# Evolution of the Ladolam Geothermal System on Lihir Island, Papua New Guinea

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**Keywords:** Ladolam, Luise, Lihir, epithermal gold, sector collapse, overprinting

## ABSTRACT

An active geothermal system and a 44 million ounce epithermal gold deposit are superimposed on Lihir (or Niolam) Island. Recent petrology studies and geophysical surveys indicate that the Ladolam geothermal system has a very complex history. Many previous authors have recognised that a major sector collapse has affected this system, but there is now evidence for two such collapse events. Those two sector collapses have had a significant effect on the geothermal system and on gold deposition.

The first collapse exposed a deep level hydrothermal system with potassic alteration and incipient porphyry copper-gold mineralisation. Subsequently a shallow geothermal system with epithermal gold mineralisation developed. Recent geophysical surveys and exploration drilling indicate that a second sector collapse then removed much (and in places all) of the clay cap from this epithermal system, exposing at the surface minerals like illite-smectite that typically form at a depth of 100 m or more.

Both sector collapse events probably contributed to gold deposition. The geothermal system has survived both of those events, and remains active and continues to deposit gold today. However, the hydrology of the system has been affected by the collapse events, with more rapid cooling where the clay cap has been removed.

## 1. INTRODUCTION

The Ladolam geothermal system is located within the Luise 'caldera' on Lihir Island in Papua New Guinea, as is a major epithermal gold deposit. Mining of the 44 million ounce gold resource began in 1997, and since 2003 the geothermal system has supplied much of the power (presently 56 MWe) for the mine and facilities. Mining was initially in the Minifie area in the south, and has gradually moved north to the Lienitz and Kapit areas (**Figure 1**). Mineralisation extends to at least 300 m below sea level, and to the north beneath the sea.

## 2. GEOLOGY

Lihir is part of the Tabar to Feni chain of Pliocene to Recent volcanic islands between New Ireland and the West Melanesian Trench. Luise Volcano comprises one of five separate volcanic centres on Lihir, and consists of Pleistocene intrusives, lava, breccia, and tuff. An elliptical 6 km by 4 km amphitheatre or 'caldera' within this volcano encloses Luise Harbour, the Ladolam gold deposit, and most of the active geothermal system.

### 2.1 Lithologies

Volcanic rocks, comprising lava, tuff and volcanic breccias, predominate in the upper parts of the gold deposit and on its margins. Lavas become less common to the north, where breccias predominate, consistent with the northern area being more distal from a volcanic centre to the south. Fragmental rocks include both pyroclastics (*e.g.* agglomerates, pyroclastic breccias, lapilli tuffs and tuffs) and epiclastics (including breccias, conglomerates and sandstones). Intrusives are exposed within both the Lienitz and Minifie pits, and were exposed at the surface in the Lienitz area prior to mining (Moyle *et al* 1990). In the Kapit area, most holes encounter intrusives at around -300 masl. Multiple intrusive phases have been observed, ranging from coarse equigranular monzonites to porphyritic varieties, and thin fine grained dykes. Results from recent deep geothermal wells within the Lienetz and Kapit sectors indicate that diorite/monzonite intrusives occur predominantly from -600 masl to around -1400 masl (geothermal well GW66). Dating of biotite inclusive to the alteration suite of these rocks gave an age of 0.9–1.0 Ma. (Leach, 2006).

In addition to the primary pyroclastic and epiclastic breccias, there are a variety of hydrothermal breccias, especially above about -500 masl. The most significant are the milled matrix breccias that host much of the ore. These comprise intensely K-feldspar altered pyrite-rich breccias. They have considerable lateral extent, and variable vertical extent, being more vertically extensive adjacent to significant structures. Anhydrite cemented breccias in the deep geothermal reservoir contain potassic and propylitic altered clasts in an anhydrite matrix. These are interpreted to have formed at the time of potassic alteration, long before the active geothermal system.

### 2.2 Hydrothermal Alteration

There have been two main phases of alteration, which produced five different assemblages: early porphyry-style potassic and propylitic alteration, and later phyllic, argillic, and advanced argillic assemblages.

