MAGMATIC-RELATED HYDROTHERMAL SYSTEMS: CLASSIFICATION OF THE TYPES OF GEOTHERMAL SYSTEMS AND THEIR ORE MINERALIZATION

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Magmatic arc-related hydrothermal systems form where both the heat that drives them and some proportion of their fluid constituents are derived from solidifying magmatic intrusive bodies. A range of types of active systems can form due to variation in the depth and age of the magmatic body and variations in the near-surface hydrological environment.

Subaerial hydrothermal systems can be broadly divided into basinal systems and stratovolcano types. A third type, giant vapour dominated systems, are rare. Intrusives tend to be deep in basinal systems with limited variation in the type of system in this setting. Stratovolcanoes can have much shallower intrusions and can evolve over time to produce a range of active systems. Submarine hydrothermal systems have been divided into arc/back arc and spreading centre systems.

There is potential for Cu-Au porphyry-style mineralisation to be directly associated with the intrusives causing hydrothermal systems in arc type settings. Basinal systems and the associated bimodal volcanism, can produce low-sulphidation epithermal deposits. Young stratovolcanic systems with shallow intrusives can produce high-sulphidation epithermal deposits. Older stratovolcano systems, or those with deeper intrusives, can form intermediate-sulphidation epithermal deposits. Submarine back arc/arc systems produce Kuroko-style deposits and spreading centres produce Cyprus-style deposits.

1. Introduction

Both active and extinct hydrothermal systems can be identified either by current thermal activity or the effects past thermal activity has had on the host rocks. Many of these systems have close spatial associations with magmatic activity and contain evidence, usually of an isotopic nature (Giggenbach, 1992), of their derivation from fluids that contain at least a component derived from magmatic activity. Parts of older systems (and more rarely some young systems) may contain economic hydrothermal ore deposits (Hedenquist *et al.,* 1996; Corbett, Leach, 1998). All these systems can be grouped together as magmatic-related hydrothermal systems (MRHS). Other tectonic-related hydrothermal systems without such a direct magmatic connection can also host ore deposits, but of different types (for example orogenic gold deposits) and are not further addressed herein.

2. Overview of system types

Since currently active MRHS are intact with clearly identified tectonic and hydrological settings and there is potential for more than one type of ore deposit to form in some hydrothermal systems, any genetic classification scheme should be based on active systems.

A problem arises however in that there is a disproportionate amount of information available from the active hydrothermal systems around the world upon which to base a classification, with much more information available from subaerial systems developed for power generation. This introduces a bias against submarine systems and those types of subaerial system that are not developable for geothermal energy production, most notably those with magmatic solfataras which, of any of the systems, are most obviously magmatically-related.

A further bias arises through the greater degree of development of systems in certain countries for historical reasons. Some countries with a large amount of information available from geothermal energy drilling, for example Italy, have high-enthalpy geothermal systems in an unusual or unique tectonic environment (continental collision zone/back arc). Bearing in mind these problems and that these developed systems are estimated to reflect less than 10 % of subaerial geothermal systems. **Table 1** presents a compilation of all the high-enthalpy geothermal systems developed for geothermal energy (up to 2004) divided up into their tectonic setting. If this compilation can be taken to reflect the worldwide distribution of all subaerial MRHS, arc stratovolcanic settings predominate.

Table 1: Tectonic settings of developed high-enthalpy magmatic-related systems (to 2004)

Tectonic Setting	#	%
Continental collision zone	3	4
Continental rift	2	3
Oceanic rift	7	10
Hot spot	1	1
Arc basin	7	10
Arc stratovolcano	41	58
Back arc	5	7
Transform basin	5	7
Total	71	100

The vast majority of magmatic solfataras occur in andesitic stratovolcanoes and while the proportion of andesitic stratovolcanoes with magmatic solfataras to those that host developable geothermal systems is not accurately known, there is possibly a similar number of both. If this is the case, subaerial MRHS are overwhelmingly found in andesitic stratovolcanoes. However the case of Mt Sabalan in Iran, that has recently been successfully drilled (Bogie *et al*., 2005), shows that they occur in intra-plate trachyandesite stratovolcanoes as well.

Hence, no other subaerial environment is as important for hosting MRHS as stratovolcanoes and some of the other environments are spatially restricted to specific areas of the world. For example the transform basin systems all lie in SW USA and NW Mexico. The main unifying aspect of the other systems is that they are, for the most part, located in basins/rift settings.

If submarine geothermal systems are considered however, the predominance of andesitic stratovolcano hosted MRHS may be balanced out by oceanic rift systems. There is approximately 55,000 km of mid-ocean rifts and back arc spreading centres. Accordingly there could be of the order of 1000 or more rift-related submarine geothermal systems.

There are also active submarine andesite stratovolcano hosted MRHS. Approximately half of the submarine andesitic stratovolcanoes examined so far have hydrothermal activity (de Ronde *et al.,* 2003). There is approximately 22,000 km of submarine arcs, which in combination with about 500 active andesitic stratovolcano systems on approximately 25,000 km of subaerial arcs, may provide an overall worldwide total of andesitic stratovolcanoes similar to, but possibly less, than that existing in oceanic rift settings. Submarine MRHS have also been found in back-arc settings away from spreading centres (Binns, 1991), however there is insufficient information to estimate how many there are worldwide. Since submarine back-arcs are more common than subaerial back-arcs there is likely to be more back arc submarine hydrothermal systems than subaerial ones. Due to the low proportion of subaerial back arc systems to subaerial andesitic systems, submarine back arc systems are unlikely to come close to the number of rift or andesitic stratovolcano systems.

The strong chemical and hydrological control provided by the sea in submarine systems, most particularly pressure, does however mean that subaerial and submarine systems are very different.

The high-temperature MRHS under study belong to the systems associated with insular-arch andesite volcanism according to the geological-hydrochemical classification by R. Henley and A. Ellis (Henley, Ellis, 1983). The near-surface geological structure and local hydraulic gradients are of great importance for the formation of high-temperature system discharge centers. At the same time it is well known that the hydrothermal cell abyssal part is concentrated around subvolcanic bodies (intrusions?)

located within the boundary of the tectonic-magmatic structure axial zones (the Vernadskogo and Karpinskogo volcanic ridges in Paramushir island, the Ivana Groznogo volcanic ridge in the central part of Iturup island and the Kambalny one in the south of Kamchatka). As a rule small intrusions of andesite volcanoes are manifested in the form of circular structures tracing the ridge axial zones. The volcanic ridge geological structures determine space distribution of supply, heating, drainage and discharge areas of the thermal water. Interaction between hydrothermal solutions and including rocks causes increase of their mineralization (The structure…, 1993). Hydrothermal chemical compositions as well as their temperature are the basic factor controlling solubility of mineral and gases. Besides, it also influences upon the type and mineralogy of hydrothermal reactions. Sulphur plays an important part in the composition of hydrothermae and minerals formed by hydrothermal solutions. The series of geologists studying the recent and paleohydrothermal ore-forming systems mark out two types of high-temperature ($T>150^0$) hydrothermal systems as per sulphur oxidation condition: low sulfidation and high sulfidation (Hedenquist, Houghton, 1987). In more details this type of MRHS is considered in a papers by S. Rychagov et al., publication in this book.

