3 STRUCTURE

Structure controls the development of epithermal and porphyry ore deposits in several ways:

- Major structures localise ore systems, particularly magmatic source rocks, generally at dilatant sites.
- Dilatant fracture systems bleed ore fluids from magmatic source rocks at depth to higher crustal levels (both epithermal and porphyry) where mineral deposition occurs, while epithermal fluids evolve during upwards migration.
- More dilatant structural sites control the setting and geometry of ore shoots.
- Structural intersections represent sites of ore deposition by fluid mixing.
- Syn-mineral structures offset ore systems to facilitate telescoping.
- Post-mineral structural offsets also influence the geometry of an ore system and require analysis in the exploration for displaced ores.

Terminology

Ore shoots (clavos in Spanish) are defined as vein portions which are typically wider and host higher precious metal grades, and are most easily discernible on long sections as plots of width x grade, commonly termed gram-metre plots.

Telescoping is most commonly regarded as telescoping inwards as younger, higher crustal level ore systems and alteration are placed upon older, deeper level systems, often with only small differences in their ages. However, telescoping outwards may occur as dilatant structures attenuate ore systems such as in the formation of sheeted vein wallrock porphyry deposits.

3.1 MAJOR STRUCTURES

In subduction-related magmatic arcs, major crustal-scale structures influence the setting of epithermal and porphyry ore systems, mainly by localisation of the magmatic source for metals (figure 3.1; Corbett, 1994, 2012; Corbett and Leach, 1998). Porphyry Cu models used throughout the 1960's and 1970's featured porphyry intrusions emplaced below stratovolcanoes as part of the magmatic source for that extrusive volcanism (Sillitoe, 1972; Titley, 1982). However, many former and recent discoveries feature porphyry mineralisation within basement of sedimentary and

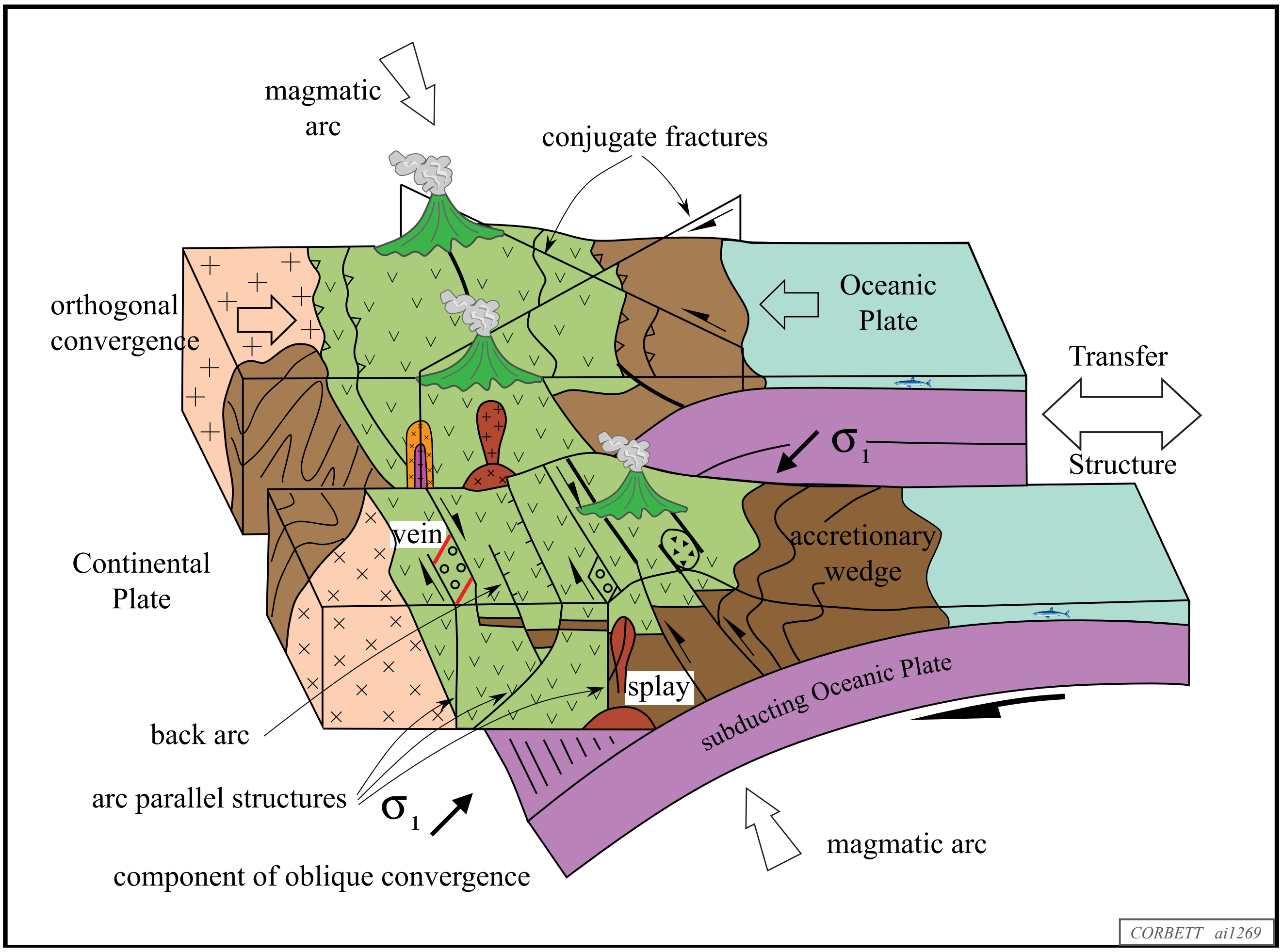


Figure 3.1 *Illustration of three classes of major structures which participate in epithermal-porphyry ore formation in magmatic arc-back arc environments and described herein.*

metamorphic host rocks without associated volcanic piles (Grasberg, Indonesia; Porgera epithermal and Golpu porphyry, Papua New Guinea; Ridgeway and Cadia porphyry deposits, Australia). Major structures localised all these porphyry intrusions above magmatic source bodies without associated extrusive volcanism. Indeed, the absence of volcanism may provide quality porphyry deposits as volatiles and metals have been constrained within the buried porphyry intrusion rather then dispersed by volcanism. Both high and low sulphidation epithermal Au deposits are related

__Figure 3.2__ Structures in Northern Chile including the Falla Oeste-Domeyko Fault system which localises many porphyry systems and epithermal deposits, locally at the intersections with conjugate fractures. See figure 3.5A for location.

to buried magmatic source rocks for metals which are commonly localised by major structures. Movement on these major structures provides the kinematic regime for the development of dilatant fractures which localise ore systems and influence ore geometry such as sheeted veins.

Three styles of major structures localise porphyry Cu-Au and epithermal Au-Ag ore systems in subduction-related arc - back arc environments (Corbett, 1994, 2012; Corbett and Leach, 1998) as:

3.1.1 Arc-parallel structures

Arc-parallel structures, also termed accretionary structures (Corbett, 1994), form within compressional magmatic arcs as part of the structural grain of the district and so commonly feature steep dips and lateral continuity as terrain boundaries between highly varied rock groups, generally of different ages (figure 3.1). Extensional structures such as range-front faults in Western US - Northern Mexico, also occur in in this group. Flat dipping thrust faults or other layer-parallel features may host ore but rarely as regionally significant structures. Arc-parallel structures display protracted histories of activity commonly with multiple senses of movement. In compressional magmatic arcs many of these structures spent much of their history as reverse faults (Domeyko Fault, Chile, figure 3.2; Gilmore Suture, NSW, Australia, figure 3.3), while others display country scale dominant senses of strike-slip movement (Philippines Fault, Philippines; Trans Sumatra Fault, Sumatra), and vary from discrete easily discernible structures (Philippine Fault) to corridors of structures (Domeyko Fault, Chile). All of these structures localise ore systems, generally in discernible dilatant settings (discussed below). Other less well studied structures have been defined from the alignment of ore systems (Kalimantan Suture, Borneo; van Leeuwen et al., 1990), or contain individual ore systems (Frieda-Nena on the Fiak-Leonard Schultz Fault, Papua New Guinea, Corbett, 1994; Bainbridge et al., 1994; figure 3.38). In extensional settings major arc-parallel structures localise ore systems as elements of the structural grain and may reflect underlying deep crustal geological contacts or discontinuities (Carlin-Goldstrike and Battle Mountain Trends, Nevada). Throughout the extensional Nevada-Sierra Madre (Northern Mexico) terrains, ore systems are localised by generally regionally extensive listric faults organised as arc-parallel packages (Sleeper, Nevada, USA; Palmarejo, Mexico). At Bilimoia, Papua New Guinea, the regional slaty cleavage changes to a crenulation cleavage close to the ore-hosting structures formed parallel to the Markham Fault, demonstrating that these arc-parallel structures formed in the order of 5 km depth prior to uplift and mineralisation closer to 1-2 km depth (figure 3.4; Corbett et al., 1994b).

