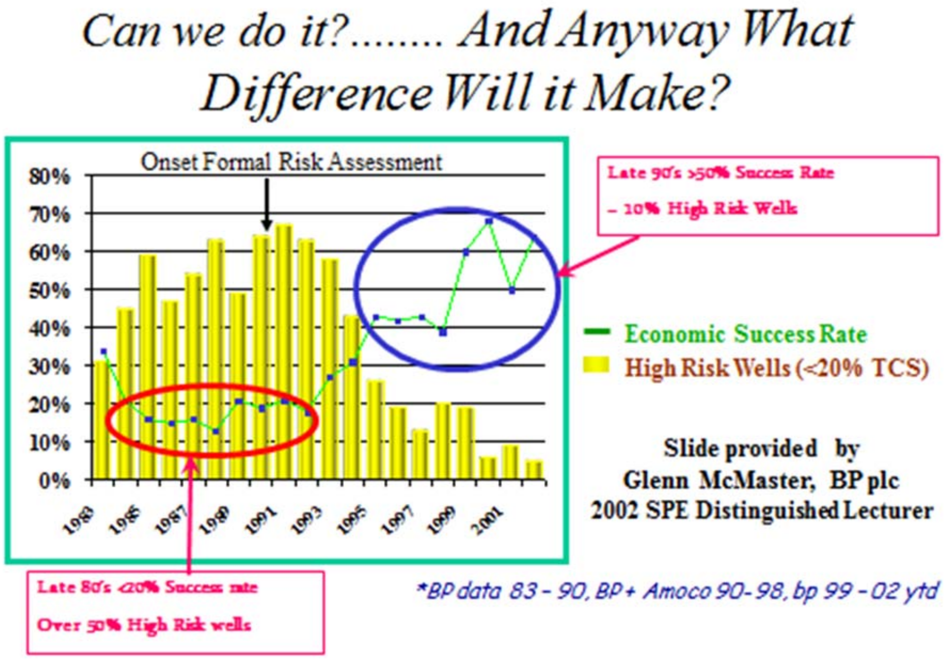
Scientific Underpinings of "Orogenic Gold" Presentation

The presentation attempts to answer the "Five Questions" used to define a mineral system.

The mineral system concept was applied to hard rock mineralisation by Tom Loutit ex-Chief Geologist at Esso's research laboratory in Texas during the Australian Geodynamics Cooperative Research Centre in 1995. These questions were developed in the 1970-80's by a cooperative research project involving all major oil companies to define the oil and gas mineral system. It proved useful subsequently to allow better exploration decision making in the oil industry. The figure below demonstrates the economic impact of this decision making.



Question 1: What is the Geodynamic Setting?

These slides show some important features for major gold events. They involve previously rifted terrain that has been involved in fractionated mafic volcanism (metasomatising and dehydrating the sub-continental lithospheric mantle) where magnetite has been extracted from the melt at depth. Orogenic gold events are post-tectonic and involve a Rayleigh Taylor Instability where the lower half of the crust is delaminated and descends into the mantle during tectonism. This research has been developed by GEMOC at Macquarie University since 2000 with Western Mining (WMC) support following on from seminal research completed by Robert (Bob) Loucks at Australian National University in the 1990's which Placer Dome and WMC both funded. Loucks is now based at University of Colorado. Dr Jon Hronsky (WMC) was the promoter of both projects. Loucks' research established copper fertility is sourced in the upper mantle and can be replenished but gold fertility is derived from the base of the sub-continental lithospheric mantle (SCLM) and cannot be replenished.

