Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

APPLICATION OF MINERAL DEPOSIT CONCEPTS TO GEOTHERMAL EXPLORATION

Ian Bogie[1] and Jim Lawless[1]
[1]Kingston Morrison Ltd., PO Box 9806, Newmarket, Auckland, New Zealand
e-mail: ib@auck.km.co.nz

Key Words: geothermal, mineral deposit, gold, dilational jog, hydrothermal alteration, acid fluids, magmatic volatiles

ABSTRACT

The recognition that epithermal and porphyry mineral deposits are the fossil equivalents of geothermal systems has led to the successful application to mineral exploration of principles learnt in the development of geothermal systems for energy extraction. Similarly, technology developed for mineral exploration can be successfully applied to geothermal exploration.

Low sulphidation epithermal gold deposits are found mainly in highly permeable tensional structures within dilational jogs. Recognition of this structural pattern in active systems allows targeting of geothermal wells into open tensional structures.

High sulphidation epithermal gold deposits produced by acid, condensed, magmatic volatiles have a wider gangue mineral suite than unmineralised alteration produced by acid oxidised steam condensates. Recognition of these gangue minerals allows identification of alteration by different types of acid fluids in active systems allowing adoption of appropriate strategies for dealing with them when developing the system.

Porphyry deposits have large concentric alteration zones. Identification of these zones in an active geothermal system can point to the identification of low-grade Cu-porphyries at depth that still retain fracture permeability that presents prime deep targets for geothermal wells.

1. INTRODUCTION

The idea that ore minerals form in geothermal systems goes back to Agricola (1556). It has subsequently received the advocacy of White (1955, 1981) and has been elucidated by Ellis and Henley (1983). In the last two decades, mainly in response to the discovery of the giant Lihir gold deposit in an active geothermal system in PNG (Moyle, et al., 1990), the mineral industry has made extensive use of concepts established during the development of active geothermal systems. This utilisation has been directed mainly towards the exploration for low sulphidation epithermal gold deposits. However, despite the considerable scientific research that goes into mineral exploration there has been limited technology transfer back to the geothermal industry. This paper considers how information from three major classes of hydrothermal ore deposit can be utilised to help solve three major geological problems in geothermal resource development.

2. TARGETING HIGHLY PERMEABLE STRUCTURES

Highly permeable zones in geothermal wells with deep reservoir water levels and deep permeability are marked by unrecoverable, total circulation losses even when drilling with air assistance. The cuttings produced just prior to the loss zone disappear into the formation. In addition, if a core is cut, recovery within the permeable zone can be poor and only the footwall of the feature sampled. Furthermore, it is modern practice to drill blind at the earliest opportunity below the production casing. As a result little geological information, other than the location of drilling breaks, is obtained from the deeper part of wells because coring at depth is usually minimised in response to concerns over costs and well integrity.

In geothermal wells, which are drilled with water, in artesian geothermal systems, with comparatively shallow permeability, a large pressure difference between the well bore and the formation may not exist. Hence, highly permeable zones will not necessarily be accompanied by a total circulation loss. Cuttings from the permeable zone may therefore be recovered. However, such material is rarely examined petrologically. This is because petrologic analysis is usually not undertaken on all cutting intervals and the location of permeable zones is usually not available at the time of cutting interval selection.

These situations give rise to two major problems. Firstly, where the well stratigraphy cannot be related to lithological permeability the actual nature of many permeable zones is poorly known. Secondly, if permeability is assumed to be fault related, circular arguments arise in relating the permeability to surficial features such as aerial photograph lineations. These problems can lead to poor targeting. However, they can be obviated if information is applied from the fossil analogues of exploitable geothermal fields, low sulphidation epithermal gold deposits.

The amount of gold in a low sulphidation epithermal deposit, tens of tonnes (Boyle, 1979), is very large in comparison to the amount of gold present in geothermal waters, at the best tens of parts per billion (Brown, 1986). Hence, a very large mass of water must pass through a given volume of rock to form an economically viable deposit. Consequently, the presence of a rich gold deposit is an indication of ultra-high permeability. So high in fact that the permeability conditions that prevail in forming economic gold deposits are transitory and/or rare, otherwise gold in localised high concentrations would be more common and not command a high value. The permeability normally found in active geothermal fields is therefore likely to be that found before or after gold deposition or may never reach that necessary to form an economically viable gold deposit. Nevertheless, this is a difference in magnitude rather than a fundamental one.