Arc-parallel structures tap deep magma melts and focus the overprinting emplacement of ore-bearing intrusions into dilatant sites, such as second order structures, commonly developed by transient changes in the nature of convergence (section 3.4).

3.1.2 Arc-normal structures

Arc-normal, also termed transfer (Corbett, 1994) or trans-arc structures (figure 3.1), transect magmatic arcs at high angles to the structural grain, cutting it and commonly extend into the underlying basement to tap mantle derived melts as sources of Au mineralisation, or focus overprinting magmatism. Ore systems are localised by arc-normal structures at Porgera and Wafi in Papua New Guinea, Grasberg in West Papua and the Cadia Valley by the Lachlan Transfer Zone, Eastern Australia (figures 3.3 & 3.4). Transfer structures locally offset (or transfer) the structural grain of the magmatic arc and accommodate variations in the rate of subduction or dip of the down-going subducting plate segments along convergent plate boundaries (Corbett, 1994). The fold-thrust belt of western Papua New Guinea is offset and changes orientation across the Porgera Transfer Structure, which localises the Porgera Intrusion System, and the Wafi Transfer Structure, which localises the Wafi-Golpu Complex, represents part of the corridor of structures formed as the contact between the western and eastern orogens of Papua New Guinea (figure 3.4; Corbett, 1994, 2005b). The Porgera Transfer Structure transects the Mesozoic basement at depth (Hill et al., 2002) and taps the interpreted deep mantle source for the alkaline Porgera Intrusion Complex. Movement on structures related to the Wafi Transfer Structure localised the Golpu Porphyry in a regional scale fault jog (Menzies et al., 2013) and facilitated the opening of the Bulolo Graben, an intra-arc basin which hosts felsic magmatism and the Morobe Goldfield, Papua New Guinea (Hidden Valley, Hamata, Kerimenge, Wau and Edie Creek Au deposits; Corbett and Leach, 1998). Many structures display protracted histories of activity. The Lachlan Transverse Zone, in Eastern Australia, which has long been recognised to host many ore systems (Scheibner and Stevens, 1974),contains individual elements formed as growth faults during volcanism and later active to localise mineralisation in the Cadia Valley where porphyry, skarn and wallrock porphyry ores are aligned along this same structural trend. Other transfer structures include the Walker Lane Trend, Nevada and the Chicama-Yanacocha Structural Corridor (Turner, 1999) which localises the Yanacocha epithermal-porphyry district, Northern Peru. The arc-normal Uinta Axis (Guen et al., 2010) is considered to have been active since the Archaen and localise the giant Bingham Canyon porphyry Cu-Au-Mo deposit. Recent workers (Cooke et al., 2014) have used the term 'slab tear' to describe what are arc-normal or transfer structures. The north-south aligned and mineralised Tabar and Lihir Island groups are localised within several roughly NS tear structures developed in the downgoing (upper) Pacific (Solomon Sea) Plate segment as it was folded above the curved New Britain Trench subduction zone (figure 3.4; Corbett and Leach, 1998).

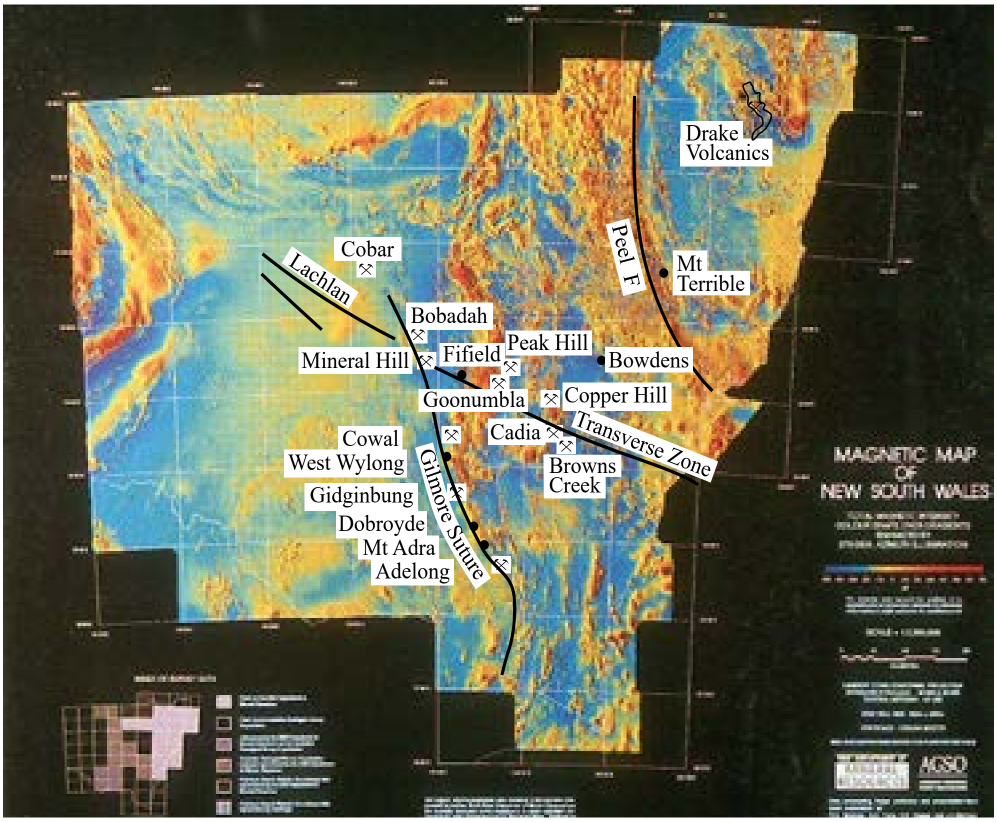


Figure 3.3 *Aeromagnetic image of New South Wales, Australia, showing several ore systems localised along the Gilmore suture terrain boundary and Lachlan Transverse Zone. Note the NS trending segments of the Macquarie Arc which host the Goonumbla, Copper Hill and Cadia districts.*
1992 image by NSW and Commonwealth of Australia Departments of Mineral Resources.