Potassic alteration is characterized by secondary biotite, K-feldspar, anhydrite and magnetite, with biotite forming over 30 volume% of some samples. Hydrothermal fluids at over 300°C and a strong magmatic signature are implied.
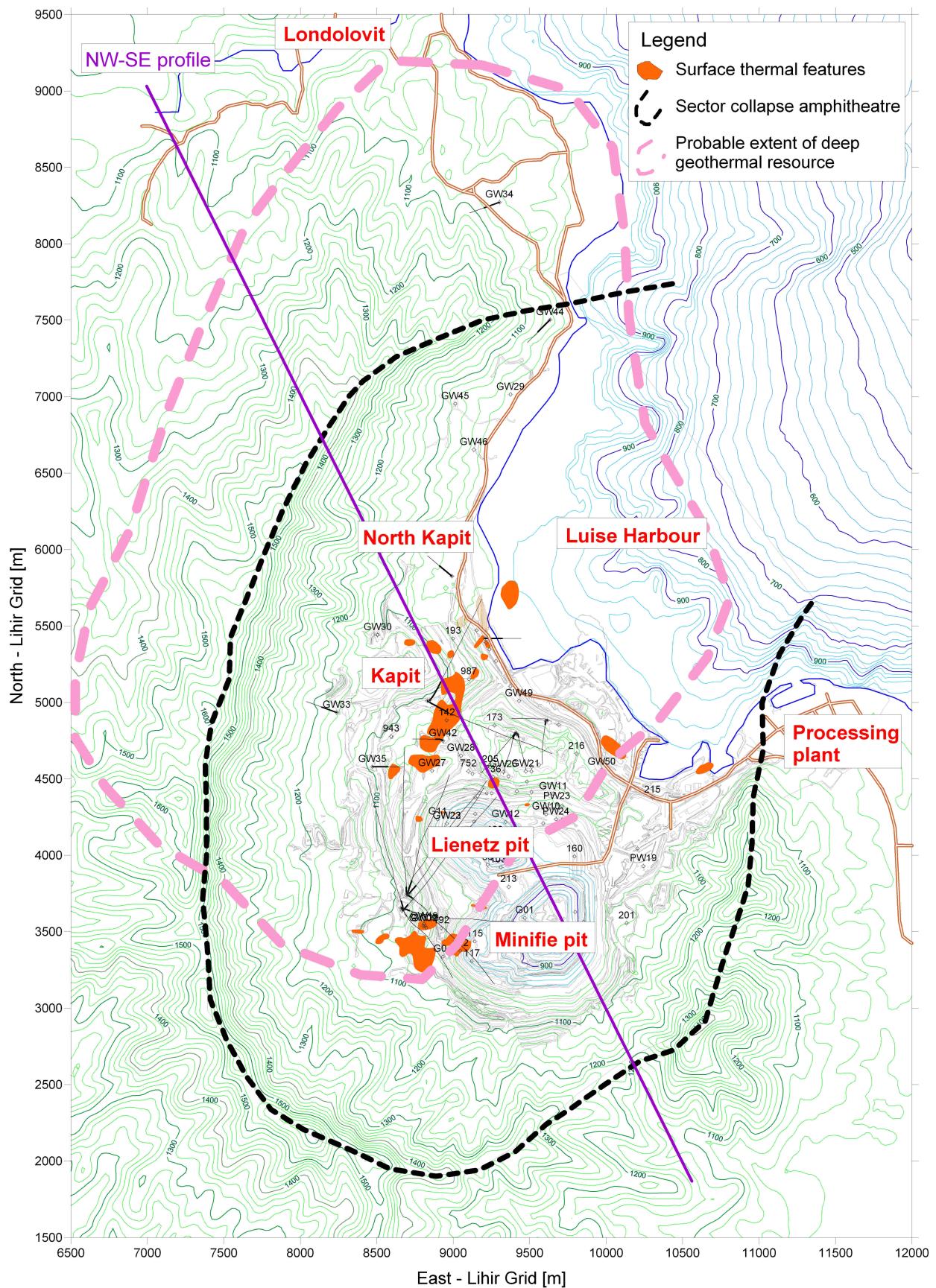
**Figure 1:** **Location map of the Lihir gold mine and the Ladolam geothermal system on Lihir Island, Papua New Guinea, showing the extent of the deep geothermal reservoir from MT data, areas of surface thermal activity, geothermal well tracks, the location of Lienitz, Minifie and Kapit pits and the line of the cross section in Figure 3. Elevations are in mine grid, which is approximately masl +1000**

Potassic alteration is most common within and adjacent to the intrusives, and is preserved as shallow as -100 masl, though it is typically overprinted by argillic and/or phyllic assemblages at these levels.

Propylitic alteration is characterised by secondary amphibole, chlorite, albite, calcite, magnetite and minor epidote. Propylitic assemblages are marginal to potassic alteration in the Lienitz, Coastal and Minifie areas, and are widespread to the north. Minerals such as amphibole and magnetite indicate a similar temperature of formation to the potassic alteration, although assemblages lacking these minerals could have formed at lower temperatures. The mineralogy reflects a lower degree of water:rock interaction than potassic alteration, consistent with lower permeability and/or peripheral locations.