3. Classification by hydrology

As discussed above, a tectonic classification of systems is complicated by the occurrence of both marine and submarine types of systems and by the occurrence of some MRHS located in unique tectonic environments around the world. A simpler and more useful system is to divide them hydrologically, firstly distinguishing between subaerial and submarine systems.

Subaerial systems can be divided further into basinal, stratovolcano (Henley and Ellis, 1983) and giant vapour dominated systems. It is tempting to apply the same distinction between stratovolcano and basinal types to submarine systems. This is because mid-ocean ridges have central grabens within which the MRHS form. However, there are also examples of submarine stratovolcanoes where the system is hosted within a summit caldera (de Ronde *et al.*, 2005), which also constitutes a basin. Hydrologically, submarine basins are not as important as they are in subaerial settings.

The key difference between the two types of submarine systems is the nature of the hydrothermal fluid. Mid-ocean ridges MRHS and back arc spreading centres have seawater as the primary source of hydrothermal fluid, whereas in andesitic stratovolcano and back-arc hosted systems not related to spreading centres it is mainly water of magmatic origin (Urabe, 1987). Thus, submarine MRHS can be divided into magmatic and seawater type systems.

Subaerial basinal type systems can be subdivided into high and low salinity systems with the former being rare and geographically localised, however the known existence of this type of system justifies inclusion as a sub-category. Subaerial andesitic stratovolcano systems can be divided into immature (more magmatic) and mature systems. **Figure 1** outlines this classification. Each type of system will be discussed in turn with emphasis given to the dominant stratovolcano type systems.

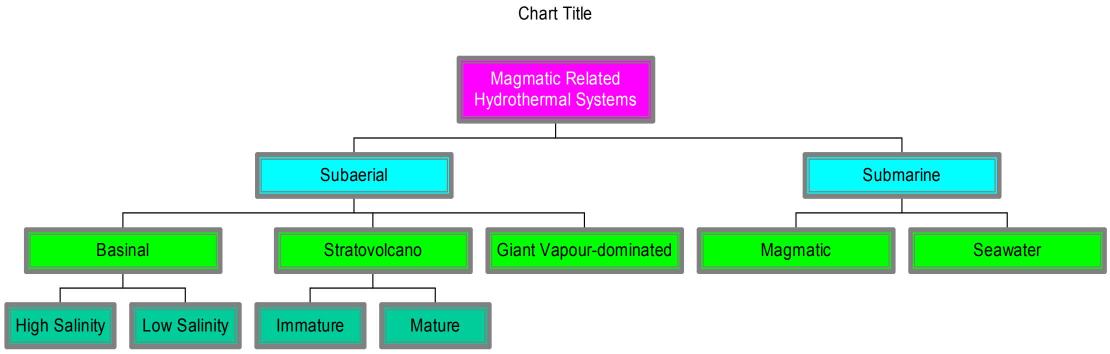

Figure 1: A classification scheme for magmatic-related hydrothermal systems

3.1 Subaerial Systems

3.1.1 Basinal Systems

As the name suggests these systems are located in topographic basins, mainly rifts. They can also be found in localised pull-apart basins on arcs, for example Suoh, Sumatra, Indonesia. These basins are zones of accumulation of low density material, and because most basins occur on thick, comparatively low density continental crust means that magmatic intrusions are usually relatively deep, because there is insufficient density difference to drive the intrusives diapirically to shallow levels. The presence of a dilatant structural pathway through basin creation does however mean that magmas are channelled into the centre of the basin **(fig. 2).** There is scope for magmatic volatiles, released from the deep intrusion, to be neutralised and reduced by rock reaction and diluted by meteoric waters before they can reach the surface. The release of volatiles under high pressure, because the intrusions are deep, also has an affect on the chemistry of the released volatiles. This favours CO_2-rich, less-oxidising volatiles. Shallower released volatiles tend to be more Cl-rich, more acid and oxidising (Fournier, 1999).

As there is a surrounding high elevation area to provide artesianal recharge and there is usually no volcanic edifice above the centre of the system, it is usual for boiling point with depth conditions to extend from shallow depths and for the deep convective hydrothermal reservoir waters to reach the surface. Hence, active systems of this type are easily recognised and can be readily studied geochemically. For example, Broadlands/Ohaaki in New Zealand has served as a test case for many studies of mineralisation in active systems (Simmons and Browne, 2000), however this can also be somewhat misleading since it is representative of only one type of system.

3.1.1.1 High salinity systems

These systems are uncommon and are geographically limited to the SW USA and NW Mexico (although basinal brines, warmed by the normal geothermal gradient, rather than magmatic activity, are relatively common world-wide and responsible for the formation of many mineral deposits of other types, e.g. Mississippi Valley type polymetallic deposits).

These systems include Cerro Prieto and Salton Sea. They are hosted in deltaic and lacustrine sediments within a transform basin and have associated bimodal basalt-rhyolite magmatism. Extremely high salinity (many times that of seawater) can be attributed to evaporites occurring within the lacustrine sediments (Mckibben and Hardie, 1997). Because they are well capped by the sediments and contain a denser than average reservoir water which impedes convection, they generally have very limited surface expression comprising only mud pots and fumaroles, or nothing at all. Some fields are only found when drilling for oil. The reservoir fluids have a high salinity and as a consequence of hydrothermal mineral buffering of the cation/hydrogen ion ratio are slightly acid. Consequently, reservoir waters have relatively high concentrations of silver and base metals which have higher solubilities in acidic Cl-rich waters due to the formation of Cl complexes (Seward and Barnes, 1997), rather than bisulphide complexes.