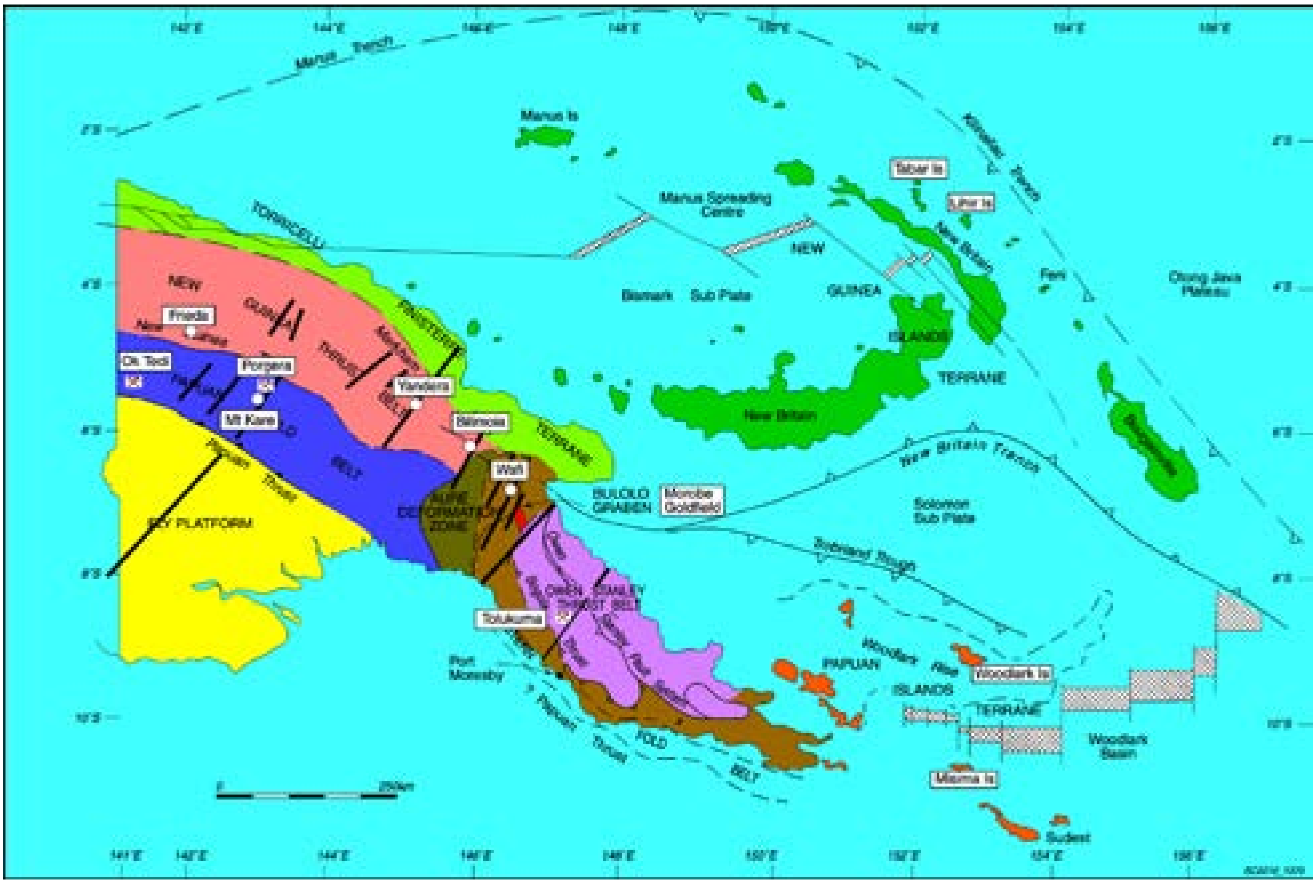


Figure 3.4 Geological framework of Papua New Guinea (from Corbett, 2005b) showing some ore systems localised by arc-normal and arc-parallel structures. The set of NE arc-normal transfer structures such as the Porgera Transfer Structure extend into the underlying Mesozoic basement, while the (set of) Wafi Transfer Structure(s) separate the eastern and western orogens of Papua New Guinea. Arc-parallel faults which localise mineralisation include the Fiak-Leonard Schultz (Frieda-Nena porphyry-high sulphidation epithermal), Lagaip (Porgera) and Markham (Bilimoia) Faults. The NS structural elongation of the Tabar and Lihir Island chains is also apparent (Corbett and Leach, 1998).

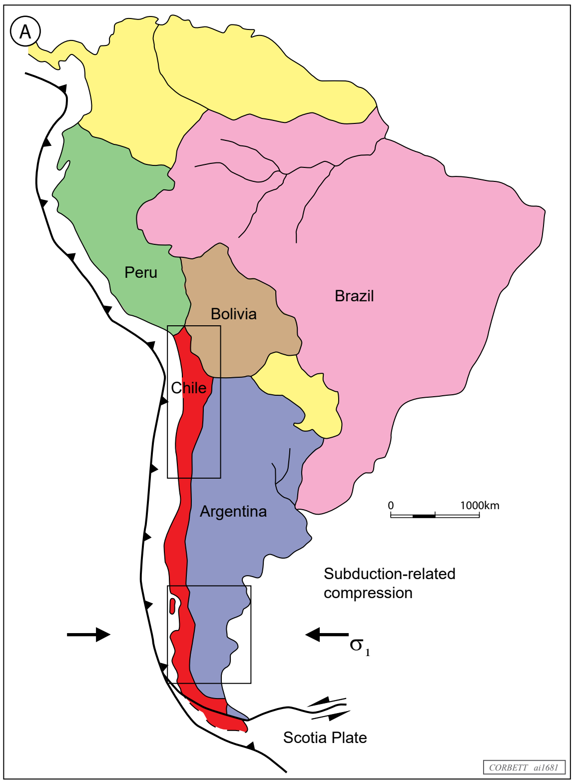
3.1.3 Conjugate fractures

Conjugate fractures are recognised at much lower angles to the arc than the arc-normal structures and appear to be best developed within orthogonal compressional magmatic arcs (figure 3.1). Some settings host similar opposing fractures in the one location or distributed throughout the arc, while elsewhere one fracture may be dominant. Although conjugate fractures are interpreted to have formed during orthogonal compression and display associated strike-slip senses of movement (figure 3.1), vein kinematics suggest many have been reactivated during extension associated with transient relaxation of compression. Vein orientations within the conjugate fractures demonstrate the Batu Hijau porphyry, Indonesia (figure 3.**) and the Mastra Au veins, Turkey (figure 3.**) were emplaced during a relaxation of compression.

There is considerable variation in the angular relationship between the conjugate fractures and the structural grain of the district. Most conjugate fractures (northern Chile, figure 3.2 and Deseado Massif, Argentina, figure 3.5) are equally aligned in relation to the arc-parallel fractures and display 60° separations typical of conjugate fractures (Price, 1966; Blés and Feuga, 1986). Variations in the angular relationship may be consistent with brittle or ductile failure (Price and Cosgrove, 1990) and hence crustal level of formation. Low angles (to 38°) are recognised at the Batu Hijau, Indonesia (figure **) and very high angles (125°) in the deeply eroded crystalline terrain of the Pontides in the Eastern Black Sea (Güven, 1993 in Moon et al., 2001; figure **).

In northern Chile-Argentina (figure 3.2) the NW conjugate fractures may dominate over NE. Some important fractures include the NW La Escondida trend which localises the La Escondida porphyry district at the intersection with the Domeyko fault system, and the NW Veladero trend which localises the Pascua-Lama, Chile-Argentina and Veladero, Argentina high sulphidation epithermal Au deposits. The El Quevar high sulphidation system is localised by the NW Co. Ricon Azure fracture, which hosts many volcanic centres, while in northern Chile the El Guanaco high sulphidation epithermal Au deposit and San Cristobal, low sulphidation Au deposit in are localised by adjacent NW and NE conjugates, respectively (figure 3.2).

The Jurassic Deseado Massif of Argentine Patagonia (figure 3.5) is dissected by conjugate fractures interpreted to have been active during low sulphidation epithermal vein formation to facilitate ore shoot formation (figure 3.41). In north Queensland, Australia, a set of conjugate fractures influence the distribution the Permo-carboniferous volcano-plutonic complexes within Proterozoic basement and localise many ore systems such as the Kidston breccia pipe (figure 3.6).



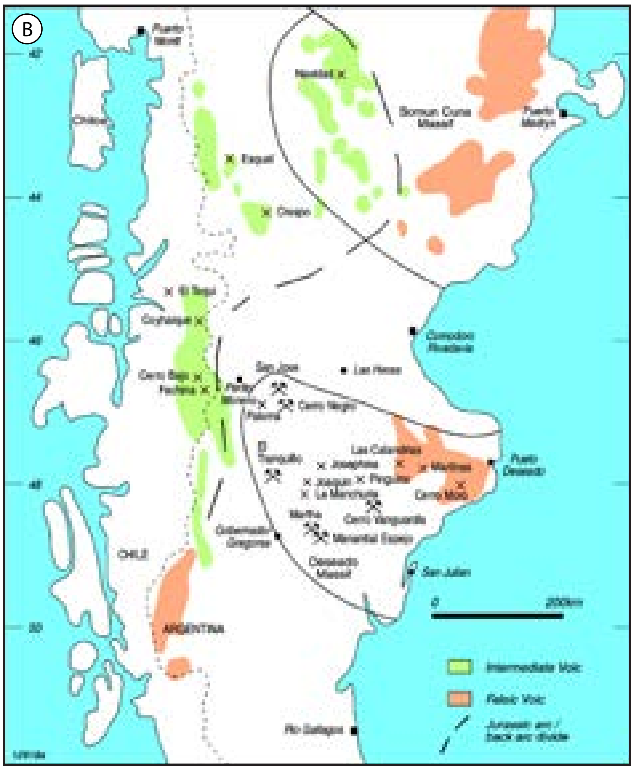


Figure 3.5 *Conjugate fractures influence ore formation in the Deseado Massif, Argentine Patagonia.*
A - *Regional setting and location, including of figure 3.2 a the top box and figure 3.5 B as the lower box.*
B - *Mines and exploration projects within the Deseado Massif.*
C - *Fractures apparent on a remote sensing image in the Cerro Moro district (from Climax Mining website). See also section 3.2.3.2.1 and figure 3.42 for discussion of these structures in ore shoot formation.*

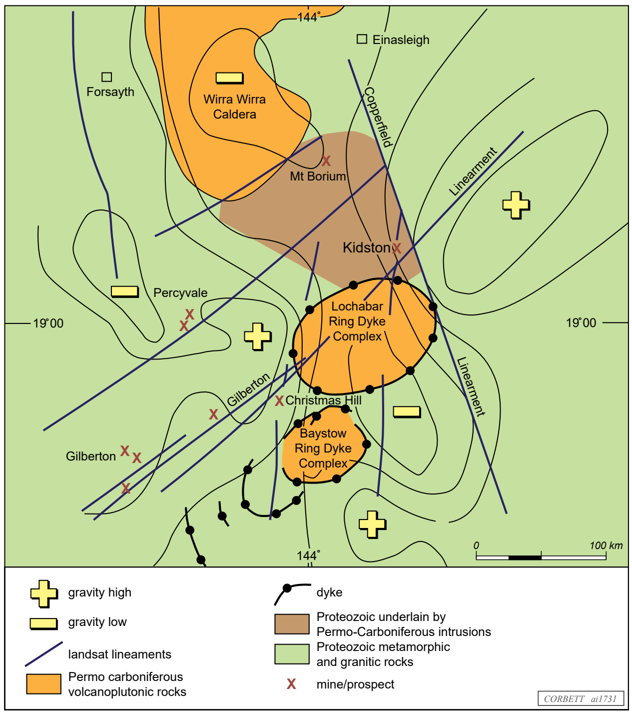


Figure 3.6 *Conjugate fractures in north Queensland influence of the distribution of Permo-Carboniferous volcano plutonic complexes and localise many Au occurrences (from Corbett, unpubl. data, 1983; Corbett and Leach, 1998).*

3.2 DILATANT STRUCTURAL SETTINGS

At prospect scale dilatant fractures control the geometry of epithermal veins, especially the development of better mineralisation within ore shoots, kinematics of the larger scale structures such that better mineralisation generally occurs in second order structures. Many porphyry deposits are localised by dilatant splay faults and some of the best mineralisation may occur within sheeted veins or breccias. Sheeted fractures not only host porphyry mineralisation, but as dilatant fractures, participate in the transport of ore fluids from the magmatic source at depth to higher crustal levels where mineralisation deposits under cooler conditions. Polyphasal activity accounts for elevated metal grades within banded and laminated veins with elevated metal grades derived from multiple episodes of mineralisation. Wallrock porphyry deposits comprise sheeted veins of porphyry mineralisation which, in dilatant settings, extend from the source porphyry into the adjacent wall rocks (figure 1.1).

