4 BRECCIAS

Breccias are broken rocks studied for their variable relationship to mineralisation, including as vectors to ore, although there are a myriad of breccia forms and modes of breccia development. Explorationists must therefore be able to distinguish different breccias and apply names to them as a means to access the exploration significance of many breccias, which occur throughout the geological record occupied by epithermal and porphyry deposits. While pre-existing volcanic breccias (McPhee et al., 1993) and to a lesser extent clastic sedimentary rocks (Petijohn, 1975) may host later mineralisation, breccias dealt with in epithermal-porphyry exploration are derived from an interaction of hydrothermal-structural-magmatic–volcanic processes (Davies et al., 2000) as well as local carbonate dissolution. The challenge for explorationists is to provide an efficient breccia nomenclature which will enable us map breccias and to communicate field studies to our peers, some of whom will have different ideas on breccias. While Roger Taylor (2009) points out the difficulty of breccia nomenclature, noting the 832 page effort by Laznicka (1988), explorationists might benefit from earlier discussions of ore-related breccias by Sillitoe, (1985), Baker et al., (1986), Taylor and Pollard (1993), Corbett and Leach, (1998), Davies et al., (2000) and Taylor (2009), which this discussion draws on.

Consequently, from the author's field experience and reference to published studies three means of breccia nomenclature might be considered:

- Descriptive breccia terminology based upon the appearance of the breccia using characteristics set out by McPhee et al. (1993) for volcanic breccias and applied by Davies et al. (2000) to porphyry and epithermal deposits.
- Colloquial breccia terminology as terms developed through common use (Corbett, short courses; Taylor, 2009).
- Genetic breccia terminology based upon the means of formation (Sillitoe, 1985; Corbett and Leach, 1998; Pollard and Taylor, 1993).

4.1 PROCESS OF BRECCIA ANALYSIS

When confronted by breccia in outcrop or drill core, a step-like process might take the explorationist (Corbett, short courses) through a naming process to identify the exploration significance of that breccia as (although other processes are available Davies et al;. 2000; Taylor, 2009):

- Describe the breccia at the first exposure providing a field name.
- Move to other exposures and refine or change that description for each breccia type as other breccias might emerge, and consider any overprinting relationships.
- Is that breccia type similar to any known breccias studied previously?
- Does that comparison place the breccia in a genetic setting?
- What is the exploration significance of that genetic setting? That is, what influence does this breccia place upon the evolving exploration model?
- Move on and test, refine or reject the breccia name and any influence upon the exploration model used as an exploration tool.

Some suggestions include:

- A field record using digital photography allows rapid comparisons.
- If a diamond saw is available, cutting breccias into slabs will aid in identification of features such as the softer matrix minerals, not exposed on weathered surfaces.
- Keep moving and do not get bogged down on one difficult breccia exposure as the solution may lie in the next exposure, or in the analysis of a group of exposures.
- Try to stand back in order to see the big picture.
- Consider the purpose of the exercise and level of detail required in conjunction with deadlines. In a 1981 at the Kidston breccia pipe, Australia, during the summary log of many thousands of metres of drill core, combined with geological mapping, this author deliberately maintained an approach of 'rapid identification' in drill core rather than time consuming and locally confusing detailed analysis, in order to provide a three dimensional model of the pipe in the required time frame (section 4.4.4.4.1).

This process of breccia analysis roughly mirrors the styles of breccia nomenclature above. The initial 'descriptive terminology' provides an accurate and complete analysis of any breccia from its appearance, but as is apparent from Davies et al. (2000), these descriptions may become long and cumbersome, in an environment where explorationists may have time pressures to reach a conclusion on the exploration implications of the breccia, provided by the more genetic interpretations. However, it is important to preserve the original description rather than use an 'interpretative terminology' too early in the field, so that as new data comes to hand the interpretation may change but it is always possible to refer back to a complete set of factual data. For instance the individual rock description 'milled matric breccia' is far superior to 'diatreme breccia', as many different breccia types make up a diatreme flow-dome complex and some of these also occur in other settings. Thus, noting the limitations of the emerging field data base during mapping, the explorationist should start to think where any breccia fits in a conceptual exploration model while still mapping. One could ask the question "where have I seen this type of breccia before" in order to understand what it means. Many geologists who have gone before us provided names for breccias and therefore allow us to communicate with our peers, and so there is a set of 'colloquial terminology'. Obviously some terms need to be discarded, but the ones in common use would not have survived for more than 50 years if they did not work. If, and only if, a breccia type is established, then comparisons may indicate how this breccia could vector to mineralisation. At this stage genetic breccia models come into use. Thus, breccia analysis is a step-by-step procedure, and the process described below seeks to identify 'stand outs' which rapidly lead to the conclusion – 'the exploration significance of a breccia'. Lastly, explorationists should keep in mind that the often time consuming breccia analysis is merely a step leading to the main game, which is ore discovery, and so breccia analysis should not become the primary task.

4.2 DESCRIPTIVE TERMINOLOGY

Descriptive breccia terminology seeks to provide a name that describes the appearance of an individual breccia that can be used for comparison with other breccias and there are many aspects to the appearance of a breccia (locally as a step-like process [Davies et al., 2000]) provided in an analysis of descriptive features including:

- Components
- Clast description
- Matrix description
- Internal structure
- External form
- Stand outs

4.2.1 The three components

of breccias which interact to provide complex forms include:

- Clasts (also termed fragments) of broken rock are dominated by wall rock and intrusion, including local clasts of rebrecciated breccia or matrix. Therefore a breccia name might acknowledge the major component type with either a monomictic or polymictic character.
- Matrix varies from: broken or milled rock clasts, commonly comminuted to form rock flour and which is commonly altered, to hydrothermal cement comprising entirely hydrothermal minerals introduced into the breccia and deposited within open space.
- Local open space occurs within vein breccias particularly within extensional (dilational) settings and collapse dissolution breccias. Open space might be included in the breccia matrix component.

A <u>stand out</u> here might be clasts which are mineralised or display alteration which might vector towards larger bodies of mineralisation. For instance, rucked up mineralised or altered clasts within breccias could prompt exploration at depth such as the Mo mineralised clasts within the rubble breccias recognised above mineralisation at the Climax mine, USA (White et al., 1981; Sharp, 1978), and quartz clasts high up in the fault which hosts mineralistion at Vera Nancy, Australia. Juvenile intrusion clasts derived from the magmatic source for brecciation are a characteristic feature of phreatomagmatic breccia pipes associated with diatreme-flow dome complexes.

4.2.2 Some aspects of clast description

(although there could be many more) include:

- Size measured in mm typically records the maximum clast size commonly focusing upon the largest clasts and may take into account the size distribution, especially if there is a variation in clast size with different clast types, as variable hardness influences degree of comminution (milling).
- Shape may refer to the degree of clast rounding by milling during clast transport, from the angular character of the original broken rock, to rounded extensively milled clasts, and is therefore influenced by the rock hardness. Some breccias feature variable working of wall rock versus intrusion clasts where there is a different degree of transport as well as variable hardness. Shingle breccias formed by collapse feature angular elongate tabular (roofing shingle- or tile-like) clasts while exfoliation breccias display a shape like an onion with exfoliated curvilinear clasts surrounding a rounded core.

A <u>stand out</u> is apparent as one of the features which helped to establish Namie Breccias at Wau, Papua New Guinea, as of a phreatomagmatic origin related to rapidly emplaced Edie Porphyry intrusions. Breccias comprise ragged clasts of juvenile Edie Porphyry intrusion, which were molten at the time of breccia formation, amongst more angular locally derived clasts of wall rock Kaindi Schist. A diatreme breccia pipe at Wau (Sillitoe et al., 1984) is one of several such bodies (figure 4.28) and phreatomagmatic Namie-like breccias within these pipes and display variable mixes of Edie Porphyry and Kaindi clasts. However, mixed porphyry and schist clasts also form contact breccias adjacent to adjacent Edie Porphyry domes.

4.2.3 The matrix,

defined as the finer grained medium which supports breccia clasts, varies from:

- Milled rock flour formed by comminution of rock clasts, such as in many phreatomagmatic breccias, which may be clay or silica altered.
- Introduced silica flooding and fine grained angular clasts found in some eruption breccias.
- Hydrothermal minerals kinematically deposited to fill open space characterised by coarse grained centrally terminating crystals or finer grained hydrothermal minerals deposited from cooling fluids which participated in rock fracture such as in magmatic hydrothermal injection, crackle, fluidised and mosaic breccias.

4.2.4 Breccia organisation

describes the relationship between clasts and matrix as breccias may be massive with no obvious structure, or bedded in the case of breccias in the upper portions of phreatomagmatic breccia pipes. Tabular or elongate clasts may display an imbricate form noted in shingle breccias which may be vertical or horizontal depending upon the setting in the breccia pipe geometry.

4.2.5 External form

represents the overall shape of a breccia body as many occur as dykes or pipes and the relationship with wall rocks, both of which may not always be apparent early in the investigation of a breccia body. Some linear fault controlled breccias are recognised as fluidised breccias or pebble dykes (which is a colloquial term), whereas many deeper crustal level pipes display ovoid forms ranging up to several kilometres in size (magmatic hydrothermal breccia, tourmaline breccia or many phreatomagmatic pipes). Fault-controlled or pipe-like breccias should cross-cut wall rocks and breccia descriptions should consider any overprinting relationships.

4.2.6 In conclusion,

descriptive breccia terminology is important to record the overall appearance of a breccia which can then be compared to others and several breccias grouped in a geological model. The breccia description and comparisons between breccias could be aided, but not replaced, by a set of quality digital photographs. However, this breccia nomenclature is hampered as descriptions might become rather long and cumbersome, and similar breccias may be formed by different processes in variable settings.

4.3 COLLOQUIAL TERMINOLOGY

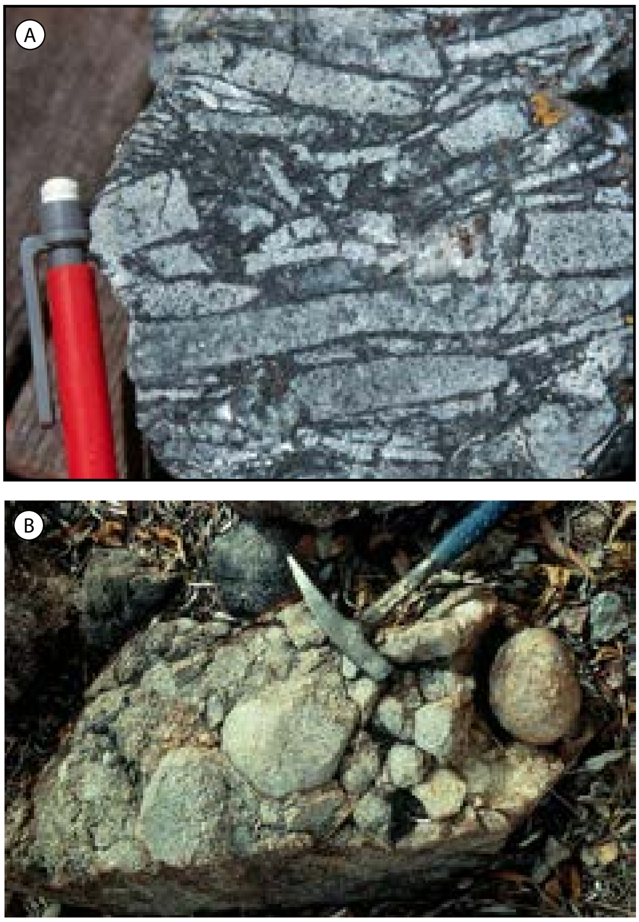
Colloquial breccia names are those that are in common use by geologists but may not be as ridged as descriptive breccia terms and certainly are not as long. These terms have evolved over many years as explorationists sought to describe breccias while working rapidly in the field and noted similar breccias in related ore deposits such as pebble dykes in porphyry deposits. Colloquial breccia terms have therefore developed over many years and would not have survived it they did not work.

Some colloquial terms listed here are described in detail below:

- Shingle breccias (Spanish ripia) are described below as breccias typically formed by collapse or pressure release and are common within tourmaline breccia pipes (figure 4.1), as characterised by tabular clasts similar to roofing shingles or tiles.
- Crackle breccias form as cracks either random or sheeted which become filled with hydrothermal minerals (figures 4.1 & 4.57) and mineralisation as a common hydrothermal breccia setting.
- Mosaic or jigsaw breccias (Spanish mosaico) are characterised as formed by a simple moving apart of the clasts with matrix fill (like a mosaic) and so if the matrix were to be removed the clasts would fit back together (like a jigsaw) (figures 4.2 & 4.57). These breccias fit within the tectonic-hydrothermal genetic terminology (section 4.4.7) below as formed in dilatant or extensional settings.
- Fluidised breccias feature substantial transport and introduction of hydrothermal fluid (with rock flour) and only minimal transport of clasts which comprise local wall rock and typically display only minor milling (figures 4.1 & 4.57).
- Pebble dykes were defined (Gustafson and Hunt, 1975) as dominated by milled transported clasts with little matrix (figure 4.1), although Baldwin et al. (1978) also cite significant matrix component, at Panguna, Papua New Guinea. They typically occur in deeper crustal level porphyry environments and locally act as vectors to buried porphyry mineralisation, especially if mineralised clasts are present (below; Section 4.4.4.4). Pebble dykes may be derived from the deeper level magmatic source for a porphyry and not neccessarily the porphyry, which might be developed as an apophysis.
- Floating clast breccias (figure 4.2), commonly recognised within fault-hosted veins, comprise

(often milled) rock or vein clasts suspended in (often banded polyphasal) matrix such that the clasts are supported entirely by the matrix. The upward fluid pressure within the fault must have been sufficient to have supported the clasts while the matrix was emplaced around them and in some cases these breccias have been rebrecciated.

- Crumple breccias form on the margins of domes, especially endogenous domes which vent to the surface and comprise mostly angular monomictic dome clasts with only minor rock flour matrix (figures 4.6 & 4.7) and are therefore described below as intrusion breccias.
- Hydrothermal breccia is an all-encompassing non-specific term for breccias associated with hydrothermal processes and so should be used with caution.
- Milled matrix breccia is the preferred term for phreatomagmatic breccias recognised within diatreme breccia pipes and dominated by (often hydrothermally altered) rock flour matrix and rounded (by comminution) rock clasts (figure 4.2) which have been milled during transport.



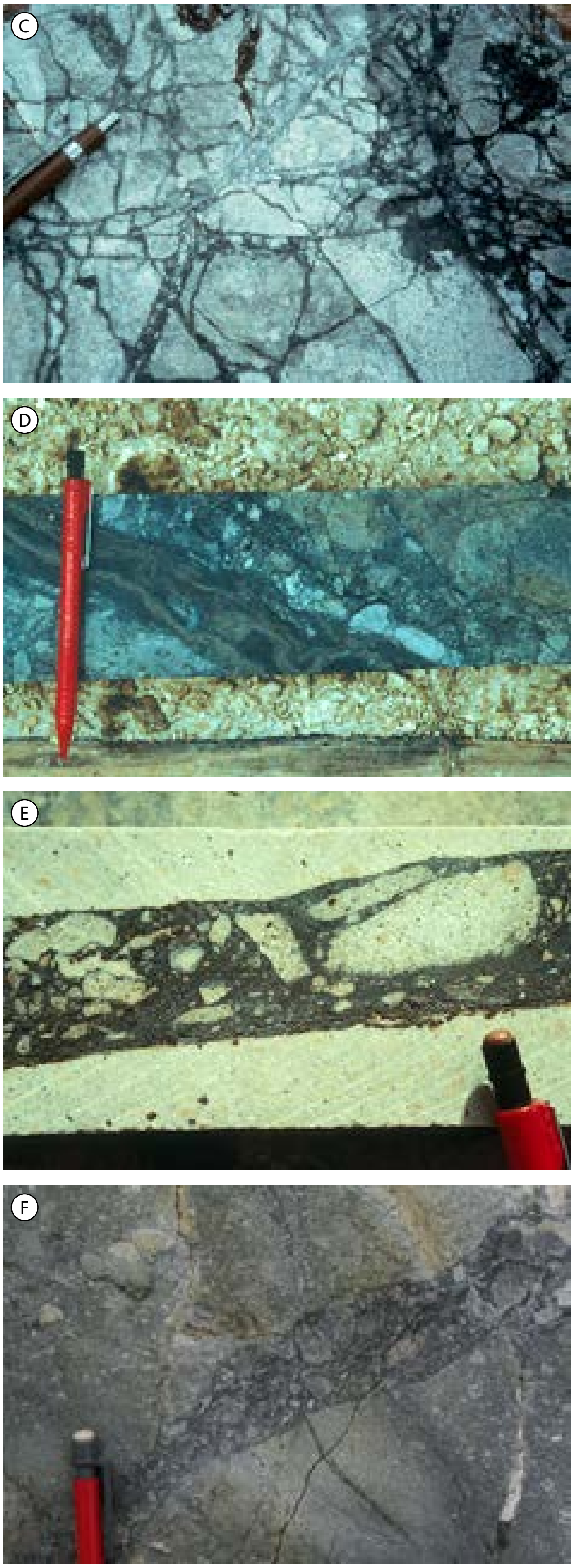


***Figure 4.1** Some colloquial breccia terms in common use in the exploration industry.*
A - *Shingle breccia with tourmaline matrix, Juarez, Peru.*
B - *Pebble dyke from Mt Turner, NE Australia.*
C - *Crackle breccia, Ladolam, Lihir Is., Papua New Guinea.*
D - *Fluidised breccia (matrix rich), Ladolam, Lihir Is., Papua New Guinea.*
E - *Fluidised breccia dyke (clast-rich), Kelian, Indonesia;*
F - *Fluidised breccia dyke with angular local clasts, Ladolam, Lihir Is., Papua New Guinea.*

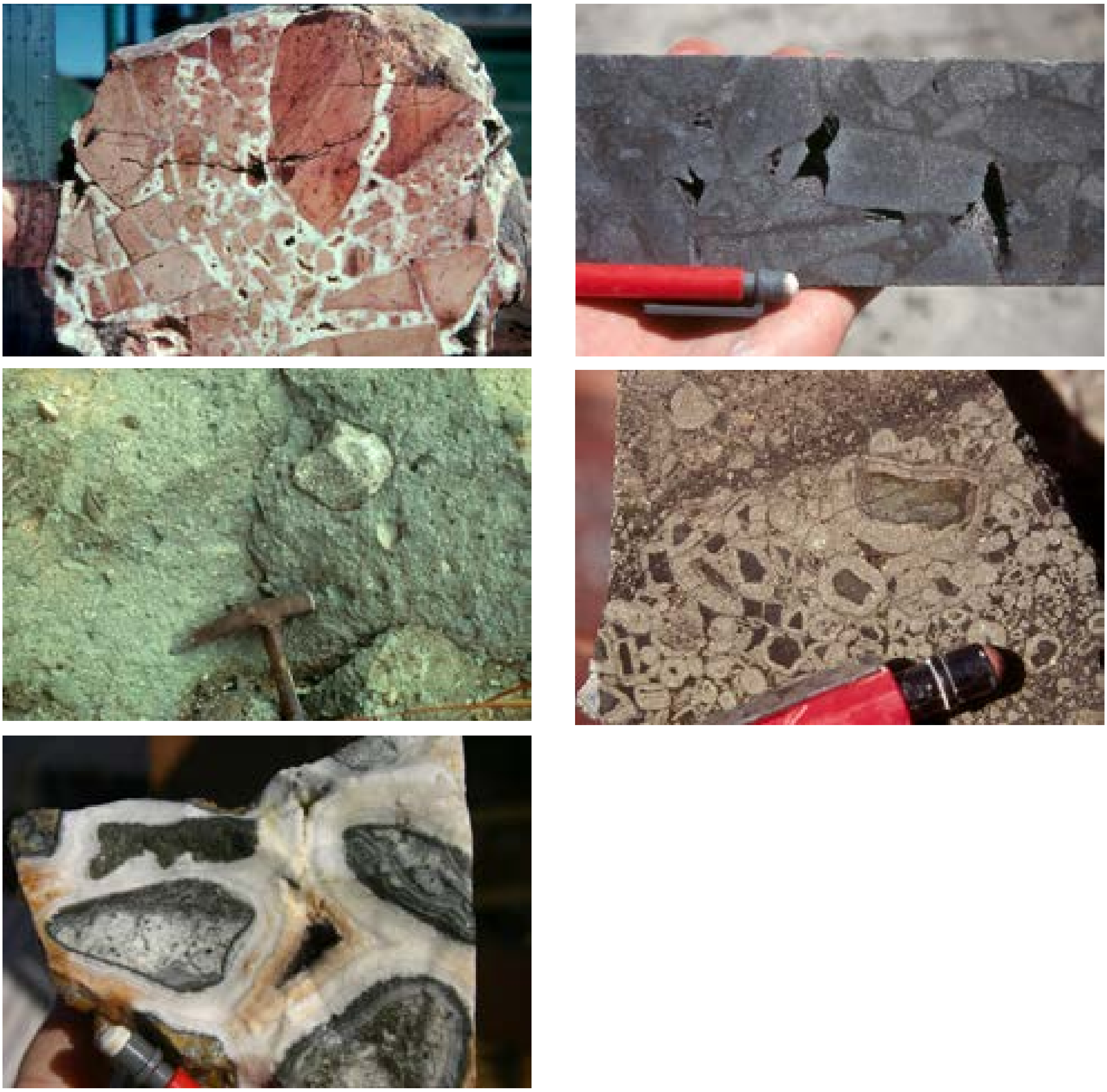


Figure 4.2 *Some colloquial breccia terms used by this author.*
A - *Mosaic breccia from the Kidston region, Australia.*
B - *Mosaic breccia, Ladolam, Lihir Is., Papua New Guinea.*
C - *Milled matrix breccia from the Acupan diatreme breccia pipe, Philippines.*
D - *Floating clast breccias with accretionary banding from the Roamane fault and Porgera Zone VII, Papua New Guinea.*
E - *Floating clast breccia with banded quartz matrix and rebrecciated breccia clasts, Cirotan, Indonesia.*

- Stope fill breccias have the appearance of sedimentary structures formed by the deposition of fill in mine workings, here by the deposition of debris within open faults (figure 4.3).
- Stockwork veins (figure 3.49 A & B) are regarded by some workers as breccias but are better considered as veins.

Figure 4.3 *Breccias formed as subsurface sedimentary structures.*
A - *Fill within open fractures, Chatree, Thailand.*
B - *Banded vein which varies from a fluidised breccia on the top left side to central bedded forms normal to banding and hence approximately sub-horizontal, Favona, New Zealand DDH UW140, 198.6m 3.25 g/t Au & 8.3 g/t Ag.*
C & D - *Open space sedimentary fill within veins, Cinola, Queen Charlotte Islands, Canada.*
E - *Layered open space fill, Mungana, Australia.*
F - *Bedded breccia overprints vughy silica clast as the transition to lower sulphidation (section 8.5.3), La Zanja, Peru.*

One stand out in the breccia types is the exploration significance of any reinterpretation of the formerly mined 0.85 M oz Au 0.387M t Cu Mt Morgan deposit Queensland, Australia. Although Mt Morgan has previously been attributed a syngeneic volcanogenic origin (Taupe, 1990, and references therein), cross-cutting pebble dykes and the crackle breccia described from early mining (Cornelius, 1967 & 1969) support an epigenetic ore introduction also discussed by other workers (section 7.2.1.1.5). Other stand outs include the geopetal aspect of stope fill breccias as sedimentary structures (figure 4.3).

In conclusion, colloquial terminology provides a rapid means of comparing different breccias in the field with a historical perspective related to similar breccias categorised by many previous explorationists.

4.4 GENETIC TERMINOLOGY

Genetic terminology, developed from the descriptive terminology (Corbett and Leach, 1998) and including colloquial terms, focuses upon the process of breccia formation, using models derived from the study of many ore systems, to determine the exploration implications of any breccia. The preservation of quality descriptive data bases allows genetic models to be updated as additional data influences earlier reconnaissance exploration findings. Care must be exercised in the use of interpretative terminology only after a breccia description has been established. A number of different ore-related breccia types can be categorised using genetic models as breccias dominated by:

- Hydrothermal-magmatic processes grading from deeper crustal level with pronounced magmatic component to shallower levels with less magmatic and greater meteoric fluid components.
- Tectonic-hydrothermal processes.
- Dissolution of carbonate.

Note much of the Au-Cu-Ag mineralisation is emplaced at the end of the brecciation process derived from the magma source at depth and so breccias with good structural connections to the metal source are generally better mineralised.

4.4.1 Hydrothermal-magmatic breccias

The dominant breccias in epithermal-porphyry ore systems are derived by an interaction of hydrothermal and magmatic components, the latter varying from porphyry intrusions at depth to high crustal level domes and dykes which contribute heat, volatiles and metals to the breccia process. The breccia classification employed here is therefore (figure 4.4) based upon a progression from deep crustal level magma-dominated breccias with magmatic fluids and little meteoric water component, to shallow level meteoric-water dominated breccias with little obvious input from magma source rocks. Naturally, some breccias are difficult to categorise within this scheme and tectonic and dissolution breccias could also be considered on the periphery of this classification. Although tectonic/structural processes may trigger breccia formation (eruption etc) these aspects may not be readily discernible in the breccia. Therefore, breccias are discussed essentially in order from deep to shallow crustal levels as there is a progressive decline in the magmatic and increase in the meteoric contributions to the breccia as: contact → intrusion → magmatic hydrothermal (containing intrusion and collapse) → phreatomagmatic → phreatic breccias.

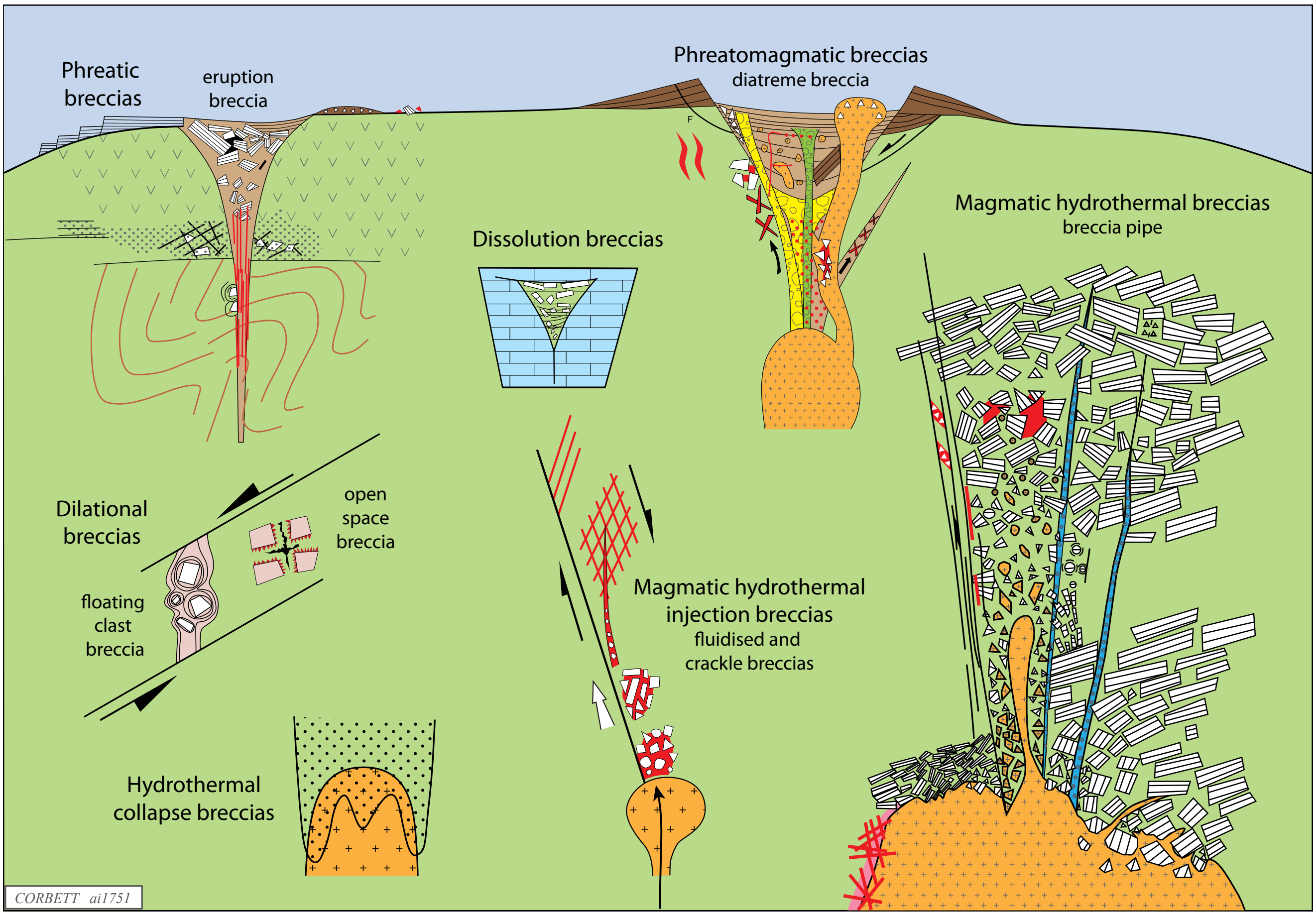


***Figure 4.4** Summary of genetic breccia classification.*

4.4.2 Contact breccias

Contact breccias develop at deeper crustal levels at the contact between an intrusion and wall rocks including other porphyry intrusions, and include crumple breccias formed at the margins of high crustal level domes, which may vent to the surface as endogenous domes. Contact breccias are dominated by intrusion clasts and distinguished as an end member in a sequence which continues to intrusion breccias in a more distal setting to the intrusion with more wall rock clasts. Contact breccias formed at a coherent intrusion margin are characterised by locally derived monomictic angular clasts which are clast supported with minor locally derived matrix (figures 4.5 A, 4.6, 4.7, 4.8, 4.9), and appear as relatively competent rocks. Some contact breccias feature clast support of mostly fine grained chilled matrix and less angular clasts that might have undergone some transport during intrusion emplacement (figures 4.5 B & C, 4.8 B & D), and are expected to occur further from a coherent intrusion, locally transitional to intrusion breccias if wall rock clasts are well developed. Nevertheless clasts are likely to be derived from the intrusion rather than the wall rocks which would mark a change to an intrusion breccia.

Crumple breccias generally include the clast supported contact breccias formed at dome margins and commonly provide open space for the deposition of mineralised magmatic fluids, especially where the domes are linked to larger magmatic sources. Low sulphidation quartz-sulphide Au mineralisation is common in brecciated dome margins where the Au grade is generally proportional to the sulphide content. The flow banded brecciated dome margins at Las Calandrias, Argentina host Au mineralisation within pyrite-marcasite which increases in Au grade from crackle to fluidised breccias near the dome margins (figure 4.7). Similar relationships are recognised elsewhere where contact breccias at Bulawan and Mt Wright have been mined, although Lone Sister at Twin Hills remains too low grade at < 1 g/t Au (figure 4.8 A, C & E). The Bulawan (figure 4.8 A) and Mt Wright (figure 4.8 F) breccias feature abundant sulphide within substantial open space and the transition from quartz-sulphide to carbonate-base metal style Au mineralisation and so displayed higher Au grades.

In high sulphidation epithermal systems brecciated dome margins provide important fluid permeability for the transit of hydrothermal fluids responsible for the development of alteration and mineralisation such as at Yanacocha, Peru or Mt Kasi, Fiji (figure 4.9), although best Au grades commonly occur at the intersection of contact breccias and feeder structures.

Figure 4.5 *Contact breccias.*
A - *At the margin of a deep level porphyry characterised by packed angular clasts with negligible transport, northern Peru.*
B - *Contact breccia between two intrusions, Copper Hill. Australia.*
C - *Contact breccia between two intrusions, Wonogiri, Indonesia.*

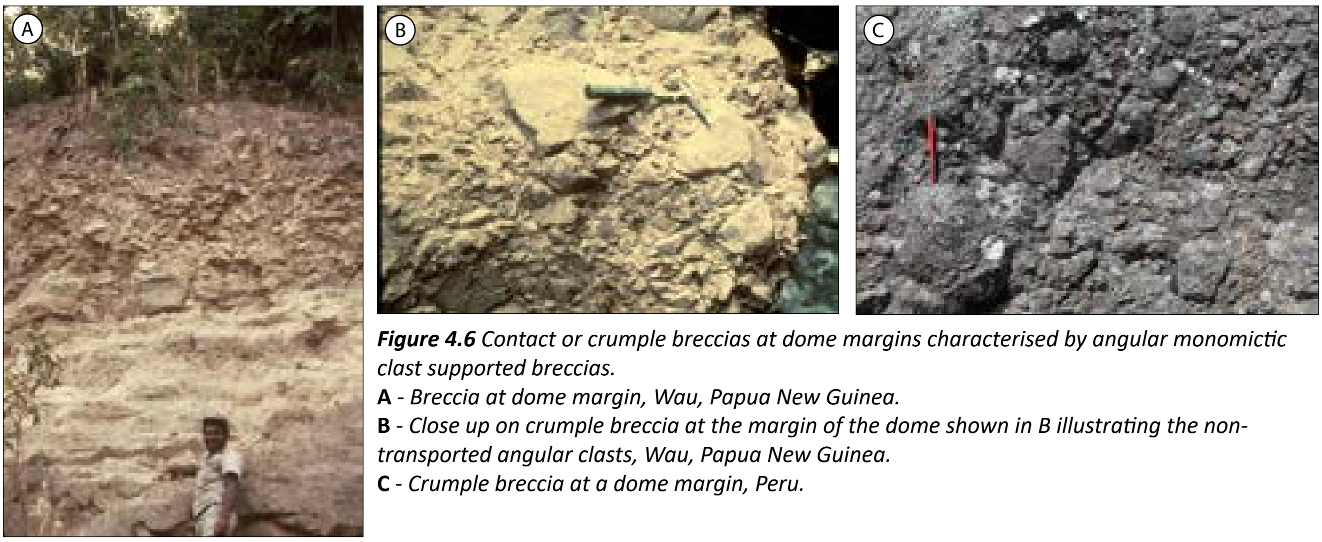


Figure 4.6 *Contact or crumple breccias at dome margins characterised by angular monomictic clast supported breccias.*
A - *Breccia at dome margin, Wau, Papua New Guinea.*
B - *Close up on crumple breccia at the margin of the dome shown in B illustrating the non-transported angular clasts, Wau, Papua New Guinea.*
C - *Crumple breccia at a dome margin, Peru.*

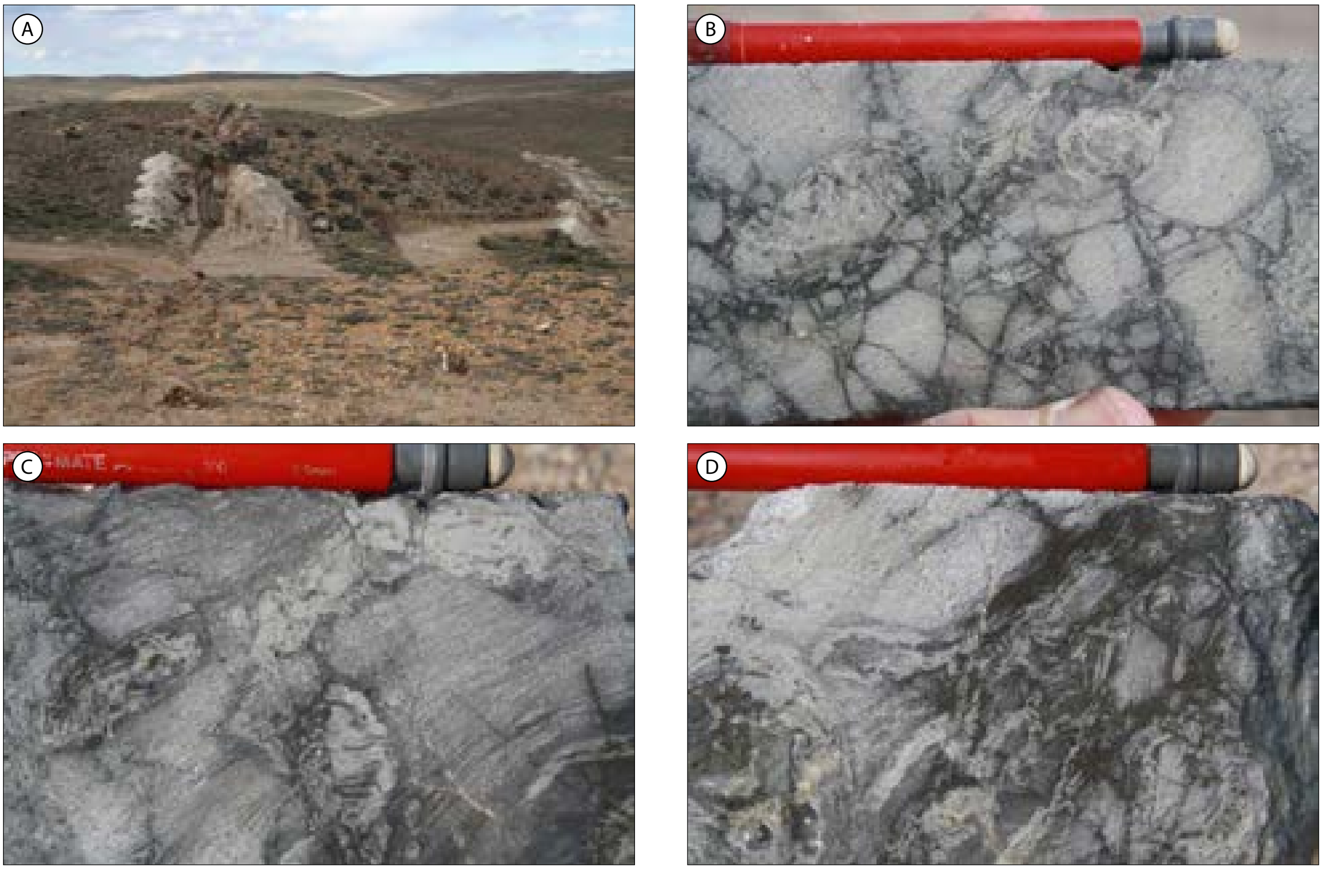


Figure 4.7 *Crumple breccias Las Calandrias, Argentina, interpreted to have formed at the margins of endogenous domes.*
A - *Dome margin.*
B - *Flow banded dome margin with spherulites and crackle breccia and limited sulphide, 0.8 g/t Au & 22.8 g/t Ag.*
C - *Flow banded dome margin with spherulites and sulphide segregations, 2.9 g/t Au & 72 g/t Ag.*
D - *Brecciated flow banded dome margin with sulphide sulphide-rich fluidised breccia, 6.7 g/t Au & 147 g/t Ag.*

