compared to the Dalam and MGI phase rocks. Photographs of polished slabs of "fresh" examples from each igneous unit are shown in Fig. 5.

Plagioclase Phenocrysts

Plagioclase is the most obvious and volumetrically abundant phenocryst in fresh to moderately altered rocks. Representative thin-section examples of plagioclase phenocrysts are shown in Fig. 6. Abundances typically

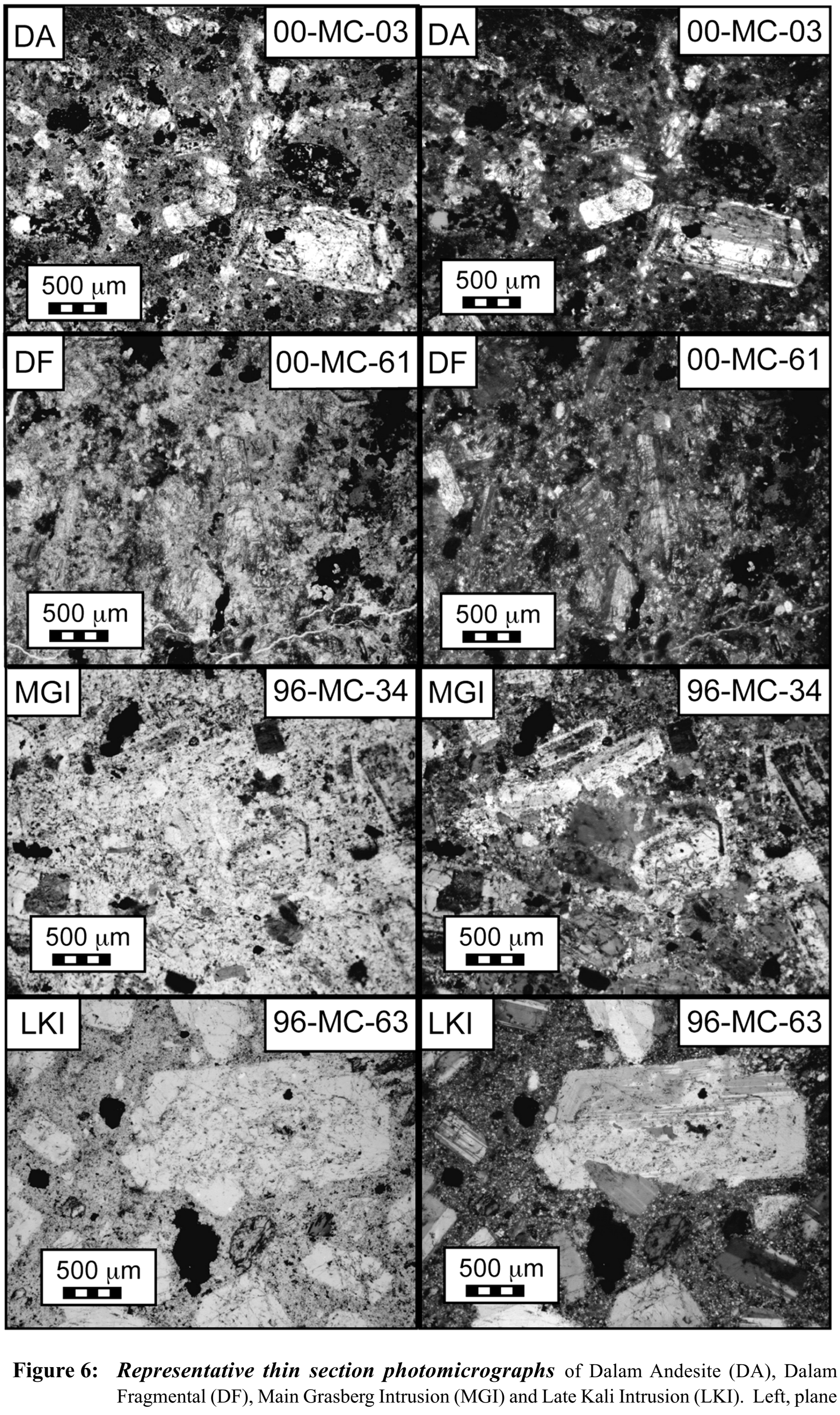


Figure 6: ***Representative thin section photomicrographs*** of Dalam Andesite (DA), Dalam Fragmental (DF), Main Grasberg Intrusion (MGI) and Late Kali Intrusion (LKI). Left, plane polarized light. Right, cross polarized light.

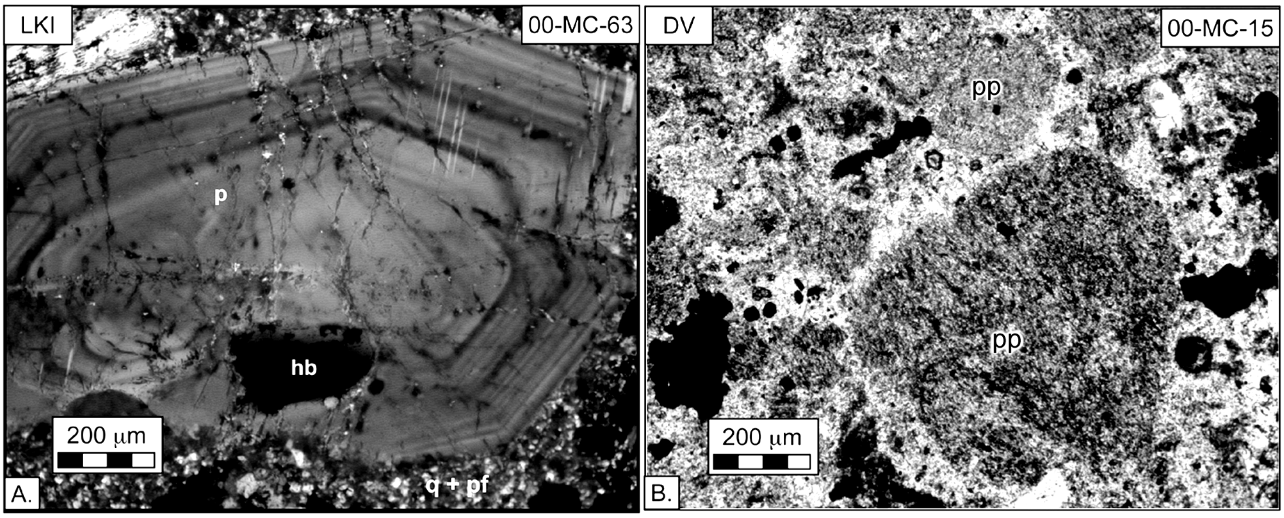


Figure 7: A. ***Plagioclase phenocryst with oscillatory zoning in the Late Kali Intrusion.*** p = plagioclase. hb = hornblende.
B. ***Plagioclase phenocryst replaced by sericite in Dalam Volcanic unit.*** pp = plagioclase pseudomorph.

range from 10% to as much as 50% of the volume of the rock, although alteration has locally caused complete destruction of plagioclase phenocrysts. The DA has a range from approximately 10% to a maximum of 35% by volume, the DV and DF range from 0% (because of alteration) to 45%, commonly approximately 20%. The abundance of plagioclase phenocrysts in the MGI ranges from 20% to 40% and those in the Kali range from 20% to 65%. Fresh plagioclase phenocrysts, which are abundant in the Kali, are strongly oscillatory-zoned (Fig. 7a). Many of the larger phenocrysts in the fresher samples have distinct core zones that indicate a cessation in growth or resorption.

