

## 2 HYDROTHERMAL ALTERATION

Hydrothermal alteration typically represents changes in mineralogy by interaction with the wall rocks of hydrothermal fluids related to the mineralising process, although some workers include gangue minerals deposited in conjunction with mineralisation as hydrothermal alteration. This section seeks to introduce the alteration minerals and define styles of hydrothermal alteration utilised in the following discussion of epithermal and porphyry mineralisation. The **exploration implication** is that alteration changes to the wall rocks adjacent to buried mineralisation identified by geophysical tools (magnetite introduction or destruction, and chargeable pyrite introduction) and zonation patterns in wall rock alteration minerals can be used as exploration tools to define drill targets.

### Terminology

Some definitions relevant to the manner in which new minerals developed as part of the alteration include: *Prograde* hydrothermal alteration minerals represent an increase in the tenure of the alteration such as the progression from primary hornblende to secondary biotite within potassic alteration.

*Retrograde* alteration minerals develop as a downgrade of the alteration style, commonly as the development of lower temperature more hydrous forms which replace prograde minerals (from Corbett and Phillips, 1981) as:

*Kinematic* development of new minerals such as the development of garnet skarn as a replacement of limestone.

*Pseudomorphous* replacement occurs as new minerals replace old ones such as retrograde chlorite replacing primary biotite.

*Pervasive* alteration may totally replace wall rock or intrusions, varying to replacement of particular mineral phases.

*Fractures* and *breccias* represent plumbing systems for the introduction of hydrothermal fluids, and so alteration grades away from crackle breccias (figure 4.8).

*Veins* cut wall rock and host kinematic mineral growth within open space and act as fluid plumbing systems to promote alteration of adjacent wall rocks, zoned away from the vein.

*Ledge* is a body of silica of variable dip and origin. *Steam heated*, *bicarbonate* and *acid sulphate* waters are described in section 1.

## 2.1 ALTERATION MINERALS

The pH vs temperature figure (figure 2.1) by the late Terry Leach, updated from Corbett and Leach (1998) for the 2008 Terry Leach Symposium run in Terry's honour, represents an ideal foundation for any discussion of hydrothermal alteration associated with epithermal and porphyry mineralisation. Terry did not place actual pH or temperature values on the original pH vs temperature figure as there are too many other variables to take into account and so any values provided herein must be treated as indicative. The pH vs temperature figure groups alteration minerals as:

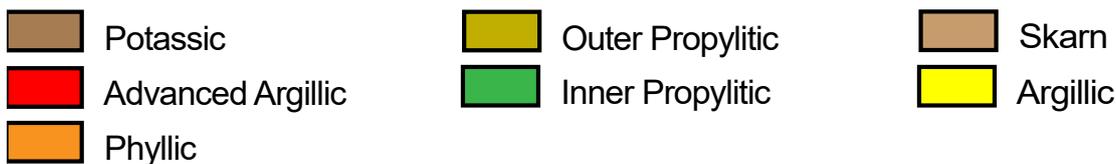
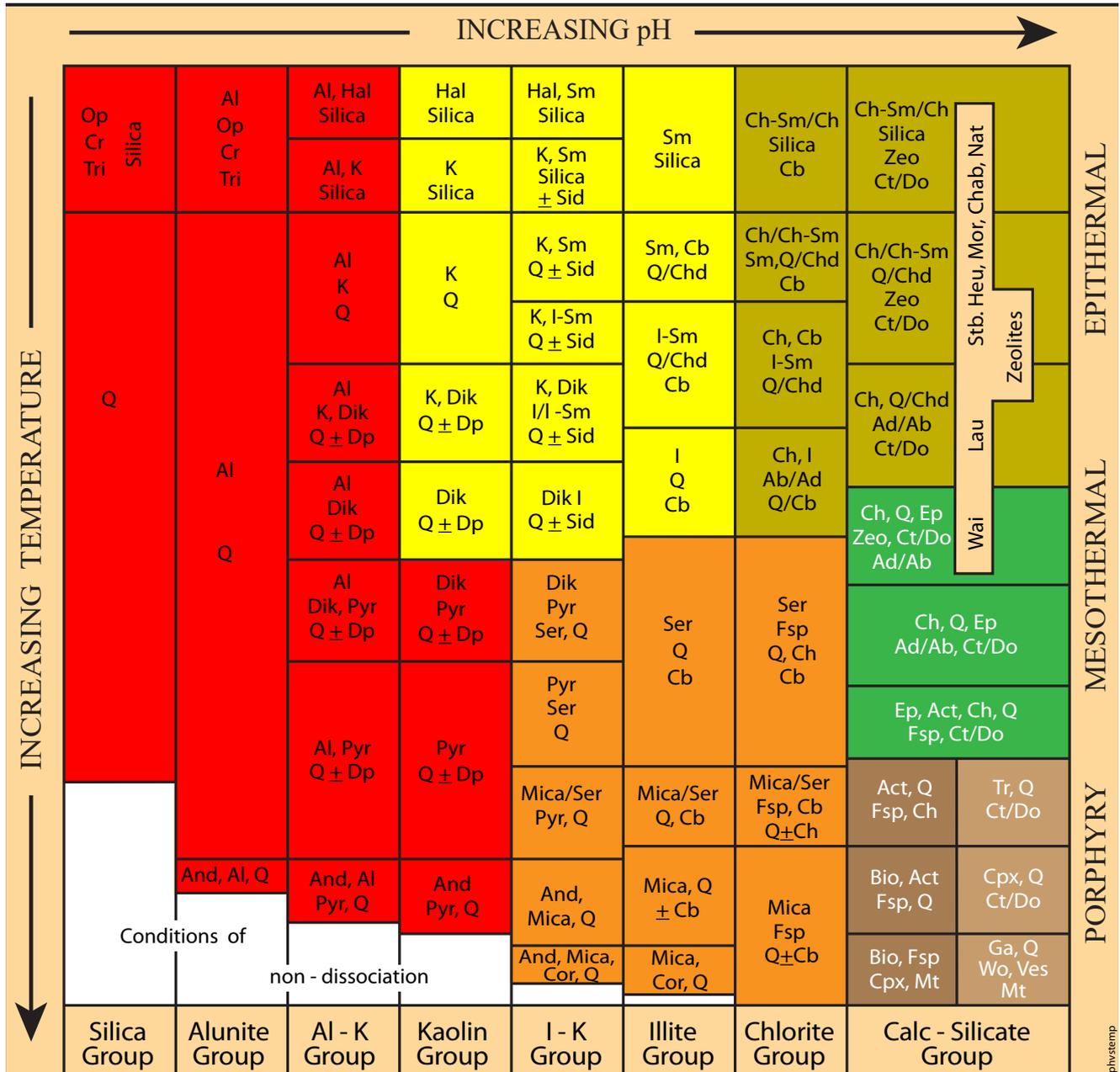
- Essentially in mineral groups of consistent pH of formation, but with variations in temperature (vertical columns on figure 2.1),

- According to the terminology in common use by the mineral exploration industry to describe hydrothermal alteration mineral assemblages as the colour variations in figure 2.1.

Common mineral groups (vertical columns in figure 2.1) described below have been categorised within temperature ranges (figure 2.2) from analyses of geothermal systems and other research (Corbett and Leach, 1998 and references therein) as:

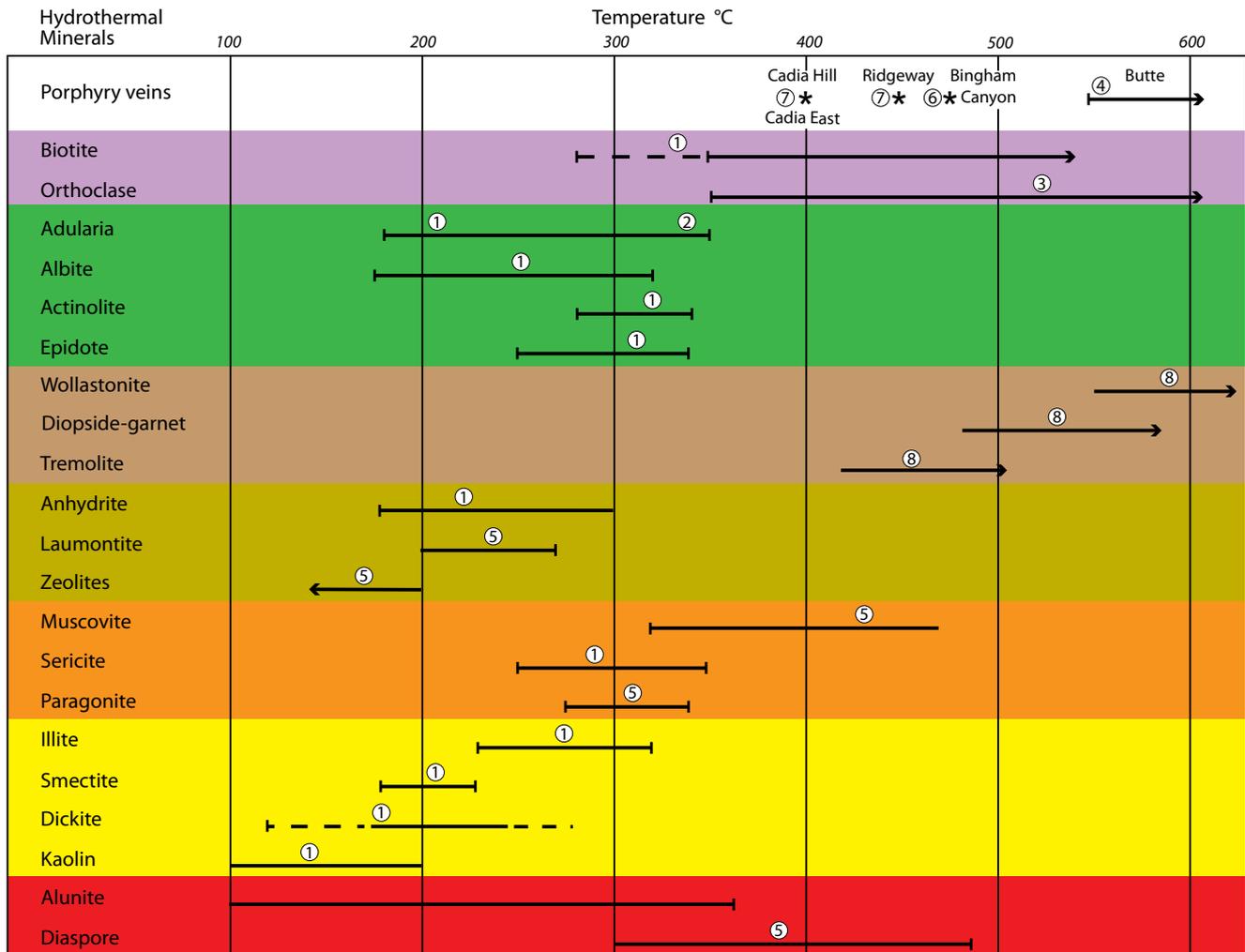
### 2.1.1 CALC-SILICATE GROUP

Calc-silicate group minerals form in near neutral conditions (pH <6-7) and with increasing temperature (figure 2.1) grade through a sequence such as: biotite-K-feldspar -> actinolite -> epidote-carbonate -> adularia/albite -> chlorite-zeolites. Studies of Philippine geothermal systems (Reyes, 1990; Reyes et al., 1993 & 2003) provide estimated lower temperature limits for the formation of many minerals, typically as the first recognition moving towards the heat source. K-feldspar as orthoclase forms with biotite in a cooling intrusion from say above 600°C and continues deposition through to 400°C (Dillies and Einaudi, 1992) and then undergoes a transition to adularia at 350°C (Reyes et al., 2003). Secondary biotite deposits throughout this temperature range down to 280°C (Reyes, 1990), as an important component of potassic alteration. Albite deposits from 175-320°C and well crystalline epidote is recognised from temperatures as low as 240°C to 340°C (Reyes, 1990), although less crystalline epidote may form as low as 150°C. Actinolite is recognised from 280 to 340°C (Reyes, 1990). Zeolites formed at lower temperatures include anhydrous laumontite 120-200°C and wairakite, 220-310°C (Reyes, 1990) and the hydrated zeolites natrolite and mordenite at 150-200°C. Laumontite is common as a low temperature overprint on higher temperature



Abbreviations: Ab - albite; Act - actinolite; Ad - adularia; Al - alunite; And - andalusite; Bio - biotite; Cb - carbonate; (Ca, Mg, Mn, Fe); Ch - chlorite; Chab - chabazite; Chd - chalcedony; Ch-Sm - chlorite-smectite; Cor - corundum; Cpx - clinopyroxene; Cr - cristobalite; Ct - calcite; Do - dolomite; Dik - dickite; Dp - diaspore; Ep - epidote; Fsp - feldspar; Ga - garnet; Hal - halloysite; Heu - heulandite; I - illite; I-Sm - illite-smectite; K - kaolinite; Lau - laumontite; Mt - magnetite; Mor - mordenite; Nat - natrolite; Op - opaline silica; Pyr - pyrophyllite; Q - quartz; Ser - sericite; Sid - siderite; Sm - smectite; Stb - stibnite; Tr - tremolite; Tri - tridymite; Ves - vesuvianite; Wai - wairakite; Wo - wollastonite; Zeo - zeolite.

**Figure 2.1** Common alteration minerals in hydrothermal systems. The Terry Leach pH versus temperature figure, updated from Corbett and Leach, (1998) for the Terry Leach Symposium in 2008. This figure illustrates groups of mineral assemblages described in the geological literature and discussed herein.



**Figure 2.2** Temperature ranges for the formation of hydrothermal alteration minerals from: 1- Reyes, 1990; 2- Reyes et al., 2003; 3- Dilles and Einaudi, 1992; 4- Rusk et al., 2008; 5- Reyes et al., 1993; 6- Redman and Einaudi, 2010; 7- Wilson et al., 2007; 8- Einaudi et al., 1981. A declining temperature range of porphyry systems is provided by the comparison of: Butte as a very hot porphyry, Bingham Canyon as a large pluton, Ridgeway as a smaller spine-like body emplaced into wall rocks and Cadia Hill Au-Cu and Cadia East Au-Mo both as wallrock porphyry deposits.

minerals in low sulphidation epithermal and porphyry systems (figures 2.2 & 2.7 D).

Carbonate, in particular calcite, deposits over a wide temperature range, although Reyes (1990) suggests dolomite forms below 180°C. In low sulphidation carbonate-base metal Au deposits, the carbonate species deposited within veins changes with rising pH (less acid waters) as: siderite, rhodochrosite, kutnahorite, ankerite, dolomite, Mg-calcite then calcite in neutral conditions (section 7.1.1.2.1).

Minerals associated with prograde isochemical skarns include wollastonite, which is stable above 550°C, diopside, andradite garnet and forsterite above 475°C and tremolite above 420°C (Einaudi et al., 1981). Retrograde skarn minerals typically form at lower temperatures (epidote, chlorite) and are commonly hydrous such as the serpentinisation of forsterite-bearing skarn.

## 2.1.2 CHLORITE GROUP

Chlorite group minerals form in the pH 5-6 range and variably coexist with illite group minerals over a wide temperature range, commonly pseudomorphing mafic minerals at low temperatures or retrograde alteration, and extending to higher temperatures to coexist with the low temperature range of epidote formation (figure 2.1).

## 2.1.3 ILLITE GROUP

Illite group minerals form at pH 5-6 in a wide temperature range with associated variations in crystallinity, although the composition may remain similar, governed by temperature of formation, which is related to depth of formation and proximity to heat source such as a vein. High temperature minerals display most crystalline forms varying to less crystalline and locally hydrated for minerals formed at low temperatures. In the terminology used

here illite group minerals are categorised (Corbett and Leach, 1998) with declining temperature as: muscovite formed at highest temperatures (>350°C), varying to sericite (250-350°C), then illite (200-250°C), illite-smectite, smectite-illite and smectite (<100-150°C). Smectite clays also form in the weathering environment. This trend in illite type (crystallinity) with temperature (depth) can be measured using spectral devices to provide temperature vectors, typically towards low sulphidation epithermal veins developed in the higher temperature portion of zoned clay alteration. There are variations in Na:K ratio from K-rich illite to Na-rich paragonite, while other illite minerals include the V-bearing roscoelite, which is associated with some alkaline Au deposits (Porgera & Mt Kare in Papua New Guinea; Emperor, Fiji). Montmorillonite is an Al-rich smectite, while the Fe-rich form is termed nontronite and saponite represents the Mg-rich form.

An **exploration implication** is provided by the ability to vector towards veins using zoned alteration described herein.

### 2.1.4 ILLITE-KAOLIN GROUP

The illite-kaolin group minerals (figure 2.1) mark the transition from illite to kaolinite groups as defined by a decline in pH to 4 and the introduction of kaolin and its high temperature polymorph dickite. Andalusite and/or corundum are typical of acidic conditions and very high temperatures of formation (400-450°C) and occur in porphyry-related environments (below), although Reyes et al. (2003) describe the first (lower temperature) appearance of andalusite at 365°C.

### 2.1.5 KAOLIN GROUP

Kaolin forms in conditions of pH <4 (Reyes, 1990) and coexists with alunite in the pH 3-4 range (Stoffregen, 1987) over a wide temperature range in a variety of alteration styles from low temperature acid sulphate and steam heated, to higher temperature advanced argillic alteration (below). Halloysite represents an hydrated form of kaolin developed at very low temperatures including weathering. Kaolin develops at low to moderate temperatures (100-180°C), passing to dickite as the high temperature polymorph from as low as 120°C (Reyes, 1990), and then pyrophyllite (200-300°C), although Reyes (1990) suggests pyrophyllite may form at much lower temperatures in the presence of excess silica. Pyrophyllite-diaspore therefore co-exist at moderately high temperature (120-320° C; Reyes, 1990) acid conditions, although this alteration is described as

diaspore dominant in silica-rich conditions (Hemley et al., 1980 in Corbett and Leach, 1998). Elsewhere pyrophyllite forms the dominant alteration mineral. Halloysite and kaolin may develop in weathering (supergene) conditions, particularly in the presence of acid ground waters, typically evidenced by the presence of associated FeO and MnO. Careful XRD studies can distinguish the more crystalline nature of hypogene kaolin from the less crystalline supergene kaolin, while in hand specimen only hypogene kaolin is likely to be in contact with fresh sulphides. Kaolin recognition is an important exploration skill as low pH acid sulphate waters, evidenced by hypogene kaolin, may collapse into the ore environment and mix with ore fluids to promote bonanza Au deposition (section 7.4).

### 2.1.6 ALUNITE-KAOLIN GROUP

Alunite-kaolin group minerals dominate in very acidic conditions at a pH less than about 2, although alunite-kaolin locally coexist in the pH 3-4 range (Corbett and Leach, 1998 and references therein). Alunite may develop by wall rock alteration, typically as a fine crystalline form but vary to coarse crystalline alunite deposited directly from magmatic fluids in veins or breccia fill. Powdery very fine alunite occurs in steam heated alteration, while poorly crystalline supergene alunite may develop in the weathering environment, particularly where acidic ground waters are derived from the weathering of pyritic alteration (figure 2.34 E & F). Although alunite typically occurs as a hydrated potassium aluminium silicate [ $K_2Al_6(OH)_{12}(SO_4)_4$ ], a sodic form termed natroalunite is also recognised.

### 2.1.7 SILICA GROUP MINERALS

Silica group minerals vary with temperature. At shallow crustal levels and low temperatures (<100-150°C) amorphous silica deposition includes cristobalite, tridymite, and opal, formed in environments such as within hot spring deposits, which with time may be transformed to chalcedony and then more crystalline quartz (Fournier, 1985a). In detail, opal dominates below 150°C and cristobalite occurs in the 100-160°C range, tridymite 150°C (but possibly lower) and quartz represents the main silica species above 180°C (Reyes, 1990). Chalcedony is most commonly recognised in epithermal environments as fine grained white to buff coloured amorphous silica varying from massive to finely colloform banded where repeatedly deposited from a rapidly cooling fluid. Although Fournier (1985a) provides 180°C as the upper temperature limit of chalcedony developed by the recrystallisation of amorphous silica, he also notes

chalcedony may deposit directly from cooling fluids, and that in these settings temperature determinations from quartz crystals will not reflect the conditions of chalcedony deposition. It is therefore argued that fine grained amorphous silica in epithermal veins described in the field as chalcedony by many explorationists, has been deposited by the rapid cooling of high temperature fluids (Heaney, 1993) during vein formation. Slower cooling fluids result in the deposition of crystalline quartz, which may be interlayered with amorphous silica or occur as comb quartz veins, locally banded and/or with centrally terminating mirror image crystals in veins with open centre lines (figure 1.11A). Banded epithermal veins develop by many discrete episodes of mineral deposition with possible variations in conditions or composition between bands.

There is an **exploration implication** that fluid inclusion studies on coarse grained quartz crystals within banded veins, from different bands to the sulphides which host Au mineralisation, may not correctly represent the conditions of Au formation (Fournier, 1985a).

Very acidic fluids <2 pH favour the removal of silica from zones of acid sulphate alteration which may be redeposited as sub-horizontal silica ledges where the fluid has been neutralised at the base of the acid sulphate blanket (Fournier, 1985a) close to the palaeo water table.

Rapid falls in confining pressure promote quartz deposition (Corbett and Leach, 1998). Venting depressurised eruption (phreatic) breccias deposit significant quartz (section 4.4.6). In porphyry systems quartz is deposited by rapid fluid pressure decrease, typically within fracture-controlled stockwork quartz veins (section 3.3.2.3). The model in common use features failure of an intrusion carapace (i.e. hornfels or chilled intrusion margin) as the build up of magmatic fluid pressure exceeds the confining pressure and tensile rock strength (Phillips, 1973). By contrast the model used herein (sections 3.3.2 & 3.4) relies upon a structural control to carapace failure, determined from the kinematic analysis of resultant quartz veins, as an exploration tool to identify the conditions of porphyry emplacement and in the search for additional mineralisation.

## 2.2 ALTERATION STYLES

In order to compare different hydrothermal systems and consider the relationship of alteration to mineralisation, in particular alteration zonation as an

exploration vector, a terminology has developed in the exploration literature to provide a classification for alteration styles. While many workers rightly believe it is better to use descriptions based upon the actual minerals, the shorter historical terms which pervade the geological literature are often less cumbersome. For instance the mineral description silica-sericite-carbonate-chlorite-pyrite alteration might be preferred by some workers whereas others are happy with the traditional term 'phyllitic alteration', for that mineral assemblage. The pH vs temperature figure of Terry Leach (figure 2.1) modified from (Corbett and Leach, 1998) provides an indication of the relationships between alteration styles, the contained minerals and conditions of formation.

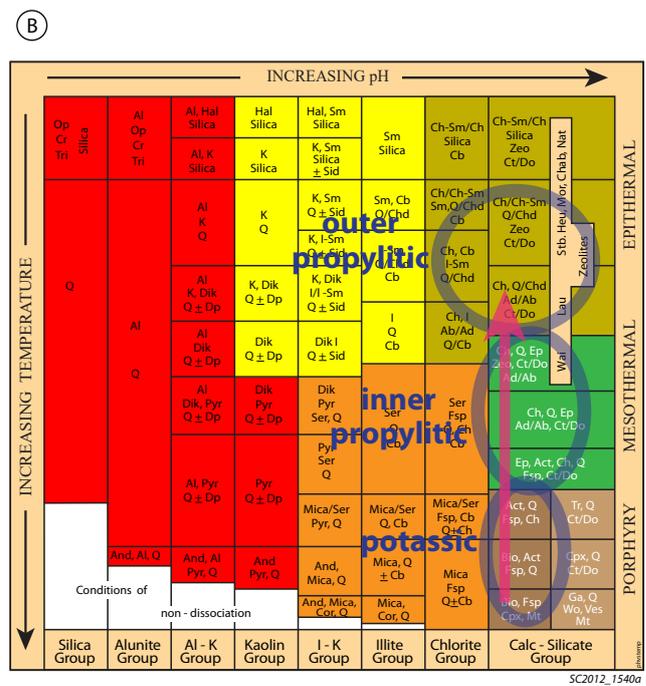
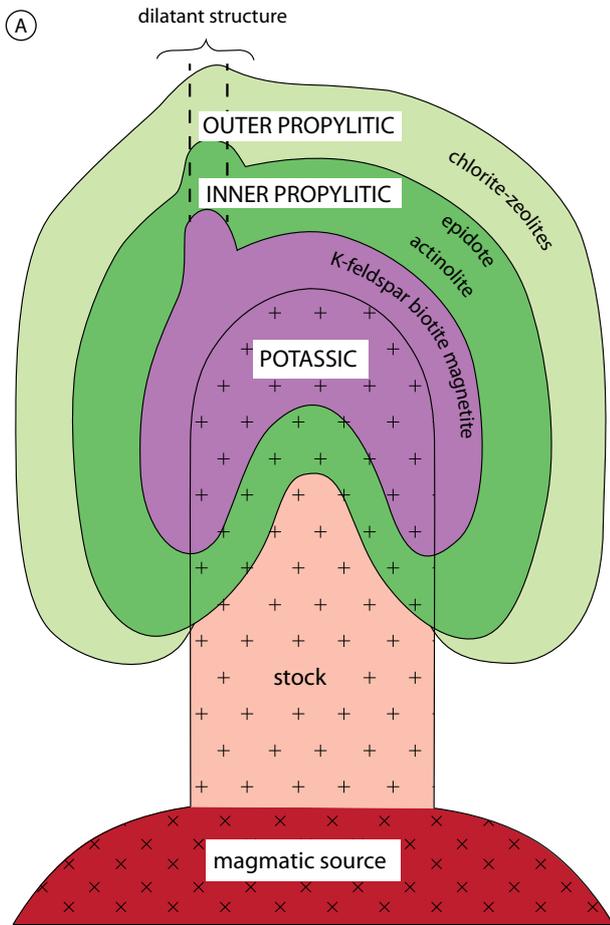
The **exploration implications** of an understanding of hydrothermal alteration overprinting relationships and zonation patterns is discussed in detail in section 9.

The standard alteration styles in common use by explorationists (figure 2.1) include:

### 2.2.1 PROGRADE PORPHYRY ALTERATION

#### 2.2.1.1 Potassic alteration

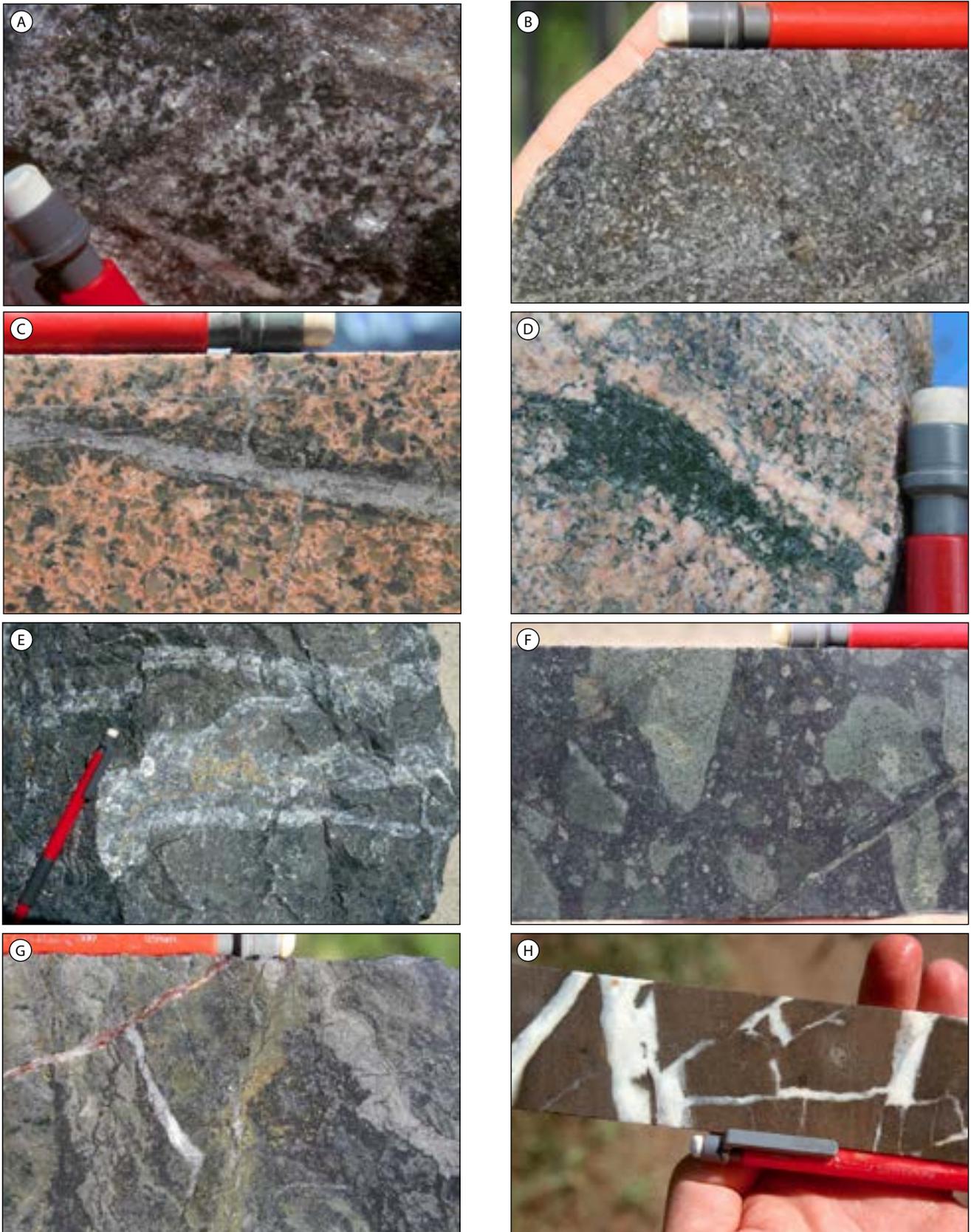
Potassic hydrothermal alteration develops in prograde high temperature (>350°C) and near neutral pH (>7) conditions, typically formed in association with porphyry intrusions and extending into the adjacent wall rocks. It is characterised by minerals such as K-feldspar (orthoclase), secondary biotite with quartz and associated magnetite, quartz and anhydrite and sulphides (figures 2.3-2.5). K-feldspar alteration varies from pervasive within the intrusion matrix and extending away from the source intrusion within permeable host rocks, to vein selvages and fracture filling veins (figure 2.4). Magnetite and secondary biotite vary from replacement of primary mafic minerals to complete flooding of the host rock, either intrusions or permeable wall rock. Anhydrite is common as breccia matrix or fracture fill veins (figure 2.5). Potassic alteration is termed K-silicate by some workers (Sillitoe and Gappe, 1984; Sillitoe, 2010). Significant porphyry Cu-Au mineralisation, typically as chalcopyrite and bornite, commonly occurs within rocks which originally displayed potassic alteration, although that alteration may have been subsequently overprinted by retrograde alteration (below). After the formation of potassic alteration, at low temperatures anhydrite hydrolyses to gypsum which requires more space and may aid rock failure in open stope underground mines.