A further difference is that the temperature range where gold precipitates in the majority of these deposits (200 to 270°C) is lower than the current optimum for power generation (270 to 290°C). However, at least in the low sulphidation epithermal gold deposits that form in upflows, the structures in which gold is deposited are fed from depth up the same structures, from a temperature environment attractive for exploitation for power generation. Thus, the large amount of information gained in establishing the structural setting of epithermal gold vein deposits has a useful application in geothermal well targeting.

An excellent example of such a deposit is the Waihi mine in New Zealand (Bogie and Lawless, 1997; 1999). The deposit consists of a series of semi-parallel, steeply dipping veins (Figure 1). Apart from some uplift and erosion, the deposit has not been structurally disturbed and the structures the veins occupy probably retain their original orientation.

The veins have stockworks on their hangingwalls in their shallower portions. In addition to gold as electrum, they contain quartz, adularia, calcite and pyrite with minor base metal sulphides. They have distinctive crustiform, banded, brecciated and vuggy textures with calcite with a platy habit pseudomorphed by quartz. These textures record cyclic dilation, boiling and sealing. Fluid inclusion evidence indicates that the veins were deposited at temperatures between 230 and 270°C from boiling, low salinity but gas rich water. The veins are directly enclosed in an envelope of phyllic alteration, which is enclosed in propylitic alteration. The veins fill faults or tensional gashes. The faults may have originally been normal but have been reactivated as reverse faults. The common feature of tensional gashes and reactivated normal faults is that both are the site of dilational opening, and hence the high permeability. Textural evidence indicates that gold was deposited in response to dilational opening. In terms of geometry, the veins are near vertical, and pinch and swell both laterally and vertically. The veins are located within a structural jog between two strike slip faults, which were not major permeable features themselves. The deeper parts of the structures, which host the veins, would have made an attractive geothermal target for directional wells during their formation.

The permeable structures themselves need not have had much surface expression as some pinch out towards the surface and the relative vertical displacements on them were small, the key movement being their moving apart to create open space. Therefore, prior to erosion they would have been difficult to directly identify on the surface. However, the controlling strike slip faults most certainly would have had a surface expression. It should be noted that this is not an isolated example and the vast majority of low sulphidation epithermal gold deposits share a similar structural setting, making identification of this structural pattern a powerful exploration tool.

Therefore, identification of dilational jogs on major (several kilometres strike length at least) strike slip faults where there is evidence for thermal activity can be used as a geothermal exploration tool. Although this structural pattern can be identified on aerial photographs, their small scale may hinder identification of regional features. However, utilisation of stereo SPOT satellite images provides a means where such strike slip faults can be examined continuously over a distance of tens of kilometres. This allows identification of parallel faults or bends in faults, where dilational jogs are found. Other useful techniques for the identification of dilational jogs are Side Looking Radar and aeromagnetics. The latter has been used in geothermal exploration to identify areas of demagnetisation produced by hydrothermal alteration. Advances in interpretation of aeromagnetics by the mining industry now means that regional structures can be identified by aeromagnetics. These techniques could be usefully applied in geothermal exploration. If these structural patterns are found within an area of low resistivity with associated thermal activity, a high priority geothermal target can be identified. The sense of movement of the strike slip faults can be established from stream offsets on the satellite images. Alternatively, they can be derived from first principles from plate motion vectors; agreement between the two methods is a valuable test. The orientation of the permeable features can then be accurately determined and directional wells targeted accordingly.

2. DIFFERENTIATING ALTERATION PRODUCED BY ACID-SO_4 AND ACID-SO_4-Cl WATERS

Acid-SO_4 waters are common in steam heated secondary geothermal reservoirs found in perched aquifers. Where the primary reservoir is deep, a feature most common in geothermal systems hosted by andesitic stratovolcanoes, these waters may drain down faults back into the primary reservoir. The acid waters are restricted to the structures so that once such acid bearing structures have been identified they can be avoided and the primary reservoir successfully exploited (Rosell and Ramos, 1997).

Acid-SO_4-Cl waters are not only found in shallow perched aquifers but can occur deep within the centre of a geothermal system (Reyes *et al*., 1993), originating from a degassing intrusive. There may not be an accompanying neutral-pH exploitable resource, or such a resource may occur downstream from the centre of the system necessitating the adoption of a very different exploration strategy than if deep acid-SO_4 waters are encountered. Indeed, injection into the central hot acid zone may be considered favourable. Therefore, early recognition of which type of acid water may be present, and what structures it is associated with, are of considerable importance.

