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Recent Exploration Drilling at Lihir Geothermal Field, PNG: Effects of Catastrophic Sector Collapse on a Magmatic-Hydrothermal System

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ABSTRACT

Detailed logging and petrological analysis of cores from three exploratory wells (GW47, GW52, GW54) at Luise Harbour, Lihir Island, reveal an intrusive complex underlying lavas and volcaniclastic breccias of the Ladolam breccia complex. The intrusive rocks consist of porphyritic to equigranular, cumulate clinopyroxene diorite, which were emplaced as sub-horizontal bodies, cut by sub-vertical porphyritic diorite and rare aplite dikes. The similar mineralogy of plutonic rocks and crosscutting dikes implies a common magmatic source, however the change in their emplacement mechanisms, along with textural differences, suggests a change in the orientation of least principal stress that may have been caused by rapid unloading during volcanic sector collapse of the Luise crater. High temperature (>300°C) hydrothermal veining (garnet, clinopyroxene, magnetite) in the intrusive complex predates the porphyritic dikes, and hence sector collapse. Recent alteration assemblages that overprint the high temperature assemblage are in thermal equilibrium with the current hydrothermal system. A moderate temperature (>240°C) propylitic assemblage (epidote, chlorite, adularia, quartz, illite) occurs beneath a shallow zone of phyllic alteration (interlayered illite-smectite, quartz, pyrite) where cooler (<200°C) fluids have infiltrated the upper, faulted, regions of the intrusive complex.

1. INTRODUCTION

Drilling by Lihir Gold Ltd. (LGL) of three exploration geothermal wells (GW47, GW52, GW54) at Luise Harbour, Lihir Island occurred between September 2007 and July 2008. All three are slim hole wells, rotary drilled to shallow depths (GW47: 450 m; GW52: 52 m; GW54: 100 m), and completed by diamond drilling to 1500 mMD (GW47: 1480.5 mMD; measured depth). The wells are located north of the Kapit Pit. Both GW52 and GW54 are close to the harbour shoreline, directionally drilled towards the north-east, beneath Luise Harbour. GW47, located high on the Luise crater rim, was directionally drilled to the south-west (Figure 1).

Recent interpretations of magnetotelluric (MT) data (SKM, 2007) show a conductive layer beneath Minifie in the south, extending north- and northwest-wards through Kapit, beneath the Luise crater rim and offshore beneath the harbour. This conductive layer probably represents a phyllic alteration cap to the geothermal system and has good correlation with the shape of subsurface isotherms, suggesting the geothermal resource extends beneath Luise Harbour (SKM, 2007). The three exploration wells were directionally drilled to target the conductive layer and any east- and north-ward extension of the Luise geothermal reservoir.

Detailed logging and petrological analysis of drill cores from GW47, GW52, GW54, reveal an intrusive complex underlying a unit of lavas, volcaniclastic breccias and tuffs. Characterization of hydrothermal mineral assemblages coupled with fluid inclusions analyses and XRD data give insights of the evolution of the geothermal system, and particularly the effects of the catastrophic sector collapse of Louise crater, on the magmatic-hydrothermal system.

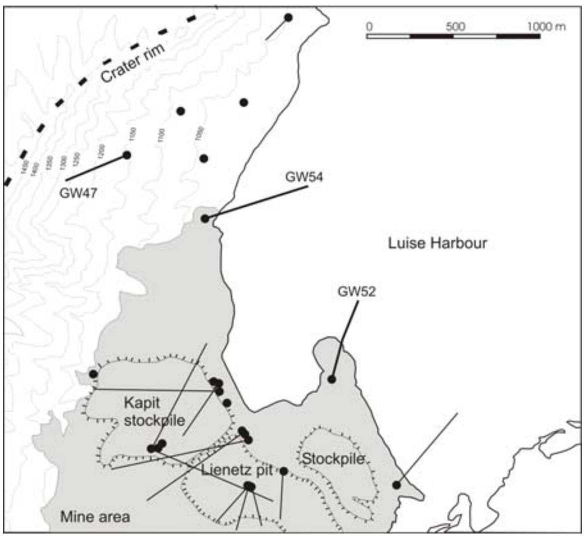

Figure 1: Location of exploration wells GW47, GW52 and GW54, Luise Harbour, Lihir. Most other geothermal wells (vertical and directional) are located in the Kapit pit and Kapit stockpile areas. Minfie pit is located ~500 m south of Lienetz pit.