**Figure 2.3** Zoned potassic-propylitic alteration. A – pH remains constant while alteration grades as potassic to propylitic away from the intrusion heat source under the influence of declining temperature, from the staged porphyry model (figure 5.1). B – Mineral assemblages on PH vs temperature (figure 2.1) with an arrow showing the cooling trend.



**Figure 2.4** K-feldspar within potassic alteration showing examples of pink orthoclase. A - Within the matrix to an intrusion, Zhongdian, China. B - Selvages to linear A veins, Caspiche, Chile. C - Matrix to a permeable volcanic breccia, Temora, Australia. D - Veinlets cutting wall rock andesite, Constanca, Peru.



**Figure 2.5** Potassic alteration characterised by secondary biotite, actinolite, magnetite and anhydrite.

**A** - Secondary biotite replacing mafic minerals from St Tomas, Philippines.

**B** - Pervasive fine grained brown matrix secondary biotite, Wamum, Papua New Guinea.

**C** - Biotite selvage to an A vein, Goonumbla, Australia.

**D** - Actinolite-orthoclase, Rawbelle, Australia.

**E** - Magnetite flooding on andesite wall rock, Ridgeway, Australia.;

**F** - Magnetite flooding of a permeable volcanic breccia, Macquarie Arc, Australia.

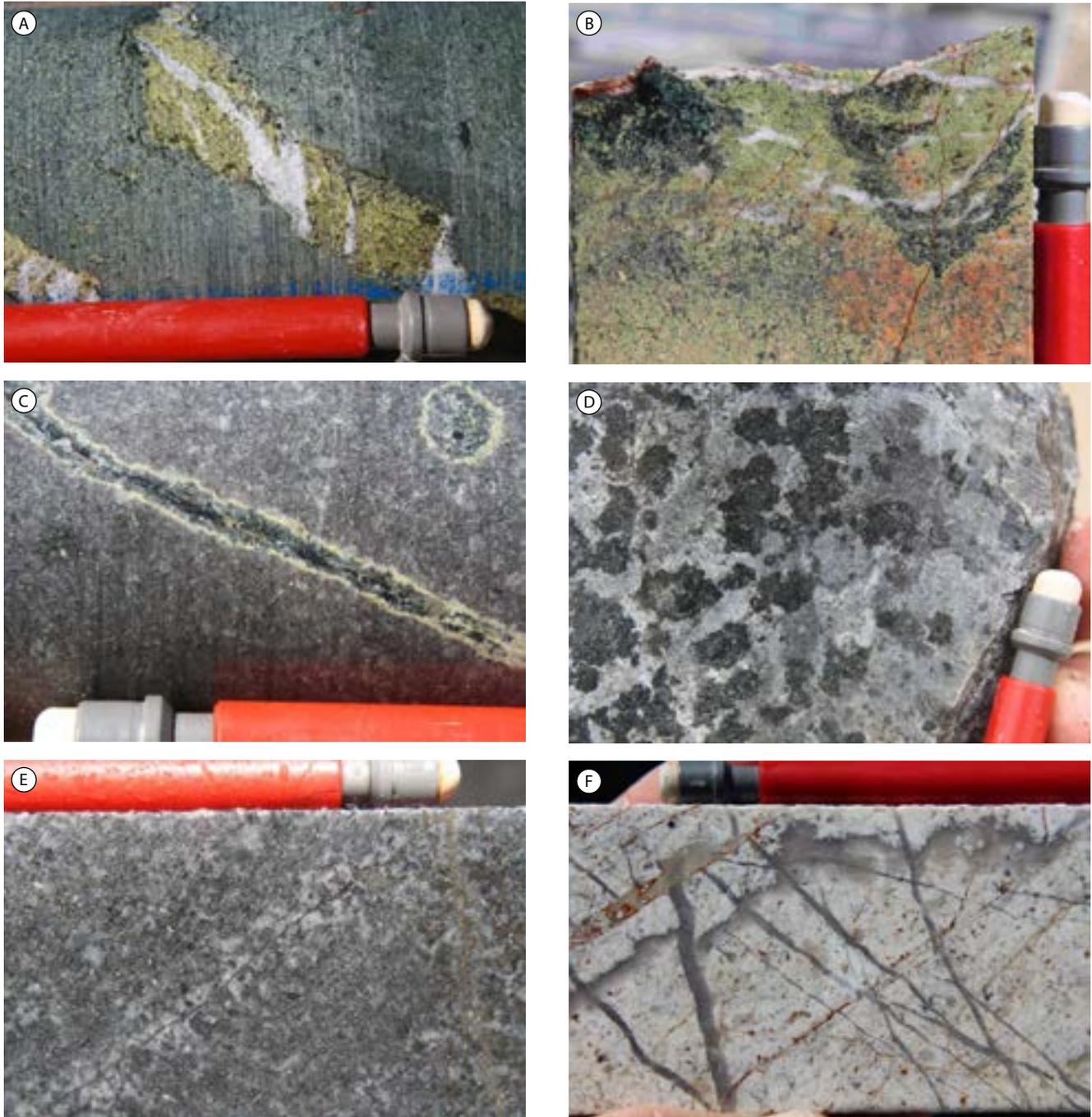
**G** - K-feldspar-magnetite-anhydrite, Taguibo, Philippines.

**H** - Anhydrite breccia fill and oxidised biotite-K-feldspar-magnetite-pyrite altered clasts, Lihir Is., Papua New Guinea.

### 2.2.1.2 Inner propylitic alteration

Inner propylitic hydrothermal alteration forms as prograde alteration at a lower temperature (250-350°C & pH >7) than potassic alteration and is characterised by actinolite, epidote, adularia (as the lower temperature form of K-feldspar), albite, chlorite, carbonate and local magnetite introduction (figure 2.3). It is common in wall rocks outboard of potassic alteration and in moderately altered intrusions. While

actinolite is placed within potassic alteration by many workers (figures 2.1 & 2.6; Corbett and Leach, 1998; Sillitoe and Gappe, 1984), and used by some workers to define outer potassic alteration, this work cites actinolite as a key indicator mineral for the inner propylitic alteration zone within wall rocks moving closer to the intrusion heat source. The discovery drill hole (NC498) for the Ridgeway porphyry, Australia, bored within the wall rocks from epidote alteration into actinolite prior to the intersection of the porphyry



**Figure 2.6** Inner propylitic alteration.

**A** - Calcite-epidote, Orange district, Australia.

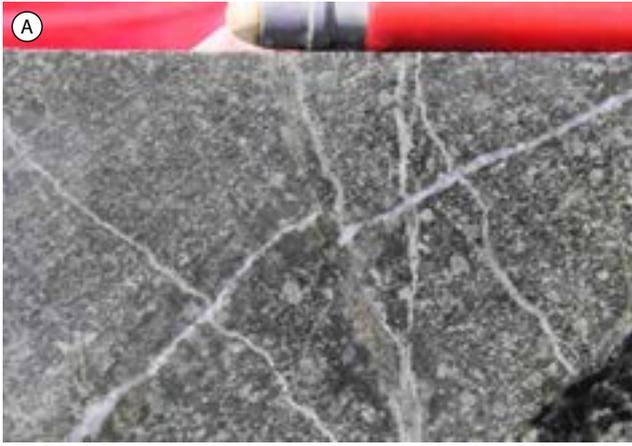
**B** - Epidote-actinolite from DDH NC498, 485m, as the first occurrence of actinolite within the wall rocks moving towards the Ridgeway porphyry, Australia.

**C** - Fracture-vein with inner high temperature actinolite and outer cooler epidote, Sumbawa, Indonesia.

**D** - White albite-actinolite, Namosi, Fiji.

**E** - Actinolite vein with selvage albite.

**F** - Pervasive albite alteration, Goonumbla, Australia.



**Figure 2.7** Outer propylitic alteration.

**A** - Chlorite-carbonate-illite-pyrite Copper Hill, Australia.

**C** - Epidote vein with haematite selvage, Goonumbla, Australia.

**B** - Chlorite-calcite-haematite, Doris, Chile

**D** - Calcite-laumontite vein/breccia, Kupol, Far Eastern Russia.

(figure 5.6). Actinolite can therefore represent an important exploration vector where recognised within the wall rocks outside the more prospective potassic alteration.

Albite may form in place of K-feldspar in Na-rich rocks extending away from the source intrusion, typically as part of the propylitic alteration assemblage (figure 2.1), as it forms at a lower temperature than orthoclase (figures 2.2 & 2.6). Albite-actinolite is a common mineral assemblage indicative of outer potassic – inner propylitic alteration (figures 2.1 & 2.3).

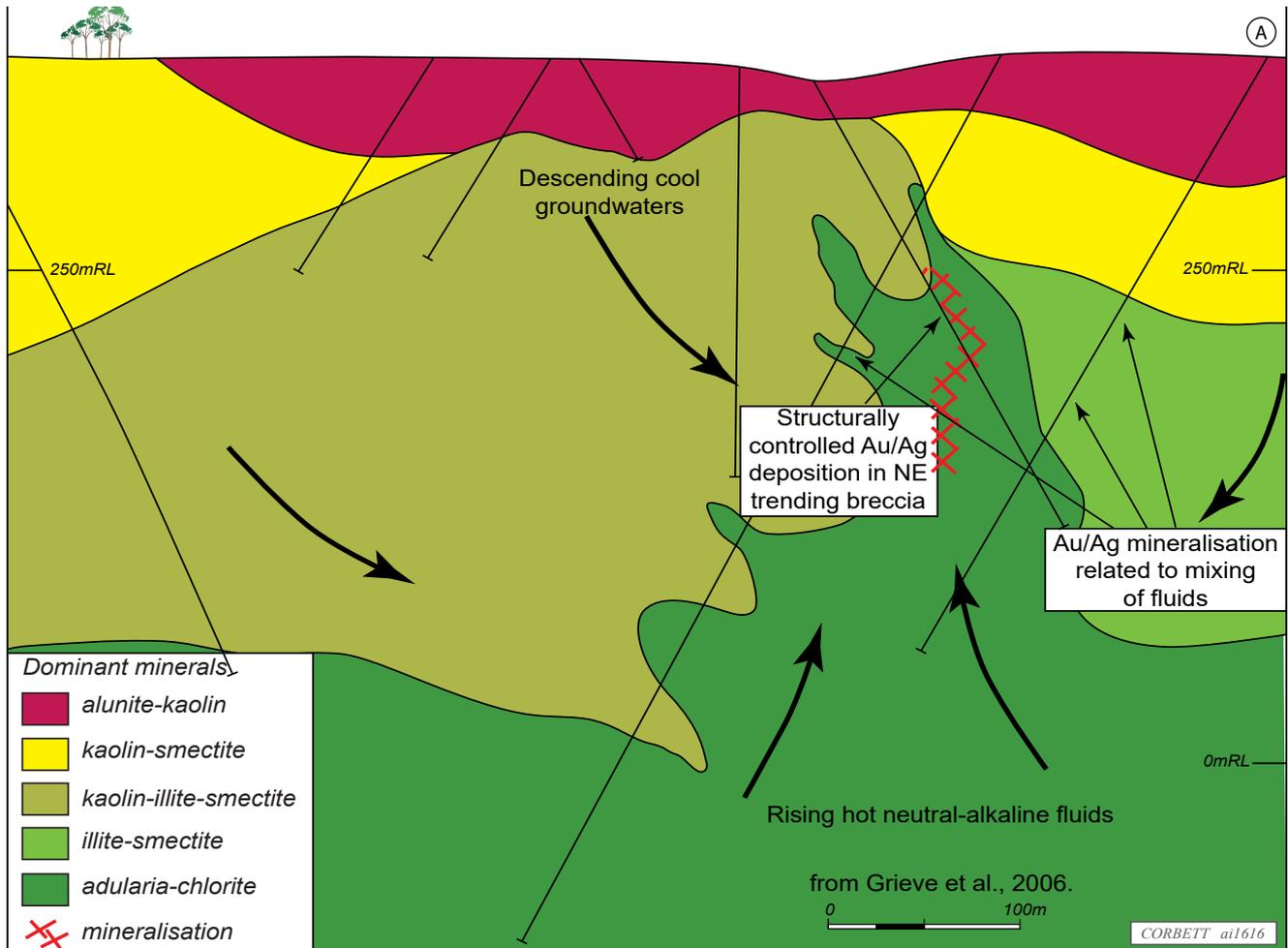
### 2.2.1.3 Outer propylitic alteration

Outer propylitic hydrothermal alteration typically occurs within wall rocks more marginal to the (commonly potassic altered) intrusion source than inner propylitic alteration, and may also be present within weakly altered stocks in epithermal environments (figures 2.1, 2.3 & 2.7). It is transitional to alteration recognised in sea floor or metamorphic rocks which is not considered here. Outer propylitic alteration (>250°C & >6 pH) is characterised by the presence of chlorite, carbonate, haematite and local

pyrite with common additional zeolites, and varies to host adularia-albite at higher temperatures and illite-smectite in slightly lower pH conditions. While calcite represents the most common carbonate, others deposited from more acidic fluids include rhodochrosite and dolomite (see section 7.4). Pervasive chlorite with fracture controlled calcite represents a common mineral assemblage (figure 2.7). Magnetite is locally present at higher temperatures.

### 2.2.1.4 Zoned potassic-propylitic

Zoned potassic-propylitic hydrothermal alteration develops over the declining temperature range at constant near neutral high pH (>6-7) grading away from a porphyry heat source into the wall rocks (figures 2.1-2.3), and therefore represents an important component of the model for the staged development of porphyry Cu-Au deposits presented herein (figure 5.1). Initial conductive heat transfer, following intrusion emplacement, might gradually be enhanced by convective heat flow associated as circulating hydrothermal cells are driven by the magma heat source. These circulating hydrothermal cells, which entrain meteoric waters with magmatic brines to form a magmatic-meteoric fluid, therefore represent a key



means for the progression of metals and volatiles to settings above and lateral to the source porphyry intrusion. Alteration mineral zonation, particularly in propylitic alteration is used in exploration to vector towards potassic alteration where mineralisation is likely to develop (section 9).

### 2.2.1.5 Epithermal propylitic (-potassic) alteration

Propylitic (-potassic) hydrothermal alteration in epithermal Au deposits occurs either as vein selvages or flooding of permeable host rocks. While this alteration is most apparent in higher temperature arc-related deposits, it is also recognised in back

arc environments. Common mineral assemblages include K-feldspar grading from orthoclase to lower temperature adularia along with quartz, chlorite and pyrite. Adularia is typically overprinted by illite clays as the hydrothermal system evolves in conditions of declining temperature and fluid pH characterised by argillic alteration. Lower temperature systems may feature an overprint of zeolites then illite-smectite, while kaolin overprints derived from collapsing acid sulphate waters are locally recognised. While some workers cite this adularia alteration, present as low temperature K-feldspar flooding, as evidence of Au deposition by boiling, other explanations are possible (section 7.4).



**Figure 2.8** Alteration and mineralisation at the Ohakuri, New Zealand.  
**A** - Cross section showing adularia alteration overprinted by the collapsing acid sulphate cap from Grieve et al. (2006).  
**B** - Adularia altered fiamme ignimbrites in outcrop.  
**C** - In drill core with some illite overprint.  
**D** - Adularia altered tuff cut by a pyrite-marcasite-opal vein.

#### 2.2.1.5.1

At the **Ohakuri** prospect, within the Taupo Volcanic Zone back arc setting, New Zealand, extremely permeable fiamme-bearing ignimbrites display initial alteration categorised as a flooding of quartz-adularia-chlorite with local clay and zeolite overprint (figure 2.8; Grieve et al., 2006). This alteration is interpreted as propylitic passing laterally and with time to zeolite (mordenite) + illite-smectite alteration as well as to argillic alteration dominated by illite-smectite clays. An acid sulphate cap which grades downwards from surficial alunite-kaolinite the deeper level kaolinite with illite-smectite, formed by cooling and neutralisation of the low pH acid sulphate waters and collapses upon the propylitic-argillic alteration. Grieve et al. (2006) cite the association of Au-Ag mineralisation with low temperature clays immediately below the acid sulphate cap to suggest mineralisation within sulphide breccias and colloform banded quartz veins with sulphide bands was deposited by the mixing of rising ore fluids with collapsing cool oxidising ground waters. Although dilatant structures are apparent the ignimbrites have been too incompetent to host quality veins (section 7).



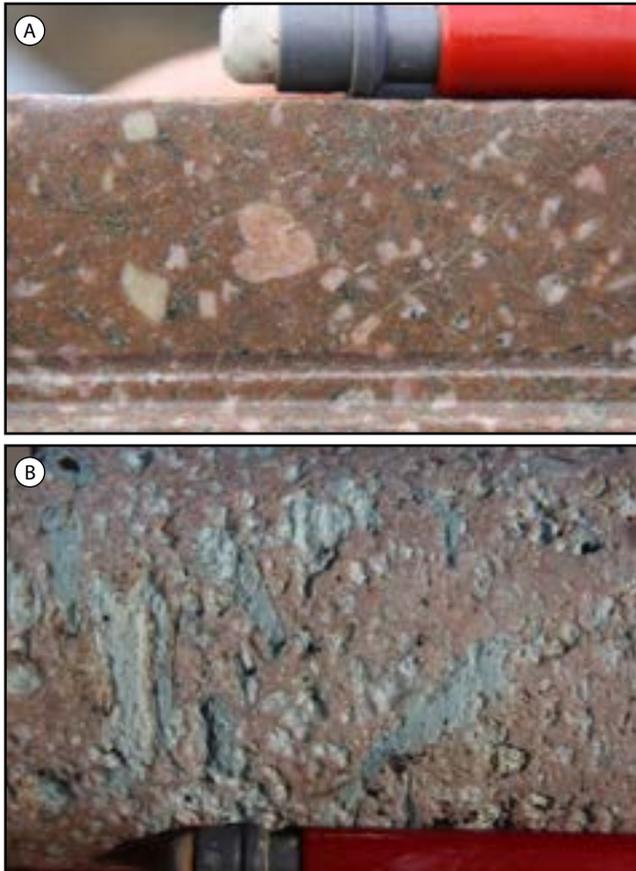
**Figure 2.9** Adularia alteration with distinctive pinhole texture, Ladolam open pit, Lihir Is., Papua New Guinea.  
**A** - Outcrop.  
**B** - Altered volcanic breccia in drill core.



**Figure 2.10** Propylitic altered permeable lithic tuff at Round Mountain Nevada, characterised by adularia flooding with associated chlorite, pyrite, calcite and albite shown as:  
**A** - Outcrop;  
**B** - Drill core.

### 2.2.1.5.2

At the **Ladolam** gold deposit Lihir Island, Papua New Guinea, unroofing by listric faults during sector collapse has promoted the rapid transition from porphyry to epithermal alteration and mineralisation (Corbett, 2005b; section 3.2.5.3). Epithermal Au mineralisation is associated with the K-feldspar (adularia) event (Corbett et al., 2001) characterised by a flooding of early orthoclase which grades to later lower temperature adularia (Carmen, 1995),



**Figure 2.11**  
**A** - Wall rock K-feldspar (adularia) flooding adjacent to a vein at Dvoinoye in the Russian Far East (Thomson B. and Golden, H., 2011).  
**B** - Pink wall rock adularia flooding of a permeable fiamme tuff from Bolnisi, Georgia with green illite alteration of the fiamme.

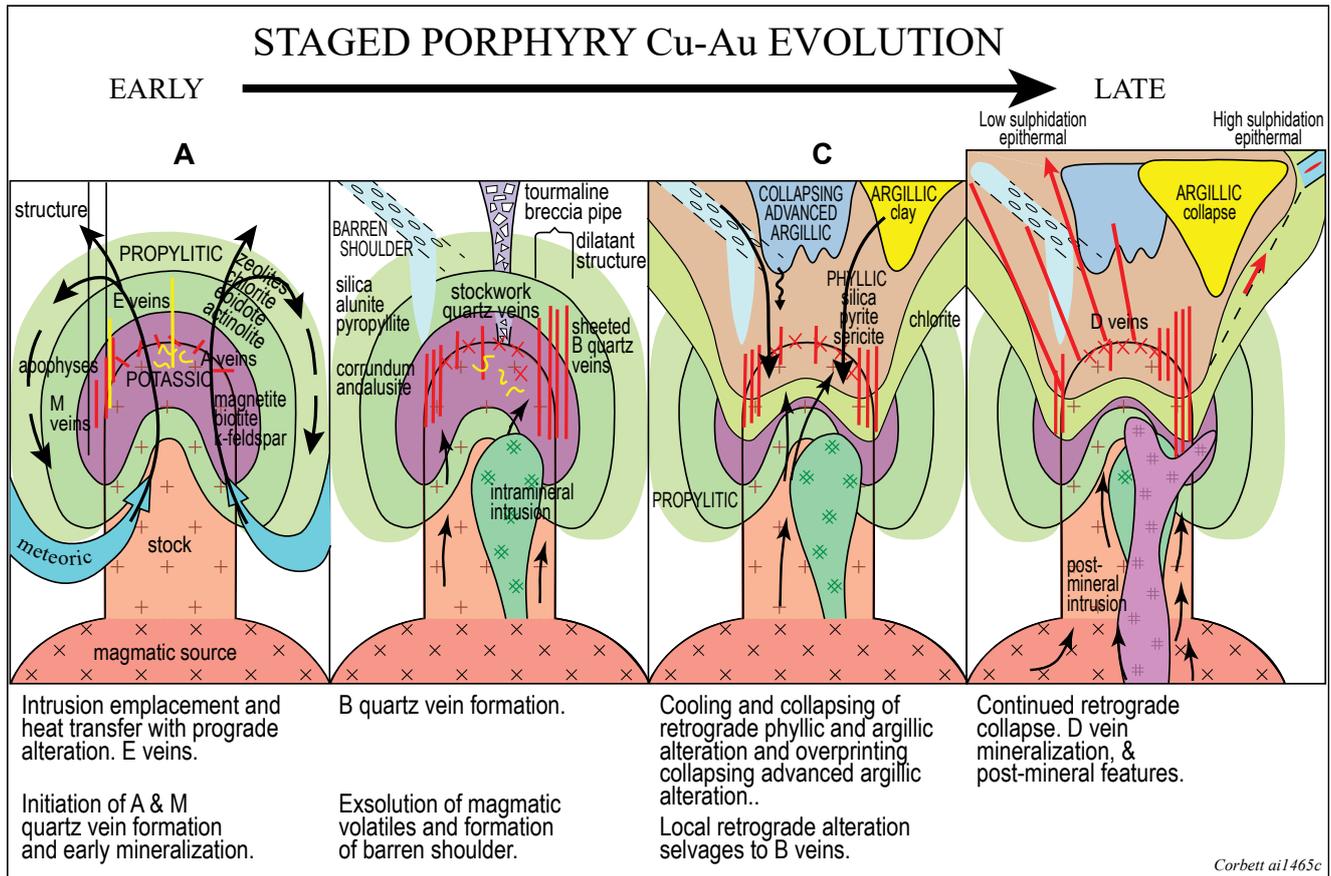
with sulphides and local illite (figure 2.9). Textural destruction has provided the distinctive ‘pinhole texture’ as the early porphyry alteration and fresh rocks are overprinted by the K-feldspar event which is in turn overprinted by collapsing acid sulphate-argillic alteration (figure 2.9; section 2.2.3.2). Gold mineralisation encapsulated in fine grained sulphides, typically arsenean pyrite, is characterised as of the low sulphidation epithermal quartz-sulphide Au + Cu style (Corbett and Leach, 1998; section 7.2.1.1.4.2). The strong correlation between this alteration and Au mineralisation (Carmen, 2003) is attributed to Au deposition by sulphidation reactions (Leach, unpubl. report, 2006 in Kidd, 2008).

### 2.2.1.5.3

**Round Mountain**, Nevada features flooding of permeable “variably welded rhyolitic tuff” by a propylitic mineral assemblage comprising: adularia, albite, chlorite, calcite and pyrite (figure 2.10; Fifarek and Gerike, 1990 after Sander, 1988) in which Au mineralisation (section 7.2.1.1.4.3) is hosted within disseminated and vein pyrite (of the low sulphidation epithermal quartz-sulphide Au+ Cu style). Some workers suggest mineralisation is best developed at the transition from propylitic to potassic alteration characterised by more “pure adularia” (Sander and Einaudi, 1990). Mine geologists attribute the flat orientation of mineralisation to preferential mineralisation of a more permeable felsic tuff unit within a sequence which contains a less permeable cap rock. Gold was deposited from a cooling fluid as disseminated pyrite within the altered tuff or cross-cutting quartz-pyrite veins (section 7.2.1.1.4.3).

## 2.2.2 RETROGRADE PORPHYRY ALTERATION

The process of retrograde hydrothermal alteration represents a fundamental change in the fluid chemistry and flow dynamics of the porphyry hydrothermal system. Prograde potassic-propylitic alteration is initiated as conductive transfer of heat from the intrusion into the wall rocks followed by convective heat transfer as that heat drives circulating cells of rising hot magmatic-meteoric waters developed as a mixture of magmatic fluid (liquid and volatiles) with meteoric waters (see Giggenbach, 1997). Volatile-rich magmatic fluids may also vent from the intrusion at this stage by different processes and form either barren shoulders of advanced argillic alteration or tourmaline breccia pipes, while a sudden pressure drop may promote the formation of quartz veins which host sulphides exsolved from the deeper magmatic source. The convective cells progress as ground waters are drawn into the magmatic hydrothermal system at the sides and entrain additional magmatic brine and the magmatic-meteoric fluid rises from the porphyry to higher levels within the overlying and adjacent wall rocks. Volatiles such as SO<sub>2</sub> and CO<sub>2</sub> exsolved from the cooling intrusion may oxidise and become acidified and those acid waters react with the wall rocks to form retrograde alteration such as vein selvages (figure 2.14). Some volatiles rise within the conductive cells to the upper portion of the porphyry environment, and there oxidise, becoming entrained within the ground waters as blankets of hot acidic waters above the porphyry. Eventually as the vertically attenuated stock-like intrusion cools the formerly outward moving (rising) circulating hydrothermal cells not only weaken



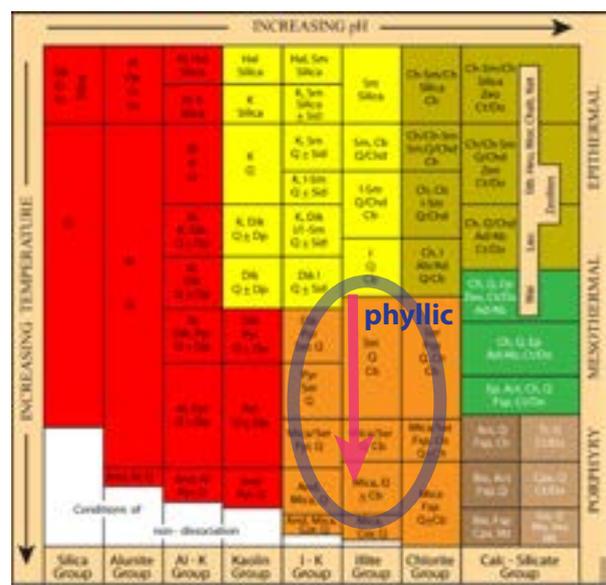
**Figure 2.12** The staged model for the development of porphyry Cu alteration and mineralisation (figure 5.1) showing the change from outward convective flow (box A) to drawdown (box C) as the spine-like intrusion cools. During prograde alteration outward moving convective hydrothermal cells develop as meteoric waters enter from the sides and magmatic-meteoric fluids leave the upper intrusion environment. Volatiles collect and oxidise to form blankets of low pH waters in the upper portion of the porphyry environment. However, during cooling of the vertically attenuated stock these hydrothermal cells collapse and the hot low pH waters are drawn down upon the intrusion and adjacent wall rocks to produce retrograde phyllic, argillic and local advanced argillic alteration.

but reverse and, in the process of drawdown, collapse onto the upper portions of the underlying porphyry environment (intrusion and wall rocks), commonly exploiting the fractured intrusion margins (figure 2.12). The collapsing hot low pH waters react with fresh rock and earlier formed prograde mineral assemblages to produce retrograde phyllic alteration about the top of the intrusion and collapsing down the permeable fractured margins in a molar tooth shape (figure 5.1; 2.12; Corbett and Leach, 1998). Permeable wall rocks may channel the hot acidic waters laterally away from the intrusion to form blankets of retrograde alteration (figures 2.25, 2.33 & 2.37).