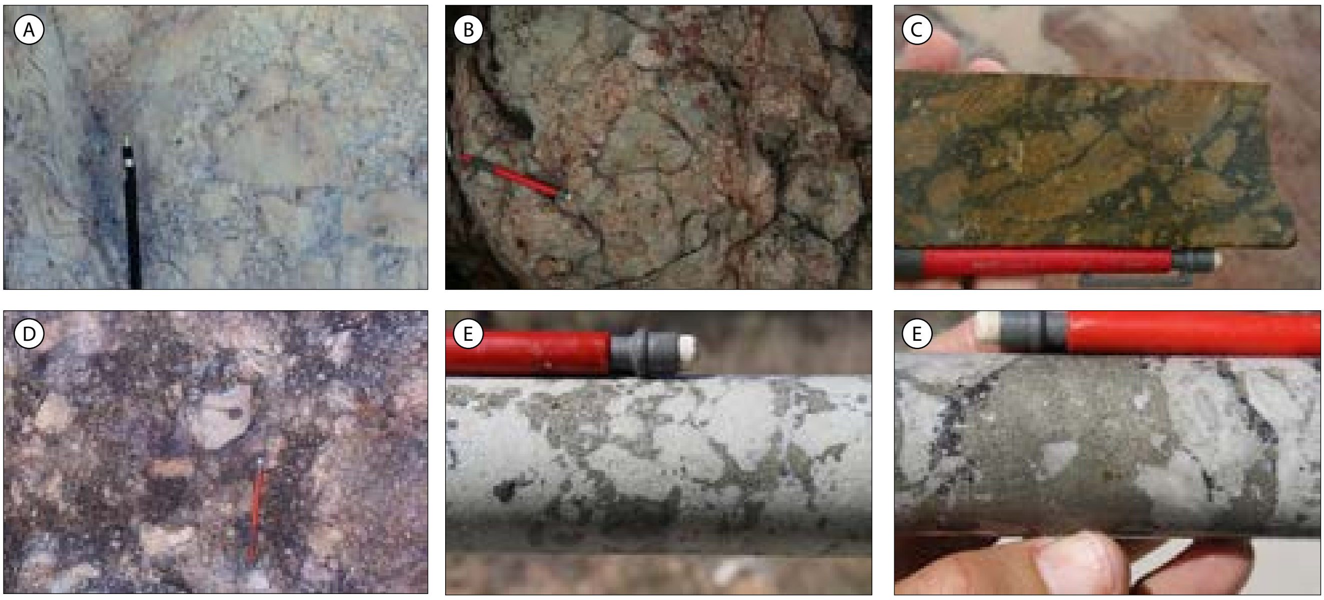


Figure 4.8 *Mineralised contact breccias.*
A - *Brecciated clast-rich dome margin with abundant open space filled by carbonate-base metal Au mineralised matrix graded 3-5 g/t Au, Bulawan, Philippines.*
B - *Brecciated matrix-rich dome margin in outcrop Twin Hills, Queensland Australia.*
C - *Monomictic clast-rich contact breccia towards the centre of the same dome as B with < 1 g/t Au in a mineralised sulphide matrix Twin Hills, Queensland.*
D - *Matrix-rich contact breccia at a dome margin in outcrop, Mt Wright, Queensland Australia.*
E - *Drill core of monomictic clast-rich contact breccia with sulphide matrix which assayed 2-4 g/t Au from closer to the dome than breccia C, Mt Wright, Queensland Australia.*
F - *Higher Au grade breccia than D with increased sulphide content and evolution to carbonate-base metal Au style mineralisation evidenced by the dark Fe-rich high temperature sphalerite, Mt Wright, Queensland Australia.*

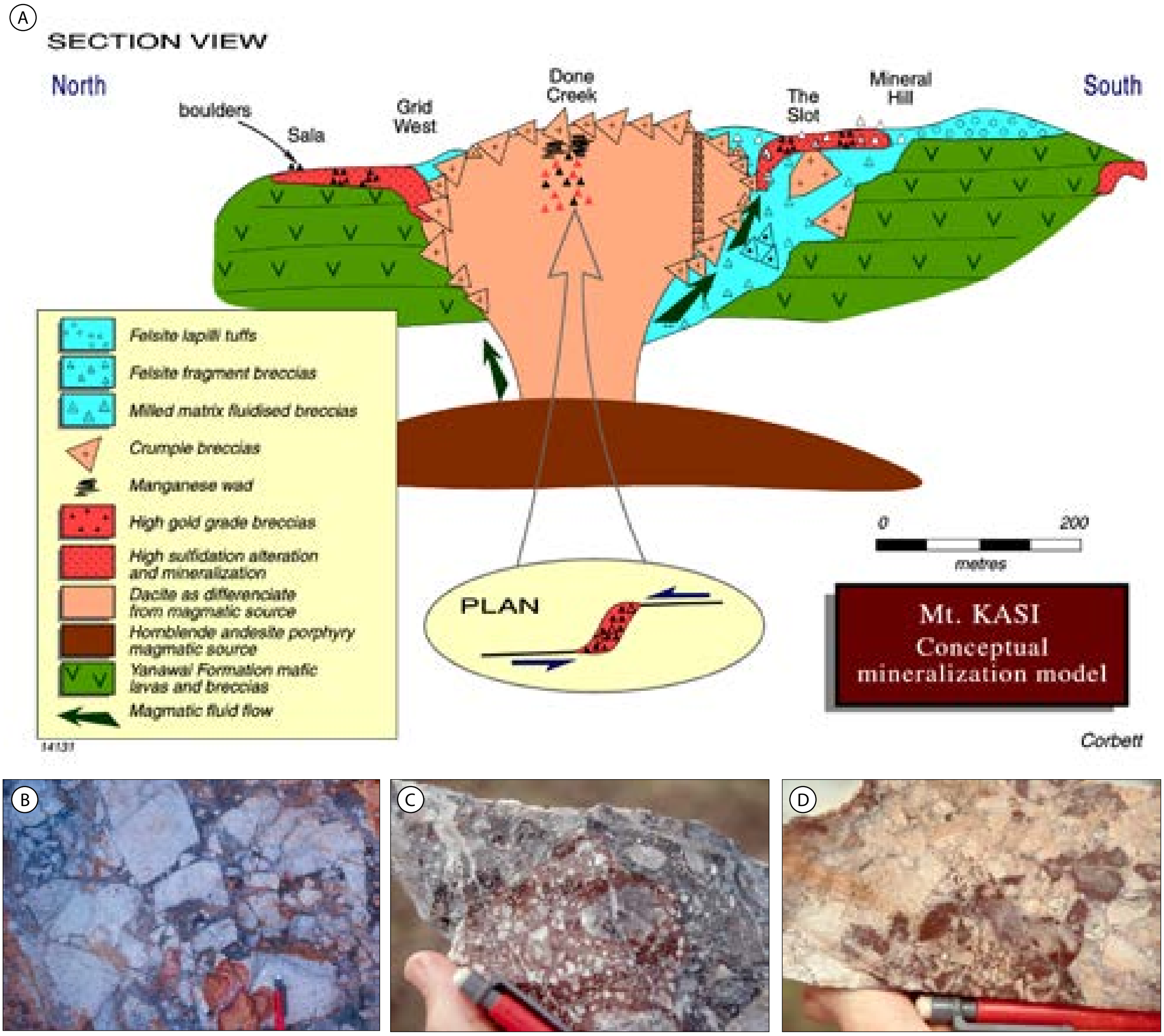


Figure 4.9 *Dome margin provides permeability control to high sulphidation alteration and mineralisation at Mt Kasi, Fiji discussed in section 8.4.1.6.*
A – *Conceptual model for mineralisation hosted in a brecciated dome margin*
B, C & D – *Contact or crumple breccias a the dome margin*

4.4.3 Intrusion breccias

The progression from contact to intrusion breccias is manifest as increased transport of magmatic clasts and mixing with wall rock clasts moving away from the intrusion and so there is some cross over between the use of the terms contact and intrusion breccia (figure 4.10). Intrusion breccias therefore display a bimictic varying to a local polymictic character with the increased mixing of intrusion with multiple types of wall rock clasts (figure 4.10). The transition to magmatic hydrothermal breccias is marked by increased entry of hydrothermal material, and clast transport, while the greater breccia matrix permeability aids mineralisation in those breccias. Permeable intrusion breccias may display extensive wall rock alteration. In porphyry settings characterised by the overprinting of similar porphyry intrusions and intense phyllic alteration, intrusion contacts might be discernible as 'vein clast breccias' formed as the later intrusion failed to assimilate A-style porphyry quartz veins present in the earlier intrusion (figure 4.10 C).

A stand out is that the vein clast breccias help establish thee polyphasal nature of some porphyry systems.

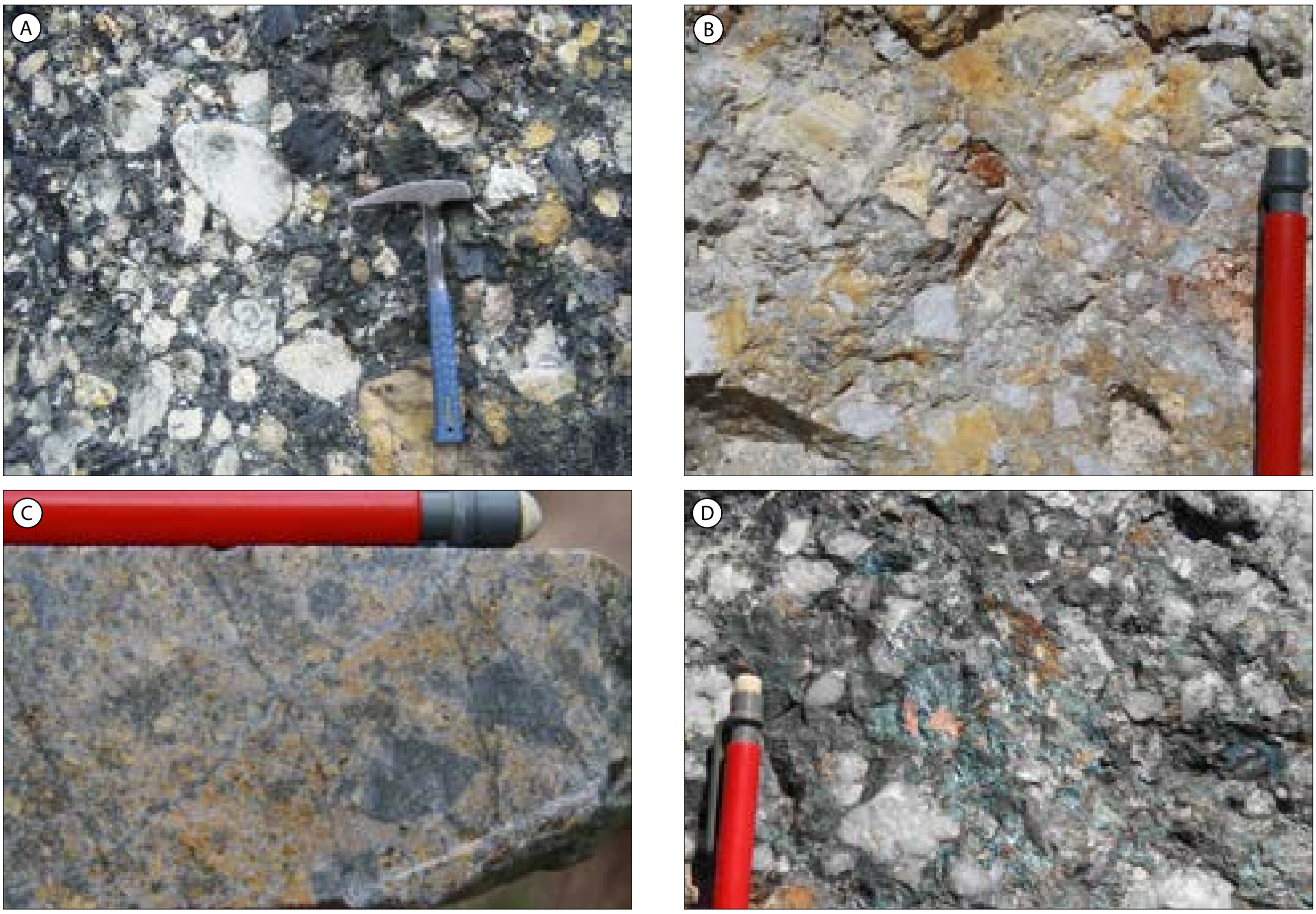


***Figure 4.10** Intrusion breccias characterised by a mix of intrusion and wall rock clasts.*
A - *Mixture of clasts comprising felsic dome and angular slate, Edie Creek, Papua New Guinea;*
B - *Mixture of wall rock sandstone/quartzite and felsic dome clasts, La Arena Peru.*
C - *Intensely phyllic altered contact between two intrusions evidenced here by residual A vein clasts and also by different intrusion geochemistry, La Arena Peru.*
D - *Intrusion breccia comprising milled wall rock and quartz vein clasts with additional matrix bornite mineralisation, Goonumbla, Australia.*

4.4.4 Magmatic hydrothermal breccias

Magmatic hydrothermal breccias display a pronounced hydrothermal component derived from commonly unseen magmatic source bodies at depth to which some link should be evident. Several variations are evident as:

- Pebble dykes
- Wall rock hosted intrusion breccias
- Magmatic hydrothermal breccia pipes
- Decompression breccias
- Collapse breccias
- Tourmaline matrix breccia pipes

Many magmatic hydrothermal breccias contain the same sequence of events recognised as: initial injection of intrusion material (eruption), and/or degassing of volatiles, collapse, and later stage emplacement of mineralised fluids into open space. Consequently, there are common themes in the development of these breccias.

4.4.4.1 A mechanism for breccia pipe formation is proposed to account for eruption, collapse and mineralisation recognised within magmatic hydrothermal breccias. Elsewhere (sections 3.4 & 5.1.4), it is proposed porphyry Cu-Au-Mo mineralisation is associated with vertically attenuated spine-like intrusions, which were forcefully emplaced into elevated crustal settings within dilatant structures, and overlie buried more major magmatic sources for volatiles and metals. The intrusion carapace may become sealed by a chilled margin and hornfelsed wall rocks. High water (Burnham, 1997) and high boron (Allman-Ward et al., 1982) contents allow the porphyry melt to rise to elevated crustal settings and there cool at low temperatures to form intrusions. As the cooling molten intrusion separates into the solid and volatile components, pressurised fluid (liquid and gas) which gathers at the intrusion carapace is fed from the substantial body of vertically attenuated intrusion and possibly the magmatic source at greater depth. In the model of retrograde boiling (Phillips, 1973), the intrusion carapace fractures when the volatile fluid pressure exceeds the lithostatic (confining) pressure

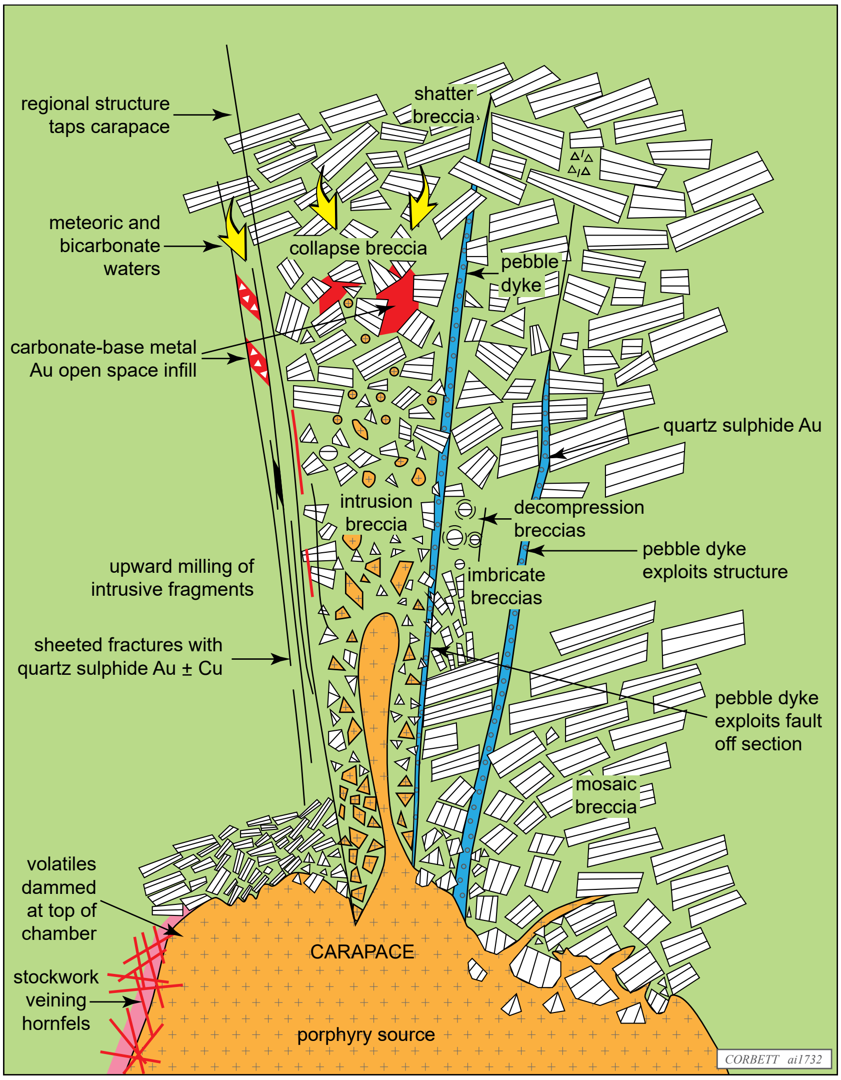


***Figure 4.11** Conceptual model for magmatic hydrothermal breccia pipes in sub volcanic terrains based partly upon Kidston, Australia (from Corbett and Leach, 1998).*

and tensile strength of the confining rock. In porphyry Cu deposits, the pressure drop which results from failure of the carapace promotes quartz deposition as stockwork veins, while the kinematics active during failure control the orientation of sheeted veins. The sudden pressure decrease to promote retrograde boiling might also be provided by sector collapse of a stratovolcano (Lihir, Papua New Guinea; Corbett et al., 2001; Corbett, 2005b), rapid uplift and unroofing (Central Chile in the late Miocene; Skewes and Stern, 1994), or fault movement (Wau, Papua New Guinea; Corbett and Leach, 1998).

Breccia pipe formation features an initial eruption event which varies from simply volatile (tourmaline fill shingle breccias) to intrusion clast emplacement (Kidston-style magmatic hydrothermal breccias). In the formation of breccia pipes, expansion of depressurised volatiles due to retrograde boiling gives rise to a volume increase. For instance, water release to form 1% weight at 2 km depth and 500°C, would provide a 10% volume increase, progressively increasing at shallower depths (Phillips, 1973), especially as a considerable quantity of buried magma may provide substantial volatiles. This sudden (virtually instantaneously) volume increase in the carapace promoted by retrograde boiling may provide explosive stress release which results in a lift of the body of rock which overlies the carapace, facilitated by shear fractures above the intrusion shoulders, commonly termed cone sheets (figure 4.12; Phillips, 1974). The formation of decompression or burst breccias (below) and flat dipping fractures that result in the later development of shingle breccias, were no doubt initiated at this stage. Explosive eruption might also fracture the carapace and tap the top of a magma chamber in order to promote the upward emplacement of volatiles with intrusion rock and entrained wall rock clasts. This eruption therefore represents the eruption breccia phase in figure 4.12.magmatic hydrothermal breccia pipes below. Once fractured the carapace provides a fluid plumbing system for the migration of ore bearing fluids from the cooling substantial magma source at depth, into the overlying breccia pipe.

The explosive degassing and also withdrawal of magma are likely to create a void at the top of the magma chamber, into which the uplifted body of rock would then collapse, aided by movement on the earlier shear fractures (figure 4.12), although there is some theoretical difference in the shape of cone sheets associated with uplift and collapse (Phillips, 1974). This collapse which follows eruption (Phillips, 1974; 1986) may enhance the development of flat-dipping hydraulic tension fractures within the pipe and adjacent wall rocks (figures 4.12 & 4.25). During continued collapse and matrix fluid introduction, the tension fractures within the pipe disaggregate to form slab and shingle breccias discussed below.

Mineralisation and continued alteration follow eruption and collapse as liquid-dominated ore fluids derived from the underlying magma body exit via the fractured carapace to exploit any pre-existing plumbing system, such as marginal steep dipping fractures and flat dipping tension fractures, and

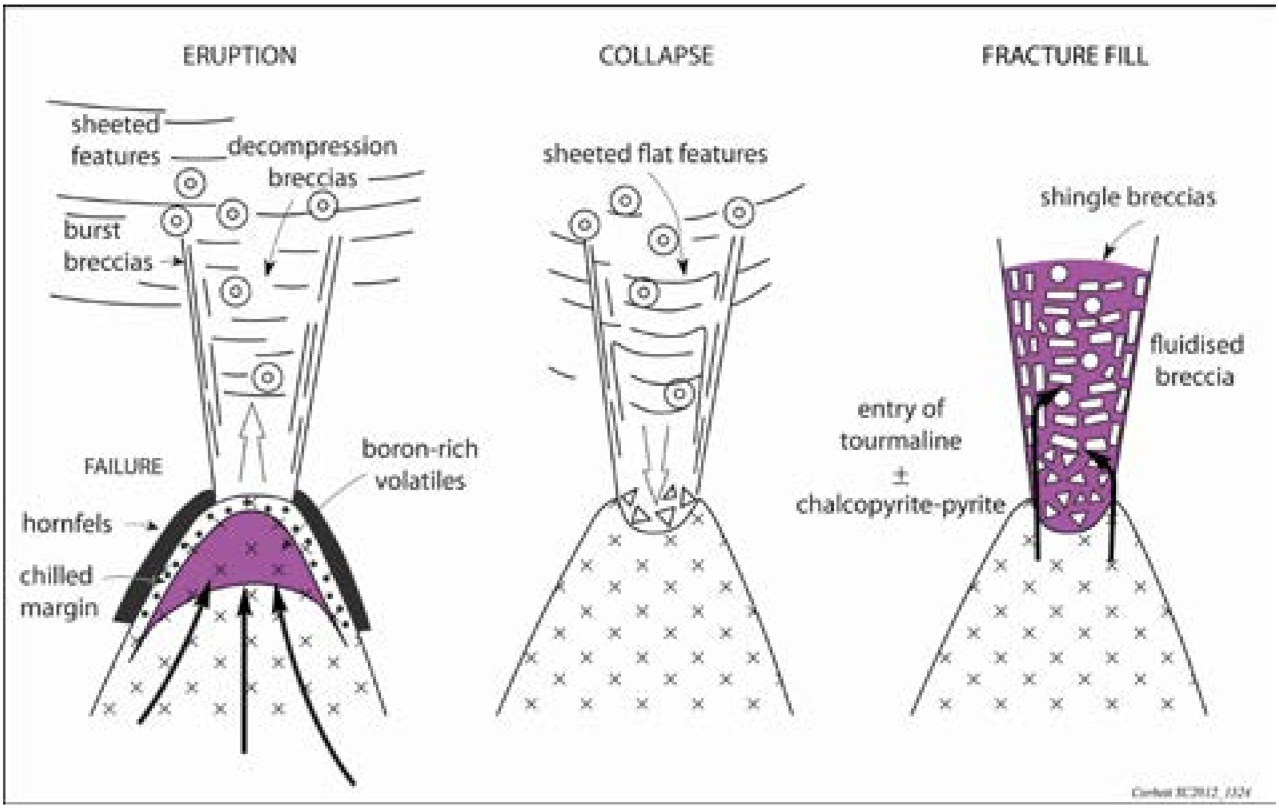


Figure 4.12 *Proposed stages in in the development of mineralised breccia pipes.*

deposit by cooling within open space to promote the development of the matrix-rich angular clast breccias. The entry of tourmaline-silica-sulphides promotes continued shingle breccia formation, although the close association with decompression breccias suggests the development of these two breccia styles was initiated at the earlier depressurisation stage.

4.4.4.2 Pebble dykes

Pebble dykes (Farmin, 1934; Bryner, 1961; Cornelius, 1967; Gustafson and Hunt, 1975) typically exploit linear pre-existing structures at near porphyry crustal levels and comprise rounded transported clasts in a polymictic clast rich breccia (figures 4.12 & 4.14). Pebble dykes result from the rapid degassing of depressurised volatiles which vent up structures from cooling porphyry intrusions at depth. Clasts rising rapidly up the narrow structure become rounded by milling, aided by hypogene exfoliation during depressurisation (as decompression breccias, below). While the common definition is clast supported, considerable matrix is also recognised, such as the 0-80% cited by Baldwin et al. (1978) for the pebble dykes which transect the Panguna Porphyry Cu deposit, Papua New Guinea. Consequently, there may be transitional relationships to milled matrix breccias below. In many settings deeper magmatic source rocks are interpreted to drive the pebble dykes, which therefore cut the mineralised porphyry intrusions (Panguna, Papua New Guinea, Baldwin et al., 1998; El Salvador, Chile, Gustafson and Hunt, 1975). As pebble dykes occur above porphyry intrusions they are used as vectors in porphyry exploration (section 9.**) and predate the emplacement of low sulphidation quartz-sulphide Au + Cu (deep) epithermal mineralisation which occurs overlying porphyry intrusions (Bilimoia, Papua New Guinea; Corbett et al. 1994; Corbett and Leach, 1998) and so may exploit the same structures and transect the pebble dykes. Note that pebble dykes are commonly derived from the magma source and transect the mineralised porphyry (figure 4.13; Panguna, Papua New Guinea, Baldwin et al., 1998) and so a variety of clast types might be expected. Pebble dykes at Mt Morgan, Australia (Cornelius, 1967) are used as part of the reinterpretation of that Cu-Au deposit as an intrusion-related quartz-sulphide Au + Cu deep epithermal system. Evaluation of wall rock hosted pebble dykes as an exploration tool should carefully check for clasts of any underlying mineralised porphyry intrusions.

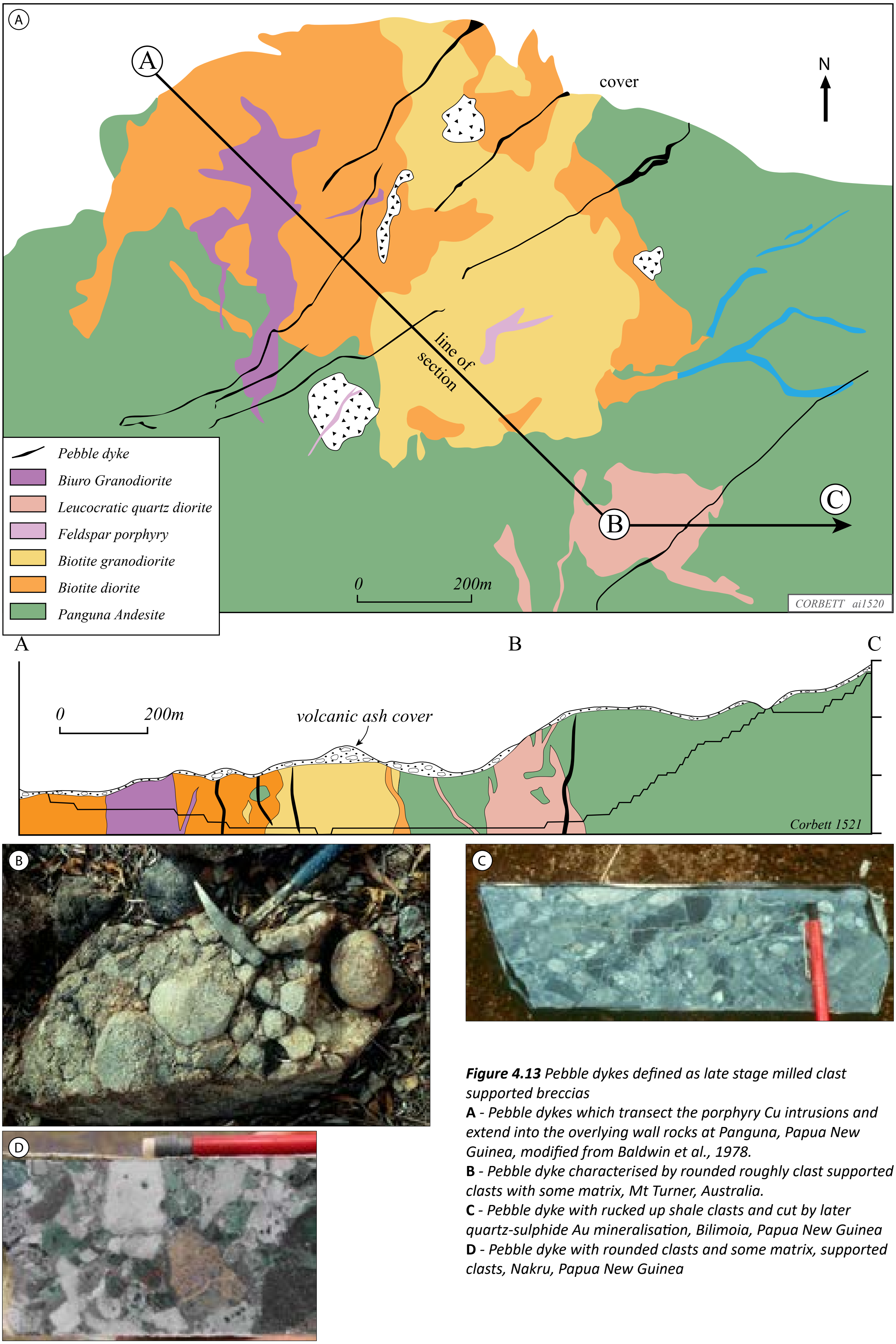


Figure 4.13 *Pebble dykes defined as late stage milled clast supported breccias*
A - *Pebble dykes which transect the porphyry Cu intrusions and extend into the overlying wall rocks at Panguna, Papua New Guinea, modified from Baldwin et al., 1978.*
B - *Pebble dyke characterised by rounded roughly clast supported clasts with some matrix, Mt Turner, Australia.*
C - *Pebble dyke with rucked up shale clasts and cut by later quartz-sulphide Au mineralisation, Bilimoia, Papua New Guinea*
D - *Pebble dyke with rounded clasts and some matrix, supported clasts, Nakru, Papua New Guinea*

4.4.4.3 Wall rock hosted intrusion breccias

Wall rock hosted intrusion breccias feature mineralisation hosted within wall rocks but commonly with a strong influence of intrusions such as dykes related to a deeper magmatic source for mineralisation. Breccias commonly vary from dominated by wall rock clasts with little milling typically in marginal settings, to those characterised by a mix of milled intrusion and/or wall rock clasts. These breccias are distinguished from the magmatic hydrothermal breccias by the lack of large scale clast transport and often display lower grade Au or Cu mineralisation, typically within open space breccias and cross cutting veins, which is derived from the magmatic source at depth. These less evolved breccias also lack significant collapse.

4.4.4.3.1 The San Cristobal Au deposit in northern Chile, which represents a complex wall rock hosted intrusion breccia, began production in December 1990 with a heap leachable resource of 10.1 M T @ 1.34 g/t Au (Egert and Kasaneva, 1995). A set of felsic dykes and breccias exploit a regional scale conjugate fracture within the metavolcanic (Zanelli Formation) wall rocks close to the intersection with the margin of an outcropping granite porphyry, interpreted as related to the source for mineralisation (figure 4.14). Wall rocks are cut by early rhyolite which is in turn cut by later quartz eye porphyry, to form breccias categorised (Corbett, unpubl. report, 1990) as (figure 4.15):

- Zanelli breccia – brecciated metavolcanic wall rocks with early regional chlorite alteration, present at the margin of the complex.
- Transitional breccia – poorly brecciated chlorite altered metavolcanic with minor large (10 cm) angular felsic clasts with moderate silica-sericite-pyrite alteration.
- Felsic breccia – well milled sub rounded typically felsic and metavolcanic clasts to only a few cm in size and with strong silica-sericite-pyrite (phyllic) alteration, present at the centre of the system.

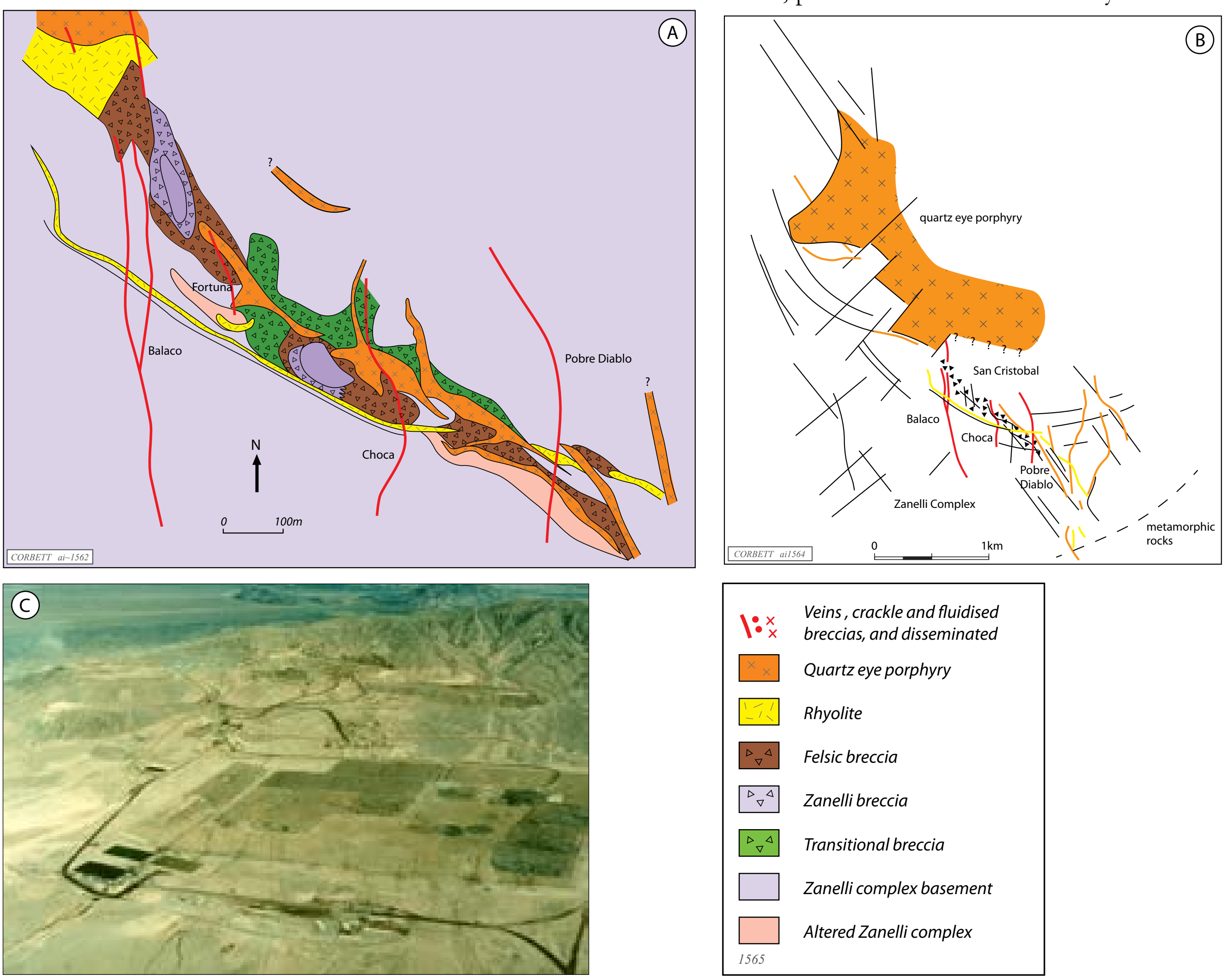
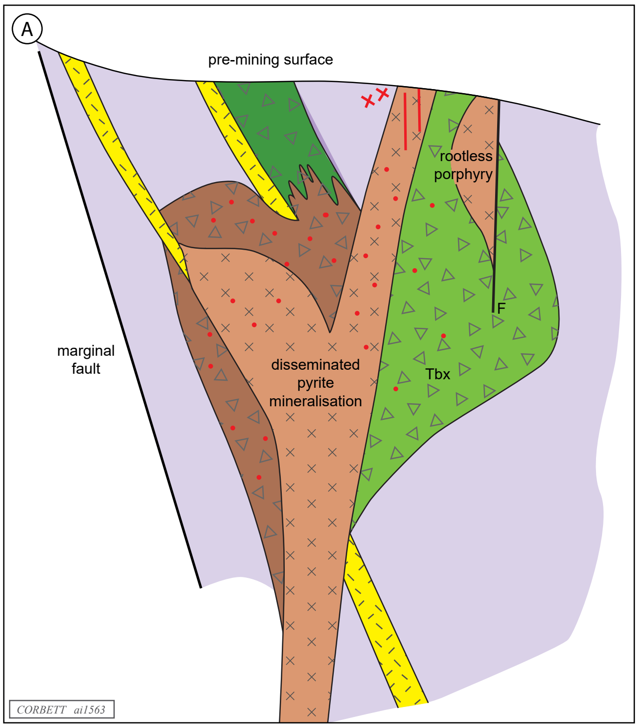


***Figure 4.14** San Cristobal mine wall rock magmatic hydrothermal breccia.*

A - *Geology of the San Cristobal wall rock hosted porphyry, from Corbett, unpubl report, 1990.*

B - *Regional setting where a NW trending conjugate fracture transects the margin of a granite porphyry, from Corbett, unpubl report, 1990.*

C - *View looing south over the poorly exposed granite porphyry on which the leach pads lie towards outcropping ridges of Zanelli Formation wall rocks with the open pit in the top left corner.*



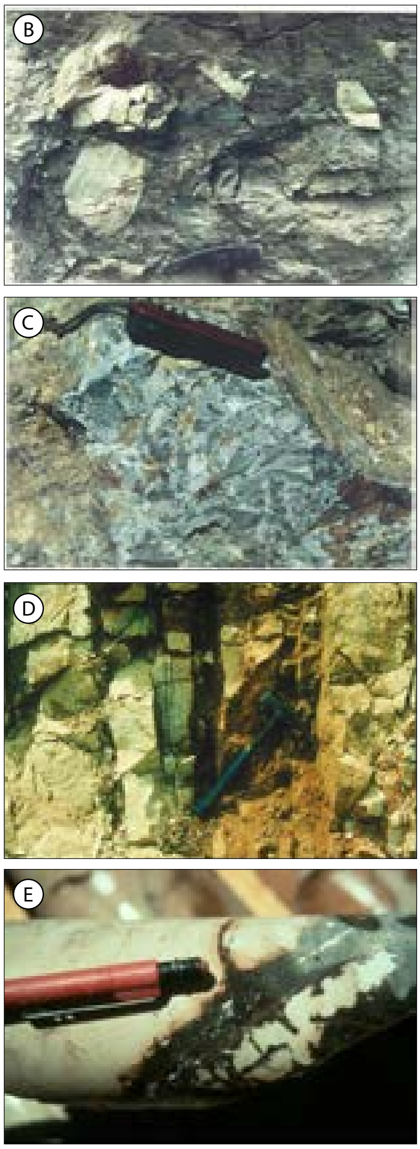


***Figure 4.15** San Cristobal mine breccia rock types.*
A - *Conceptual model for formation of the breccia body, from Corbett, unpubl report, 1990.*
B - *Transition breccia characterised by felsic dyke clasts in a brecciated chlorite altered Zanelli wall rock.*
C - *Felsic breccia characterised by milled silicified felsic and wall rock clasts.*
D - *Quartz eye (granite) porphyry cut by oxidised mineralised sheeted quartz-pyrite veins.*
E - *Weathered carbonate-base metal Au vein evidenced by MnO.*

Mineralisation is of the low sulphidation quartz-sulphide Au + Cu and carbonate-base metal Au style (sections 7.1.1 & 7.1.1) which is heavily oxidised and no doubt contains a component of near surface supergene Au enrichment, as typical of quartz-sulphide mineralisation (section 7.5.2). While larger veins with strong MnO stain (typical of carbonate-base metal Au deposits) have previously been exploited, the San Cristobal mine was worked (by Inca del Oro a subsidiary of Niugini Mining Ltd) as a bulk low grade heap leach operation which extracted ore comprising oxidised disseminated sulphides in the breccias as well as stockwork veins and lodes, best developed in the most competent quartz eye porphyry, which is no doubt linked to the magmatic source (figures 4.14 & 4.15). There are strong similarities with Kidston as the breccia types, style of mineralisation and the manner in which coarser grained quartz eye porphyry cuts rhyolite, interpreted to represent a progression in magma source from the margin the more central region of the magma body at depth. However, San Cristobal is a smaller, more proximal to the interpreted intrusion source and less evolved system than the Kidston breccia pipe (below). San Cristobal is not a breccia pipe and so does not feature collapse followed by mineralisation with a well developed link to the more deeply buried magma source.