Two features are apparent from the distribution of plagioclase phenocrysts (Fig. 8). In the Kali, MGI and DA units, relict plagioclase phenocrysts are commonplace, but in the DV and DF units, many samples only contain pseudomorphs (Fig. 7b) and in some areas clusters of samples lack any evidence for the former presence of any magmatic phases (plagioclase, biotite, or hornblende). The largest area with complete textural destruction covers approximately 250 x 1300 m in the DF in the southwestern part of the complex (Fig. 8). Pseudomorphs of plagioclase phenocrysts are typically almost entirely composed of hydrothermal biotite in the interior, and sericite in the exterior part of the complex.

A subtle, but distinctive attribute of the GIC that was discovered during petrographic analysis is the distribution of broken plagioclase phenocrysts (Fig. 9). Broken

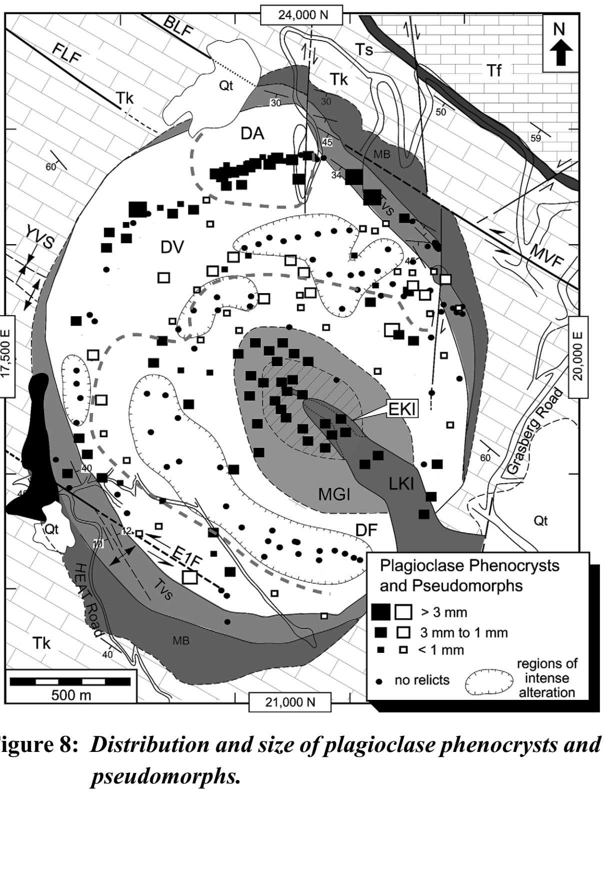


Figure 8: ***Distribution and size of plagioclase phenocrysts and pseudomorphs.***

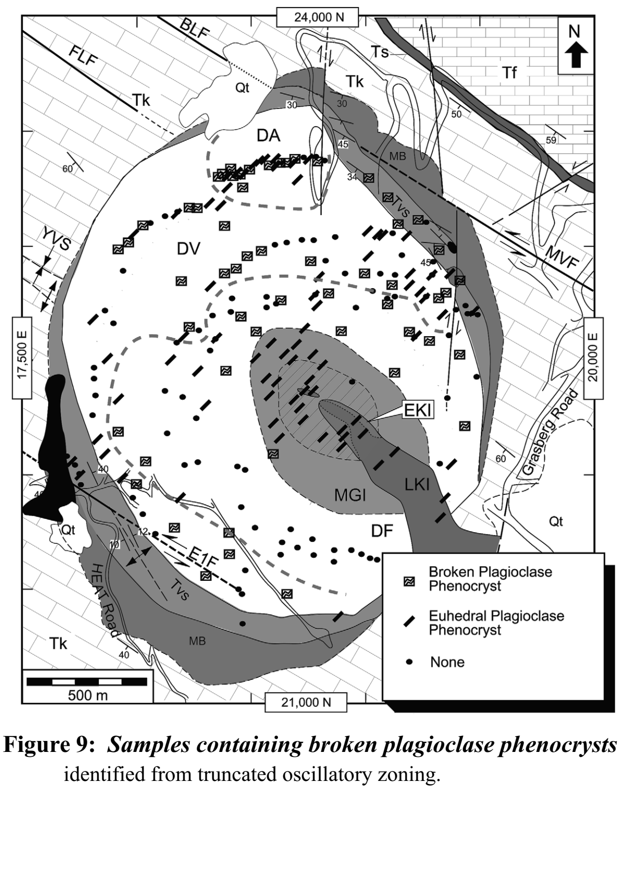


Figure 9: ***Samples containing broken plagioclase phenocrysts*** identified from truncated oscillatory zoning.

phenocrysts, recognised from the truncation of oscillatory zoning, are common in the Dalam. They are absent in the MGI and Kali phase rocks.

Biotite Phenocrysts

The distinction between magmatic and hydrothermal biotite has been based upon crystal morphology. Fresh magmatic biotites are large euhedral grains with clean and sharp edges (Fig. 10a). Hydrothermal biotites occur as distinctive 'shreddy' aggregates of fine grains (Fig. 10b). Whereas relict igneous plagioclase is present in most samples, magmatic biotite is commonly only recognised as pseudomorphic replacements (Fig. 11). The main alteration products of biotite are shreddy hydrothermal biotite in the interior, and sericite in the exterior, parts of the complex.

In many samples, the former abundance of magmatic biotite is estimated from pseudomorphic outlines. Overall, it appears that biotite typically composed about 15% of the phenocryst population. In both the MGI and the DA, biotite abundance ranges from 5% to 25%. In the Kali, biotite abundance ranges from 10% to 20%. In the DV and DF relict magmatic biotite preservation is patchy, but pseudomorph outlines indicate the abundance ranged from at least 3% to 20%.