3.1.1.2 Low salinity systems

These are the most common basinal type systems, as exemplified by the majority of systems within the Taupo Volcanic Zone of New Zealand such as Wairakei and Ohaaki, with boiling neutral-Cl hot springs and geysers occurring at the surface. Since boiling point with depth conditions extend to the surface, they are prone to hydrothermal eruptions and many hot pools occupy hydrothermal eruption craters. Significant areas of silica sinter can form around the springs. Areas of higher ground can contain fumaroles and acid steam-heated features. These differ from magmatic solfataras because they contain H_2S and its associated oxidation products, rather than SO_2. These reservoirs contain low salinity, reduced, neutral-Cl waters. Dissolved base metals are comparatively low, but gold has been estimated to be close to saturation, in some instances (Brown, 1986), as bisulphide complexes.

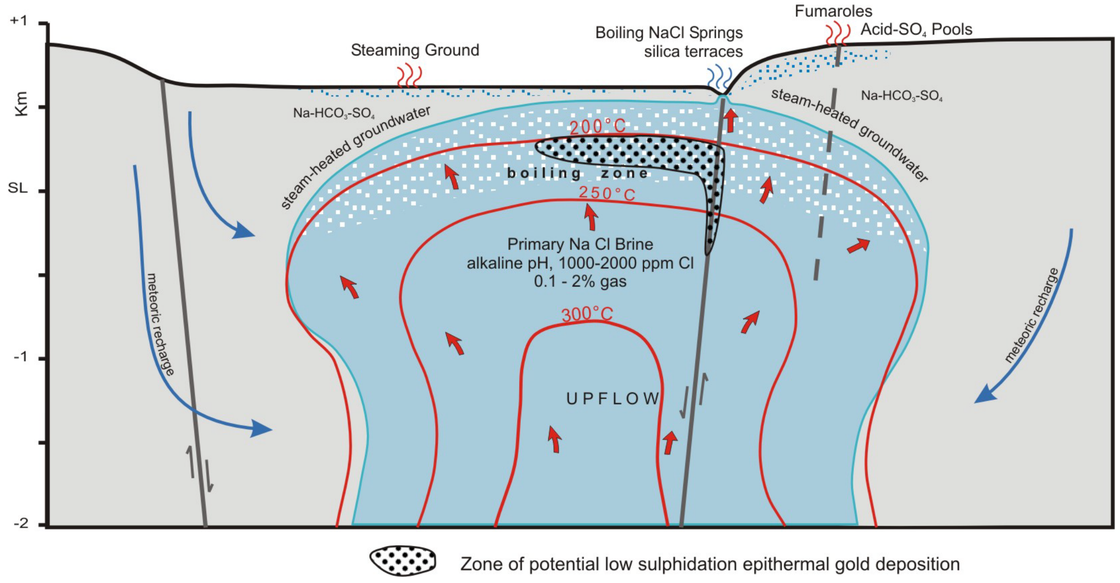

Figure 2: A schematic model of a basinal type hydrothermal system

3.1.2 Stratovolcano Systems

These are hosted by stratovolcanoes that allow intrusives to reach shallow levels, possibly as shallow as one kilometre. The minimum depth is controlled by how effectively volatile-bearing melts can be contained by the volcanic pile without having a volcanic eruption **(fig. 3)**.

As stratovolcanoes can form on continental crust of varying density and thickness there is also scope for much deeper intrusions to form due to variations in the density contrast between the melt and the crust, and the volatile content of the melt. Intrusives with a higher volatile content have a density favourable to upward movement however also require the highest pressure to contain the volatiles. Upward movement triggers volatile loss resulting in the melt freezing within the crust (Burnham, 1967) and forming typical porphyritic textures.

The most volatile rich melts are therefore confined to depth and it is the less volatile rich melts that make it up into the volcanic pile and which can remain without erupting. The different pressure constraints of volatile release between shallow and deep intrusives means that variation exists in the volatile chemistry of each type, with a shallow intrusive favouring the formation of a magmatic solfatara with its distinct chemistry with SO_2-HCl in its discharges (Fournier, 1999).

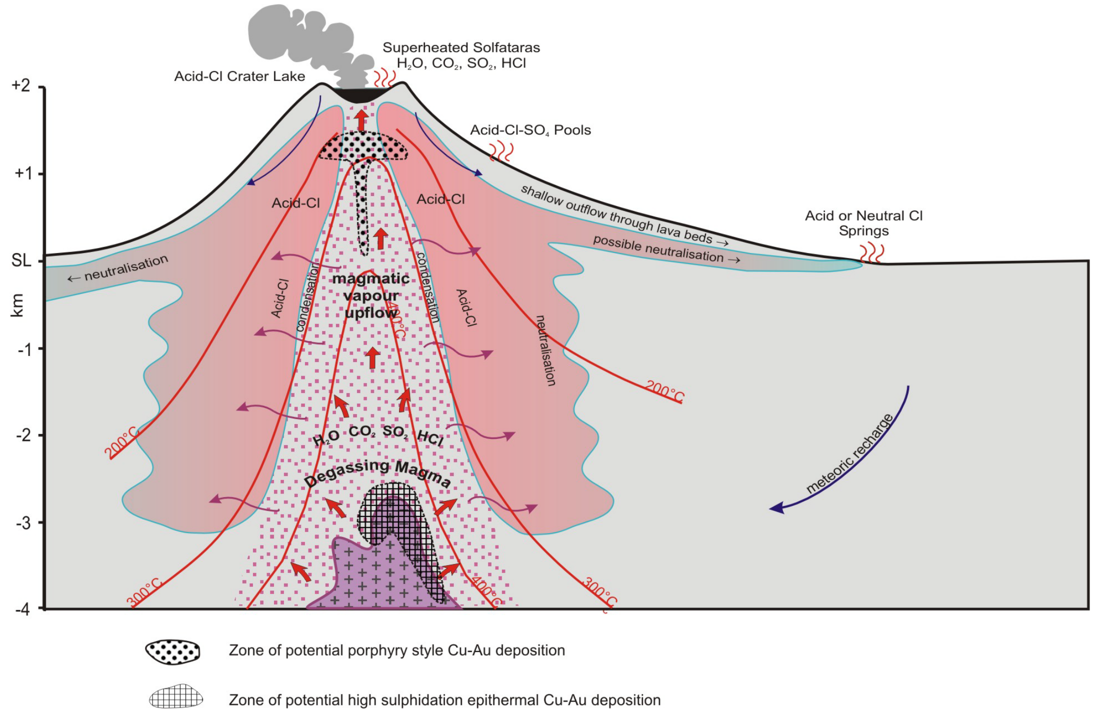

Figure 3: A schematic model of an immature stratovolcanic type hydrothermal system

A convective system will be initiated in surrounding meteoric waters and, with time, the water in the system will neutralise forming a high temperature, mature system suitable for power generation. Deeper intrusives need less time to produce neutralised waters, but require movement of a larger volume of meteoric water before a full convective cell forms. A time lag exists in both cases before a mature system forms; the difference is that one will have immediate surface activity in the form of magmatic solfatara while establishment of surface activity will be delayed in the other. There is however a strong possibility that immature systems with associated magmatic solfataras may not evolve into a mature system, because they will be destroyed by volcanic eruptions, for example Mt Pinatubo in the Philippines. The convective hydrothermal system there was explored by geothermal drilling done before the eruption in 1991 (Delfin *et al*., 1996). It is therefore only the last solfatara following volcanic activity that may mature into an exploitable geothermal system.