Argillic altered material forms clay-rich rocks, dominated by smectite, kaolinite and interlayered illite-smectite clays, together with quartz, pyrite and gypsum. These assemblages indicate cool fluids of near neutral pH. Argillic alteration extends from the surface to about -100 masl in the Coastal, Lienitz and Kapit areas, and shallower in the Minifie area.

Below about -100 masl, argillic alteration grades down into phyllic assemblages, which range from clay-rich to quartz-rich. The clay appears to be mainly illite, along with quartz, K-feldspar (adularia) and pyrite. This alteration indicates somewhat hotter, near neutral pH conditions.

Advanced argillic alteration comprises quartz-alunite-kaolinite assemblages, which are exposed at the surface in the Minifie, Lienitz, Kapit and Coastal areas, and extend down steeply dipping fractures to -200 masl at Lienitz and Kapit (Leach 2004). These assemblages indicate strongly acid fluids, produced at the surface as $H_2S$ gas (originating from boiling at depth) condenses into shallow oxidised groundwaters, and also by the oxidation of sulphide minerals. This assemblage indicates low pH fluids, and in this setting, low temperatures.

### 2.3 Alteration Overprinting

Based on boiling point for depth constraints (Figure 2), potassic and high-temperature propylitic alteration formed at a depth of over 1100 m, meaning that more than 1100 m of overlying material has been removed since they formed. These assemblages are very obviously not in equilibrium with current conditions, consistent with mineralogical evidence of overprinting by advanced argillic, argillic and phyllic assemblages (*e.g.* biotite has been replaced by clay, and magnetite by pyrite). Overprinting ranges from slight to moderate below about -100 masl to complete at shallow levels. The presence of relict potassic alteration near the surface implies that a large amount of overlying rock was removed after this alteration event, and prior to phyllic, argillic, and advanced argillic alteration.

Further overprinting is seen within the phyllic and argillic assemblages, which are also not entirely in equilibrium with present conditions. In other geothermal systems, pure smectite typically gives way to interlayered illite-smectite where temperatures exceed about 150°C, then illite appears at about 230°C, and sericite at 270°C. These temperatures correspond to minimum depths (based on boiling point for depth constraints) of about 40, 280 and 590 m, respectively, below the water table (Figure 2), assuming a 10% NaCl fluid. Lower salinities and dissolved gases would increase these depths (Figure 2), but a 10% NaCl fluid approximates to the conditions at Lihir. If there was a deep water table,

as could well have been the case, the thickness of overlying rock could have been much greater. The present temperature profile in the Kapit area is close to a boiling point gradient, with the 150°C isotherm at about -50 m, 230°C at -330 m, and 270°C at -600 masl.
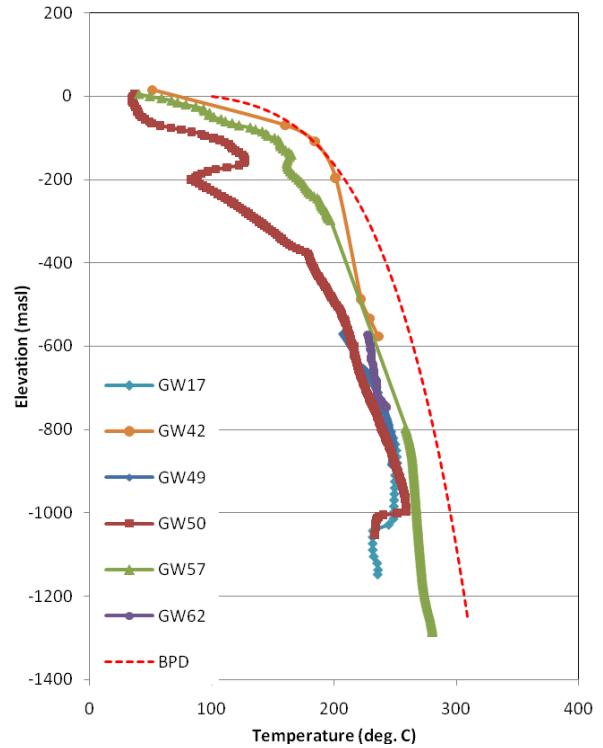


**Figure 2: Temperature (°C) – depth (m asl) plot showing a theoretical boiling point for depth (BPD) curve, and actual temperature profiles for selected geothermal wells at Lihir**