Hornblende Phenocrysts

Hornblende is much more highly susceptible to alteration than is plagioclase or biotite. Hornblende phenocrysts are only present in parts of the DA and most of the LKI. In the freshest Late Kali, the abundance of hornblende ranges from 3% to 15%. In the freshest DA samples, hornblende phenocryst contents are typically about 10%, but in nearby altered samples, hornblende pseudomorphs typically comprise less than 3% of the rock. From this, it is evident that the volume of pseudomorphs is only an indicator of the minimum former abundance of hornblende. Hornblende has been replaced by shreddy biotite in the interior and sericite where present in the outer parts of the complex.

MacDonald and Arnold (1994) concluded there was a two-stage division of the Kali phase of magmatism based upon the degree of mineralisation/alteration wherein a late stage of the Kali postdated nearly all hydrothermal activity. Hornblende is lacking in parts of the Kali. Based upon field observations in the open pit mine and thin sections from eight sample locations, it appears that the Kali can be subdivided into hornblende-bearing and hornblende-absent. The samples lacking hornblende are located in the interior and near the contact of Kali with the MGI (Fig. 12). Because petrographic analysis is needed for confirmation, the boundaries of the two Kalis is very poorly constrained. Drill core relationships indicate they probably interfinger at depth (MacDonald and Arnold, 1994). Their location, combined with observations on the hydrothermal mineralogy, indicate the hornblende-absent Kali is earlier (Early Kali Intrusion, EKI), whereas the hornblende-bearing Kali is the later phase (Late Kali Intrusion, LKI). More work on sub-surface samples is needed to properly understand the phases of Kali magmatism.

Hornblende was a common component of the Dalam Andesite and petrographic analysis indicates it was probably ubiquitous. In striking contrast, only four samples of the Dalam Volcanic and three of the Dalam Fragmental contain pseudomorphic evidence for hornblende. It is certain that alteration is intense enough in many samples to destroy all evidence, but it appears that hornblende was absent or at most a sparse component during most of Dalam phase magmatism.

In the MGI, amphibole pseudomorphs replaced by hydrothermal biotite are common. The former abundance of hornblende was probably up to 5%.

Clinopyroxene and Actinolite

Some samples of the Late Kali Intrusion contain as much as 2% of optically identifiable clinopyroxene. In these rocks, actinolite is observed to topotactically replace clinopyroxene (Fig. 12; McMahon, 1994a). Clinopyroxene/ actinolite was not found in all samples of the Late Kali

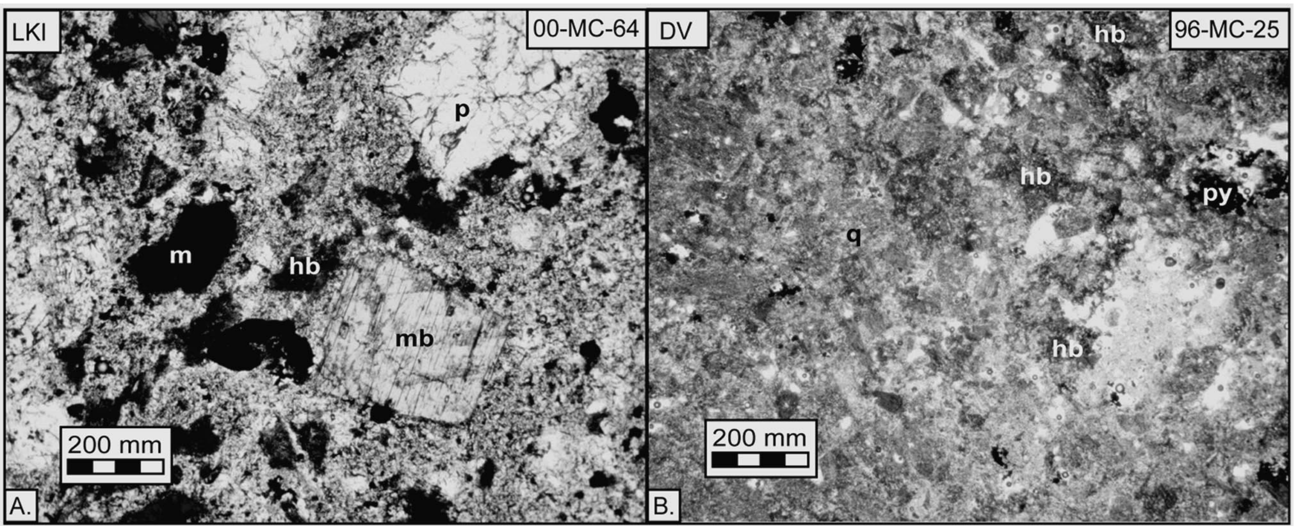


Figure 10: ***A. Magmatic biotite in Late Kali Intrusion. B. Magmatic biotite pseudomorphed by hydothermal shreddy biotite in Dalam Volcanic***. mb = magmatic biotite, p = plagioclase, m = magnetite, hb = hydrothermal biotite, py = pyrite, q = quartz.

examined, and it is absent in the few samples of the Early Kali examined in this study. None of the Dalam samples contain actinolite, indicating the former presence of clinopyroxene.

In the MGI, alteration is extensive and petrographic investigation aided by BSE images reveals that the only amphibole now present in most samples is actinolite. Hornblende was completely replaced by an aggregate of biotite grains in most samples. Actinolite, on the other hand, commonly occurs as irregular, but optically continuous single grains. The critical observation comes from Kali samples in which hornblende is partially to totally replaced by hydrothermal biotite and clinopyroxene is replaced by actinolite. Extrapolating these observations to the MGI, indicates that both hornblende and clinopyroxene existed in abundances of about 5%, with the former replaced by clusters of hydrothermal biotite and the latter via a largely topotactic replacement by actinolite.

Magnetite

Magnetite (+biotite) is a major alteration product in the interior of the GIC. Veins of magnetite are common, indicating direct precipitation from fluid in fractures. Disseminated magnetite locally comprises as much as 10% of intensely altered rocks. As the morphology of primary and secondary disseminated magnetite is the same, it is not possible to petrographically differentiate most of the magnetite in the MGI and Dalam phases into a magmatic or hydrothermal assemblage. However, the abundance is so great in many of the samples, that the bulk of the magnetite must be hydrothermal. Magmatic magnetite was probably present in all of the igneous units, but it is only evident in the freshest Kali samples. Several samples of Late Kali that lack evidence of hydrothermal alteration contain 1% to 2% magnetite.

Apatite

Apatite of small grain size is ubiquitous. X-ray mapping with an electron microprobe reveals trace volume concentrations (<1%). Apatite abundance and textures appear similar in fresh and altered rocks. As apatite is a common trace phase in igneous rocks, its occurrence in the GIC is thought to be magmatic.