4.4.4.3.2 Similar wall rock hosted mineralised breccia at the East Breccia, Cananea porphyry Cu-Mo district, comprises tongues of quartz monzonite dykes within brecciated volcanic wall rock and a partly domed contact with overlying volcanics along with a breccia matrix of quartz, pyrite, chalcopyrite and molybdite (Perry, 1961). While brecciation continues to depth, sulphide mineralisation has accumulated at the top of the pipe close to the contact with wall rocks (figure 4.22, section 4.4.4.4.2 below).

4.4.4.4 Magmatic hydrothermal breccia pipes

Magmatic hydrothermal breccias may occur within distinct pipes developed as a result of hydrothermal eruptions at porphyry and sub-volcanic crustal levels without venting to the surface. Pipes commonly display earliest magmatic injection followed by collapse prior to the main event of mineralisation which fills open space. Breccias therefore vary in different portions of pipes from breccias dominated by transport of milled intrusion clasts within the injection phases, to tabular locally derived less milled clasts in the collapse phases (figure 4.16). Hydrothermal alteration is dominated by silica-sericite-chlorite-pyrite and local clay as phyllic-argillic alteration. Sheeted fractures locally promote collapse and act as channel ways for later hydrothermal fluids and so may host most mineralisation, and also act as feeders for mineralisation within adjacent breccias. Magmatic hydrothermal breccias are most commonly associated with deeper epithermal (quartz-sulphide Au + Cu to carbonate-base metal Au) mineralisation at Kidston, Australia or Golden Sunlight, Montana, USA, varying to deeper level Cu breccias overlying porphyry deposits such as in the Cananea District (Perry, 1961, below).

4.4.4.4.1 The Kidston Au

deposit (>4 M oz Au production from an initial 2.7 M oz Au @ 1.58 g/t Au resource; Baker and Tullemans, 1990) is localised where the intersection of regional scale conjugate NE and NW factures tap the buried Permo-carboniferous felsic magmatic source rocks and cuts an intrusive contact between Precambrian granodiorite and metamorphic host rocks (figure 3.6; Corbett and Leach, 1998 and references therein). The buried magmatic source is evidenced by the numerous Permo-carboniferous dykes and hydrothermal alteration within a gravity low arch (from Oversby et al., 1980) which is coincident with outcropping Precambrian metamorphic rocks between the Wirra Wirra Caldera and Lochaber Ring Dyke Complex, and includes the Au-anomalous Mt Borium breccia-dome complex (figure 3.6).

The Kidston breccia pipe is elongate to the NE as a 1200 x 800 m body emplaced at the same time as sub-volcanic felsic dyke activity, as the pipe cuts some rhyolite dykes while others cut the pipe margin followed by coarser grained quartz feldspar porphyry dykes (figure 4.16). While the spherulitic nature of the earlier rhyolite dykes is consistent with a volatile-rich source, a major coarse grained quartz-feldspar porphyry dyke is constrained wholly within the pipe and no doubt emplaced at a late stage after the pipe has formed. The earlier rhyolites are interpreted to have been derived from the margins of the magma source and then the later quartz feldspar porphyry

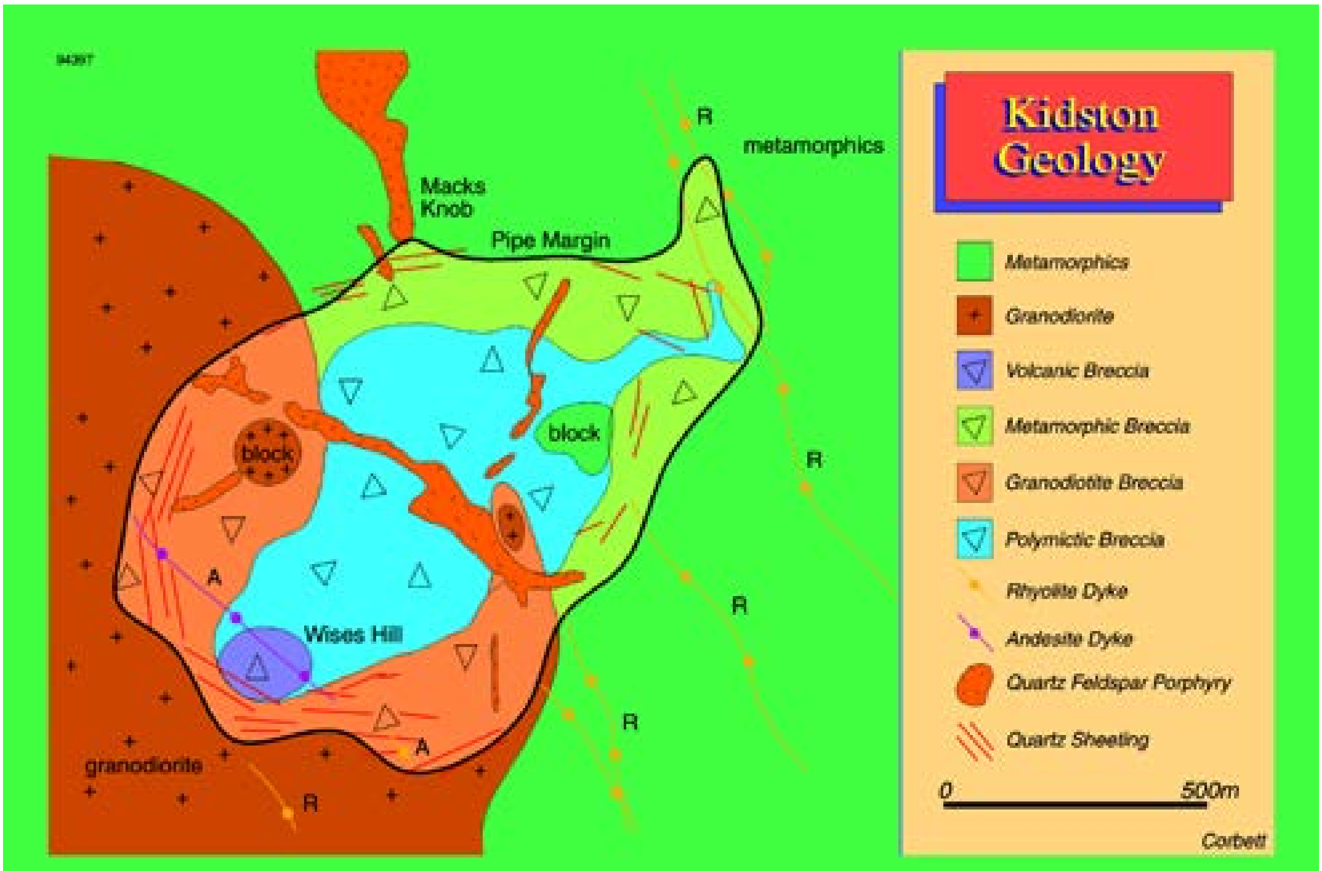


Figure 4.16 *Magmatic hydrothermal breccia. Geology of the Kidston breccia pipe, from mapping by Corbett, 1981. The initial open pit exploited the sheeted quartz veins at the SW pipe margin, while the Eldridge Mineralisation was mined from below the block in the eastern portion of the pit and no doubt accounts for high grade mineralisation identified near there during 1981 exploration.*

dykes from a more central portion of the intrusion after it had been tapped by explosive eruption. The presence of rucked-up clasts comprising porphyry intrusion with quartz-Mo veins and others with UST (unidirectional solidification textures) quartz vein textures and local tourmaline fill breccias (figure 4.17), all suggest a Mo porphyry-style intrusion was involved in the breccia pipe formation. The UST textures are typical of an intrusion carapace.

Breccias at Kidston were characterised (Corbett, unpubl., 1981) as (figures 4.16 – 4.18):

- Intrusion breccia (termed 'volcanic breccia' in 1981) represents the centre of breccia activity and features injected rock clasts such as milled quartz feldspar porphyry along with the rucked-up rock clasts described above with common sulphide matrix emplaced into open space (figure 4.18).
- Polymictic breccia rims the intrusion breccia as a mix of variably milled injected and locally derived breccia clasts (figure 4.18). The harder intrusion clasts which have travelled further from depth are typically more milled and rounded than locally derived softer angular metamorphic clasts. This breccia is interpreted to display an injection and collapse character.
- Collapse style granodiorite and metamorphic breccia bodies which extend from the polymictic breccias to the breccia pipe margin (figure 4.16) are matrix poor and clast supported, with clasts which are not mixed or milled by significant transport (figure 4.18). The breccias which feature only rare intrusion clasts are dominated by basement granodiorite or metamorphic clasts which mirror the basement contact.

A mega block breccia discernible only on the open pit wall close to the polymictic collapse breccia contact comprises flat dipping elongate (shingle-like) blocks to tens of metres long of rebrecciated earlier breccia formed by collapse (figures 4.18 & 4.19). Open space where NW fractures cut the NE pipe margin hosts low grade Au with sulphides and carbonate. The metamorphic foliation provides a marker to gauge the decreased rotation of blocks, moving outwards at the pipe margin.

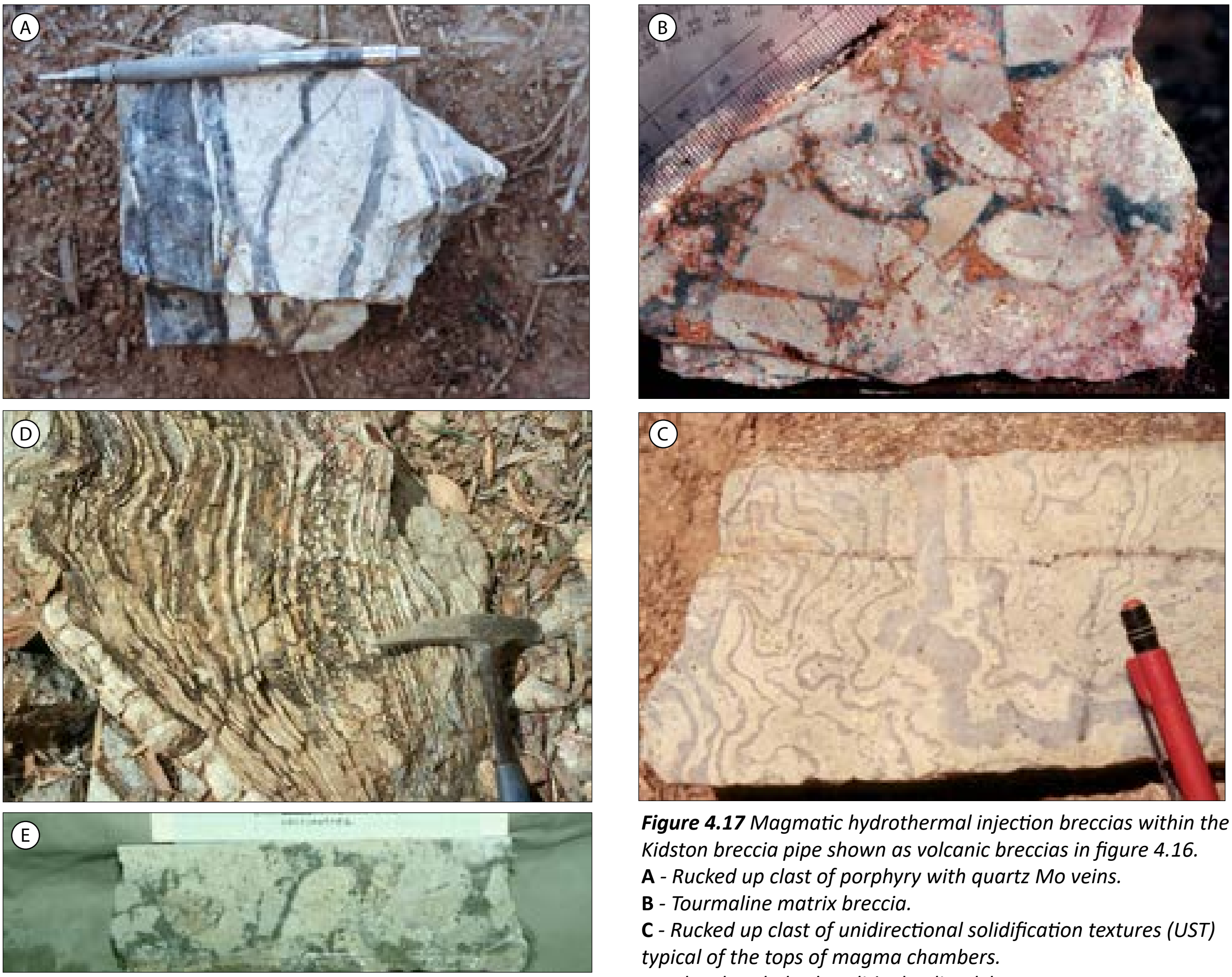


***Figure 4.17** Magmatic hydrothermal injection breccias within the Kidston breccia pipe shown as volcanic breccias in figure 4.16.*
A - *Rucked up clast of porphyry with quartz Mo veins.*
B - *Tourmaline matrix breccia.*
C - *Rucked up clast of unidirectional solidification textures (UST) typical of the tops of magma chambers.*
D - *Flow banded spherulitic rhyolite dyke.*
E - *Injection breccia comprising quartz-feldspar porphyry clasts and sulphide matrix.*

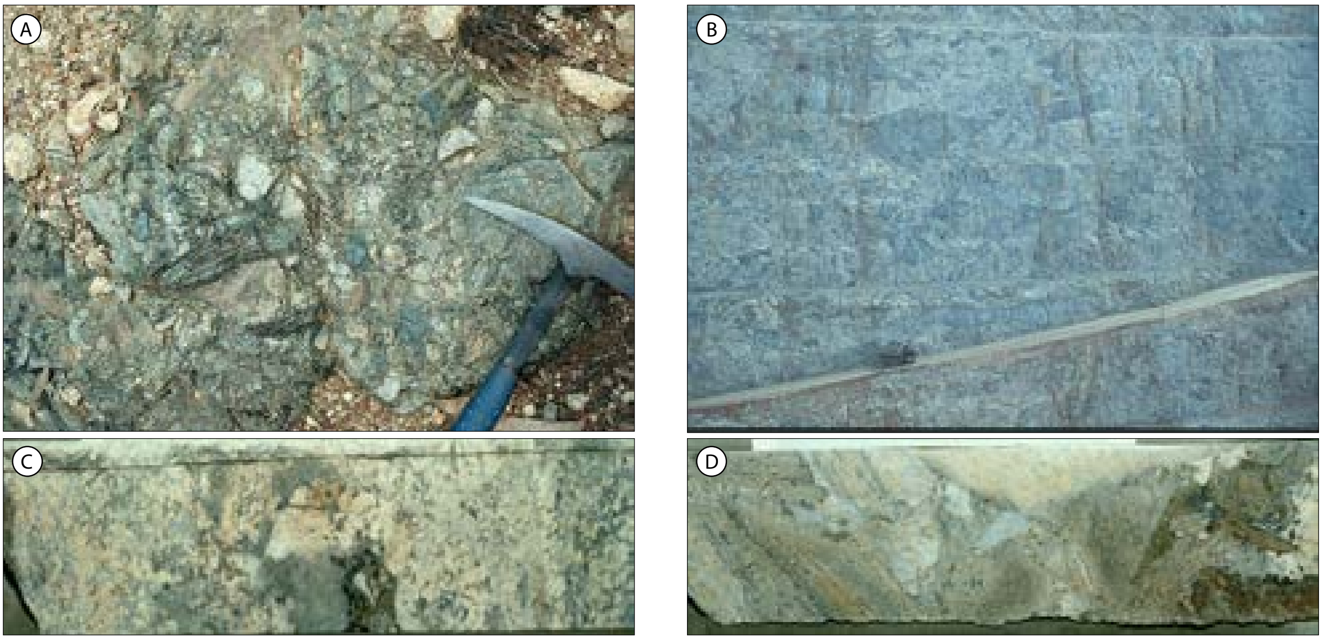


***Figure 4.18** Kidston collapse breccias developed within the central portion of the breccia pipe (figure 4.16).*
A - *Polymictic breccia in outcrop from the centre of the pipe.*
B - *Polymictic breccia on the open pit wall at Wises Hill, viewed from outside the pipe, showing flat lying mega blocks of polyphasal breccia (with mine truck for scale).*
C - *Collapse breccia dominated by granodiorite clasts with minor sulphides in the matrix.*
D - *Collapse breccia dominated by metamorphic clasts with minor sulphides in the matrix.*

The Kidston breccia pipe is interpreted (Corbett and Leach, 1998) to have developed by explosive eruption of volatiles venting from the carapace of a speculated buried magmatic source, of probably porphyry Mo-Au style, as evidenced by clast types (above). Magmatic activity began with the emplacement of volatile-rich spherulitic rhyolite dykes. Brecciation followed with the explosive injection of the intrusion breccia dominated by felsic (quartz feldspar porphyry) clasts emanating from the fractured magmatic source, and originally provided with the 'volcanic breccia' field term (figure 4.17). Hard clasts are well milled from extensive (upward) transport within the polymictic breccia. Collapse, which followed the venting of volatiles from the underlying carapace and creation of open space, is manifest as the collapse breccia (above) with angular poorly milled soft metamorphic and granodiorite clasts which underwent only modest collapse transport, discernible from the reorientation of the metamorphic foliation. The intervening polymictic breccia developed in the region of breccia mixing and limited milling between the strongly milled injection breccia and essentially unmilled collapse breccia (figure 4.16). Collapse was no doubt facilitated by movement on the sheeted fractures which kink around the pipe margin (figures 4.16 & 4.19) and correspond to shear fractures discussed above.

Later mineralisation vented from a magmatic source at depth into open space in the breccias and sheeted veins. The injection breccias and sheeted veins display the strongest connection to the magmatic source and so are best mineralised (figure 4.19). Some mineralisation associated with faults within the pipe was later found to have ponded under larger collapsed wall rock blocks within the pipe. The low sulphidation carbonate-base metal Au style, quartz-sulphide-carbonate vein and breccia mineralogy (with high temperature pyrrhotite and black Fe-rich sphalerite; section 4.20), is consistent with a deeply eroded pipe which Max Baker (Baker, 1987; Baker and Andrew, 1991) suggests did not vent to the surface.

Kidston illustrates the sequence of events from injection to collapse brecciation and later mineralisation within a breccia pipe related to sub-volcanic intrusions and containing rucked up deeper level porphyry clasts as an indication of an interpreted magmatic source. The progression from rhyolite to quartz eye porphyry dykes suggests initial eruption was derived from the marginal carapace of the magma source which became fractured to allow deeper level magmas to vent into the pipe and adjacent wall rocks (figures 4.11 & 4.12). Mineralisation, of the intrusion-related low sulphidation epithermal styles, mostly post-dates the initiation of brecciation and collapse.

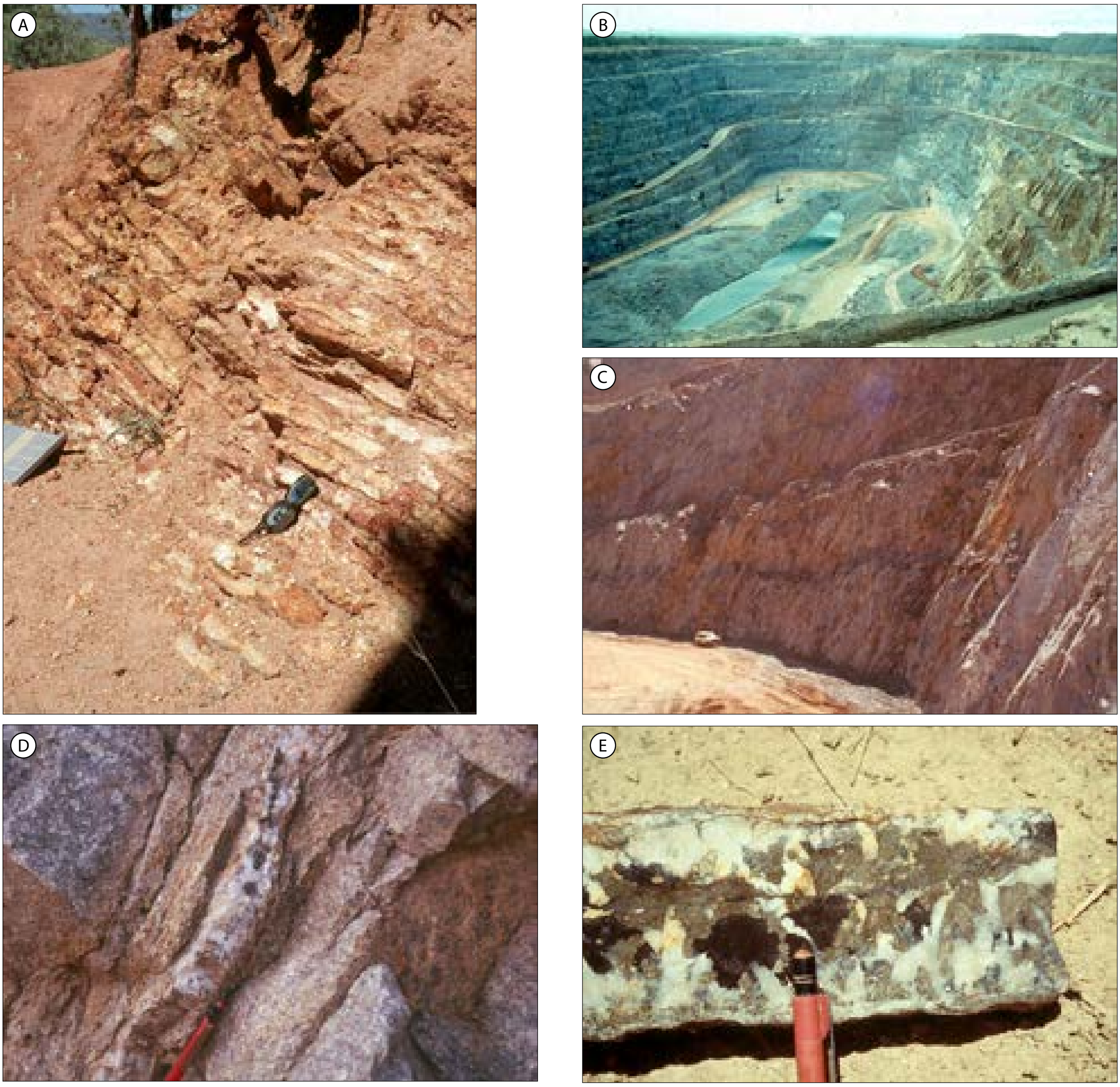
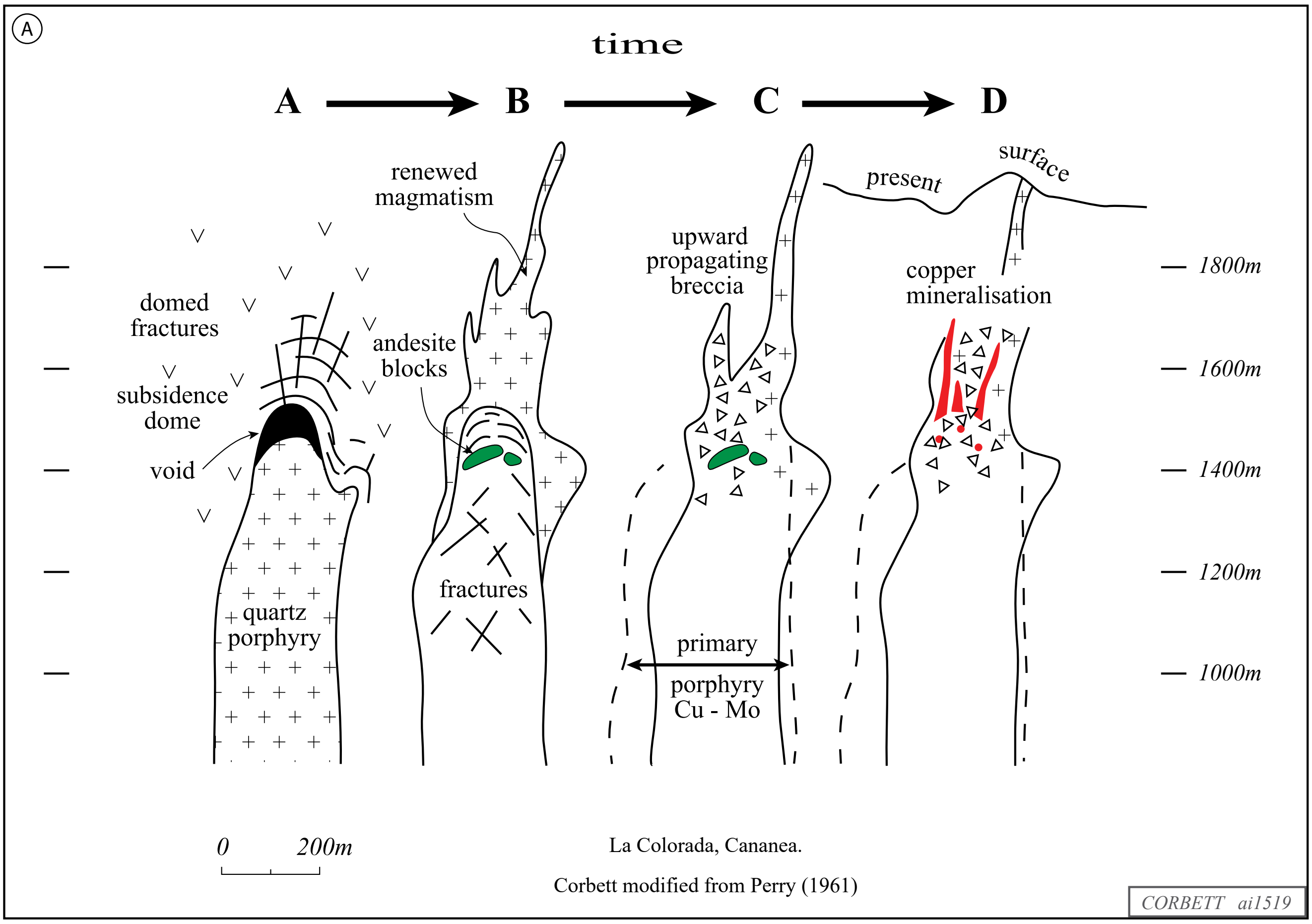


***Figure 4.19** Mineralisation at the Kidston breccia pipe.*
A - *Sheeted quartz veins in a 1980 surface exposure.*
B - *Open pit about 1994 looking east and showing the sheeted fracture/veins. The figure 4.18 B breccias are on the left wall.*
C - *Sheeted fractures on the pit wall at the breccia pipe margin.*
D - *Sheeted fractures with a typical quartz vein.*
E - *A specimen of a particularly thick quartz vein showing open space fill textures comprising centrally terminated quartz, dark Fe-rich high temperature sphalerite, lesser galena-sulphide and the Fe sulphides, pyrite, chalcopyrite and pyrrhotite.*

4.4.4.4.2 The La Colorada pipe at the Cananea porphyry Cu-Mo district, Mexico (Perry, 1961) provides an example of the mechanism for the formation of mineralised sulphide breccias associated with porphyry Cu-Mo emplacement (figure 4.20). Perry (1961) describes an interpreted sequence of events associated with the uppermost portion of a vertically attenuated plug of polyphasal quartz porphyry. A dome-like fracture pattern developed within andesite wall rock overlying a void at the top of an original spine-like intrusion stock, and some andesite collapsed as renewed intrusion progressed to higher levels. Perry (op cit) goes on to describe upward propagating brecciation which was eventually cut by quartz-sulphide followed by Cu-Mo mineralisation such that some angular Cu sulphide clasts occur within a comminuted breccia matrix (figure 4.20). This is similar to the quartz-clast, sulphide-matrix breccias at Goonumbla, Australia (figure 4.20 D). The Cu breccia matrix therefore post-dates quartz and caps an intrusive stock which hosts typical porphyry Cu-Mo mineralisation. Rupture associated with a vertically attenuated porphyry Cu has focused the development of Cu sulphide breccias at the top of the intrusion. The late sulphides were derived from the cooling much larger magmatic source at depth.



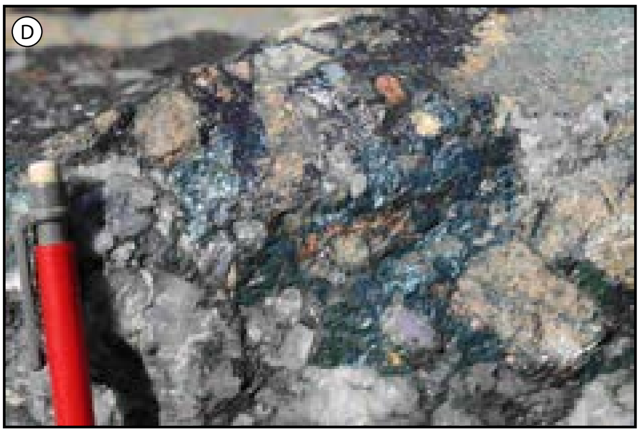


***Figure 4.20** Sulphide breccias develop from fluids exsolved from porphyry intrusions.*
A - *Illustration of the model for the La Colorada pipe, Cananea, Mexico, grading from: A - intrusion, venting of volatiles and subsidence of the carapace, B - renewed magmatism and collapse, C - upward breccia propagation and, D – Cu mineralisation, modified from Perry, 1961.*
B - *Sulphide matrix breccia, Ok Tedi, Papua New Guinea.*
C - *Sulphide matrix breccia, Cadia district, Australia.*
D - *Sulphide matrix breccia, Goonumbla, Australia.*

4.4.4.4.3 At the Cargo porphyry Cu-Au prospect, Australia, a magmatic hydrothermal breccia displays a polyphasal activation in a setting in the upper region of porphyry intrusions characterised by altered wall rock and near-porphyry radial D veins (figure 3.52). The variety of clasts in the Cargo breccia include andesite and dacite wall rock with pre-breccia quartz veins, sericite altered dacite, potassic altered monzonite and K-feldspar altered dacite, all set in a dacite matrix with K-feldspar alteration extending into the adjacent wall rocks (figure 4.21). The breccia hosts porphyry quartz vein clasts with K-feldspar selvages and contains later quartz-carbonate-pyrite-chalcopyrite veins and breccia fill typical of deep epithermal wall rock settings above porphyry intrusions as "out of porphyry mineralisation". The potassic (magnetite - K-feldspar) altered monzonite with chalcopyrite on fractures, occurs as larger and less milled clasts, that appear to have been incorporated in the breccia late in the brecciation process and are cut by later actinolite-quartz-carbonate veins. The same monzonite is recognised as a dyke in the wall rocks with quartz-Mo and sheeted quartz veins with K-feldspar selvages, and may be derived from a buried monzonite source for the extensive magnetite flooding of the wall rocks. Local elongate shingle-like andesite wall rock clasts suggest some collapse has taken place.

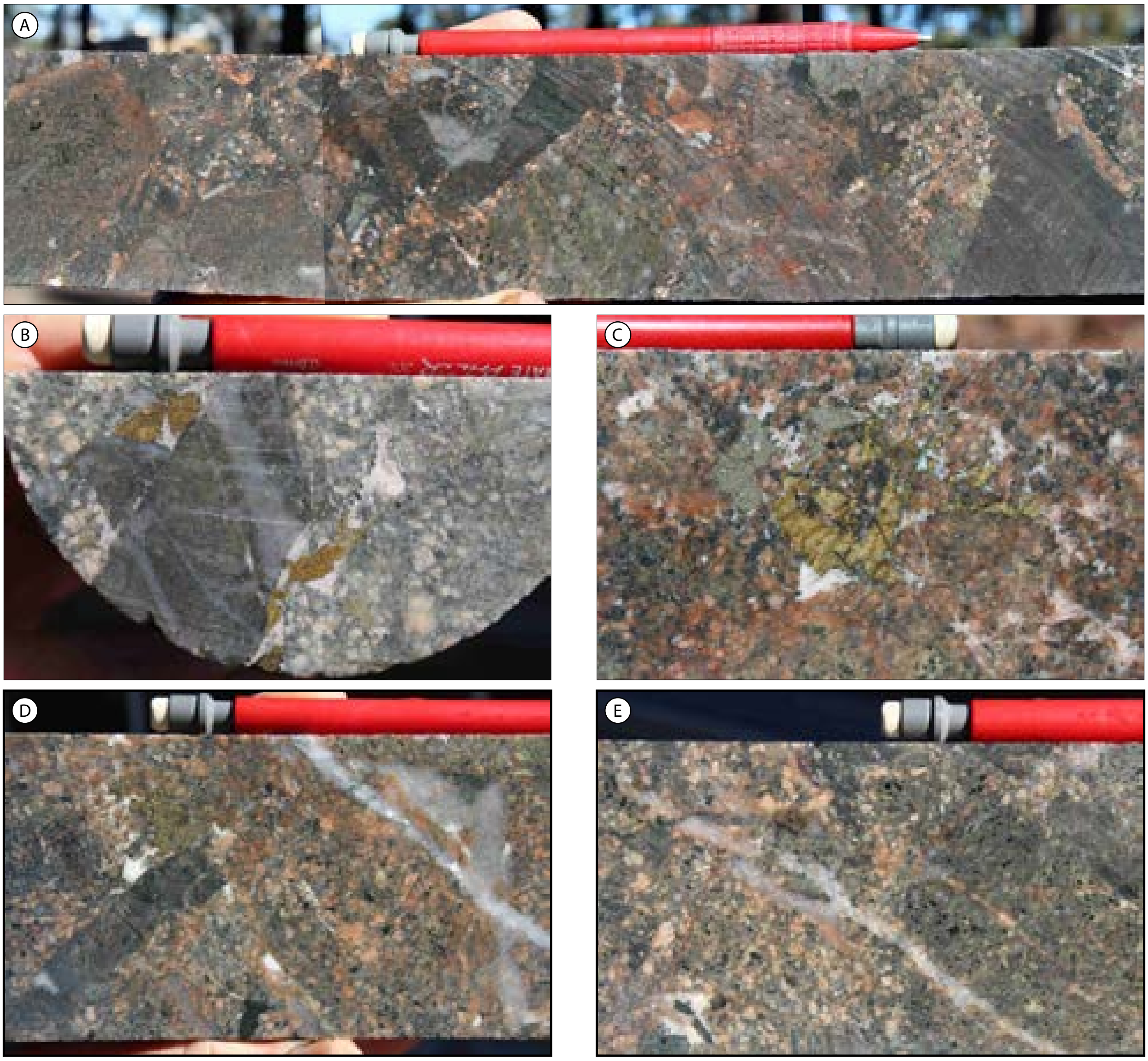


Figure 4.21. *Magmatic hydrothermal breccias, Cargo, Australia. Drill hole 91CN1 Londonderry Drillcore Library, WB Clarke Geoscience Centre, NSW Planning & Environment Resources & Energy.*
A - *Polyphasal magmatic hydrothermal breccia.*
B - *Quartz veined wall rock andesite clast in a breccia with sulphide-carbonate fill.*
C - *Monzonite porphyry breccia with sulphide-carbonate breccia fill.*
D - *Polyphasal breccia cut by quartz veins.*
E - *Polyphasal breccia cut by quartz veins.*

4.4.4.5 Decompression breccias

Rapid depressurisation of a rock body may result in the formation of onion-skin style breccias characterised by a central ovoid core and curvilinear sickle-shaped exfoliated clasts, termed (Baker et al., 1986) decompression breccias. Clasts may undergo pressure reduction by rapid transport to elevated settings or rapid unroofing. One example from Borneo cropped out adjacent to a fault where a body of host rock was either up-faulted or the fault movement rapidly relieved the confining pressure, resulting in the rapid depressurisation of the rock body and formation of the decompression breccia (figure 4.22 A & B).

Decompression breccias are common in association with shingle breccias and tourmaline breccia pipes discussed below where they are interpreted to have formed by rapid decompression in association with breccia pipe formation (below), and may then have been in-fill by tourmaline matrix (figure 4.11). Depressurisation results in the explosive expansion of any body of rock to provide the onion skin breccia character which be in-filled by tourmaline matrix, or become dismembered by later breccia movement and transport, especially if collapse follows brecciation (figure 4.22).