Acid-SO_4 and acid-SO_4-Cl waters both produce advanced argillic hydrothermal alteration characterised by the presence of alunite with a kandite at low temperatures and pyrophyllite and diaspore at higher temperatures. Quartz, anhydrite, sulphur, and a polymorph of FeS_2 may accompany them. Such mineral assemblages are also found associated with high sulphidation epithermal gold deposits (Figure 2). Fluid inclusion evidence from the Lepanto deposit in the Philippines (Mancano and Campbell, 1995) indicates that acid-SO_4-Cl waters produced these assemblages in this deposit. However, there are also ore minerals present most notably gold, luzonite and enargite, and in some cases covellite, famantinite, tetrahedrite-tennantite, bismuthinite and tellurides (Sillitoe, 1983 and Bonham, 1983). The occurrence of these minerals is very localised. However there is a more widespread occurrence of zunyite, woodhouseite group minerals (woodhouseite, svanbergite, plumbogummite and goyazite), barite, topaz and dumorteirite (Lawless *et al*., 1999). These minerals serve to distinguish potentially mineralised advanced argillic alteration produced by acid-SO_4-Cl waters from barren advanced argillic alteration produced by acid-SO_4 waters. Fluid inclusion analysis can be useful (Reyes, 1991 and Reyes *et al*., 1993) as acid-SO_4-Cl waters reveal their presence in fluid inclusions by high salinities and the occurrence of daughter crystals. The associated mineralogy may also indicate acid-SO_4-Cl waters. In addition to the minerals listed above, such indicator minerals reported include; apatite (particularly replacing anhydrite), gadolinite, danburite and lazulite (Reyes, 1991 and Reyes *et al*., 1993). The analysis of alunite for both oxygen and sulphur isotopes can also distinguish the type of altering fluid (Rye *et al*., 1992).

The same approach can be used to differentiate the two in active geothermal systems. The identification of the above indicator minerals provides the ability to recognise advanced argillic alteration produced by fluids of an acid-SO_4-Cl chemistry. However, this does not necessarily mean that such fluids are present, as it is always possible that these minerals are relict. Therefore, other minerals indicating current fluids must also be recognised. Such minerals are characterised by being chemically reactive within a later neutral hydrothermal system and hence unlikely to survive. The two important minerals are sulphur and marcasite, accompanied by alunite (Reyes, 1991). Marcasite can also occur and be preserved under near neutral conditions however (Hoskin *et al*., 1994), so its occurrence without alunite can not be considered diagnostic of acid conditions.

It is important to note that the indicator minerals are not always present with acid-SO_4-Cl waters. Therefore, their absence can not be used as evidence that acid-SO_4 waters are present.

3. TARGETING HIGH PERMEABILITY AT INTRUSIVE CONTACTS

Deep, laterally continuous permeability forming domes or ridges that is difficult to unequivocally relate to faults has been reported in a number of geothermal fields. These are associated with andesitic volcanism in island arcs, for example at Mutnovsky, Russia (Kiryukhin, 1993). This permeability is related to intrusive margins. Such permeable zones are very attractive targets in fields with deep reservoirs because other deep permeability can be limited and difficult to predict. Intrusive margin zones are usually very permeable and form large, more easily predicted continuous targets. They are also less likely to receive acid drainage from perched acid-SO_4 aquifers, as they do not provide vertically continuous permeability from shallow parts of the system.

Cores recovered from such zones include a mixture of medium and fine grained intrusives, often with porphyritic textures and dioritic compositions, interfingered with country rock, that is commonly andesitic. They contain stockworks of quartz and/or anhydrite veins containing magnetite and traces of chalcopyrite and bornite. The veins making up the stockworks exhibit textures indicating plastic deformation. The rock is altered to biotite, quartz, magnetite and anhydrite, which are partially overprinted by illite and pyrite. These features are very similar to those found in Cu-porphyry deposits in island arcs. There are two important differences however; the Cu mineralisation is weak, secondly, overprinting is limited. The illite and pyrite overprint that corresponds to the phyllic assemblage of Cu-porphyry deposits is not complete and the late stage argillic overprint common in porphyry deposits is absent. As the illite and pyrite are the currently forming minerals, the implication is that the intrusive margins are low-grade porphyry deposits receiving their phyllic overprint and they will possibly receive an argillic overprint when the system wanes.