Mineral Chemistry

The occurrence of plagioclase and biotite phenocrysts in all units necessitates an investigation into potential compositional differences that could record cryptic chemical changes in the parent magma chamber. The freshest samples identified during petrographic analysis from across the GIC were selected for microprobe analysis of plagioclase and biotite. Standard analytical procedures were followed and described in Paterson (2004). Two forms of compositional mapping were utilised by scanning thin sections with the electron beam: backscattered electron (BSE) imaging and x-ray mapping of major elements. The magnitude of the electron backscattering is a measure of the average atomic number of elements in scanned areas (Potts *et al.,* 1995), hence variations in brightness on a BSE image indicate a variation in composition. X-ray mapping involves setting a spectrometer to detect x-rays characteristic of a particular element. Eight samples containing fresh plagioclase and biotite along with five samples containing only fresh plagioclase were selected for substantial analytical work with the electron microprobe.

Plagioclase Phenocrysts

Fig. 13a shows the results of quantitative analysis of the Ca-rich cores of plagioclase phenocrysts. The ternary plot indicates that there is no systematic variation in the core compositions of plagioclase between the analysed samples

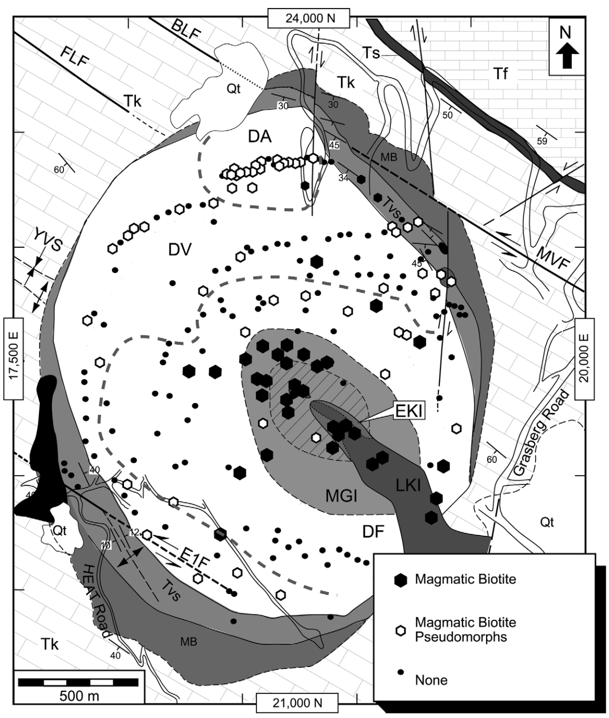


Figure 11: ***Distribution of magmatic biotite phenocrysts and pseudomorphs.***

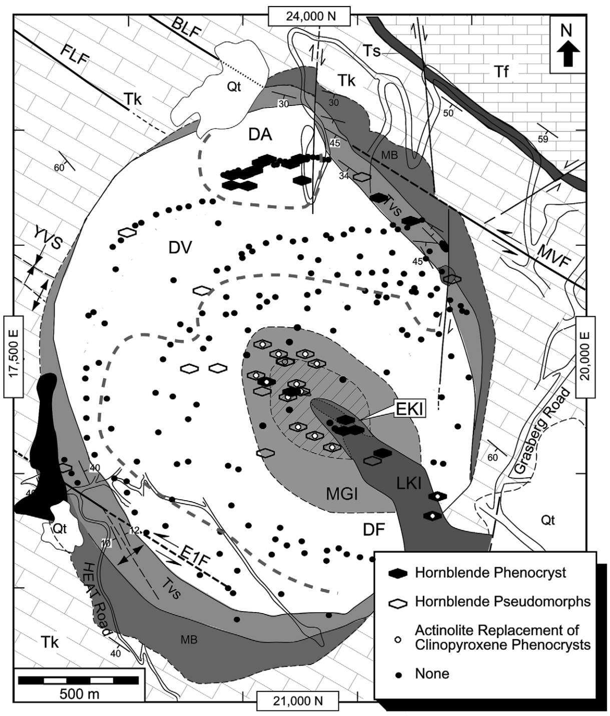


Figure 12: ***Distribution of hornblende phenocrysts and pseudomorphs, and actinolite.***

from the Dalam Andesite, MGI or Kali. Nearly all of the core analyses range between An_{50} to An_{25}. The lower values are probably from crystals that are not central sections.

The oscillatory zoning in plagioclase phenocrysts that is observed optically is readily detectable with both BSE imaging and x-ray mapping. Most of the zoning appears to range between An_{35} to An_{10} (Fig. 13b). X-ray mapping shows the margins of plagioclase phenocrysts are albitic and, not surprisingly, very similar in composition to plagioclase in the groundmass (Fig. 14a).

Both BSE imaging and x-ray mapping revealed small masses of potassium feldspar inside many plagioclase phenocrysts (see small bright spots Fig. 16a and b). The compositions of the inclusions are similar to potassium feldspar in the groundmass (Fig. 14). They are found in plagioclase from the freshest samples of the Kali and thus at least some of these masses do not appear to be products of alteration. It is possible that they are exsolution phenomenon, but their irregular orientations suggests they are small inclusions. Potassium feldspar inclusions in the interior of plagioclase grains could be relicts of phenocrysts that were largely remelted during a magma mixing event at depth. Alternatively, potassium feldspar inclusions may be slowly growing phenocrysts that were engulfed by more rapidly growing plagioclase.

Biotite Phenocrysts

Biotite is second only to plagioclase in terms of volumetric significance in the phenocryst population. BSE imaging of biotites revealed few differences within individual grains or between separate grains. Magmatic biotite was far more susceptible to alteration than plagioclase, and few thin sections contained large, unaltered grains. Reported biotite compositions are an average of four spot analyses per grain.

Variations in biotite chemistry commonly involve the substitution of Ti, Mg, Fe and Al (Spear, 1993). A useful method for describing variations in biotite chemistry is plotting the number of Ti cations against both magnesium number and the number of Si cations (Fig. 15). Analysed biotites show considerable variation in Ti concentration, as much as 60%.

The magnesium numbers (Mg # = Mg/(Fe+Mg) for biotite show up to 10% variation within a unit. As with the quantitative analysis of plagioclase, the results from the biotite study detected no systematic differences between the different units, although the data set is small.

Groundmass

MacDonald and Arnold (1994) stated that, where preserved, the magmatic groundmass of the GIC rocks is a combination of potassium feldspar, plagioclase and quartz. The volume of groundmass is commonly about 40% of the rock volume. Petrographic identification of groundmass phases is extremely difficult because grain sizes are extremely small and the optical properties of un-twinned feldspars and quartz are very similar. X-ray element maps produced with a microprobe enable quick identification of feldspars and distinction from quartz.