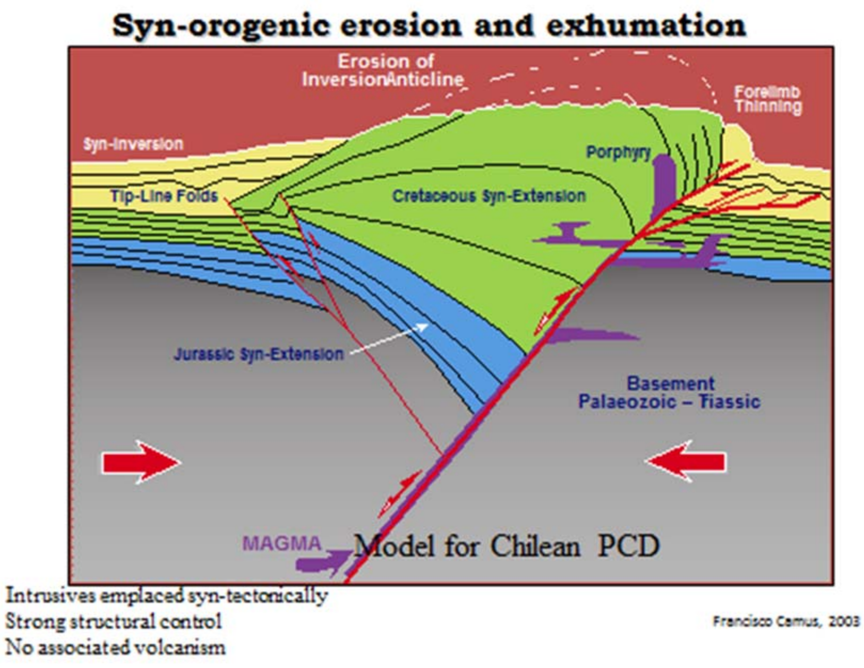
It is possible the oxygen enrichment of the SCLM allows formation of thio-sulphate complexes during the Raleigh Taylor event and these complexes will readily carry gold in high concentrations.

A further consideration is deposit spacing which in a district appears to be controlled by crustal thickness (30km at Kalgoorlie, 60km at Wiluna in the Yilgarn). The districts appear to be spaced at the combined thickness of Crust (30km) and SCLM (100km) in the Yilgarn. Not all possible locations are mineralised.

Question 2: What is the Architecture?

Seismic reflection sections of the full crust have repeatedly shown major goldfields lie over crustal scale joins of pre-existing crust. Canada completed such profiles in the 1980's and Australia in the 1990's. These joins have to connect with similar metasomatised joins in the SCLM to become productive. The GEMOC project has been mapping these joins in the SCLM world-wide for nearly twenty years led by Dr Graham Begg. Crustal joins can be recognised in the surface geology as two different terrains but the dip is usually only evidenced in seismic reflection profiles. Major goldfields lie immediately above the piercement point of the join with the SCLM (base of the crust) not in the join itself. Mapping of joins in the SCLM requires more regional datasets like gravity, magneto-tellurics, whole earth seismic modelling etc. Often the lower crust is extensively metasomatised so it loses texture in seismic reflection profiles and becomes conductive in magneto-telluric data. This extensive conductivity may be due to precipitated carbon.

A large scale anticline in the hangingwall of the crustal suture is necessary to host major gold deposits. Often these anticlines are inversion anticlines where the anticline created during extension as a roll-over anticline, is amplified during subsequent compression. Similar features control the location of giant porphyry copper deposits in Chile. The transfer fault intersection with the basin margin fault is usually a preferred location for giant ore deposits. These transfer faults are usually only identified by detailed stratigraphic mapping of thickness and facies changes in the basin fill. Another indicator of inversion is where the youngest preserved stratigraphy lies behind the major fault implying the entire basin fill has been uplifted and eroded.