The reason why copper should have failed to deposit in any quantity can be found by comparing this situation to the Sto. Tomas II deposit in the Philippines (Sillitoe and Gappe, 1984). This is a large and rich Cu-Au porphyry deposit. It has very little phyllic overprint or surrounding hydrothermally altered rock because the surrounding country rock has very low permeability. Hence, it has been very well sealed such that the ore forming fluids have been trapped and given up all their metals in one place and have not been diluted by inflowing groundwater. It is clear that mineralisation was produced prior to the limited phyllic overprint because mineralisation is present where there is no phyllic overprint.

The low-grade porphyry deposits that are considered to provide deep permeability in geothermal systems may therefore have failed to deposit significant ore minerals because they were not well sealed and the metal bearing fluids have been dispersed. Thus if the ore minerals and the associated gangue have not fully deposited, the original permeability produced by fracturing in response to the release of volatiles from the intrusive (Burnham, 1979) should be partially preserved. In addition, these fractures will be interconnected with the existing fracture network that channelled away the metal bearing fluids and hence be part of a much larger hydrothermal system. Hence it is likely that hydrothermal systems which produce good porphyry deposits are not good geothermal energy prospects and *vice versa*.

The fracturing produced by volatile release from an intrusive will be concentrated mainly around its margins. Typically, the intrusives that produce such fracturing are near vertical stocks about one square kilometre in plan (Sillitoe and Gappe, 1984). Thus, the fracturing produces a significant volume of permeability with a domed shaped distribution. Where multiple intrusions are aligned in response to regional tectonics, the domes of permeability can overlap to form a ridge.

The failure to deposit significant copper does not mean that other geological features of copper porphyry deposits are not preserved. Since these features provide a means for locating fractured stocks rather than being a direct guide to the mineralisation, these geological features can also be applied to finding permeability in island arc geothermal systems.

The main geological feature that provides a guide to the location of fractured stocks is alteration zonation. The alteration zone described above containing biotite is within the area of permeability. This is surrounded by zone where secondary amphibole, K-feldspar and magnetite are present. Secondary garnet and diopside may also be present but are less commonly found. This zone is in turn enclosed in a fieldwide zone of alteration dominated by the presence of epidote, albite and chlorite. A similar but a less well developed assemblage of epidote, albite and chlorite will be found at depth and/or at the centre of the intrusive where permeability is lacking. An idealised zonation is presented in Figure 3.

In active systems, the alteration zones surrounding the permeable zone can be overprinted by the alteration produced by the current system. This will usually take the form of near vertical zones of phyllic alteration surrounding faults, in which case these can have associated permeability themselves. However, as discussed above these are unlikely to be recognised geologically because wells are usually drilled blind at his stage and only widely spaced cores obtained. To be useful a geological feature must be extensive. Therefore, it is the recognition of the zone containing secondary amphibole, K-feldspar and magnetite that is important. This can be applied on a wide scale and the distribution of the minerals plotted in three dimensions can be used to locate possible intrusive margins as future well targets. Alternatively, as these mineral assemblages can be recognised using a binocular microscope during drilling, they provide an incentive to drill the well deeper to find intrusive margin permeability.

CONCLUSIONS

Recognition of the structural pattern of low sulphidation epithermal gold deposits where there is evidence for thermal activity can be used to target geothermal wells into permeable dilational structures at depth.

Minerals diagnostic of high sulphidation epithermal gold mineralisation in areas of advanced argillic alteration can be used to distinguish alteration produced by oxidised steam condensates from that produced by acid magmatic volatiles in active systems. Appropriate strategies can then be used in dealing with any associated acid fluids.

The alteration zonation pattern of Cu-Au porphyry deposits in island arcs can be used to locate fracture permeability at intrusive margins that make prime deep geothermal drilling targets.

ACKNOWLEDGEMENTS

We gratefully acknowledge the review of this paper by paper by our colleagues in Kingston Morrison Ltd, namely P. R. Barnett, P. J. White and A. J. Cartwright.