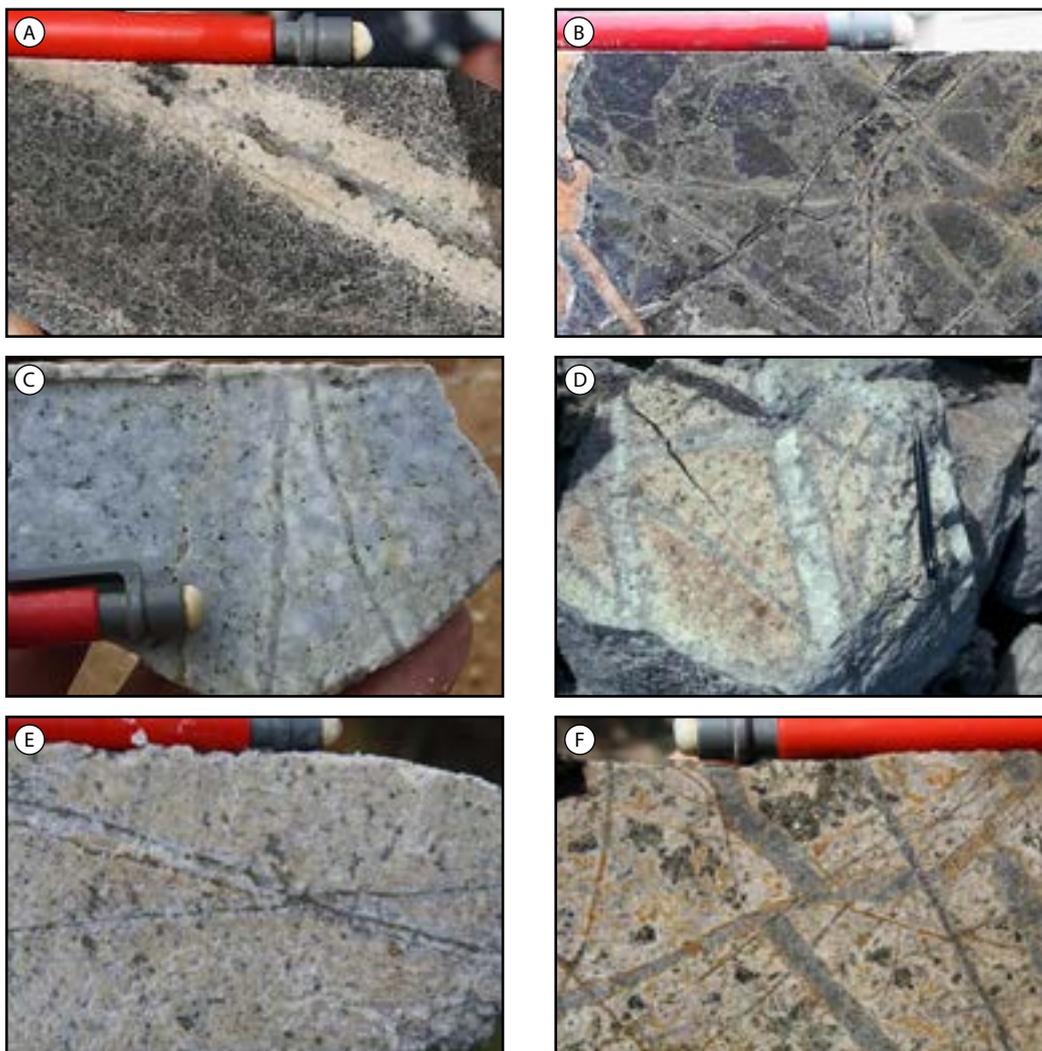
### 2.2.2.1 Phyllic alteration

Phyllic hydrothermal alteration forms in acidic (4.5-7 pH), high temperature (>350°C) conditions variably association with porphyry systems, where it is characterised by silica, sericite, pyrite and chlorite, with lesser anhydrite, while local siderite represents a common carbonate and is typical of acidic conditions (figures 2.1, 2.2, 2.13 & 2.14). At high temperatures sericite is dominated by white mica, and corundum and andalusite may also occur, while at

low temperatures, sericite passes to illite and chlorite as part of the transition to argillic alteration (figures 2.12-2.14). In more acidic conditions phyllic alteration may contain pyrophyllite passing to dickite at lower temperatures. As discussed below, in extremely acidic



**Figure 2.13** Retrograde phyllic alteration on pH vs temperature with an arrow showing mineral assemblages developed as the retrograde fluid collapses into the hot porphyry environment.



**Figure 2.14** Phyllic alteration dominated by mineral assemblages.

**A** - Sericite vein selvage to quartz-sulphide vein.

**B** - Sericite crackle breccia selvage in andesite wall rock.

**C** - Bleaching due to increased silica closest to the quartz vein, Chatree, Thailand.

**D** - Coarse muscovite alteration occurs with stockwork quartz veins, the Highland Valley, Canada.

**E** - Sericite-pyrite, La Arena, Peru.

**F** - Stockwork quartz occurs with pervasive silica-sericite-pyrite-siderite wallrock alteration from Caspiche, Chile.

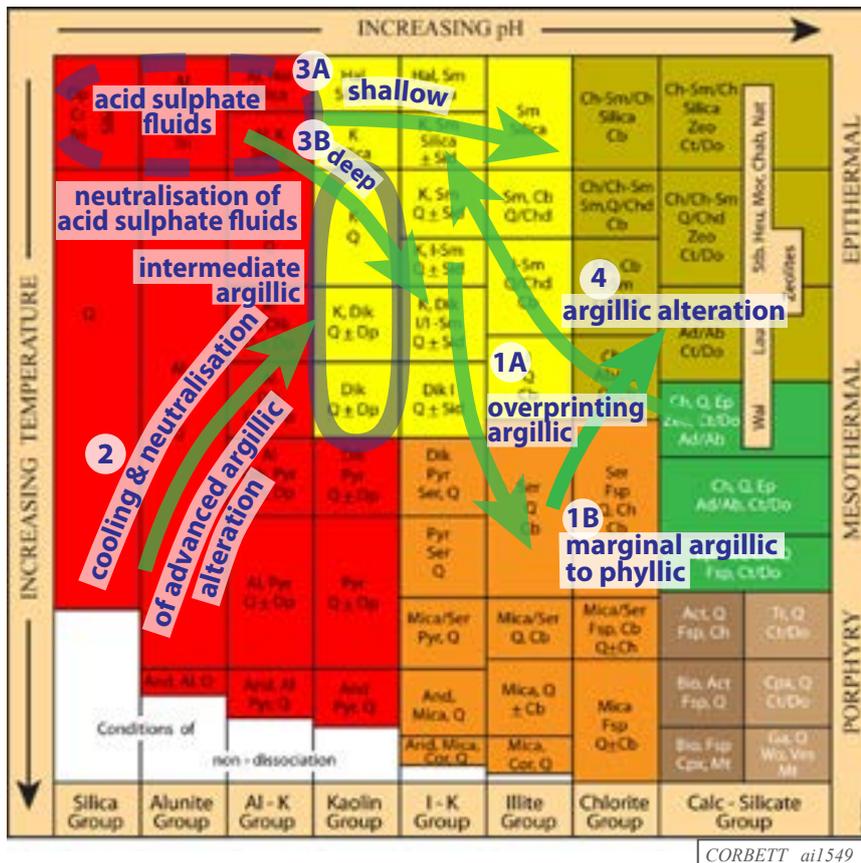
conditions phyllic may pass to advanced argillic alteration characterised by alunite, where phyllic alteration occurs at the deeper margins of what is described as lithocaps in the geological literature (Sillitoe, 1995b).

Phyllic alteration results in the replacement of K-feldspar by silica-sericite-pyrite and mafic minerals, comprising primary hornblende-pyroxene-biotite and secondary biotite, are replaced by initially chlorite, then sericite-pyrite with stronger alteration, while magnetite is replaced by martite with a destruction of the magnetic character. The margins of many alteration systems pass from sericite to outer chlorite alteration as an indication of the progressive cooling and neutralisation of the collapsing hot acid fluids. Exploration is influenced by destruction of magnetic anomalies to form regions of subdued magnetic

signatures and in induced polarisation surveys, silica-sericite alteration forms resistive anomalies, while pyrite provides chargeability anomalies as a distinctive aspect of porphyry-related retrograde (phyllic-argillic) alteration. The locally intense pyrite oxidises in the supergene environment to produce acidic waters which account for intense supergene leaching such as the development of leached caps and associated remobilisation of Cu to form chalcocite blankets of enriched Cu (section 5.4).

### 2.2.3 ARGILLIC ALTERATION

Argillic hydrothermal alteration, defined in figure 2.1, develops in a variety of settings (figure 2.15), and displays considerable internal variation. The minerals which constitute argillic alteration form at relatively low temperatures (<250°C) and a range of pH from



**Figure 2.15** Fluid flow paths for the formation of zoned wall rock argillic alteration, discussed herein.

- 1A. Argillic collapse upon cooling phyllic alteration.
- 1B. At the cooled and neutralised margin of phyllic alteration.
2. Cooling and neutralisation marginal to advanced argillic alteration.
- 3A. Mainly lateral fluid flow and wall rock reaction to neutralise the fluid responsible for acid sulphate caps to low sulphidation epithermal mineralisation.
- 3B. Heating of the low pH fluid in 3A as it collapses deeper into the hydrothermal system.
4. Marginal to low sulphidation epithermal veins which overprint from earlier propylitic cores to zoned alteration

Intermediate argillic alteration is circled in grey.

near neutral (pH 5-6) to moderately acidic (pH 4-5) in the region between advanced argillic and outer propylitic alteration (figure 2.1). Some workers describe intermediate argillic alteration as having formed in the lower pH (say 4-4.5) portion of argillic alteration shown in figure 2.15, transitional to advanced argillic alteration and so the remainder of the argillic field might then be regarded as near neutral argillic (pH say 4.5-6). That division was not done in Corbett and Leach (1998) nor herein.

As argillic alteration forms in relatively lower temperature (<250°C) less acidic (4-6 pH) conditions than phyllic alteration, it might be regarded as typical of epithermal settings or a later stage collapse upon a cooling porphyry environment (figure 2.15). The illite-sericite transition at about 250°C (Corbett and Leach, 1998) represents the boundary between argillic and higher temperature phyllic alteration. One of the most distinctive features of argillic alteration is the variation in settings of formation with associated differences and similarities in alteration minerals, which contributes to internal variations in this alteration style.

Argillic alteration occurs in several settings (figure 2.15) described in detail below as:

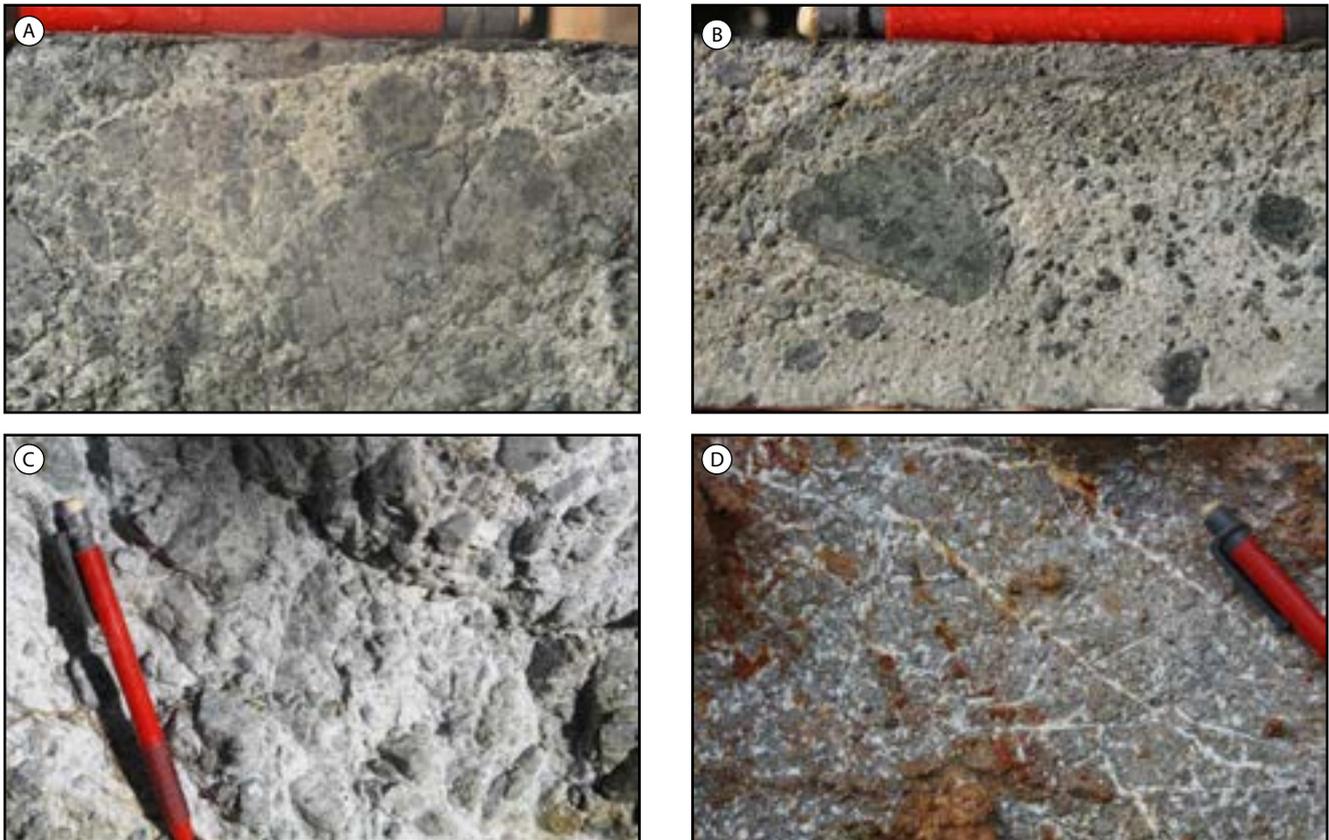
- A late stage overprint on the phyllic alteration of porphyry Cu-Au deposits (section 2.2.3.1).
- Neutralisation of the fluid responsible for acid sulphate alteration (section 2.2.3.2).
- Wall rock alteration in low sulphidation epithermal

Au-Ag deposits (section 2.2.3.3).

- Outer limits of advanced argillic alteration related to high sulphidation epithermal Au-Ag deposits or formed in association with porphyry Cu deposits.
- Barren shoulders (section 2.2.4), grading through possible intermediate argillic grading to neutral argillic, locally to outer propylitic alteration.

### 2.2.3.1 Overprints of argillic upon earlier phyllic alteration

Argillic alteration may overprint earlier phyllic hydrothermal alteration as the fluid responsible for phyllic alteration is cooled and neutralised by wall rock reaction during collapse (figure 2.15) to deposit illite, kaolin and pyrite and local chlorite and carbonate. This overprinting alteration occurs as the matrix to breccias commonly termed clay matrix breccias (section 4.4.7.7; figure 2.16 A-C), or as cross-cutting fracture-veins and pervasive alteration (figure 2.16 D). In the examples shown here a discernible fluid plumbing system facilitates an argillic overprint upon phyllic alteration. Overprinting alteration results from fluid collapse during continuation of the drawdown process as a prograde porphyry heat source progressive cools and shuts down as described above (above, section 2.2.2 & figure 2.12). This argillic alteration may overprint pre-existing phyllic alteration as a composite phyllic-argillic alteration (figure 2.16), or migrate from the retrograde environment and overprint fresh rock or pre-existing



**Figure 2.16** Rock textures formed by the collapse of argillic upon phyllic alteration as shown in figure 2.13A, from the staged porphyry model (figure 5.1).

**A** - Crackle breccia as clay overprints sericite alteration.

**B & C** - Intense clay alteration and the formation of clay matrix breccias.

**D** - Clay fracture-veins. All photos are from projects in Philippines.

potassic-propylitic alteration (figure 2.17). Thus the alteration mineralogy depends upon the fluid pH, varying from kaolin in the presence of low pH fluids, to illite in near neutral conditions and temperature as kaolin varies to dickite in higher temperature conditions (figures 2.1 & 2.15). Mafic wall rocks may provide alteration rich in chlorite and pyrite (the latter by the use of Fe).

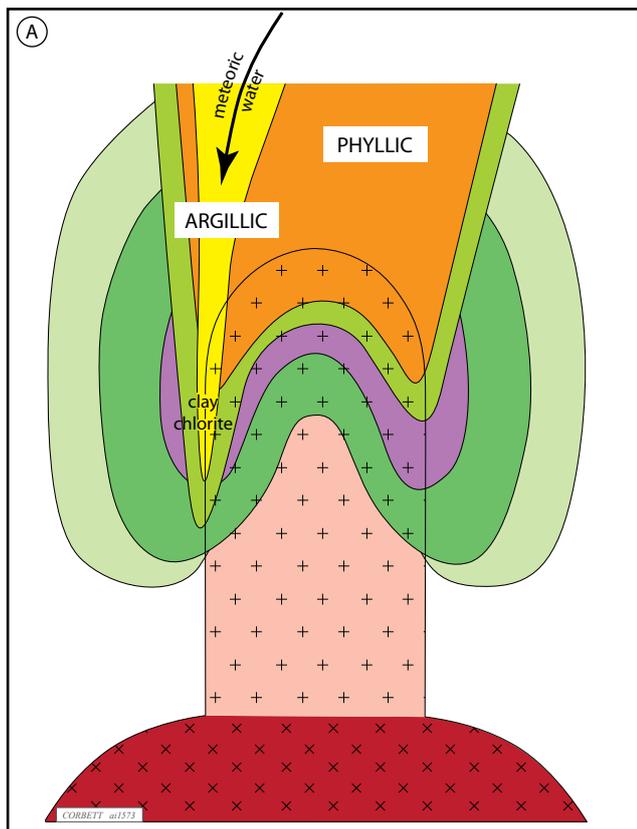
As for phyllic alteration, argillic or composite phyllic-argillic alteration contains abundant pyrite which may oxidise to produce FeO-rich weathered exposures, transported gossans and acidic ground waters. Clay matrix breccias (section 4.4.7.7) display a fill of clay grading away from fractures into the wall rock which then occurs as remnants of silica-sericite altered host rock. Breccias vary from no clast movement to fault or shear zones with extensive clast transport and milling (figure 2.16). The composite phyllic-argillic alteration is described by some workers as SCC for sericite-clay-chlorite alteration (Sillitoe and Gappe, 1984; Sillitoe, 2010) comprising sericite as well as later kaolin-illite deposited from a less acidic lower temperature fluid, although chlorite could be of a phyllic or argillic origin. As this term applies to a composite of two separate alteration events, formed under different (but related) conditions, it was not used in Corbett and

Leach (1998) or herein.

### 2.2.3.2 Argillic alteration below acid sulphate caps

Argillic alteration results from the reaction with wall rocks of the collapsing warm, low pH fluids, described below (section 2.4.6) as responsible for the formation of near surficial acid sulphate caps, which may overlie low sulphidation epithermal Au-Ag deposits. The mixing of meteoric waters combines with wall rock reaction to provide significant cooling and neutralisation of these fluids. Similar alteration is also locally recognised below steam heated blankets which overlie high sulphidation epithermal Au-Ag, although commonly obscured by collapse of the steam heated alteration upon the epithermal alteration.

The cooling and neutralisation of acid sulphate waters provides zoned argillic alteration grading from: kaolin  $\pm$  alunite dominant, to illite-kaolinite and then illite at depth in slightly warmer conditions, locally with chlorite-carbonate, while smectite might dominate laterally in cooler conditions (paths 3A & 3B respectively on figure 2.15 & figure 2.18). All mineral assemblages are pyrite-bearing and supergene gypsum



**Figure 2.17** Collapse of argillic alteration beyond the retrograde environment onto earlier prograde alteration.

**A** - Graphic derived from the staged model for porphyry development (from figure 5.1).

**B** - Illite-kaolin overprint upon propylitic alteration, Ohio Creek, New Zealand.

**C** - Illite-kaolin overprint onto potassic (biotite-magnetite) alteration, Ladolam, Lihir Is., Papua New Guinea.

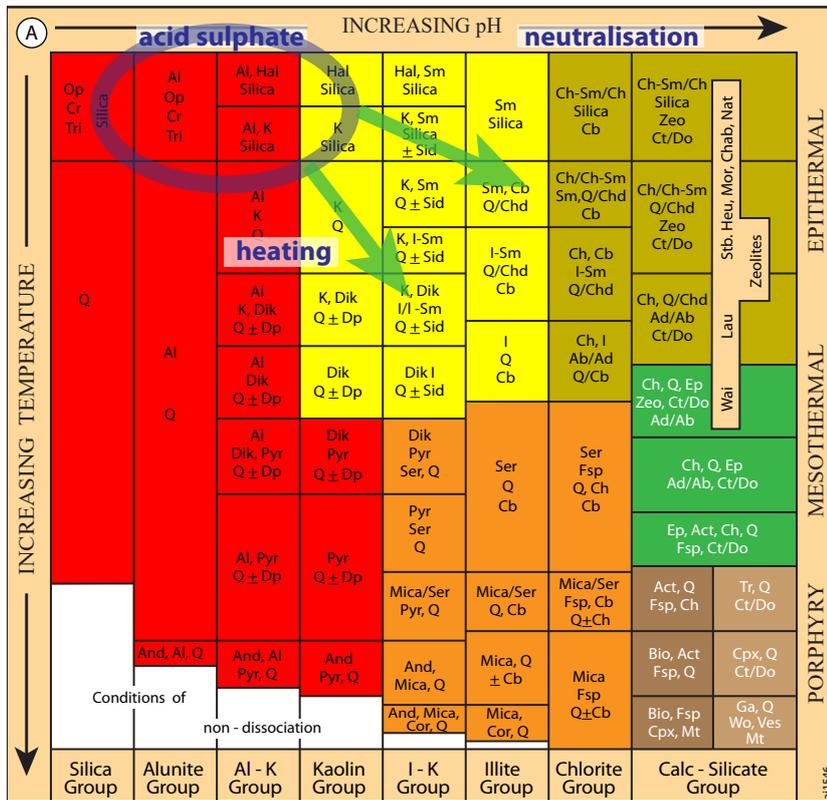
is common as the sulphides oxidise to acid ground waters which react with the wall rocks. Alteration is influenced by wall rock permeability and may extend some distance within permeable lapilli tuffs which may be constrained between less permeable rock units such as andesite lavas. Swelling (smectite) clays hydrolyse and expand and so destroy the host rock, recognised in drill core (figure 2.22). Acid sulphate waters may be

drawn down up to 1000 metres into the hydrothermal system and so kaolin is recognised as evidence of Au deposition by fluid mixing several hundred meters below the surface in mineral exploration projects (in section 7.5 - Palmarejo, Mexico; Kapit, Lihir Is., Papua New Guinea). In some instances (Sleeper, Nevada, USA) these waters become heated and deposit dickite the higher temperature form of kaolin (path 3B on figure 2.15). The soft acid sulphate caps and underlying clay alteration are only preserved in poorly eroded youthful (Lihir, Papua New Guinea) or arid (Palmarejo, Mexico) terrains.

### 2.2.3.3 Argillic alteration marginal to low sulphidation epithermal veins

Wall rock-hosted zoned argillic hydrothermal alteration formed adjacent to low sulphidation epithermal veins represents the most common style of argillic alteration recognised in association with these Au-Ag deposits, either as pervasive alteration best developed within permeable host rocks and breccias, or as vein selvages. It is characterised by illite group minerals, pyrite, quartz, chlorite and carbonate, as an essentially retrograde alteration (figures 2.1, 2.19-2.24). Argillic alteration may locally overprint a propylitic precursor adjacent to fissure veins or within permeable wall rocks (path 4 in figure 2.15; section 2.2.1.5, figures 2.8 & 2.11, above). A fluid flow path and alteration zonation forms as the hydrothermal fluid cools and exsolves volatiles to become slightly more acidic and so in this case later, distal mineral assemblages developed at higher crustal levels may contain kaolin and siderite (figure 2.15), rimmed by illite-smectite, zeolites and carbonate as those acidic fluids are neutralised by wall rock reaction. The variation in temperature within argillic alteration is most apparent as a decrease in the crystallinity of illite group minerals without any change in composition as: higher temperature illite, passes to illite-smectite, smectite-illite and lowest temperature smectite (path 4 in figure 2.15). Note smectite and kaolinite clays also occur in the weathering environment. Alteration zonation therefore varies with crustal level, host rock permeability and position relative to the fluid source, above and below the fluid flow trend shown in figure 2.15. Although kaolin is described above in the outer portions of alteration zonation at low temperatures, dickite is locally recognised at high temperatures at depth. Carbonate is common as calcite, developed in neutral conditions, in propylitic alteration, varying through mixed carbonates (rhodochrosite etc), to siderite in the acid spectrum of argillic alteration (section 7.2.1.2.3).

In the field, clays such as illite clays are distinguished

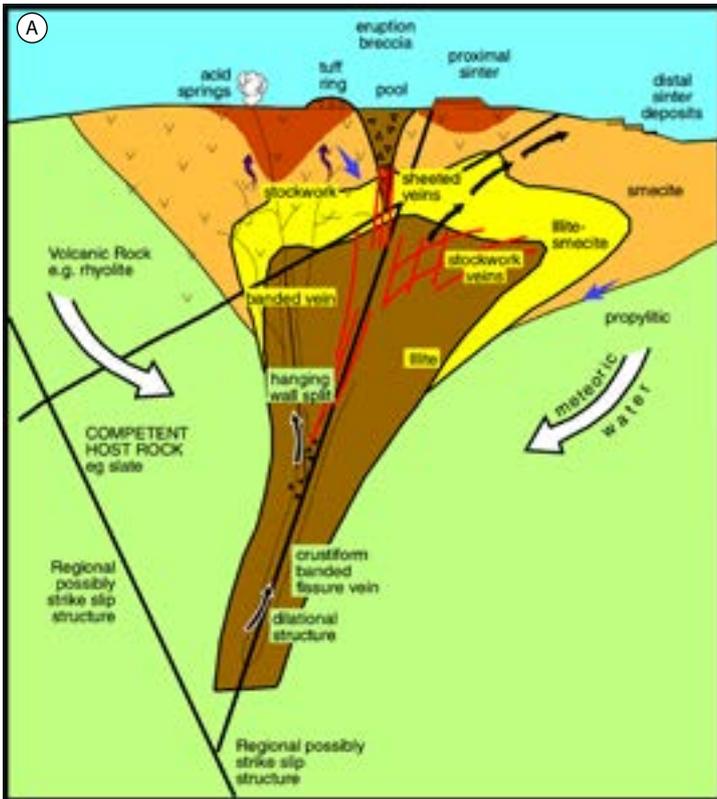


**Figure 2.18** Neutralisation of acid waters below an acid sulphate cap, using specimens from the Lienetz open pit at the Ladolam mine, Lihir Is., Papua New Guinea.

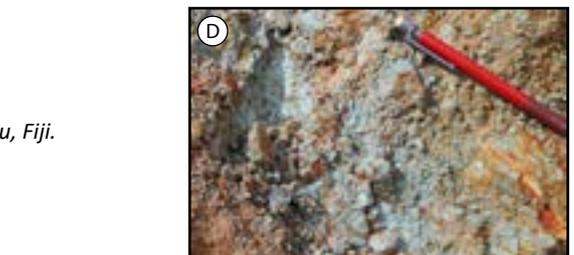
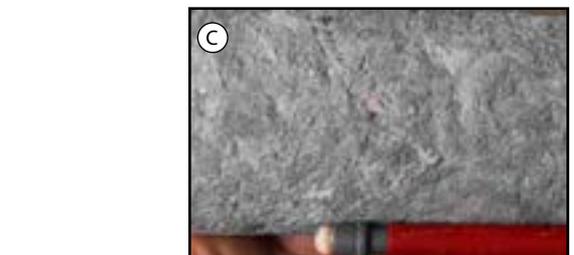
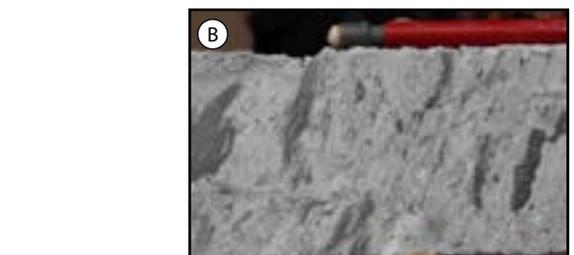
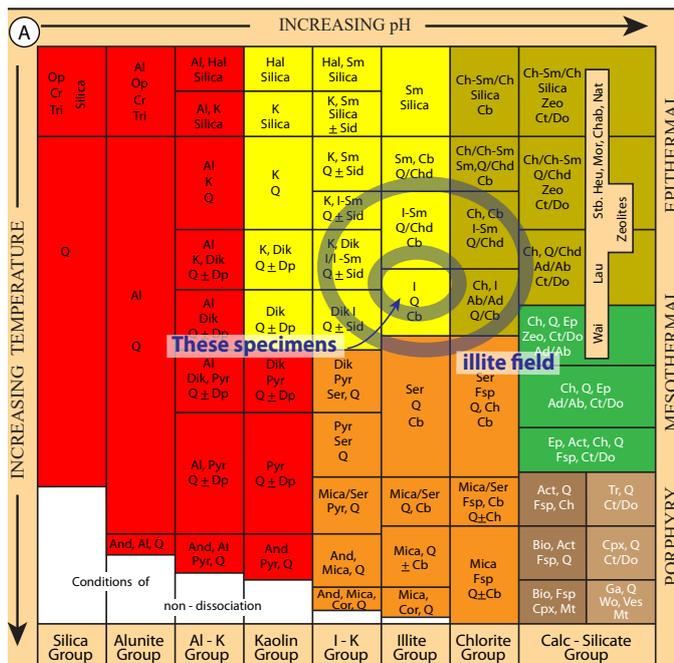
- A** - Fluid flow path on pH vs temperature, also including the path for a fluid heated during collapse.
- B** - Pre-mining 1984 photo shows the location of the Lienetz pit below the central hill and the Kapit acid sulphate cap at the right.
- C** - Pervasive illite-kaolinite clay alteration.
- D** - Pervasive alteration with kaolinite vein.
- E** - Breccia with kaolin in fill.

as soft, varying from white to pale green with a local waxy character (figures 2.20), although crystal faces are only discernible as clays vary to crystalline sericite. Smectite is apparent as a swelling clay responsible in the disintegration of drill core in humid atmospheric conditions (figure 2.21). It is common for smectite alteration to destroy the host rock competency and then restrict vein formation. The altered volcanic units will also feature magnetite destruction. Kaolin, if dry sticks to the tongue, and if hydrated such as the halloysite form, displays a white soap-like character when scratched. As kaolin, including the

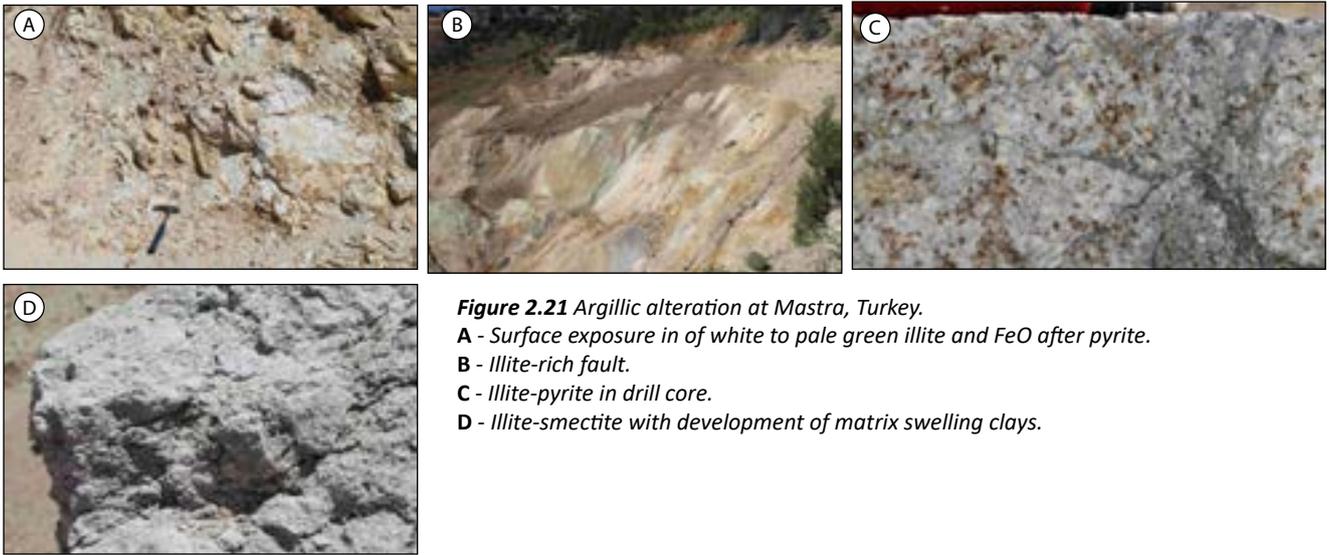
hydrated form halloysite, develops in the weathering environment, it is important for explorationists to verify the hypogene nature of kaolin where it may be used as evidence of Au deposition by fluid mixing (section 7.5). Supergene kaolin is often associated with FeO whereas hypogene may be in contact with fresh sulphides.