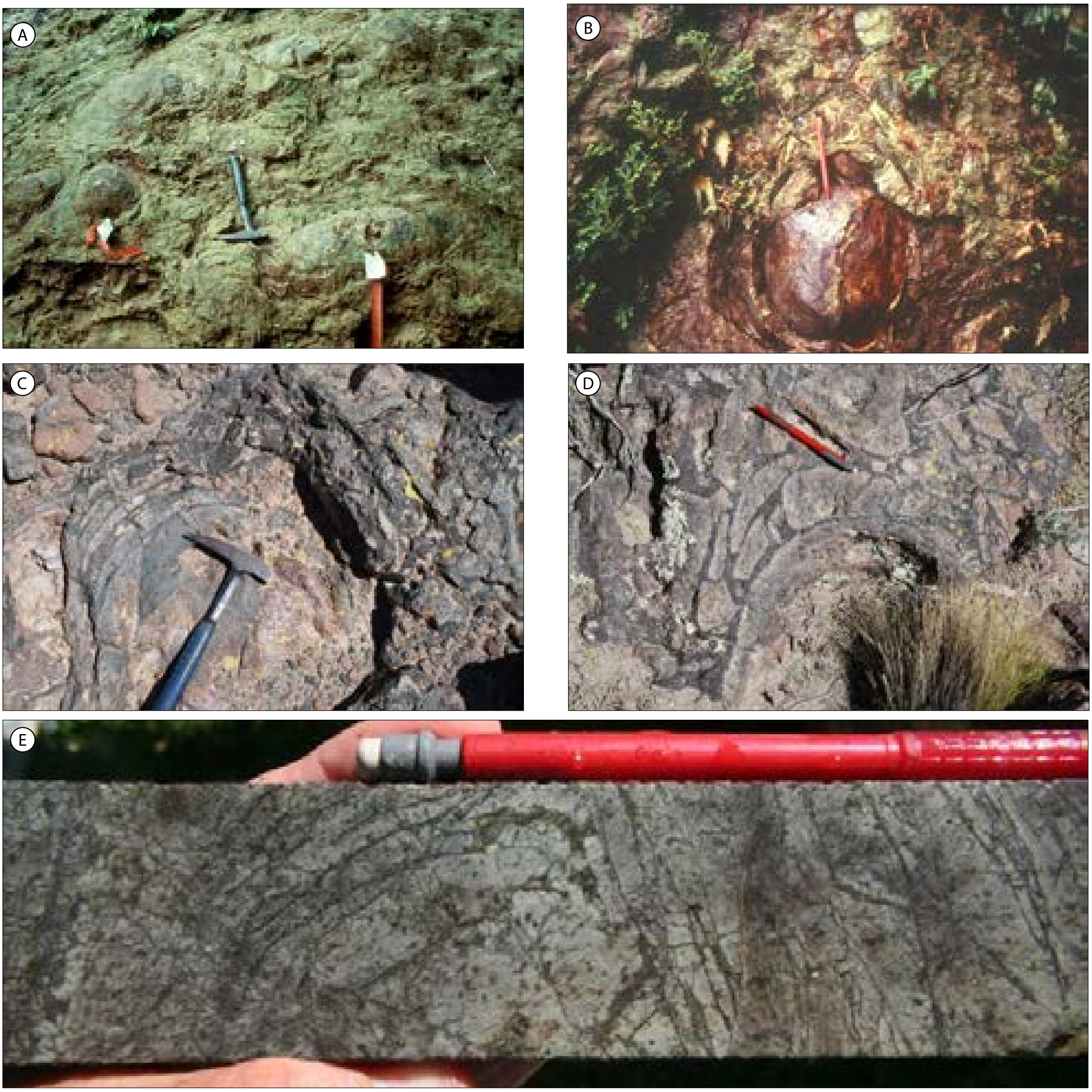


Figure 4.22 *Decompression breccias showing the characteristic onion form and sickle-shaped clasts.*
A & B - *Decompression breccias within a fault plane, Borneo.*
C & D - *Tourmaline matrix decompression breccias showing central core and sickle-shaped marginal clasts, Yabricoya, Chile.*
E - *Decompression breccia, Tooloom, Australia, with shingle-like clasts.*

4.4.4.6 Collapse breccias

Collapse breccias in hydrothermal ore systems commonly feature slab-like blocks with a sub-horizontal orientation, locally comprising pre-existing breccias and varying from metre to many tens of metres in size (figures 4.12). The Kidston breccia pipe is interpreted to display collapse on the ring fractures, evidenced by flat-lying blocks of rebrecciated breccia discernible on the pit walls and large blocks of wall rock mapped inside the pipe (figures 4.16 - 4.18). Similar slab-like breccias are recognised within larger areas of pyrite flooded breccia in the Ladolam open pit, Lihir Island, Papua New Guinea (figure 4.41 D). Slab breccias recognised at the Ardlethan Tin Mine, Australia by Taylor (2009) were provided with a collapse mechanism of formation by Clarke et al. (1985) to account for the inward dipping slab breccia form filled with quartz-tourmaline-sulphide matrix. At Cornwall, England, Allman-Ward et al., (1982) cite the presence of blocks of overlying wall rock as evidence of collapse within breccias at the granite carapace (cupola, upper margin or apophysis). These and other quartz-tourmaline breccias (below) feature collapse as a primary mechanism of formation (Corbett and Leach, 1998). At the Donoso Breccia Complex (section 4.4.4.8.1) wall rock clasts have collapsed 300 metres into the breccias. Perry (1961) noted the presence of andesite wall rocks within the porphyry cupola as evidence for collapse at La Colorada breccia pipe, Cananea, Mexico (figure 4.20; section 4.4.4.4.2).

While a variety of mechanisms are proposed to account for development of collapse breccias, the escape of volatiles from the top of the magma chamber and subsequent collapse is preferred (Corbett and Leach, 1998). Similarly, collapse into a carapace void created by volatile escape was provided by Clarke et al., (1985) as the preferred mechanism at Ardlethan Tin Mine, Australia, who also considered several other possibilities as:

- Magma withdrawal (Perry, 1961).
- Withdrawal following escape of a volatile bubble (Norton and Cathles, 1973).
- Dissolution by corrosive fluids (Sillitoe and Sawkins, 1971).
- Late collapse in the upper portion of an intrusive breccia.
- Mineralisation stoping and block caving (Locke, 1926).

Thus, collapse is a common feature in many breccia pipes as discussed below.

4.4.4.7 Shingle breccias

Shingle breccias (also called ‘domino breccias’, Sillitoe, 1985; or ‘imbricate breccias’, Baker et al., 1986) occur mostly as stacked angular elongate clasts similar to roof shingles or books, generally a few cm thick and up to a metre long (figure 4.2 A, 4.23 & 4.24). Shingle breccias display some transitional relationships to slab breccias although the former are smaller and commonly display a silica-tourmaline matrix. As there is little clast transport, shingle breccias are generally monomictic, except where near intrusion contacts and significant collapse is recognised. Most shingle breccias display a fluidised matrix comprising of rock flour and tourmaline-silica + sulphide which provides a variable separation between clasts and also contributes towards the alteration of clasts. Retrograde shingle breccias with kaolin fill were recognised within wall rock above a porphyry intrusion in a deeply dissected terrain associated with low sulphidation polymetallic Ag-Au epithermal mineralisation at Tahuehueto, Mexico (figure 4.23 E). Tourmaline matrix decompression breccias may be included within the shingle breccia group as they commonly occur together (figure 4.22 E).

Shingle breccias display remarkable similarity from a variety of different locations. Some are recognised in wall rocks above speculated porphyry intrusions in terrains characterised by low sulphidation (deep) epithermal mineralisation such as Tooloom and Mt Terrible, Eastern Australia (figure 4.23), with local onion skin style decompression breccias (figure 4.22 E). Many of the best examples of shingle breccias occur within tourmaline breccia pipes described from the Andes (Sillitoe and Sawkins, 1971; Corbett and Leach, 1998) where they are prospected for Cu-Au mineralisation, or Cornwall (Allman-Ward et al., 1982), Eastern Australia (Clarke et al., 1985; Baker et al., 1986), and Korea and elsewhere, where they are prospected for Sn mineralisation. There must be common themes in the mode of formation for similar breccias to occur in different terrains. Shingle breccias are therefore represent an important component of tourmaline breccia pipes and indicative of collapse (below).

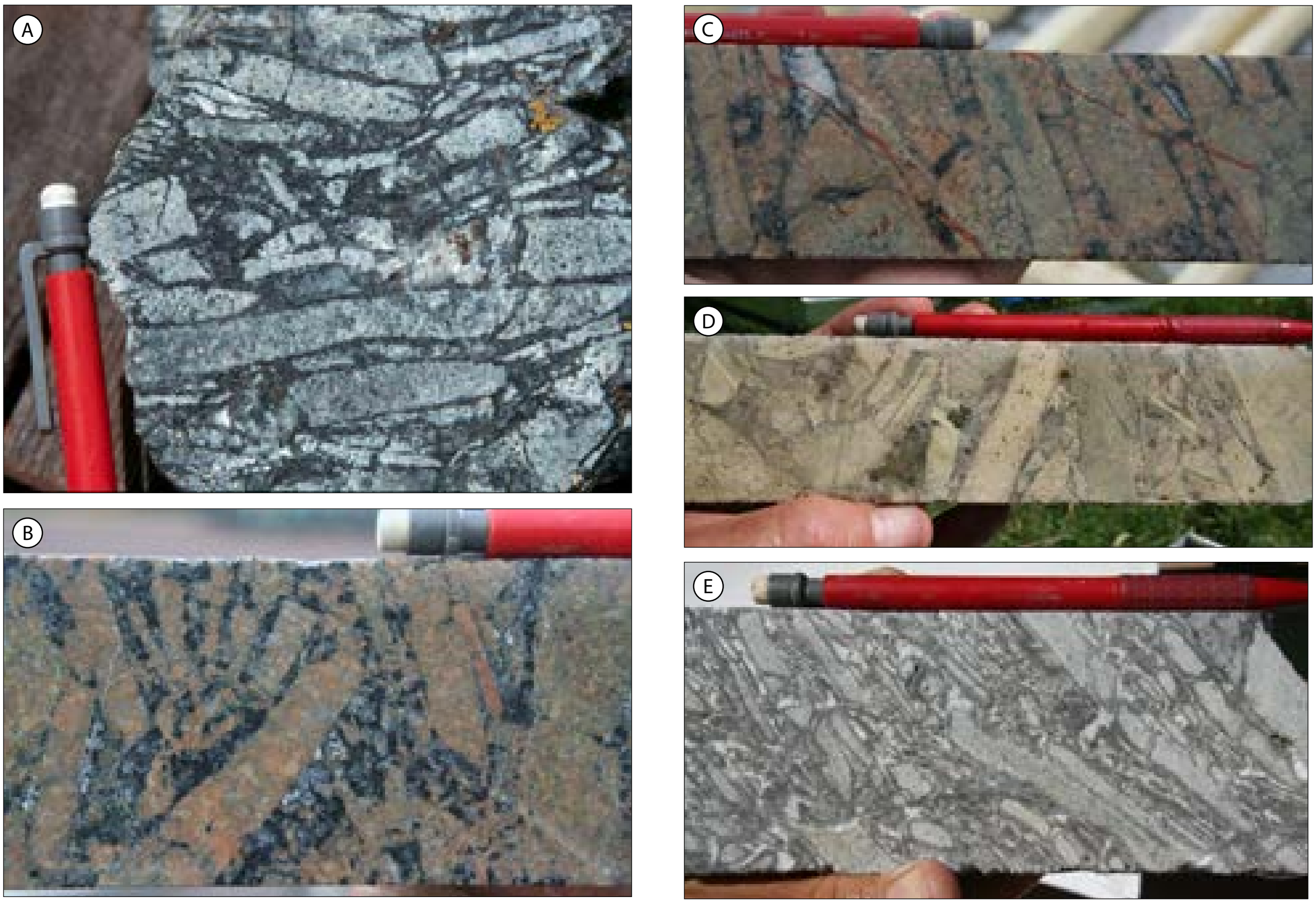


Figure 4.23 *Shingle breccias comprise stacked elongate angular clasts.*
A - *Tourmaline filled shingle breccia, Huaraz, Peru.*
B - *Disaggregated shingle breccia as the shingle clasts separate with increased tourmaline matrix fill, Mt Terrible, Australia.*
C - *Shingle breccia characterised by parallel elongate clasts with tourmaline in-fill, Mt Terrible, Australia.*
D - *Shingle breccia with quartz-sulphide mineralisation infill, Tooloom, Australia*
E - *Shingle breccia with kaolin matrix, Tahuehueto, Mexico.*

4.4.4.8 Tourmaline breccia pipes

Tourmaline breccia pipes (references above) display ovoid shapes in plan view and are commonly rimmed by steep dipping sheeted fractures which may be kinked as straight segments about the pipe margin and contain quartz-sulphide veins. Both the ovoid shape and sheeted veins may be accentuated to reflect local stress conditions. Pipes, which are not considered to have vented to the surface during formation, tend to display vertically continuous cylindrical forms with steep margins although some are flared in the upper portions and others might taper significantly in the lower portions. Tourmaline breccia pipes are filled with wall rock clast shingle and decompression breccias, characterised by little clast transport with matrix dominated by silica-tourmaline + anhydrite-specularite-sulphide and are locally mined for Sn, Cu and minor Au in different terrains (figure 4.24). Sericite alteration of clasts may grade inward from the clast margins where the flat dipping tension fractures and steep dipping collapse fractures provide the fluid plumbing system.

The model proposed for the development of tourmaline breccia pipes (above; Corbett and Leach, 1998) features eruption, collapse and mineralised hydrothermal fluid injection into fractured wall rocks above the upper portions (cupolas, carapace or apophyses) of intrusions varying in size from batholiths to plutons as cooling and degassing magma source bodies. The source intrusions all contain primary boron which migrates to apophysis during cooling where the boron allows a hydrous melt to cool to very low temperatures and hence at an elevated crustal setting (Allman-Ward et al., 1982). Some workers note zoned tourmaline wall rock alteration parallel to the upper contact of tourmaline granites (Charoy, 1979 in Allman-Ward et al., 1982).

Depressurisation of over pressurised fluids formerly constrained at a failed intrusion carapace may result in the sufficient fluid expansion described during instantaneous retrograde boiling (above, Phillips, 1973; Burnham, 1997) to lift a body of wall rock overlying the intrusion, typically utilising shear fractures developed within the wall rock shoulders to the underlying intrusion (Phillips, 1974, 1986). Flat-

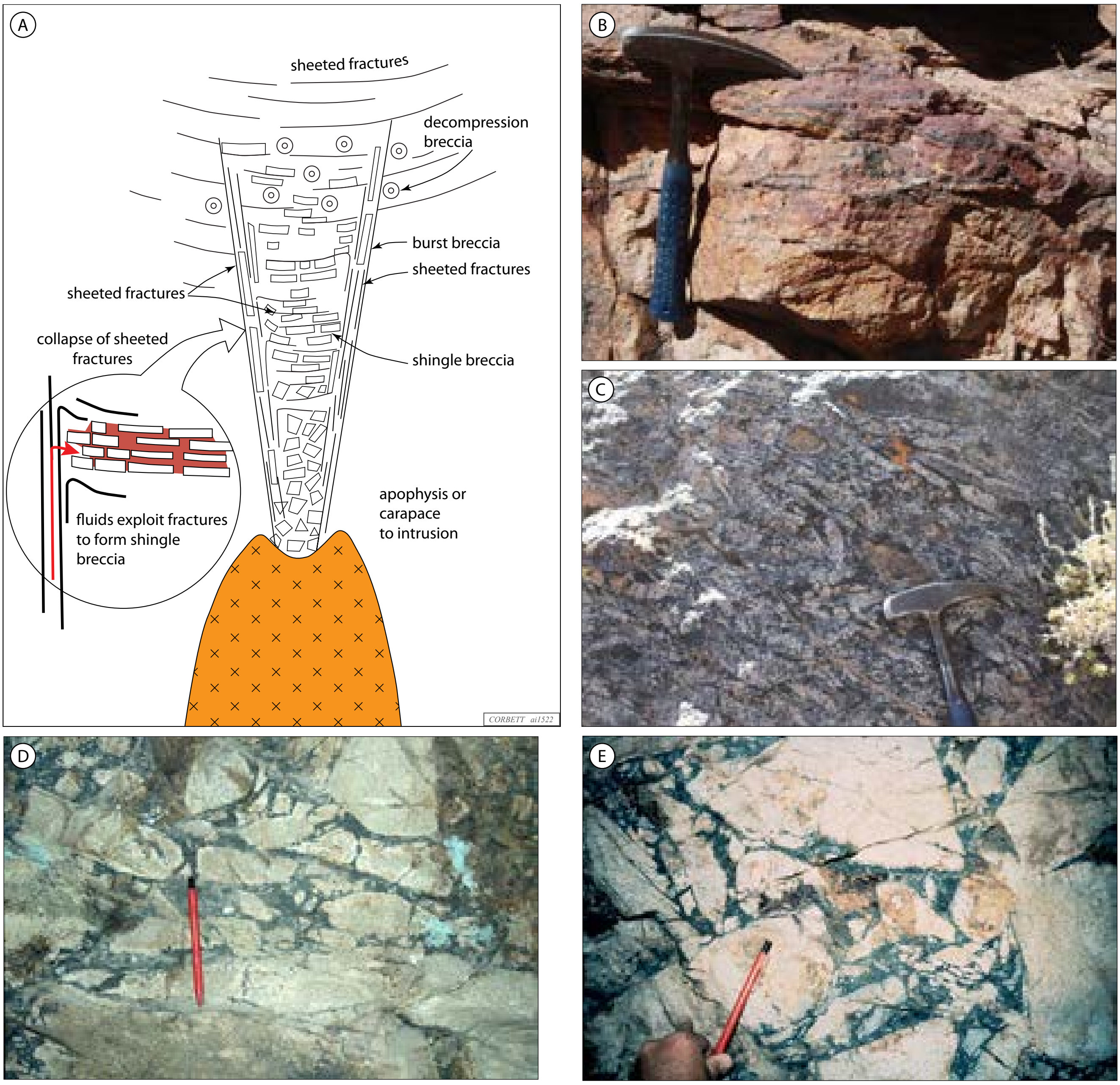


Figure 4.24 *Model for the formation of tourmaline breccia pipes characterised by eruption, collapse and matrix fill.*
A - *Graphic illustrates the vertical zonation from uppermost fractures which grade downwards to shingle breccias and then to less elongate breccias.*
B - *Flat dipping tourmaline-filled fractured wall rocks in the vicinity of the upper portion of a tourmaline breccia pipe, Yabricoya, Northern Chile.*
C - *Initial development of flat dipping shingle breccias with tourmaline matrix, Yabricoya, Northern Chile.*
D - *Shingle breccia with tourmaline-quartz-pyrite-chalcopyrite fill in the central portion of breccia pipe geometry, Remolinos, Central Chile.*
E - *Tourmaline breccia with less elongate clasts and increased matrix in the deeper levels of breccia pipe geometry, Remolinos, Central Chile.*

dipping fractures (figure 4.24) may form at this stage. Steep-dipping burst breccias, formed in settings such as proximal to the shear fractures, as well as onion skin decompression breccias are indicative of the rapid pressure reduction followed by the fill of open space with a silica-tourmaline + sulphide matrix (figure 4.12 & 4.24). In the model described above, a void created at the top of the magma chamber by evacuation of volatiles and magma withdrawal (apparent on the data of Perry, 1961), promotes collapse of the raised body of wall rock within the pipe, aided by the pre-existing shear fractures at the margins. Collapse promotes the opening of flat lying hydraulic tension fractures within the pipe, extending into the adjacent wall rocks (figure 4.24). Where there is greatest collapse inside the pipe the sheeted fractures disaggregate to form shingle breccias by the fill of open space by the tourmaline matrix, locally with fluidised textures (Corbett and Leach, 1998). Allman-Ward et al. (1982) document collapse evidenced by the mixing of overlying wall rock clasts in a tourmaline breccia at Cornwall, U.K, while Clarke et al. (1985) cite the slab-like tabular breccia clasts as evidence for collapse at Ardlethan Tin Mine, Australia. The shingle breccias pass with increased depth to equidimensional angular clast matrix supported breccias with little appreciable transport or rounding (Remolinos breccia pipe, Chile; figure 4.24).

Mineralisation includes Sn as cassiterite at Cornwall and the Herberton district of northeast, and typical near porphyry Cu ± Au (chalcopyrite-pyrite) in Andean pipes, while deep low sulphidation quartz-sulphide Au ± Cu mineralisation is associated with other shingle breccias such as Tooloom and Mt Terrible, Australia and Tahuehueto, Mexico shown in figure 4.24. Current thinking is that brecciation occurs after the initial porphyry emplacement and potassic-propylitic alteration, but before drawdown and imposition of major sericite alteration, as evidenced by the alteration of tourmaline to dumortierite in some porphyry systems (Caspiche, Chile), and pebble dykes (Rio Blanco - Los Bronces, Chile; Warnaars et al., 1985), allowing some breccias to be well placed for fill by (deep low sulphidation epithermal) quartz-sulphide Au mineralisation (Tooloom, Eastern Australia).

4.4.4.8.1 In Central Chile the Rio Blanco - Los Bronces tourmaline breccias provide a good example of breccias formed in the main porphyry Cu belt (here Los Pelambres to El Teniente) and also present in batholiths to the west at lower altitudes. The Donoso breccia complex (figure 4.25), no doubt comprising several pipes, at Los Bronces, displays a surface extent of 500 x 700 m and has been traced to a depth described by different workers as 800-1100 m (Warnaas et al., 1985; Skewes et al., 2003). Copper grades mined underground exceed 1% Cu, although early mining following the 1864 discovery produced supergene ores in the order of 20% Cu, while chalcocite coatings on sulphides provided high grades at deeper levels in the 1980's (Warnaas, op cit). The above workers describe generally angular tourmaline-bearing matrix-supported monomictic breccias developed by explosive eruption and collapse formed after the main porphyry Cu mineralisation from 7.4 to 4.9 m.y. followed by dacite porphyry and breccia emplacement. Wall rock andesite clasts have collapsed 300 m into the brecciated porphyry host. Considerable erosion (Skewes et al., 2003) has exposed the central portion of the pipe dominated by equidimensional clasts. Mineralisation as pyrite-chalcopyrite and minor bornite entered the matrix after brecciation and deposited by rapid cooling (Skewes et al, 2003) and the data of Warnaars et al (1985) illustrates high grade Cu is best developed within the permeable pipe margins and collapse zones (figure 4.25). Molybdenite to 0.1% near the margin of the breccia body was emplaced into the breccia matrix after pyrite-chalcopyrite (Warnaars, op cit). Late pebble dykes cut the tourmaline breccias. Skewes and co-workers suggest brecciation was initiated late in the porphyry event by rapid uplift and erosion due to the flattening of the subduction angle (Skewes and Stern, 1994; Skewes et al., 2003).

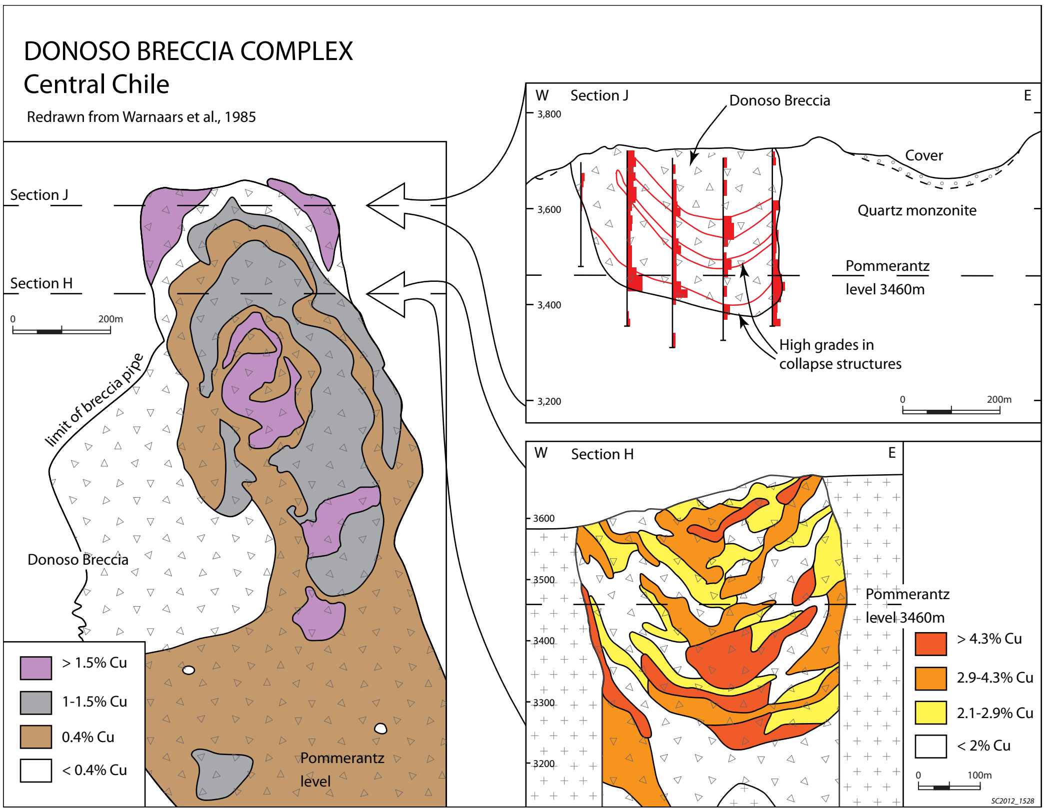


Figure 4.25 *The Donoso breccia complex (pipe), Rio Blanco - Los Bronces, Chile, as a plan view at left and two cross sections at the right, showing high grade Cu zones within collapse features and at the margins (modified from Warnaars et al., 1985).*

4.4.4.9 Conclusion - magmatic hydrothermal breccias

These breccias dominate in the crustal region immediately overlying source porphyry intrusions extending to a higher crustal level to display an association with sub-volcanic intrusions, although breccia bodies are interpreted not to have vented to the surface.
There is a typical sequence of events as:
- Pressure build up at the carapace
- Eruption, degassing of the underlying intrusion and fracture formation
- Collapse and continued fracture development
- Mineralisation as liquid dominant fluids vent from deeper magmatic source

The **exploration implications** of the successful identification of the different styles of magmatic hydrothermal breccias might be an understanding of the relationship to mineralisation. Some such as pebble dykes might vector towards porphyry systems, while sulphide matrix breccias occur in the upper portions of porphyry and tourmaline breccia pipes. Although locally mined for porphyry and deep epithermal ores, most pipes display more enigmatic relationships to buried porphyry source rocks. Similarly, some epithermal ores might be associated with breccia pipes, commonly as breccia fill and vein ores.

4.4.5 Phreatomagmatic breccias

Phreatomagmatic breccias form by the interaction of hydrothermal fluid and a hot magmatic component as the term suggests, phreato for pressurised water turning to steam and magmatic for the hot intrusion driving force. Individual breccias are characterised by clasts which are strongly milled during extensive upward transport and mixing, set in a rock flour matrix with associated hydrothermal alteration, while the brecciation process features both upward injection then collapse and later stage mineralisation, as also recognised for other magmatic hydrothermal breccias (figure 4.26). Diatreme breccia pipes vent to the surface as vertically attenuated bodies, commonly occurring in association with flow dome complexes and are defined by a characteristic set of features described below (figure 4.27). Where poorly eroded, the surficial expression of a diatreme breccia pipe is termed a maar volcano and may be filled with lacustrine deposits, while ejecta forms tuff rings outside the pipe overlying the adjacent wall rocks.
The scale of phreatomagmatic breccia bodies varies from several mm scale phreatomagmatic breccia dykes (which need not vent to the surface) to diatreme pipes with surface expression of up to > 5.5 x 2.5 km scale for the Cripple Creek diatreme, Colorado (figure 4.39), and similar dimensions Nauti diatreme, Morobe Goldfield, Papua New Guinea (figure 4.36). Phreatomagmatic breccias associated with epithermal Au-Ag deposits tend to feature shallow crustal level felsic intrusions such as dacite domes, whereas diamond-bearing kimberlite breccia pipes are associated with mafic source rocks derived from considerable crustal depths. Endogenous domes may vent to the surface forming marginal crumple breccias (figure 4.6), and 'juvenile intrusion clasts' derived from brecciation of the driving intrusion represent an essential and characteristic component of diatreme breccia pipes where they may display ragged shapes indicative of emplacement while still molten (figures 4.26 & 4.29).

4.4.5.1 The term 'diatreme breccia'
is avoided for individual breccias as there is considerable variation in breccia style within any breccia pipe and many aspects must be confirmed before a breccia body might be considered a diatreme breccia pipe. Indeed some possible diatreme breccia pipes have remained uncertain for many years (Gold Ridge, Solomon Islands; figure 4.40). Rather, the preferred term for the majority of breccias formed by phreatomagmatic processes is <u>milled matrix breccia</u>, as a description of characteristic breccia composed of rounded rock clasts which are generally supported by a rock flour matrix formed by the comminution and alteration (below) of rock material during brecciation (figure 4.26). In some cases (Kelian, Indonesia, figure 4.35; Nauti breccia in the Morobe Goldfield, Papua New Guinea, figure 4.38) locally derived softer wall rock clasts will be less milled than harder intrusion clasts which underwent much greater transport. Although clasts are dominated by wall rocks or juvenile intrusion (described below) rebrecciated mineralised or other sulphide clasts are common, along with local competent rebrecciated breccia (figure 4.34 B). Milled matrix breccias locally display a fluidised textures, especially where constrained as phreatomagmatic dykes which exploit fractures (figure 4.29; Cinola, Canada; Chatree, Thailand; Woodlark Is., Papua New Guinea). However, the term fluidised breccia dykes is avoided here as fluidised breccias are defined herein as characterised by substantial matrix and typically only minor clast transport. Phreatomagmatic breccia dykes typically predate mineralisation, display polyphasal activity and locally include geopetal structures such as graded bedding and slump structures (figure 4.3 & 4.30). The term breccia dykes is commonly used as the phreatomagmatic nature might not be established for an individual dyke.

Elsewhere, fine grained milled breccias are termed tuffisites (Corbett and Leach, 1998 and references therein) which may be bedded or occur as cross-cutting, locally polyphasal, breccia dykes (Mt Leyshon; Paull et al., 1990; Orr, 1995; Wormald, in press). Diatreme breccia pipes display pronounced polyphasal activity with later breccias cutting earlier with common rebrecciated breccia clasts as a feature to help distinguish hydrothermal from volcanic breccias. The magma associated with the phreatomagmatic eruption may be evidenced as domes (locally endogenous with crumple breccias), dismembered dykes within the pipe or as juvenile intrusion clasts.Felsic (dacite to rhyodacite) compositions dominate (figure 4.26).

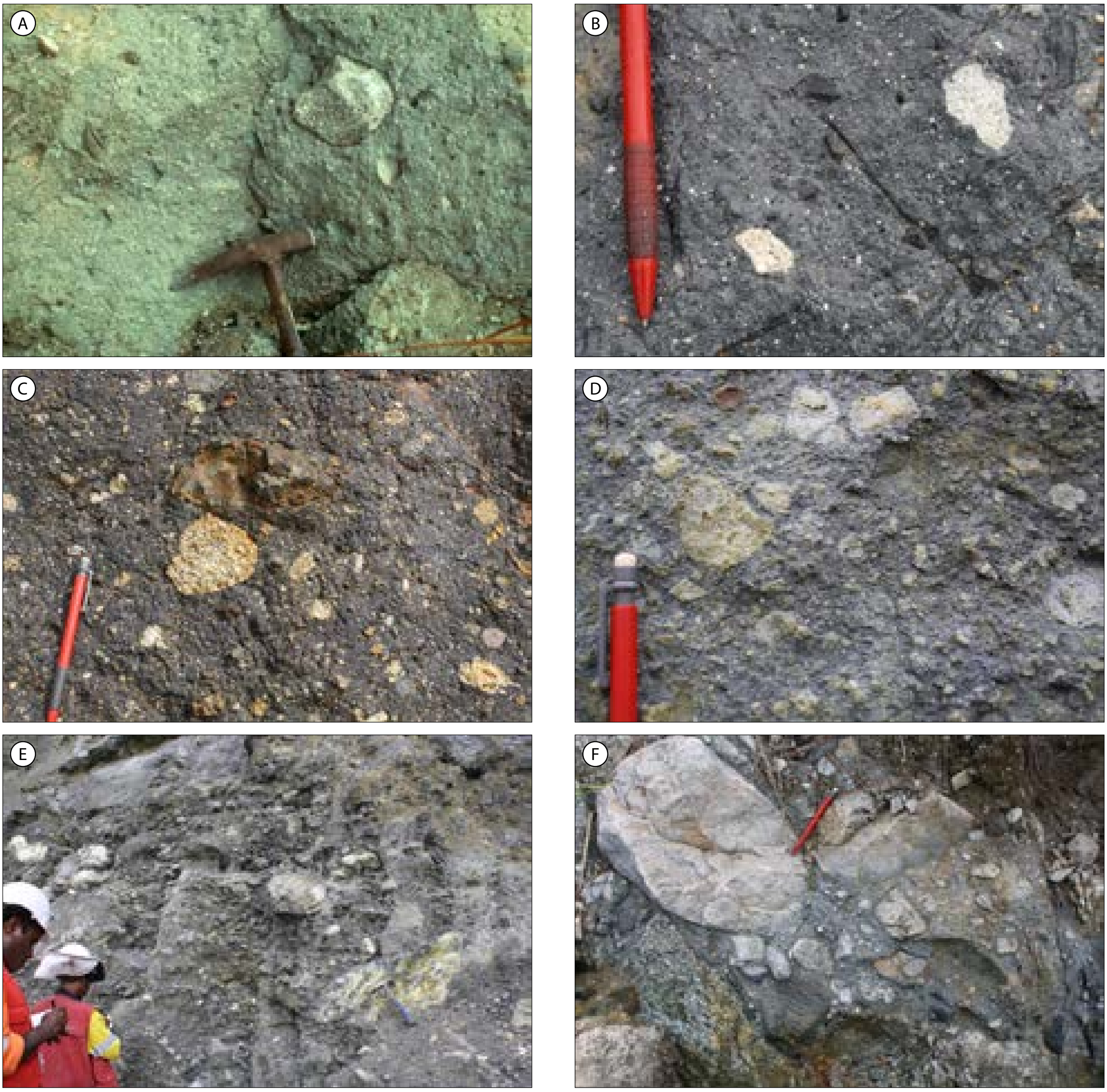


Figure 4.26 *Phreatomagmatic milled matrix breccias typical of diatreme breccia pipes.*
A - *Milled breccia with rounded clast, the Balatoc plug, Acupan, Baguio district, Philippines.*
B - *Milled breccia with ragged juvenile felsite clasts and accretionary lapilli, Nauti, Morobe district, Papua New Guinea.*
C & D - *Milled matrix breccias, Red Mountain, Philippines and Ladolam, Lihir Is., Papua New Guinea.*
E - *Chaotic breccia with coasts milled clast and sub-horizontal collapse structure, Lihir Is., Papua New Guinea.*
F - *Chaotic coarse rounded clast polymictic breccia with milled clasts and matrix, Nauti, Morobe district, Papua New Guinea.*

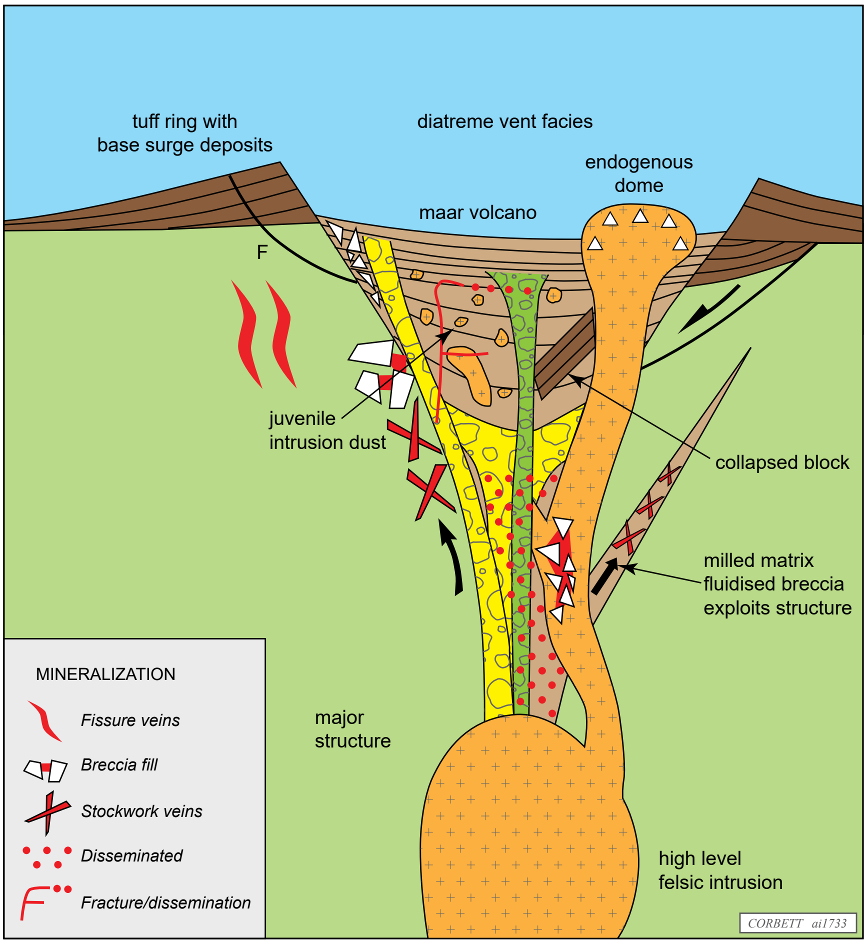


Figure 4.27 *Conceptual model for a typical diatreme breccia pipe and associated domes, modified from Corbett and Leach (1998).*

Figure 4.28 The youthful diatreme breccia pipe at Wau, Morobe Goldfield, Papua New Guinea lies in the hanging wall of the Escaprment Fault (fault plane marked by smoke) which dips towards the viewer. Endogenous domes crop out to the right and left of the central pipe, while marginal crumple breccias are shown in figure 4. 6. Soft breccias have been eroded from the centre, which has also been subject to alluvial Au mining of gold derived from high elevations. The allothonous Upper Ridges Mine block is apparent from the grey Namie Breccia to the left of the photo centre is interpreted (Corbett and Leach, 1998) to have originially formed earlier at a deeper crustal level and slid from the region of the Riboraster Mine on the skyline. The Edie Creek mining district is over the hill.