2. GEOLOGY

2.1 Volcaniclastic Breccias and Lavas

Volcanic rocks belonging to the Ladolam Breccia Complex (Carman, 2003) mainly consist of intensely altered and brecciated lavas, breccias and locally intercalated ash falls and lapilli tuff. In the three wells this formation varies between ~400 and ~570 m thick. The dominant lithology is a series of light to medium grey, porphyritic lavas, of likely andesitic composition, with altered phenocrysts of plagioclase and lesser pyroxene, set in a fine-grained, altered groundmass. Volcaniclastic lithologies include matrix-supported, poorly to moderately sorted, monomictic and polymictic breccias and agglomerates. Brecciation is variable, however crackle breccias are the dominant type. At GW52 and GW54 the base of this unit is marked by ~70 m of clast-supported, monomictic breccia of diorite clasts and muddy, clay-altered matrix. The lower ~20 m of this unit has been intruded by thin porphyritic diorite dykes (Figure 2).

2.2 Intrusive Complex

2.2.1 Clinopyroxene Diorite

A clinopyroxene diorite dominates the intrusive complex (Figure 2). Two textural groups of diorite are distinguished and represent two end-members of a series of compositionally similar but texturally different shallow intrusions.

A fine grained clinopyroxene diorite comprises the bulk of the intrusive complex (Figure 3a). It is pale brown to pink, or pale to dark grey, and ranges between porphyritic and equigranular. The igneous mineral assemblage consists of plagioclase feldspar, clinopyroxene, magnetite and apatite, with hornblende, biotite and possible orthopyroxene pseudomorphs present as accessory minerals. Plagioclase and clinopyroxene comprise the phenocryst assemblage, with accessory biotite enclosing plagioclase phenocrysts.

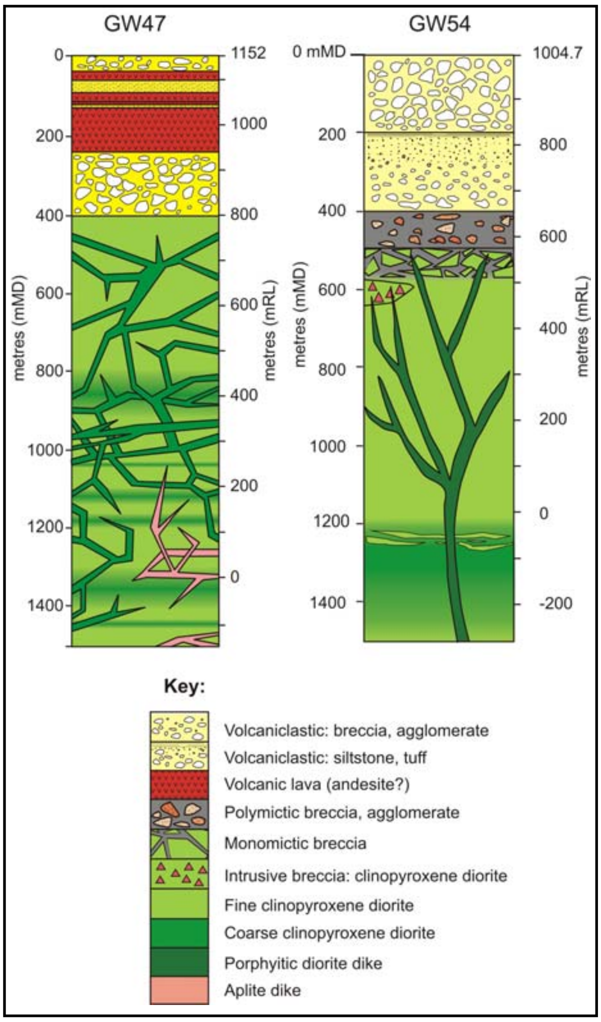

Figure 2: Schematic stratigraphic columns for GW47 and GW54.

A coarse variety of the clinopyroxene diorite is texturally heterogeneous, with porphyritic to equigranular and cumulate textures recognized (Figure 3b). It has the same mineral assemblage as the fine grained variety. Cumulate rocks contain interlocking crystals of subhedral to euhedral plagioclase feldspar and clinopyroxene, with interstitial anhedral magnetite and euhedral apatite and late stage overgrowths of hornblende and biotite on plagioclase, clinopyroxene and magnetite,

Contacts between fine and coarse grained clinopyroxene diorite are both gradational and sharp (Figure 2). Rare to abundant, rounded to subangular, enclaves of coarse clinopyroxene diorite, commonly crowd the fine grained diorite such that the rock is essentially a clast-supported, intrusive breccia.