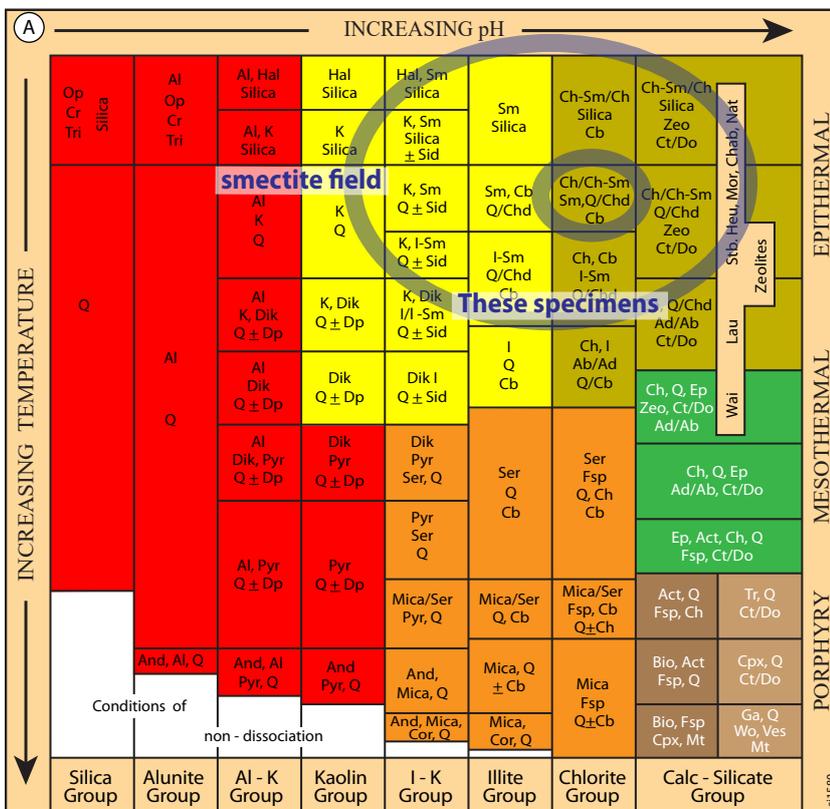
**Figure 2.19** Zoned argillic alteration formed marginal to low sulphidation epithermal veins.  
**A** - Model showing typical zoned clay wall rock alteration marginal to a vein.  
**B** - A 20 m alteration zone terminating at the colour change adjacent to the mined quartz vein, Ovacik open pit, Turkey.  
**C** - Several metre wide zone of declining intense alteration grading outwards from strong illite to illite-carbonate adjacent to an epithermal vein/breccia, Jampang, Indonesia.  
**D** - a few mm clay selvage alteration selvage adjacent to a stockwork quartz-pyrite vein, Nolans, NE Australia.



**Figure 2.20** Example of the illite component of argillic alteration from Cirianiu, Fiji.  
**A** - The region of illite formation on the pH vs temperature figure 2.1.  
**B** - Pale green illite flooding of a permeable lapilli tuff volcanic unit.  
**C** - Grey illite-pyrite alteration.  
**D** - In outcrop green illite and red FeO from the oxidation of pyrite.



**Figure 2.21** Argillic alteration at Mastra, Turkey.  
**A** - Surface exposure in of white to pale green illite and FeO after pyrite.  
**B** - Illite-rich fault.  
**C** - Illite-pyrite in drill core.  
**D** - Illite-smectite with development of matrix swelling clays.

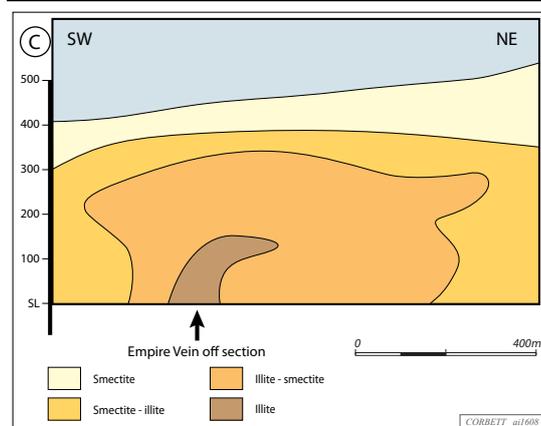
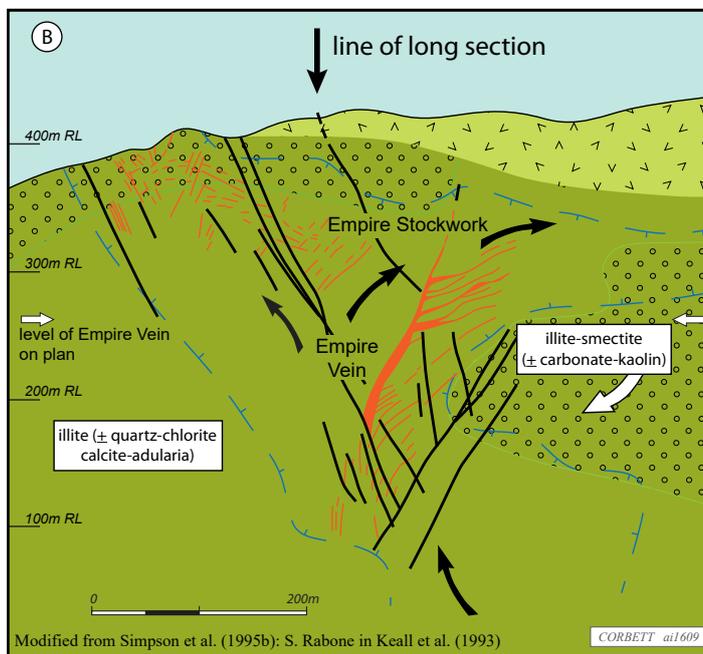
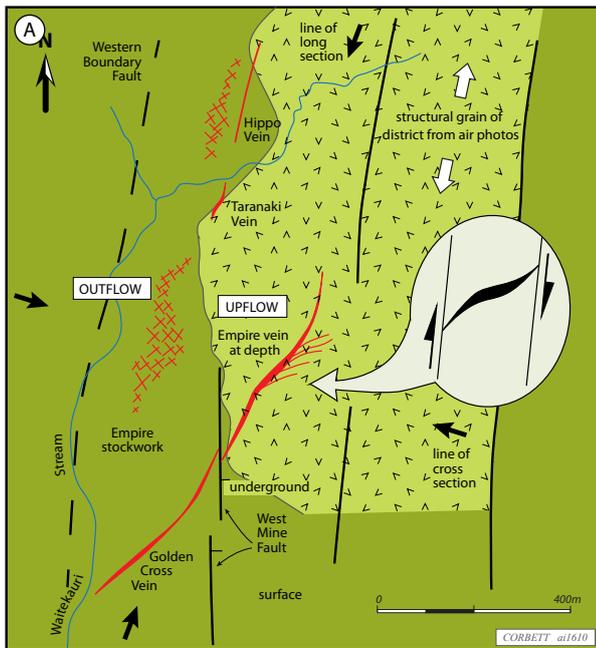


**Figure 2.22** Smectite component of argillic alteration.  
**A** - Field plotted on the pH vs temperature figure.  
**B** - Destruction of drill core by swelling clays, Mastra, Turkey.  
**C** - Swelling clays with gypsum, Mastra, Turkey.  
**D** - Swelling clays with Fe sulphate, Kupol, Eastern Russia.

### 2.2.3.3.1 Golden Cross

Au-Ag mine, in the Hauraki Goldfield of the Coromandel Peninsula, New Zealand, represents a classic banded chalcedony-ginguro Au-Ag low sulphidation epithermal vein system with associated wall rock hydrothermal alteration (Simpson et al., 2001; Corbett and Leach, 1998). The structure of the fissure vein system from Corbett and Leach (1998), and updated with post-mining data is considered in section 3.2.2.5.2. During the exploration of Golden Cross, Terry Leach carried out an XRD analysis of

the clay alteration with an emphasis upon changes in illite crystallinity with distance from the Empire fissure vein (figure 2.23; Corbett and Leach, 1998). The cross section shows the change from illite with chlorite, K-feldspar (adularia) and calcite, close to the vein, grading to more marginal illite-smectite with carbonate and kaolin. The long section passes close to the Empire vein but does not intersect it. Here, the change in illite crystallinity is most apparent moving towards the vein as: smectite at the highest crustal level and distal to the fissure vein, to illite-smectite



**Figure 2.23** Illite species zonation at Golden Cross, New Zealand, consistent with path 4 argillic alteration on figure 2.15 (from Corbett and Leach, 1998)..

- A** - Plan view showing the position of long and cross sections.
- B** - Cross section geology and alteration.
- C** - Zoned illite-smectite clays in part of the long section.

closer, and illite closest to the vein to (figure 2.23). In an exploration program it should be apparent that the highest temperature portion of the hydrothermal system defined here by illite should occur closest to the vein, which is off section but in the vicinity (figure 2.23). Thus, these data could have aided exploration for the Empire fissure vein. Terry's work, carried out after discovery therefore provides an excellent example of how this science could be used in exploration. Simpson et al. (2001) distinguished two chlorites in the Empire Vein wall rock speculated as proximal more crystalline and distal less crystalline forms.

### 2.2.3.3.2 Kupol

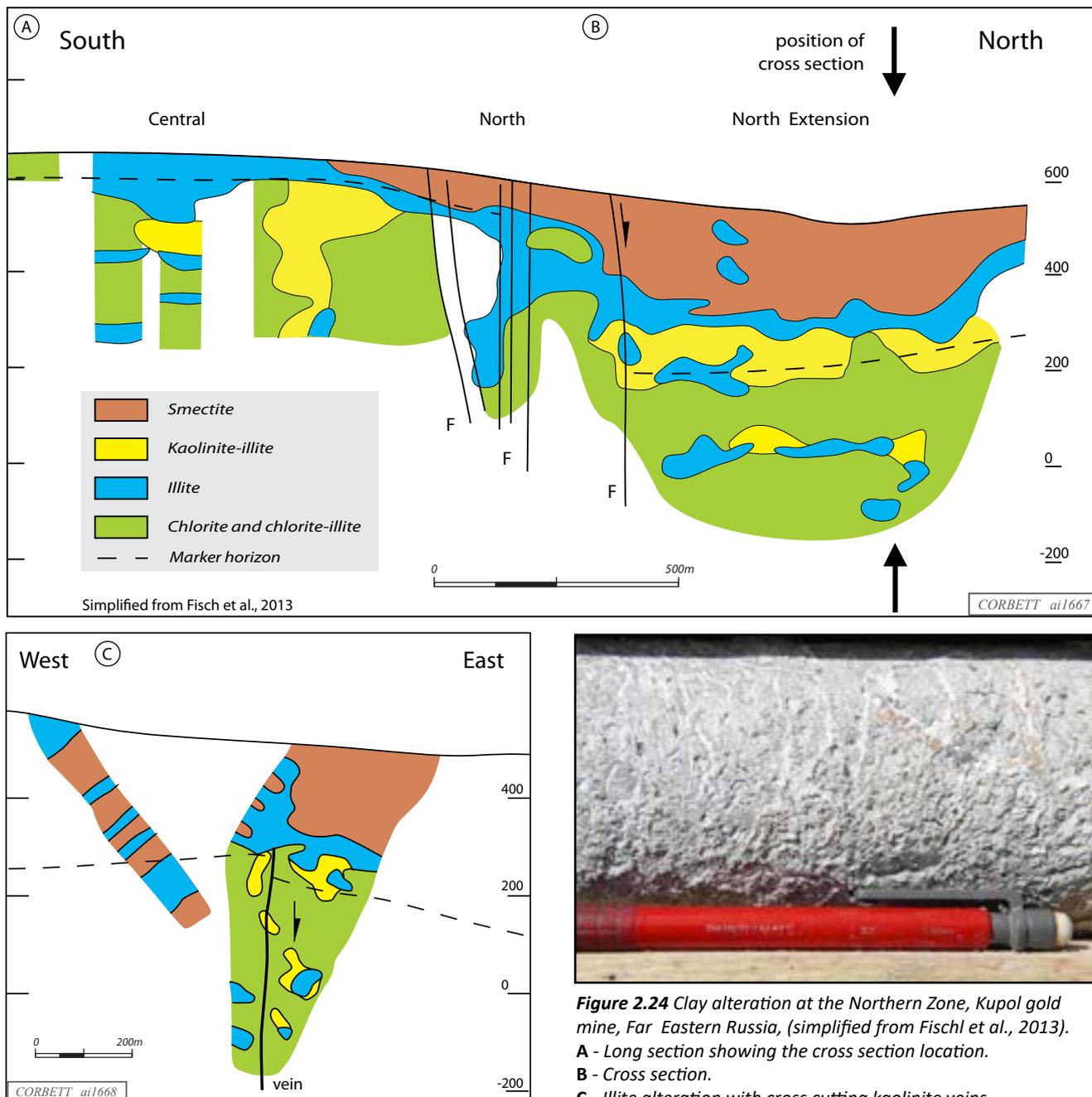
Au-Ag mine, Far Eastern Russia lies within the NE trending Cretaceous Okhotsk – Chukotka Volcanic Belt which stretches for over 2500 km from opposite Alaska towards the SW, developed in relation to NW directed subduction below older cratons (Tikhomirov et., 2012; figures 1.2 & 5.3). Other low sulphidation epithermal Au-Ag mines within that magmatic arc include the Ducat carbonate-base metal Au-Ag district, localised within a NS extensional graben (section 7), and the now closed Kubaka and Dvoynoye chalcedony-ginguro style deposits.

Kupol occurs as a 4 km long fissure vein with a NS strike and steep easterly dip, mineralised to 350 m depth and generally 4 m wide, grading to 20 m within the Big Bend ore shoot (Thomson and Golden, 2011). Host rocks comprise a shallow east dipping sequence of andesitic lavas, tuffs and sediments deposited at the transition from subaqueous to subaerial conditions (Cumming unpubl. in Fischl et al., 2013), cut by syn-mineral felsic dykes. As common for many low sulphidation vein systems (section 3.5), the onset of mineralisation was triggered by the initiation of extension and change to felsic magmatism. Minor normal fault movement is recognised on the fault which hosts the NS fissure vein, while more extensive block fault movement is apparent on the cross faults. The central portion of the Kupol vein cropped out at the level of a chalcedony-ginguro vein mineralisation with associated illite wall rock alteration within the vertically zoned system. Block faulting no doubt accounts for the exposure of deeper level polymetallic mineralisation to the south at the 650 Zone and a near surficial acid sulphate cap at the Northern Extension (figure 2.24).

Hydrothermal alteration is zoned moving away from the vein zone (Golden et al., 2011; Fischl et al., 2013). At depth illite-chlorite alteration close to the vein zone grades laterally to chlorite as the ore fluid was

cooled and neutralised by reaction with wall rocks. Elsewhere, such as in high temperature systems with an intrusion component, early K-feldspar alteration recognised adjacent to the veins may be overprinted by illite (Dvoynoye figure 2.11; Corbett, unpubl. in Thomson and Golden, 2011). Kupol clay alteration is characterised by a vertical zonation from illite to smectite as the crystallinity declines with temperature (figure 2.24). The extensive smectite alteration in the down-dropped Northern Extension exploits permeable host rocks (figures 2.22 & 2.24). Kaolin, as illite-kaolinite alteration within steep dipping

structures and flat zones related to permeable rock units, was formed as a result of the reaction of low pH waters collapsing from an acid sulphate cap at the Northern Extension (figure 2.24), which is locally preserved in surface exposures. As discussed in section 7.4.4.4 the acidic waters evidenced by kaolin have promoted bonanza Au deposition (Corbett, unpubl. in Fischl, et al., 2013).



**Figure 2.24** Clay alteration at the Northern Zone, Kupol gold mine, Far Eastern Russia, (simplified from Fischl et al., 2013). **A** - Long section showing the cross section location. **B** - Cross section. **C** - Illite alteration with cross cutting kaolinite veins. Smectite dominant alteration is shown in figure 2.22.

### 2.2.3.4 Argillic marginal to advanced argillic alteration

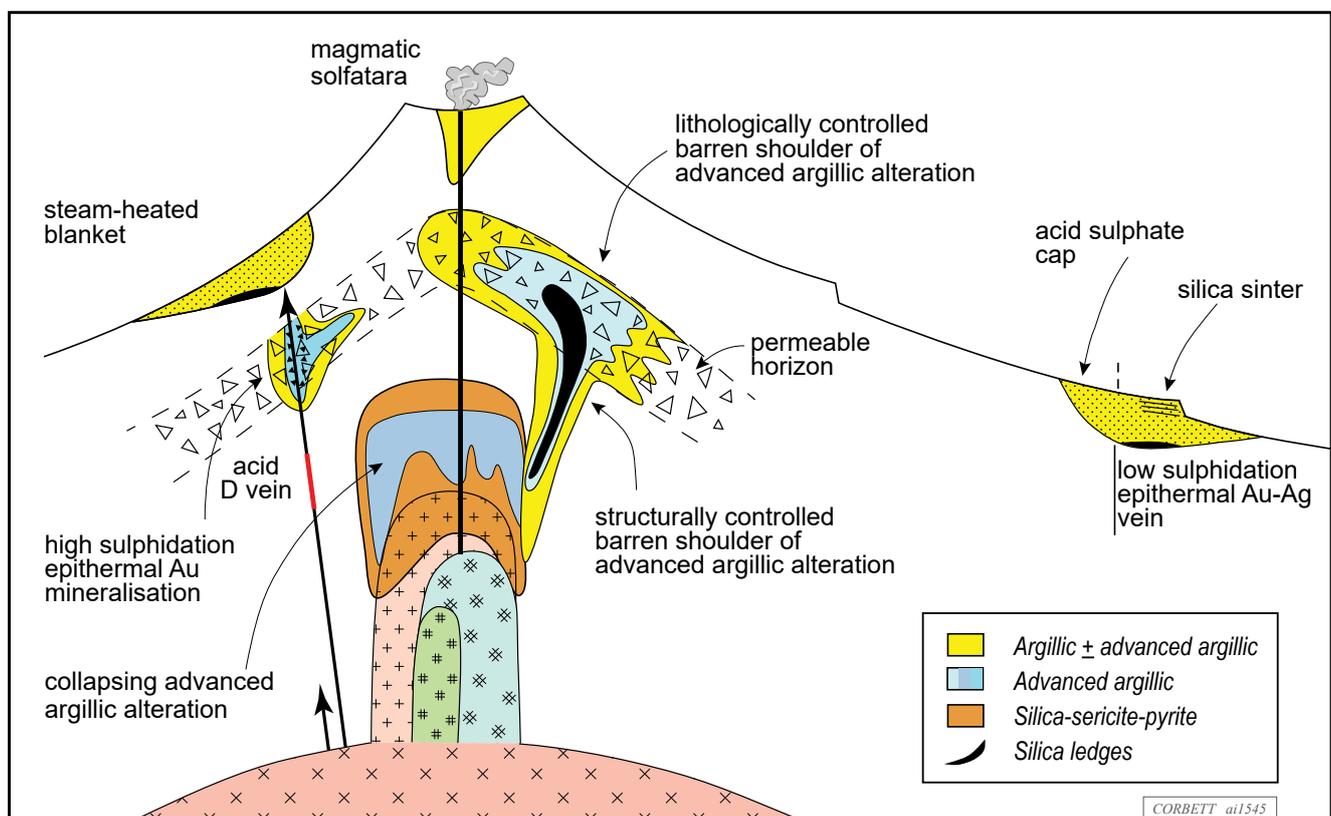
Argillic alteration forms adjacent to advanced argillic hydrothermal alteration outboard of the fluid plumbing system, as the causative hot acidic fluids are progressively cooled and neutralised by reaction with wall rocks and mixing with ground waters. Although the overall argillic alteration (figure 2.1) field lies in the pH range of 4-6 and to about 250°C temperature, some workers describe the argillic alteration developed by reaction of more acidic waters (pH 4-5) as intermediate argillic alteration thereby providing a zonation from advanced to intermediate and then argillic alteration grading outward to relict (generally outer) propylitic alteration as the hot acidic fluids are cooled and neutralised (figure 2.15). This transition is illustrated in figure 1.12 as alteration grades from vuggy silica, to alunite, to pyrophyllite to kaolin, to illite-smectite discernible as smectite is a swelling clay. Intermediate argillic alteration is characterised by a dominance of kaolinite-dickite varying to diaspore at highest temperature over illite clays which are more typical of argillic alteration.

### 2.2.4 ADVANCED ARGILLIC ALTERATION

Advanced argillic alteration develops in very acidic

conditions (pH <4 commonly 1-2, and locally cited as negative) over a wide temperature range (figures 2.1 & 2.2). Alunite is probably the most characteristic mineral of advanced argillic alteration, varying to pyrophyllite at high temperature in slightly less acid conditions (figure 2.1). The different styles of advanced argillic alteration are often grouped by many workers in the collective term 'lithocap' and the term acid alteration is locally used to as an abbreviation for advanced argillic alteration.

The term lithocap is one of the most troublesome aspects of hydrothermal alteration in epithermal-porphyry mineral exploration. While lithocaps are popularly regarded as regions of hypogene acid alteration which might obscure porphyry Cu mineralisation at depth (Sillitoe, 1995, 2010), the term is also used by some workers to describe supergene leached caps which might cap porphyry Cu or epithermal deposits, and locally even post-mineral cover. At the request of Kaylene Camuti, for the Symposium convened to honour the late Terry Leach, Corbett (2008) provided a break-down of the different elements of hypogene hydrothermal alteration which are commonly grouped into the lithocap terminology. These alteration styles display different relationships to mineralisation and so should be distinguished in order to be used as exploration vectors rather than grouped together.



**Figure 2.25** Typical environments for the formation of advanced argillic grading to argillic alteration discussed herein (modified from Corbett, 2008).

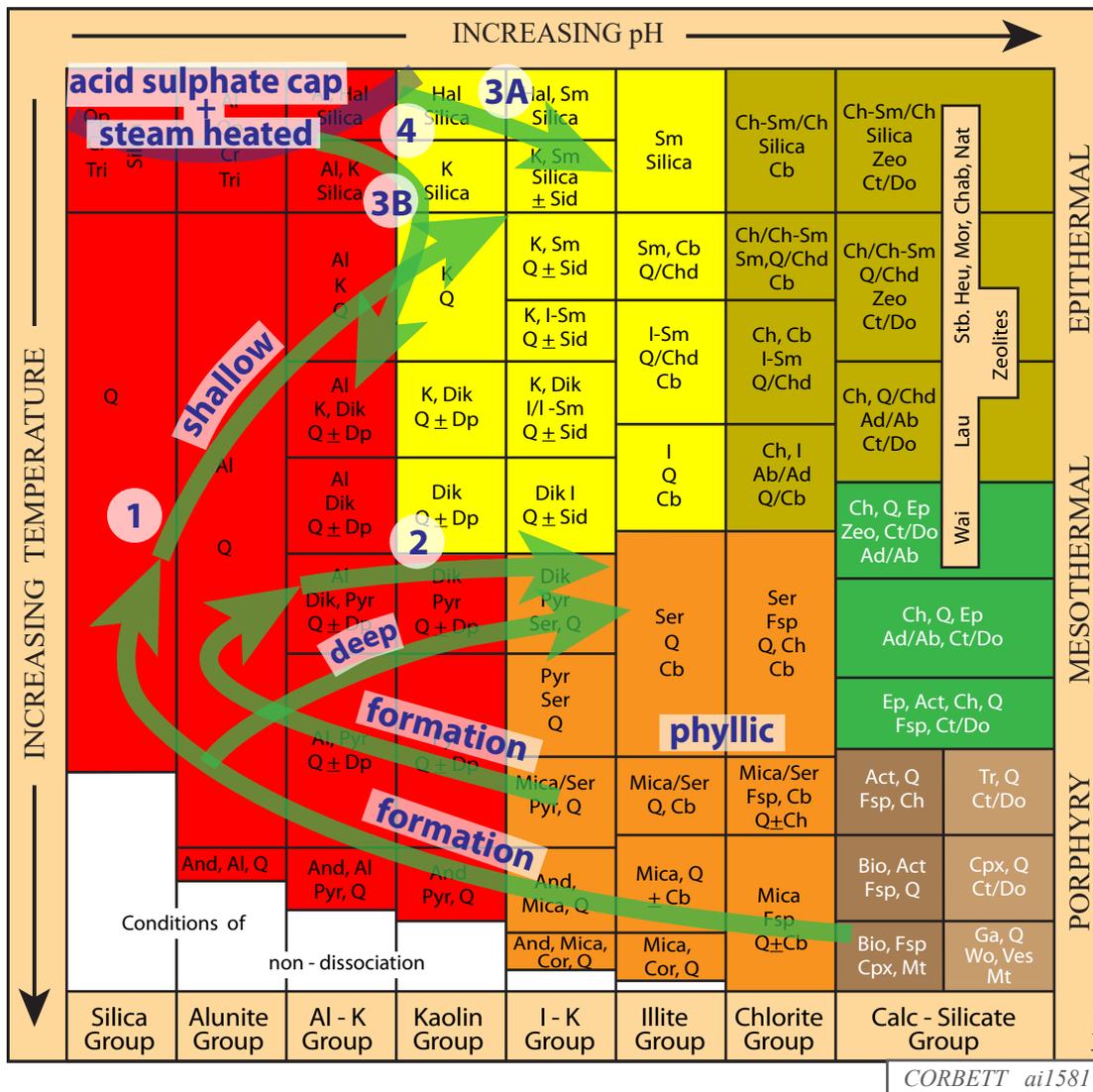
Classes of advanced argillic alteration considered here include (figures 2.25):

- Barren shoulders developed by the reaction with wall rocks of rising hot magmatic volatiles which become acidic during depressurisation and cooling (Corbett and Leach, short course notes 1992-7, 1998).
- Collapsing advanced argillic alteration within phyllic alteration interpreted to overlie porphyry intrusions.
- Zoned advanced argillic-argillic alteration formed in association with high sulphidation epithermal Au mineralisation or acid D veins.
- Steam heated caps to high sulphidation Au deposits,
- Acid sulphate caps to low sulphidation Au-Ag deposits,

- Magmatic solfataras,
- Supergene advanced argillic alteration may develop where acid ground waters formed by weathering of pyrite react with wall rocks.

### 2.2.4.1 Barren shoulders of advanced argillic alteration

Barren shoulders of advanced argillic hydrothermal alteration (Corbett and Leach, 1998; Corbett, 2008) represent bodies of zoned advanced argillic alteration developed by reaction with the wall rocks of rising hot acidic fluids derived from magmatic source rocks at depth and grade laterally to argillic alteration. As early work by Terry Leach on alteration in the Philippine geothermal systems (Mitchel and Leach, 1991, and references therein) was applied to mineral



**Figure 2.26** Different styles of advanced argillic alteration illustrated as fluid flow paths for cooling and neutralisation of acid fluids to provide zoned alteration, and also some formation paths.