Figure 4.29 *Breccia dykes, some of which have been attributed a phreatomagmatic origin.*
A - *Sub-vertical phreatomagmatic breccia dyke dominated by a milled breccia matrix and cut by later carbonate-base metal Au mineralisation including a bedded geopetal structure, Woodlark Is., Papua New Guinea.*
B - *Phreatomagmatic breccia dyke dominated by a milled breccia matrix in the vicinity of dacite domes and cut by later carbonate-base metal Au mineralisation, Woodlark Is., Papua New Guinea.*
C - *Polyphasal breccia dyke with angular clasts and pervasive silicification, from Cinola, British Columbia, Canada.*
D - *Breccia dyke with angular clasts, pervasive wall rock silicification and a geopetal structure, from Cinola, British Columbia, Canada.*

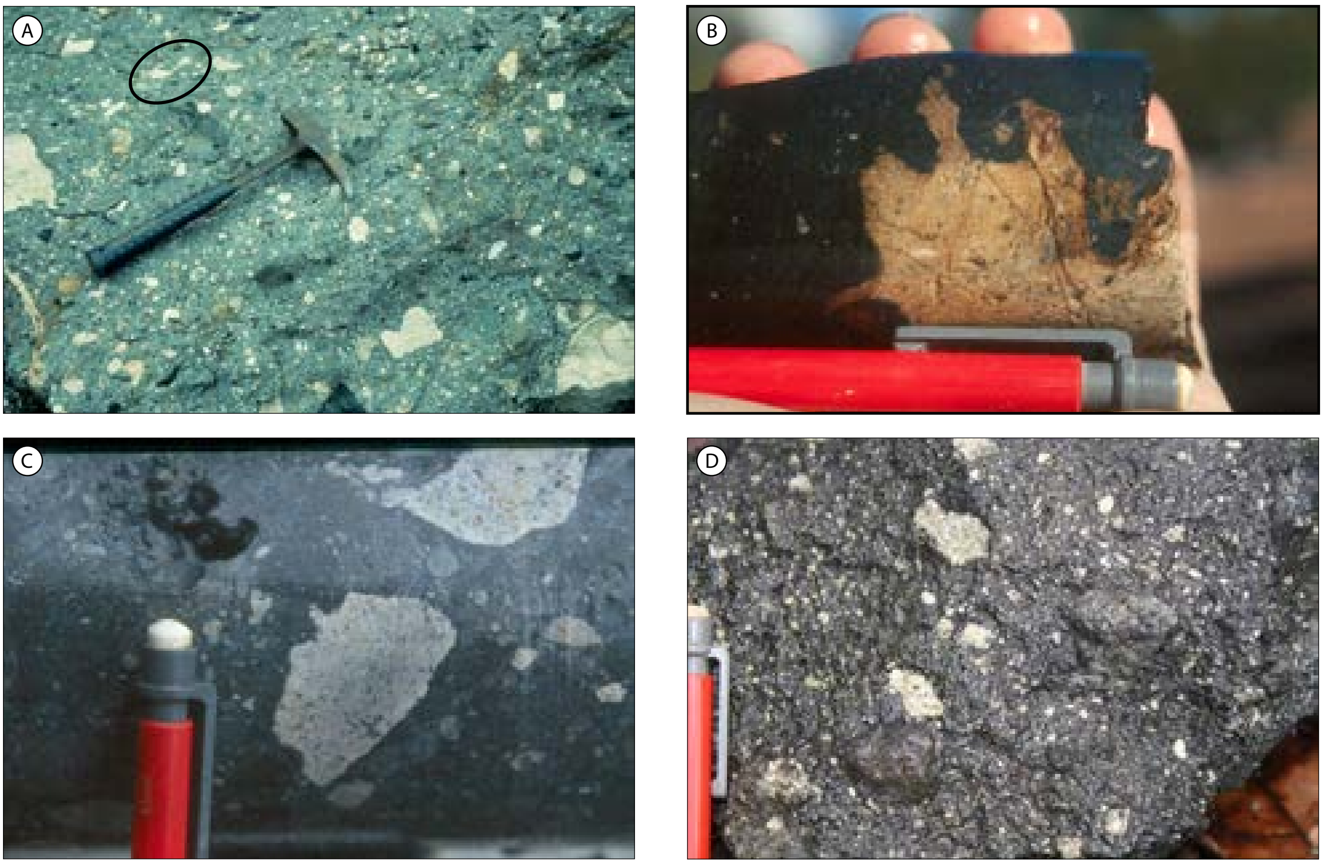


***Figure 4.30** Juvenile intrusion clasts within phreatomagmatic breccias which feature a ragged character derived from emplacement of molten magma.*

A - *The Namie milled matrix breccia which comprises milled Kaindi phyllite and jagged Edie porphyry clasts interpreted to have been molten at the time of emplacement (see circled clast), from figure 4.28, Wau, Papua New Guinea.*

B - *Jagged felsite clast from a milled matrix breccia dyke, Mineral Hill, Australia.*

C - *Jagged juvenile intrusion clasts within a milled matrix breccia from a diatreme breccia pipe, Ladolam, Lihir Is., Papua New Guinea.*

D - *Pale juvenile felsic intrusion clasts which are less milled than shale/phyllite within a milled matrix breccia from a diatreme breccia pipe, Red Mountain, Philippines.*

E - *Jagged Edie porphyry clasts within the Nauti diatreme breccias, Wau, Papua New Guinea.*

4.4.5.2 Collapse is an important aspect of diatreme breccia systems. Clasts of high crustal level wall rocks or wood (figure 4.31) are commonly recognised to collapse several hundred metres to deeper levels within breccia pipes (see Cripple Creek below). Similarly, the walls of a diatreme breccia pipe may become unstable and allow portions of the tuff ring and underlying basement to collapse into the breccia pipe. Large wall rock blocks are also common as a reflection of collapse after initial explosion. By contrast smaller scale collapse provides localised bedding within otherwise chaotic breccias (figure 4.26 E).

Accretionary lapilli, interpreted to have formed above any volcanic vent as steam condenses and falls as rain accreting suspended mud, are traditionally regarded as an indication of a surficial environment, although accretionary fabrics are also recognised in faults (figure 4.2 D). Accretionary lapilli are common within milled matrix breccias and bedded accretionary lapilli developed within tuff rings may collapse into the body of a breccia pipe. Reverse grading is common in these rocks as the coarser lapilli deposit after fine tuff (figure 4.31 E).

Figure 4.32 Surficial features and collapse within diatreme breccia pipes.
A - Collapsed block within the Nauti diatreme breccia pipe, Wau, Papua New Guinea.
B - Collapsed wood clast within breccias, Ladolam, Lihir Is., Papua New Guinea.
C - Milled matrix breccia with accretionary lapilli and juvenile intrusion clasts, one jagged at the bottom, Ladolam, Lihir Is., Papua New Guinea.
D - Milled matrix breccia with accretionary lapilli and juvenile intrusion clasts, Kelian, Indonesia.
E - Bedded milled matrix breccia with reverse grading defined by coarser lapilli in the upper portions of each bed, Kelian, Indonesia.

4.4.5.3 Milled matrix breccias vary from massive diatreme breccia pipe fill, to tuff-like layers in the upper portions of diatreme breccia pipes, and cross-cutting breccia dykes which may be polyphasal (figure 4.29). Clastic material ejected from diatreme breccia pipes collapses as base surge deposits to form tuff ring deposits outside the diatreme breccia pipe (figure 4.32 C) characterised by low angle cross bedding. Elsewhere tuff ring deposits may be well bedded and commonly contain accretionary lapilli, especially as layers, which are a characteristic feature in the upper portions of diatreme breccia pipes (figure 4.32). Layers of accretionary lapilli derived from polyphasal eruptions and fine milled matrix breccia often display reverse grading (Kelian, Indonesia; figure 4.31).

Finely comminution of volcanic material, locally termed tuffisite (above), is deposited in layers by polyphasal eruptions, to display the appearance of bedded volcanic rocks, although clay-chlorite-pyrite pyrite alteration commonly provides some linkage to the hydrothermal process. Similarly, many phreatomagmatic breccias comprised of milled clasts are similar to conglomerates and may be bedded as in the case of Gold Ridge in the Solomon Islands (figure 4.40) which remains to be classed as a breccia pipe with certainty (section 4.4.5.10). The soft hydrothermally altered breccias in the Bulolo Graben, Guinea, are dissected by Webiak and Nauti Creeks as well as the road to Hidden Valley Mine, to expose a compete section through tuff ting deposits at high elevations grading down to coarse boulder conglomerates.

4.4.5.4 Hydrothermal alteration in phreatomagmatic breccias associated with epithermal Au-Ag deposits is derived from the interaction of the volatile-rich fluids involved in phreatomagmatic brecciation (the 'phreato' part of the term) with brecciated rock, and divided between alteration typical of high or low sulphidation epithermal mineralisation. Phreatomagmatic breccias associated with high sulphidation epithermal Au deposits (Yanacocha, Pucamarca & La Virgin, Peru; Veladero & Lama Argentina; Pascua, Chile; Lepanto, Philippines) typically display silicification locally grading outwards to silica-alunite and thence clay alteration. The diatreme at Wafi, Papua New Guinea, which is interpreted to pre-date high sulphidation alteration and mineralisation, provided enhanced permeability for fluid flow and so is strongly altered (figure 4.42). The rapid rise and expansion of depressurised fluids within phreatomagmatic eruptions could provide the mechanism for formation of the acidic fluids responsible for alteration associated with high sulphidation epithermal deposits (section

Figure 4.32 *Bedded phreatomagmatic breccias and tuff rings.*
A - *Bedded Namie breccias characterised by milled shale and felsite clasts along with accretionary lapilli indicative of a surficial deposit, Wau, Papua New Guinea.*
B - *Bedded layers of fine and coarse grained breccias, Pascua, Chile.*
C - *Tuff ring overlies wall rocks at the margin of a breccia pipe, Ladolam, Lihir Is., Papua New Guinea.*

1.2.2.3). Phreatomagmatic breccias associated with low sulphidation epithermal Au deposits display zoned argillic alteration of the milled matrix breccias provided by reaction with evolving near neutral chloride fluids. Deeply eroded pipes (Mt Leyshon & Mt Terrible, Australia; Carolina, Argentina; Cripple Creek, Colorado) may be dominated by silica-sericite alteration providing more competent breccias which are more likely to host a mineralised matrix. At higher crustal levels to less competent breccias characterised by illite-pyrite alteration (Lihir, Wau, Kerimenge, Nauti, Crater Mountain in Papua New Guinea; San Cristobal, Bolivia; Kelian, Indonesia; Acupan, Philippines), and local smectite-kaolinite alteration at highest crustal levels. As the illite altered breccias in the upper portions of diatreme breccia pipe tend to be incompetent, mineralisation may be better developed in the more competent adjacent wall rocks and pipe margin (Kelian, Indonesia, figure 3.24; Acupan, Philippines, figure 4.34; Kerimenge, Papua New Guinea, figure 4.37). Indeed some phreatomagmatic breccias at Kelian were originally termed 'muddy breccias' because of the soft and incompetent character derived from milled basement shale (figure 4.35 A). Volatiles released from cooling fluids during the deposition of sulphide minerals may rise and oxidise in the vadose zone to form low pH groundwaters which react with the wall rocks to form acid sulphate caps in the uppermost near surficial portions of some diatreme breccia pipes (San Cristobal, Bolivia, figure 4.43).

4.4.5.5 Gold mineralisation post-dates initial phreatomagmatic brecciation within diatreme breccia pipes and fluidised breccias as host rock competency represents a prominent control to mineralisation. Deeply eroded systems with more competent sericite alteration are more likely to contain mineralisation in open space breccias (Mt Leyshon, Australia; figure 4.33 A), whereas the incompetent nature of higher crustal level illite-smectite altered diatreme fill (above) promotes the development of mineralisation within marginal competent host rocks close to the margin (Kelian, Indonesia, figure 4.35; Kerimenge, Papua New Guinea figure 4.37; Acupan, Indonesia, figure 4.34). For high sulphidation epithermal Au deposits phreatomagmatic eruptions provide the rapid venting and depressurisation for the essential fluid evolution, for mineral deposition within the matrix (Yanacocha, Peru, figure 4.33), or at the margins (Lepanto, Philippines). Many low sulphidation quartz-sulphide Au - carbonate-base metal Au deposits are associated with phreatomagmatic breccias commonly as diatreme breccia pipes (Kelian, Indonesia; Acupan, Philippines; Wau, Kerimenge & Lihir Is.; Papua New Guinea; Cripple Creek, Montana Tunnels, USA; Carolina, Argentina), which tap the magmatic source at depth and provide open space environments for mineral deposition.

***Figure 4.33** Gold mineralisation deposited as matrix within phreatomagmatic breccias.*
A - *Carbonate-base metal Au style characterised by galena-sphalerite-pyrite in which dark high temperature sphalerite is consistent with a deep level of erosion, Mt Leyshon, Australia.*
B - *Quartz sulphide style Au characterised by Au within pyrite, Carolina, Argentina.*
C - *Sulphide matrix high sulphidation epithermal Au mineralisation, Yanacocha, Peru.*

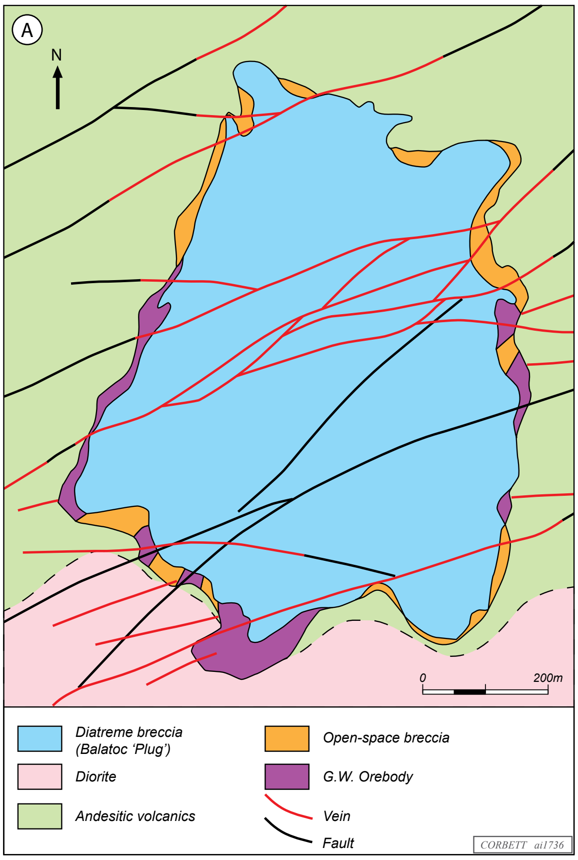


Figure 4.34 *Gold mineralisation at the margin of a diatreme breccia pipe, as the GW breccia pipes marginal to the Balatoc plug diatreme breccia pipe, Acupan gold mine, Philippines*
A - *Plan of the Balatoc plug showing location of the GW breccia pipes, from Damasco and Guzman (1977)*
B - *Milled matrix breccia within the Balatoc plug, Acupan, Philippines. Note the FeO stain derived from the weathering of pyrite clasts.*
C - *A GW breccia comprising an open space wall rock clast breccia filled with carbonate-base metal Au mineralisation, 15-30 g/t Au.*

4.4.5.6 The verification of diatreme breccia pipes as exploration tools which might vector towards mineralisation should focus upon the presence of:

- Evidence of felsic magmatic activity, varying from juvenile intrusion clasts within a milled matric breccia, to domes, including endogenous domes, and dykes which may be dismembered.
- An overall form of the breccia as a pipe or dyke-like fluidised breccias localised within structures.
- Evidence that the breccia body has vented, such as the presence of bedded tuff ring deposits, collapsed carbonised wood and accretionary lapilli.

High and low sulphidation epithermal mineralisation broadly occurs adjacent to shallow level breccia pipes and within deeper ones.

Lastly, the intense hydrothermal alteration within permeable breccias associated with high sulphidation epithermal Au deposits may make verification of the magmatic component difficult, and so some breccias might initially be regarded as phreatic-phreatomagmatic (below).

4.4.5.7 At the Kelian Au deposit carbonate-base metal Au mineralisation is associated with a diatreme flow dome complex localised within a dilatant structural setting provided by a pull-apart basin (section 3.2.2.3.1) in Kalimantan, Indonesia (Corbett and Leach, 1998; Baldwin, 2008). Epiclastic rocks of the pull-apart basin are intruded by andesite laccoliths and later diatreme breccia pipes with associated felsite domes while dismembered dykes and juvenile clasts are recognised within the breccia pipes (figure 3.24). The Runcing diatreme appears to be less eroded in the setting at the northern pull-apart basin margin and so exhibit adjacent bedded deposits typical of tuff ring settings dominated by reverse graded accretionary lapilli and felsite clasts (figures 3.24 & 4.32). The milled matrix breccias which constitute the breccia pipes display considerable variation depending upon source material (figure 4.35). Breccias dominated by soft basement shale are well milled and were termed 'muddy breccias' during exploration as a recognition of the incompetent character which would not host fracture-vein mineralisation. Breccias dominated by andesite or reworked epiclastic material, especially where the latter is silicified, tend to be more competent and host some open space breccia or vein mineralisation. Nevertheless, most breccia and sheeted vein mineralisation occurs outside the diatreme breccia pipes within the silicified permeable epiclastic rocks and andesite. Post-mining detailed descriptions are provided by Davies et al. (2008a) and Davies et al. (2008b).

***Figure 4.35** Milled matrix breccias from within diatreme breccia pipes at the Kelian Au mine shown in figure 3.24.*
***A** - Milled breccia muddy breccia dominated by finely comminuted shale to form an incompetent rock.*
***B** - Milled matrix breccia in drill core with felsite clast to the left with only poor vein formation.*
***C** - Oxidised polymictic milled matrix breccia wit abundant felsite clasts.*
***D** - Fresh clast-rich milled breccia with andesite, shale and felsite clasts.*

4.4.5.8 The Bulolo Graben which hosts the Morobe Goldfield in Papua New Guinea, formed as an intra-arc extensional graben by movement on NE trending transfer structures (Corbett, 1994), partly occupied by the mapped Snake River and Lakekamu faults (figures 3.4 & 4.36). Felsic magmatism within the Morobe goldfield is apparent as the Edie Porphyry dacite and rhyodacite as well as numerous phreatomagmatic breccias exposed by varying degrees of erosion (figure 4.36). While the age relationships between individual breccia pipes remains unknown, regional scale tilting may account for increased erosion in the south where Cretaceous Morobe Granodiorite and Kaindi Schist crop out, passing northwards to Pliocene Bulolo Ignimbrite with associated domes and breccias, overlain by Pleistocene Otabanda Formation sediments further north (figure 4.36). Care is required to distinguish between tuffs of the Bulolo Ignimbrite and phreatomagmatic tuffisites.

The youthful diatreme breccia pipe at Wau displays features typical of the upper portions of diatreme breccia pipes (Sillitoe et al., 1984) such as the endogenous domes discernible about the dome margin (figure 4.28). It is localised in the hanging wall to the regionally significant Escarpment Fault which displays normal displacement, separating the Wau diatreme from more deeply eroded high temperature mineralisation at Ribroaster (Corbett and Leach, 1998). Carbonate-base metal style Au mineralisation mined from within the Namie Breccia at the Upper Ridges open pit, is allothonous (Sillitoe et al., 1984) and formed at quite high temperatures at considerable depth (Corbett and Leach, 1998). Tuff ring deposits and carbonate-base metal style Au mineralisation occur at Edie Creek and so the Upper Ridges material is interpreted as derived from that vicinity as a down-faulted block by the Escarpment Fault. High temperature mineralisation also occurs as Ribroaster on the Escarpment Fault (Corbett and Leach, 1998). Consequently, substantial extension and collapse is apparent on the intra-graben Watut, Escarpment and Wandumi Faults (figure 4.3.6).

At Kerimenge, a diatreme breccia pipe is localised by the intersection of a NS structure with a more major NW fracture which hosts the nearby Lemenge mineralisation and extends to the Nauti (figure 4.3.6). While the barren diatreme was not prospected (figure 4.37), carbonate-base metal Au mineralisation is localised by tension veins (Corbett, unpubl. report, 1985) developed by a component of sinistral strike slip movement on the NS structure (Corbett and Leach, 1998). While fault movement provides the tension vein setting for mineralisation, the diatreme is interpreted to be linked to the source for mineralisation, and eruption may have fractured the top of the magma chamber as a trigger for mineralisation.

The Nauti Diatreme (figures 4.36 & 4.38), which could be as much as 7 km long and is discernible over several hundred metres elevation, displays changes in

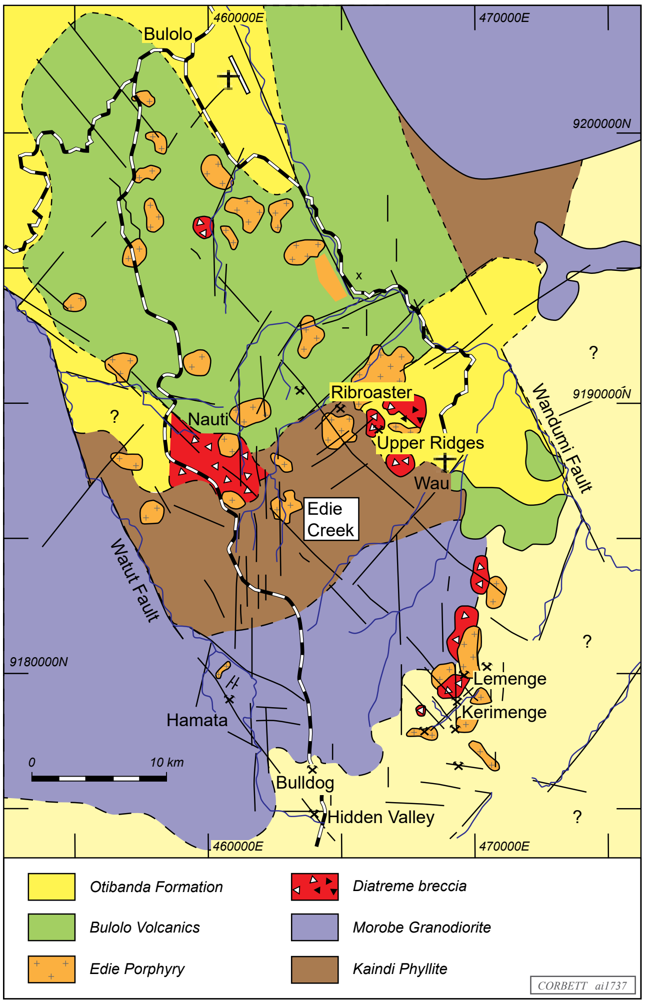


***Figure 4.36** Bulolo graben, Papua New Guinea (location in figure 3.4) showing the diatreme breccias discussed herein, updated from Corbett (1994, 2005b) and Corbett and Leach (1998).*

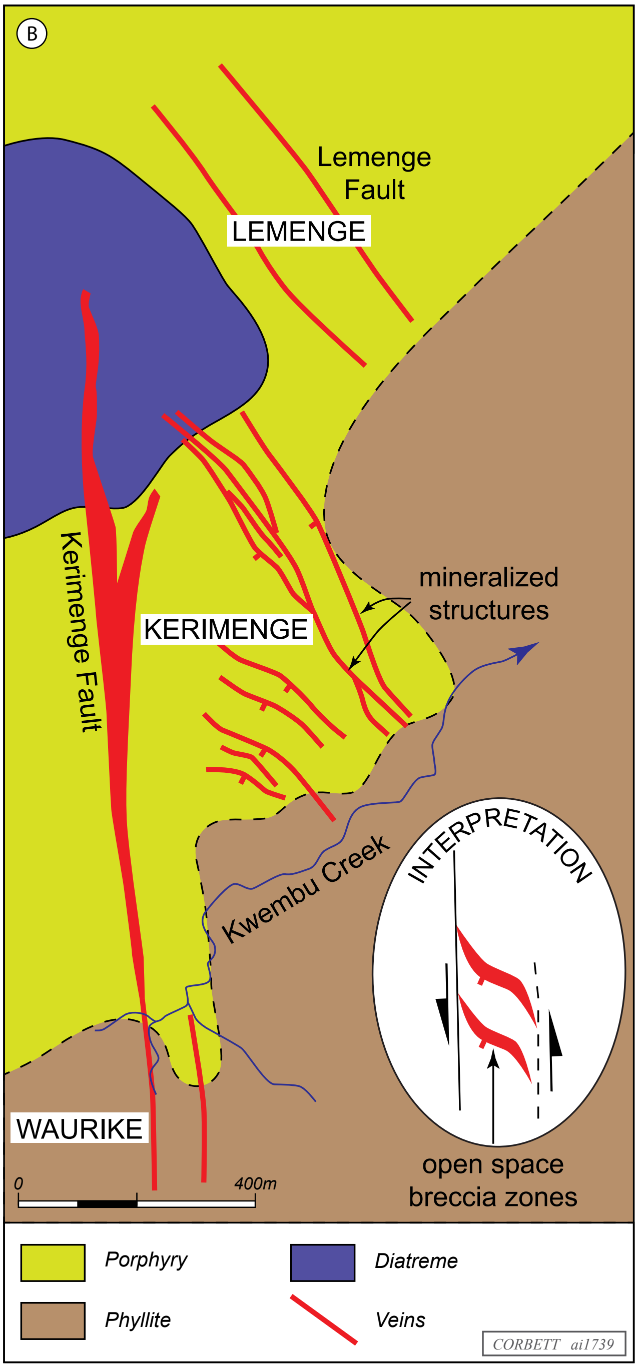


***Figure 4.37** The Kerimenge diatreme breccia pipe – tension vein environment for mineralisation.*
A - *View of Kerimenge which covers about 300-400 m vertically and shown in part B. The Kerimenge fault lies in the drainage to the left and the lower region of secondary growth marks the mineralised tension vein setting prospected several years before the photo was taken, while virgin rainforest covers the diatreme breccia pipe at the top of the hill.*
B - *Plan view of the region shown in A with interpretation of mineralised tension vein formation.*

breccia type from east, near Edie Creek, to west, close to the Upper Watut river. In the east between Edie and Webiak creeks well bedded breccias (figure 4.39 A) within a tuff ring sit on top of phyllite and obscure mineralised carbonate-base metal Au veins at the Enterprise Mine. While some veins penetrate the tuff ring they are only well developed in the underlying competent phyllite. The road to the Hidden Valley gold mine (figure 4.36) provides magnificent exposures of deeper level diatreme breccias (figure 4.38) which include massive and bedded milled matrix breccias dominated by phyllite and Edie porphyry clasts set in a milled phyllite matrix with local accretionary lapilli and slump structures. Quartz-sulphide veins are much better developed within the adjacent phyllite than the milled breccias. Breccias dominated by rounded cobbles of Morobe granodiorite and andesite porphyry, exposed in some road cuttings progressively contain larger porphyry boulders several metres across at lowest elevations to the west where breccias become obscured by alluvium near the confluence of Nauti creek and the Upper Watut river (figures 4.36 & 4.38).

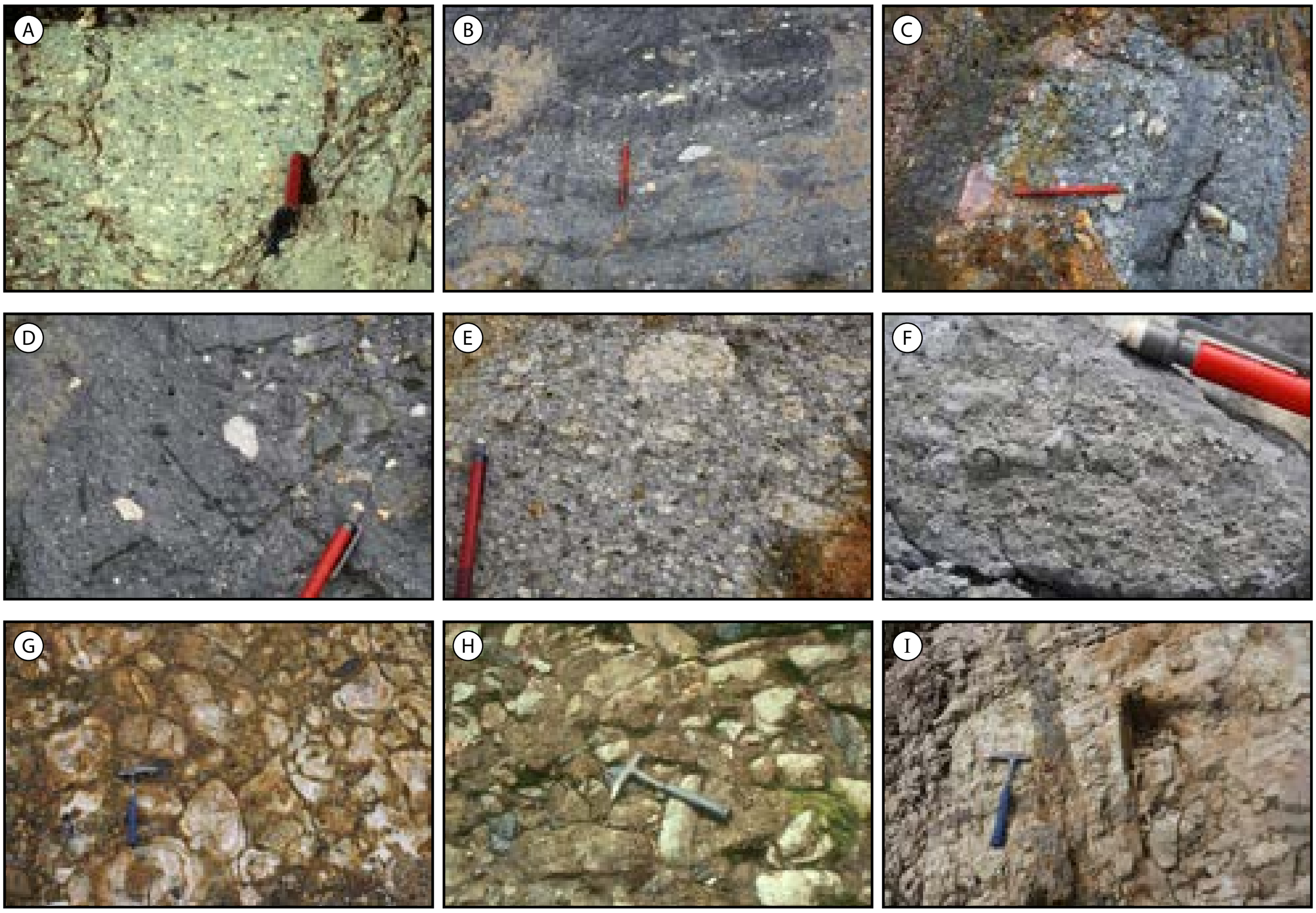


Figure 4.38 *Milled matrix breccias exposed over a several hundred metre vertical range from within the Nauti Diatreme.*
A - *Bedded breccia dominated by phyllite and Edie porphyry clasts, Webiak Creek.*
B & **C** - *Bedded milled matrix breccia dominated by phyllite and Edie porphyry material, Hidden Valley mine road.*
D & **E** - *Massive milled matrix breccia of phyllite and Edie porphyry, Hidden Valley mine road.*
F - *A layer of accretionary lapilli in milled matrix breccia, Hidden Valley mine road.*
G - *Cobble breccia dominated by milled Morobe granodiorite clasts, Hidden Valley mine road.*
H - *Cobble breccia with Morobe granodiorite and porphyry clasts Hidden Valley mine road, lower Nauti creek close to the Upper Watut River.*
I - *Pyrite vein within basement phyllite close to the diatreme margin, Hidden Valley mine road.*
J - *Green illite alteration in the milled matrix breccia.*

4.4.5.9 Cripple Creek Au mineralisation is associated with a 32 Ma (Kelly, 1996 in Harris et al., 2002; Vardiman et al., 2006) diatreme breccia pipe up to 7 x 4 km in size, or more likely a series of diatremes aligned along a NW structure (Harris et al., 2002), which cut Precambrian granite and gneiss. Brecciation appears to have been driven by alkaline intrusions of dominantly phonolite composition and grades to final radial lamprophyre dykes (Thompson, 1992). Historic gold production since 1891, has extracted approximately 23.5 M oz Au with a recent resource estimate of 3.3 M oz Au (Vardiman, et al., 2006). The presence of large blocks of basement (figure 4.39) without significant tuff ring deposits suggest the diatreme pipe has undergone moderate erosion, although significant collapse is apparent from the presence within the diatreme of carbonised logs 300 m below surface (Thompson et al., 1985) and lacustrine sediments >600 m below surface (Thompson, 1992). The diatreme breccia rocks comprise typical milled matrix breccias with characteristic illite alteration (figure 4.39). Gold mineralisation occurs as veins, fractures and breccia fill (Thompson, 1992). Veins, with a dominantly radial distribution, are best developed in the competent basement rocks adjacent to and below the flared diatreme rim, rather than the incompetent milled matrix breccias. The Cresson deposit (figure 4.39), described as a phreatic breccia pipe (Harris et al., 2002), is dominated by lamprophyre clasts, post-dates the main diatreme, and produced >14 M oz Au @ 18.8 g/t Au in the 1904-1959 period, from the breccia matrix and marginal veins (Thompson, 1992). Hydrothermal breccias described (Thompson, 1992) are well developed near structural intersections, as upward extensions of veins and with vein clasts, contain kaolin as an indicator of possible fluid mixing as a mechanism of Au deposition in these settings, although the kaolin may be derived from deep weathering. Fracture and breccia matrix MnO recognised in the field (figure 4.39) along with carbonate, galena and sphalerite within published descriptions (Thompson, 1992 and references therein) indicate Au mineralisation is of a carbonate-base metal Au style as recognised in many other diatreme breccia pipes (section 7.1.1.2).

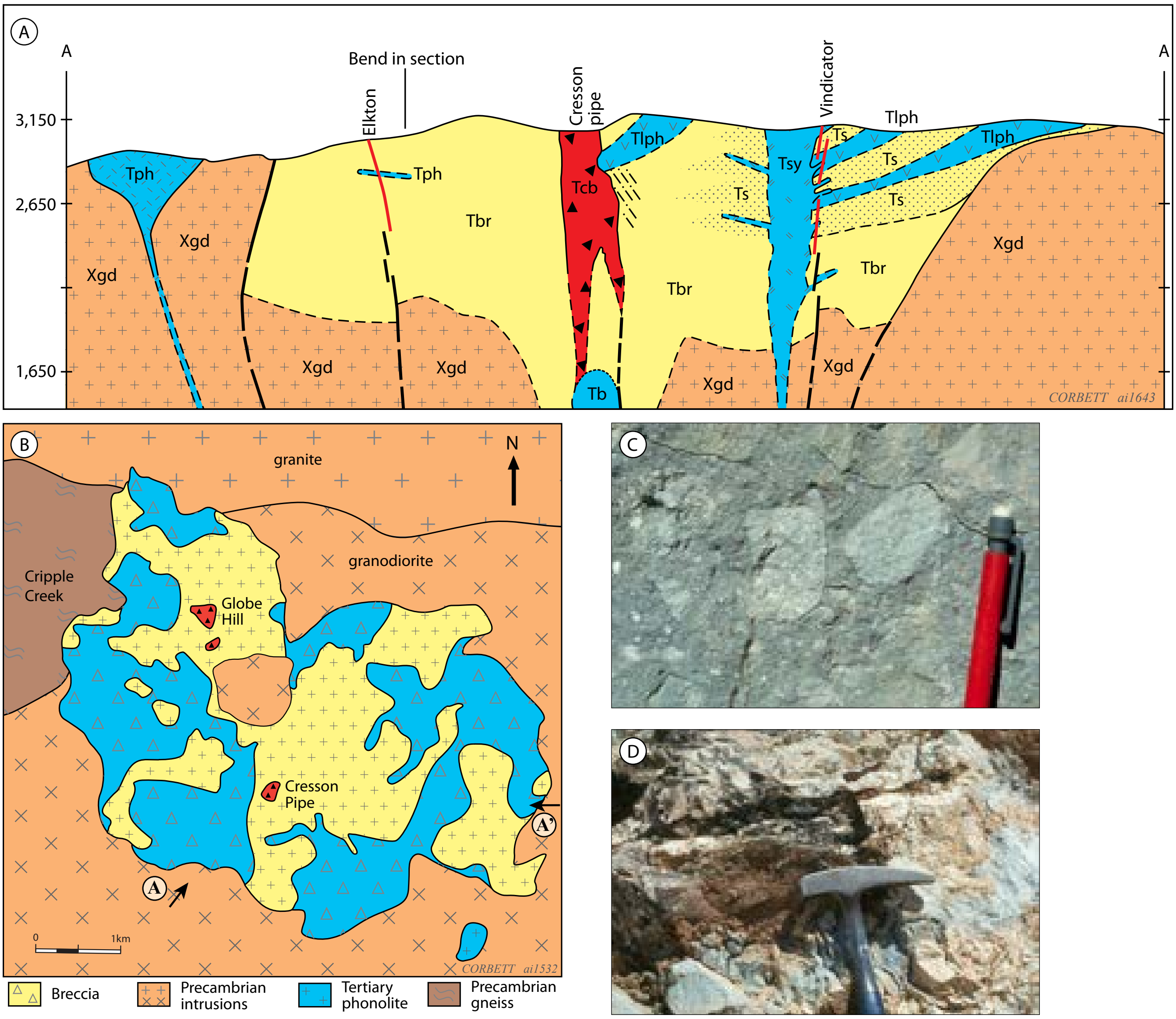


Figure 4.39 *The Cripple Creek diatreme breccia.*
A - *Cross section from Thompson et al. (1985).*
B - *Geological map redrawn from Harris et al. (2002).*
C - *Illite altered milled matrix breccia.*
D - *MnO stain indicative of oxidised carbonate-base metal Au mineralisation.*
E - *Cresson breccia pipe in outcrop.*

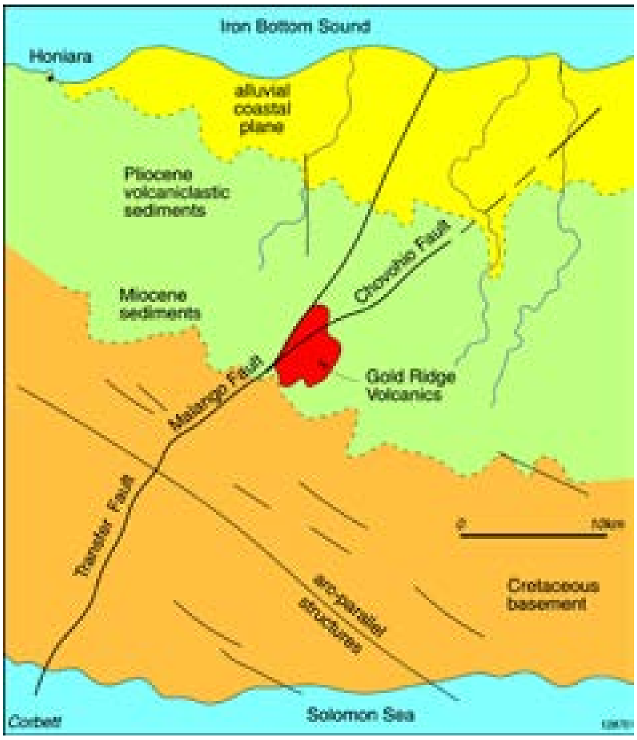


Figure 4.40 *Breccias at the Gold Ridge Au deposit, Solomon Islands interpreted as of an phreatomagmatic origin.*
A - *Location of Gold Ridge at a splay on a major structure which transects Guadalcanal.*
B - *View of the Valehaichichi open pit in which a low angle fault extends from top left to lower right.*
C - *Milled matrix breccia with kaolin-carbonate-illite alteration and mineralised disseminated pyrite.*
D - *Milled matrix breccia with kaolin-carbonate-illite alteration and mineralised disseminated pyrite and a carbonate-base metal Au vein.*
F - *Mineralised milled breccia with kaolin in the open space, 1-2 g/t Au.*
G - Milled breccia with carbonate vein clast.