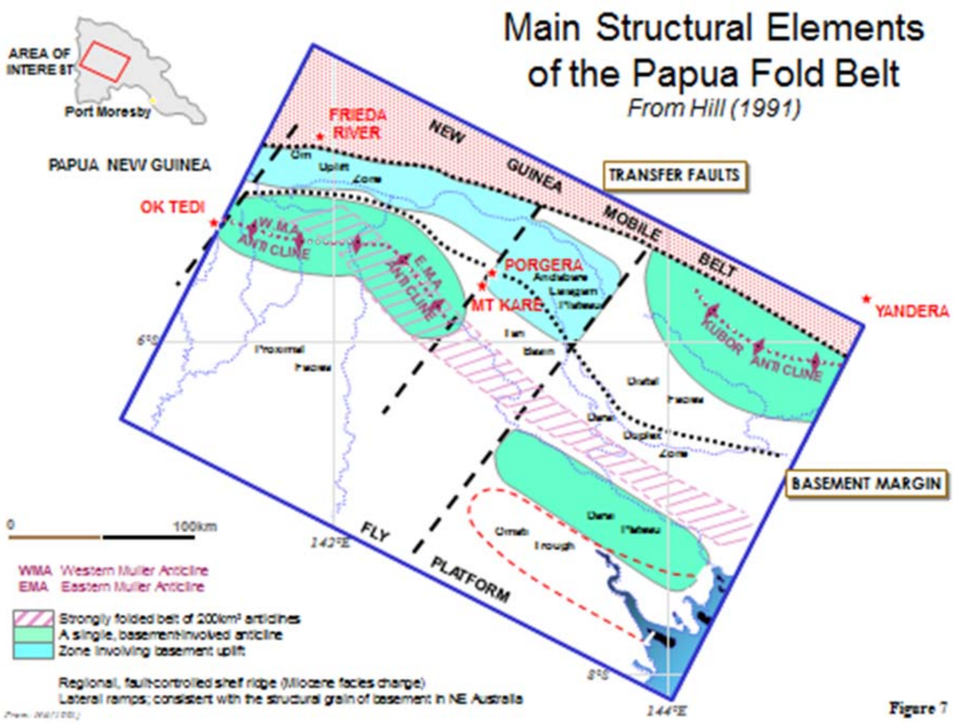
Question 3: What are the Fluid Sources?

We have identified metasomatised SCLM as the ultimate source for gold but there are at least three delivery mechanisms.

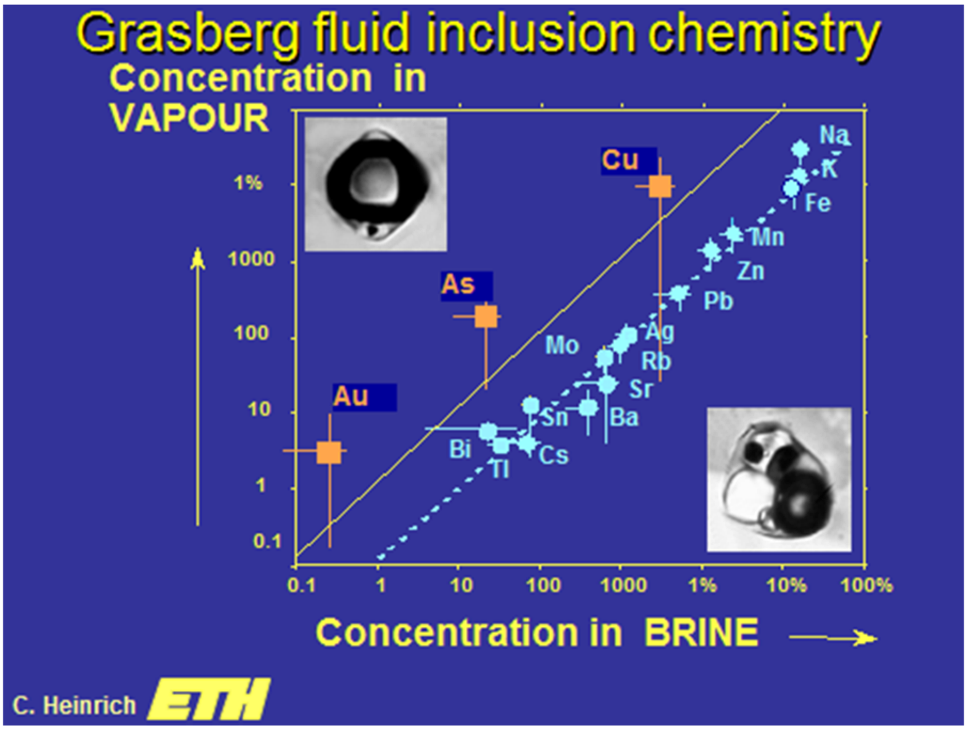
1 Fluid alone and direct: I infer this mechanism to explain the very high grade veins in Archaean deposits that show no water at gold stage and lots of gas, phosphate carbonate etc and whose strontium isotope signal is pure mantle (no crustal signature although hosted by the crust). These veins and their mineralogy are described in various MERIWA reports for veins at St Ives and Sunrise gold mines in Western Australia. This gold source is inferred for Witwatersrand and Victorian slate belt deposits also.