In a recent study of the Kapit area, illite-smectite, illite and sericite were reported as shallow as 62, 90 and 144 m, respectively (Leach 2004). This means that illite is present at least 190 m shallower than where it could have formed, and sericite is 445 m too shallow. Disequilibrium is also indicated by the presence of two clay species (smectite and illite-smectite, or illite and illite-smectite) in many samples, while two samples were reported to contain smectite, illite-smectite and illite. In one drillhole (1105), smectite (at 312 and 320 m) and illite (at 320 and 344 m) occur below sericite (at 293 m). In at least one sample, Leach (2004) described illitic clay overprinting 'micaceous clay' (sericite).

An estimated fluid inclusion temperature of >~250° for a sample from 129 m (drillhole 1115) is equally inconsistent with the abundant smectite in this sample, and with a maximum possible temperature at this depth assuming boiling conditions at the surface, of 195°C (250°C implies a depth of at least 400 m).

Thus, the petrology data indicates that not only are the potassic and propylitic assemblages overprinted, but there has been overprinting of phyllic and argillic assemblages. Some of the phyllic and argillic minerals formed at greater depths than where they presently occur. Evidently, at least 450 m of material has been removed from the top of the system, and possibly more, depending on the depth to the water table during the period of hydrothermal activity.

Since the argillic (smectite) clays are largely responsible for the zone of low resistivity that outlines geothermal systems, an abnormal MT pattern might be expected.

## 4. GEOPHYSICS

Various geophysical methods were used at Lihir during exploration of the gold deposit. Of these, aeromagnetic surveys in 1987-1988, which extended across and beyond the Luise 'caldera', assisted with assessing the geothermal system. A magneto-telluric (MT) resistivity survey was conducted in 2004 specifically to investigate the extent of the geothermal system. That survey covered the 'caldera' and an area to the north-west that could be accessed reasonably easily (without overnight camps). An extended MT survey in 2007 added more points in the coastal area to improve and extend coverage of the resource under Luise harbour.

The aeromagnetic surveys indicated that the zone of hydrothermal alteration may extend 1 or 2 km to the northeast from Kapit under Luise harbour. This indicates that the deep reservoir may also extend in this direction.

The MT surveys defined a shallow conductive layer that is interpreted as mainly due to argillic alteration. Drilling has since confirmed that much of the area beneath the conductive cap comprises geothermal reservoir.

Within the 'caldera', the low resistivity layer is truncated by the ground surface (**Figure 3**). This is an unusual feature of Lihir that is not typical of active geothermal fields. However, it is consistent with petrographic evidence that the upper part of the system was removed after the low resistivity clay layer had formed, and subsequent overprinting by new a new equilibrium assemblage is incomplete. Resistivity cross sections are consistent with the upper part of the Ladolam geothermal system having been removed.

The base of the conductive layer typically corresponds to a temperature of about 230°C (from the upper temperature limit of clays containing smectite), and therefore a minimum depth of 310 m, based on boiling point for depth constraints. In places, the clay layer is completely absent, though it is partly preserved over much of the mine area

## 5. DISCUSSION

### 5.1 The Origin of Luise 'Caldera'

The common definition of a caldera is a wide, shallow depression of volcanic origin, formed by volcanic collapse, and triggered by the emptying of the magma chamber beneath the volcano, often due to a large eruption. The Luise 'caldera' has been variously attributed to volcanic explosion (*e.g.* Plimer *et al* 1988), volcanic collapse, or sector collapse (*e.g.* Moyle *et al* 1990). Several features point to Luise 'caldera' originating as a non-volcanic sector collapse, rather than being a true caldera or a volcanic crater. These include:

- A caldera forms by collapse or subsidence into the top of a magma chamber (*e.g.* Cole *et al* 2005). Caldera-forming events are associated with volcanic eruptions, which typically deposit hundreds to thousands of metres of ash within the caldera, and tens to hundreds of metres outside it. Yet at Lihir, a deep level of the volcanic pile is exposed, and intrusive rocks crop out at the surface. There is a lack of young volcanic ash, or any young volcanic features such as vents, cones, domes, craters or lava flows within or close to the Luise 'caldera'. This indicates that all volcanic activity had ceased before the collapse event.

- Raised coral reefs surround most of the island, but are absent from Luise Harbour. This may be because the reef was removed during sector collapse, although the presence of sea-floor hydrothermal vents in the harbour may prevent them from forming.