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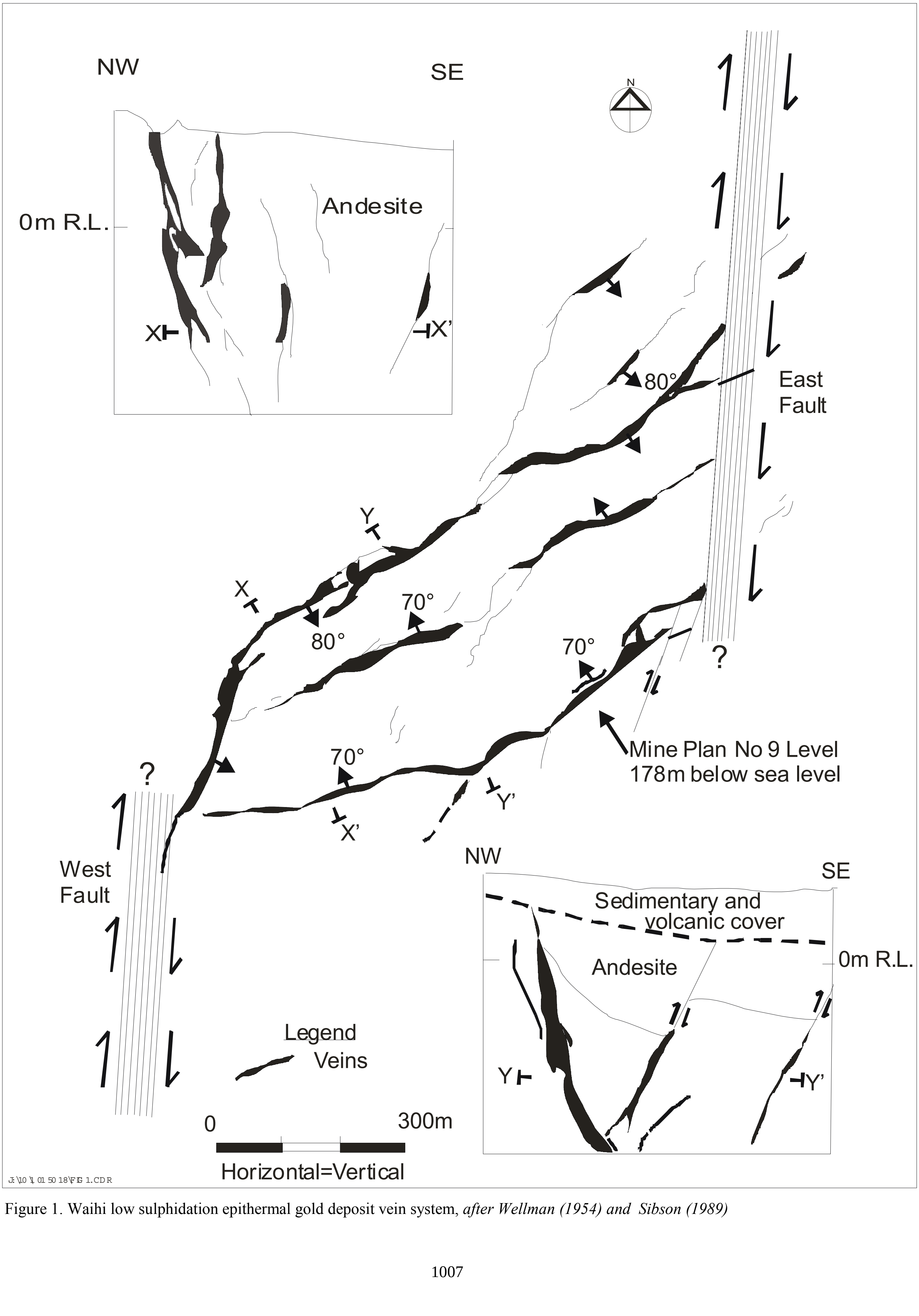

Figure 1. Waihi low sulphidation epithermal gold deposit vein system, *after Wellman (1954) and Sibson (1989)*