As a consequence, andesitic stratovolcanoes that contain hydrothermal systems suitable for power generation have mature volcanic landforms with overlapping summit calderas and dome complexes, and depending upon the local weathering environment can exhibit significant erosion. Some of this erosion will be occasioned by hydrothermal alteration, weakening the volcanic pile. Many systems have sector collapses which can be related to mineralisation because of the profound hydrological disturbances created (e.g. Ladolam gold deposit, Lihir Island, Papua New Guinea, Carman, 2003).

3.1.2.1 Immature systems

Nearly all andesitic stratovolcanoes that can be regarded as active and are not in eruption are de-gassing and in some rare instances can produce exotic sublimates, for example the molybdenum and rhenium rich deposits found on Kudrjavy volcano in the Kuriles, Russia (Znamenskiy *et al.*, 1997). Gold rich sublimates from magmatic gases have been reported at Tolbachik, Kamchatka (Karpov and Naboko, 1990). The point at which a degassing volcano can be regarded as an active hydrothermal system is difficult to define since degassing volcanoes containing hot water in the form of steam can be regarded as hydrothermal systems *sensu lato*. There can also be a very limited time interval before meteoric waters in the surrounding volcanic pile are heated and begin to convect after degassing starts.

These systems can be marked by fumarolic discharge containing magmatic volatiles HCl, HF and SO_2. They may also be superheated. If there has been significant subsurface condensation the distinctive volatiles can be lost, but the gas chemistry of fumarole gases will have a distinct “quenched” composition that serves to distinguish them from a mature system (Bogie and Lovelock, 1999). However, there is a well documented instance, Alto Peak, Philippines, where the degree of condensation is such that the fumarole gas chemistry re-equilibrated to that of a mature system, but upon deep drilling a magmatic vapour plume was encountered (Reyes *et al.*, 1993).

Usually, magmatic solfataras have abundant sulphur deposition with characteristic sulphur chimneys around fumaroles and rarely molten sulphur pits and flows, such as Biliran in the Philippines (Lawless *et al.*, 1982). In some volcanoes where the crater is filled by a lake the magmatic volatiles condense into it to produce a hot acid lake, for example that on Mt. Mutnovsky in Kamchatka. Down slope from the fumarole field or lake there may be hot springs with HCO_3-SO_4-Cl chemistry that tend to deposit travertine. Some systems have evolved sufficiently to develop neutral-Cl reservoirs suitable for power generation such as Mt Apo in the Philippines (Sambrano, 1998). Other systems are likely to be ephemeral because they will be destroyed by further volcanic eruptions.

3.1.2.2 Mature systems

Mature systems can be marked by thermal features over a wide area, although some well-capped systems can have very limited surface manifestations **(fig. 4)**. The thermal features have a very distinctive pattern with elevation. At high elevations solfataras or kaipohans (areas of cold gas release where there has been considerable sub-surface condensation to remove steam) are found (Bogie *et al.,* 1987). The gas chemistry of the fumaroles differ significantly from that of fumaroles in magmatic solfataras. Acid-SO_4 springs can be found either in the solfataras or by themselves at similar elevations. At lower elevations neutral-Cl springs are found with a HCO_3/SO_4 ratio increasing with decreasing elevation. These can have increased Cl concentrations at lower elevations. Neutral-Cl springs occur as the lowest elevation thermal features and in some instances geysers, silica sinters and hydrothermal eruption craters can be found, but typically on a smaller scale than those found in basinal systems (Lawless *et al*., 1995).

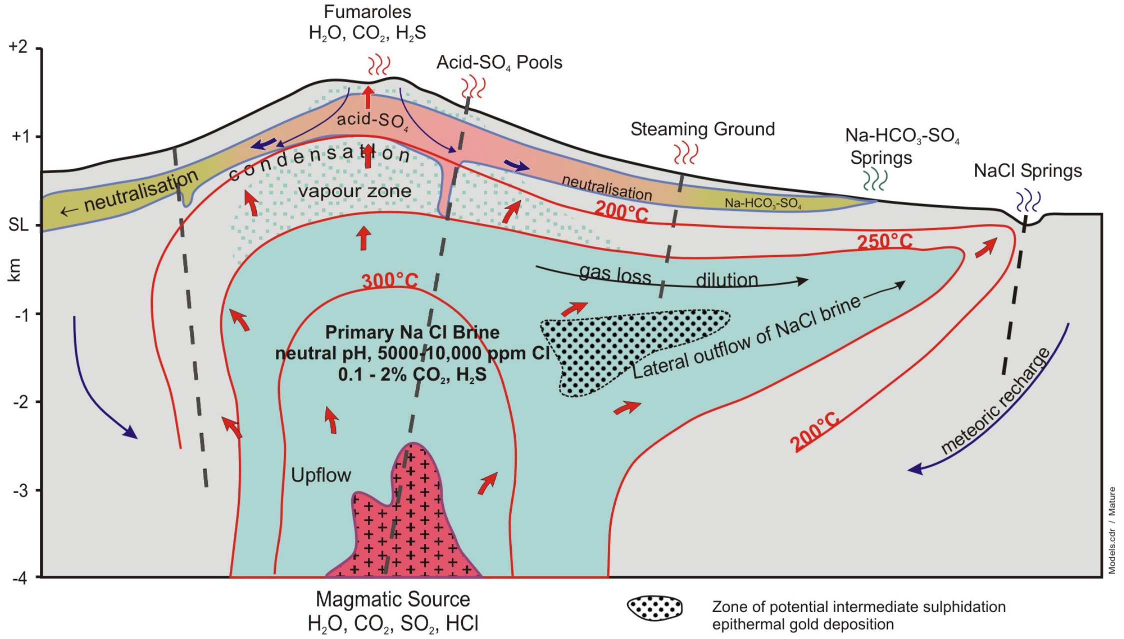

Figure 4: A schematic model of a mature stratovolcanic hydrothermal system

The variation in spring chemistry with elevation is a consequence of the formation of perched secondary geothermal aquifers within the volcanic pile of the stratovolcano. Close to the system's upflow, acid-SO_4 perched aquifers are found. As waters from these perched aquifers flow outward and down the volcanic pile, they are neutralised by rock reaction allowing dissolved gaseous CO_2 to form carbonic acid which reacts with the rocks to forming HCO_3. Underlying the perched aquifers is the primary neutral–Cl aquifer that boils in the upflow providing the steam and gases necessary for the formation of the secondary aquifers. As the primary waters flow out from the upflow they can meet with and mix with the secondary aquifers at lower elevation. This is a key difference to immature systems, which can also have Cl-bearing spring waters, but at high elevations.