1. High sulphidation epithermal Au and barren shoulders as shallow and deep.
2. Collapsing advanced argillic alteration.
- 3A. Neutralisation (and cooling) on acid sulphate cap.
- 3B. Collapse of steam heated alteration into an active high sulphidation epithermal system.
4. Magmatic solfataras.

exploration, the initial description of alteration zones as caps in early short course presentations (Corbett and Leach 1992-4), moved to shoulders in later short courses (Corbett and Leach, 1994-1998), to reflect the common setting of these bodies overlying the margins of some SW Pacific rim porphyry bodies (Lookout Rocks, New Zealand; Ekwai Debom at Horse Ivaal, Frieda River, Papua New Guinea), including active geothermal systems (Southern Negros, Philippines), and later supported by continued studies of Andean and Tethyan examples (Corbett, unpubl. data).

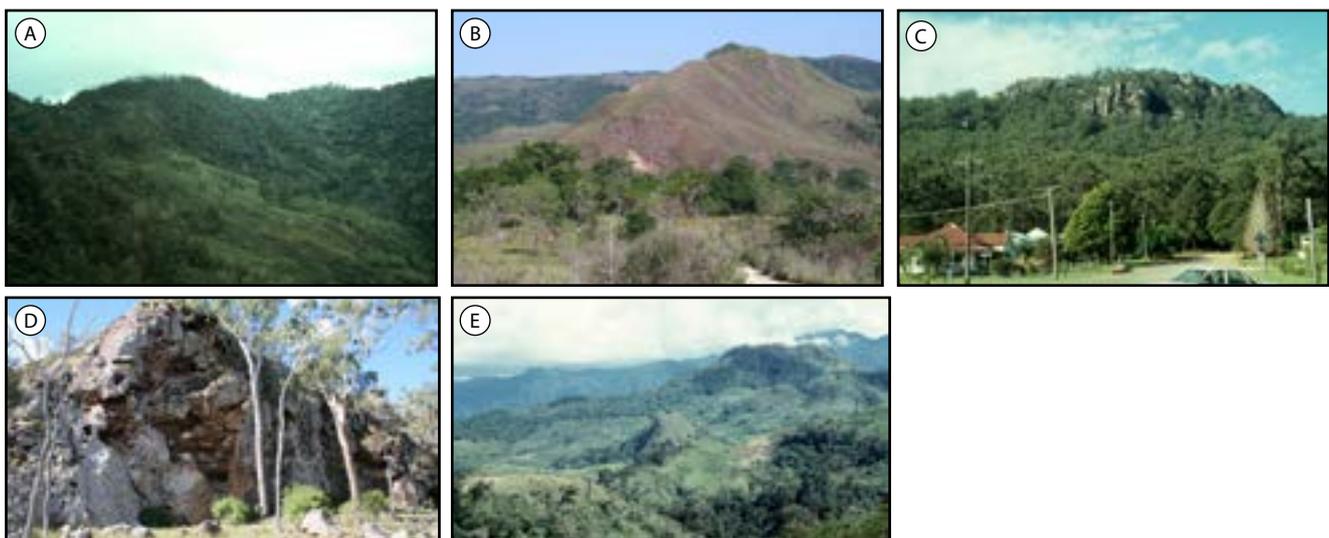
Two end member controls to permeability influence the overall shape of barren shoulders (figures 2.25 & 2.26) as:

- Structurally controlled alteration tends to develop at deeper crustal levels and so is exposed in systems that have been eroded to near porphyry levels (figures 2.30 & 2.31). Hydrothermal fluids are interpreted to have exploited dilatant structures which are likely to cross-cut the local stratigraphy and produce relatively narrow steep-dipping alteration zones.
- Lithologically controlled alteration develops by exploitation of permeable lithologies and so is commonly discernible as broad flat dipping alteration zones conformable to the local stratigraphy (figures 2.33 - 2.35). Many lithologically controlled alteration zones form as extensive mantos (blankets) at shallow crustal levels and may include low temperature alteration minerals.

Many barren shoulders display aspects of both steep-dipping structurally controlled feeders and flat-lying lithologically controlled alteration zones (figures 2.32 & 2.33). Alteration zones may extend some kilometres from the interpreted magmatic source, enhanced in settings of dilatant structures or permeable lithologies (figure 2.37).

Barren shoulders are characterised by zoned hydrothermal alteration (figure 2.26) which typically grades away from a silica core (where present) outwards through zones of mineral assemblages dominated progressively by: massive silica, silica-alunite, pyrophyllite-diaspore, then dickite-kaolinite, and marginal sericite-illite alteration, with substantial variations depending upon:

- Crustal level, as in deep crustal level, high temperature settings zoned alteration may contain by andalusite and corundum grading out to mineral assemblages which include substantial diasporite locally dominant over pyrophyllite, and then more marginal dickite clay. Shallow crustal levels feature low temperature minerals such as kaolinite clay with chalcedony as the silica species (figure 2.26). In the marginal alteration sericite at depth grades to higher crustal level illite.
- Permeable and reactive host rocks provide wider lithologically controlled alteration zones (figure 2.37).
- Although dilatant structures provide mechanisms to bleed acid fluids responsible for alteration to higher crustal levels and further from the



**Figure 2.27** Some barren shoulder exposures in addition to others discussed in detail below.

**A** - The Oro prospect alteration which lies at the highest topographic level in a region of epithermal and porphyry mineralisation (section 7.2.1.1.4.1), Bilimoia, Papua New Guinea.

**B** - Pelitalira, Sumba Is., Indonesia.

**C** - Bulahdelah, Australia.

**D** - Wasp Hill, Esk Trough, Australia.

**E** - Didipio, Philippines showing the Dinkidi porphyry outcrop in the centre surrounded by advanced argillic alteration with an intervening gap.

magmatic source, most deeper crustal level alteration zones tend to be structurally controlled.

- Alteration zones are likely to be thicker close to the fluid source and thinner in more distal settings, notwithstanding (structural and lithological) permeability controls to fluid flow.
- Zones of hydrothermal alteration are essentially rootless as a reflection of the fluid evolution described below.

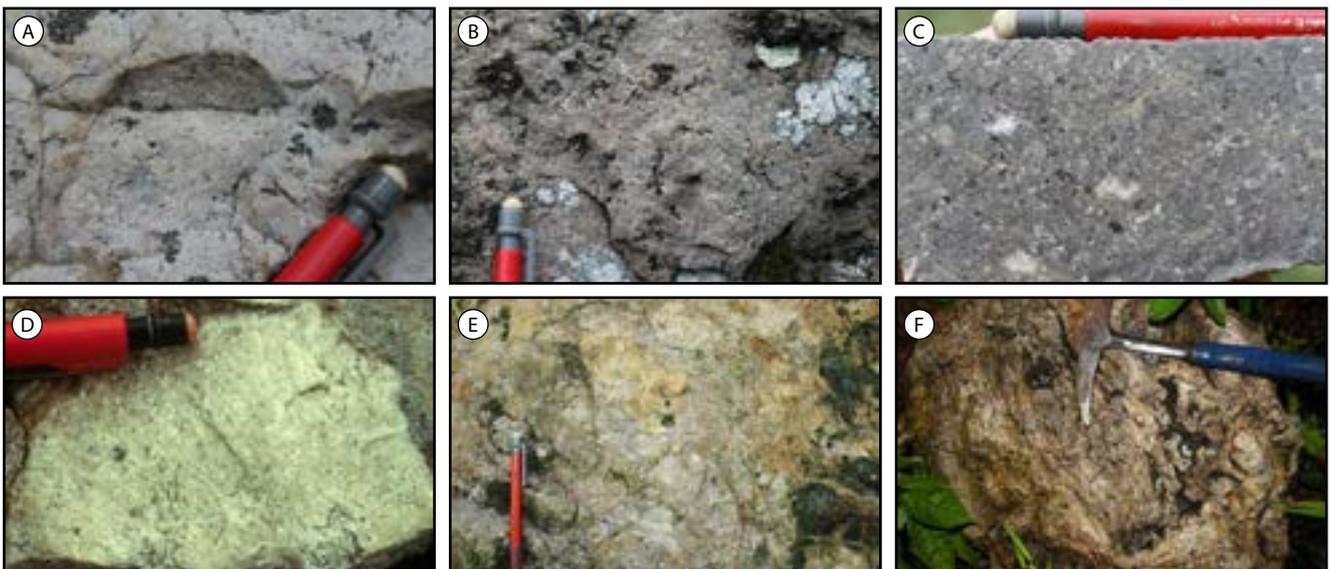
Ledges comprising substantial silica are resistant to erosion, and so form prominent topographic features which characterise barren shoulders, and may crop out as either steep dipping structurally controlled, or shallow dipping or lithologically controlled, bodies. The soft marginal clay alteration is readily removed by erosion to leave the remnant resistive silica, especially in the wet tropics. Explorationists have often been drawn to these prominent silica outcrops which have then been subject to considerable unwarranted exploration effort, as most are barren.

Barren shoulders display mineralogical characteristics recognised as:

- Silica is generally massive (figure 2.28), locally with textures indicative of replacement of original volcanic rocks or structural laminations and brecciation, and distinct from the typical vughy silica of advanced argillic alteration associated with high sulphidation epithermal Au deposits (figures 1.12, 8.2 & 8.3). These latter textures

should not be confused with open space breccias and minor saccharoidal or granular silica in some barren shoulders which must be put in the context of the total system by geological mapping.

- At shallow crustal levels chalcedony and opal may be apparent in the silica ledge.
- Barren shoulders are rich in pyrite which weathers to provide acidic ground waters and leached wall rock replacing the hypogene alteration (figure 2.29 & 2.34). Liesegang rings are recognised as pyrite grades from feeder fractures, or more commonly FeO deposited during weathering. In the absence of substantial vegetation cover, weathered barren shoulders provide spectacular red-yellow colour anomalies, while in the wet tropics, anomalously poor vegetation such as scrubby ferns, may develop in the acidic and leached soils. In outcrop gossanous caps are common and transported gossans develop at redox boundaries. Pyritic drill core readily oxidises in damp conditions to provide fibrous growths of hydrated sulphates (melanterite  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ) (figure 2.29).
- Topaz  $[\text{Al}(\text{F},\text{OH})_2]\text{AlSiO}_4$  and zunyite, an hydrated Al silicate,  $(\text{Al}(\text{OH},\text{F},\text{Cl})_2)_6 \text{Al}_2\text{Si}_3\text{O}_{12}$ , (Dana, 1932) are commonly present and indicative of development of the alteration from a volatile-rich fluid and recognised in spectral studies of barren shoulder alteration zones.
- Other minerals such as alunite, pyrophyllite and diaspore may exhibit coarse crystalline shapes if developed slowly and near porphyry crustal levels.



**Figure 2.28** Some examples of massive silica in barren shoulders.

**A** - Replaced ignimbrite, Pelitalira, Indonesia.

**B** - Flat dipping silica ledge, Halilaga, Turkey.

**C** - Replaced tuff, Quimsacocha, Ecuador.

**D** - Massive silica, Southern Negros, Philippines.

**E** - Pervasive silicification with a replaced clastic volcanic texture, Taguibo, Philippines.

**F** - Pervasive silicification with a possible structural fabric, Sandayong, Philippines.



**Figure 2.29** Pyrite flooding within barren shoulder advanced argillic alteration.

**A** - Pyrite flooding within silica-alunite alteration, Quimsacocha, Ecuador.

**B** - Supergene melanterite growing on pyrite flooded drill core, Quimsacocha, Ecuador.

**C** - Liesegang rings developed during weathering, Vuda, Fiji.

#### 2.2.4.1.1 Formation of barren shoulders

A model for the formation of barren shoulders has been postulated from the comparison of geothermal and exploration examples (Corbett, 2008). Barren shoulders are interpreted (Corbett and Leach, 1998) to have developed early in the staged model for porphyry Cu deposit development (Corbett, 2009; figure 5.1), before other styles of advanced argillic alteration. Analysis of the active Alto Peak geothermal system in the Philippines (Reyes et al., 1993; Giggenbach, 1992a) suggests a plume of hot magmatic volatile-dominated fluid may vent early in the cooling history of a porphyry intrusion at depth, after initial prograde alteration, and rapidly migrate to a higher crustal setting without significant reaction with the wall rocks or entrainment of ground waters. This fluid chimney at Alto Peak overprints zoned propylitic-potassic alteration derived from a buried recent quartz-diorite intrusion present as higher crustal level dykes. The rapidly rising fluid becomes progressively depressurised to exsolve volatiles which in turn oxidise upon cooling to provide an increasingly acidic character to the rising fluid.

Wall rock alteration displays a commonly vertical zonation trend indicative of the fluid flow path characterised by a progressive increase in fluid acidity (lower pH) as the volatile-rich fluid is depressurised and cools during the rapid rise from hot intrusion source at depth (figure 2.26). At Ekwai Debom, Frieda River, Papua New Guinea (figure 2.31) this zonation is apparent as: silica-andalusite + sericite, passing upwards to cooler lower pH (more acidic) conditions dominated by minerals such as pyrophyllite, and then alunite at the most elevated crustal setting and acidic conditions. A similar trend at Hatchobaru, Japan (figure 2.52) contains lesser andalusite, but also topaz and zunyite within the pyrophyllite, rising to a silica core within the alunite alteration. A different, commonly lateral, alteration path forms as the hot acidic fluid is then progressively cooled and neutralised by reaction with wall rocks. Here, zoned hydrothermal

alteration grades outward from silica formed in the most acidic conditions, to alunite, to pyrophyllite-diaspore, dickite-kaolinite and into near neutral illite clays (between fluid flow paths 1 and 2 on figure 2.26). The core of the zoned alteration may comprise silica-alunite without massive silica if the causative fluid is not sufficiently acidic.

This model places a common gap between the buried source intrusion and any associated advanced argillic alteration (lithocap), which therefore appears to display a rootless appearance, and alteration does not sit directly upon the source intrusion, as:

- There is a region between to magmatic source and the advanced argillic alteration in which the magmatic-derived fluid has not yet evolved sufficiently to form the acidic fluid responsible for development of the advanced argillic alteration.
- At high temperatures (above 400°, no dissociation occurs to form acidic fluids (figure 2.1; Corbett and Leach, 1998) thereby placing a shallow depth constraint on the development of advanced argillic alteration (Giggenbach, 1992a).

Where barren shoulders (or mineralised advanced argillic alteration associated with high sulphidation epithermal Au deposits) appear to cap a porphyry, the fluid responsible for the alteration may have been derived from a deeper level magmatic source, often facilitated by rapid uplift and erosion synchronous to intrusion emplacement and hydrothermal activity.

In the model for staged porphyry development (figure 5.1), barren shoulders result from the early venting of volatiles from a cooling porphyry. By contrast, epithermal alteration and mineralisation develop during the later venting of a liquid-bearing fluid from a magma source at depth. The minor steep dipping structurally controlled high sulphidation Cu-Au mineralisation recognised in association with some larger flat lying barren shoulders may therefore have formed later (Halilaga, Turkey and Bilimoia, Papua

New Guinea, Corbett, pers. observ.). The competent silica core of barren shoulders commonly fractures well as a vein host for later low or high sulphidation mineralisation (Wild Dog, Papua New Guinea, Corbett and Leach, 1998; Vuda, Fiji, Corbett, pers. observ.). Also many districts host barren shoulders and also high and low sulphidation epithermal mineralisation (Quimsasocha, Ecuador) as well as porphyry Cu mineralisation (Frieda-Nena and Bilimoia Papua New Guinea; Corbett and Leach, 1998; Bainbridge et al., 1994; Corbett et al., 1994b), especially if different crustal levels in the hydrothermal system are exposed. Explorationists need to be aware of the exact source of geochemical anomalies. For instance Au derived from nearby epithermal mineralisation is easily panned downstream from the barren shoulders at Vuda, Fiji (Corbett and Leach, 1998) or Bilimoia, Papua New Guinea, which are not targets. The Lookout Rocks barren shoulders at Thames, New Zealand (Corbett and Leach, 1998) lie between the sub-economic Ohio Creek porphyry Cu-Au and the 1 M oz of bonanza Thames Goldfield (figure 3.20).

The correct interpretation of barren shoulders is one of the most difficult aspects of epithermal-porphyry mineral exploration and the incorrect interpretation can be quite detrimental to any exploration program. In many instances geologists have been distracted by the upstanding topography of barren shoulders, whereas discoveries have been made at lower elevations and laterally to the barren shoulder (Halilaga, Turkey; Bilimoia, Papua New Guinea). While not definitive, features such as the massive rather than vuggy silica, excess pyrite, topaz-zunyite and locally andalusite-corrundum, are all indicative of barren shoulders, but must be placed in the context of a competent geological map. More deeply eroded structurally controlled barren shoulders may more easily provide vectors to source buried porphyry intrusions than higher level lithologically controlled alteration which may form extensive sub-horizontal blankets (also termed mantos), often at more elevated crustal settings (figure 2.25).

#### 2.2.4.1.2 Examples

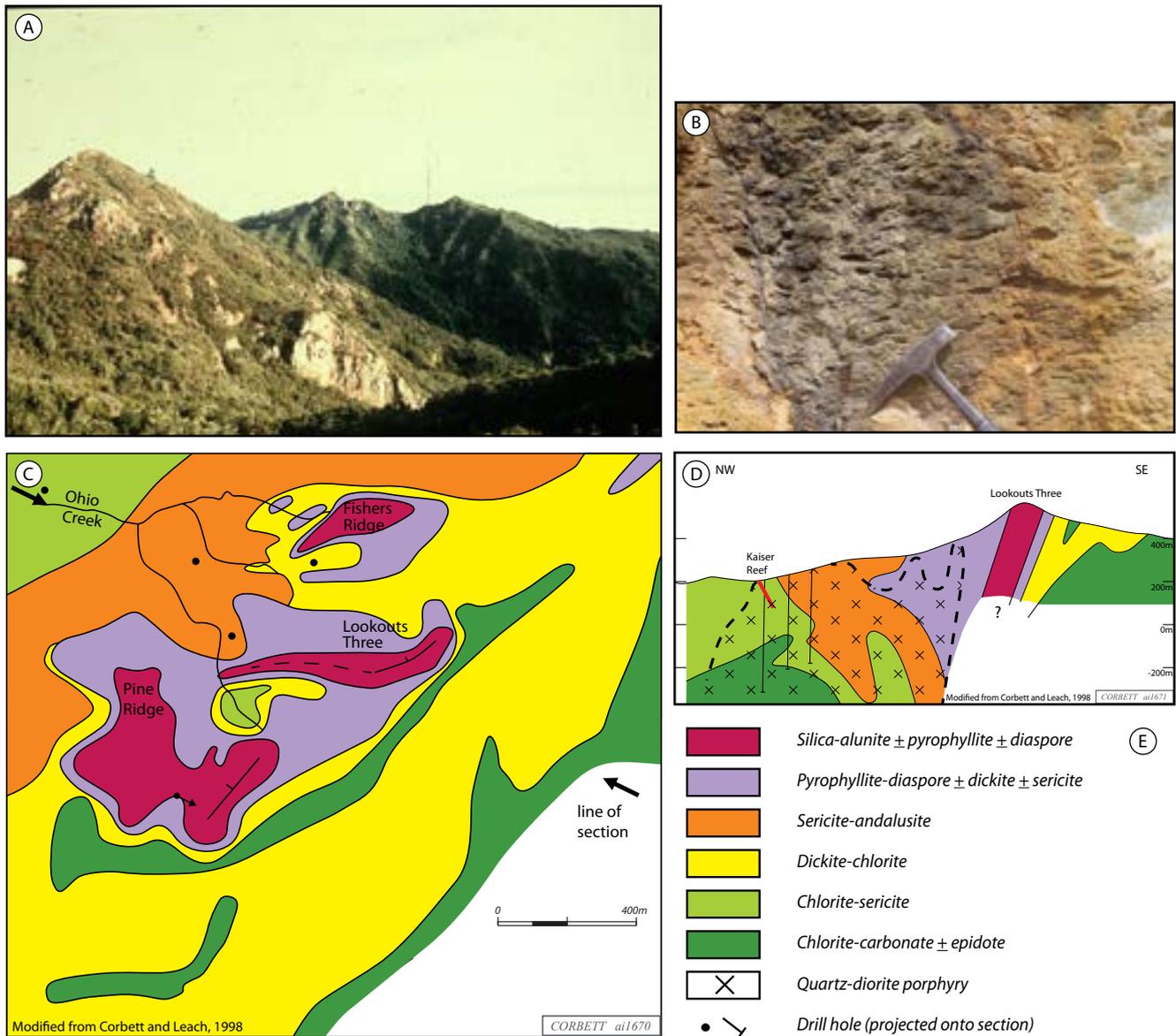
The examples below illustrate the place of barren shoulders in an overall porphyry Cu model with associated high and low sulphidation epithermal Au deposits, which may provide the distraction of panable alluvial Au, often wrongly attributed to upstanding silica ledges. Only the understanding of the entire hydrothermal system will allow the barren shoulders to contribute as vectors towards mineralisation. These examples include deeper level structurally controlled

followed by higher crustal level lithologically controlled systems.

##### 2.2.4.1.2.1 The Lookout Rocks

advanced argillic alteration barren shoulder crops out as prominent ridge exposures 4 km NE of Thames, New Zealand (Corbett and Leach, 1998), localised, along with other porphyry manifestations, within a regional scale fault jog in the Hauraki Fault which separates the Coromandel Peninsula and Hauraki Graben (figure 3.20). The resistant Lookout Rocks alteration crops out to over 500 m elevation to the south and east of the Ohio Creek porphyry Cu-Au exposed in valley floor (figure 2.30). To the SW of the porphyry, dilatant link structures formed by the Thames fault jog host quartz-sulphide lodes including the Thames bonanza Au ore shoots at structural intersections, extending to sea level (figure 3.20). The 9.3-12.6 + 0.3 m.y. quartz diorite porphyry hosts stockwork quartz vein mineralisation in outcrop, tested by 6 diamond drill holes which yielded results such as an average of 0.23% Cu and 0.26 g/t Au from 300 to 596m in DDH 5 (Merchant, 1986). In outcrop, the Lookout Rocks ledges dip towards the porphyry and grade from cores of silica-alunite-pyrophyllite ± diaspore outwards to pyrophyllite-dickite and more marginal dickite while sericite grading to chlorite-sericite is present close to the porphyry and illite on the other margins of ledges, at high crustal levels overprints porphyry-related chlorite-carbonate + epidote propylitic alteration (figure 2.30). Merchant (pers. commun. 1988) identified andalusite as an indication of the high temperature alteration proximal to the outcropping silica ledge. The uppermost permeable Pliocene Whitianga Group ignimbrites have facilitated lateral flow of the fluids responsible for alteration adjacent to the ledges as dickite-kaolinite alteration. However, it remains unknown whether there is any association with the clay alteration in road cuttings 5 km east of Thames at the 'Roadshow' alteration zone. The zoned alteration (figure 2.30) was delineated using about 200 surface XRD samples taken in 1989 (Corbett, unpubl. data).

Lookout Rocks illustrates how the ledges of alteration and quartz-sulphide lodes might vector towards a porphyry Cu-Au source and the high temperature advanced argillic alteration is not acid sulphate style as first considered. While the Kaiser Reef (figure 2.30) represents a proximal D vein, other quartz-sulphide lodes link the Thames Goldfield and the same speculated magmatic source as the Ohio Creek porphyry and Lookout Rocks alteration (Corbett and Leach, 1998).



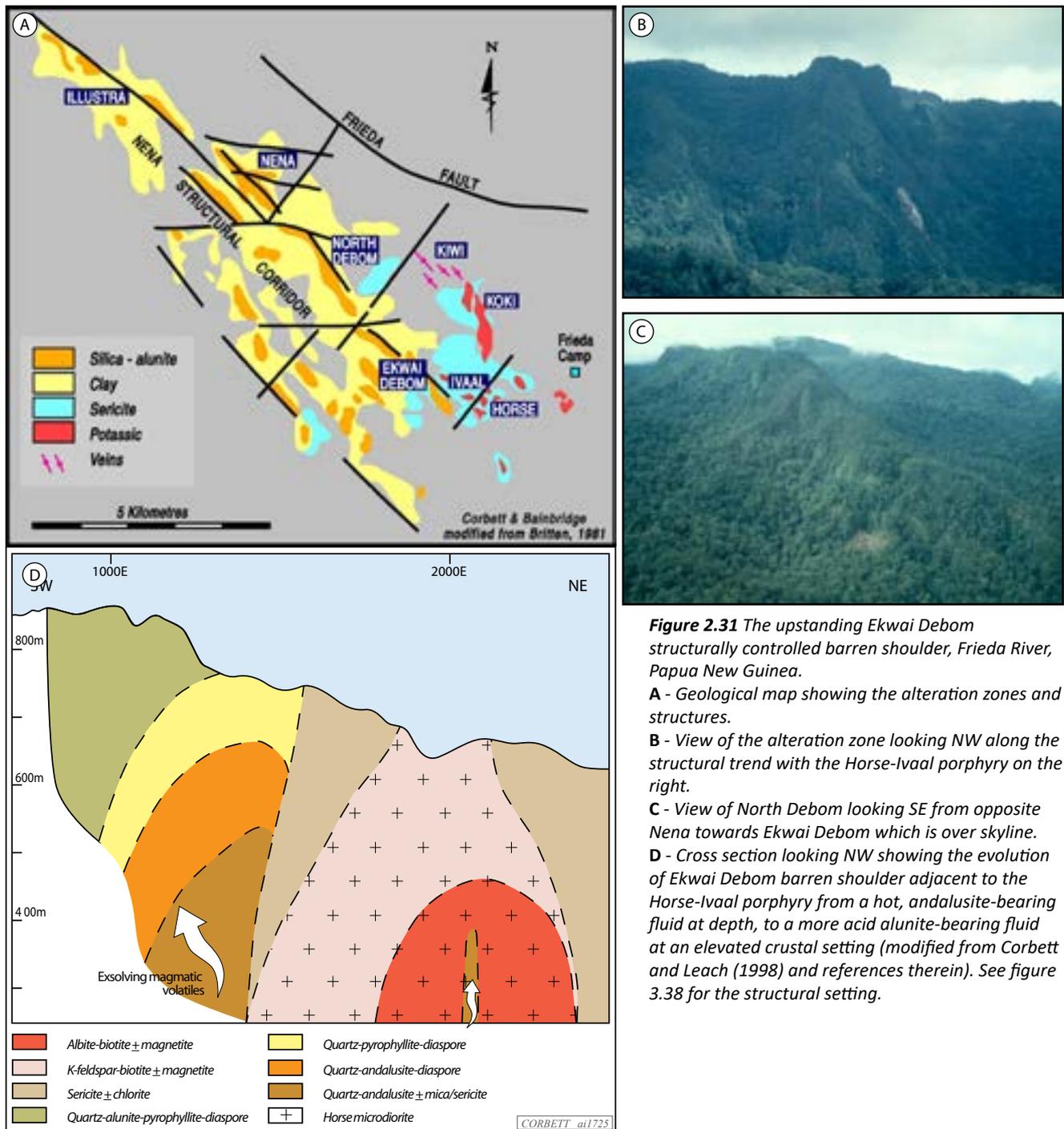
**Figure 2.30** Structurally controlled barren shoulders at Lookout Rocks, New Zealand, from Corbett and Leach (1998). **A** - A view from the NE of the plan C of the Pine Ridge (far) and Lookouts Three (close). The silica-alunite ledges which dip towards the Ohio Creek porphyry identified as outcrop in the valley at the bottom right of the view. The Thames 1 M oz Au bonanza goldfield lies on the other side of Pine Ridge on the skyline. A drill site in the saddle on the skyline is shown on Pine Ridge in figure C. **B** - Pervasive clay alteration of the fiamme-bearing ignimbrite adjacent to the ledges. **C** - Zoned alteration in plan view. **D** - Conceptual cross section based upon the data to hand. **E** - Legend for the colours used herein.

#### 2.2.4.1.2.2 At Frieda River,

Papua New Guinea, a splay fault associated with a component of strike-slip movement on the regional Fiak-Leonard Schultz fault is interpreted to have localised the Horse-Ivaal porphyry deposits and the marginal advanced argillic alteration extending for over 10 km strike within the associated dilatant structure developed as part of the splay fault (Corbett, 1994; figures 2.31 & 3.38). The Ekwai Debom barren shoulder advanced argillic alteration lies immediately adjacent the Horse-Ivaal porphyry and grades vertically from high temperature andalusite-sericite at depth, through pyrophyllite-diaspore mineral

assemblages to highest crustal level alunite (Corbett and Leach, 1998). This trend displays alteration (above) derived from reaction with the wall rocks of a very hot moderately acidic fluid at depth which has become progressively more acidic during the rise to a higher crustal level. This fluid is interpreted to have been derived from a deeper magmatic source than the porphyry and block faulting separates that deep level alteration from higher crustal level high sulphidation epithermal Au-Cu alteration and mineralisation 10 km to the NW at Nena (Bainbridge et al., 1994; Corbett and Leach, 1998).

It will be argued later that, while only structural



control is discernible for the Debom barren shoulder, a combined structural-lithological control has been proposed for the pencil-shaped less eroded Nena high sulphidation system (Section 8.4.1.1).