Dilatant settings for the development of epithermal vein mineralisation categorised as orthogonal extension, oblique extension and transpression, and compression, influence the geometry of ore shoots (figure 3.7), either separately or combined. Ore shoots, defined earlier as containing the widest and highest metal grade vein portions, are most easily identified using gram x metre plots, typically on long section data.

3.2.1 Orthogonal extension

Orthogonal extension responsible for epithermal vein formation is commonly manifest as sets listric faults with sub-parallel strike and normal senses of movement which may define the structural grain of the district (Sierra Madre, northern Mexico; Great Basin, US; southern Peru; Argentine Patagonia; Gosowong, Indonesia; Hidden Valley, Papua New Guinea). Bedding may be reoriented while subsidiary faults develop in the hanging wall to the principle fault with dips towards that structure (figure 3.7). Drag on the fault tips during normal movement provides a curvature to each structure in plan view with opposite senses (Arcata, Peru; figure 3.8). Vein and lode mineralisation typically exploit the most dilatant portion of the listric (including subsidiary) faults and so flat pitching ore shoots dominate in the steep dipping portion of the listric fault and veins decline in thickness and Au grade as the listric fault flattens (figure 3.7; Corani, Peru; figure 3.9, Corbett in Swarthout et al., 2010; Palmarejo, Mexico, figure 3.10; Gosowong, Indonesia; figure 3.43 Sleeper, Nevada, US). Smaller scale parallel tension veins may from stockwork veins arrays within the wall rocks adjacent to listric faults or between listric fault elements (Hidden Valley, Papua New Guinea).

In many exploration examples vein thickness and precious metal grades have declined as the dip of listric faults shallowed. Variations of just a few degrees dip of the listric fault may account for the limitation of ore shoots with depth. This is well illustrated in the exploration data for Palmarejo, Mexico where on the long section vein portions steeper than 55° dip hosted ore shoot metal grades (figure 3.10), although in many systems inflection point is steeper (66° for Kupol in eastern Russia). Consequently, some exploration projects may host significant exposures of flat dipping listric faults with extensive hydrothermal alteration but little mineralisation (Corani, Peru, figure 3.9).

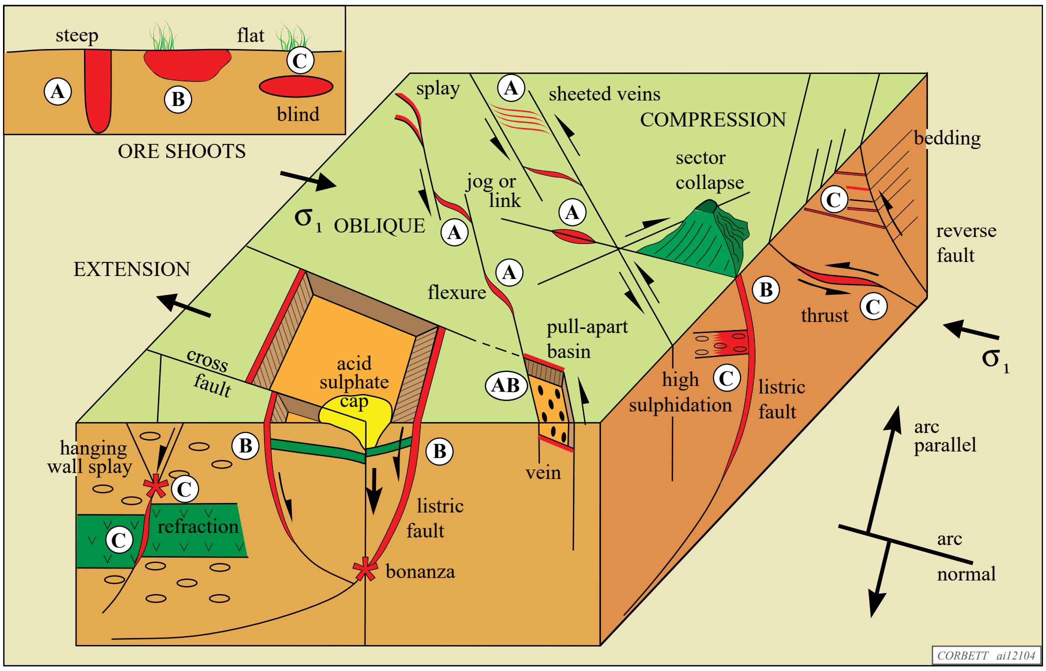


***Figure 3.7** Model illustrating the three main structural settings in which mineralised epithermal veins occur, showing the ore shoot geometry for each (from Corbett, 2012).*

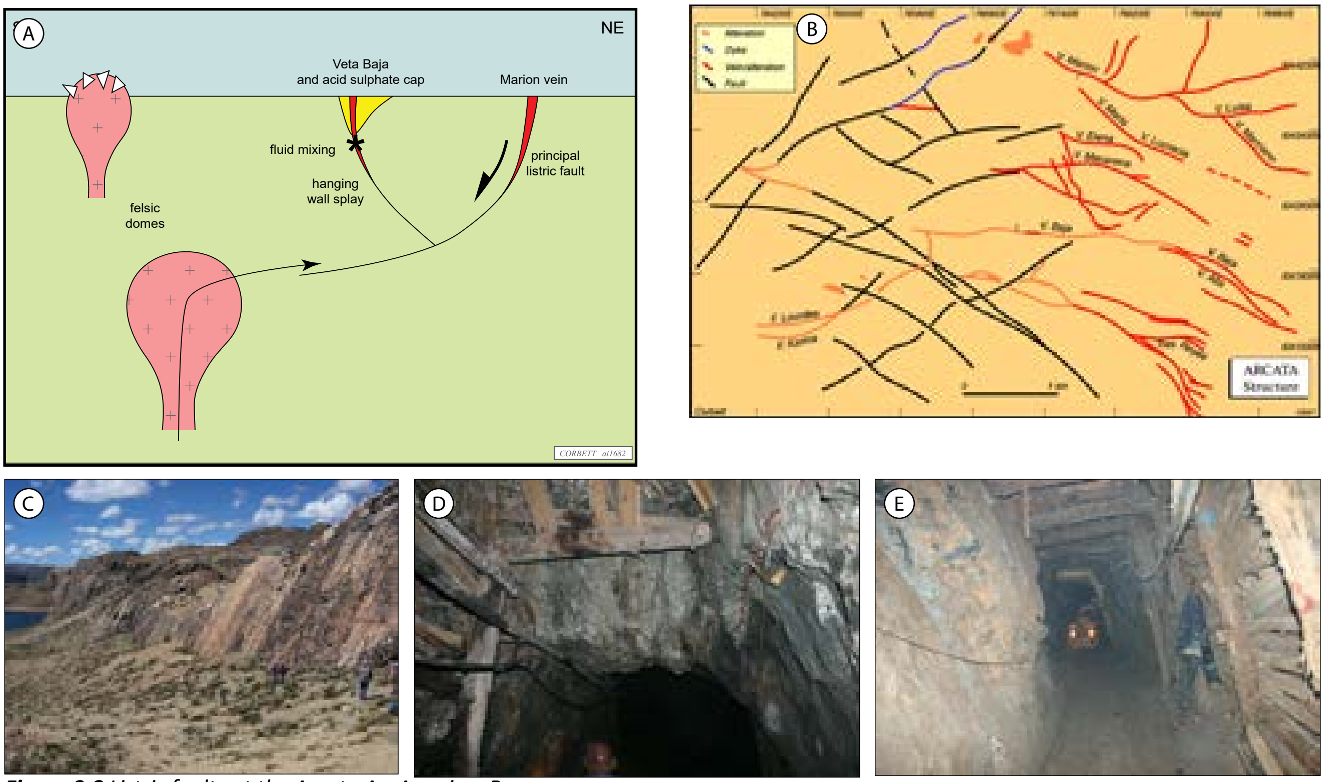
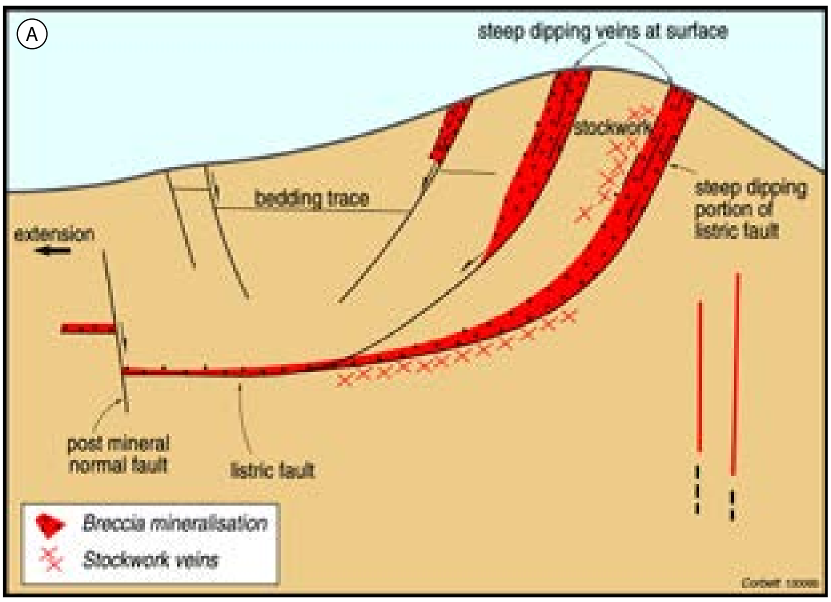