- A large submarine debris flow is visible on detailed bathymetric maps (Herzig *et al* 1994), extending for more than 10 km to the northeast of Luise Harbour (Figure 4).



**Figure 3: Northwest to southeast cross section through the Lihir gold mine and the Ladolam geothermal system, showing the MT survey points (black spots), subsurface resistivity pattern from 3D modelling, geothermal wells and subsurface temperature contours. The location of this section is shown on Figure 1.**
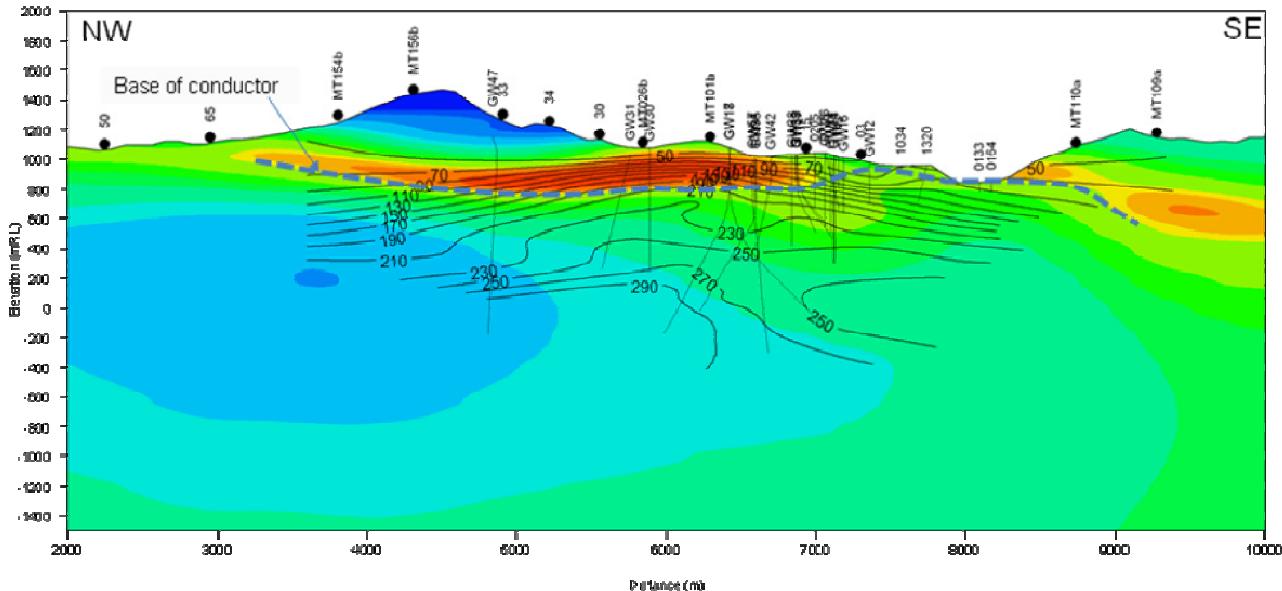
- Retrograde, rather than prograde hydrothermal overprinting. Subsidence associated with a caldera means that surface rocks will be buried beneath pyroclastics and/or sediments, and so will be overprinted by higher temperature alteration assemblages. In contrast, a sector collapse removes material, so that deeply buried rocks are exposed at the surface, and high temperature alteration assemblages are overprinted by lower temperature assemblages (Figure 5). Furthermore, the accompanying rapid (instantaneous) depressurization that accompanies sector collapse would initiate widespread boiling over a significant depth interval, which might explain the laterally extensive hydrothermal breccias within the Luise caldera.

- Petrographic and geophysical evidence indicates that several hundred metres of material was removed from above the Ladolam geothermal system relatively recently. With a lack of evidence for recent tectonic or volcanic activity, a sector collapse seems the most likely mechanism.

Geophysical and petrographic evidence presented here indicates that the most recent sector collapse within the Luise amphitheatre removed at least 450 m, and possibly more, from the top of an active geothermal system. This produced a debris flow that can be seen on sea-floor bathymetry images, extending more than 10 km out to sea (Figure 4). The topographic signature of the older collapse event is no longer distinguished, and the size and scale of this event are uncertain. Potassic alteration is exposed at the surface now, but may still have been buried after the first collapse event.



**Figure 4: Topography of Lihir Island and bathymetry of the surrounding sea floor (from Herzig *et al* 1994), showing a debris flow extending offshore to the northeast from Luise Harbour. This figure covers an area about 30 km by 40 km; Lihir Island is 22 km long**

Therefore the Luise sector collapse is not a caldera according to normal usage of the term, and it would be more appropriately called an amphitheatre or basin.