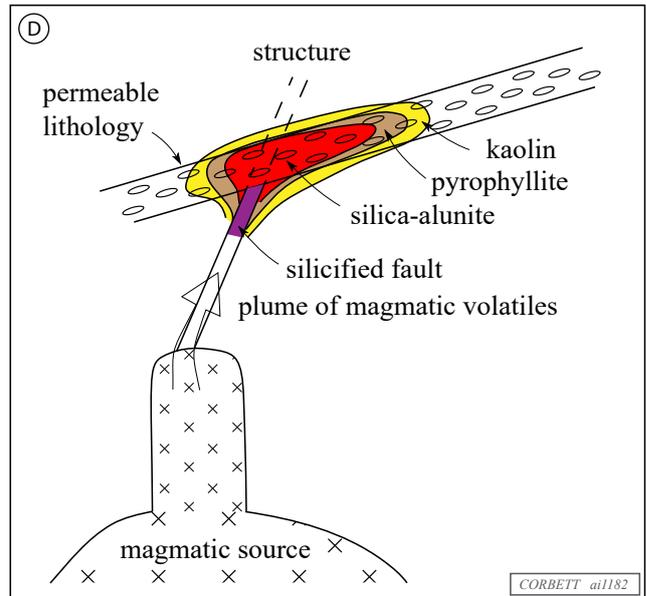
### 2.2.4.1.2.3 The Queen Elizabeth

alteration system in Northern Chile comprises a 12 km long flat dipping (manto-like) body of silica-alunite-clay alteration developed by the pervasive replacement of a highly permeable fiamme tuff (figure 2.32). Features such as phreatomagmatic breccias, propylitic alteration, veins and an IP chargeability anomaly are consistent with the formation of the alteration as a lithologically controlled barren shoulder lithocap

related to an unseen magmatic source. However, the extensive lateral distribution of alteration makes it difficult to generate porphyry exploration targets in systems such as this. A steep dipping structure exposed in one creek with increased silicification over the general silica-alunite alteration, may represent a structural feeder for the fluid responsible for alteration (figure 2.32).

### 2.2.4.1.2.4 Halilaga

in western Turkey occurs as a flat dipping lithologically controlled barren shoulder of silicification grading to advanced argillic alteration developed by replacement of permeable tuff within the sequence of Miocene andesites. Extensive drilling below the silica ledge has



**Figure 2.32** The Queen Elizabeth alteration zone in northern Chile.

**A** - A view of a portion of the extensive blanket of silica-alunite-clay alteration.

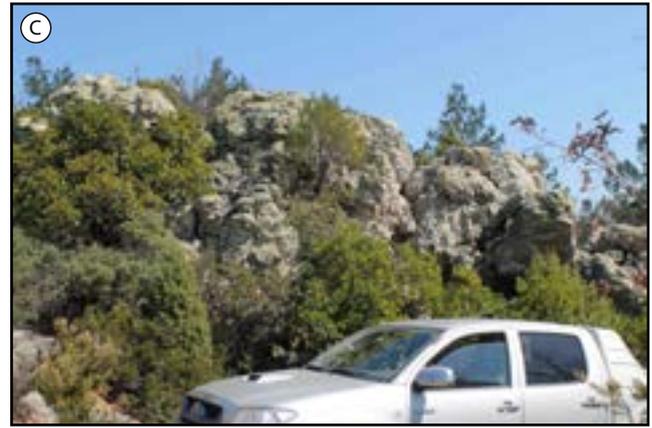
**B** - Permeable fiamme tuff which facilitated lateral fluid flow in order to form the extensive alteration blanket.

**C** - Steep dipping structure which may represent a feeder structure.

**D** - Conceptual geological model developed to illustrate the interpreted relationships (from Corbett, unpubl. report).

identified some enargite bearing structures grading to 0.3 g/t Au. However, the silicification is generally barren and distinct from the typical vuggy silica of high sulphidation epithermal Au deposits. Silica displays a massive to saccharoidal character with local open space brecciation, but is not classed as vuggy silica (figures 2.28 & 2.33). Two silica ledges lie within a km laterally from an outcropping porphyry with stockwork quartz veins at surface, which, on the geological interpretation ([www.pilotgold.com](http://www.pilotgold.com)), has been upfaulted and so now lies at an elevation of less than 100 m below the barren shoulder ledges.





**Figure 2.33** The flat-lying lithologically controlled barren shoulder at Halilaga, Turkey.

**A** - View of the alteration zone from the porphyry Cu outcrop.

**B** - Flat-lying silica alteration ledge.

**C** - Bedding discernible in the silica ledge.

**D** - Massive to brecciated pervasive silicification.

**E** - Marginal clay alteration with FeO after oxidised pyrite.

#### 2.2.4.1.2.5 At Bilimoia,

Papua New Guinea, gold panned during reconnaissance investigations in the early 1980's was interpreted to have been derived from the upstanding silicified basement slates, with steep dipping slaty cleavage, at the hill-top, termed the Oro prospect at that time (figure 2.27 A). Subsequent intensive exploration failed to find any Au anomalism or vughy silica typical of high sulphidation epithermal Au mineralisation within the silicification. Minor enargite float was traced to fault related breccia-fill without obvious silica-alunite alteration at the Headwaters prospect. Later exploration identified a series of low sulphidation epithermal Au lodes (section 7.2.1.1.4.1) between 2 and 4 km from the alteration zone, and including what became the Irumafimpa Au mine, as the probable source of the alluvial Au (Corbett, et al., 1994; Corbett and Leach, 1998; Corbett, 2005b ). Porphyry Cu manifestations crop out at the lowest elevation in the valley. The Oro prospect is now interpreted as a flat dipping barren shoulder in a region of porphyry and epithermal manifestations. However, it has not been established that the porphyry and epithermal features belong to the same event. At Irumafimpa, the regional slaty cleavage becomes

a crenulation cleavage close to the faults which host the veins, as an indication these structures were active at least 5 km below the current surface prior to progressive uplift, mineralisation and erosion.

#### 2.2.4.1.2.6 The Nash's Hill

barren shoulder of advanced argillic alteration lies within the Goonumbla (North Parkes) porphyry district (Owens et al., in press, and references therein) of the Ordovician to earliest Silurian Junee-Naramine Belt within the Tasmanide Arcs, in Eastern Australia (section 3.3.3.3.1). Cu-Au mineralisation is mined from vertically attenuated spine-like porphyry intrusions which overlie a batholithic quartz-biotite monzonite, but the source for mineralisation may lie at greater depth. The NS trending Tenandra structural corridor (Corbett and Leach, unpubl. report, 1995), locally apparent as a shoulder-like batholith margin, hosts the E26 and E48 porphyry intrusions and the Nash's Hill alteration zone, the latter localised at the intersection with a prominent circular gravity low provided by the contrast between the monzonite and host andesitic volcanics (figure 3.55). Surface exposures are dominated by massive silica in which the original clastic volcanic texture is commonly discernible, as

the overlying softer clay alteration has been eroded (figure 2.34). In a quarry constructed for road-building material, permeable clastic rocks within the flat-lying volcanic rock sequence have acted as fluid pathways and so display massive pervasive silica alteration (figure 2.34 A). Adjacent less permeable host rocks include alteration dominated by silky pyrophyllite grading to more marginal kaolin, which sticks to the tongue, locally dominates in the less permeable and less altered rocks. Leisegang rings and other Fe oxides, along with

supergene alunite and kaolin, attest to the an original high pyrite content, which has weathered to provide acidic ground waters (figure 2.34). The Nash's Hill alteration zone where examined therefore occurs as a lithologically controlled barren shoulder, characterised by modest temperature clay alteration minerals, which have eroded to expose a large area of massive silica.



**Figure 2.34.** Nash's Hill barren shoulder of advanced argillic alteration.

**A** - Surface silica, Goonumbla, Australia, with original clastic texture and abundant FeO.

**B** - Quarry exposure in which erosion has ceased at the uppermost resistant silica developed by preferential alteration of a permeable flat-lying volcanic unit, while pyrophyllite and kaolin alteration dominate in the underlying units.

**C** - Close up of the uppermost permeable unit of B showing the sliced clastic texture.

**D** - Liesegang bands of FeO typical of the originally pyrite-rich barren shoulder advanced argillic alteration.

**E** - Supergene alunite vein cuts silica

**F** - Supergene kaolin cuts hypogene clay.

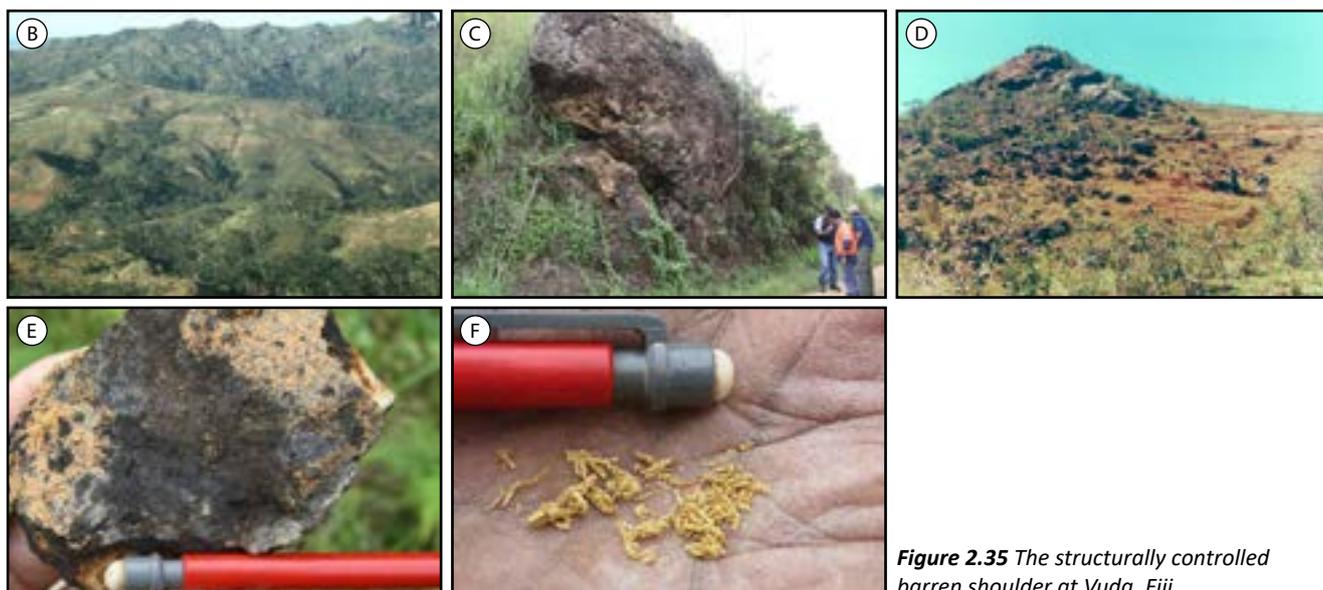
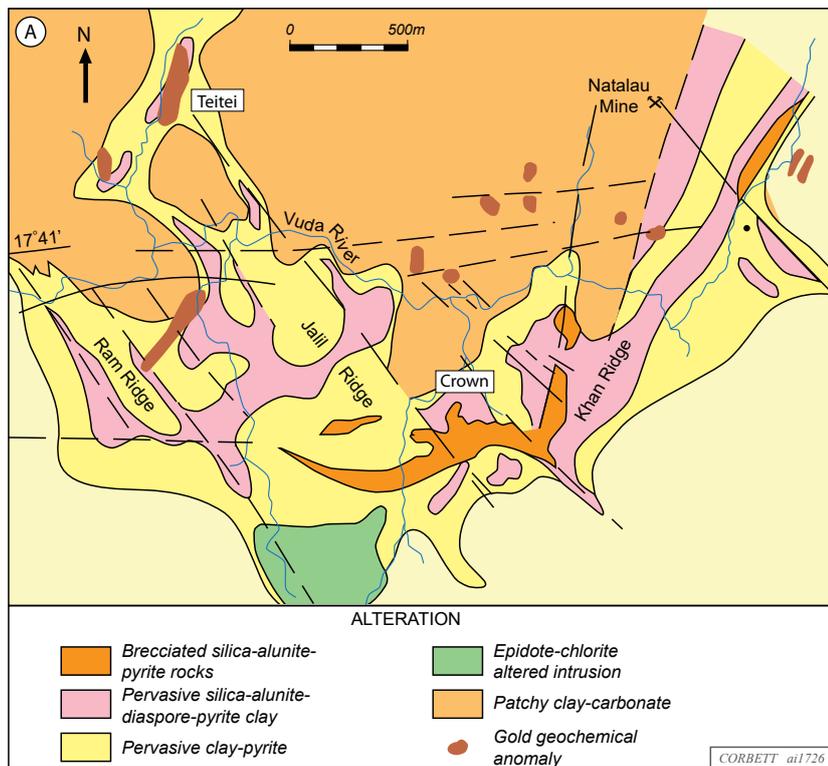
### 2.2.4.1.2.7 Vuda,

The Vuda, Fiji, advanced argillic alteration (Corbett and Leach, 1998) occurs as an arcuate ridge comprising ledges of silica-alunite breccia which grades to marginal pyrophyllite-diaspore and clay-pyrite alteration within shoshonitic lava host rocks (figure 2.35). Drilling of the advanced argillic alteration passed down to (phyllitic) sericite-chlorite-anhydrite alteration marginal to a silica-alunite-pyrite

ledge, interpreted as a feeder structure, but without the identification of mineralisation or any porphyry intrusion. An outcropping propylitic altered diorite is interpreted as post-mineral. The Natalau mine which exploited a Au-bearing pyrite-base metal lode is typical of D veins developed marginal to a porphyry intrusions. Gold can be panned in Vuda Creek and traced to open fractures with low temperature K-feldspar (adularia) alteration in weakly illite-chlorite

altered K-rich shoshonitic lava outside the advanced argillic alteration zone. The presence of MnO and panned Au (figure 2.35 E & F) within the Teitei advanced argillic alteration zone (figure 2.35 A) is indicative of later carbonate-base metal Au mineralisation which cuts the advanced argillic alteration and may contain a supergene Au component.

The Vuda advanced argillic alteration represents a typical barren shoulder with subjacent phyllic alteration and local associated D vein mineralisation typical of an above porphyry environment. Extensive surface exploration demonstrated that the advanced argillic alteration is essentially barren, except where cut by later lower temperature intrusion-related low sulphidation epithermal Au mineralisation.



**Figure 2.35** The structurally controlled barren shoulder at Vuda, Fiji.

- A - The 1985 geological map made early in the understanding of these systems showing gold in soil anomalies mostly outside the alteration (from Corbett unpubl. report).
- B - View of Khan's ridge which is to the right of the map in A.
- C - Close up of the steep dipping silica ledge at Khan's ridge.
- D - Typical silica ledge exposure.
- E - MnO cutting advanced argillic alteration at Teitei in A, as evidence of later carbonate base metal Au style epithermal mineralisation (see section 7.2.1.2).
- F - Wire gold panned from the exposure shown in E.

In **summary**, barren shoulders:

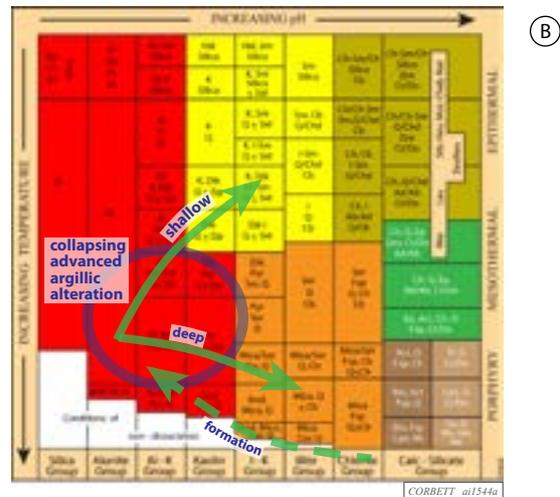
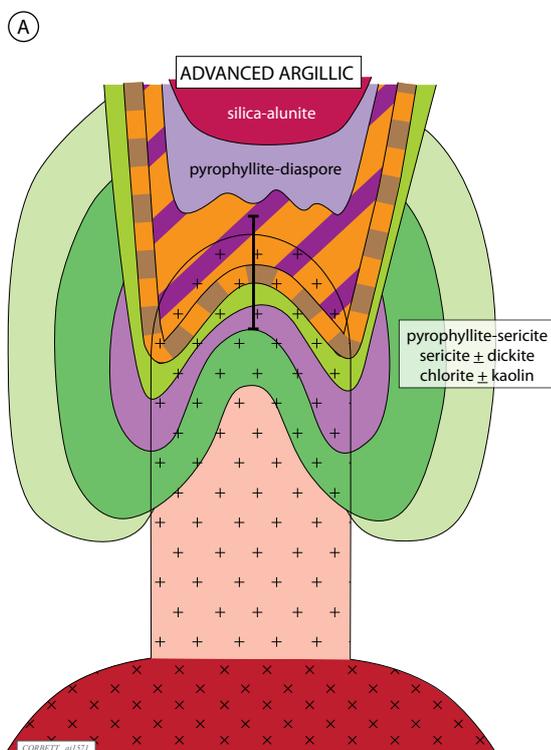
- Develop by reaction with wall rocks of an evolving rising hot, acidic, magmatic fluid early in the porphyry cooling history following intrusion emplacement and prograde alteration.
- Display wall rock alteration with a vertical zonation related to the progressive increased acidity of the rising hydrothermal fluid and then lateral zonation as the hot acid fluids are cooled and neutralised marginal to the feeder structure, generally present as a massive silica core.
- Exploit steep dipping structures, commonly at deeper crustal levels, or flat dipping conformable permeable horizons, locally as extensive mantos at higher crustal levels.
- Are barren unless overprinted by later mineralisation.
- Form part of the larger model which may vector to porphyry mineralisation.

The **exploration implications** are that a correct identification of barren shoulders may seriously expedite any exploration program as these bodies do not represent mineralisation, but if placed within the overall prospect geological model by geological mapping, may act as vectors towards porphyry mineralisation.

### 2.2.4.2 Collapsing advanced argillic alteration

Collapsing advanced argillic hydrothermal alteration has no doubt contributed to the opinion held by some explorationists that wall rock hosted lithocaps immediately overlie porphyry Cu style intrusions. The collapsing style of advanced argillic alteration post-dates the barren shoulder alteration and pre-dates advanced argillic alteration associated with high sulphidation epithermal Au-Ag mineralisation. Importantly, each style of advanced argillic alteration formed by a different mechanism displays different relationships to mineralisation and may be distinguished by subtle differences in the mineralogy and form.

As described above, the porphyry model (figure 2.12) features a hot intrusion driver for convective hydrothermal cells which may take volatiles into the upper porphyry environment where they combine with ground waters and oxidise to form hot acid fluids. Later, as the spine-like porphyry cools (figure 2.12), in the process of drawdown the outward moving convective cells reverse and the acid waters collapse upon the intrusion and adjacent wall rocks to react with the pre-existing prograde and fresh



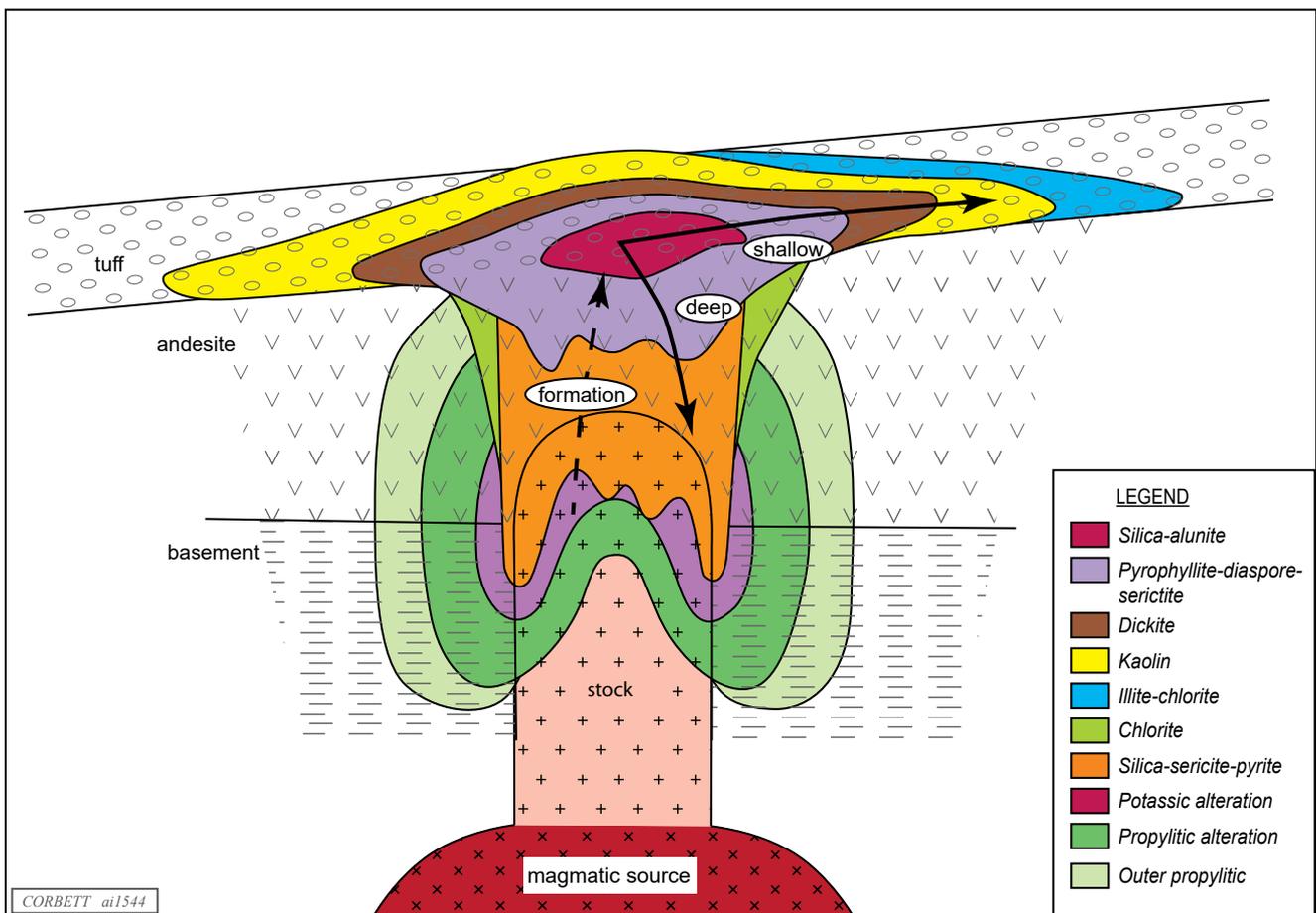
**Figure 2.36** Collapsing advanced argillic alteration.  
**A** - Model as part of the staged model for porphyry development.  
**B** - Fluid flow paths on the pH vs temperature figure.  
**C** - View of this alteration at Tantahuatay, Peru, cut by vertical silica ledges related to later high sulphidation epithermal Au mineralisation.

minerals to produce retrograde phyllic alteration characterised by minerals such as silica, sericite, chlorite, pyrite, carbonate (typically siderite). The alteration assemblage varies with temperature and pH of the collapsing waters (figure 2.26). Sericite grades with depth to muscovite at high temperature locally with andalusite, and laterally to illite-chlorite at low temperature, while chlorite is more prevalent where alteration is less intense. In more acidic conditions phyllic alteration may contain pyrophyllite, more typically associated with advanced argillic alteration.

Consequently, in conditions of extremely low pH (locally described as negative) advanced argillic alteration develops in the upper portion of the porphyry environment by reaction of those fluids with the intrusion and wall rocks. Drawdown (above) causes the extremely acidic fluids to collapse into the porphyry environment and produce characteristic zoned advanced argillic hydrothermal alteration grading to sericite as they are cooled and neutralised by wall rock reaction. In these conditions existing prograde and fresh minerals are altered to silica-alunite passing downwards to pyrophyllite-diaspore assemblages, as the acidic fluid collapses and is progressively cooled and neutralised, while andalusite is likely to be present at higher temperatures.

Advanced argillic alteration grades laterally to dickite, then kaolinite dominant mineral assemblages, in cooler conditions (figure 2.36). The deeply eroded high temperature El Salvador porphyry is overlain by advanced argillic alteration dominated by pyrophyllite with lesser alunite and diaspora which overprints earlier andalusite-sericite alteration (Gustafson and Hunt, 1975). The poorly eroded Bacon-Manito geothermal field, Philippines, grades from alunite-cristobalite advanced argillic alteration at the upper central portion to marginal low temperature kaolin-illite then smectite, and at depth to anhydrite-pyrophyllite-diaspore (Mitchell and Leach, 1991; Corbett and Leach, 1998).

The distribution of alteration zonation at the upper portion of the porphyry environment is governed by permeability during drawdown and fluid pH. Structures and fracture zones, such as at intrusion margins, are likely to focus downward collapse, while lateral fluid flow may persist for some distance in permeable volcanic lithologies (figure 2.37) to form laterally continuous sub-horizontal blankets (mantos) of advanced argillic - argillic alteration.



**Figure 2.37** Formation of a manto-style collapsing advanced argillic alteration by exploitation of a permeable volcanic rock by hydrothermal fluids.

#### 2.2.4.2.1 Ovoid alteration textures

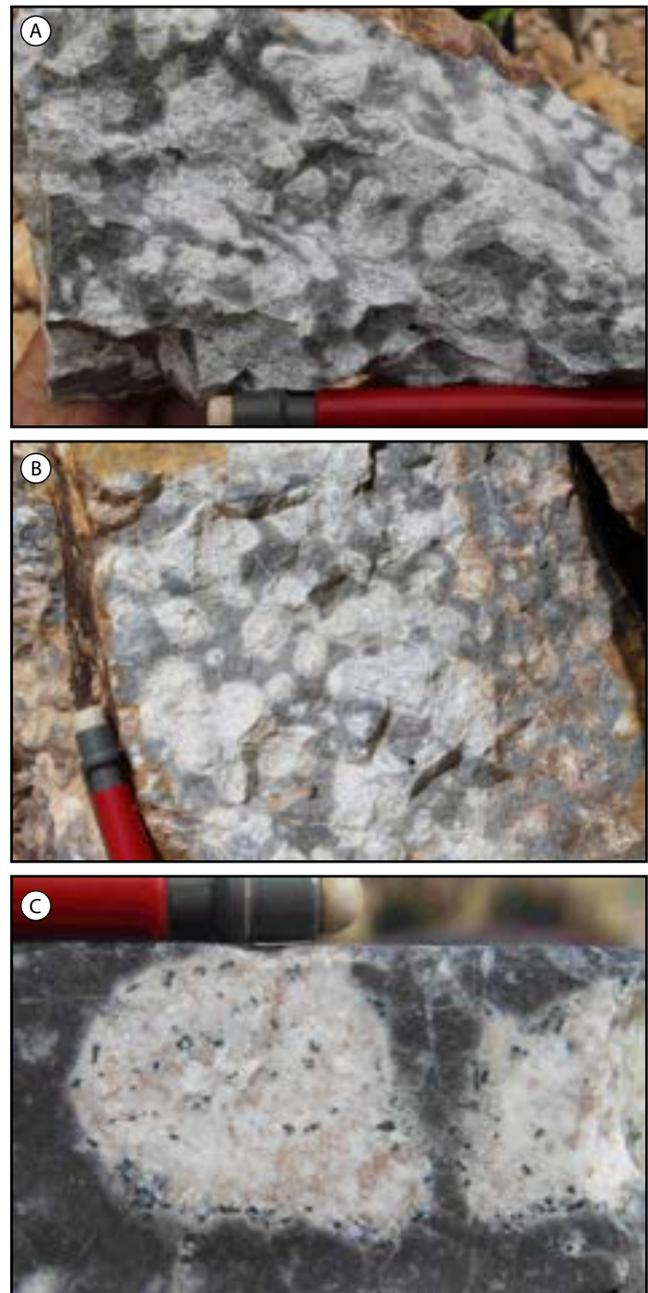
are recognised in several well developed bodies of collapsing advanced argillic alteration (figure 2.38). The texturally destructive ovoids are distinct from wormy black quartz veins which are described as having formed later by Nobel et al. (2010) and developed at a deeper level at Kupfertal, Yanacocha, Peru, (Gustafson et al., 2004). The fluid inclusion-rich wormy veins are interpreted to be derived from a volatile-rich fluid. Banded black quartz veins lie immediately below the advanced argillic lithocap at Marte, Chile (figure 5.13). The termed ‘gunaso’ (Spanish for worm), locally used to categorise these textures is not preferred by Noble (op cit) who described the ovoids as comprising dominantly silica-pyrophyllite and some alunite along with local diaspore, enargite and covellite (Noble et al., 2010). The enargite-covellite is more abundant towards the outer rims of the ovoids which are typically set in a dark silica matrix rich in vapour inclusions (figure 2.38). This texture is recognised within several advanced argillic lithocaps in the Cajamarca district Peru (Gustafson, et al., 2004), Tantauatay, Peru (Miranda et al., 2014) and Oyu Tolgoi, Mongolia (Crane and Kavalieris, 2012). In several instances the advanced argillic alteration overlies and collapses upon silica-sericite-pyrite (phyllic) alteration which may contain chalcopyrite-bornite-pyrite mineralisation (Gustafson et al., 2004; Miranda et al., 2014; Nobel et al., 2010). The enargite-covellite within the ovoids might therefore contain metals remobilised from earlier prograde mineralisation by the collapsing extremely acidic fluids responsible for this retrograde alteration.

In **summary**, collapsing advanced argillic alteration develops in the upper portions of porphyry environments, including wall rocks, where the low pH fluids, normally responsible for phyllic alteration, are especially acidic. Local texturally destructive ovoid textures have been derived from a volatile-rich fluid and demonstrate a strong association with a magmatic source. Minor enargite-covellite within the ovoids has been remobilised from earlier prograde mineralisation.

The **exploration implication** is that collapsing advanced argillic alteration is expected to overlie porphyry Cu-Au style intrusions but are much less common than barren shoulders in this author’s experience.

#### 2.2.4.3 Acid D veins

Acid D veins are characterised by the presence of enargite-barite-alunite and possible advanced argillic



**Figure 2.38** Ovoid textures in the Tantauatay, Peru. **A & B** - Hand specimen scale from the open pit shown in figure 2.36.