Figure 3.8 *Listric faults at the Arcata Au-Ag mine, Peru.*
A - *NE-SW conceptual cross section showing the Marion SW dipping principle listric fault and Veta Baja as one of the many hanging wall splay faults.*
B - *Map of the listric fault system locally exploited by known veins (adapted from data in a Hochschild Mining presentation, 2010).*
C - *Veta Baja listric fault in outcrop showing steep pitching slickensides indicative of normal fault movement, with geologists for scale.*
D - *Veta Baja vein underground helmet for scale.*
E - *Veta Baja vein mining.*



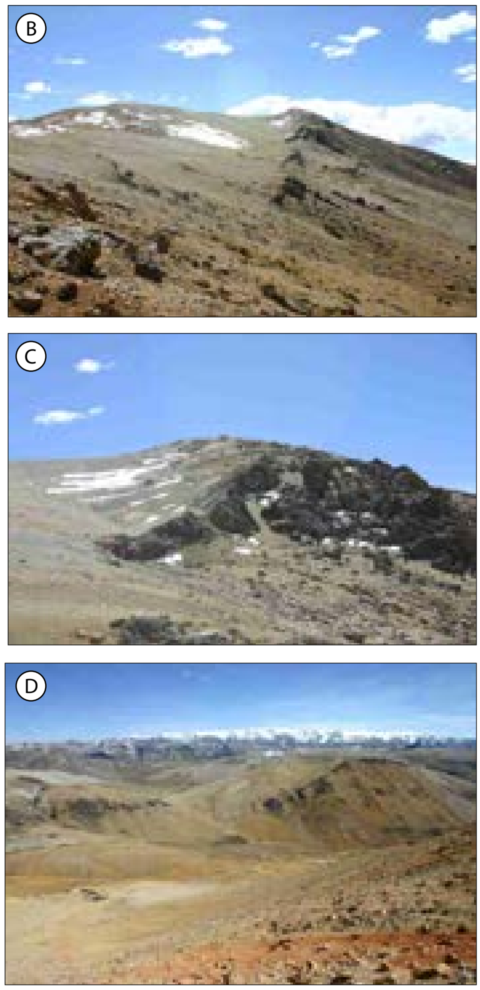


Figure 3.9 *Listric faults at Corani, Peru.*
A - *Conceptual graphic (from Corbett, unpubl. report used in Swarthout et al., 2010) which illustrates the restriction of best Ag to the steep dipping fault portions and hanging wall stockwork veins.*
B - *Steep dipping portion of the listric fault.*
C - *Flattening of listric fault with a group of geologists at the base for scale.*
D - *Flat dipping portion of the listric fault with extensive alteration but no mineralisation.*

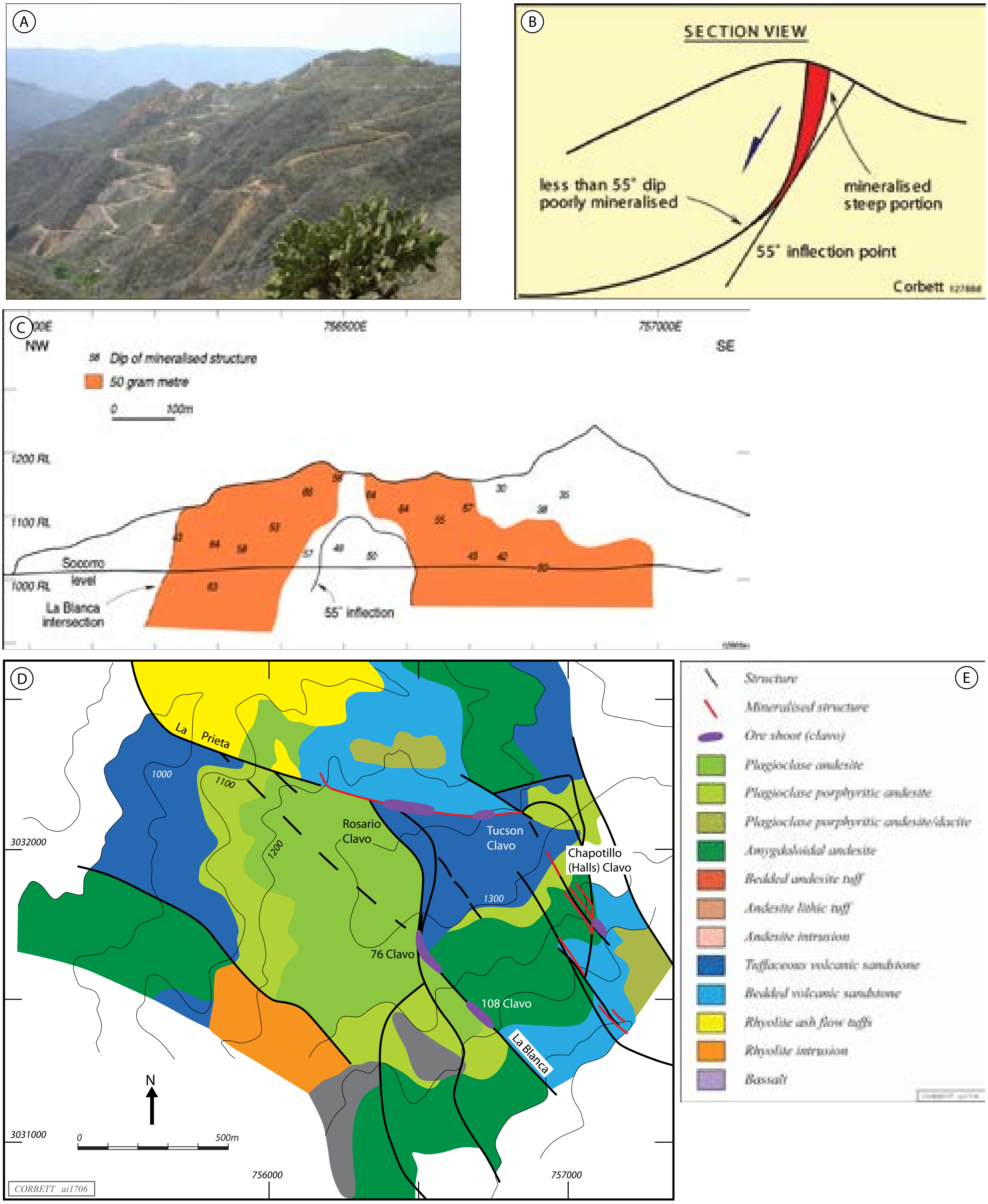


***Figure 3.10** Listric fault at Palmarejo, Mexico.*

A - *View of Palmarejo during exploration with drill roads on the ore shoots.*

B - *Conceptual cross section.*

C - *Long section aligned along the La Prieta structure showing the Rosario-Tuscon clavo as >50 gram x metre vein portion restricted to the > 55° dip fault segment.*

D - *Map showing the location of ore shoots and long section section (adapted from Masterman et al., 2005)*