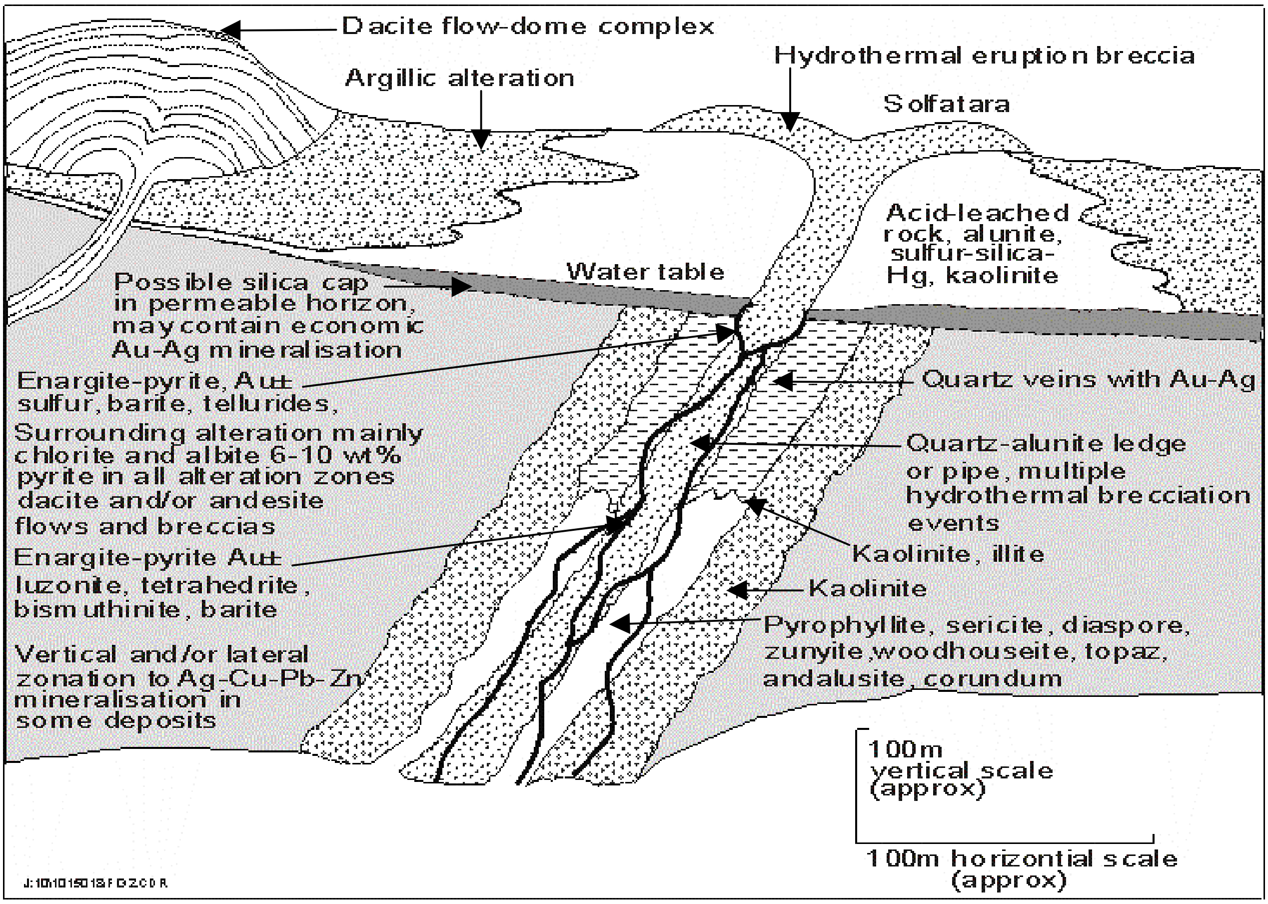

Figure 2. Idealised high sulphidation epithermal gold deposit, *after Bonham (1989)*

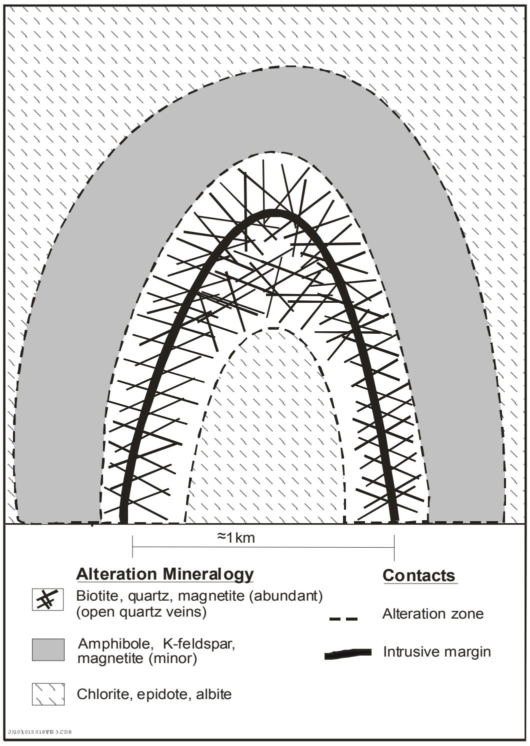

Figure 3. Idealised alteration zonation of an island arc porphyry deposit prior to phyllic and argillic overprinting