2.2.2 Dikes

Dike swarms occur throughout the diorite pluton and in GW47, two dike types are petrographically distinguished (Figure 2, Figure 4).

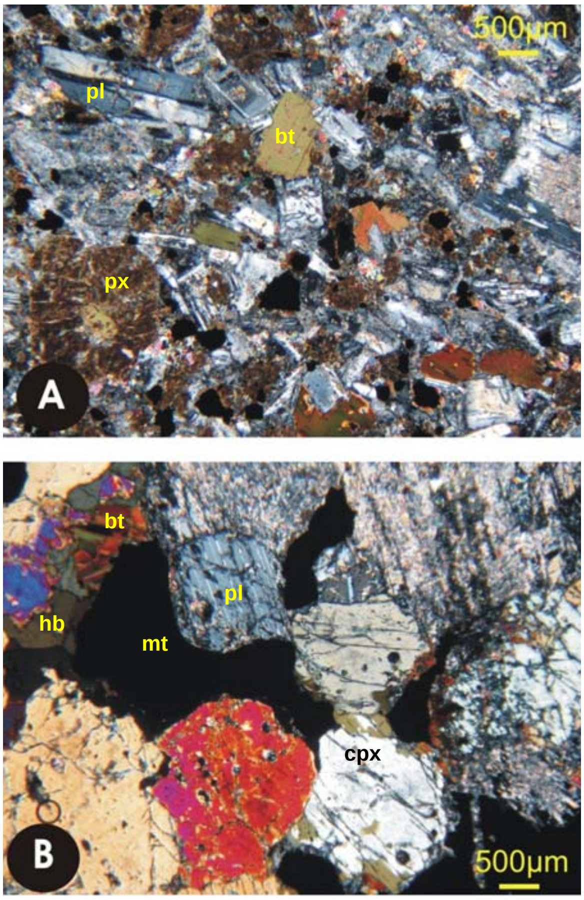

Figure 3: Photomicrographs: A) Fine diorite, GW47 628.4 mMD depth. Crystals of plagioclase feldspar (pl), pyroxene (px; completely replaced) and biotite (bt) in a framework of interlocking plagioclase laths. Crossed polarised light. B) Coarse grained diorite, GW47 1402.1 mMD depth. Cumulate texture with interlocking crystals of subhedral to euhedral plagioclase (pl), clinopyroxene (cpx) and interstitial magnetite (mt), green hornblende (hb) and brown biotite (bt). Crossed polarised light.

The swarms of crosscutting porphyritic diorite dikes occurring throughout the intrusive complex (Figure 2) have maximum apparent thicknesses of ~20 m, but are typically less than a few metres thick. Diorite dikes are pale to dark grey, porphyritic, rarely amygdaloidal and contain phenocrysts of plagioclase feldspar, clinopyroxene and magnetite with accessory hornblende, biotite and orthopyroxene in a fine grained, variably trachytic groundmass (Figure 4a). The dikes have fine grained margins where there is subparallel alignment of lath-like phenocrysts. In thicker intervals, the dikes become coarsely porphyritic, with phenocrysts in dike centres up to 15 mm in length. Cross-cutting relationships suggest multiple dike emplacement events (Figure 2).