2 Fluids in SCLM magma: This fluid source is classically described at Porgera whose magmas are the composition of lamprophyre (44%SiO2) derived from 130km in the SCLM below the crust. There is no crustal contamination in this magma so no copper is present in this system. Porgera is in the same trend Grasberg, OK Tedi and Wafi which all show copper and gold metal enrichment (type 3). All deposits are located at transfer fault and basin margin contacts and were emplaced post-collision as an adjacent block was being uplifted and eroded (which accelerates fluid release from the magma source.

3 Fluids in Crustal Magmas: This fluid source is the most abundant and often involves copper as well. This style has been described as adakites and is well documented by Gary Beakhouse in Canada and Cassidy and Champion in the Yilgarn as part of a 10 year AMIRA based study of Yilgarn granites. It is clear that metasomatised mantle material is added to crustal melts and brought to the surface. These magmas have a slightly shifted composition with high Mg, Ni, Cr numbers reflecting the SCLM contamination.



The really important documentation of these fluids was initiated by Chris Heintich at ETH Zurich in 1994 involving in-situ analysis of quartz hosted fluid inclusions from a brain rock collected by Vic Wall at Grasberg. This study showed there are two co-existing fluids in the magma at that stage (pre-exsolution) one is saline brine and hosts all the elements that complex with chlorine (nearly every metal) the other is vapour and in particular hosts significant As and Au (5-15ppm) contents.



Chris could not assay sulphur but he believes the fluids are very sulphur rich with total sulphur > total metal. The gas component is likely only 5% of the total magmatic fluid budget but carries 100% of the gold. That is the primary reason orogenic gold deposits (low fluid rock ratio) are different to porphyry copper deposits where both fluid sources alter the rock (high fluid rock ratio). A powerpoint from 1995 shows the main consequences of that discovery.

(i) Gas leaves the magma at 800C and does not condense to liquid at 400C and can have travelled a very long way

(ii) Gas will immediately precipitate gold if acidity is not buffered by feldspar (as intrusive or arkose) or carbonate

(iii) Gas that is buffered will carry the gold until it is forced to precipitate

(iv) Main forcing agents that are effective (fast kinetics) are acidity if host rock has already been leached (HIGH SULPHIDATION EPITHERMAL), boiling if within 1 kilometre of the surface (LOW SULPHIDATION EPITHERMAL) or reduction by carbon (INTERMEDIATE SULPHIDATION, OROGENIC, INTRUSIVE RELATED). Other mechanisms like wall rock reaction are too slow.

The downside in these studies is that older gold only deposits rarely preserve the fluid inclusions intact. I helped Chris investigate the brain rock from Kidston gold mine in 1991 while he was at BMR (now Geoscience Australia). He found all the inclusions were broken but some had chalcopyrite inclusions implying the mechanisms he subsequently documented at Grasberg.

Placer Dome also sponsored a Heinrich student Paulo Garofalo to study Sigma and Lamaque in 1992. Paulo found intact primary fluid inclusions in vertical skinny blue quartz veins at the side of the intrusion with very high Au and Boron contents which he calculated were in similar proportions to gold and tourmaline as found in the flat lying mineralised veins. All previous fluid inclusion studies documented fluid inclusions in quartz in these veins but this is the “spent” fluid.

There is an ambient fluid carrying the carbon (likely as methane). It is responsible for most of the alteration visible in Orogenic Gold deposits. Methane is derived from heating any carbon source rock and the late basins of the Archean are usually very carbon rich and full of water.

There is a simple metric to explain these differences derived from porphyry copper exploration

ALBITE alteration is cold water going hot, and is found on the lateral sides of porphyry copper deposits +/- magnetite if the water is salty

K SPAR alteration is hot water going cold and is found in the heart of a porphyry copper.

Scott Halley has shown in his numerous geochemical studies of orogenic gold deposits, sericite and albite are the main alteration end members. Ore grade samples often sit above the tie-line of sericite and albite in the molal diagrams Scott favours implying excess potassium although no K spar is observed. Muruntau is an exception being awash with K spar.