The deep neutral-Cl reservoir waters have moderate salinities and thus are capable of transporting gold, silver and base metals by both bisulphide and chloride complexing.

Another, rarer, type of mature system is the vapour-dominated system hosted by an andesitic stratovolcano. Some of the best known examples are found in a cluster in West Java, Indonesia and include Darajat and Kamojang. They exhibit evidence of the existence of earlier liquid dominated systems and at least in the West Java geological setting can be regarded as the ultimate stage in the evolution of an andesitic stratovolcano hydrothermal system. These reservoirs are approximately 240°C and contain a mixture of steam and water, with the water of bicarbonate chemistry. It is hypothesised that hypersaline waters (the strongly boiled neutral-Cl waters) underlie them, but this has yet to be proven by deeper wells.

3.1.3 Giant Vapour-dominated systems

The two known giant vapour-dominated systems of the Geysers, USA and Larderello, Italy differ significantly from the vapour-dominated systems in andesitic volcanoes. Apart from being very much larger, they are hosted within and adjacent to large intrusive bodies that have intruded thick sedimentary sequences. They contain evidence for early phases of contact metamorphism and development of a water-dominated system that dried out with time. Although the wells produce dry steam, there is a mixture of steam and water with bicarbonate chemistry in the reservoir fluids. These fluids in the system are derived from a combination of sources including meteoric water, connate or metamorphic water and magmatic water (Lowernstern and Janik, 2003).

3.2 Submarine systems

Samples of waters flowing from submarine vents at spreading centres show that the water is overwhelmingly chemically modified seawater that has circulated within and reacted with the largely basaltic volcanic pile. Vents from submarine andesitic stratovolcanoes produce mixtures of seawater and magmatic water. The presence of magmatic fluids produces differences in the nature of and patterns of hydrothermal alteration and associated mineralisation to that of the systems in which seawater is the circulating fluid.

3.2.1 Magmatic systems

As exploration of these systems is still in its early stages, a clear distinction between immature and mature systems has not yet been established. There is a significant overburden of seawater on these systems, such that volatile-bearing igneous intrusives can closely approach the seafloor without erupting, although too close an approach is likely to lead to a phreatomagmatic eruption. Consequently, very high temperatures can be found close to the seafloor and the vertical distance between the system's heat source and the point of egress of fluids is limited. Thus magmatic volatiles undergo very little dilution by seawater and are vigorously produced. Once this fluid meets cold, slightly alkaline seawater at the seafloor severe chemical dis-equilibrium results producing the immediate precipitation of sulphides and barite. Alteration of the host rocks to alunite and pyrophyllite may also occur.

3.2.2 Seawater systems

These occur in spreading centres, both along mid-ocean ridges and back-arc spreading centres. Surface expression on the seafloor occurs in the form of black smokers, where hot water emerges from the system into the sea and mixes with cold seawater to deposit sulphides. They produce chemically modified seawater, with little evidence for magmatic volatiles except during times of volcanic eruption. As the intensity of hydrothermal activity increases following volcanic eruption, there is a very close magmatic association with estimates for the depth of dyke intrusion approximately 200 m below the seafloor. This is reflected in the high temperatures of water coming out of these systems, which can reach 408°C, the critical temperature of seawater but otherwise the high hydrostatic pressures mean boiling is very limited. Since the magmas building up the spreading ridge have low volatile contents, the predominant fluid in the system is seawater.

4. Mineralisation in magmatic related hydrothermal systems

4.1 Introduction

It is now well accepted that hydrothermal ore deposits are formed in active hydrothermal systems. One of the initial impediments to this acceptance was the failure to actually find economic ore deposits in active systems. This has now been answered by the finding of the giant (> 600 tonnes of recoverable Au) Lihir epithermal gold deposit in Papua New Guinea (Carman, 2003) that is hosted by an active geothermal field from which electricity is currently being generated to run the processing operation. Additionally, actively forming VHMS (volcanic hosted massive sulphide) mineralisation has been found through submarine exploration. These contain black smokers chimneys of which fossil examples have been found in some VHMS deposits, for example Yaman-Kasy in the Urals, Russia (Maslennikov et al., 2003).

The question remains why mineralisation is not more common in active geothermal systems. While there are the constraints of different sampling and analysis regimes between mineral and geothermal exploration the answer to this can be found in the ratio of hydrothermal mineral prospects and economic mines. While it is difficult to put an exact figure on this it would be of the order of thousands to one. Mineralisation is common but economic deposits are rare.

This still leaves the question of why economic ore deposits are not more common. One possible reason is that since very large amounts of fluid flow are required to form ore deposits it is only the most permeable hydrothermal systems, where fluid flow is focused, that can form economic ore deposits, while a hydrothermal system may be viable as a source of power generation at much lower permeabilities. The degree of concentration required to lift mineralisation to an economic grade also means that some special, usually hydrological combination of circumstance in time and space is required.

A further factor is that an association between particular types of magmas and major economic ore deposits suggests that associated magmas must have particular compositions for a system to form a major ore deposit. As these are minor magma types, the majority of hydrothermal systems are associated with the wrong sort of magma to form major economic ore deposits. Favoured magmas are potassic calc-alkaline ones (Muller and Groves, 2000) and the most favoured magmas are adakitic (Mungall, 2002) e.g. those at Lihir, Papua New Guinea.

These magmas are particularly favourable associates of major ore deposits because they have sufficiently high oxidation states that sulphides are unstable in them. Cu and Au in sulphides (the main host for Cu and Au) in the magma source regions can thus be incorporated into melts and sulphide cumulates can not form as the melt moves upwards, to remove Cu and Au from them. These magmas therefore can be effective transport mediums for Cu and Au from the mantle to shallow accessible levels in the earth's crust.