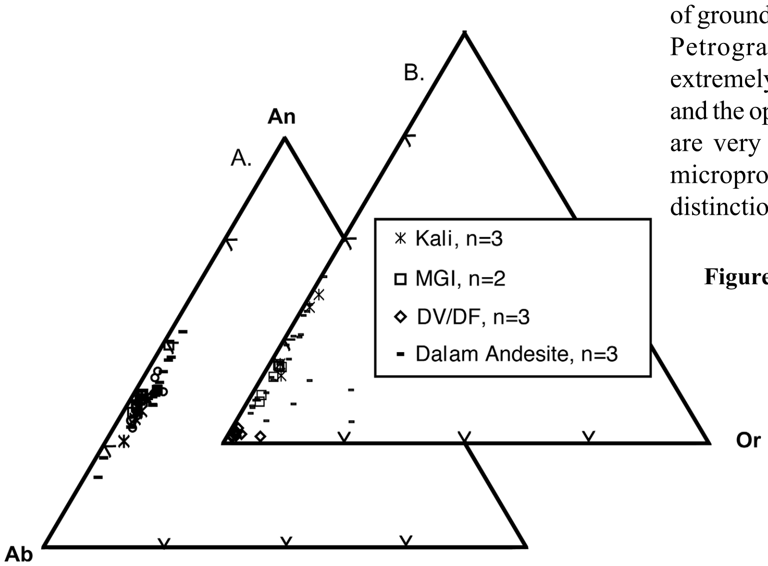


Figure 13: ***A. Compositions of the cores of plagioclase phenocrysts. B. Compositional variations of oscillatory zones in plagioclase.*** n = number of samples with analyzed grains.

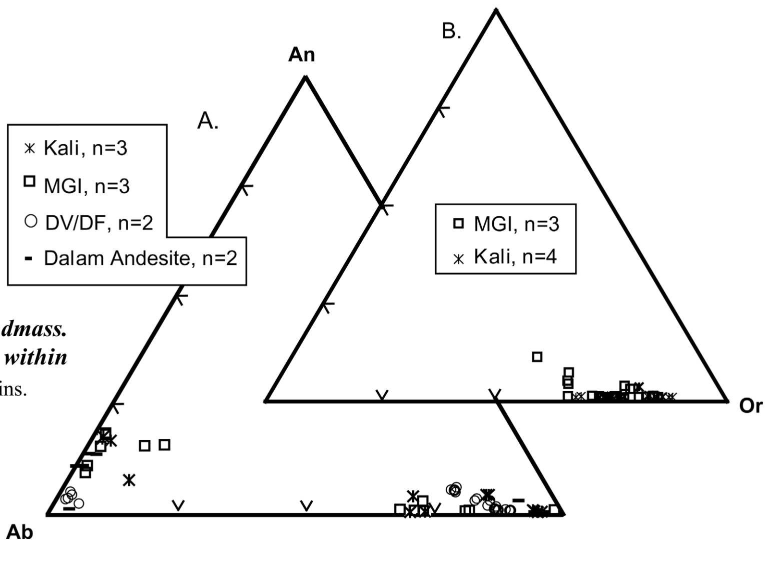


Figure 14: ***A. Analyses of feldspar grains in the groundmass. B. Analyses of potassium feldspar inclusions within plagioclase.*** n = number of samples with analyzed grains.

Table 1: ***Magmatic mineralogy of the igneous units in the Grasberg Igneous Complex***

youngest	**Late Kali Intrusion (LKI)**		
		phenocrysts	plagioclase (20% to 65%) + biotite (10% to 20%) + hornblende (3% to 15%) ± clinopyroxene (altered to actinolite) (~2%)
		groundmass	potassium feldspar (10% to 30%), quartz (10% to 30%), biotite (~5%), albitic plagioclase (~5%), magnetite (~2%) and apatite (tr.)
		texture	porphyritic: ~100x variation in grain size
	Early Kali Intrusion (EKI)		
		phenocrysts	plagioclase (20% to 65%) + biotite (10% to 20%)
		groundmass	potassium feldspar (10% to 30%), quartz (10 to 30%), biotite (~10%), albitic plagioclase (~5%), and apatite (tr.)
		texture	porphyritic: ~100x variation in grain size
	Main Grasberg Intrusion (MGI)		
		phenocrysts	plagioclase (20% to 40%) + biotite (5% to 25%) + hornblende (3% to 15%) + clinopyroxene (altered to actinolite) (~5%)
		groundmass	potassium feldspar (~15%), quartz (~15%), biotite (~5%), albitic plagioclase (~5%), and apatite (tr.)
		texture	comparatively equigranular: ~10x variation in grain size
	Dalam Andesite (DA)		
		phenocrysts	plagioclase (10% to 35%) + biotite (5% to 25%) + hornblende (3% to 15%)
		groundmass	potassium feldspar (~10%), quartz (~20%), biotite (~10%), albitic plagioclase (~5%), and apatite (tr.)
		texture	porphyritic: ~100x variation in grain size
	Dalam Volcanic/Dalam Fragmental (DV/DF)		
		phenocrysts	plagioclase (up to 45%) and biotite (3% to 20%) +/- hornblende (< 2%)
		groundmass	thoroughly altered in almost all samples, may have been glassy, apatite (tr.)
oldest		**texture**	brecciated, with broken plagioclase crystals

X-ray mapping shows the freshest rocks from the Kali and the least altered samples from the MGI and Dalam Andesite contain potassium feldspar and quartz that occur in a roughly two to one ratio and together comprise 20% to 30% of the rock volume (Fig. 16). The groundmass in the Kali and less altered MGI and Dalam Andesite also contains small grains of magmatic biotite (<30 microns) and plagioclase grains, each approximately 5% of the volume. Magnetite and apatite are common, minor components of the groundmass of the LKI.

Analyses of the groundmass (Fig. 14a) from the least altered samples show albitic plagioclase (Ab_5 to Ab_{15}) and potassium feldspar (Or_{65} to Or_{95}) are coexisting. Notably, the compositions of groundmass potassium feldspar overlap the field on the ternary plot for the potassic feldspar inclusions (Or_{95} to Or_{75}) in the plagioclase feldspar (Fig. 14b).

The groundmass of all samples of the DV and DF are highly recrystallised in nearly all thin sections. Nonetheless, the feldspars in the groundmass from two of the less recrystallised samples of DF were analysed (Fig. 14a). Near end-member albite is present suggesting the co-existing feldspars are probably secondary. In most samples from the outer part of the GIC, potassium feldspar does not occur in the groundmass, because of extensive alteration to sericite. A likely explanation for the thorough recrystallisation of the Dalam phase rocks is that the groundmass was originally glassy.