4.4.5.10 The Gold Ridge gold deposit, Solomon Islands, lies within a 7 x 5 km oval body of clastic rock, termed the Gold Ridge Volcanics, in Central Guadalcanal, localised at the splay in a major trans-island structure (figure 4.40). Gold reported to have been panned in the region by the Spanish explorer Mendana in the 16th century is likely to have been derived from the deeply eroded Gold Ridge deposit. While some mining took place from the 1930's, main production by Ross Mining yielded about 200,000 oz Au from August 1998 to June 2000, when the mine was closed by an insurgency. The bedded nature of clastic rocks at the Valehaichichi open pit, and the lack of any igneous component recognition to date, has led many workers to promote a sedimentary origin for the Gold Ridge Volcanics. However, Hackman (1980) suggested an explosive origin might account for the pervasive hydrothermal alteration and rapid variation in rock types within the Gold Ridge Volcanics. Coleman et al. (1988) described these rocks as a “bewildering mixture of chaotic and polymictic conglomerate”, which comprise carbonised logs amongst hard resistant rounded clasts and deep sea limestone clasts. Some milled breccias appear similar to conglomerates and clastic rocks may develop within a down-dropped block. Bedding plane shears and low angle faults Valehaichichi open pit are indicative of considerable collapse at Gold Ridge. Throughout Gold Ridge, diamond drill core displays an appearance of strongly altered polymictic milled matrix breccias, many with Au anomalism associated with disseminated cubic pyrite (figure 4.40 C-F) similar to many phreatomagmatic breccias. The fill of open space with kaolin and/or carbonate in a mineralised breccias (figure 4.40 E) and presence of milled vein clasts within the breccia (figure 4.40 F), suggest there is a link between brecciation, alteration and mineralisation.

While more detailed work is required, there is strong case that the carbonate-base metal Au mineralisation at Gold Ridge is genetically related to a diatreme breccia pipe. Zoned carbonate alteration (Corbett and Leach, 1998) is similar to other carbonate-base metal Au deposits (section 7.5.4.3).

4.4.5.11 The Ladolam gold deposit, Lihir Is. Papua New Guinea hosts a tremendous variety of breccias with different relationships to mineralisation that have formed progressively over time. Permeable volcanic breccias promoted hydrothermal fluid flow and have become further brecciated by expanding depressurised ore fluids (figure 4.41 A). Anhydrite matrix breccias, which developed during porphyry emplacement and early potassic alteration, appear to have acted as a base for slide planes developed as listric faults in order to facilitate sector collapse (figure 4.41 B) and locally display a polyphasal character (figure 4.41 C). Sub -horizontally aligned breccias given the field term ‘slab breccias’ (figure 4.41 D) are interpreted to result from early collapse evidenced by wood clasts (figure 4.32 B). Mineralised breccias host sulphides within crackle, fluidised and mosaic breccias in which Au grade is proportional to sulphide content (figures 4.1 B & C). Clay matrix breccias developed by the collapse of argillic alteration upon the prograde alteration (figures 2.18 E; & 4.41 E - H). Eruption or phreatic breccias, which develop by the explosion of depressurised waters without magmatic influence, form at shallow crustal levels with angular poorly milled clasts (figure 4.41 I).

Phreatomagmatic breccias developed in response to the dramatic pressure reduction derived from sector collapse and unroofing of the early porphyry and high level dome emplacement, at the initiation of mineralisation. Ladolam phreatomagmatic breccias are similar to many others formed at a relatively high crustal level and feature chaotic mixes of clasts (figure 4.41 H) in which the permeable matrix may display intense illite-pyrite alteration (figure 4.41 E & F) varying to additional smectite and/or kaolin. Milled matrix breccias vary from those dominated by a muddy clay altered matrix (figure 4.26 E), to others in which the matrix is pyrite flooded, and those with evidence of venting to the surface provided by accretionary lapilli (figure 4.31 C & 4.41 F), locally with bedded forms (figure 4.41 K). The incompetent clay alteration generally restricts the development of sulphide mineralisation within the diatreme breccia rocks.

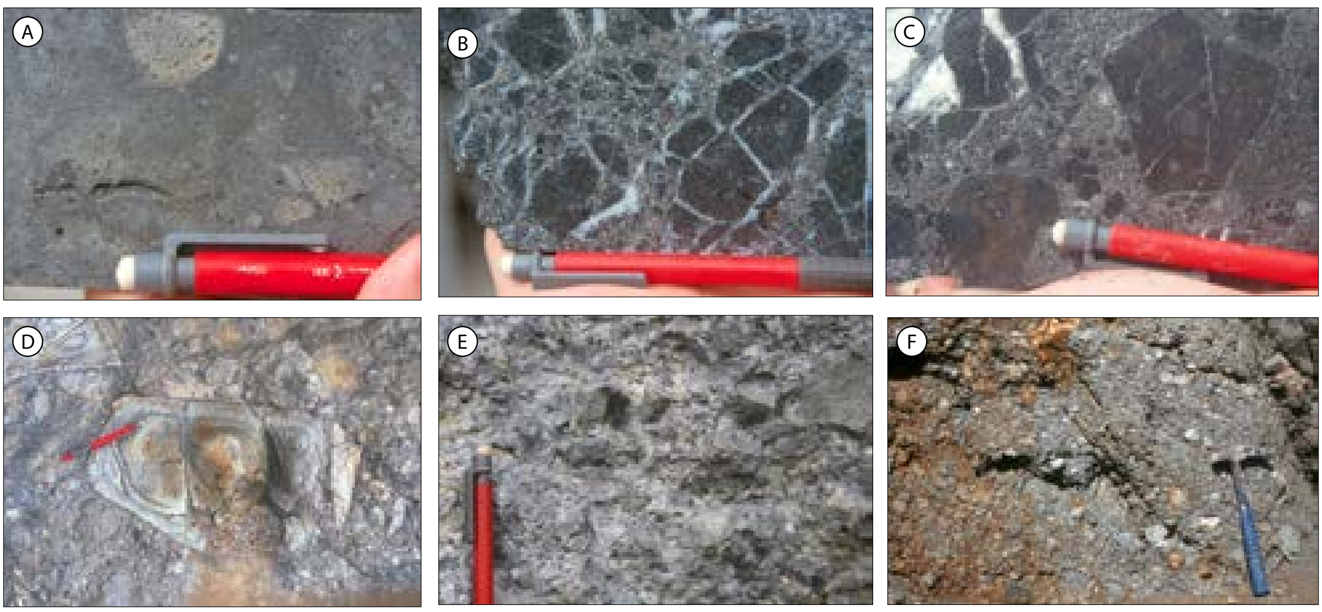


Figure 4.41 *Breccias at the Ladolam Au mine Lihir Is., Papua New Guinea.*
A - *Volcanic breccia exploited by hydrothermal fluids which deposited silica-pyrite-K-feldspar hydrothermal fluid alteration.*
B - *Potassic altered porphyry cut by anhydrite filled mosaic breccia.*
C - *Anhydrite matrix breccia with rebrecciated breccia clasts.*
D - *Slab breccia with large angular horizontally aligned clasts interpreted to have formed by collapse.*
E - *Clay matrix breccia formed by argillic alteration overprint.*
F - *Milled matrix breccia in outcrop with marginal oxidation of the intense pyrite flooding.*
G - *Milled matrix breccia.*
H - *Sub-horizontal layering within a generally chaotic milled matrix breccia.*
I - *Eruption or phreatic breccia characterised by bleached angular clasts, Costal Zone 1984.*

4.4.5.12 The Wafi-Golpu Project, Papua New Guinea, is localised by the Wafi transfer structure which represents part of the suture between the western and eastern orogens of Papua New Guinea (Corbett, 1994, 2005b). Layered metasedimentary host rocks at Wafi are cut by a 800 x 440 m steep sided diatreme breccia pipe filled with polyphasal milled matrix breccias and dacite porphyry, best developed about the margin and as breccia clasts (figure 4.42). The diatreme breccias and fractured metasediments at the pipe margin provide permeability for the east to west lateral fluid flow of the hot acid fluids responsible for development of the zoned advanced argillic alteration which cross-cuts the diatreme (figure 2.41; Corbett and Leach, 1998; Leach, 1999). Consequently, alteration increases in thickness within the more permeable milled matrix breccias. The diatreme breccias contain clasts of the earlier porphyry (Leach, 1999) dated at 14 Ma, while the younger 13 Ma (Tau-Loi and Andrews, 1998) advanced argillic alteration transects it, rather than is directly related to the diatreme breccia pipe (figure ***). As discussed later (sections 5 & 8) the advanced argillic alteration is interpreted to have been derived from a deeper level intrusion source adjacent to the Golpu porphyry and remobilised metals to provide high Cu grades associated with covellite, as it transected the top of the earlier Golpu porphyry (figure ***). Although there is apparent paragenetic sequence of: Golpu porphyry -> diatreme flow dome complex -> Wafi high sulphidation Au event and Cu enrichment of the Golpu cap, this sequence could result from the rapid during uplift and erosion of a single rather than multiple magma sources. A similar diatreme breccia pipes cut the Dizon porphyry Cu, Philippines (Malihan, 1987; Sillitoe and Gappe, 1984), and El Teniente, Chile (Vry et al., 2010).

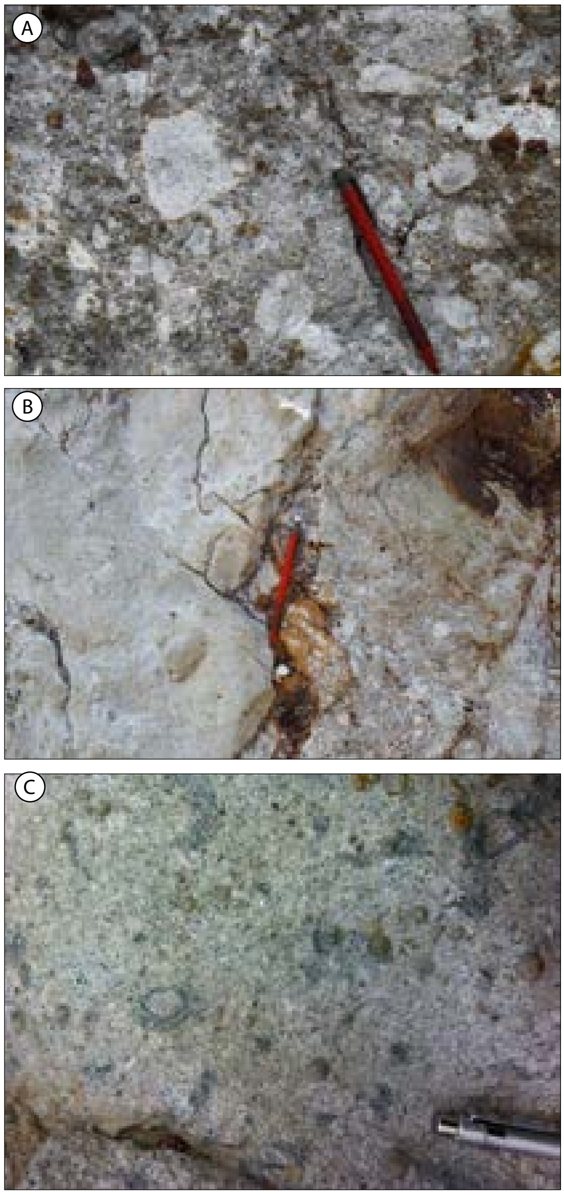


Figure 4.42 *Wafi diatreme breccia pipe.*
A - *Milled matrix breccia with abundant juvenile dacite porphyry clasts.*
B - *Contact between two milled matrix breccias.*
C - *Fine grained milled matrix breccia with accretionary lapilli.*

4.4.5.13 The San Cristobal, polymetallic Ag-Zn-Pb mine in southern Bolivia lies within an oval shaped diatreme breccia pipe about 1.5 x 1.9 km which is rimmed by a series of weakly Zn-Ag anomalous dacite domes, while some intrusions are also recognised within the breccia pipe. The low temperature white sphalerite within the domes is consistent with a very high crustal (near surficial) level of dome emplacement. The diatreme breccia has developed by repeated phreatomagmatic eruption evidenced by cross-cutting variable phreatomagmatic breccias and common layered breccias in which disconformities in road cuttings are indicative of collapse during deposition. Breccias vary from matrix supported cobble size to mostly finely layered tuffs with common juvenile intrusion clasts in which ragged shapes are indicative of breccia formation while the intrusion clasts were molten (figure 4.43). Although some fracture/vein mineralisation is recognised within competent domes at the pipe margin, the dominant sulphide breccia matrix ores are interpreted to have formed as post-breccia replacement by sulphide fill of open space matrix within bedded breccias (figure 4.43). This bedded form has led some workers to prefer volcanogenic massive sulphide origin for this deposit and some fine pyritic lacustrine-like sediments may fit that model (figure 4.43 H). However, the red moderate-high temperature is more consistent with the deeper crustal level low sulphidation epithermal polymetallic Ag-Au style preferred herein (figure 4.43 I). Higher temperature sphalerite within the breccias formed from a deeper level fluid than the cooler higher crustal domes (above). High Ag grades associated with the mixing of collapsing acid sulphate fluids with rising ore fluids is discussed in section 7.4 and also typical of epithermal settings.

***Figure 4.43** The San Cristobal diatreme breccia pipe, Bolivia.*
A - *View of the San Cristobal diatreme breccia pipe at the start of mining showing the Jayula dome in the background and some acid sulphate alteration to the left.*
B - *Milled breccia with volcanic and sulphide clasts and a muddy finely comminuted matrix.*
C - *Fine grained milled breccia with volcanic and sulphide clasts and a muddy finely comminuted matrix.*
D - *Bedded breccias with dacite material in the coarser layers.*
E - *Breccia with ragged juvenile dacite clasts.*
F - *Cobble size breccia clasts in an adit with celandonite altered clast.*
G - *Milled matrix rich breccia formed as a cross cutting dyke.*
H - *Bedded fine grained sulphide possibly formed as a lake bed sediment.*
I - *Red sphalerite matrix to a milled matrix breccia.*

4.4.5.14 Phreatomagmatic breccias – conclusion

Phreatomagmatic breccias result from the explosive depressurisation of volatiles associated with rising high level generally dacitic domes and the interaction with ground waters and therefore include magmatic features such as juvenile intrusion clasts and are associated with endogenous domes. Characteristic milled matrix breccias of strongly comminuted clasts fill breccia pipes which vent to the surface, although intrusive breccia dykes are also noted. Post-eruption collapse is common. In low sulphidation epithermal Au deposits, steam derived from depressurised water and volatiles provides clay alteration to render the breccias within the upper cooler portions of pipes incompetent and unable to host fracture mineralisation. Consequently, here mineralisation is more likely to occur in the adjacent competent wall rocks, while at deeper levels sericite alteration will be more competent and mineralisation may occur within the breccia matrix. In high sulphidation epithermal systems phreatomagmatic breccias might provide permeability for hydrothermal fluid flow within the pipe (Wafi) or at the pipe margin (Lepanto). Furthermore the rapid rise of fluids during diatreme breccia pipe formation may promote the development of acid fluids responsible for the development of zoned advanced argillic alteration.

The **exploration implication** of the successful identification of phreatomagmatic breccias and understanding of a diatreme breccia pipe geometry might allow explorationists to better gauge the likely setting and style of mineralisation. Phreatomagmatic breccias are typically associated with low sulphidation carbonate-base metal Au mineralisation, locally with the quartz-sulphide Au precursor and evolving to epithermal quartz Au. High sulphidation epithermal Au deposits also use the permeability provided by phreatomagmatic breccias to promote fluid flow leading to alteration and mineralisation.

4.4.6 Phreatic or eruption breccias

Phreatic or eruption breccias develop by the violent release of pressurised steam, locally constrained below an impermeable silicified rocks which might act as a barrier, typically at shallow crustal levels and locally forming pipe-like bodies varying from a few metres many tens of metres in diameter (figure 4.45; Corbett and Leach, 1998 and references therein). Pipes are localised by structures, which by continued movement, trigger many eruptions. Breccia pipes that range to only a few tens of metres in diameter vent to the surface to form shallow eruption craters which remain as hot pools in youthful terrains such as the Taupo Volcanic Zone and White Island, New Zealand (figures 4.46, 4.47 & 4.60; Simmons et al., 1992, and references therein) or Japan, some of which deposit metals (Beppu, figure 4.45, Corbett and Leach, 1998). Early terms included hydrothermal explosion breccias (Baker et al., 1986) and the pressure release mechanism might be used to also include the class of hydrothermal breccias such as crackle and fluidised breccias (below) amongst phreatic breccias. However, as these latter breccias may contain a significant magmatic component (below) this term is not preferred. In this definition for phreatic breccias, steam is commonly provided by meteoric-dominant geothermal sources, which may have been heated by a proximal magmatic source, although phreatic or eruption breccias are defined as containing minimal direct magmatic input. Magmatic clasts and dismembered dykes are recognised in the Twin Hills eruption breccia described below. Eruption is recognised at many scales in place and time. Regular steam pressure build up and release provides a cyclical display at geysers such as Old Faithful at Yellowstone National Park, USA, or the former Waimangu Geyser, New Zealand (below). Other triggers for the dynamic phreatic or eruption include mostly the removal of confining pressure by rapid unroofing, common in earthquake-prone geothermal settings as well as local changes in hydrology such as increased ground water by elevated rainfall or a flood as well as any increase in heat flow, such as rising magma at depth. In the Taupo Volcanic Zone, the Waimangu Geyser, which erupted frequently early in the 19th century was initiation by the Tarawera Rift, and Champagne Pool is interpreted (Corbett and Leach, 1998) to lie in a dilatant setting in a rift structure. The constraining impermeable barrier (above) is typically provided by silicified wall rocks, especially in volcanic rock sequences where originally permeable units may become silicified and display repeated brecciation and silicification. Pressure drop upon eruption promotes silica deposition and enhances development of the brecciated impermeable barrier through repeated eruption, brecciation and silica deposition.

There is a gradation from silica flooding to clay alteration of eruption breccias (described below), dependent mainly upon whether the vent has acted as an outflow for silica-rich hydrothermal fluids, in which case silica sinter deposits commonly form, locally varying to carbonate-dominant travertine or mixed deposits (Wau, Papua New Guinea; El Peñón district, Chile; Cerro Negro district, Argentina).

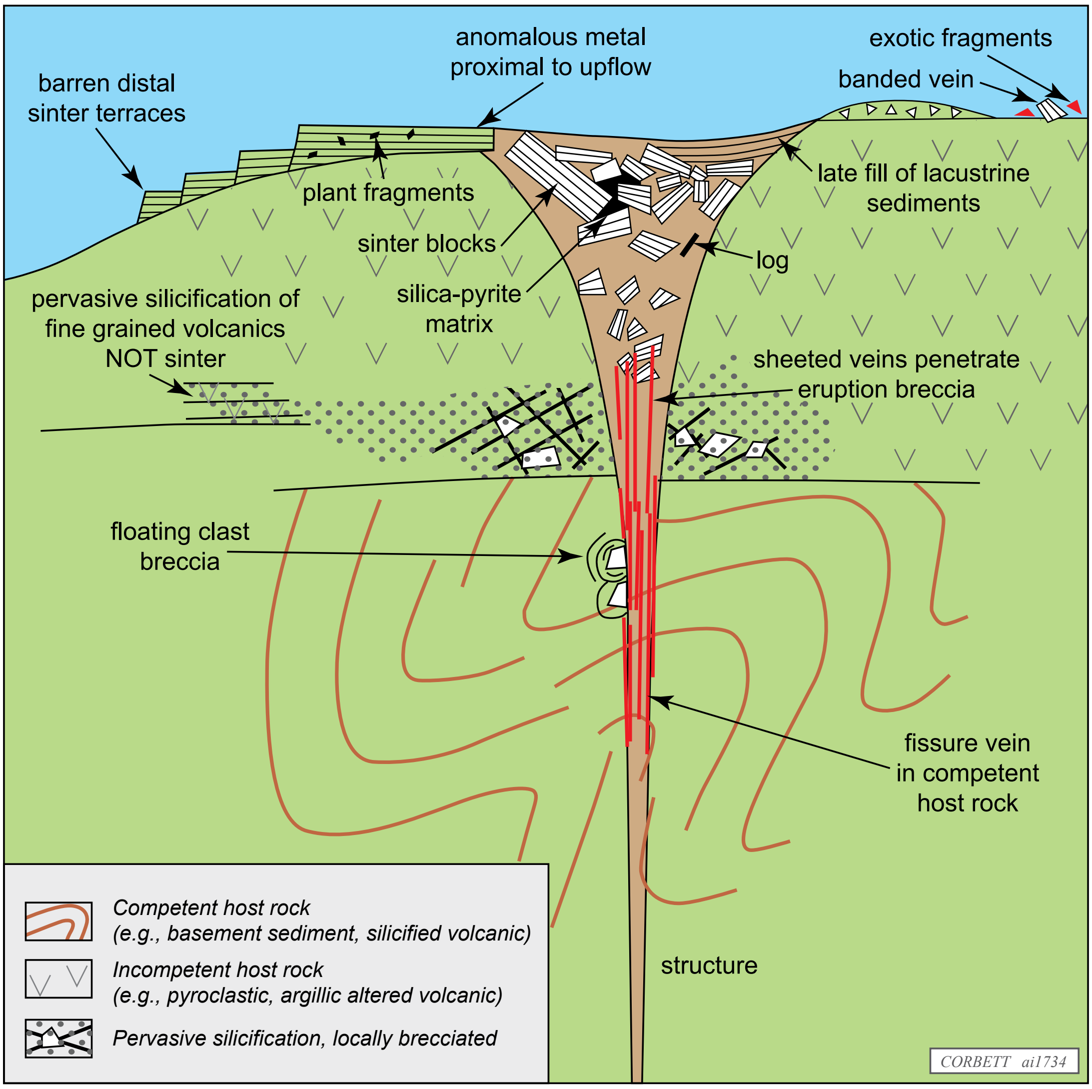


Figure 4.44 *Conceptual model for the formation of phreatic or eruption breccia pipes.*

4.4.6.1 Phreatic eruption pipes typically occur as youthful, commonly poorly eroded features recognised in many geothermally active districts such as the Taupo Volcanic Zone, New Zealand, or Japan (figure 4.45). Breccias include tuff ring facies and ejecta preserved in youthful terrains or vent breccias recognised inside pipes, which may include silica or clay altered breccias described below. Tuff ring breccias to eruption breccia pipes typically occur as chaotic mixes of sub-angular clasts in a rock flour matrix blasted out from the pipe and might be expected to grade away from any pipe with variations according to topography, wind direction and the clast type. Common exotic clasts include mineralised vein material within the ejecta adjacent to eruption breccia pipes at Ozorozan, Japan (figure 4.48). Vent breccias developed within breccia pipes (described below) are typically dominated by sub-angular wall rock clasts within a rock flour matrix with either clay or silica alteration. Exotic clasts, including of mineralised veins, are also noted in the clay-silica altered breccias at Broken Hills, New Zealand (figure 4.55).

4.4.6.1.1 The Waimangu (black water) eruption breccia began as a geyser in late 1900 within the structure developed by the 1886 violent basalt driven Tarawera eruption, and continued to 1904. A 129 x 74 m and 14 m deep crater erupted periodically to eject black mud and rocks up to 150 m high and dispersed up to 460 m from the vent (figure 4.46; Lloyd and Keam, 1975; Houghton and Scott, 2002). There is no record of significant outflow (Simmons et a., 1993). Without warning in late 1917 violent eruption to the SW along the same fissure resulted in development of Frying Pan Lake, which continues to be active as a steaming lake along with the adjacent steaming acid sulphate altered Cathedral Rocks (figure 4.46). As discussed in (section 7.3) metal deposition results from the mixing of pregnant fluids rising along the same fissure with the low pH waters venting from frying pan lake (Corbett and Leach, 1998 and references therein).

Figure 4.45 *Small scale eruption breccia craters.*
A - *A small crater with boiling waters at Upper Atiamuri, Taupo district, New Zealand.*
B - *Margin of a crater at Beppu, Kyushu, Japan, now used as a tourist attraction.*
C - *Sampling a Beppu pipe red precipitate which is rich in As, Sb & Hg*

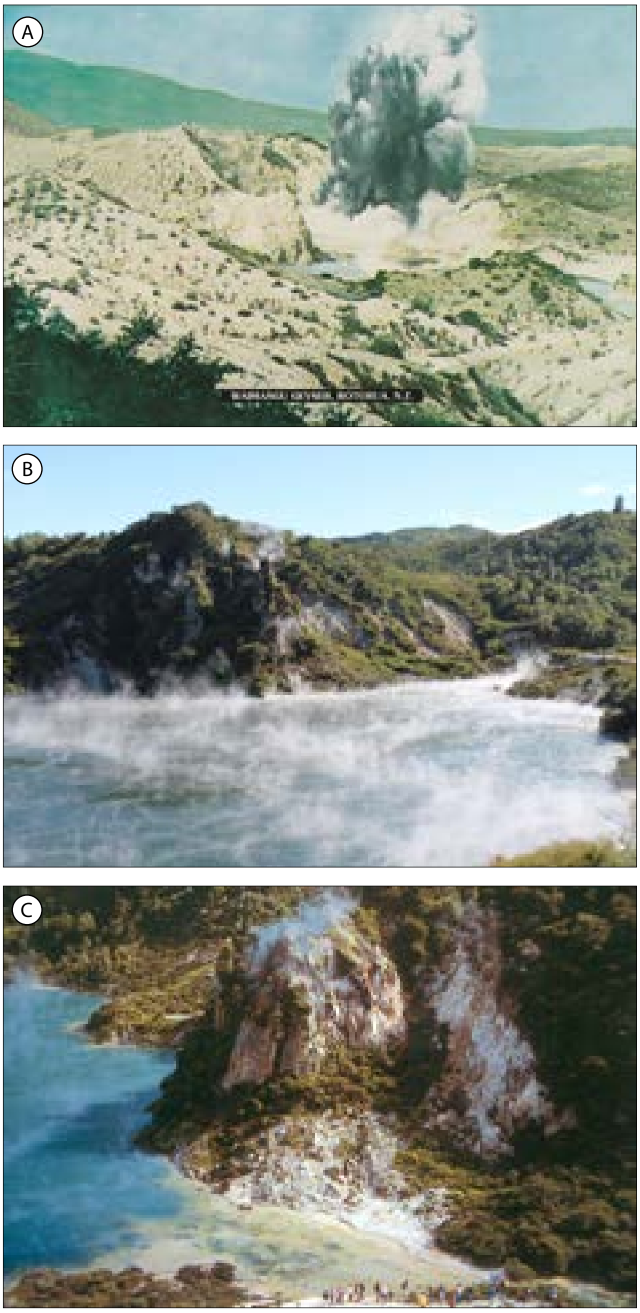
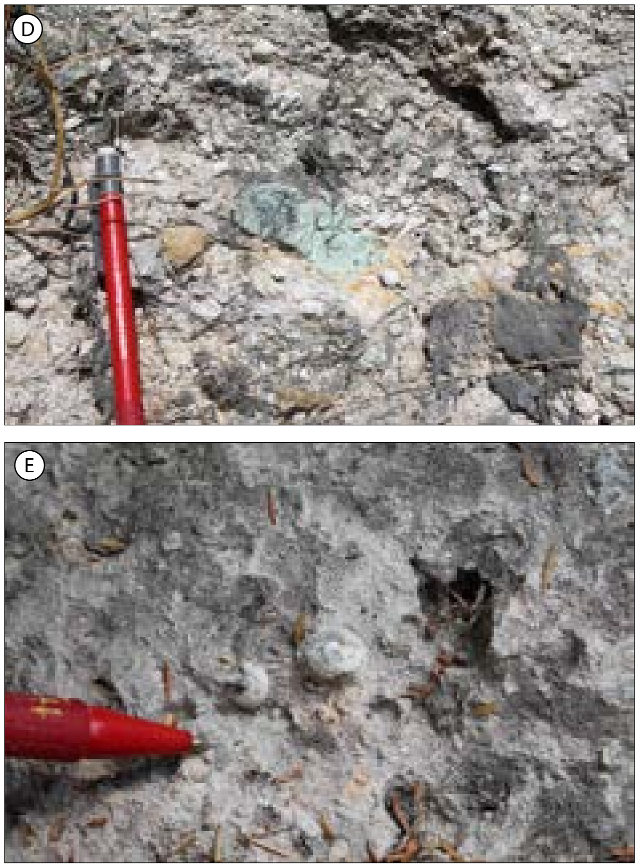


Figure 4.46 *The Waimangu eruption breccia and Cathedral rocks.*
A - *Eruption of the Waimangu Geyser in early 1904, showing remarkably close viewing sites. This colour image from a postcard, see Houghton and Scott (2002) for details.*
B - *Looking north across steaming Frying Pan Lake towards Cathedral Rocks*
C - *Looking west towards Cathedral Rocks at low water level showing acid sulphate alteration, steam, and precipitates deposited by the mixing of pregnant waters rising up the structure with low pH waters flowing downstream.*
D - *View looking along the Tarawera rift with Frying Pan Lake in the foreground towards the Waimangu crater, centre.*

4.4.6.1.2 Champagne Pool at Waiotapu, in the Taupo Volcanic Zone, New Zealand represents one of the best examples of an eruption breccia pipe (figure 4.47), which Corbett and Leach (1998) suggested is localised within a dilatant flexure in a Taupo Volcanic Zone graben structure. Champagne pool is about 60 m in diameter and lies within a 17 squ km thermal area of acid sulphate alteration. Current activity includes degassing CO2 which provides the name, and a hot water fluid out-flow with associated silica sinter deposition (figure 4.47). It is estimated to have formed about 600-700 years ago which is younger than the adjacent 150,000 y.o. Maungaonaonga and



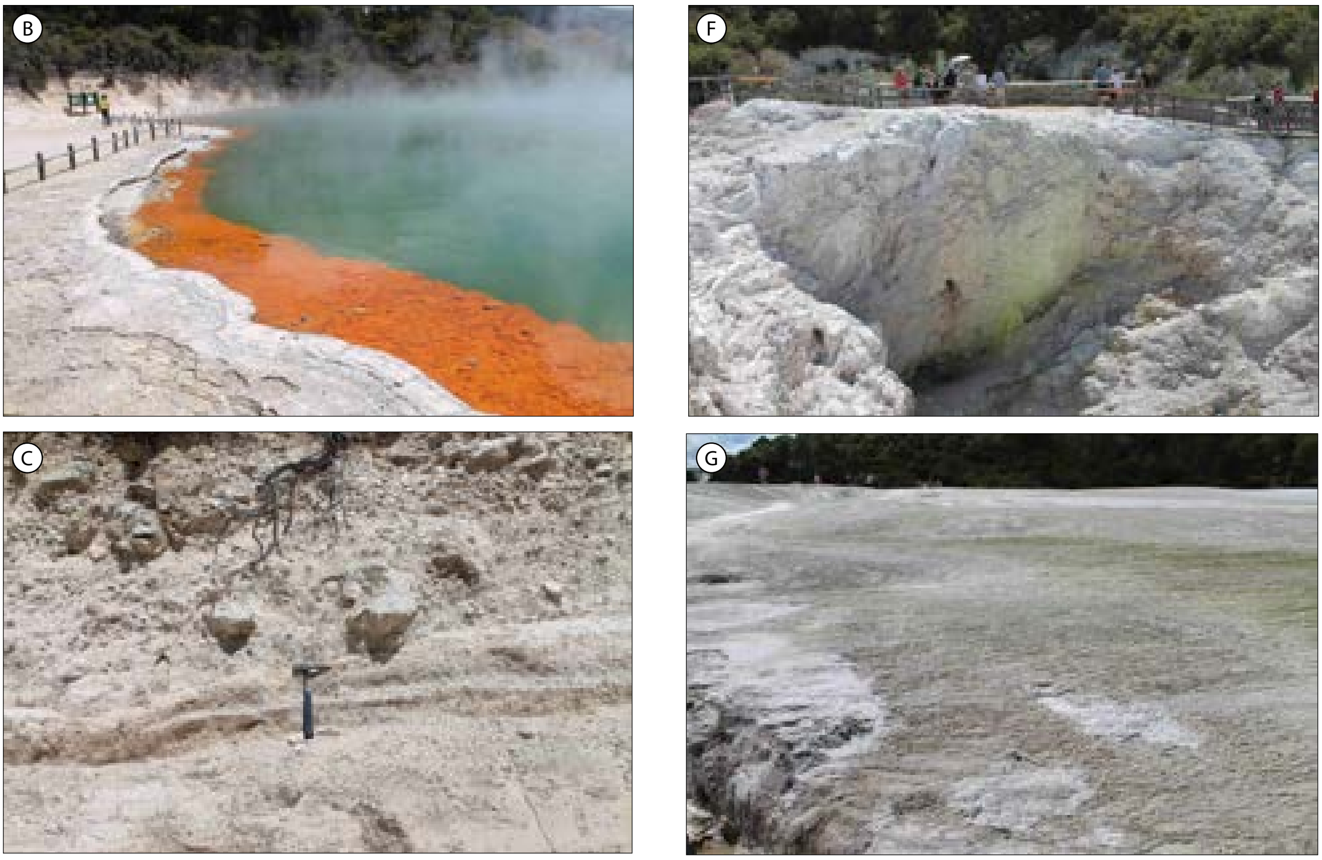


Figure 4.47 *Champagne Pool, Waiotapu, New Zealand.*
A - *View of Champagne Pool showing the colours of Artists Palette and* CO_2 *venting from the lake waters.*
B - *Red precipitate rich in Sb, S, Au, Ag, Hg, Tl and As, at the margin of Champagne Pool.*
C - *Chaotic eruption breccia immediately adjacent to Champagne Pool.*
D - *Eruption breccia further from Champagne Pool.*
E - *Accretionary lapilli within the eruption breccia further from Champagne Pool.*
F - *Acid sulphate alteration with sulphur deposited from a vapour vent.*
G - *Silica sinter in the Champagne Pool fluid outflow.*

Maunakakaramea dacite domes (Houghton and Scott, 2001). The youthful age has facilitated preservation of chaotic eruption breccias which as permeable rocks have readily undergone acid sulphate alteration to display variable resistant silicification or much softer clay (kaolin) alteration (figure 4.47). The Artists Palette hosts brilliant colours such as orange from Sb including realgar, yellow from sulphur and green from ferrous iron (Houghton and Scott, 2002) while the red precipitate at the lake margin contains Sb, S, Au, Ag, Hg, Tl and As, deposited in 1957-8 (Weissberg, 1969). Elevated Au (to 543 ppm Au, Pope, 2005) is interpreted to result from the mixing of the rising pregnant neutral chloride waters with the low pH acid sulphate waters responsible for development of the acid sulphate blanket (section 7.4).

4.4.6.1.3 The Osorezan, Japan steaming ground, within the youthful Usori caldera in northern Honshu, has long been a sacred site and hosts an ancient temple after which the site is named (figure 4.48 A). Dacite domes (dated as 0.17 m.y.; Aoki, 1990) rimed by permeable breccia/tuff deposits are overprinted by acid sulphate alteration which also contains sinter deposits and eruption breccia pipes (figure 4.48 B). Hot spring precipitates associated with eruption breccia craters contain anomalous sulphur and metals as: Au (to 6,510 ppm), As, Sb, Hg Te, Se, Tl, Cu, Pb, Zn and Cd (Aoki and Thompson, 1990) (figure 4.48 C & E). Aoki (1993) further suggests there is a zonation from a core of Au, Hg, Sb, As Se and Tl associated with the 'silica cap' grading out to Pb, Zn, Cu and Cd. Of interest to explorationists is that the eruption breccia pipes have ejected clasts, which include banded quartz veins with free Au and coarse crystalline stibnite with chalcedony, derived from a potential vein system at depth (figure 4.48 D & F). Fluids

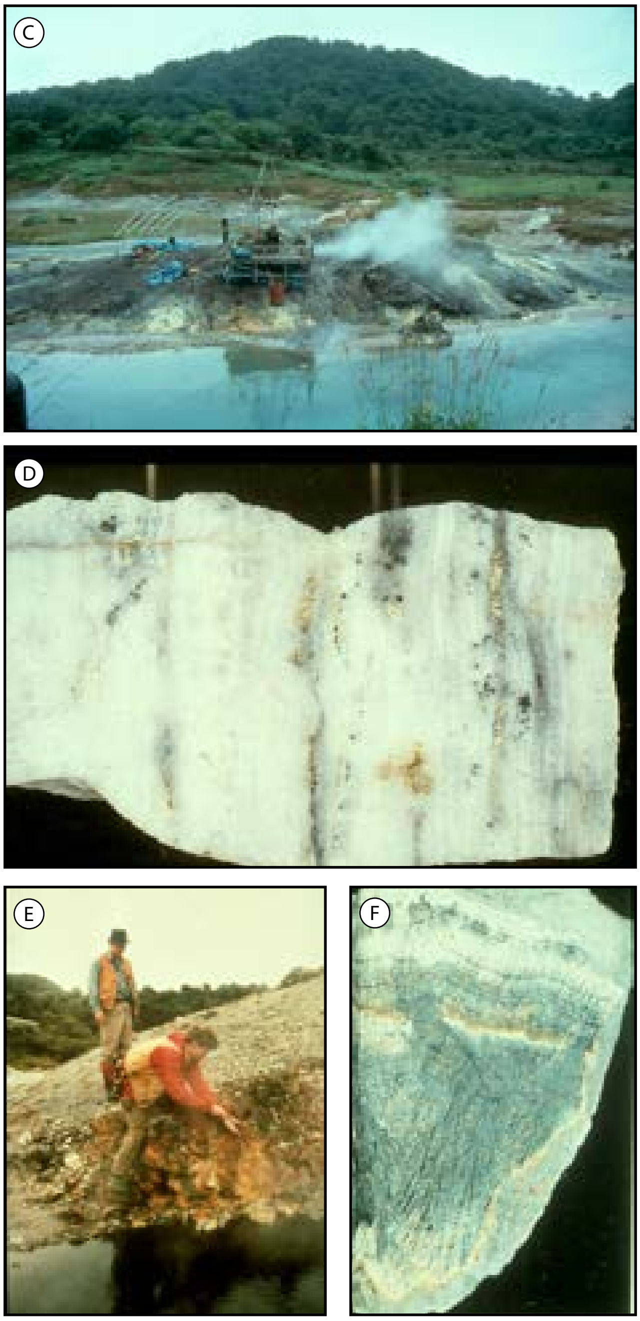


***Figure 4.48** Osorezan Japan eruption breccia clasts.*
A - *View across Lake Usori towards the steaming ground, from Aoki (1989).*
B - *Acid sulphate alteration crops out in an area of domes with adjacent tuff ring deposits and eruption breccia pipes. The path the gateway to the temple are visible.*
C - *Sulphur deposited from drilling in 1987.*
D - *Banded quartz with free gold identified as an eruption breccia clast.*
E - *Orange and yellow metal anomalous precipitates from a recent drill hole sampled by the Austpac Gold- Nissho Iwai joint venture in 1987 and also reported by Aoki (1989) as highly anomalous in As, Sb and Hg.*
F - *Coarse bladed stibnite clast, from Aoki (1989).*

emanating from recent drill tests continue to deposit metal-anomalous precipitates (figure 4.48 C & E) and in 1989, hot springs were depositing precipitates with Au to 47 ppm in pools near the eruption breccia pipes (Aoki, 1989; Aoki and Thompson, 1990) and so appear to be linked to a potential vein source. Thus, it is possible the eruption (phreatic) breccias have evolved within the same structure which hosts epithermal vein mineralisation at depth, and the vein clasts rucked up from depth and ejected at the surface by the breccia pipes, can be used elsewhere as exploration tools to vector to the buried veins, especially as As, Sb and Hg anomalous precipitates are deposited at the surface from recent drill holes.