In the case of potassic melts these represent partial melts with very low degrees of partial melting which favours high K and Fe^{3+} contents, and high SO_4 and Cl solubility (Muller and Groves, 2000). This not only mitigates the formation of sulphides, it also means that there is an abundant available complexing agent in the Cl, to transfer Cu and Au from the melt into hydrothermal fluids.

In the case of adakites, they are oxidising because they are slab melts. The down-going slab in subduction zones has its upper portions oxidised by prior submarine hydrothermal activity, most notably the deposition of SO_4 from seawater and can be covered in oxidised sediments. If a partial melt forms from the slab it can be as oxidised as the slab is and at low degrees of partial melt even more oxidised.

Slab melts are relatively rare because the slab does not often reach sufficient temperatures to produce partial melts. The circumstances where temperatures are hot enough are: where the subduction zone is young and the slab has yet to cool the surrounding mantle, where the slab is comparatively young and has not completely cooled, or where a slab window has formed. A slab window is where a gap forms in the slab allowing hotter mantle material from beneath the slab to move upwards and heat the upper oxidised part of the slab from the side as well as the top. Slab windows form where ridges are subducted, where there is oblique subduction or where there is a sudden change in the geometry of the down going slab. The best example of the latter circumstance is at the meeting of the Kamchatka and Aleutian subduction zones. This has produced adakitic volcanism in central Kamchatka (Defant and Drummond, 1990), which means if there has been sufficient erosion this area has a high potential for the occurrence of major mineral deposits.

Before it is metasomatised by waters driven off the descending slab, the overlying mantle wedge has a relatively low oxidation state. The metasomatising water can make it more oxidised, but it is limited by how oxidised that water can become. It can transport SO_4, but not Fe^{3+} (Mungall, 2002), so the metasomatised mantle produced and its derived partial melts can not be as oxidised as the slab and its partial melts. As a result, the vast majority of hydrothermal systems that are hosted by andesitic stratovolcanoes that are formed from wedge melts are unlikely to produce major ore deposits.

A further factor is that since adakites are dacitic they have sufficient density contrast to reach the upper parts of the crust without forming magma chambers in which potentially “gold-robbing” cumulates can form. The more typical wedge partial melts are basaltic and tend to form magma chambers at the base of the crust where cumulate formation changes their composition to andesitic melts, but is also likely to rob them of gold.

There is however an additional association of specific magmas and ore deposits. This is the association of bimodal basaltic-rhyolitic volcanism with low sulphidation epithermal gold deposits (Sillitoe and Hedenquist, 2003). In this case there is also an association with rifting and since these systems have indications of the least proportion of magmatic waters of any of the subaerial systems, the tectonic association may be more important than the magmatic one. Thus the key factor in this type of system is likely to be more hydrological than magmatic. This is because zones of very high permeability can be created in basins and since there are artesianal forces, convection can be strongly driven to give systems that have large throughputs of water from which mineral deposits can accumulate.

The tendency in these deposits for silica-laden hydrothermal fluids to reach near the ground surface can also be favourable for self-sealing and the opportunity for subsequent vigorous boiling events.

4.1.1 High salinity basinal systems

Although only minor mineralisation has been reported within these systems (McKibben and Hardie, 1997), zinc has been commercially extracted from the waters of the Salton Sea geothermal system, one of the high salinity basinal systems in SW USA. This leaves obvious scope for the natural production of an epithermal base metal-silver deposit, but it is difficult to exactly identify such a deposit. A possible contender is the Creede deposit in Colorado, USA, however there are indications of a significant input of magmatic waters into this deposit and it is classified as a high salinity intermediate sulphidation deposit (Einaudi et al, 2003). Such a deposit has no known precise current day analogue.

4.1.2 Low salinity basinal systems

Low sulphidation (Einaudi et al., 2003) epithermal-gold deposits are produced in low salinity basinal systems, particularly when they are associated with bimodal basaltic-rhyolitic volcanism. These are the “classic” epithermal gold deposits (Hedenquist et al., 1996), formed principally by de-compressive boiling of fluids containing gold and silver as bisulphide complexes, following dilatational opening of structures, though locally fluid mixing can also be a minor cause of mineralisation. They frequently host bonanza ore bodies and have distinctive vein textures. These include fine rhythmic banding, colloform textures and quartz pseudomorphs after calcite. The ore minerals are electrum and acanthite with gangue quartz, chalcedony, adularia and calcite. Pyrite is the most commonly found sulphide but there can be small amounts of base metal sulphides. Immediately surrounding veins, adularia is found as an alteration mineral, enclosed in a sheaf of illite, quartz and pyrite with regional chlorite, albite, calcite, pyrite alteration.

The shallowest examples (for example McLaughlin, California, USA) occur as stockworks and have preserved sinters above the mineralisation. Deeper deposits occur as veins occupying dilatant faults.

A good example of this type of deposit is Baley in Russia which is estimated to have produced more than 1000 t of gold (Zoren *et al.*, 2001). Examples of low sulphidation epithermal gold mineralisation are found at Asacha and Rodnikovoye in southern Kamchatka within pull-apart basins.

4.1.3 Immature stratovolcano systems

4.1.3.1 High sulphidation epithermal deposits

High sulphidation (Einaudi et al, 2003) epithermal gold deposits form in andesitic stratovolcanoes, particularly those that host subsidiary dacite dome complexes. These have mineralisation hosted in "vuggy" quartz, also known as monquartzite (Karpov and Naboko, 1990). This is usually a silicified porphyritic rock with quartz replacing the groundmass and the phenocrysts leached out. The "vuggy" quartz is surrounded by alunite rich alteration, which is surrounded by kaolinite rich alteration that at deeper structural levels may contain pyrophyllite, dickite and diaspore. This alteration is contained in regional chlorite, albite, calcite, pyrite alteration. A thin zone of smectite-rich alteration may separate the kaolinite and chlorite rich alteration. The inner alteration zones can also contain more unusual alteration minerals that are useful diagnostically in identifying these deposits. These minerals include zunyite, barite, woodhouseite, svanbergite, dumortierite, and at deeper levels andalusite, topaz, corundum and andalusite. Native sulphur and cinnabar are found at shallow levels in some deposits.

Copper mineralisation usually precedes the majority of the gold mineralisation and at shallow levels includes luzonite, enargite, famatinite, chalcocite and covellite. Some electrum can be hosted in the copper minerals, but gold usually forms later and in some deposits there is a intermediate sulphidation gold rich overprint (Sillitoe and Hedenquist, 2003).