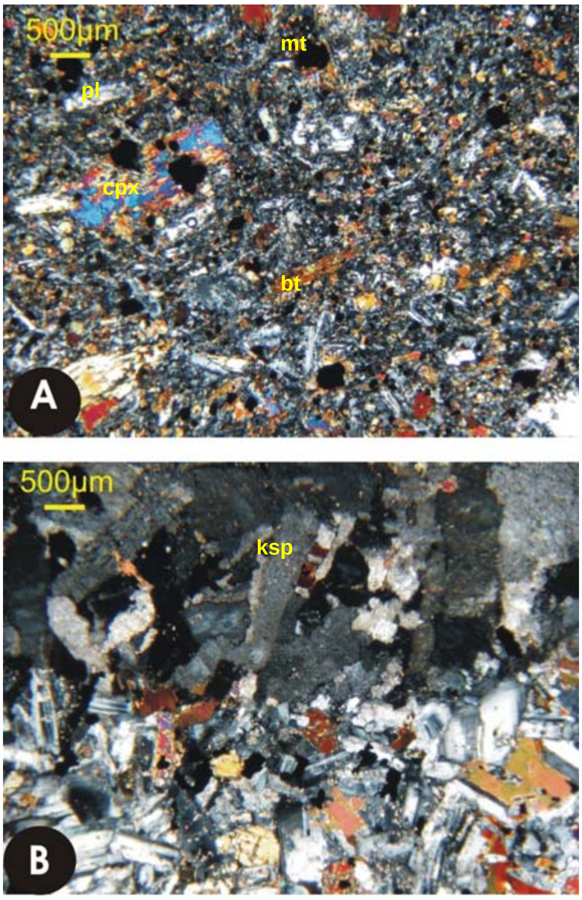

Figure 4: Photomicrographs: A) Porphyritic diorite dike, GW47 1298.4 mMD depth. The dike is fine grained and porphyritic, with phenocrysts of clinopyroxene (cpx), magnetite (mt), biotite (bt) and plagioclase (pl). Crossed polarised light. B) lithological contact between aplite dike (top) and fine clinopyroxene diorite (bottom), GW47 1289.8 mMD. The aplite dike is composed primarily of interlocking, tabular alkali feldspar crystals (ksp). The clinopyroxene diorite has a framework of plagioclase feldspar, magnetite, biotite and clinopyroxene. The contact between the two rock types is planar. Crossed polarised light.

Pale grey to pink, feldspathic aplite dikes are a minor component of the intrusive complex, occurring within the lower ~500 m of GW47. Typically the dikes are thin (<10 cm), but maximum apparent thicknesses of a few metres are present. The aplite is porphyritic to equigranular and composed primarily of interlocking tabular alkali feldspar crystals with minor clinopyroxene, biotite and magnetite (Figure 4b). These dikes intrude both clinopyroxene diorite and porphyritic diorite dikes (Figure 2). Dike contacts with the clinopyroxene diorite are planar (Figure 4b). As for the diorite dikes, cross-cutting aplite dikes suggest multiple aplite dike emplacement events.

3. HYDROTHERMAL ALTERATION

Four types of hydrothermal alteration are distinguished in rocks from GW47, GW52 and GW54. These are: phyllic, propylitic, potassic and calc-silicate. In GW47 these alteration zones occur beneath a weathering zone (up to ~200 m thick) where rocks are altered to clays and Fe-oxyhydroxides.

3.1 Phyllic alteration

Phyllic alteration affects both the volcano-sedimentary sequence and the top of the intrusive complex. In GW52 phyllic alteration is only 350 mMD thick. In GW47 it is ~1000 mMD thick, with an intense zone between 400-600 mMD. In GW54 it occurs 560 mMD, however relatively narrow intervals at greater depth alter rocks between 700-750 mMD and 880-1080 mMD. Phyllic alteration is a pervasive style of hydrothermal alteration, characterised by the occurrence of clays (smectite, interlayered illite-smectite and/or illite), quartz and pyrite with accessory chlorite, calcite, anhydrite and Fe-oxyhydroxides.

Generally, phyllic alteration is weakly to moderately developed, and is most intense proximal to fault zones. Conversely, it is most weakly developed in diorite dikes. There is selective replacement of phenocrysts and crystal fragments by clay, chlorite and calcite, and pervasive alteration of lavas and breccias by clay, calcite and pyrite. With increasing depth clay minerals are smectite, interlayered illite-smectite and illite.

Veining is weakly to strongly developed throughout the phyllic alteration zone. These contain calcite and quartz with accessory pyrite, quartz and anhydrite. Overall they appear to have a random orientation, are typically < 10 mm, and some are spatially related to fault zones.

The zone of intense phyllic alteration between 400-600 mMD in GW47 contains interlayered illite-smectite, quartz and pyrite, with accessory anhydrite and calcite, and is cut by quartz, pyrite, calcite and anhydrite veins. Vein quartz contains fluid inclusions with homogenisation temperatures that range between 164-195°C. These temperatures are consistent with formation temperatures for interlayered illite-smectite (i.e., <210°C; Browne and Ellis, 1970)

3.2 Propylitic alteration

Propylitic alteration occurs in the intrusive complex beneath the phyllic zone. The typical propylitic mineral assemblage includes chlorite, epidote, quartz, calcite, pyrite, albite, anhydrite and illite. It is both a selective and pervasive style of hydrothermal alteration that is weakly to strongly developed, with greatest intensity proximal to fault intersections. In propylitically altered rocks, igneous plagioclase is selectively replaced by albite, epidote, calcite, illite, adularia or rare prehnite, whereas igneous ferromagnesian minerals (e.g., clinopyroxene, hornblende, biotite) are altered to chlorite, epidote, calcite, anhydrite, pyrite or leucoxene. An alteration mineral assemblage containing epidote implies temperatures of formation >240°C (Reyes, 1990).