E - *Legend*

F - *La Prieta listric fault in underground workings.*

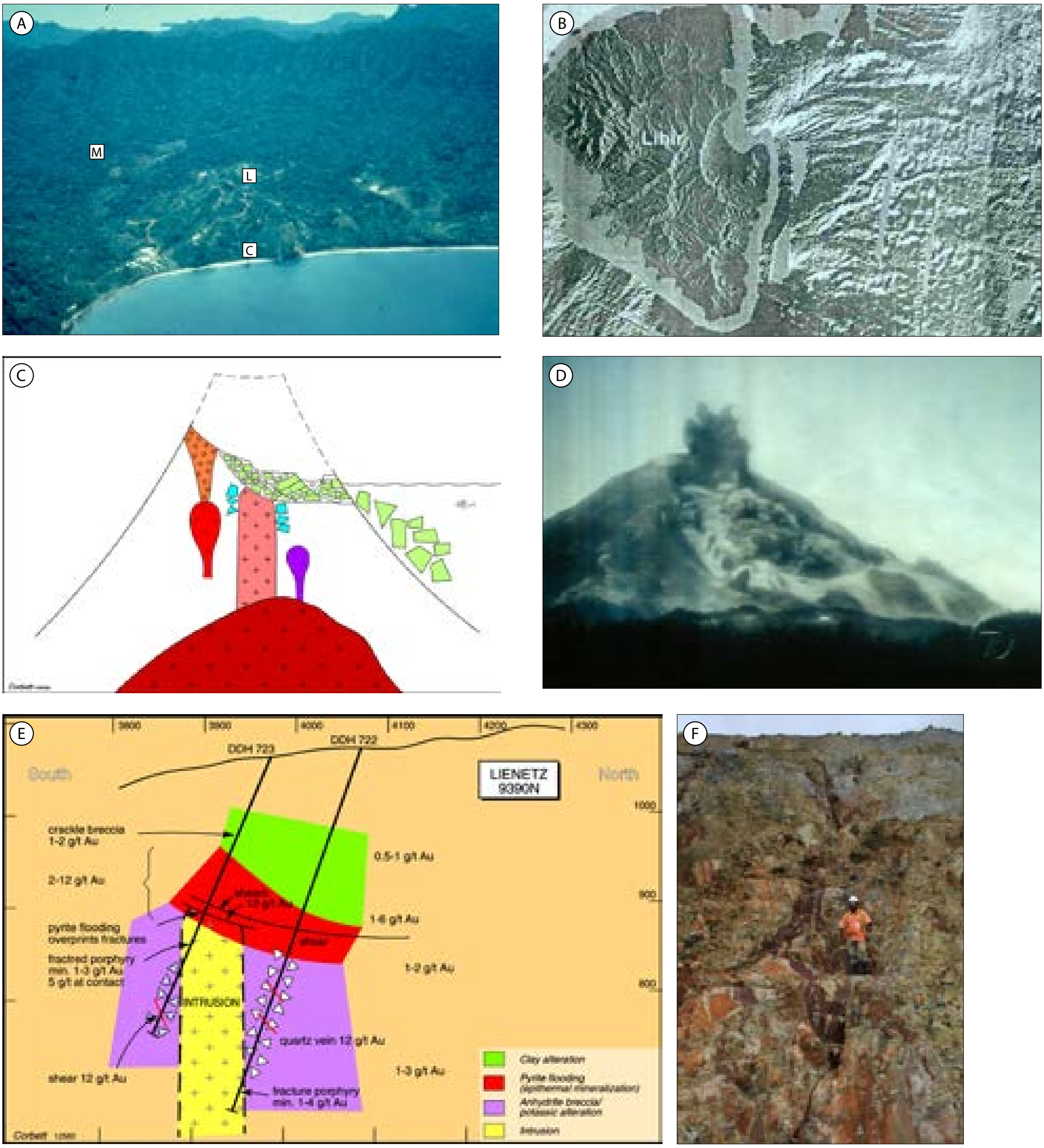


Figure 3.11 *Listric fault hosted mineralisation at Ladolam, Lihir Is., Papua New Guinea.*

A - *1984 view of the Luise Caldera shows the yet undiscovered Minifie (M) as well as Lienetz (L) and Coastal (C) Zones under exploration.*

B - *Composite onshore slide looking radar and off shore bathometric map of Lihir island showing detritus derived from sector collapse (from Corbett, 2005b)*

C - *Conceptual model for sector collapse of the Luise volcanic ediface.*

D - *Listric faults facilitated Mt St Helens-style sector collapse for comparison.*

E - *A cross section, located between the Minifie (left) and Lienetz (right) zones, showing steepening of the listric fault which cuts the earlier porphyry event and is exploited by the epithermal mineralisation.*

F - *Steep dipping Minifie fault in the open pit (2004) which hosted elevated Au grades.*

3.2.1.1 At the Ladolam Au deposit, Lihir Island, Papua New Guinea, epithermal gold mineralisation was localised by listric faults developed during sector collapse of a stratovolcano, much like the sector collpse failure at Mt St Helens in 1980 (figure 3.11; Corbett et al., 2001; Corbett 2005b). As collapse took place only 100,000 years ago detritus is discernible on the sea floor bathymetry. Similar sideways sector collapse is recognized in many other youthful stratovolcanoes throughout Papua New Guinea. Early exploration at Ladolam identified the flat dipping buried mineralisation at the Coastal and Ladolam Zones, but the project only advanced when sub-crop of better quality mineralisation was identified within the steep dipping Minifie Zone close to the caldera wall. It was proposed (Corbett, 2005b) listric faults which facilitated the sector collapse slid on an interface formed between the upper plate brecciated volcanics and underlying earlier anhydrite matrix potassic altered porphyry breccia. Flat dipping fault portions of the listric fault near Luise Harbor, are less mineralised than the steep dipping portions such as the Minifie Zone close to the caldera rim. The early identification of K-feldspar as the low temperature form adularia, promoted in the geological literature as evidence of precious metal deposition by boiling (Simmons and Brown, 2000b), led to the use of the "boiling zone" model to focus exploration at Ladolam within the flat dipping fault zones (Moyle et al., 1990). Later steep dipping fault portions were subsequently identified as more prospective (Corbett, unpubl. reports) for higher grade Au mineralisation interpreted to have been deposited by cooling and sulphidation reactions (Leach, unpubl. report, 2007).

3.2.1.2 Hanging wall splays

Hanging wall splays develop as dilatant tension fractures within the wall rocks above steep dipping normal faults (figure 3.7), including listric fault arrays (Arcata, Peru, figure 3.8; Waihi, New Zealand, figure 3.31). Continued normal fault movement dilates hanging wall splays as settings of repeated and enhanced flow of mineralised hydrothermal fluids which may host high Au grade banded veins. Furthermore, intersections of hanging wall splays and principle normal faults represent common settings for the development of bonanza epithermal Au mineralisation within pencil shaped ore shoots, aligned along the intersection lineation of the two structures. Here, the rapid rise of depressurised ore fluids up a normal fault may draw near surficial waters down the hanging wall splay, (somewhat similar to a venturi pump) and promote fluid mixing at the fault intersection, described in section 7.5.4 as an efficient mechanism of Au deposition (Leach and Corbett, 2008). These ore shoots are most pronounced where the hanging wall splay taps low pH waters associated with acid sulphate caps or bicarbonate waters (section 7.5.4).

3.2.1.2.1 At Porgera, Papua New Guinea, low sulphidation epithermal Au mineralisation of the carbonate-base metal Au style related to augite-hornblende diorite stocks (section 7.2.1.2.4.1) is overprinted by epithermal quartz Au style mineralisation related to feldspar porphyry dykes (section 7.2.1.3), best developed in the Romane Fault and overprinting the earlier veins. While early veins exploit NNE elements of the Porgera Transfer Structure, syn-mineral uplift and thrust erosion (below) focus later feldspar porphyry within the Roamane Fault extending into a hanging wall splay and also a smaller sub-parallel fault (figure 3.12). A blind ore shoot of as much as 8 M oz Au developed at the intersection of the Roamane Fault and the hanging wall splay as rising fluids became quenched at the structural intersection (Corbett and Leach, 1998 and references therein).

3.2.1.2.2 At the Tolukuma gold mine in Papua New Guinea, the throughgoing Tolukuma vein lies within a hanging wall splay fracture localised above the graben-like structural contact between the Cretaceous Owen Stanley Metamorphic basement rocks and overlying Pliocene Mt Davidson Volcanics (figure 3.13; Semple et al. 1995, 1998; Corbett and Leach, 1998; Corbett, 2005b). Here, the dilatant hanging wall splay has facilitated the rise of saline mineralised ore fluids to an elevated setting where mixing with near surficial bicarbonate waters promoted the deposition of high grade Au, which is best developed at the intersection of the two structures (figure 3.13). Early lower grade Au mineralisation, deposited by boiling within banded quartz veins with adularia and quartz after platy calcite, is overprinted by more abundant electrum with siderite-clay (chlorite-kaolin-smectite) deposited by fluid mixing within the hanging wall splay (Corbett et al., 1994c; Corbett and Leach, 1998 and references therein).