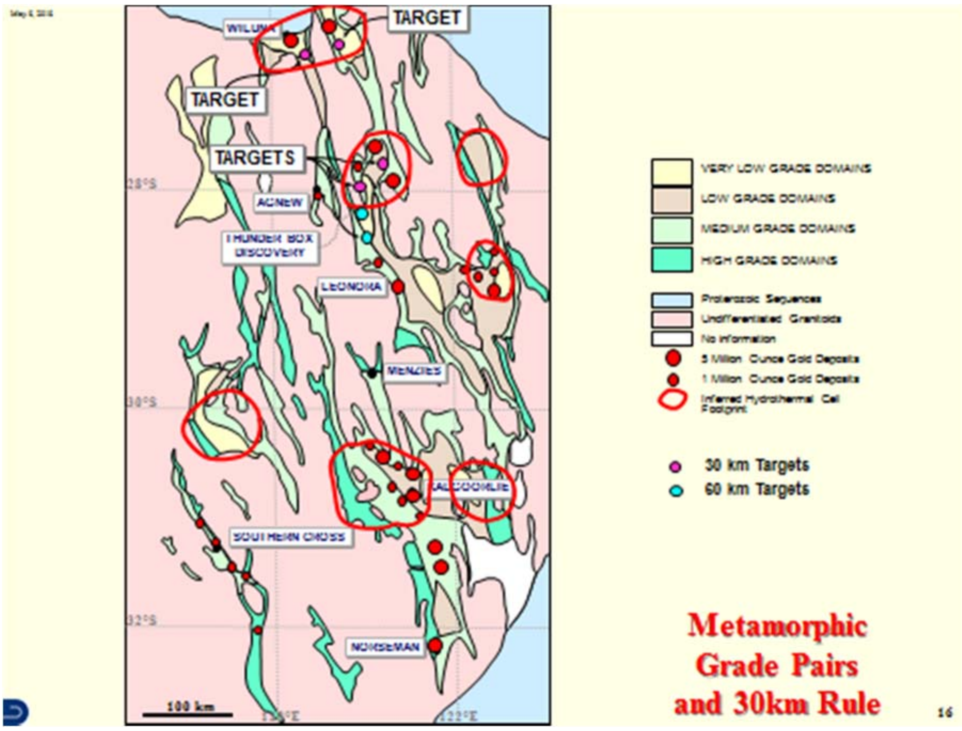
At St Ives the porphyries all carry different gold contents and very little alteration (auto-metasomatism). If there is quartz veining there will be lots of alteration and no gold. I interpret this observation to mean if the fault goes into the porphyry the gold goes up the fault. If there is no faulting the porphyry stews in its own juice. In this case the grade is always sub 1 gram Au. Most of the gold at St Ives is in the porphyries but most production is from the mafic and sedimentary host rocks related to faulting.

In the science space there are no studies of fluid in magma at usual orogenic depths like 14km at Muruntau where wall rock temperatures are +300C and pressures much greater than normal porphyry depths 1 to 5km. The inference being salty brine will be too dense to leave the magma but gas is free to travel as it may usually vertically up from the sides or top dead centre of the causative pluton as documented by Vic Wall (1989) in his masterful PhD “Fluids and Metamorphism” and his Thermal Aureole Gold (TAG) model.

Question 4: What are the Fluid Pathways and Drivers?

The primary driver for gas is buoyancy and the pathway is straight to the surface unless it is constrained in a trap site where fluid pressures will build up until the friction angle of the seal is overcome and the whole fluid leaches to the surface. Such trap sites are often home to ambient fluid with methane accumulations before the magmatic gas arrives. Such a happy event promotes fluid mixing which then drives gold precipitation e.g. Goldstrike gold deposit. Kidston breccia pipe is representative of other “trap” configurations.

The primary driver for the ambient fluid is convection albeit modified by fault geometries and layering etc. These variations often lead to unusual metamorphic aureoles. Where fluid can circulate in a fault the fluid will convect the heat away faster than conduction so asymmetric metamorphic gradients are very likely. These gradients are often preserved in regional metamorphic maps. Such maps can be used for targeting as is attempted below.



Question 5: What are the Deposition Mechanisms?

In orogenic gold deposits the primary deposition mechanism is reduction by fluid mixing. Extensive isotope and other mineralogical studies (litho-geochemistry and hyperspectral mapping) have produced results consistent with this interpretation.