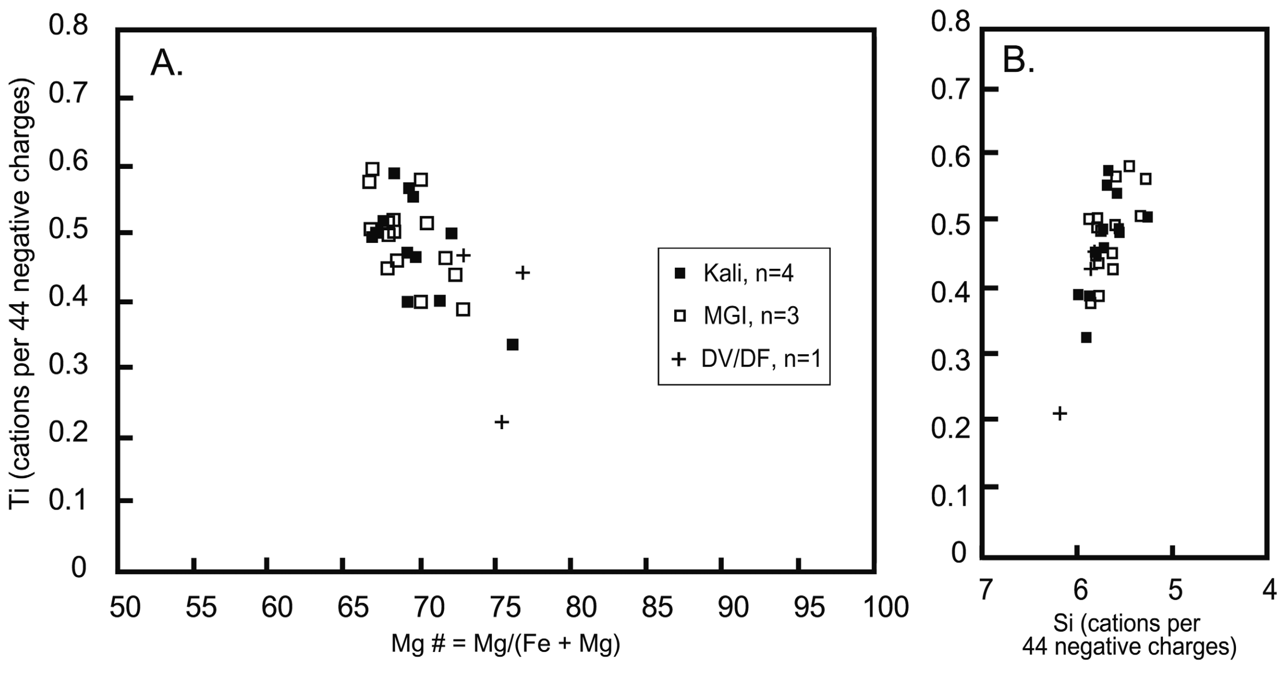


Figure 15: ***Composition of magmatic biotite.*** **A.** ***Ti versus Mg number.*** **B.** ***Ti versus Si content.*** n = number samples with analyzed grains.

Discussion

Table 1 summarises the magmatic mineralogy and textural characteristics for the units forming the GIC based upon the systematic petrographic analysis supplemented by electron microprobe analysis. The mineralogic differences record evidence on the behaviour of the parent magma chamber and the rates of cooling after intrusion to shallow depths. The gross textural differences between each unit primarily reflect differences in emplacement processes.