4.4.6.2 Silicified eruption breccias are generally recognised within phreatic or eruption breccia pipes associated with significant silica out-flows and development of sinter deposits and may cap low sulphidation chalcedony-ginguro Au-Ag epithermal veins. These are also termed hot spring Au deposits. Breccias typically comprise sub-angular polymictic wall rock, sinter and vein clasts in a silica-pyrite altered rock flour matrix. Wood and other plant material or lacustrine sediments may be present. Mixed silica-travertine deposits are recognised in association with carbonate-base metal Au deposits (Wau, Papua New Guinea; Cerro Negro, Patagonia). Eruption breccia vents commonly act as the fluid out-flows for sinter deposits which might be proximal or flow considerable distances (>100 m) from the vent as laterally extensive sheets to several metres thick (section 8). Breccias have become silicified as silica is rapidly deposited from depressurised waters upon eruption or cooling followed by fluid out-flow from the vent. Silicification may seal the fluid out-flow and polyphasal eruption and sealing can result in the development of crack-seal breccias (McLaughlin, below). While eruption breccias are typically barren, or contain only very low grade Au mineralisation, dilatant sheeted veins may penetrate the base of the breccia pipe (below, Mclauchlin, USA and Twin Hills, Australia) or silicified competent breccias may provide good hosts for later stockwork vein mineralisation.

4.4.6.2.1 McLaughlin, California, USA, is well described as an eruption breccia-sinter system which grades downwards from lower Au grade polyphasal stockwork vein hosted mineralisation within the breccia-sinter, into the deeper level higher gold grade sheeted low sulphidation epithermal Au vein mineralisation within competent metamorphic basement host rocks (figures 4.49 & 4.50; Lehrman, 1986; Tosdal, et al., 1993; Sherlock, 1993; Sherlock et al., 1995). Eruption breccias are dominated by angular sinter and/or wall rock clasts in a silica matrix within an overall region of intense silicification. Interlayering of breccias and sinter (figure 4.49) are indicative of a recurring (crack-seal) sequence of events comprising: gas pressure build up -> rupture by movement on a structure or when the gas pressure exceeds the tensile

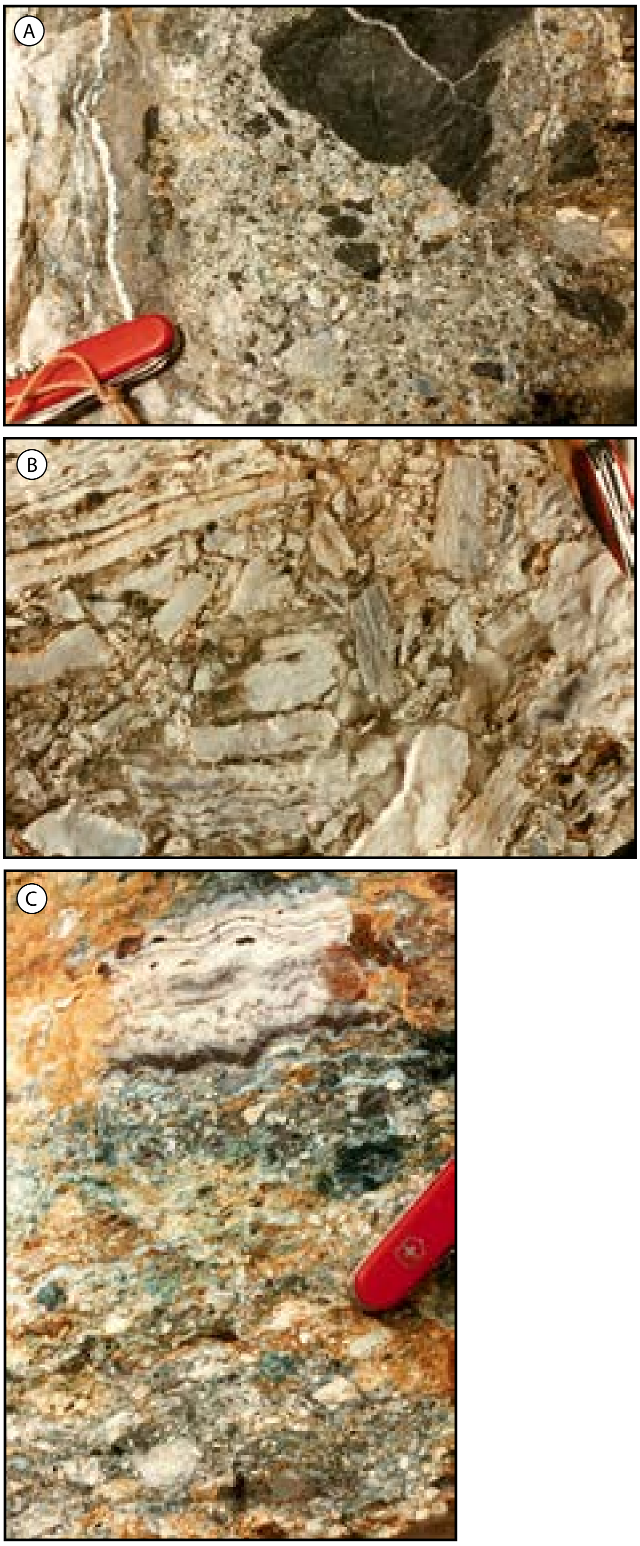


Figure 4.49 *Eruption breccia, McLaughlin Au mine, California, USA.*
A - *Eruption breccia dominated by silicified angular wall rock clasts.*
B - *Eruption breccia dominated by angular sinter clasts within a silica matrix.*
C - *Crack-seal developed as an eruption breccia is silicified and capped by sinter in the process described herein.*

strength of the silicified wall rock and load pressure (although very low in this near surficial setting) -> eruption breccia pipe formation + silica deposition due to the pressure drop –> sinter out-flow and continued silicification of the underlying permeable breccias -> sealing by silica deposition -> pressure build up -> eruption, and so on. The orientation of the sheeted veins is consistent with development as tension veins in response to strike-slip movement on the local structural grain parallel to the San Andreas Fault and of the same dextral sense of movement. An exploration model evolved from the McLaughlin mine, that epithermal vein mineralisation might lie below sinter sheets (figure 4.50), was used throughout the Pacific rim from the early 1980's. However, exploration models must now take studies of additional examples into account which suggest silica-rich fluids might flow some distance from the eruption breccia pipe to more distal sites of silica sinter formation. Models should also include the setting of dilatant structural sites of fluid up-flows.

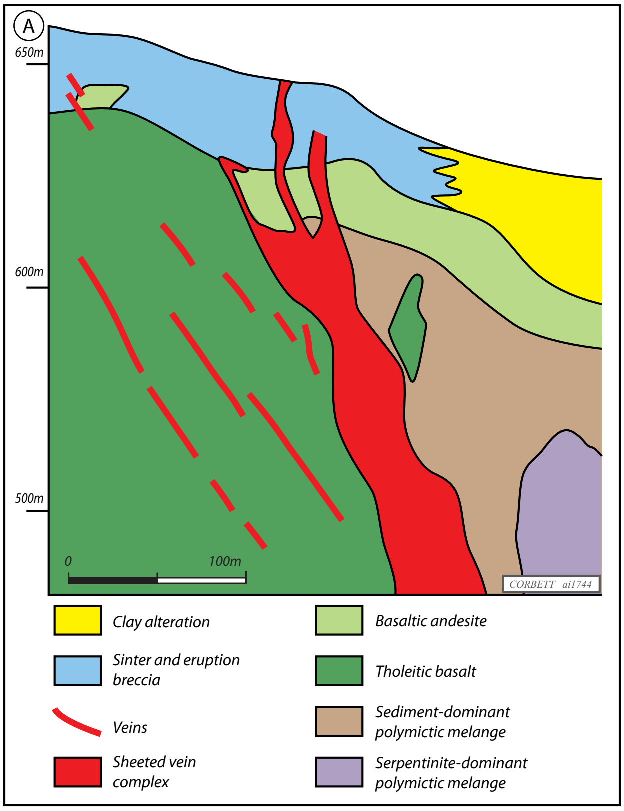
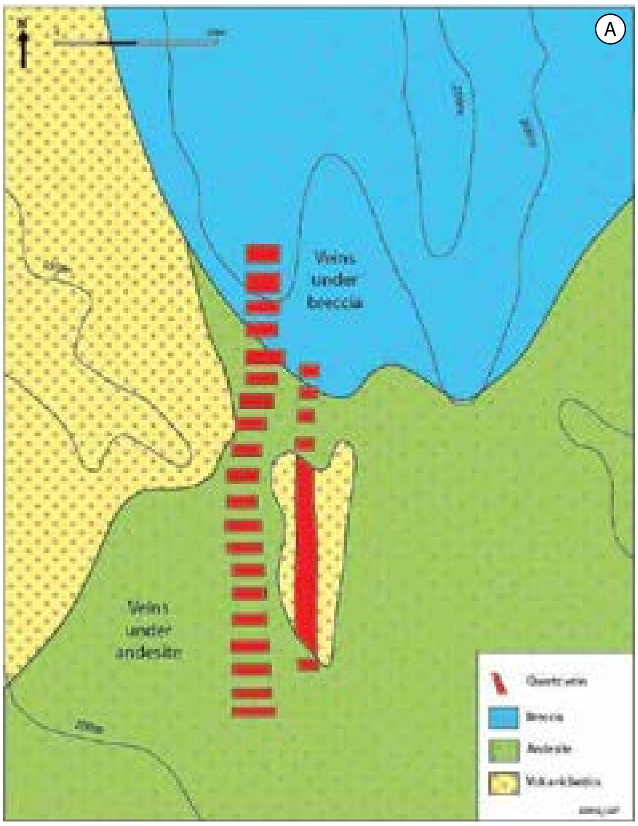


***Figure 4.50** McLaughlin mine mineralisation.*
A - *Graphic of the field relationships showing sheeted vein mineralisation capped by breccia and sinter, redrawn from Sherlock et al. (1995)*
B - *Low temperature silica including white chalcedony and blue opal.*
C - *Stockwork veins cut the low temperature chalcedony breccia.*
D - *Sheeted quartz veins within the basement metamorphic rocks, sledge hammer for scale in the lower right centre (photo D. Heberlein).*

4.4.6.2.2 At Toka Tindung, Indonesia, a Miocene to Pliocene volcaniclastic and andesite sequence is capped by a breccia which "contains angular to sub-rounded fragments of altered Maen Volcanics, carbonised wood, vein and sinter supported by multiple generations of hydrothermally altered lithic sand, silt and mud matrix." (Wake et al., 1996) interpreted (Corbett, unpubl report, 1996; Corbett and Leach, 1998) as eruption breccia (figure 4.51). A polyphasal character, rebrecciated clasts and the fluidisation textures, help to distinguish the intensely silicified eruption breccias from the volcaniclastic host rocks. There is a strong association between sinter blocks and the flat-dipping base of the breccia body below which veins have been traced supporting the flared eruption breccia pipe interpretation (Corbett, unpubl. report, 1996). A young andesite and recent tephra also locally cover the veins (Wake et al., 1996). Drilling designed to test enhanced fluid up-flow near the intersection of the veins with breccia pipe identified good Au grades (Corbett and Leach, 1998), although the interaction of structure and host rock competency became an important control to mineralisation as the project evolved. Consequently, at Toka Tindung, an eruption breccia pipe localises better Au grades within the associated epithermal vein, and is also interpreted as a fluid up-flow for the now partly eroded sinter apparent only as blocks.



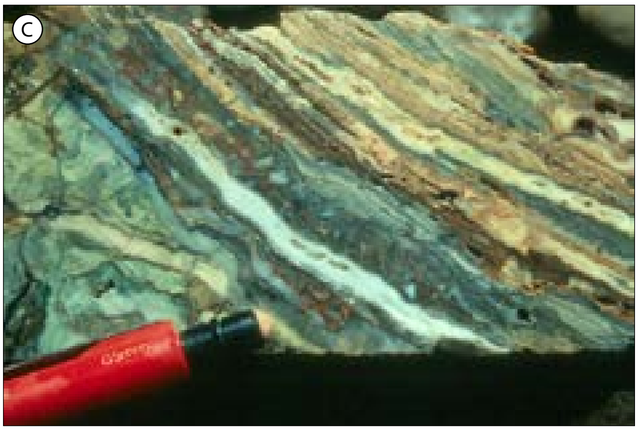


Figure 4.51 *Eruption breccia, vein and sinter, Toka Tindung, Indonesia.*
A - *Graphic showing the relationships of the eruption breccia to vein and sinter, from Wake, et al. (1996).*
B - *Eruption breccia with clasts of sinter and wood in a silica-rock flour matrix with polyphasal activation.*
C - *Banded chalcedony vein with a fluidised breccia band.*
D - *Block of sinter showing layering and algal mats shown in detail in figure 8.**.*

4.4.6.2.3 At Twin Hills, in the Late Devonian-Early Carboniferous Drummond Basin of North Queensland, Australia, eruption breccias host sheeted low sulphidation epithermal Au veins with nearby sinter deposits (Corbett and Leach, 1998). Early workers noted epithermal vein and sulphide clasts as well as "evidence for the upward expulsion of fluids" in rocks described as conglomerates (Alston et al., 1991). However, these characteristics and the presence of rebrecciated clasts (figure 4.52 E & G) and other locally irregular clasts of bleached fine grained possibly felsic material with pyrite pseudomorphs (figure 4.52 C), led Corbett (unpubl. report, 1996) to suggest an eruption breccia origin for these intensely silicified rocks. Later exposures of dismembered dykes provided by a decline underground access verified the eruption breccia rather than conglomerate interpretation (Corbett, unpubl. report, 2006). The Twin Hills eruption breccias are intensely silicified with angular to rounded wall rock clasts which are variably supported by the silicified rock flour matrix and are no doubt genetically linked to the source of epithermal veins and sinter deposits (figure 4.52). Key exploration aspects would have been the recognition of the exposure by erosion of only a near surficial palaeo surface, characterised by sinter and eruption breccias in association with soil geochemical anomalies which might be used as vectors to buried sheeted vein mineralisation. Although juvenile intrusion clasts and dismembered dykes are recognised, the presence of sinter deposits and chalcedony-ginguro veins places Twin Hills in the eruption (phreatic) breccia and not phreatomagmatic-phreatic breccia class.

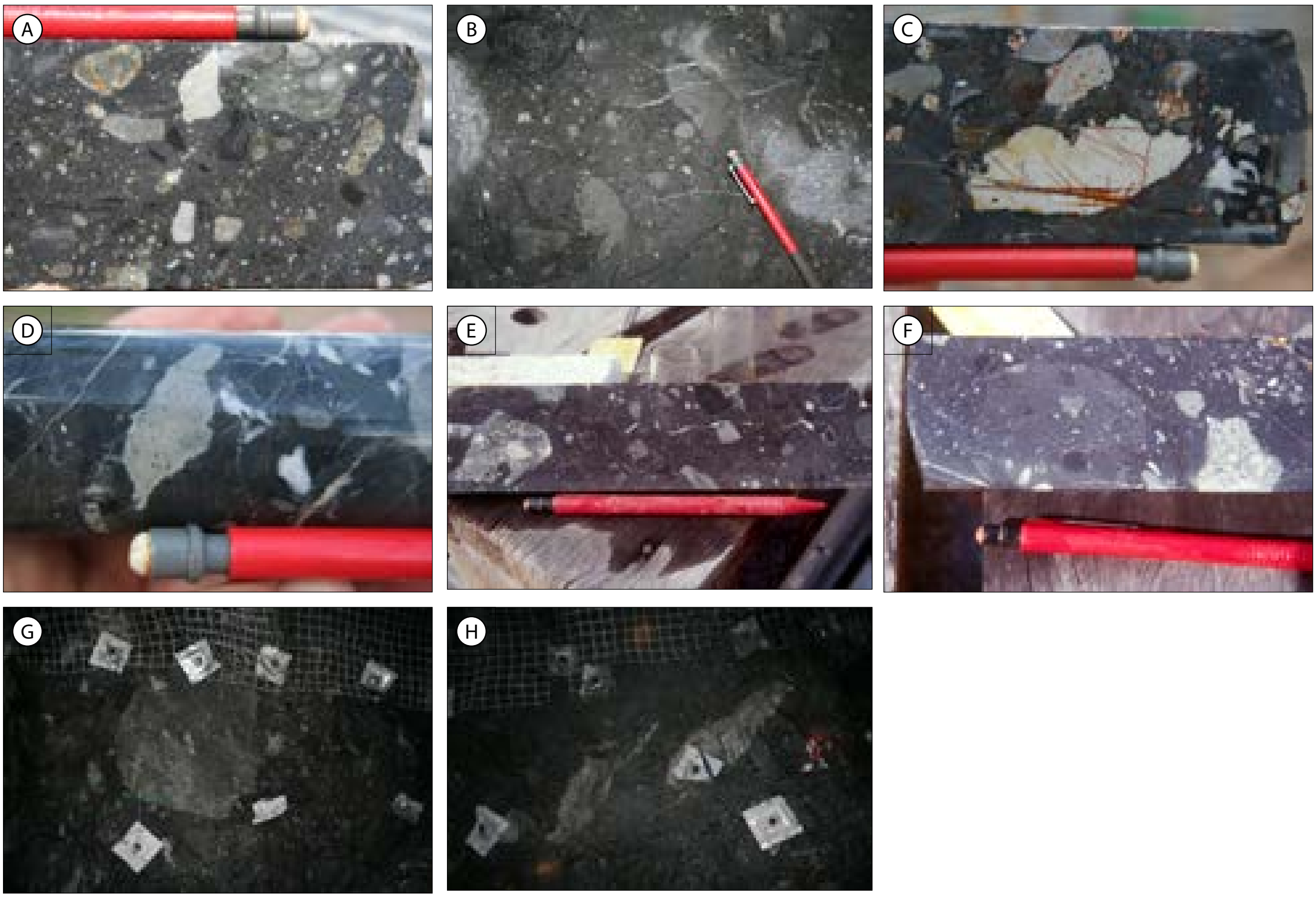
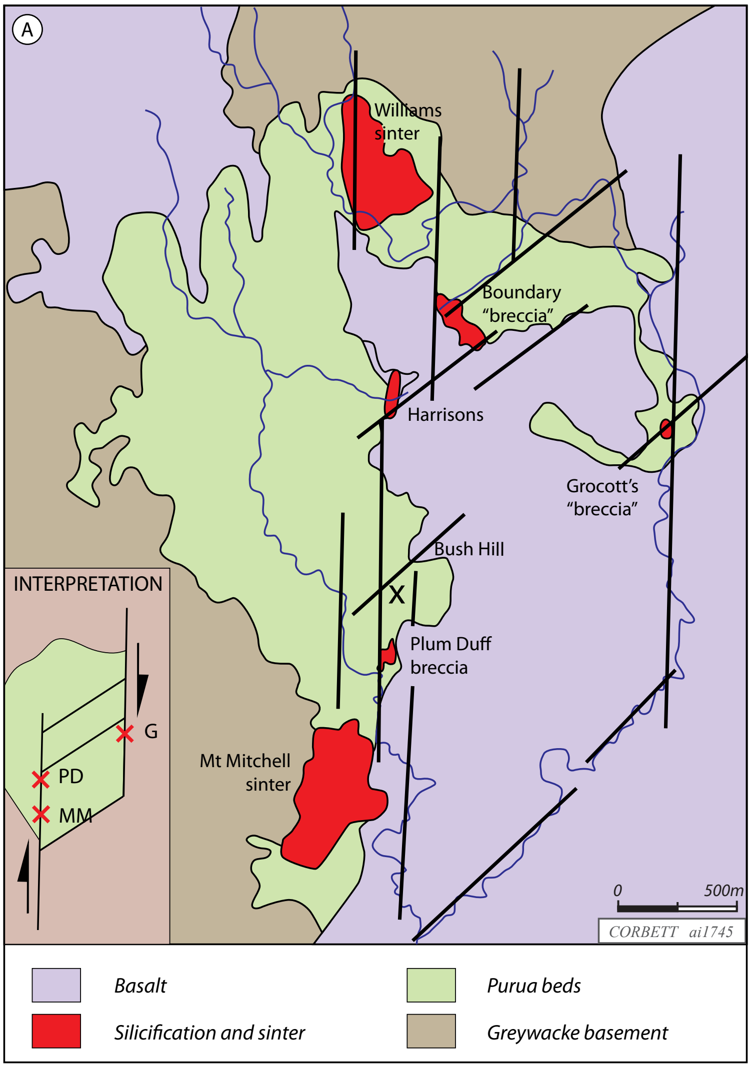


***Figure 4.52** An eruption breccias which did not fit a conglomerate interpretation, Twin Hills, Australia.*
A - *Eruption breccia with milled clasts although the pale felsite is angular.*
B - *Underground exposure of the eruption breccia.*
C & D - *Eruption breccias with ragged felsite clasts which include pseudomorphs after pyrite.*
E, F & G - *Eruption breccias with rebrecciated breccia clasts in a silica-rock flour matrix.*
H - *Dismembered dyke in an underground exposure.*

4.4.6.2.4 Puhipuhi, Northland, New Zealand contains extensive sinter sheets which have been locally mined for mercury and so was extensively explored the 1980's using a McLaughlin model (above) that epithermal Au veins might lie below the sinter deposits, but without great success (White, 1986). Later, Grieve et al. (1997) provided a similar dextral sense of movement to the NS structural grain at Puhipuhi, interpreted for the derivation of Coromandel Peninsula Au-Ag vein deposits (Corbett, unpubl. data) and including the Thames district (figure 3.20), to suggest NE trending dilatant structures control development of a pull-apart basin and later fluid up-flow zones at Puhipuhi. The Purua Beds, which fill and extend outside the speculated pull-apart basin to overlie adjacent basement greywacke, contain quartz vein clasts and are also locally silicified, and so may constitute essentially syn-mineral epiclastic rocks (figure 4.53). Younger basalts overlie the Purua Beds and felsic domes crop out within the NS structural corridor to the south (Grieve et al., 1997). The Mt Mitchell sinter, which covers a 24 ha area and is up to 23 m thick and represents the largest of several sinter sheets, (although some are transitional to silicified Purua Beds). It lies about 500 m along strike within a dilatant structure from the Plumb Duff and more distal Bush's Hill interpreted eruption breccias (figure 4.53; Grieve et al., 1997). Plumb Duff, which is the most significant of several eruption breccias, contains blocks of sinter cut by fluidised grits as well as geyserite (White, 1986) along with stibnite and botryoidal sinter (Grieve et al., 1997), which contrast with bedded sinter of Mt Mitchell and are typical of a proximal setting to an up-flow vent (Corbett and Leach, 1998). Grieve and co-workers therefore suggested eruption breccias such as at Plumb Duff, might represent the fluid up-flow zones for sinter deposits (which may have originally been more extensive, and so warrant further exploration for vein mineralisation (figure 4.53).



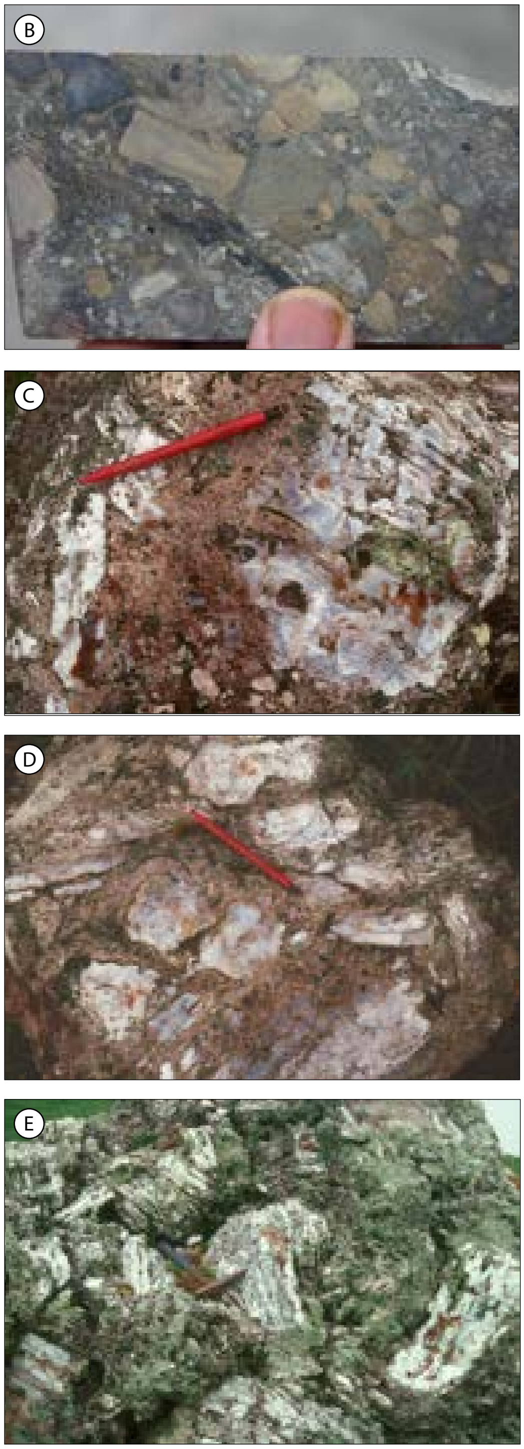


***Figure 4.53** Eruption breccias and sinter deposits, Puhipuhi, New Zealand.*
A - *Puhipuhi showing the structural relationships and locations of sinter and breccias, from Grieve et al. (1997).*
B - *The Plumb Duff eruption breccia in drill core characterised by sub-angular clasts Purua Beds in a silicified matrix at depth in drill core.*
C - *Plumb Duff sinter cut by fine grained eruption breccia*
D & E - *The Plumb Duff eruption breccia characterised by brecciated sinter clasts.*

4.4.6.3 Clay matrix eruption breccias represent a class of breccias associated with eruption breccia pipes formed by depressurised gas eruptions as above, but without the pronounced flow of silica saturated meteoric-dominant waters to provide silicification and silica sinter deposits. However, many individual pipes vary from clay to silica-rich portions or stages of development. Pipes examined in the exploration environment are typically small from a few to tens of metres in diameter and are interpreted to have vented. Many of the eruption craters recognised in youthful poorly eroded systems may represent the upper levels of clay matrix eruption breccias examined in exploration settings. Some contain mineralised clasts and so display some post-mineral activity.

4.4.6.3.1 The Favona epithermal veins lie about 1.5 km east of the Waihi vein system, New Zealand, and like Waihi occur as hanging wall veins associated with down-drop on the eastern side of a normal fault (figure 3.31). As different to Waihi which displays an estimated (Brathwaite and Faure, 2002) 160 m of erosion, Favona is almost intact as the veins are overlain by hydrothermal eruption breccias which are in turn partly obscured by post-mineral ignimbrite and dacite (figure 4.54; McKay et al., 2004; Torkler et al., 2006). These workers describe the breccias as comprising a mix of sub-angular to rounded andesite, vein, sinter and wood clasts with hydrothermal alteration which varies from intense clay to silica within a body 800 m long by 300 m wide and 100 m deep. The drill core containing low temperature smectite altered breccias quickly disaggregated. Favona therefore contains both clay and silica altered breccias. The veins did not rise to the palaeo surface and so the Favona veins represented blind exploration target below the eruption breccias and younger cover. As the eruption breccias contain vein fragments they display weak toxic and precious metal anomalism. Fluidised breccias, locally with subsurface sedimentary structures (figure 4.3) are well developed within the veins and interlayered with banded chalcedony, and this material tends to be weakly mineralised. These structures are indicative of open space veins and so rapid dilation may have helped to promote eruption breccia formation. The strongly flared eruption breccias occur in the same NNE trending structural corridor as mineralisation, but do not directly pass down into veins, and display a post-vein component of activation.

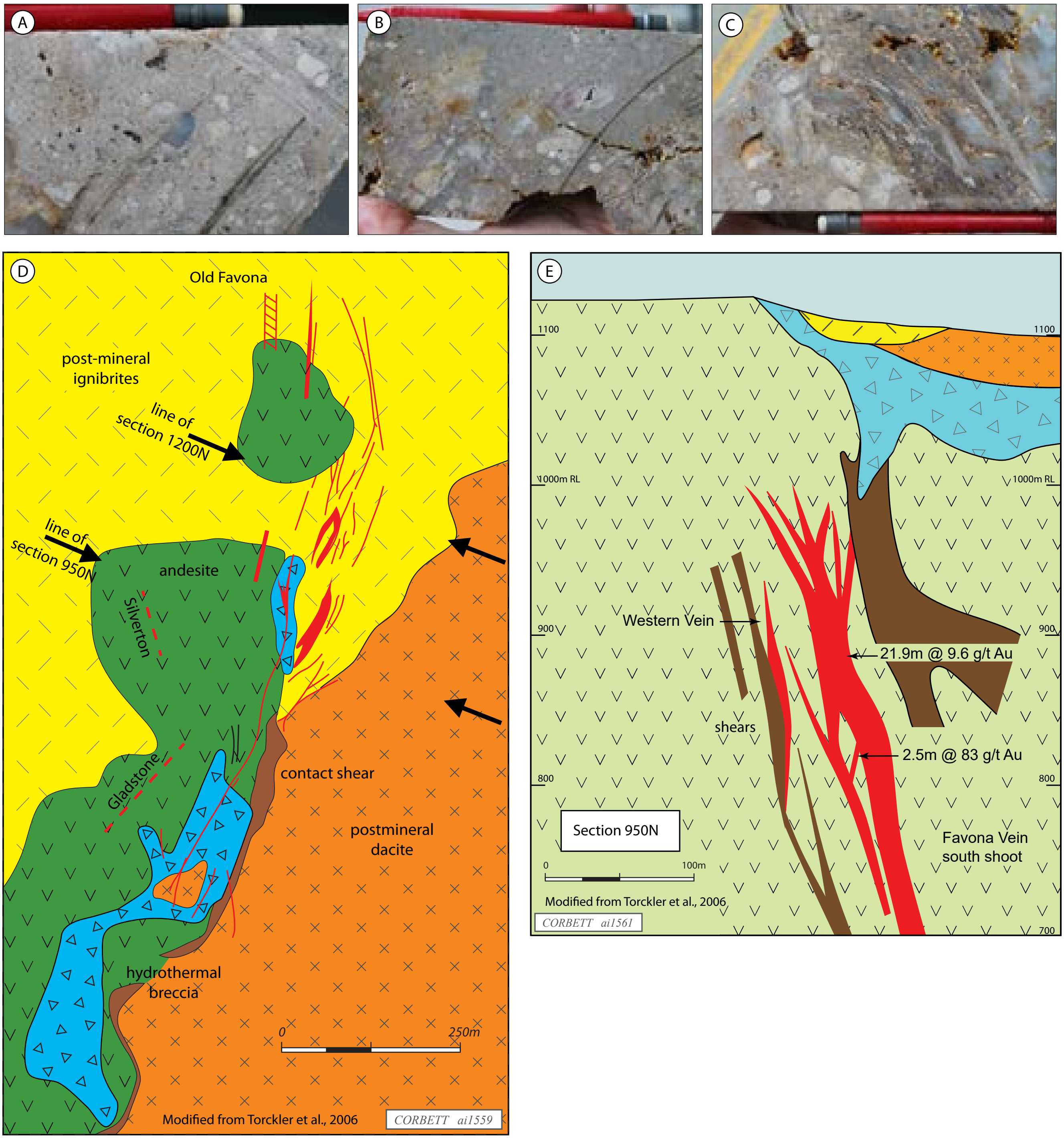


Figure 4.54 *Eruption breccias at the Favona vein system, Waihi District, New Zealand.*
A - *Silicified eruption breccia, Favona, Waihi, New Zealand.*
B - *Silicified eruption breccia, Favona, Waihi, New Zealand.*
C - *Silicified eruption breccia with sinter clast, Favona, Waihi, New Zealand.*
D - *Plan of the Favona eruption breccia, post mineral cover and veins projected to the surface, modified from Torkler et al., (2006).*
E - *Cross section through the Favona vein system at line 950N, modified from Torkler et al., (2006).*

Best Au grades are reported from 'oatmeal breccias' (figure 4.58; Torkler et al., 2006) which contain clasts of finely banded chalcedony with abundant ginguro-like material set in a chalcedony-opal matrix. The clasts are assumed to contain high Au grades deposited by rapid cooling in low temperature conditions. As discussed in detail in section 7.4, interaction of low pH waters evidenced by the presence of kaolin and rising ore fluids has contributed towards the development of elevated Au grades at Favona, well developed in hanging wall veins. Permeability associated with the eruption breccias may have aided the collapse of acid sulphate waters to promote and high grade Au deposition.

4.4.6.3.2 At Broken Hills, New Zealand, chalcedony-ginguro style Au-Ag vein mineralisation is best developed within steep pitching ore shoots controlled by a combination of several factors (as per section 7) defined from an analysis of the data (G. Corbett, pers. insp., 2000, Moore, 1979; Rabone 2006; Crocker et al., 2013) as: lithological control as the competent underlying flow banded rhyolite which fractures well for vein formation rather than the overlying incompetent pyroclastic rocks, flexures formed by dextral movement on NS structural control (the same direction as Golden Cross, Waihi, and Thames district), and the mixing of collapsing oxidised near surficial waters evidenced by kaolin with rising pregnant waters. Best Au grades occur close to hydrothermal breccia pipes (figure 4.55; Moore, 1979) which allowed access of near surficial acid sulphate waters to the vein system. Breccias comprise sub-angular wall rock and some vein clasts with mostly clay and also some silica alteration. Rabone (2006) stressed the breccias do not pass downward to veins but exploit the same structures and so the breccias are herein regarded as syn- and post-mineral eruption (phreatic) breccias. High Au grades within banded vein clasts recognised within the breccia pipes (figure 4.55) may result from mixing of near surficial acidic waters with ore fluids. Rabone (2006) also describes a several hundred metre wide "possible hydrothermal explosion crater" at the southern end of Broken Hills which is cut by one vein. Boulders of pervasive silica on flat ground adjacent to the mine are typical of eroded segments from a shallow crustal level silica ledge (section 9).