The deposits vary in form, with the mineralised zone of silicification following structures to produce planar ledges, or in shallow deposits may be confined to permeable pyroclastic beds, taking on their geometry. Mineralisation can be found at a range of depths from the paleo-surface. Barite rich bonanzas have been found close to the original surface and more copper rich mineralisation at depths of up to two kilometres. With increasing depth the deposits become increasingly structurally controlled and copper rich.

These deposits form as a result of magmatic volatiles condensing into ground waters. Early volatiles form very acid waters that leach the rock and prepare the ground by increasing permeability due to leaching. Later volatiles produce less acid and contain more copper and gold, mineralisation occurs as the result of cooling and dilution of the volatiles.

Examples of high sulphidation mineralisation are found at Alnei and Chashakondzha in Kamtchatka, Russia (Karpov and Naboko, 1990). The high sulphidation mineralization and, may be, Cu-Au-Ag-Mo…-porphyry mineralization are form now in central part of high temperature Island arc hydrothermal-magmatic systems (Rychagov *et al.,* 2001).

4.1.3.1 Porphyry and Skarn Deposits

Porphyry deposits are closely related to porphyritic intrusives and can host a variety of mineralisation including Cu, Mo and Au. Currently, to be economic deposits of this type of deposit either have to be very large and have supergene enrichment or be gold rich.

When the host rocks for a porphyry type deposit are carbonates skarn mineralisation can be found and in some deposits, for example Grasberg in Indonesia (Pollard and Taylor, 2002), there can be both styles of mineralisation associated with the same intrusives.

In porphyry-style deposits mineralisation usually occurs in a stockwork of quartz veins at the apex and sides of the porphyritic intrusive. Gold rich deposits tend to contain abundant secondary magnetite and anhydrite reflecting the high oxidation state of the magma. Chalcopyrite is the main ore mineral along with gold. The latter is frequently associated with bornite and in the richest deposits bornite can form exsolution textures with chalcopyrite as an unmixing product of intermediate solid solution copper sulphide that is unstable at lower temperatures. In addition to that found in the stockworks, ore minerals can be disseminated in the rock or occur as sulphide stringers.

The mineralisation is accompanied by alteration of the rock to biotite, orthoclase and quartz, with biotite most strongly developed in gold-rich deposits. Sericite, quartz, pyrite alteration; pyrophyllite, quartz, diaspore, and kaolinite alteration, and smectite, zeolite alteration can overprint the earlier biotite-bearing alteration. Surrounding these types of alteration is chlorite, calcite, epidote and pyrite alteration. At shallower levels a lithocap can be found, some of which can host high sulphidation epithermal gold mineralisation and overall the lithocap has the same type of alteration as high sulphidation deposits, but tends to lack the more unusual of the alteration minerals, especially the P-bearing phases. Copper may also be associated with the sericite rich alteration. It is unclear if this involves redistribution of the existing mineralisation or there has been further introduction of copper from a later deeper source.

Skarns usually form at the interface of the porphyritic intrusive and the surrounding carbonate host rock and thus have a variety of geometries. There can also be distal skarns where mineralised fluids are released from the contact zone and travel sufficiently far from the intrusive that its presence may not be obvious.

There is initial formation of a zoned prograde skarn mineral assemblage that varies according to the composition of the carbonate. Calcic skarns contain such minerals as garnet, diopside, vesuvianite, wollastonite and monticellite. Magnesian rich skarns can contain clinopyroxene, forsterite, melilite and phlogopite. Mineralisation is introduced during retrograde alteration of the skarn in which the early garnet is replaced by epidote, chlorite and calcite, actinolite replaces pyroxene, and serpentine replaces forsterite.

A variety of mineralisation is found in skarns of which Au, Cu, Fe, Zn, Mo, W and Sn are of most economic importance. Perhaps of greatest interest are gold skarns. The ore mineral in these is gold with a high fineness that is usually found in the actinolite retrograde alteration zone.

Evidence from fluid inclusions indicates that porphyry deposits are formed from the volatiles exsolved from the porphyritic intrusive. As this is usually part of a much larger intrusive complex the intrusive that produces the mineralisation is referred to as the progenitor porphyry. The volatiles unmix to form hypersaline brines and vapour at temperatures that can be in excess of 600°C. The brines are slightly acid and these produce the deep mineralisation as they cool, depressurise and are neutralised by rock reaction. Chemical analysis of inclusions indicates that both the brine and the vapour contain Cu and Au. The brine, because of its density remains at depth but the vapour can rise. It can thus move to the surface to form the fumarole sublimates discussed above or can condense into ground waters to form acidic waters that react with the rocks to form the lithocap and under some circumstances form high sulphidation epithermal mineralisation.

Examples of Cu-Mo porphyry mineralisation are found in Kamchatka at Krasnogorskoye and Tumanoye. The presence of molybdenum-rich fumarole sublimates at Kudrjavy in the Kuriles (Znamenskiy *et al.*, 1997) is suggestive of the formation of Mo-porphyry mineralisation at depth, providing that not all the molybdenum is being lost to the surface.

4.1.4 Mature stratovolcano systems

Intermediate sulphidation (Einaudi et al, 2003) epithermal gold deposits are hosted in mature andesitic stratovolcano hydrothermal systems, although usually at levels below the active volcanic pile and consequently can have a variety of country rocks. These deposits differ from low sulphidation epithermal deposits in that base metal sulphides and silver are much more abundant. There are also differences in vein textures and mineralogy and as this type of mineralisation is most common as veins it thus appears to form at deeper levels than low sulphidation deposits where stockworks are more common.

The veins have a banded and crustiform texture, but mineralisation is frequently associated with breccias and there can be strong cockade textures. Adularia is uncommon and quartz is the dominant gangue mineral. Barite and manganiferous minerals including rhodochrosite, kutnahorite, rhodonite and alabandite can be found. Illite is found in and immediately surrounding the veins with regional chlorite, calcite, epidote, pyrite alteration. Gold and acanthite are the main ore minerals, but some deposits can contain complex telluride and silver sulphosalt assemblages.

Similarly to low sulphidation epithermal deposits, deposition is due to de-compressive boiling following dilatancy. The higher salinity and lower pH of the waters in these types of systems, in comparison to basinal systems, means that in addition to bisulphide complexing of Au and Ag, base metals can be deposited from chloride complexes and adularia is less likely to deposit. Because of the greater vertical extent of the systems allowing chemical stratification, and the tendency for outflows, there is also more potential for mineralisation by fluid mixing (Bogie and Lawless 1999).