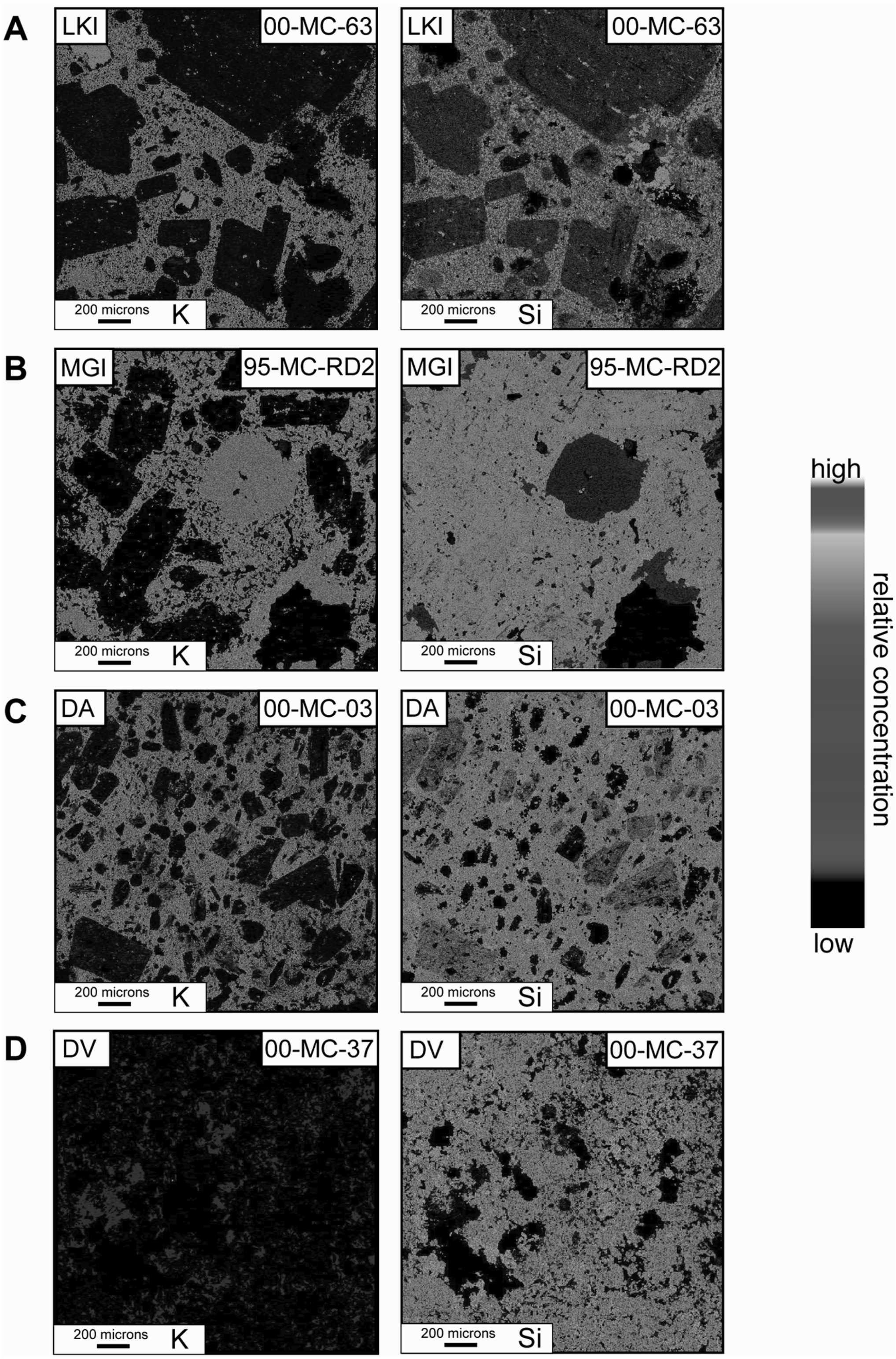


Figure 16: ***Potassium (left) and silicon (right) x-ray maps of the groundmass of representative samples.*** Note abundance of potassum feldspar in the groundmass of the LKI (A), MGI (B), andDA (C). Complete replacement of groundmass potassium feldspar is evident in the DV (D).

Evolution of the Parent Magma Chamber

The phenocryst mineral assemblages in each phase of magmatism are similar, indicating no profound differences in the pressure and temperature conditions during crystallisation of the magmas forming the GIC. Plagioclase and biotite phenocrysts are ubiquitous and the chemical analysis reported in this investigation, albeit limited, indicate compositional variations within units are overlapping. These observations suggest, but do not prove, the three phases of magmatism were sourced from the same chamber. However, the differentiation trend defined by mineralogy or by chemical data is not unidirectional. This could be interpreted to indicate tapping of different levels of the parent chamber or that the parent chamber was recharged by compositionally similar magmas.

Cryptic evidence for recharging is suggested by the presence of plagioclase phenocrysts in the DA, MGI and Kali with cores that record two distinct stages of growth. The petrographic observations suggest the parent magma chamber was recharged during the Dalam magmatism and between MGI and Kali intrusive activity.

The major mineralogic differences are the presence or lack of hornblende and clinopyroxene in the different units. This is explainable by differences in the depth of crystallisation. In intermediate composition magmas, higher pressure conditions (>2-3 kb) stabilise hornblende as a phenocryst phase whereas lower pressure conditions stabilise clinopyroxene (Naney, 1983).

The fact that hornblende is abundant in the DA but apparently sparse or lacking in most of the DV and DF suggests recharging of the parent magma chamber or some other fundamental change during Dalam phase magmatism. In the northern part of the complex, the DA overlies the Tvs (Sapiie, 1998). Clasts identical to the DA are found in the DV indicating at least some, probably most, DV magmatism post-dates the DA. This indicates Dalam magmatism tapped a chamber that was differentiated to varying degrees (more crystallised, cooler, sidewall zones, versus a hotter, less crystallised interior) or that the parent chamber for the Dalam was recharged at least once. The lack of clinopyroxene indicates rapid solidification at low pressures suggesting the DF and DV units are composites of magma batches emplaced in small pulses.

The presence of hornblende and clinopyroxene in the MGI indicates substantial growth of mafic phases at both high and low pressures. The comparatively equigranular texture indicates the MGI cooled much more slowly than the Dalam phase magmas. This suggests the cone-shaped plug of MGI was intruded as one large batch (~1 km^3) into fully solidified, but still hot, Dalam wall rocks.

The Kali phase of magmatism post-dates essentially all of the economic copper mineralisation. Hornblende and clinopyroxene appear to be absent in the small, porphyritic Early Kali plug in the centre. This indicates either less recrystallised, probably deeper parts of the parent magma chamber were tapped than which supplied the MGI and/or the parent chamber was recharged with the addition of heat destabilising the hornblende. The lack of clinopyroxene is attributed to the small size of the batch of the Early Kali magma (~0.1 km^3) that intruded the core of MGI after substantial cooling.

Hornblende and clinopyroxene are abundant in the large, wedge-shaped Late Kali dyke that extends outwards from the centre of the GIC. The presence of hornblende indicates substantially more crystallised batches of magma escaped from the parent magma chamber. The growth of clinopyroxene largely resulted from the relatively slow cooling of the Late Kali magma which was emplaced as several large batches (totalling ~1 km^3).

In summary, the phenocryst mineralogy of the GIC (plagioclase + biotite ± hornblende) requires only one parent magma chamber at depths of greater than about 8 km, most probably located near the interface between crystalline basement and passive margin sedimentary layers at depths of at least 12 km. However, the volume of copper in the Grasberg orebody indicates that the parent chamber supplying the fluids causing mineralisation had a volume of several hundred cubic kilometres; that is a chamber with batholithic dimensions. Isotopic studies (Housh and McMahon, 2000) indicate the chamber was supplied by magmas that assimilated substantial volumes of lower Precambrian continental crust. Hence, it appears that the magmas that resupplied the parent stock/batholith chamber came from a still deeper chamber, probably near the crust/mantle boundary.

Emplacement of the Dalam, MGI and Kali

The Dalam unit has been described by previous authors (MacDonald and Arnold, 1994; Pollard and Taylor, 2002) as a diatreme. A space-generating explosive emplacement of the unit into the carbonate host rock is implied. A distinctive attribute of forceful intrusion and diatreme formation is the incorporation of wall rock clasts, commonly voluminous, into the magmatic breccia (Hack, 1942; Lorenz, 1975; 1986; Philpotts, 1990, p. 57; Best and Christiansen, 2001, p. 232).

Sapiie (1998) suggested and Luck (1999) developed a model of GIC formation that did not invoke an explosive, space-generating event for Dalam emplacement. A 100 m or so wide zone of brecciated carbonate rocks occur along the margins of the GIC. The clasts are rounded by dissolution, rather than explosively fragmented (Sapiie, 1998). The critical field observation is that clasts of the sedimentary wall rock have not been found in the magmatic breccia units. The dense sample coverage and petrographic analysis of this study has failed to reveal fragments of sedimentary wall rock within the Dalam Volcanic or Fragmental units. The only exception to this generalisation is found in two samples of LKI from near the southeasternmost edge of the complex. These samples, which are otherwise very fresh, contain a few grains of epidote that could be replaced micro-xenoliths of carbonate wall rock.

Within the Dalam, there are areas of outcrop from which we collected hand samples that contain clasts with layering (Fig. 17). However, these layered clasts are all fragments similar to the bedded volcanic units (Tvs) along the northeast and southwest edges of the GIC (Fig. 2). Moreover, these samples with relicts of volcanic layering are confined to the periphery of the complex. They are particularly abundant in the Dalam Andesite near where they overlay the bedded volcanics (Tvs) in the northern part of the GIC (Sapiie, 1998).