**C** - In drill core showing covellite-enargite bearing rims.

alteration within the wall rock alteration selvage (Poposa, Argentina) which would normally be expected to be dominated by silica-sericite-pyrite. Although the original D vein definition by Gustafson and Hunt (1975) features enargite in the vein and some kaolin in the wall rock alteration, most D veins (in this author’s experience) fall into the low sulphidation deep epithermal class (section 5.2.1) with silica-sericite-pyrite (phyllic) wall rock alteration and ore mineralogy dominated by pyrite-chalcopyrite. Some enargite-barite-alunite with advanced argillic alteration selvages lie below high sulphidation epithermal Au deposits (La Coipa, Chile; Pierina, Peru) and so may provide a link between the epithermal and porphyry environments within the palaeo plumbing system for the epithermal

alteration and mineralisation.

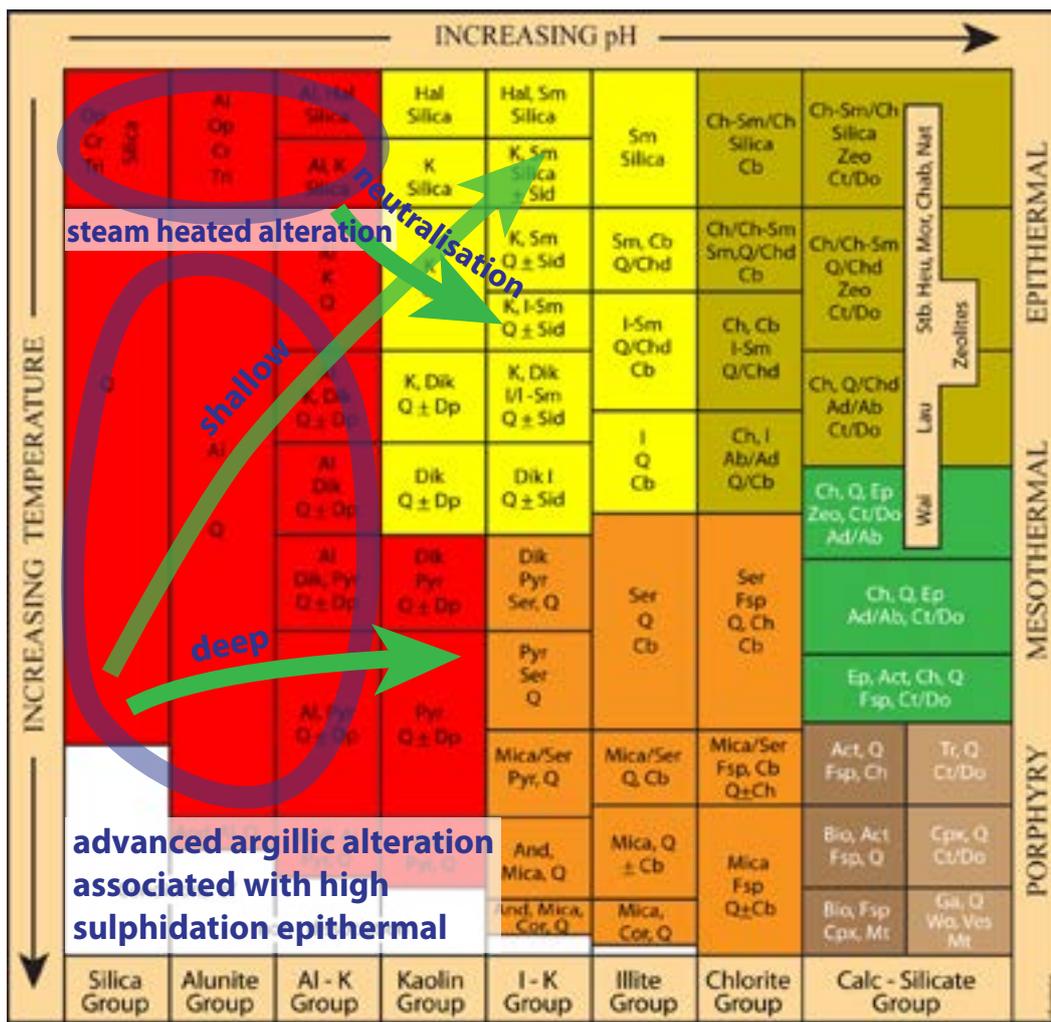
#### 2.2.4.4 Alteration associated with high sulphidation epithermal Au-Ag deposits

High sulphidation epithermal Au deposits are characterised by zoned advanced argillic grading to argillic alteration of the wall rocks adjacent to mineralisation while alunite represents an important gangue within mineralised veins and breccias.

*Terminology:* The terminology is high sulphidation epithermal Au-Ag mineralisation and advanced argillic alteration, and not high sulphidation alteration nor advanced argillic mineralisation.

High sulphidation epithermal Au-Ag ( $\pm$  Cu) deposits are associated with zoned advanced argillic wall rock alteration which grades laterally to intermediate argillic then neutral argillic alteration (figure 2.39), and displays variations in alteration mineralogy with depth of formation, while the geometry of the alteration zonation varies according to the structural, breccia and lithological permeability controls (section 8.4).

Commonly flat dipping, wide lithologically controlled alteration zones hosted by permeable host rocks (Pierina, Peru) contrast with narrow, structurally controlled alteration zones with typically steep dips and form within competent wall rocks which have fractured well (El Indio, Chile). Variable geometries which result from breccia control include brecciated dome margins (Yanacocha, Peru; Mt Kasi, Fiji), or steep dipping phreatic-phreatomagmatic breccia pipes (Veladero, Argentina), or flat dipping intersections of pipes and dilatant structures (Lepanto, Philippines). The most common settings for high sulphidation epithermal ore systems is at the intersection of steep dipping feeder structures and flat dipping permeable lithologies (Pierina & Sipan, Peru; El Guanaco, Chile; Nena, Papua New Guinea), or related to diatreme flow dome complexes (Veladero & Lama, Argentina; Yanacocha & La Virgin, Peru; Lepanto, Philippines; Pascua, Chile; Wafi, Papua New Guinea; Miwah & Matabe, Indonesia). Some of these intersections form flat dipping pencil like ore shoots at the structure-lithology intersection (figure 1.12).

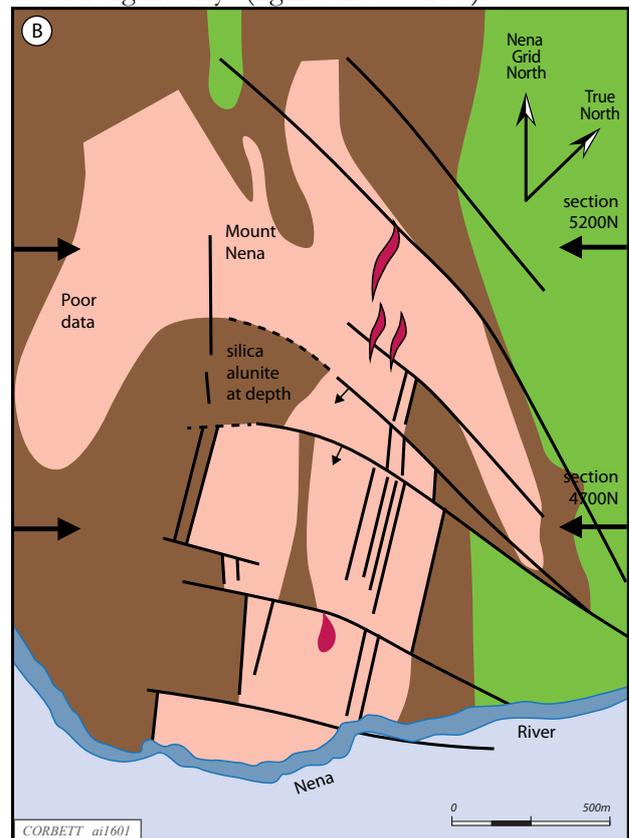
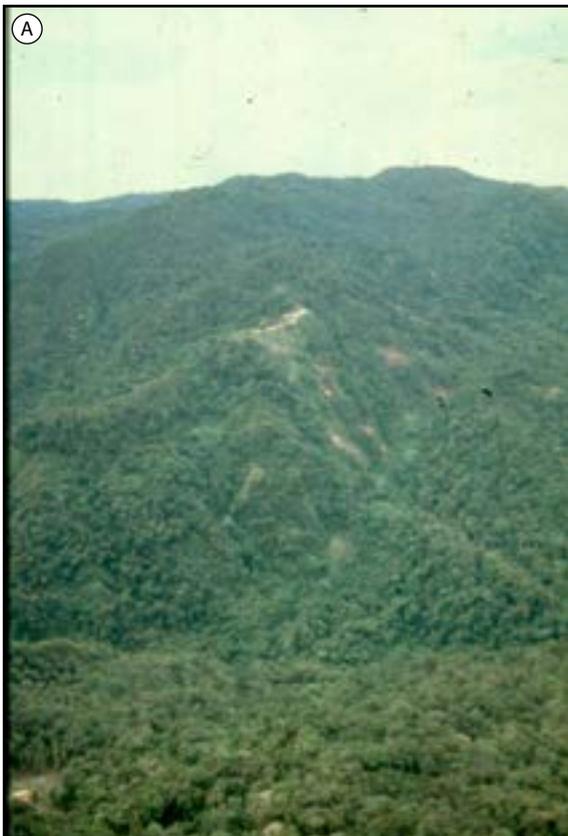


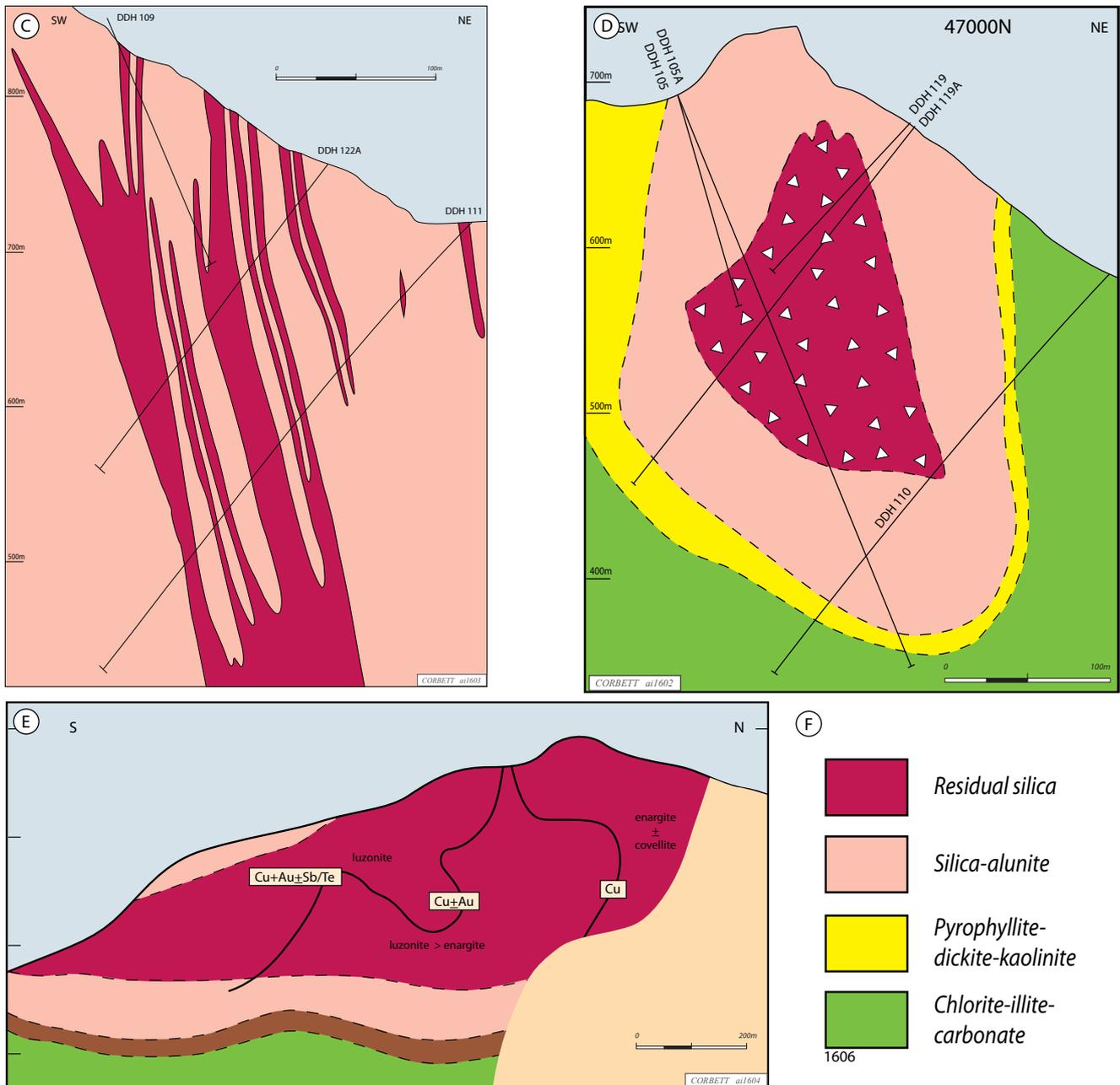
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Figure 2.39 Zoned advanced argillic alteration associated with high sulphidation epithermal Au deposits.

As pointed out in section 1.2.3, the magmatic fluid responsible for formation of high sulphidation epithermal mineralisation and associated advanced argillic alteration, is interpreted (Corbett and Leach, 1998 and references therein) to have developed by evolution of a volatile-rich magmatic fluid (brine) during the rapid rise from porphyry to epithermal crustal levels, without significant interaction with wall rocks or entrainment of meteoric waters (figure 1.6). This fluid which might be likened as a bubble progressively becomes depressurised while rising from a buried magmatic source up a major structure, causing the formerly dissolved volatiles dominated by  $\text{SO}_2$  (but also including  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{HCl}$  and  $\text{HF}$ ) to come out of solution and oxidise to form  $\text{H}_2\text{SO}_4$  (figure 1.6). Thus, a magmatic fluid which was hot and near neutral at porphyry crustal levels has become hot and acidic in epithermal regimes. There should be a clear gap between the porphyry and epithermal environment in which the fluid evolution occurs, especially as the no disassociation occurs above about  $400^\circ\text{C}$ . At epithermal levels this hot acidic fluid becomes progressively cooled and neutralised by reaction with wall rocks to provide the distinctive alteration zonation (figures 2.39 & 2.43). The fluid breaks into a faster moving volatile-rich phase which is progressively cooled and neutralised by reaction with the wall rocks to produce the distinctive zoned wall rock alteration, while the slower moving liquid phase deposits sulphides, commonly later (section 8.3).

The characteristic alteration zonation derived from the progressive cooling and neutralisation of a hot acidic fluid (above and at  $250\text{-}300^\circ\text{C}$  and pH of 0-2, section 1.2 .2.3) by wall rock reaction grades outwards from a silica core through mineral assemblages dominated by advanced argillic silica-alunite then pyrophyllite-diaspore, grading to intermediate argillic dickite-kaolinite, and more marginal neutral argillic illite and then smectite alteration (figures 2.39 & 2.43). That is, as the fluid is progressively cooled and neutralised, there is an outward change to alteration minerals within the wall rocks typical of less acidic and lower temperature conditions. The central zone may be called residual silica as only quartz and some rutile remain after the extreme leaching in the centre of the alteration zone by the intensely hot acidic fluid, although the also used term vuggy silica denotes the characteristic texture, apparent either as tabular shapes pseudomorphing leached feldspars (figures 1.12 & 8.2), or with ovoid forms developed by total textural destruction in a permeable host rock (figure 2.41 D & 8.2). Open space vuggy textures are commonly especially well developed where fiamme-bearing tuffs have provided primary permeability resulting in flat dipping bodies (figure 2.42 C & 8.16). Alteration mineralogy varies with depth of formation and in part wall rock permeability. At deeper crustal levels alteration zones host more abundant pyrophyllite-diaspore, while at shallower crustal levels dickite passes outward to the low temperature form kaolinite and then to marginal illite and more marginal smectite neutral argillic clays (figures 2.39 & 2.43).





**Figure 2.40** Zoned advanced argillic alteration associated with the Nena High sulphidation epithermal Au deposit at Frieda River, Papua New Guinea.

**A** - 1990 view looking NW covers a similar area to the map.

**B** - Map of the alteration zonation.

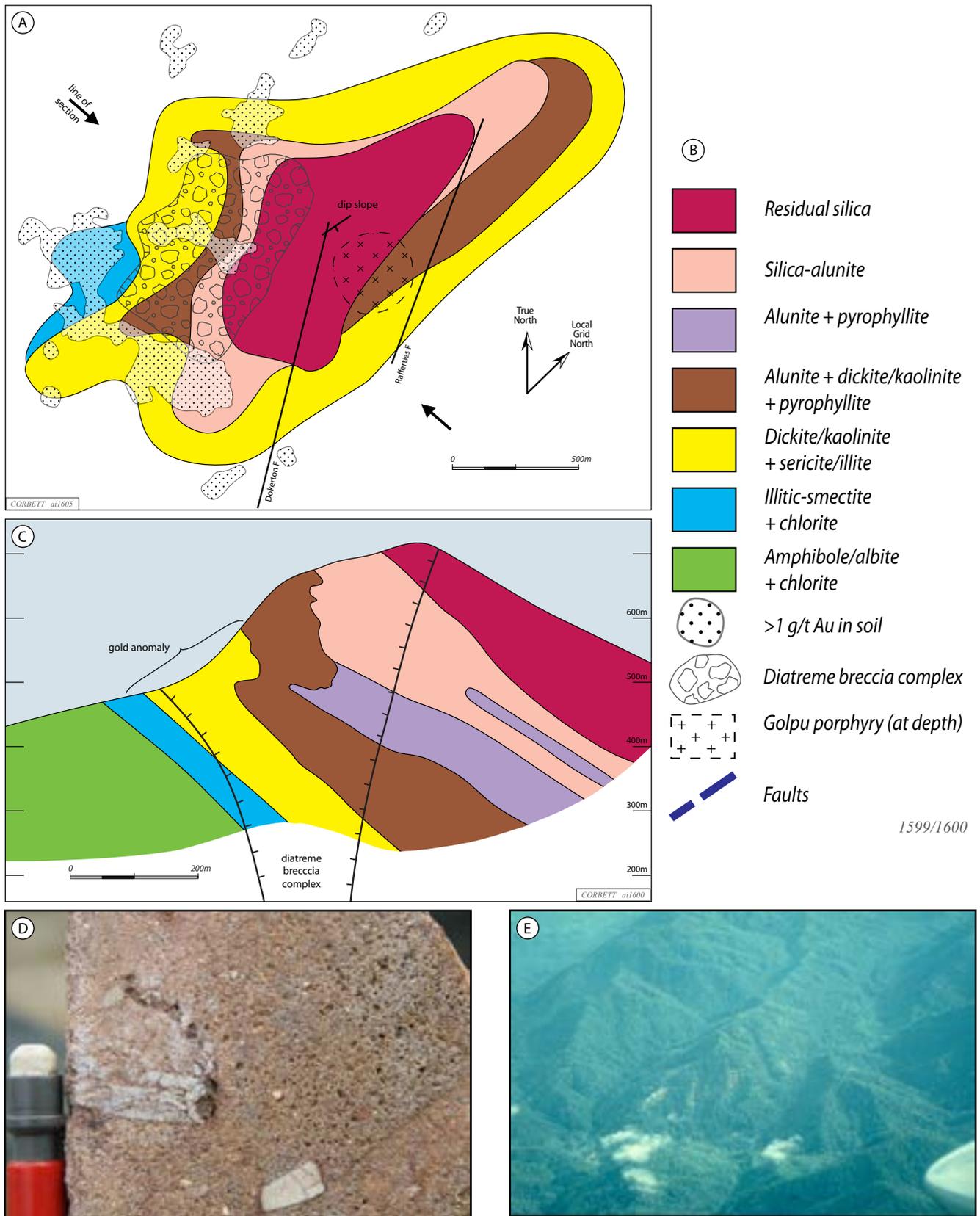
**C** - Northern cross section 5200N closer to the structurally controlled fluid up-flow.

**D** - Southern cross section 4700N showing the horizontal pencil-like ore zone developed at a distal fluid out-flow setting at the intersection of a permeable horizon and fault and also with relatively narrow alteration zones derived from rapid fluid cooling and neutralisation at the alteration margin.

**E** - Long section which illustrates the north to south fluid flow and shows the rootless nature of the high sulphidation system.

**F** - Legend of advanced argillic alteration assemblages.

All data from Bainbridge et al. (1994) and Corbett and Leach (1998).



**Figure 2.41** Advanced argillic alteration associated with the Wafi high sulphidation epithermal Au deposit, Papua New Guinea.

**A** - Plan view.

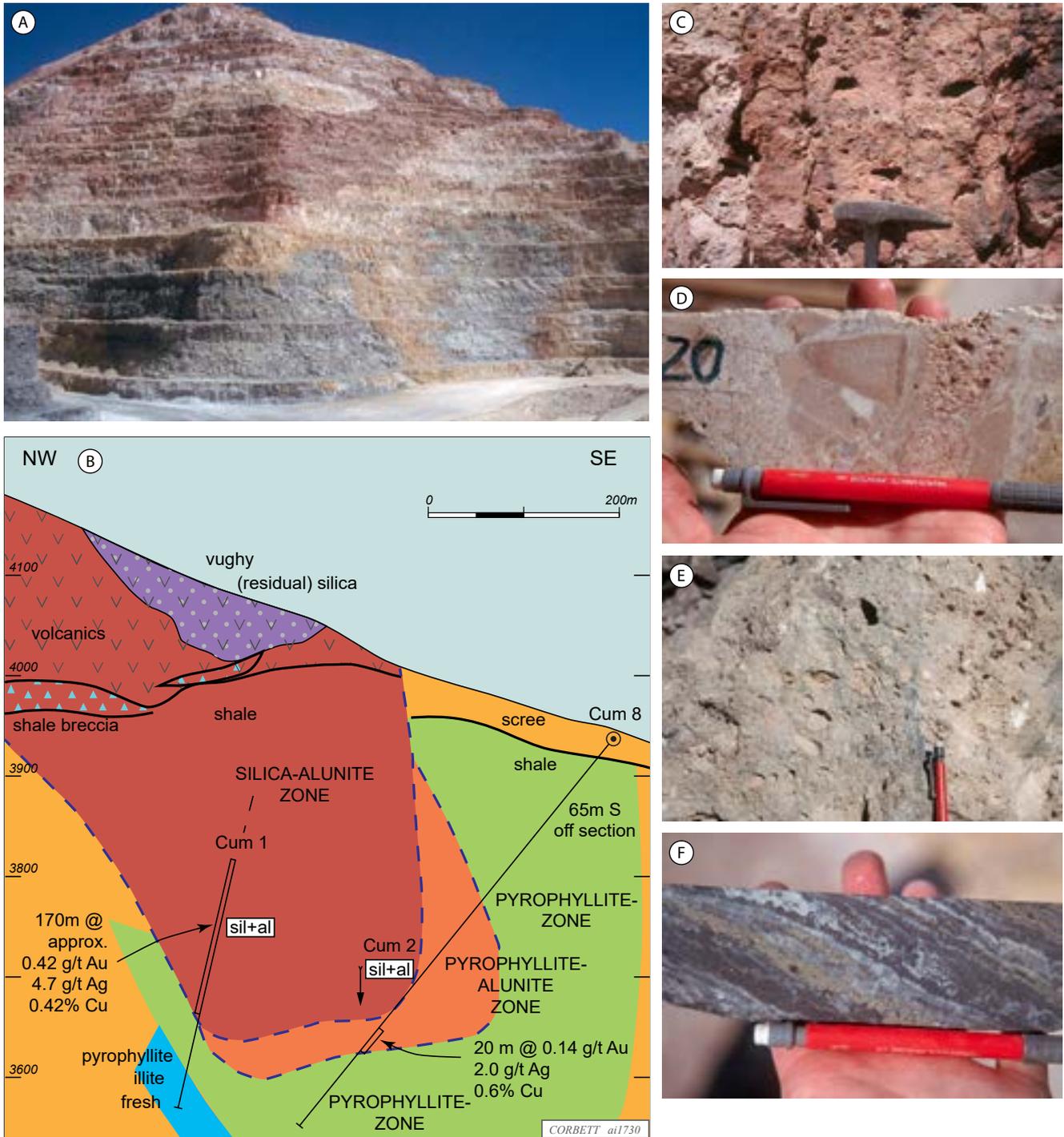
**B** - Legend.

**C** - Cross section.

**D** - Vuggy residual silica altered milled matrix breccia which would have provided permeability within the diatreme.

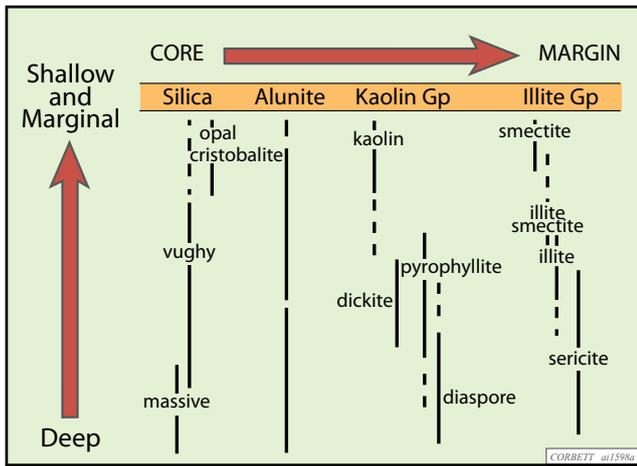
**E** - View of Wafi about 1992 showing the central ridge along which the alteration is located.

All data from Corbett and Leach (1998) and Leach (1999).



**Figure 2.42** Zoned advanced argillic alteration and mineralisation at the La Coipa high sulphidation epithermal Au deposit, Chile.

- A - The open pit about 1999 after mining of the oxide ore.
- B - Cross section of geology and zoned alteration extending below the open pit.
- C - Vuggy silica altered fiamme tuff
- D - Silica-alunite altered volcanic breccia.
- E - Later dark coloured sulphide mineralisation cross cuts earlier vuggy silica.
- F - Banded quartz-pyrite-enargite-barite vein hosted within the basement slate blow the open pit.



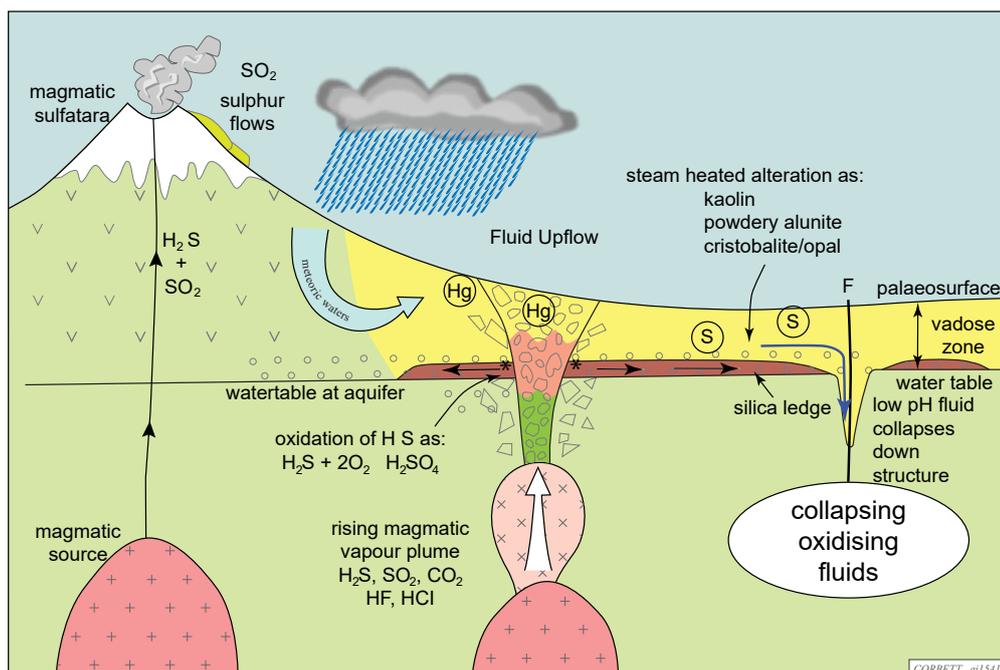
**Figure 2.43** Zoned advanced argillic alteration in high sulphidation epithermal Au deposits from deep to shallow and core to margin.

### 2.2.4.5 Steam heated alteration,

Steam heated alteration, as categorised herein (section 1.2.3), represents the uppermost portions of intact high sulphidation epithermal Au alteration and mineralisation systems, formed at the vadose zone, and so locally preserved in arid and youthful environments (figure 2.44). Alteration commonly occurs as laterally extensive blankets in which total destruction of the original rock texture is associated with the formation of a mineral assemblage comprising: cristobalite, powdery alunite, kaolin and sulphur (figures 2.44 - 2.46). Note some workers use the term steam heated alteration in a much wider sense to describe all alteration above the vadose zone including within low sulphidation epithermal environments.

Volatiles (mainly H<sub>2</sub>S) evolved from cooling high sulphidation epithermal Au alteration and mineralisation rise and become oxidised at the vadose zone, possibly phreatic zone, to form warm acidic waters, which then react with the wall rocks to produce the characteristic alteration. These terms are explained in figure 1.5 and Corbett and Leach (1998). While alteration blankets may extend laterally for considerable distances, neutralisation of the acid waters at the water table commonly results in the formation of a basal silica zone which is locally brecciated with a fill of kaolin and powdery alunite. Steam heated alteration is formed from a vapour phase and so is typically barren of Au-Ag sulphide mineralisation, although Hg is common as cinnabar, typically with cristobalite (figure 2.46 C).