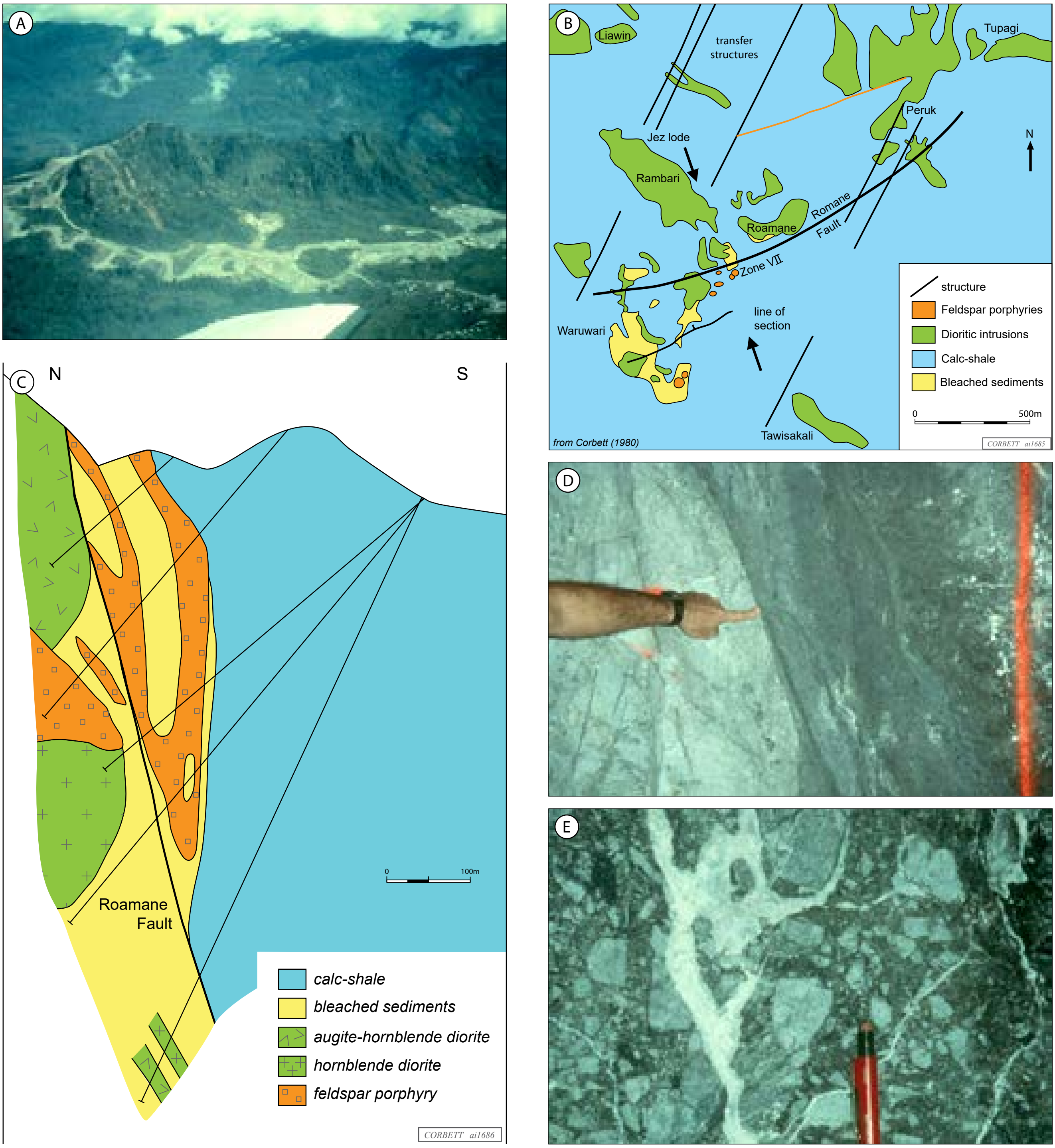


Figure 3.12 *Hanging wall splay fault at Porgera, Papua New Guinea.*
A - *View of Porgera about 1991 from the south, with the Waruwari carbonate-base metal Au mineralisation to the left, two adit levels and the line of drill sites in the hanging wall to the Romane fault in which each peak represents a resistive intrusive.*
B - *Porgera geology showing augite hornblende diorite stocks, adjacent bleached sediments and some structural elements stock (adapted from Corbett unpubl. map 1980 and other sources).*
C - *Cross section 22,410N through the Roamane fault showing the feldspar porphyry which locally exploits the hanging wall splay (from Porgera Joint Venture data 1989).*
D - *Roamane fault underground in about 1991.*
E - *Bonanza Au grade roscoelite breccia in the immediate hanging wall to the Roamane fault about 1991.*

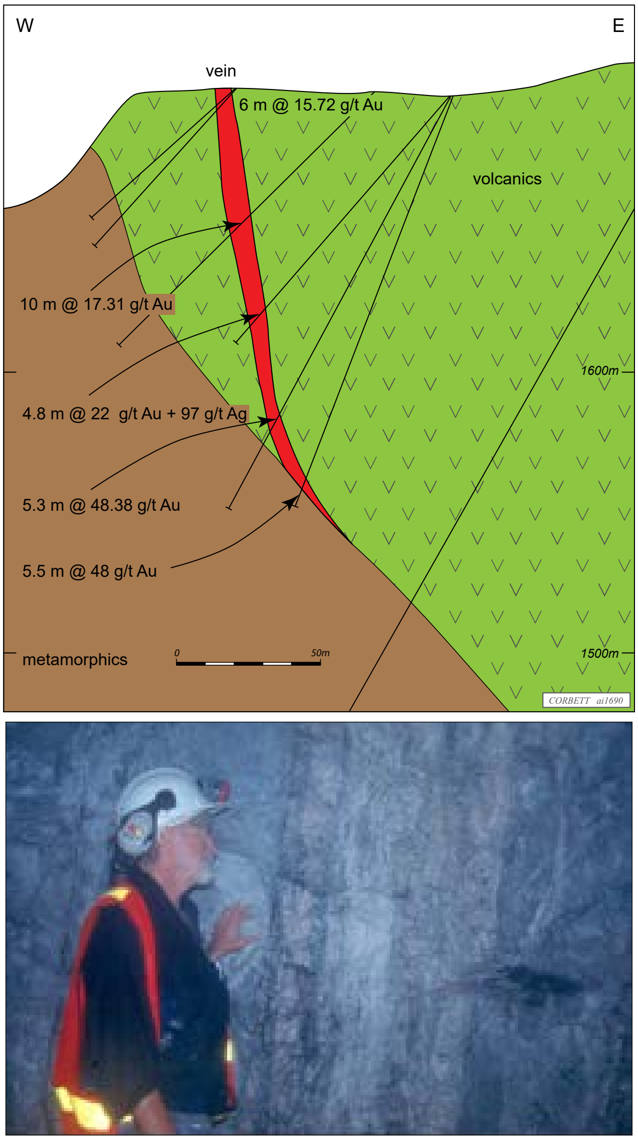


Figure 3.13 *Hanging wall setting of the Tolukuma vein, Papua New Guinea.*
A - *Cross section through the Tolukuma vein showing high Au grades near the intersection with the graben structure (from Corbett and Leach, 1998).*
B - *Tolukuma vein underground showing the banded texture.*