### 5.2 Effects of Sector Collapse on the Geothermal System

Various authors (e.g. van Wyk de Vries *et al* 2000) have proposed that volcanic edifices are initially built at the angle of repose of scoria, pyroclastics, and lava flows, producing a stable structure. However, with time the internal strength of this structure can be reduced by hydrothermal alteration, until it becomes mechanically unstable, with an inherently high potential for catastrophic failure. Many large volcanic cones, especially those that overlie geothermal systems, are scarred by sector collapses, underlining the link between altered volcanic materials and slope collapse. Examples of sector collapses on hydrothermally altered volcanoes include Mt St Helens, USA (*e.g.* Glicken 1996), Casita and Mombacho in Nicaragua (Cecchi *et al* 2005), several Caribbean volcanoes (Boudon *et al* 2007), Egmont, New Zealand (Palmer *et al* 1991), Papandayan, Indonesia (Hadisantono 2006) and Ritter Island, Papua New Guinea (Johnson 1987).
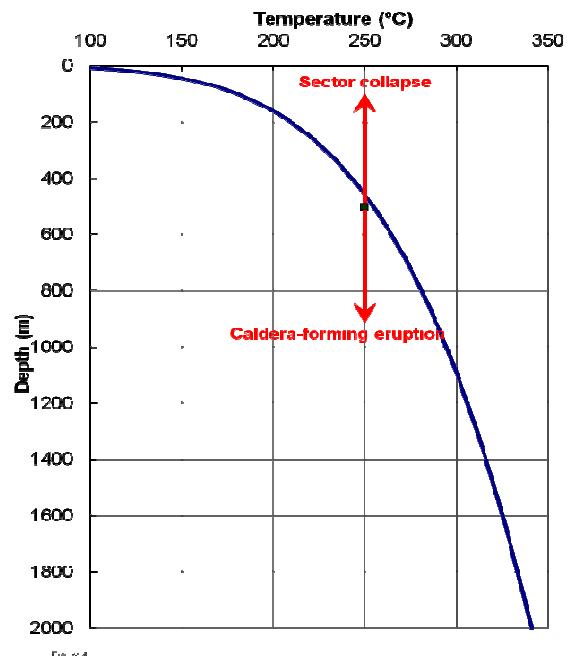


**Figure 5: Temperature – depth plot, showing a boiling point for depth curve and the effects of sector collapse (removal of material) and a caldera- forming eruption (deposition of material) on a point originally at a temperature of 250°C and at a depth of 500 m in a hydrothermal system.**

The second collapse event removed a variable thickness of material, ranging from 100-200 m in some places (where just part of the conductive layer was removed) to more than 310 m (from geophysics) and possibly over 450 m (based on petrology) locally. In total, more than 1100 m was removed by both events, so the first collapse must have been even larger than the second, removing a package of material more than 500 m thick. Dating of secondary K-feldspar inclusive to the mineralizing event indicates that these collapse occurrences happened 0.3 to 0.7 My ago (Leach, 2006).

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Overprinting of both events is incomplete, with mineralogical evidence remaining of the older regimes. However, there was sufficient time after the first collapse

event for a clay cap and associated conductive layer to form, meaning the geothermal system reached a state of equilibrium that was maintained for some time. There has not been sufficient time for a new conductive layer to form after the second collapse event, meaning that the second sector collapse is relatively recent.

The base of the second sector collapse was located within the smectite-rich clay cap above the system. This layer would have been inherently weak, due to the abundant smectite clays. Failure of this material could have been triggered by seismic activity, an intense rainfall event, or the sudden acceleration of a gradual creep process.

The base of the previous large collapse event was probably deeper, for more than 1100 m to have been removed in total by the two collapse events, and for potassic alteration to be exposed at the surface now. That failure was not assisted by weak smectite-rich clays, but must have involved a different process.

Sector collapse amphitheatres are relatively common on island arc volcanoes, although to date, no others have been found that are mineralised to the same extent. Therefore, a sector collapse above an active hydrothermal system cannot be the reason for the large gold deposit on Lihir, although it could be a contributing factor. The large flux of gold through the Lihir system, estimated at 24 kg per year by Simmons and Brown (2006), must play an important role in the scale of this deposit.

So it would appear that Lihir was destined to become a significant gold deposit before the collapse event occurred.