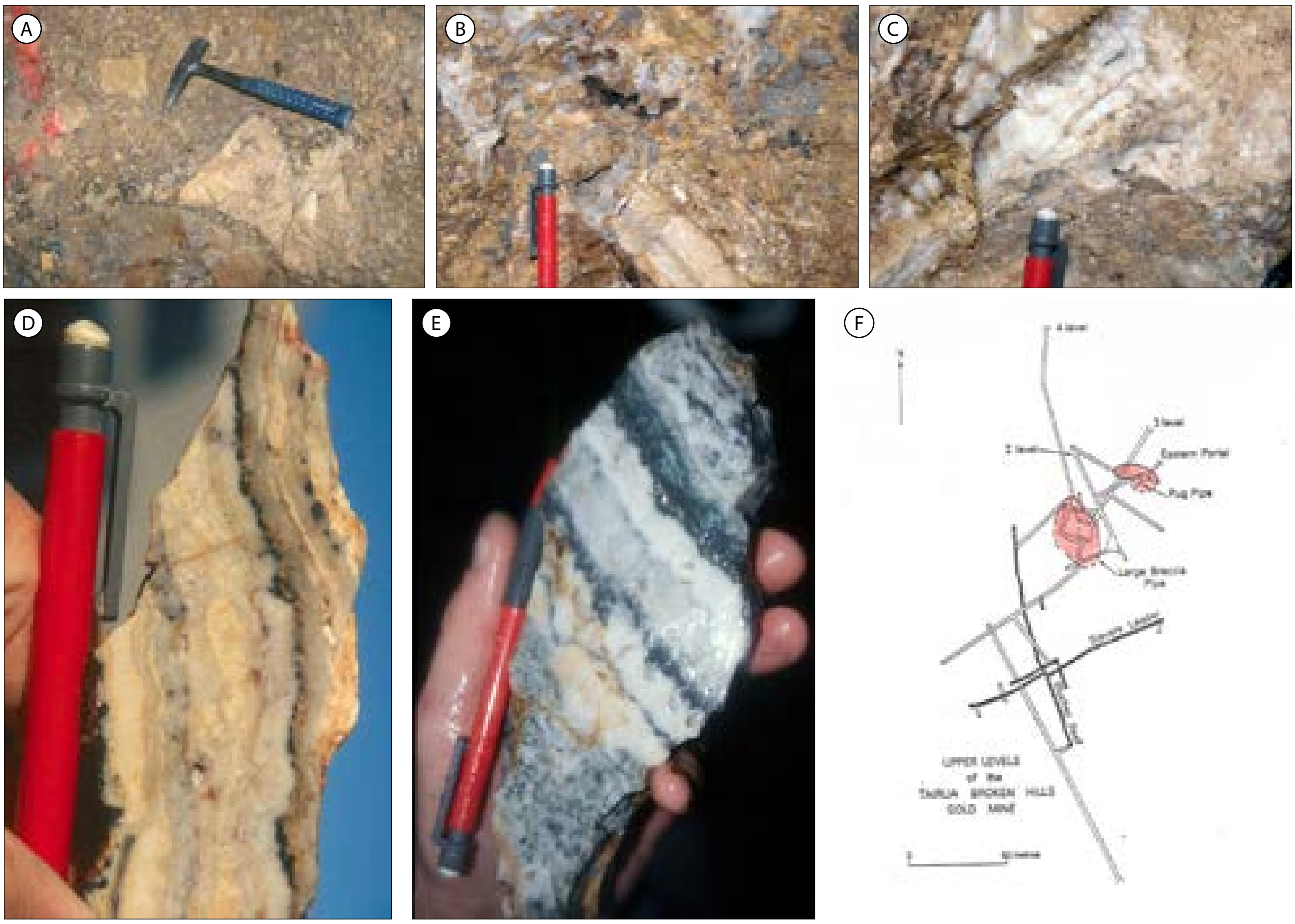
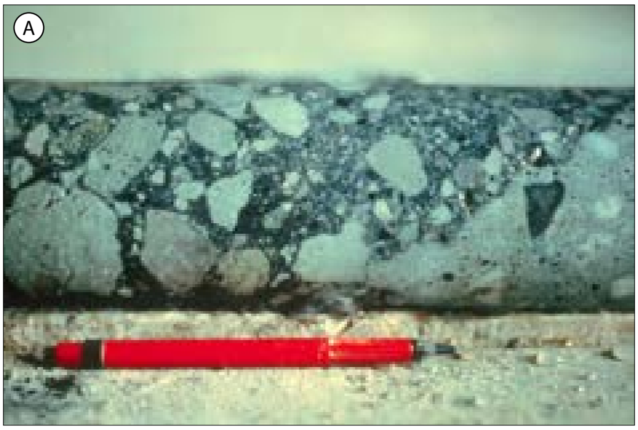
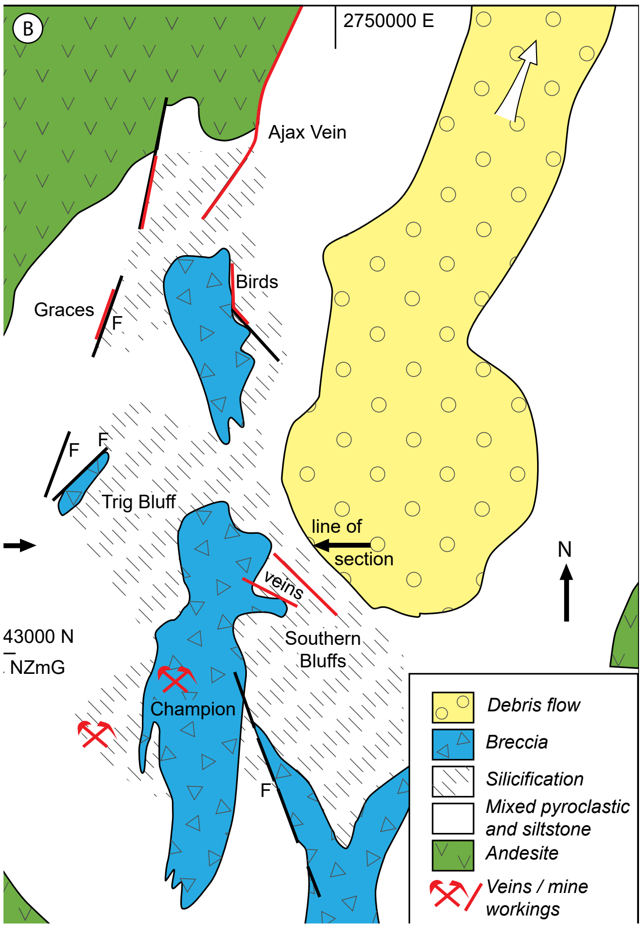


***Figure 4.55** Eruption breccia pipes with mineralised vein clasts.*
A - *Clay altered eruption breccia with angular wall rock clasts.*
B - *Clay-silica altered eruption breccia with angular wall rock clasts.*
C - *Eruption breccia with mineralised vein clasts and strong silicification.*
D & **E** - *Mineralised clasts extracted from the eruption breccia by S. Rabone during small scale mining.*
F - *Sketch of the veins in the upper level mine workings and eruption breccia pipes, from Moore (1979).*

4.4.6.3.3 Neavesville, New Zealand, lies towards the western side of the Coromandel Peninsular where a stronger magmatic character is discernible in other systems such as Thames (Ohio Creek porphyry Cu-Au, Lookout rocks barren shoulder of advanced argillic alteration and Thames quartz-sulphide Au and epithermal quartz bonanza Au) and Karangahake (with a transitional carbonate-base metal Au – chalcedony-ginguro Au-Ag character). Mineralisation at Neavesville is not of the chalcedony-ginguro style typical of the eastern Coromandel Peninsular, but Au-Ag occurs as free electrum with comb quartz and adularia within competent silicified siltstones and also as electrum hosted within pyrite-marcasite,





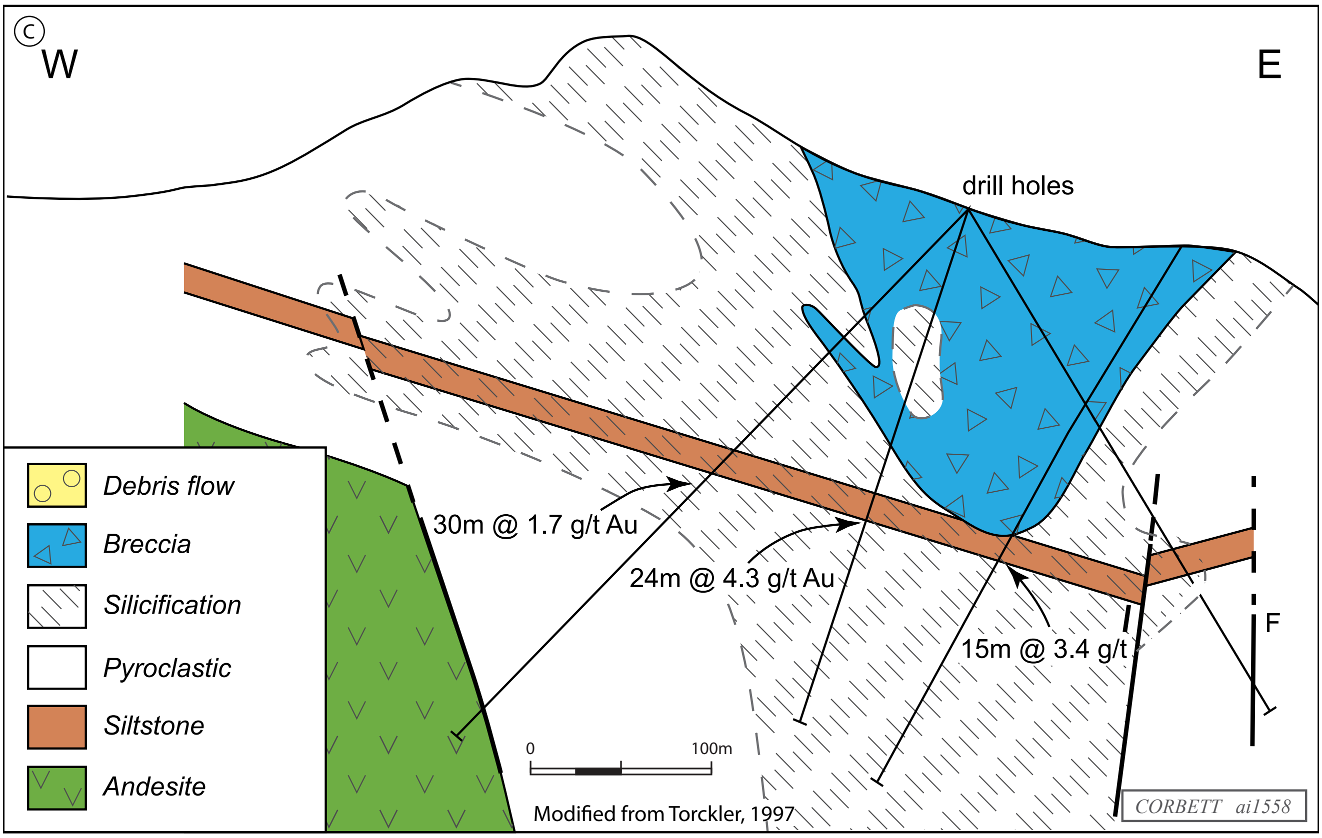


***Figure 4.56** Small scale clay matrix breccia pipes at Neavesville, New Zealand.*

A - *Typical clay matrix phreatic breccia with angular clasts formed by the polyphasal injection clay altered rock flour into a brecciated rock.*

B - *Plan view showing the proximal relationship of gold workings to breccia pipes, modified from Barker et al. (2006).*

C - *Cross section which shows Au mineralisation best developed within or close to the competent siltstone and as this section is located at the northern margin of a pipe, it appears to be rootless, modified from Barker et al. (2006).*

associated with anomalous Mo. This mineralisation is typical of intrusion-related low sulphidation quartz-sulphide Au±Cu and epithermal quartz Au styles. Clay matrix breccias within several pipes vary from polymictic milled injection style breccias, to mosaic styles with angular wall rock clasts moved apart and filled with clay altered rock flour matrix (figure 4.56). Although the clay matrix breccias are mostly impermeable, the eruption process may have fractured the silicified wall rocks to provide permeability for mineralised fluid flow and so mineralisation is well developed at the pipe margins (figure 4.56; Barker et al., 2006). Furthermore there is a strong lithological control to mineralisation which is hosted by the more competent siltstone rather than the less competent pyroclastic rocks, although these are locally silicified to display some competency in order to host veins at pipe margins (figure 4.56). The depressurised fluid responsible for breccia formation and mineralisation is interpreted to have used the same structural plumbing system. The lack of significant milling and intrusion material favours the classification of the Neavesville breccias as of a phreatic rather than phreatomagmatic style. The initiation of breccia pipe formation must, to some extent, have pre-dated mineralisation, in order to provide the wall rock permeability for mineralisation.

The **exploration implication** of the successful identification of phreatic or eruption breccias is that low sulphidation epithermal veins might exploit the same structure and remain buried close to the base of the breccia pipe, and locally within it. Rucked up mineralised clasts which provide weak metal anomalism to these breccias suggest which breccias are prospective. They also locally occur within high sulphidation epithermal deposits as explosive events close to mineralisation. Phreatic or eruption breccias vary from silica to clay alteration, as shallow small bodies, commonly with limited clast milling and generally without any magmatic influence.

4.4.6.3 Conclusion - hydrothermal magmatic-phreatic breccias

There is a continuous progression from monomictic breccias developed at intrusion margins with little hydrothermal fluid introduction and cast milling or transport, to polymictic breccias with a mix of clasts which were extensively milled during transport and underwent substantial syn-eruption hydrothermal alteration. The change in breccia types is partly coincident with crustal level. Breccia pipes are commonly driven by volatile fluid pressure release, although possibly triggered by structural processes, and play an important role in the mineralisation process by tapping the apophysis of magma source rocks at depth and also by the provision of permeability either within the breccia body or adjacent wall rocks. Thus, many breccias are pre-mineral but represent an important part of the mineralisation process. However, some eruption breccias which are associated with polyphasal banded epithermal quartz vein mineralisation have continued to be active after mineralisation.

4.4.7 Tectonic-hydrothermal breccias

The interaction of tectonic and hydrothermal processes may produce tectonic-hydrothermal breccias previously described using terms such as dilational or magmatic hydrothermal injection breccias (Corbett and Leach, 1998). These two terms could be regarded as end members of a continuum for the formation of hydrothermal injection breccia dominated by either extensional structural processes or forceful injection of hydrothermal fluids from an over pressured source (Phillips, 1972), whereas both processes are generally involved. Hydrothermal injection breccias represent important mechanisms of ore fluid introduction with common clear relationships between the quantity of introduced sulphide and Au-Ag grades and have therefore been classified (Corbett and Leach, 1998; figure 4.57) with increasing breccia matrix quantity (and approximately towards the magma source) as:

4.4.7.1 Crackle breccias comprise fractured rocks with orthogonal to random stockwork or parallel sheeted fractures filled by hydrothermal minerals which occupy considerably less volume than the host rock (figure 4.1 & 4.7). Crackle breccias occur in many epithermal and porphyry deposits and represent mediums for hydrothermal fluid introduction and so host mineralisation while hydrothermal alteration commonly grades from fracture feeders into the wall rock clasts (figure 2.14 B). Individual fractures of only mm thickness might form networks extending for many metres, typically with only low grade mineralisation, because of the low matrix to wall rock ratio. The term 'hydrothermal breccias' used by some workers to describe crackle breccias is too generalised and so not preferred.

4.4.7.2 Fluidised breccias (dykes) are characterised by the transport of hydrothermal fluid within a fracture but without significant clast movement or milling (figure 4.1 E & F). Some rock flour is likely to be combined with introduced hydrothermal matrix. These breccias are distinguished as matrix supported with locally derived monomictic sub-angular clasts, whereas pebble dykes contain transported, milled, rounded, polymictic clasts, typically within larger scale structures. Furthermore, fluidised breccias may be well mineralised, due to the mineralised matrix, whereas pebble dykes might only contain the occasional mineralised clast. Fluidised breccias may be identified as feeders for crackle breccias in many hydrothermal systems (figure 4.7).

4.4.7.3 Fluidised crackle breccias therefore represent the transition from fluidised to crackle breccias and so display intermediate precious grade mineralisation (figure 4.7 & 4.57).

4.4.7.4 Jigsaw or mosaic breccias are those in which the clasts can be more or less joined back together by the removal of the matrix, as descriptive terms for breccias also categorised as extensional or dilatant in process-related terminology (figures 4.2 A & B). Clasts are therefore angular and the breccias monomictic. Shingle breccias are related to these. Therefore little transport is envisaged of the angular locally derived wall rock clasts varying from shingle shapes (figures 4.24 & 4.25) to equidimensional, although the matrix may display local fluid transport (introduction) textures. Clearly, by the addition of sufficient matrix as hydrothermal fluid, a crackle breccia might progress to a jigsaw or mosaic breccia, locally with increasing metal grade related with the increased sulphide matrix content.

4.4.7.5 Rotational breccias are defined (Corbett and Leach, 1998) as breccias in which the jigsaw or mosaic texture has been disrupted by rotation of breccia clasts as a result of the introduction of additional matrix, which is typically mineralised and so these breccias display higher Au grades than the jigsaw or mosaic breccias (figures 4.8 A, 4. 9 B, 4.20 B, 4.24 D). The matrix may be fluidised and some clasts may have been weakly milled during rotation. Rotational breccias may occur as significant hydrothermal fluid feeders.

4.4.7.6 Vein-breccias are characterised as veins dominated by breccia textures, rather than banded or massive forms. They may develop by repeated brecciation of existing veins and in-fill of open space by new hydrothermal mineral matrix (figure 4.58 A), as a dilatant fracture continues to open, locally combined with a component of eruption and clast transport within the existing structure. Consequently, open space fill breccias are most common within veins boundedby discrete fractures and might contain fluidised, mosaic or floating clast breccias, discussed above. Breccia clast and matrix commonly differ. The bonanza Au grade 'Oatmeal Breccias' from the Favona, Waihi district, New Zealand, shown in figure 4.58 A, feature transported of well mineralised clasts with Au-bearing

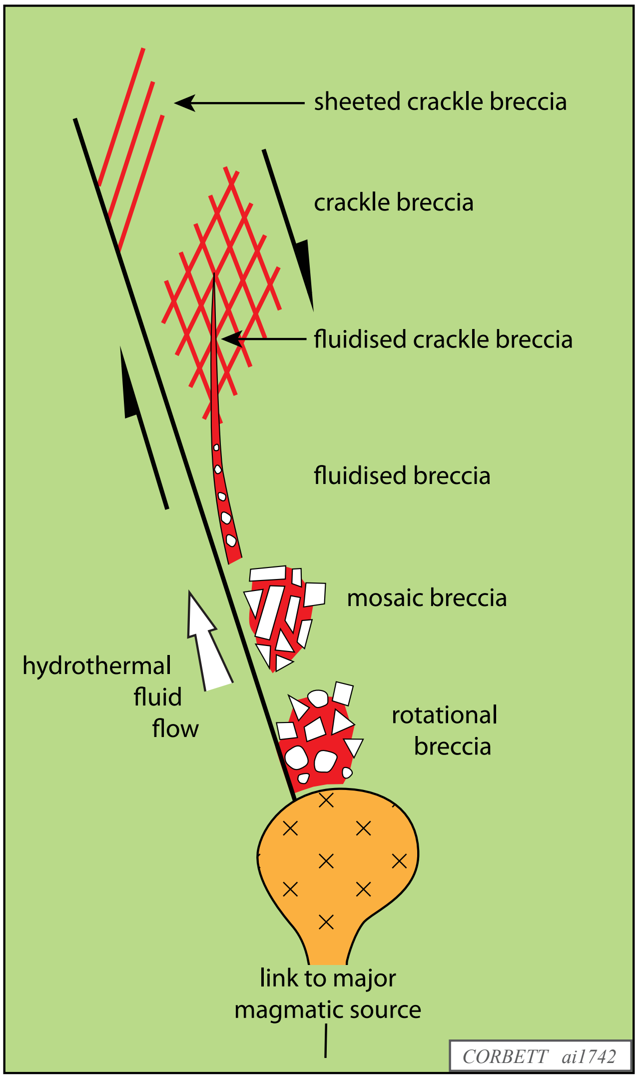


Figure 4.57 *Hydrothermal injection breccias.*

ginguro bands, in-filled by chalcedony which was probably deposited by meteoric-dominant waters and so is expected to be essentially barren. As the clasts cannot be joined back to together this is not a mosaic breccia. The breccia in figure 4.58 B similarly contains erupted clasts, no doubt ripped from the immediate wall rock, while new vein is deposited on the other vein margin. The breccia illustrated in figure 4.59 C is from the Talang Santo vein, Indonesia, and like the 'Oatmeal breccia' above features clasts of mineralised ginguro material which account for the high Au grade and have been repeatedly brecciated with infill of new chalcedony.

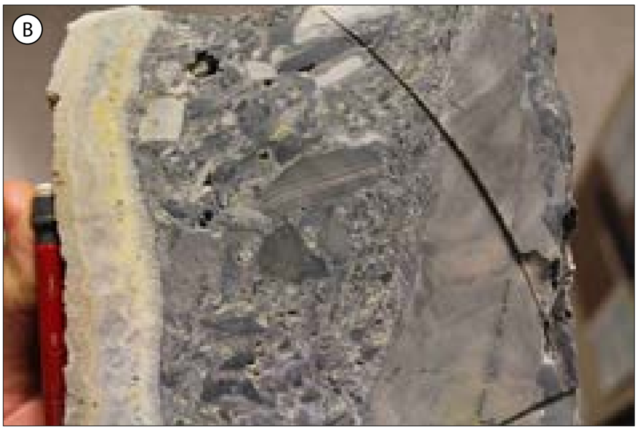


Figure 4.58 *Vein-breccias.*
A - *'Oatmeal breccia' which comprise clasts of finely banded black Au-bearing ginguro material in a chalcedony matrix, and host very high Au grades in the upper part of the main mineralised fluid up-flow.*
B - *A vein-breccia may contain clasts derived from the wall on the right, where geopetal banding may be present, and is overprinted by the banded vein on the left.*
C - *Breccia formed by the repeated brecciation and in-fill within a vein and includes ginguro-bearing mineralised clasts within a chalcedony matrix, Talang Santo mine, Way Linggo, Sumatra, Indonesia, 658 g/t Au.*

4.4.7.7 Clay matrix hydrothermal breccias occur in the upper portions of the porphyry environment. The staged model for the development of porphyry Cu alteration and mineralisation features the collapse, by drawdown, of hot low pH fluids upon the upper portion of the porphyry environment which may display earlier retrograde as well as prograde potassic-propylitic alteration (section 2.2.3.1). The resulting breccia is characterised by a matrix of typically clay alteration derived from reaction of the collapsing hydrothermal fluids with the existing wall rock, commonly grading into the wall rock from crackle breccia fluid plumbing systems to leave clasts of relict rock (figures 2.16 & 2.17). The term pseudobreccia is used by some workers to describe these breccias as there may not be a clear separation between the clast and matrix and the clasts display no transport. Matrix alteration may include kaolin-illite-smectite-pyrite as argillic alteration associated with low sulphidation epithermal Au deposits (Lihir Is., Papua New Guinea) or the collapse of phyllic-argillic alteration or advanced argillic collapse (Lookout Rocks, New Zealand) in the upper portions of margins of porphyry systems. These breccias tend not to be mineralised.

4.4.8 Dissolution breccias

Dissolution breccias develop by the removal of a soluble material, mostly carbonate, with the resulting contraction of the remaining rock or the formation of open space locally leading to collapse. As carbonate represents a common soluble material dissolution breccias are regularly recognised in sediment hosted replacement (Carlin-style) deposits where weakly acidic oxygenated meteoric waters dissolve carbonate from the marl host rocks (figure 4.59). Fluid flow paths are commonly discernible as stylolites of relict insoluble carbonaceous material of a typical dark colour (figure 4.59 C). Stylolites may also contain sulphides deposited by the hydrothermal fluid and feature adjacent clay alteration by reaction of those acidic fluids with wall rocks. Increased dissolution may result in collapse and the formation of chaotic polymictic collapse breccias with increased clast mixing (figure 4.59 B). Angular clasts may become slightly rounded during collapse and sedimentary structures are common while the matrix may vary from carbonate to insoluble material such as sand or carbonaceous residue (figure 4.59 A). Dissolution breccias may be pronounced in settings where acid sulphate caps have provided low pH ground waters for the removal of substantial quantities of carbonate and the promotion of considerable collapse. These dissolution breccias might then be well mineralised by the reaction of those low pH waters with ore fluids in order to destabilise the bisulphide complexes which transport Au (section 7.4).

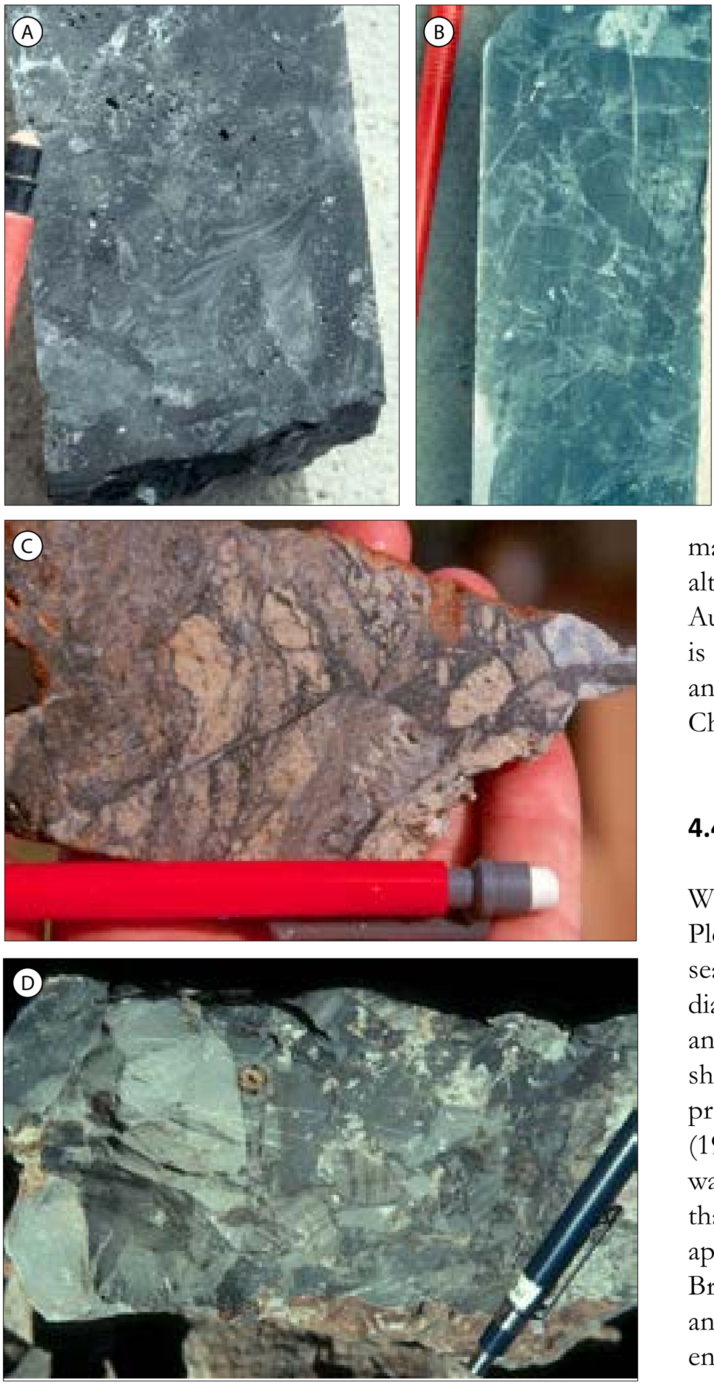


Figure 4.59 *Dissolution breccias.*
A - *Dissolution breccia showing a sedimentary structure filling open space, Carlin Trend, USA.*
B - *Collapse breccia comprising marl clasts and a carbonate matrix, Goldstrike, USA.*
C - *Stylolites and clasts within dissolution breccia, Mesel, Indonesia.*
D - *Collapse breccia in marl from the Carlin Trend, Nevada.*

4.4.9 Composite breccia systems

4.4.9.1 Phreatomagmatic-phreatic breccias

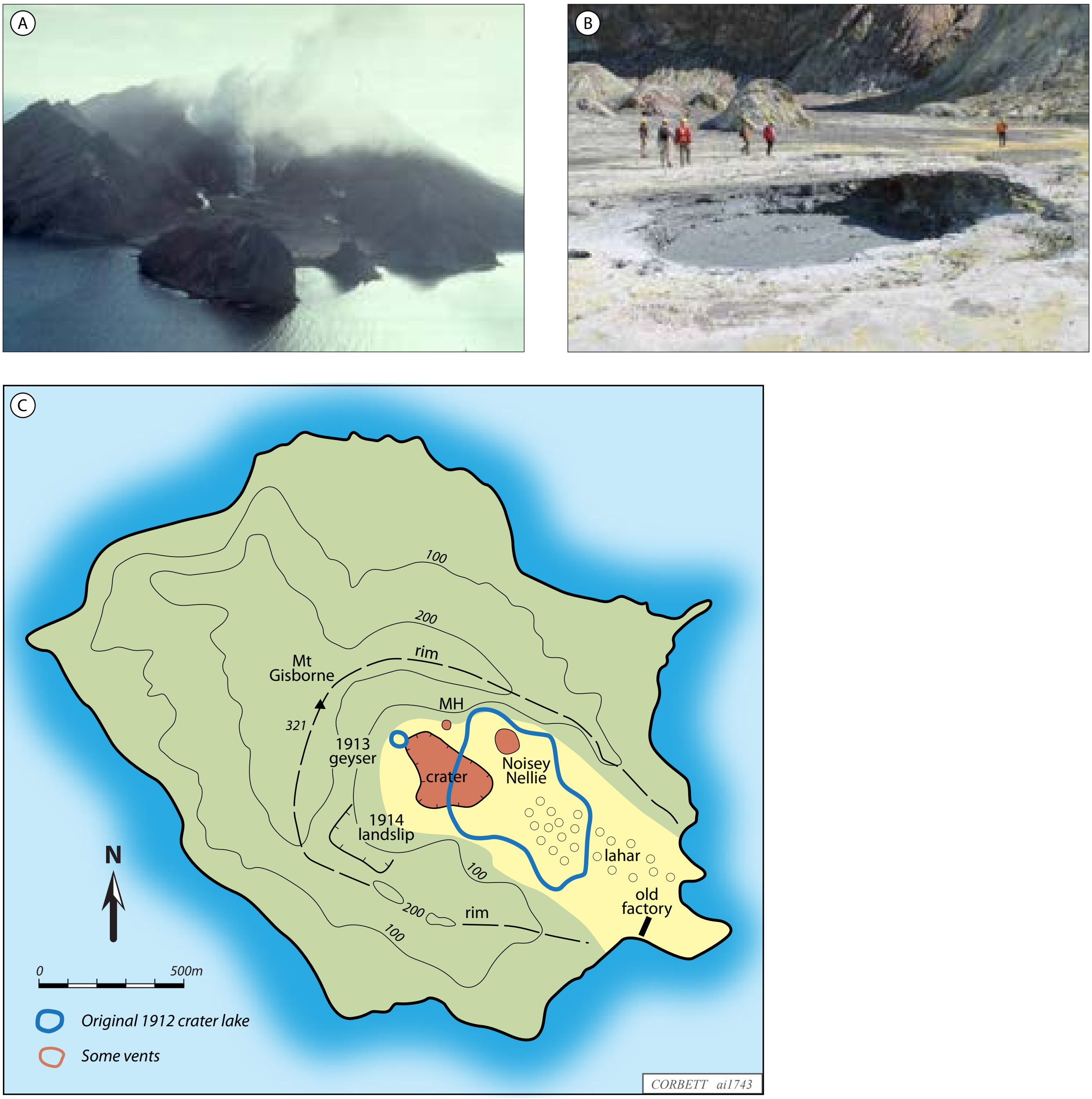
Phreatomagmatic and phreatic breccias occur in the same terrain at many ore deposits (Ladolam deposit Lihir Is., Papua New Guinea) and magmatic bodies at depth may represent the ultimate heat sources for both breccia types. The presence or absence of juvenile intrusion clasts or larger features (domes or dykes) derived from the magmatic source which might drive any breccia eruption are currently regarded as one of the main characteristics to distinguish between the two breccia groups. However, hydrothermal alteration may obscure clast types, particularly advanced argillic alteration associated with high sulphidation epithermal Au deposits, and so a phreatomagmatic-phreatic class is attributed to the breccia pipe at Pucamarca, Peru, and smaller outcropping breccia bodies at Pascua, Chile.

4.4.9.1.1 White Island (Whakaari), New Zealand

White Island lies about 48 km offshore in the Bay of Plenty north New Zealand, rising 600-700 m from the sea floor as the summit of a submarine volcano, 17 km diameter at the base (figure 4.60; Nairn et al., 1996) and which has been dissected by sector collapse. This shape has retained meteoric and magmatic water to provide the wet character which Houghton and Nairn (1991 and references therein) describe as free of sea water. White Island has been more active since 1976 than the previous few hundred years of its 16,000 year apparent hydrothermal history (Nairn et al., 1996). Breccia eruptions are associated with the advancement and withdrawal of a buried magma source in a wet environment in which clay alteration restricts rock strength and fluid permeability. Relatively small (to tens of metres) phreatic, phreatomagmatic and magmatic (strombolian) eruptions display processes of explosion followed by collapse with extension to depth (Houghton and Nairn, 1991; Letham-Brake, 2013 and references therein) as multiple vents coalesce to form larger craters.

Prior to 1912-3 the crater floor was covered by a steaming lake with a marginal geyser and steam vents (figure 4.60 C), which was drained prior to sulphur mining in 1914. However, in September 1914 an avalanche resulting from the failure of the SW crater wall buried that operation killing 11 miners, leaving the hammock-like character to the lahar on the crater floor. From 1914 a series of mainly phreatic explosive ash eruptions resulted in the development of steam vents which became significantly larger in the 1960's. From 1976 the rise of the buried magma heat source drove initial wet phreatomagmatic eruptions which evolved to strombolian forms as craters progressed downwards and erupting magma provided volcanic bombs (Houghton and Nairn, 1991). Coalesced vents formed the "1978 Crater Complex" and heating of the water saturated crater floor provided continued steam explosions (phreatic eruptions) as part of the hydrothermal activity (Nairn et a., 1996; figure 4.60).

This author visited White Island in 20 July 2000 at a time when the MH vein was actively venting steam prior to the eruption of 27 July and associated failure within the crater apparent in a later visit of February 2015 (figure 4.60).



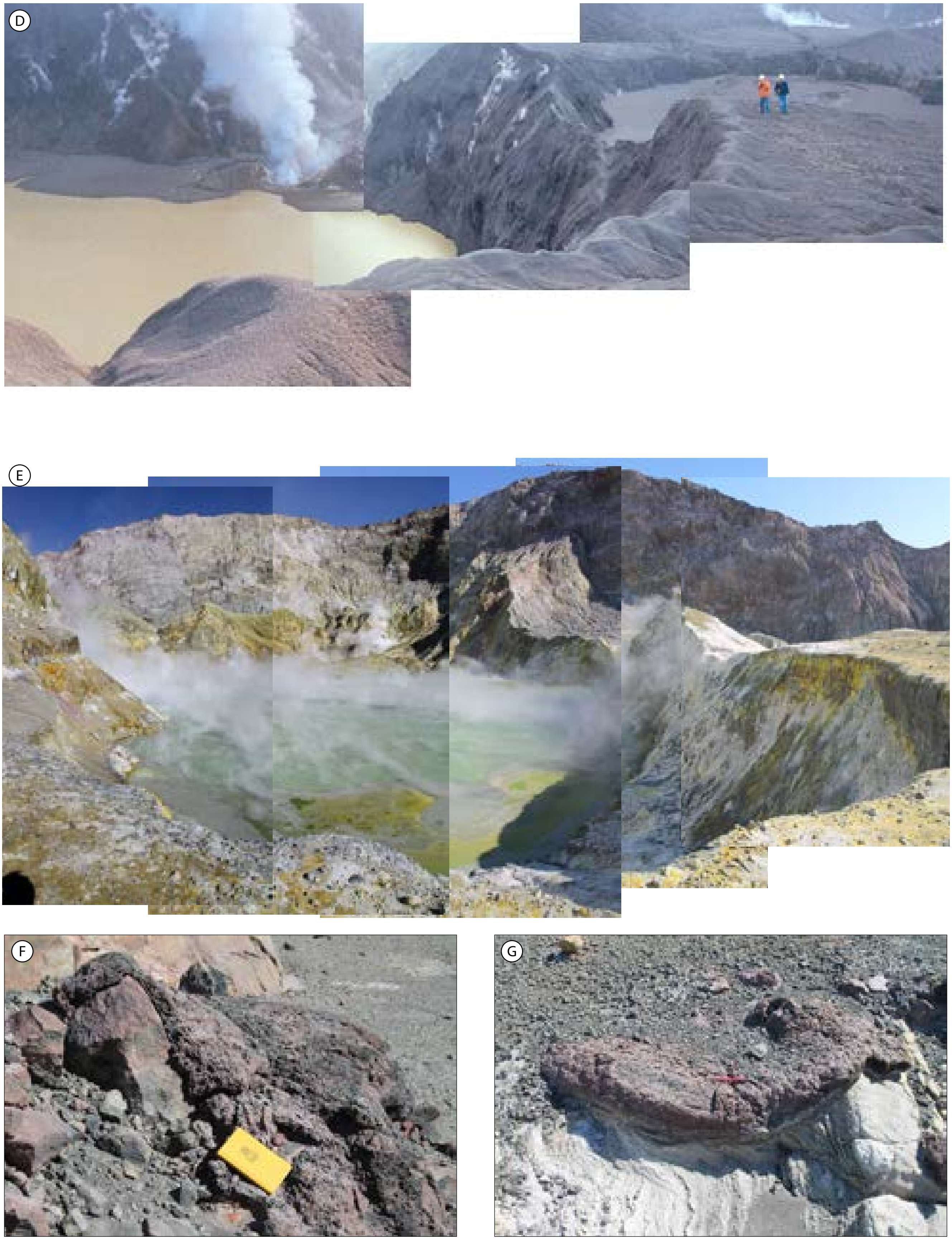


Figure 4.60 *White Island (Whakaari) New Zealand composite breccias.*
A - *View in July 2000 of White Island looking along the crater floor towards the eruption from the MH vent.*
B - *Mud pool on the crater floor east of C in 2015.*
C - *Composite map showing some relations at White Island.*
D - *View in July 2000 over the 1978-1990 crater complex towards the MH vent showing the narrow wall which retains the elevated lake on the right.*
E - *View from about the same position in February 2015 showing an evacuated and collapsed crater.*
F & **G** - *Volcanic bombs.*

4.5 CONCLUSIONS AND EXPLORATION IMPLORATIONS

Explorationists need to understand breccias sufficiently to incorporate different types in any geological map or model, and to be able to communicate with their peers in the description of exploration projects. However, breccias represent just one tool used in the primary task to find ore, and so breccias should not become the entire focus of interest. In the field, individual breccia exposures are best understood in context and so explorationists should avoid getting bogged down in one difficult exposure, but keep moving, so as to compare many breccia bodies. Rapid evaluation may be important and might be aided by the use of digital photography.

Breccia nomenclature can be a significant challenge. The approach here has been to build up an understanding of a breccia from an initial description which might allow the observer to compare it to another breccia in their repertoire of breccia types. Colloquial terms often allow easy and quick descriptions and comparisons with breccias described by other workers. Genetic geological models account for the mode of formation of any breccia, and by comparisons with other better known systems provide an understanding of the exploration implications of a breccia system. As with all geological mapping it is important to preserve factual data which can always be returned to as ideas change or new data comes to hand, rather than engage in interpretations too early in a mapping programme.

Breccias of interest in epithermal-porphyry exploration form by the interaction of structural, magmatic and hydrothermal processes at varying crustal levels. Common themes discernible in many breccias include; volatile pressure build up, explosive activity, collapse and then later liquid phase fluid flow and mineralisation. Thus, many breccias are pre-mineral and provide ground preparation for later ore fluids and also tap the buried magma source as a link to the higher crustal level setting of mineral deposition. Some epithermal stage breccias might overprint porphyry ores (Bradden Formation at El Teniente, Chile). An understanding of breccias might vector towards ore and many breccias contain stand outs which readily aid their placement in a genetic context with exploration implications.

Exploration implications of an understanding of breccias include:

- Pebble dykes transect wall rocks above the upper margins of intrusion source rocks and so provide evidence of porphyry environments and may vector towards porphyry targets.
- Phreatomagmatic breccia pipes host ore in different settings governed by several factors such as crustal level. At shallow levels clay alteration provides incompetent breccias and so mineralisation is likely to occur within brecciated wall rocks. However, breccias at deeper levels within pipes are commonly more competent at depth and so host ore within breccia matrix. Juvenile intrusion clasts represent a stand out feature for the identification of phreatomagmatic breccia pipes.
- Phreatic (eruption) breccias, which vary from silicified to clay altered, often represent fluid outflows for sinter formation and may pass downwards to mineralised veins possibly hosted by the same structure.
- Many breccia bodies may contain "rucked up" clasts of mineralisation or alteration as an indication of exploration targets which might lie at depth.