Veins in the propylitic alteration zone are weakly to moderately developed. Typically, the veins are <10 mm wide and can contain quartz, calcite, anhydrite, epidote and pyrite. In GW47, chalcopyrite and bornite occur in some anhydrite, quartz, pyrite veins. Fluid inclusion measurements obtained from vein quartz from GW47 and GW54 indicate homogenisation temperatures between 243° and 277°C, consistent with formation temperatures for epidote.

Petrography and XRD analyses suggest that propylitic alteration is likely to have extended throughout the intrusive complex, into the base of the volcanic unit, and has been overprinted by phyllic alteration.

3.3 Potassic alteration

Potassic alteration is most strongly developed in GW52 rocks between 350-1500 mMD. Weakly to moderately developed, it is a pervasive and selective style of alteration. It is characterised by sporadic intervals of biotite, magnetite and K-feldspar development, within the propylitic alteration zone and overprinted by propylitic alteration minerals.

Veins include quartz, anhydrite and pyrite, with both biotite and K-feldspar occurring as haloes of pervasive wallrock replacement adjacent to these veins.

3.4 Calc-silicate alteration

Calc-silicate alteration is only recognised in GW47 drill core. It manifests as veins containing clinopyroxene, magnetite, garnet, prehnite, apatite and albite (Figure 5). Garnet is present in samples from 1298 m and 1458 mMD and was only recognised using thin section petrography. It is likely to have a more widespread distribution.

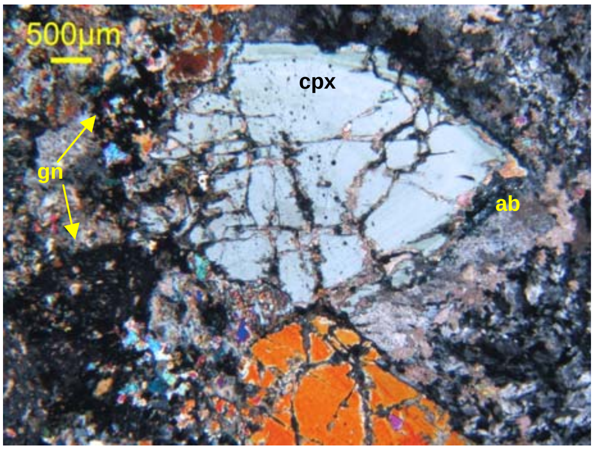

Figure 5: Clinopyroxene-albite vein in diorite, GW47 1458.0 mMD. Euhedral vein clinopyroxene (cpx) lines the vein (right; top to bottom), with albite (ab) filling the vein centre. Albite is partially altered to calcite. Fine grained (isotropic) garnet (gn) alters wallrock, in an alteration halo adjacent to the vein. Crossed polarised light.

The calc-silicate mineral assemblage with garnet, clinopyroxene and magnetite indicates high temperatures of formation (>300°C) (Bird et al., 1984), similar to magmatic-hydrothermal systems such as skarns and porphyry systems. Vein magnetite occurs between 770 m and 850mMD, within the phyllic zone and overprinted by a phyllic mineral assemblage (e.g., magnetite is replaced and overgrown by pyrite). In addition, clinopyroxene, garnet and albite have all been partially altered epidote, calcite and/or anhydrite (Figure 5). This, along with aplite dikes cutting calc-silicate veins, indicates that the high temperature calc-silicate veins are an early, precursory relict assemblage.

5. SUMMARY AND DISCUSSION

The intrusive complex encountered by GW47, GW54 and GW52 is dominated by texturally heterogeneous (i.e., cumulate, equigranular and porphyritic) clinopyroxene diorite.

Generally, an early coarse grained dioritic (equigranular to cumulated) phase has been intruded by a later fine grained diorite (equigranular to porphyritic). The texturally different shallow intrusions are compositionally similar, suggesting a common source.