The unloading that accompanied sector collapse will have caused large-scale boiling and hydrothermal brecciation, which focused gold deposition in a subhorizontal, near-surface brecciated zone. Unlike many epithermal deposits, where the gold is present within veins or disseminated in host rocks, at Lihir the gold largely occurs within the matrix of laterally extensive sulphide-rich breccias (*e.g.* Carman 2003, Blackwell *et al* 2007).

The partial removal of the conductive clay cap from above the Ladolam geothermal system means that its geophysical signature is more akin to an old, eroded hydrothermal system, rather than to an active system. Because the clay cap has been completely removed in one area, the hot reservoir is no longer completely insulated from the overlying cool groundwaters. Normally, the clay cap forms an impermeable blanket, which minimises the inflow of cool groundwater (or seawater) down into the system. Since the sector collapse, it has been possible for those waters to enter that part of the system that no longer has a clay cap, so that more cooling has occurred there than in the parts where the clay cap is preserved (Figure 6).

## CONCLUSIONS

The gold mine and geothermal system at Lihir are located where there has been not one but two separate major sector collapses on the flanks of an island volcano. Each of those collapse events removed a pile of material several hundred metres thick. Both collapse events appear to post-date all volcanic activity. Physical processes (*e.g.* boiling) that resulted from sector collapse may have helped to focus gold deposition, but the high gold flux within this geothermal

system probably had a greater effect in creating the major gold deposit.

## REFERENCES

Blackwell, J., Cooke, D.R., McPhie, J., New, B., and Robinson, J. (2007), Alkalic epithermal and porphyry-style mineralization, Ladolam, Lihir Island, Papua New Guinea. In Circum-Pacific Tectonics, Geologic Evolution, and Ore Deposits, a symposium in honor of William R. Dickinson, Tucson, Arizona, sponsored by the Arizona Geological Society.

Boudon, G., Le Friant, A., Komorowski, J.-C., Deplus, C. and Semet, M. P. (2007), Volcano flank instability in the Lesser Antilles Arc: Diversity of scale, processes, and temporal recurrence, Journal of Geophysical Research, 112: B08205.

Carman, G. (2003): Geology, mineralisation and hydrothermal evolution of the Ladolam gold deposit, Lihir Island, Papua New Guinea: Society of Economic Geologists, Special Publication No. 10, 247-284.

Cecchi, E., van Wyk de Vries, B., Lavest, J-M. (2005): Flank spreading and collapse of weak-cored volcanoes. Bulletin Volcanol. 67: 72-91.

Cole, J.W., Milner, D.M. and Spinks, K.D. (2005): Calderas and caldera structures: a review. Earth Science Reviews 69: 1-26.

Glicken, H. (1996): Rockslide-debris avalanche of May 18, 1980, Mount St Helens Volcano, Washington. USGS Open-file Report 96-677.

Johnson, R.W. (1987): Large-scale volcanic cone collapse: the 1888 slope failure of Ritter volcano, and other examples from Papua New Guinea. Bulletin Volcanol. 49: 669-679.

Hadisantono, R. D., (2006): Devastating landslides related to the 2002 Papandayan eruption. Jurnal Geologi Indonesia, Vol. 1 No. 2: 83-88

Herzig, P.M., Hannington, M.D., McInnes, B., Stoffers, P., Villinger, H., Seifert, R., Binns, R., and Liebe, T., 1994, Submarine volcanism and hydrothermal venting in Papua New Guinea: EOS, American Geophysical Union Transactions, v. 75, p. 513.

Leach, T.M. (2004): Alteration and mineralization in the Kapit deposit, Lihir Gold Mine. Unpublished report prepared for Lihir Gold Mine.

Leach, T.M. (2006): Field comments on the alteration and mineralization, Kapit ore body, Lihir, PNG. Unpublished report prepared for Lihir Gold Limited.

Moyle, A. L., Doyle, B. J., Hoogvliet, H., and Ware, A. R., (1990): Ladolam gold deposit, Lihir Island. In Hughes, F.E. (ed.) Geology and mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy, Monograph 14: 1793-1805.

Palmer, B.A., Alloway, B.V. and Neall, V.E. (1991): Volcanic-debris-avalanche deposits in New Zealand – lithofacies organization in unconfined, wet-avalanche flows. In Fisher, R.V. and Smith, G.A. (eds.) Sedimentation in Volcanic Settings. Society of Sedimentary Geologists (SEPM) Special Publications 45: 89-98.

Plimer, I.R., Andrew, A.S., Jenkins, R., Lottermoser, B.G. (1988): The geology and geochemistry of the Lihir

gold deposit, Papua New Guinea. Bicentennial Gold 88, Melbourne, May 1988.