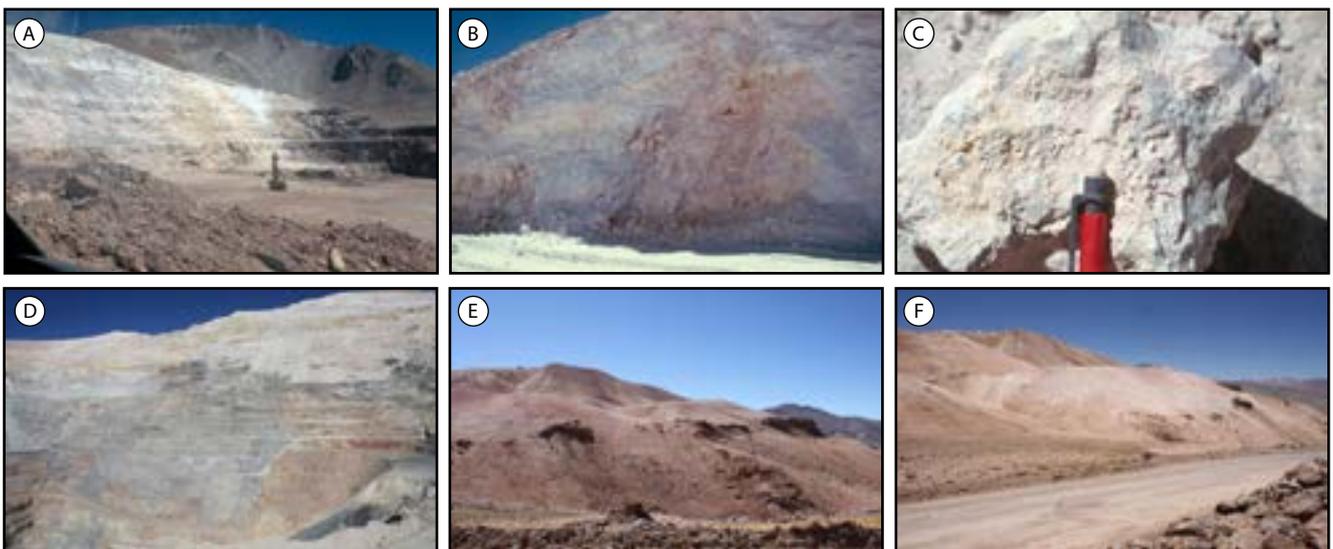
Barren advanced argillic steam heated alteration zones overlie many poorly eroded high sulphidation deposits (Pascua, Guanaco & La Coipa, Chile; Veladero, Argentina; Pierina, La Arena, Peru; Quimsacocha, Ecuador) where they may obscure blind mineralisation (Quimsacocha), or locally collapse upon ore (Coipa Norte, Chile; Veladero, Argentina; Guanaco; Chile). Mixing of ore fluids with these intensely oxidising waters may promote elevated Au deposition in association with hypogene oxidation to deposit covellite (Guanaco, Chile; Pierina, Peru; figure 8.16) or hypogene jarosite (Veladero, Argentina). There is a health caution as the distinctive powdery alunite may become windborne and turns acidic upon contact with moisture in the eyes.



**Figure 2.44** Model for the development of steam heated alteration in high sulphidation epithermal environments.



**Figure 2.45** Steam heated alteration in the Pascua-Lama-Veladero region.  
**A** - Pascua-Lama alteration blanket from the Pascua side (Chile).  
**B** - The same blanket from the Lama side (Argentina).  
**C** - Textural destruction in cristobalite-powdery alunite, kaolin rock, Veladero, Argentina.  
**D** - Basal silica ledge overprinted by collapsing steam heated powdery alunite-kaolin alteration, Lama, Argentina.  
**E** - Detail of brecciated basal silica with powdery alunite-kaolin in-fill Lama, Argentina.



**Figure 2.46** Steam heated alteration in the La Coipa region.  
**A** - At Coipa Norte pit in 1998 at the start of mining.  
**B** - Close up of steam heated alteration at the Coipa Norte pit face in 1998.  
**C** - Silica-cinnabar in the Coipa Norte pit in 1998.  
**D** - The steam heated blanket collapses upon mineralisation at the Coipa Norte pit in 2009.  
**E & F** - Steam heated alteration blankets showing basal silica ledges.

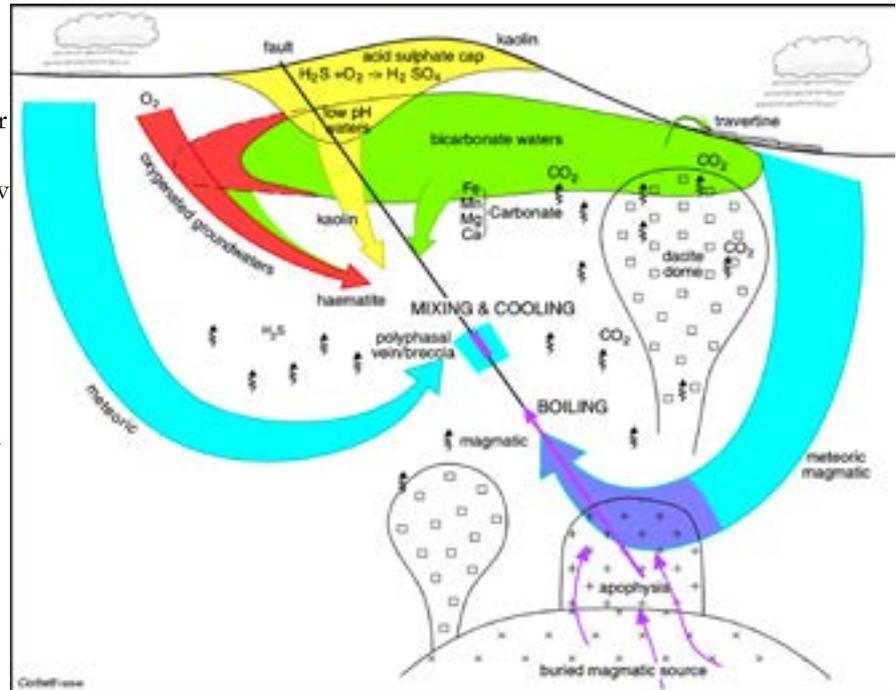
#### 2.2.4.6 Acid sulphate alteration,

typical of low sulphidation epithermal environments (section 1.2.2.1.1), characterised by kaolin, cristobalite with lesser alunite and local sulphur forms by the interaction with wall rocks of warm acidic ground waters typically developed above the water table by the oxidation of volatiles ( $H_2S$ ) in the vadose zone. Ledges of massive silica are common at the base defined by the palaeo water table (figures 2.47 & 9.\*\*\* ) as neutralisation of the low pH fluids by mixing with ground waters promotes silica deposition. Acid sulphate caps are herein categorised as near surficial blanket-like zones of acid sulphate advanced argillic

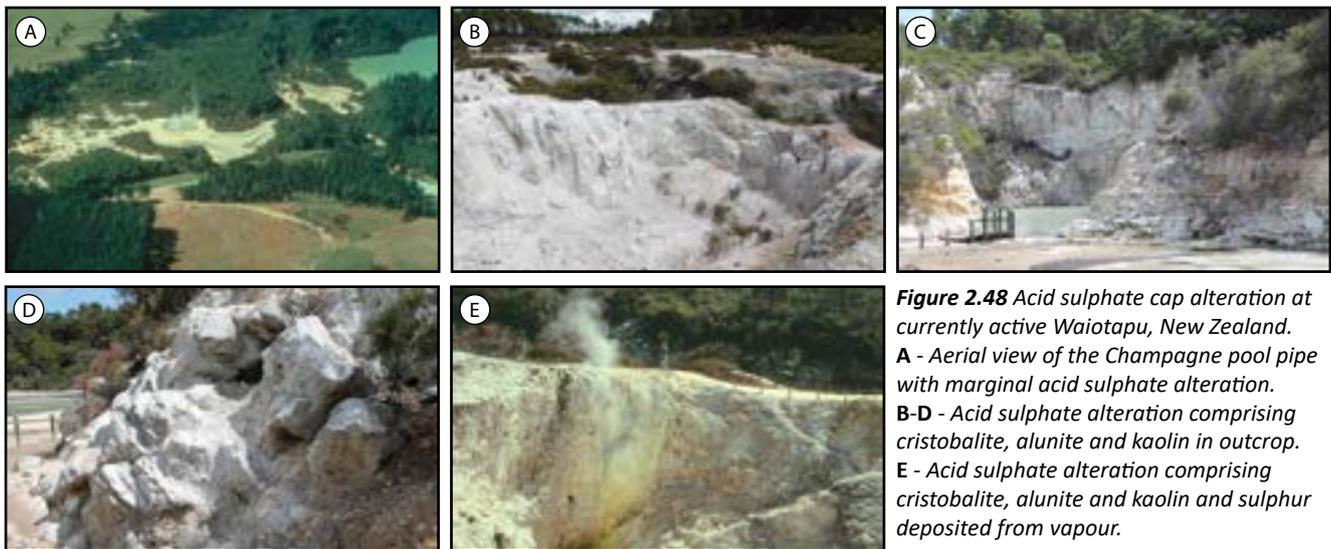
alteration (kaolin, cristobalite, lesser alunite and local native sulphur) which may cap flat-lying silica ledges and/or overlie low sulphidation epithermal Au mineralisation (section 9). Acid sulphate caps tend to be only preserved in youthful low rainfall settings (figure 2.47). In regions of elevated rainfall the softer clays are eroded and the exposed silica ledge which may break up into a boulder train (Broken Hills, New Zealand figure 9.\*\*). Acid sulphate caps pass downwards and laterally into argillic alteration characterised by illite, carbonate, chlorite and pyrite, (section 2.2.3.2 above), locally termed steam heated alteration by some workers, as collapsing acid waters

have become cooled and neutralised by rock reaction.

Acid sulphate caps may overlie feeder structures for low sulphidation epithermal mineralisation and the low pH waters responsible for alteration may collapse to quite deep levels within epithermal ore environments (figures 2.47-2.52), mixing with ore fluids to promote elevated Au deposition (Section 7.5.4.4; Leach and Corbett, 2008). Hypogene kaolin recognised to collapse up to 1 km below the paleo surface is typically deposited late in the paragenetic sequence with mineralised sulphides and so has been interpreted by some workers as post-mineral, but is here interpreted as commonly syn-mineral. The lack of supergene oxidation where kaolin is in contact with sulphides is indicative of hypogene rather than supergene kaolin. Dickite, the high temperature polymorph of kaolin, is locally developed, typically at depth, as the collapsing low pH fluids become heated (Sleeper, Nevada; figure 2.51) and elsewhere alunite, pyrophyllite or diaspore have also been recognised.



**Figure 2.47** Model for the development of near surficial acid sulphate caps, also showing the presence of oxygenated ground waters and bicarbonate waters, in the upper portions of low sulphidation epithermal environments (from Leach and Corbett, 2008).



**Figure 2.48** Acid sulphate cap alteration at currently active Waiotapu, New Zealand. **A** - Aerial view of the Champagne pool pipe with marginal acid sulphate alteration. **B-D** - Acid sulphate alteration comprising cristobalite, alunite and kaolin in outcrop. **E** - Acid sulphate alteration comprising cristobalite, alunite and kaolin and sulphur deposited from vapour.

Whereas traditional geological models suggest sulphur-rich volatiles are derived from boiling fluids, field studies by this author suggest cooling pyritic intrusions such as sub-volcanic domes and veins might also represent effective sources of sulphur. Dilatant structures (Arcata, Peru; figure 2.49) and phreatic breccia pipes (Champagne pool, New Zealand, figure 2.48) localise acid sulphate caps, although permeable host rocks might aid the lateral spread of the alteration

blanket (figure 2.50), often only discernible in the silicified portion, as the clay alteration is texturally destructive. Sulphur is locally mined and Hg might be present.



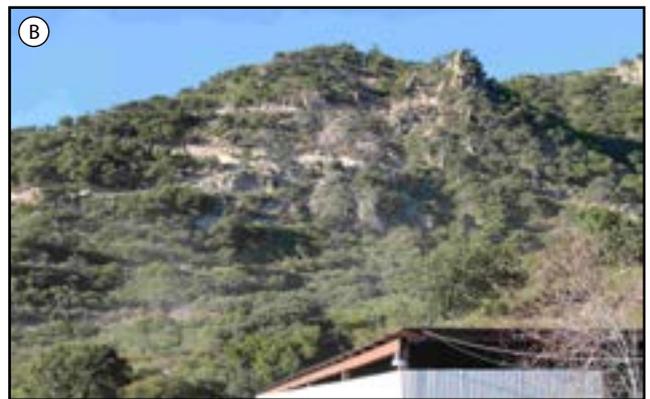
**Figure 2.49** Acid sulphate cap alteration.

**A** - Localised on the Veta Baja fault, Arcata, Peru

**B** - Arcata, Peru.

**C** - Alteration formed by acidic waters collapsing within permeable milled matrix breccia and with domes in the distance, San Cristobal, Bolivia.

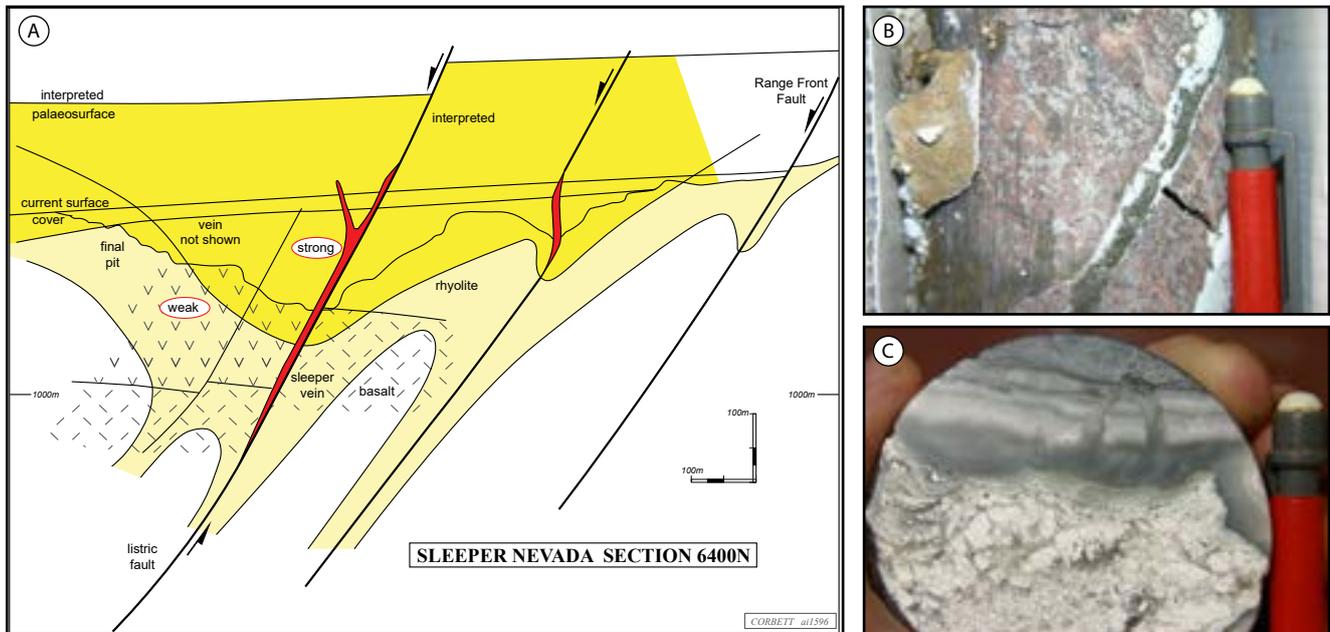
**D** - View of the acid sulphate alteration exposed by early mining with domes at the margin of the diatreme in the background, San Cristobal, Bolivia.



**Figure 2.50** Acid sulphate cap alteration.

**A & B** – Barren surficial relict alteration which passes down to high Au-Ag mineralisation with kaolin at Guadalupe, Palmarejo, Mexico.

**C & D** - Sierra Moreno, Argentine Patagonia, where spectral studies demonstrated kaolin veins cut an illite-kaolin wall rock alteration.



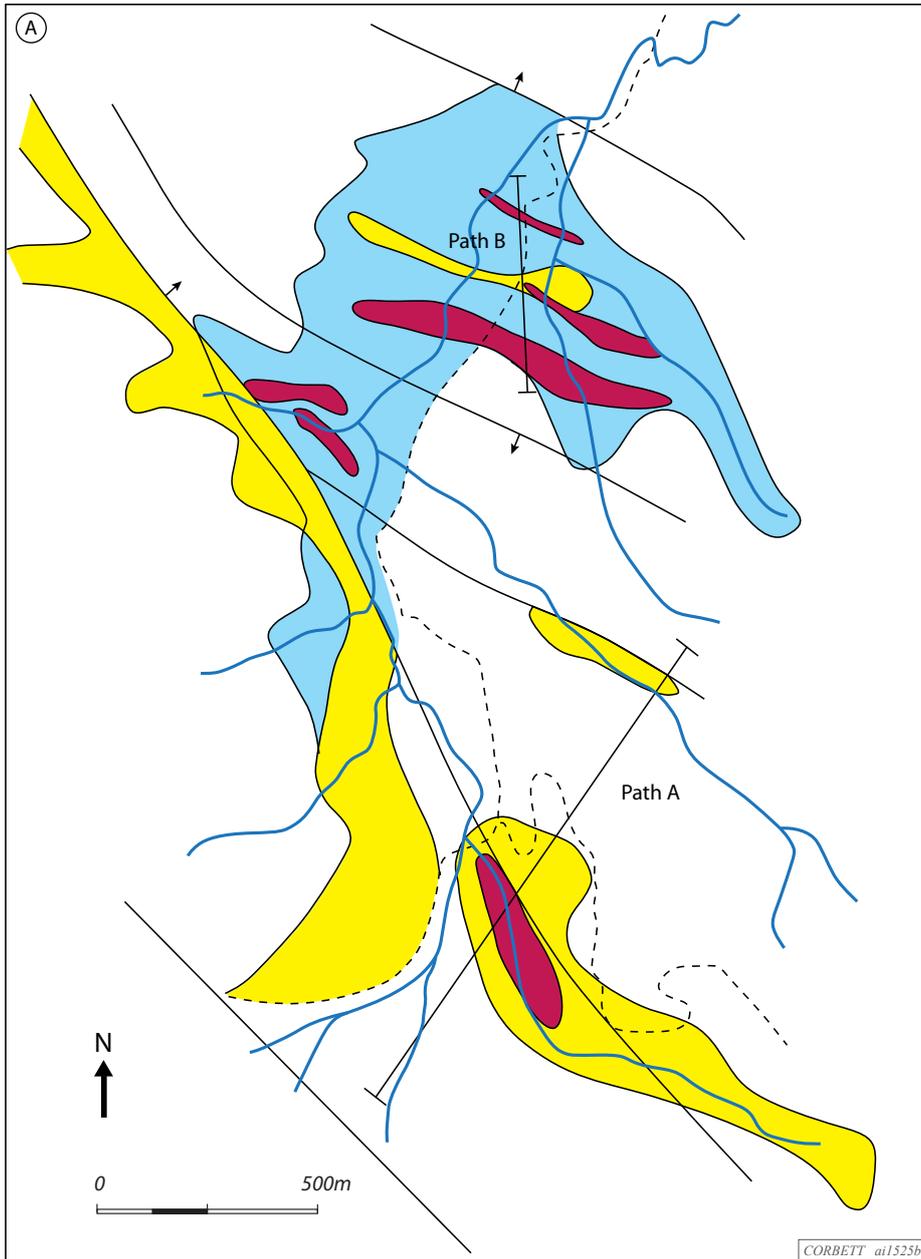
**Figure 2.51** Evidence of a now eroded acid sulphate cap and associated Au mineralisation at the Sleeper mine Nevada.  
**A** - Cross section of spectral data showing decreasing kaolin intensity with depth collapsing down structures.  
**B** - Kaolin in contact with fresh pyrite as a demonstration that it is of a hypogene rather than supergene origin.  
**C & D** - Quartz with Au in contact with kaolin.

#### 2.2.4.6.1 At the Hatchobaru geothermal field,

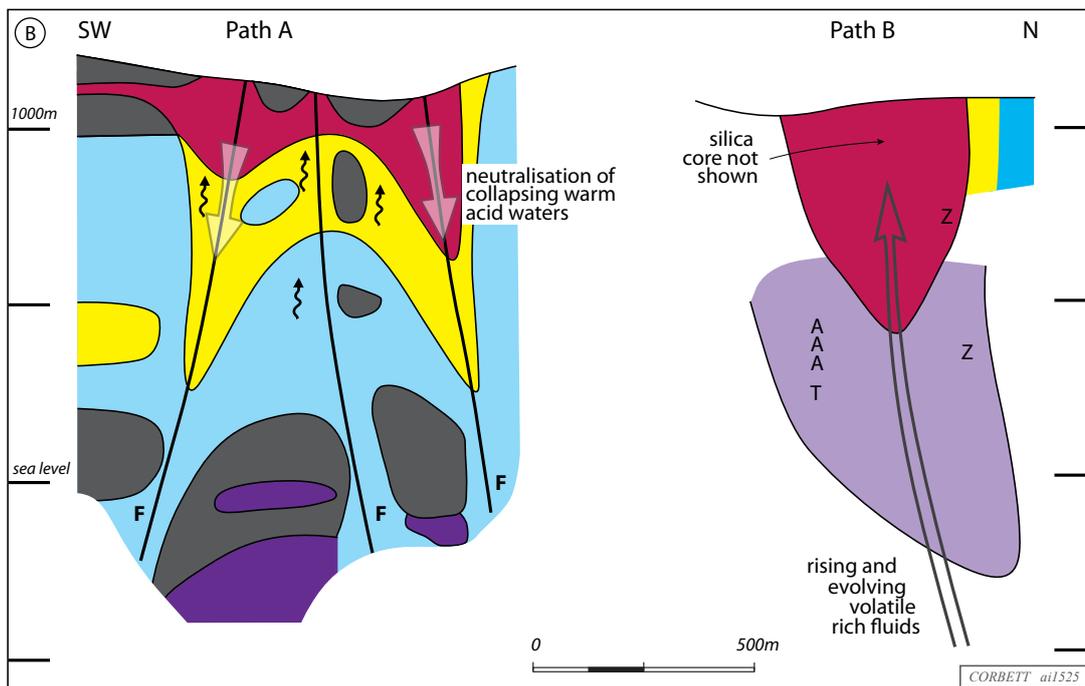
Kyushu, Japan, geothermal drilling has allowed the delineation of two styles of advanced argillic alteration (Taguchi et al., 2006; Taguchi et al., 2003; Kiyosaki et al., 2003; Takuchi and Hayashi, 1984). An acid sulphate cap crops out in the south where initial exploitation from 1967 was the first water only geothermal power produced in Japan, while a barren shoulder can be discerned from the drill data pertaining to a 1990 power plant which was the largest geothermal power producer in Japan (figure 2.52). A youthful geothermal system in the southern part area hosts early prograde zeolite-feldspar alteration as an indication of a magmatic source for H<sub>2</sub>S volatiles which are interpreted to have oxidised to provide the warm acidic waters for the formation of the later collapsing acid sulphate cap. Reaction of the acidic waters collapsing down faults with wall rocks has produced a shallow alunite zone which passes to marginal kaolin and smectite. The intensity of alteration declines (fluid flow path A in figure 2.52) due to the progressive cooling and neutralisation of the warm acidic fluids by wall rock reaction. By contrast the 1990 exploration program identified surface alunite which passes down to pyrophyllite with local, andalusite, zunyite and topaz in the northern area. Clearly this alunite is typical of hot acid conditions, which decline laterally due to rock

reaction to deposit pyrophyllite, while the included andalusite and topaz form in high temperature conditions. The volatile-rich topaz is typical of barren shoulders. Taguchi et al. (2003) suggest these acid waters were derived from the disproportionation of SO<sub>2</sub> at depth and so the alteration here results from the reaction with wall rocks of a hot extremely acidic fluid (fluid flow path B in figure 2.52). The progressive evolution of the rapidly rising fluid to become more acidic is apparent from the alteration zonation of alunite grading down to pyrophyllite (fluid flow path B in figure 2.52). Furthermore, these workers (op cit) and Kiyosaki et al., (2003) suggest the light δ<sup>34</sup>S isotopes in the southern area are typical of meteoric hot springs, whereas the heavy δ<sup>34</sup>S in the north are typical of a magmatic source, as might be expected from the application of the models in use here to the field data.

Consequently, similar alteration minerals may be associated with different styles of advanced argillic alteration with highly variable relationships to mineralisation. Analysis of the geological setting allows the distinction between advanced argillic alteration derived from different hydrothermal processes.



**Figure 2.52** Cartoon illustrating alteration mineral assemblages at the Hatchobaru geothermal district, Japan.  
**A** - Plan view showing the location of the two sections.  
**B** - Two sections at the same scale, one showing collapsing acid sulphate waters (left) and the other, rising progressively acidified magmatic volatiles (right).  
**C** - Legend.  
 Data compiled from Taguchi et al., 2006; Taguchi et al., 2003; Kiyosaki et al., 2003; Taguchi and Hayashi, 1984.





**Figure 2.53** Magmatic solfataras, White Island, New Zealand.  
**A** - View of the eroded stratovolcano.  
**B-D** - Sulphur deposited from vapour.

#### 2.2.4.7 Magmatic solfataras

Magmatic solfataras form as magmatic gases deposit native sulphur at the surface with variable adjacent advanced argillic – argillic alteration. Some, such as Kava Iazhen and Kawah Ijen in Indonesia, are currently mined for sulphur, while others in the Philippines (Mitchell and Leach, 1991), White Island, New Zealand (figure 2.53) and throughout the Andes have been important historical sources of sulphur. Some zones in the Andes may be associated with substantial colour anomalies, and like White Island occur within stratovolcanoes.

#### 2.2.4.8 Supergene weathering

Supergene weathering of sulphides provides acidic ground waters which react with wall rocks to deposit supergene kaolin, local alunite (figure 2.54) and a host of secondary minerals (Chavez, 2000). Kaolin grades to smectite clays as wall rock reaction neutralises the acid fluids. Iron and other oxides with boxwork textures are indicative of original sulphide minerals (Blanchard, 1968).

### 2.3 Conclusion and exploration implications

**In conclusion**, variable styles of wall rock

hydrothermal alteration, with well documented zonation in time and space, characterise different epithermal-porphyry mineralisation sub-types (table 2.1). Consequently, an understanding of these alteration zonation patterns may facilitate the development of 3 dimensional models for mineral exploration projects and aid in the discovery of blind mineralisation. The application of time to the staged model for porphyry mineralisation allows an understanding of overprinting alteration relationships.

Explorationists should build a skill set that will enable them to identify the important mineral assemblages in the field using tools such as a hand lens and scratcher. Spectral devices might define larger scale alteration pattern data bases, which need to be placed in a geological context by field examination.

Some **exploration implications** apparent from an understanding of hydrothermal alteration in epithermal and porphyry deposits include:

- Porphyry systems display patterns of zoned prograde alteration grading inwards from wall rock propylitic to magnetic potassic altered intrusions which might be used to target hidden intrusions.

- Retrograde alteration of porphyry deposits is characterised by magnetite destruction and increased chargeability (associated with pyrite introduction) discernible on geophysical data which represent exploration tools if correctly interpreted.
- In low sulphidation epithermal Au-Ag deposits, the zonation towards higher temperature illite clay (argillic) alteration might identify hidden vein zones.
- Low sulphidation epithermal Au vein systems may be capped by acid sulphate alteration and collapsing acid sulphate waters are associated with bonanza Au deposition (section 7.4).
- In high sulphidation epithermal Au deposits, zonation patterns in advanced argillic – argillic

Type	Setting	Distinguishing features
Barren shoulders	Magmatic arc overlying margins to buried intrusion source	Wall rock alteration vertically and laterally zoned from feeder Structural and lithological control Massive not vughy silica Volatile-rich – topaz & zunyite Local high temperature andalusite Strongly pyritic
Collapsing AAA	Where phyllic alteration results from very low pH fluids	Characterised by alunite-sericite-silica-pyrite within phyllic alteration Ovoid textures of silica-alunite with enargite
AAA with high sulphidation epithermal	Magmatic arc removed from intrusion source	Zoned outwards from core of vughy or residual silica Structural, lithological and breccia control Mineralisation commonly as a later overprint
Steam heated	Blankets overlying high sulphidation epithermal Au	Fine grained with destruction of original rock texture Comprise cristobalite, powdery alunite, kaolinite, sulphur and local cinnabar Basal silica
Acid sulphate caps	Overlie low sulphidation epithermal Au-Ag	Funnel shaped rising around feeders and locally collapsing to deeper levels Fine grained cristobalite, kaolin lesser alunite and local sulphur. Kaolin veins.
Magmatic solfatara	Commonly close to volcanic vents in magmatic arcs	Abundant sulphur with variable kaolin-alunite alteration
Weathering	Commonly weathering of pyritic alteration	Abundant FeO commonly with boxworks after pyrite and with quartz veins. Liesegang rings from pyrite & water access and variable FeO deposition.

**Table 2.1** Summary of characteristics of different types of advanced argillic alteration.

alteration may vector towards mineralisation within the silica cores.

- The several types of advanced argillic alteration, which are often grouped together in the lithocap terminology, display variable relationships to mineralisation and should be categorised separately in order to facilitate effective exploration as discussed herein. Importantly, magmatic hydrothermal fluids evolve to take on an acidic character during the rise from porphyry environments and so advanced argillic alteration

is not expected to immediately overlie the source intrusion. Syn-mineral uplift and erosion may locally telescope the distance between them and cause alteration to cap intrusive stocks derived from the same magmatic source at depth. Elsewhere, epithermal mineralisation and advanced argillic alteration commonly cap older porphyry deposits.