The intrusive complex is a discontinuous accumulation of successive magma intrusions. In this scenario, new injections of magma will react in various ways depending on the total volume and flow rate of the magma pulse, along with the crystallinity and hence, rheology of the partially crystallised mush being intruded. If the host rock (or crystal mush) is solid and cold, then one would expect simple dikes with little or no remelting of the host rock. As the temperature of the host rock/mush approaches its solidus, the effect of heating from the new magma batch would be expected to cause some marginal melting, which might be indicated by simple 'backveining' (Wiebe et al., 2004). As temperatures rise above the solidus, the strength of the host rock may drop rapidly as melting occurs, and the new injections may begin to break down into either brittle or pillow-like segments characteristic of synplutonic dikes (Pitcher, 1991).

The rheological behavior of the coarse diorite and how it reacts with new diorite batches, results in a series of different rock textures and contact types that range from irregular and gradational to sharp, and/or enclave rich zones. Textural differences within the clinopyroxene diorite complex are related to the emplacement/cooling conditions of the diorite magmas that were probably emplaced as sills. The sub-horizontal contacts between different intrusive batches, the vertical textural and mineralogical variation observed in GW47, GW54 and GW52 implies multiple events of sub-horizontal intrusions.

The clinopyroxene diorite has been intruded by swarms of porphyritic diorite and aplite dikes. The diorite dikes have the same mineral assemblages as the clinopyroxene diorite pluton, implying the continuous emplacement of the same magma type. Aplite dikes, a relatively minor, late-stage event, intrude both the clinopyroxene diorite pluton and dikes, and cross-cut veins containing high temperature magmatic-hydrothermal mineral assemblages (i.e., clinopyroxene, garnet and magnetite), but they are propylitically altered. The switch from sub-horizontal to sub-vertical magma emplacement (dikes), implies a change of the least principal stress field, from vertical to horizontal. This stress field change is likely to have been caused by sector collapse of the Luise crater (Sillitoe, 1994).

Hydrothermal alteration types are phyllic, propylitic, potassic and calc-silicate. In GW47 there is an upper ~1000 m thick interval of phyllic alteration, with an intense zone at the top of the diorite pluton between 400 m and 600 mMD. This zone correlates with the MT conductive layer described by SKM (2007) that extends from Minifie northwards to the Luise Crater rim. XRD analyses demonstrate that interlayered illite-smectite is the dominant clay mineral within this zone, suggesting temperatures of formation below ~210°C (Browne and Ellis, 1970). These temperatures are consistent with fluid inclusion homogenisation temperatures obtained from vein quartz from the phyllic zone (sample 535.7 m), which are between 164°-195°C. Thus the conductive zone represents an interval where fluids (<200°C) have infiltrated the upper parts of the intrusive complex. GW47 drill core logging indicates that ~50% of the significant fault intersections occur within the phyllic zone, between 475-650 mMD. These faults have provided the necessary pathways for the infiltration of dilute fluids at these depths.

In GW47 the propylitic alteration (chlorite, epidote, quartz, calcite, pyrite, anhydrite, albite, illite) extends below 1060 m down to 1480.5 mMD (TD). Potassic alteration (K-feldspar, biotite) occurs sporadically between 1100 m to 1400 mMD. Thin section examination shows that both propylitic and potassic alteration zones extended to shallower depths (e.g., 628.4 mMD) and have been overprinted by phyllic alteration assemblages. Epidote occurrence indicates reservoir temperatures >240°C and these temperatures, comparable to the homogenisation temperatures in vein quartz sample 675 m (243 - 260°C), are more likely to be representative of present reservoir conditions.

Calc-silicate alteration is recognised by hydrothermal garnet, clinopyroxene and magnetite, only in GW47. These minerals are typically associated with high-temperature magmatic-hydrothermal systems, such as skarns and porphyry systems, and generally form at temperatures exceeding 300°C (Bird et al., 1984). Garnet is fine grained, incipiently developed and in relatively minor abundances, whereas clinopyroxene and magnetite occur as coarse grained crystals in veins filled with albite. These magmatic-hydrothermal minerals occur in veins cut by late-stage aplite dikes and have been partially replaced by epidote, calcite and anhydrite. They represent a pre-sector collapse, high-temperature, relict alteration assemblage, no longer in thermal equilibrium with present reservoir conditions.

The dominant hydrothermal alteration assemblage present in the area drilled by GW47 and GW54 is different to that in GW52 and the mine area (Moyle et al., 1990; Carman, 2003). Potassic alteration, the predominant hydrothermal alteration assemblage at depth in the region of the mine (and GW52), is not strongly developed in the two exploration wells north of the mine area (GW47 and GW54). Instead, propylitic assemblage that is marginal to the mine area (SKM, 2007) is intensely developed in the two northern wells.

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