The igneous processes that generated the Dalam were not entirely passive. Broken plagioclase phenocrysts recognised from the abrupt truncation of oscillatory zoning are present in many samples (Fig. 9). Most of the Dalam samples that do not contain broken grains are from locations that do not contain any plagioclase phenocrysts owing to intense hydrothermal alteration.

The absence of clasts of sedimentary wall rock fragments at the outcrop, hand-sample and now petrographic scale, strongly argues against a model of Dalam magmatism involving a space generating, diatreme-forming explosion. Broken phenocrysts are lacking in the MGI and Kali phases. Either phenocryst breakage was associated with very near-surface eruptive process or the conduit for magma intrusion at depth was much narrower during Dalam magmatism. The petrology and structure of the Dalam is most consistent with a model wherein volatile saturation of rising magma was only a near-surface (<1 km) phenomenon. The DA overlies the Tvs and clasts of DA are present in the DV which is, in turn, clearly genetically related to the DF in the centre of the complex. The small area of the three million year old GIC, and the presence of bedded volcaniclastic sediments along the margins, leads to the conclusion that the Dalam phase of magmatism occurred in a low-relief maar volcano setting, rather than in the throat of a tall composite volcano. The overall structural relationship of the DF with the DV suggests the igneous activity in the centre of the system was concurrent with subsidence along the edges. A caldera in the maar volcano is inferred.

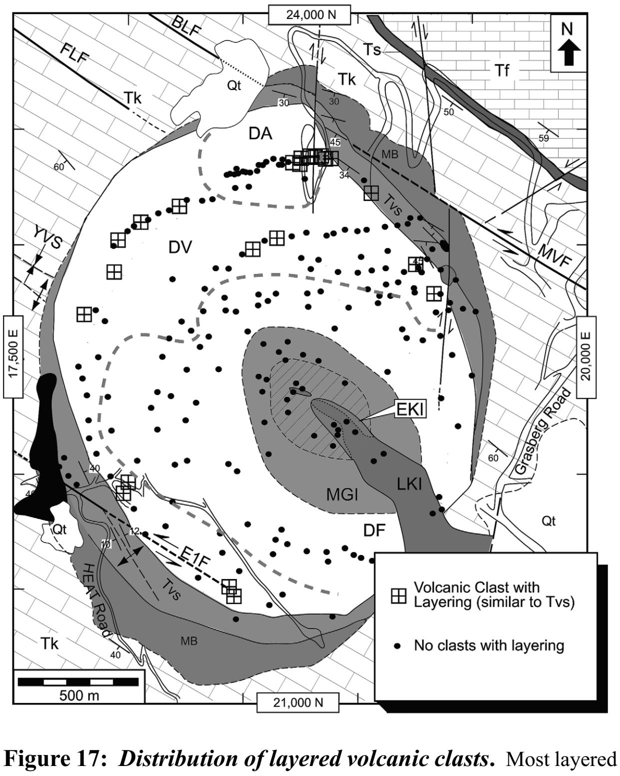


Figure 17: ***Distribution of layered volcanic clasts.*** Most layered clasts are very similar to the Tvs.

In striking contrast to the Dalam phase, broken phenocrysts are absent in the MGI and Kali indicating a different flow process during their emplacement. The Kali units are distinctly porphyritic with a variation in grain size between phenocrysts and groundmass of roughly 100-fold, whereas the MGI is comparatively equigranular with a typical variation of grain size between phenocrysts and groundmass of 10-fold or less. These textural differences are interpreted to indicate the MGI cooled more slowly than the Kali. These relations are most simply explained as the passive emplacement of the MGI into the still hot core of the Dalam phase rocks. This was followed by the similarly passive intrusion of the Early Kali as a very small plug into the centre of the substantially cooled MGI followed by the later, larger intrusion of the Late Kali as a wedge-shaped dyke splitting the substantial cooled intrusive complex.

Conclusions

Based on 225 hand samples, polished slabs and thin sections from the Grasberg open pit mine, this study confirms that the tripartite division of the GIC reported by MacDonald and Arnold (1994) into the Dalam, MGI and Kali phases is robust. Petrologic refinements include:

i) The phenocryst mineralogy in all Dalam phase rock is plagioclase and biotite. Hornblende is a sparse constituent except in the Dalam Andesite, a massive unit restricted to the northern part of the GIC.
ii) The MGI had a magmatic mineralogy of plagioclase, biotite, hornblende and clinopyroxene.
iii) The Kali can be subdivided into an Early and a Late phase. Both are relatively unaltered in comparison to the MGI, Dalam Andesite, Dalam Volcanic and Fragmental units. The mafic phases in the Early Kali are biotite and probably magnetite. The mafic phases in the Late Kali are biotite, hornblende, clinopyroxene and magnetite.
iv) Broken plagioclase crystals are very common in the Dalam Volcanic and Fragmental units, resulting from flow processes which are probably related to near-surface volatile saturation. Broken plagioclase crystals are absent from the MGI and Kali phase intrusions, indicating their comparatively passive intrusion.
v) Clasts of sedimentary wall rock are absent. Layered clasts that are present, are all similar to the bedded volcaniclastic unit along the margins the complex. Intrusion of all units occurred without detectable physical interaction with the sedimentary wall rocks exposed in the district.
vi) In reconnaissance microprobe analysis, no systematic variation in plagioclase or biotite phenocryst chemistry was detected among the three igneous phases.
vii) The magmatic groundmass in the Dalam Andesite, MGI and Kali was a combination of potassium feldspar, albite, quartz and biotite. Destruction of the magmatic groundmass was complete in the Dalam Volcanic/Dalam Fragmental units. The groundmass in the Dalam units was probably glassy.

viii) There are areas in the Dalam Fragmental/Dalam Volcanic with complete textural destruction of all phenocryst phases by hydrothermal alteration. The largest of these areas, in the southwest part of the GIC, covers approximately 250 x 1300 m.

ix) Magmatism probably occurred in a low relief maar-caldera. The parent chamber was recharged at least twice, and possibly many times with magma of similar composition.

Acknowledgments

From logistical to financial support, none of this work would have been possible without a large number of people from Freeport-McMoRan, Inc. and PT Freeport Indonesia: James R. Moffett, Dave Potter, George MacDonald, Wahyu Sunyoto, Sugeng Widodo, Noris Belluz, Keith Parris, Paul Warren, Clyde Leys, Herry Susanto, Chris Christenson, Bambang Irawan, Ben Coutts, Stephen Hughes, Nico Sambur, Aditya Pringgoprawiro, Boedijono, Yahul and Bambang Antoro. A special thanks goes to Benyamin Sapiie. Ertsberg Project Contribution No. 23.

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