Examples of this type of mineralisation are found in Kamchatka, near the Mutnovsky and Apapelskaya geothermal fields (Karpov and Naboko, 1990).

4.1.5 Giant vapour dominated systems

Old examples of these have yet to be identified, let alone associated mineral deposits. There has been past mercury mining of the near surface of the Geysers geothermal field, although at present such deposits are uneconomic.

4.1.6 Submarine seawater systems

There are major similarities between the accumulation of sulphides in active spreading centre submarine seawater hydrothermal systems and Cyprus type VHMS deposits. A difference exists in that in many major deposits (for example those on Cyprus) are hosted in atypical oceanic crust that is thinner than that produced at mid-ocean ridges. A possible reason for this is that it is only thin oceanic crust that can be obducted to provide onland mineable deposits. Therefore it is likely that only the hydrothermal systems formed at back-arc spreading centres form Cyprus type deposits.

These consist of an upper quartz-goethite layer overlying massive pyrite enclosing chalcopyrite and sphalerite which overlies altered basalt that can contain quartz sulphide stringer zones. There can be varying proportions of Cu and Zn mineralisation between deposits with some deposits containing gold. In other deposits the pyrite can be the most valuable constituent as a feed stock for sulphuric acid manufacture.

The best examples of these deposits are on Cyprus itself (Sawkins, 1990).

4.1.7 Submarine magmatic systems

These type of systems produce Kuroko style VHMS deposits with intermediate and high sulphidation variants, possibly representing variation in the proportion of magmatic fluids in the systems. There is also a tendency for the high sulphidation variants to be found associated with arcs rather than back arc settings within which the classic Kuroko deposits of Japan are located.

The upper part of the intermediate sulphidation deposits may be siliceous and barite rich with significant gold contents. This sits on sphalerite and galena ore with variable amounts of chalcopyrite and pyrite that sits on chalcopyrite rich ore that sits on a rock surface. A feeder zone below the massive sulphide beds consists of a quartz rich stockwork that contains chalcopyrite and pyrite. There can be strong central alteration to sericite, particularly where the host is a dacitic dome and this is surrounded by chlorite, albite, pyrite alteration.

High sulphidation variants differ by containing enargite and tennantite in the copper mineralisation, with less Pb and Zn and there can be high concentrations of barite, to the extent it can be a valuable byproduct. Gold mineralisation associated with the barite can also be stronger. In parts of the deposits diaspore, kaolinite and alunite alteration can be found, in addition to alteration similar to that in intermediate sulphidation Kuroko deposits.

Ore deposition is by cooling and dilution as mineralised fluids mix with seawater.

Porphyry-style mineralisation is yet to be found associated with Kuroko-style deposits, although the underlying feeder zones have some similarities to a porphyry stockwork. It is possible that the limited distance between the intrusive and the rock surface means that the majority of magmatic volatiles are expelled into the ocean rather than remaining to form porphyry style mineralisation. If this is the case, the more shallow the water the systems form in, the greater possibility that there could be porphyry style mineralisation.

The Kuroko deposits of Japan best exemplify the intermediate sulphidation type deposits (Sawkins, 1990). Examples of the high sulphidation type mineralisation are found on the Indonesian island of Wetar (Sewell and Wheatly, 1994), where the submarine part of the Banda arc has been uplifted by the collision with the Australian plate.

4.1.8 Others

In addition to the various types of deposits discussed above there are also some magmatically related hydrothermal ore deposits in which it is unclear what sort of active system they were associated with. This is because the deposits are formed at such great depths that they may not necessarily have surface expressions or the type of magmatism is sufficiently rare that there are currently no existing current day analogues. In the first category are intrusion-related gold deposits such as Fort Knox, Alaska, USA (Thompson *et al*., 1999) and greisen deposits. The latter are very telluride-rich epithermal deposits such as Cripple Creek (Sillitoe and Hedenquist 2002). There are also some deposits upon which a consensus has yet to be reached with regard to their origin, that may be of magmatic origin for example Carlin-type deposits (Muntean et al., 2004).

5. Conclusions

Magmatic related hydrothermal systems can be divided into four major variants. A fifth, giant vapour dominated systems, are rare and not obviously associated with mineralisation. In subaerial settings, basinal systems can be subdivided from stratovolcano systems. Basinal systems can either be high or low salinity depending upon the presence of evaporites in the basin, but low salinity systems overwhelmingly predominate. Stratovolcano systems can be subdivided into immature and mature systems depending both upon the depth of the intrusive driving the system and the age of the system.

Submarine systems that occur at spreading centres, both in back arc and mid-ocean settings can be distinguished from hydrothermal systems associated with andesitic stratovolcanoes by their production of chemically modified seawater whereas stratovolcano systems produce mainly magmatic fluid.

The ore deposits that form in the various types of hydrothermal systems are indicated in **Figure 5**.

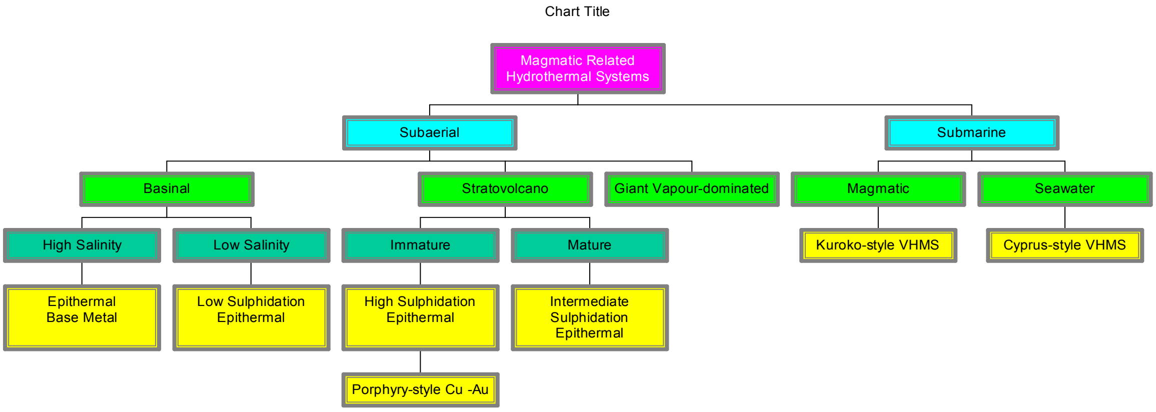

Figure 5: Economic ore deposits that have the potential to form in particular types of hydrothermal systems

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