Simmons, S.F. and Brown, K.L. (2006): Gold in magmatic hydrothermal solutions and the rapid formation of a giant ore deposit. Science 314 (5797): 288-291.

van Wyk de Vries, B., Kerle, N. and Petley, D. (2000) A sector collapse forming at Casita volcano, Nicaragua. Geology 28(2): 167–170.
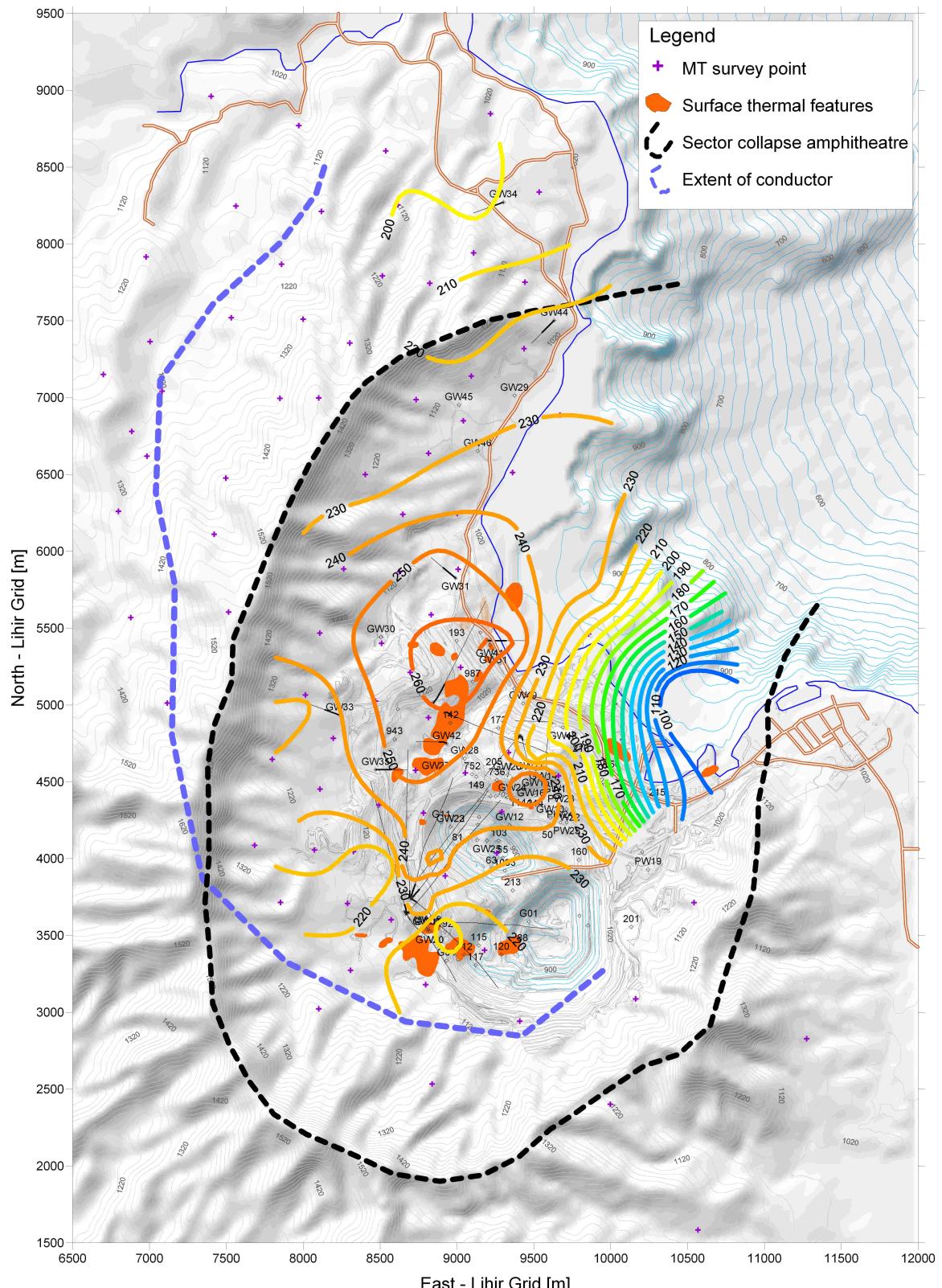


**Figure 6: Map showing the extent of the clay cap (blue dashed line) over the Ladolam geothermal system, as determined from MT surveys, and subsurface temperature contours at -600masl based on measurements from geothermal wells (coloured lines)**