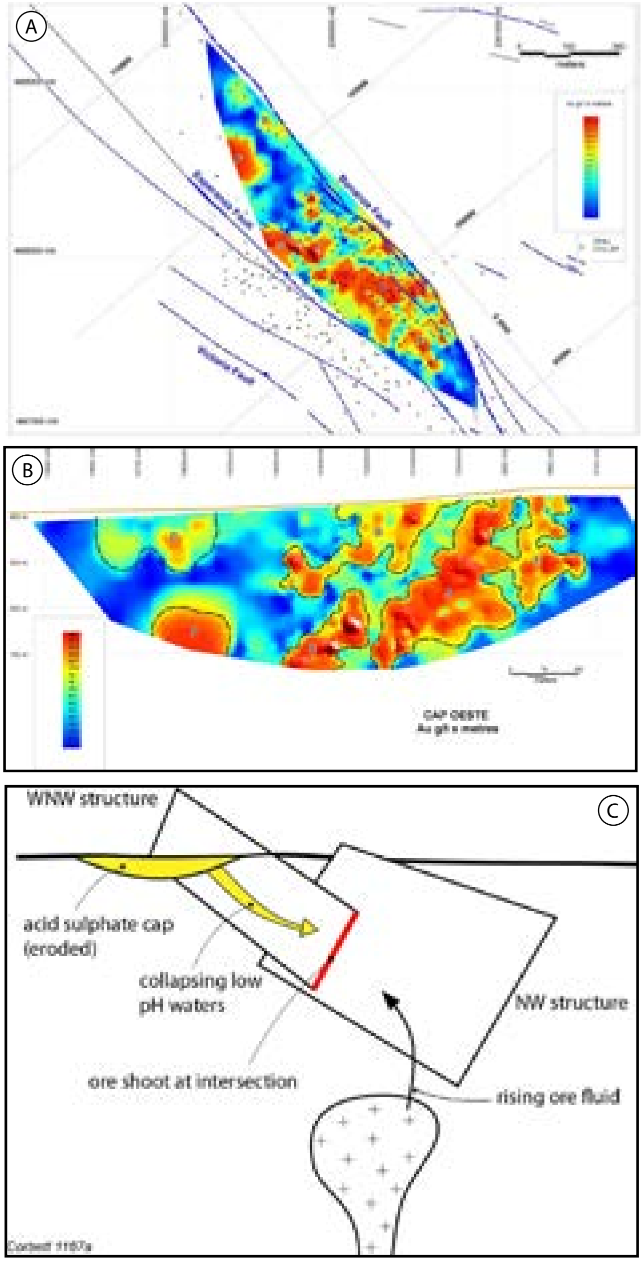


Figure 3.14 *Cap Oeste bonanza ore shoot El Tranquillo, Argentine Patagonia, (from Bow, 2012 in www.patagoniagold.com).*
A - *Plan view.*
B - *Cross section with red > 30 g/t Au*
C - *Interpretation showing the formation of a pencil-like ore shoot at the structural intersection.*

3.2.1.2.3 The Cap-Oeste, El Tranquillo, Argentine Patagonia (Bow, 2012 in www.patagoniagold.com), epithermal Au mineralisation is localised by NW trending structures formed as part of the conjugate fracture pattern of the Deseado Massif, in which EW trending dilatant zones would be expected to develop in conditions of orthogonal compression (section 3.2.3.2.1; figure 3.41). The Cap-Oeste high Au grade zone occurs as a moderate pitching pencil-like EW trending ore shoot (figure 3.14) developed by the mixing of pregnant fluids rising up the principle NW trending structure with low pH acid sulphate waters collapsing down the hanging wall splays. Kaolin intergrown with the bonanza Au grade ore provides evidence of mineral deposition by fluid mixing (section 7.5.4.4.5).

Hanging wall tension veins in exploration drill tests are considered below (section 3.2.2.4.4).

3.2.1.2 Refraction

Just as light refracts moving from air to more dense water, dipping fractures which host mineralised veins refract to steeper dips upon entering more competent host rocks (figures 3.7 & 3.15). As discussed in section 7.3 vein mineralisation is likely to be best developed in the more competent rock units, in these settings. At El, Peñón, Chile, mineralisation is hosted by a competent felsic sill within incompetent lapilli tuffs, while silicified sandstone/arenite units constrained within volcanic rocks host veins at Palmarejo, Mexico and Chatree, Thailand. A moderate dipping normal fault refracts to a steeper dip as it passes from incompetent to competent host rocks so that it then displays a more dilatant character during continued normal fault movement and a flat pitching ore shoot develops at the intersection of the steep normal fault portion and competent host rock (figure 3.15).

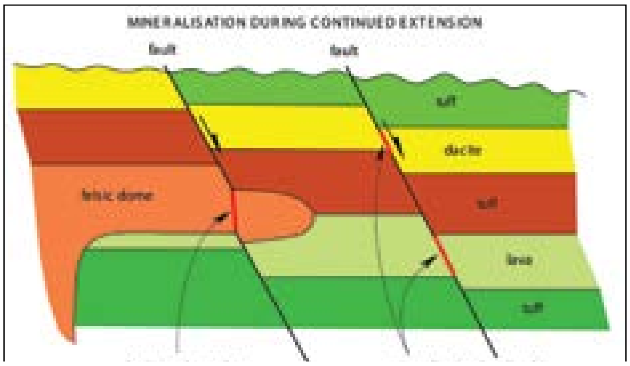


Figure 3.15 *A moderate dipping normal fault refracts to a steeper dip as it passes through a competent rock unit interlayered within an incompetent volcanic sequence. During continued normal fault movement this steep fault portion is more dilatant and so a flat pitching ore shoot develops at the intersection of this steep dipping fault portion and the competent rock unit.*

3.2.2 Oblique convergence

Oblique tectonic settings including transpression (oblique compression) and transtension (oblique extension) are characterised by strike-slip movement on structures which may create dilatant ore hosting environments, either within perturbations in the throughgoing strike-slip structure or within adjacent second order structures, commonly constrained within corridors of strike-slip faults. The terminology used here to describe different dilatant ore settings developed in this environment includes (figure 3.16):

- Fault jogs form where strike-slip fault movement transfers or steps-over from one controlling structure to another in a corridor of strike-slip structures.
- Link structures and cross-overs represent fractures which facilitate the transfer of fault movement from one controlling structure to another within a fault jog and become dilated as hosts for mineralised fissure veins. Sheeted vein arrays may also develop in this setting. Controlling structures and link structures may be viewed in plan or in section, the latter as normal faults and hanging wall spalys.
- Pull-apart basins, which form by down-drop on the basin margin link structures, represent the surficial portions of fault jogs and may be distinguished by the typical rhomboidal shapes and the presence of epiclastic sediment fill. Pull-apart basins represent the surficial portions of negative flower structures (below).
- Tension fractures develop by the application of a shear component to a brittle rock and host open space which becomes filled with hydrothermal minerals to form tension veins. Some exploit link structures and cross overs while others form en echelon vein arrays.
- A flexure is a dilatant bend in a throughgoing structure which may represent a dilatant perturbation.
- Splay faults or horse tails commonly represent short dilatant faults adjacent to a major strike-slip structure that form at deep crustal levels and locally represent the terminations of strike-slip structures. Splays are the deepest parts of fault jogs within negative flower structures.

In settings of simple oblique (strike-slip) movement the dilatant ore-hosting features described above form steep pitching ore shoots which host wider and higher precious metal grade vein portions (figures 3.7 & 3.16). Combinations with normal or reverse fault movement provide a moderate pitch to ore shoots (below). Dilatant fractures are oriented to link the tails of arrows which illustrate the movement direction on faults, whereas fractures oriented to join the arrow heads will be compressional and so form restraining bends characterised reverse or thrust faults or domes (Corbett and Leach, 1998), considered in section 3.2.3.3.1.

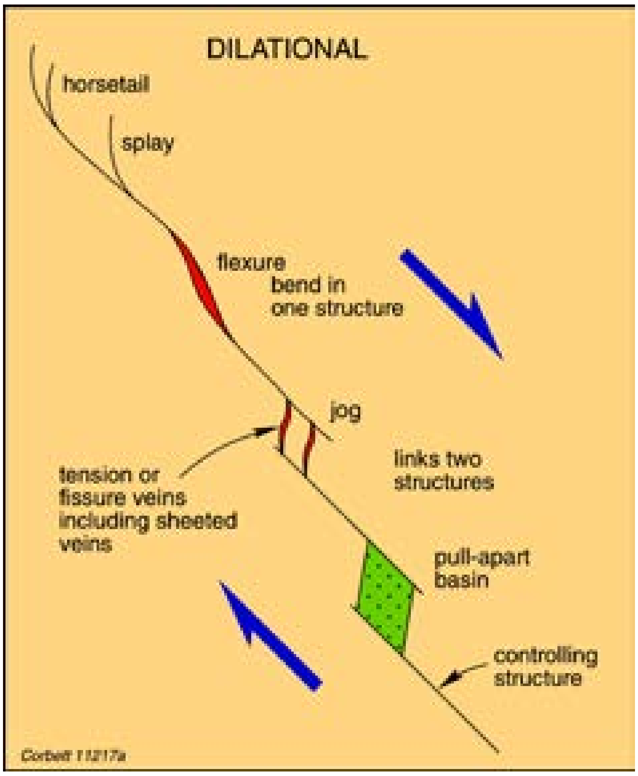


Figure 3.16 *The terminology used herein to describe subsidiary dilatant structures developed in environments of oblique convergence.*

3.2.2.1 Negative flower structures

Negative flower structures (figure 3.17) provide a 3 dimensional section through the various dilatant structural elements of a fault jog passing from surficial pull-apart basins down to link structure-hosted tension vein arrays that host epithermal Au-Ag veins and deeper level splay faults as sites of porphyry Cu-Au emplacement. Hydrocarbons collect in domes formed by positive flower structures in compressional settings (Lowell, 1985). The same tectonic and structural environment may continue to be active from volcanism and sedimentation to mineralisation and so it is common for mineralised structures to display earlier activation as growth faults, and in many districts there is more pronounced growth fault activity on the better mineralised structures (Gympie goldfield, Australia and Waihi, New Zealand in Corbett and Leach, 1998; Palmarejo, Mexico; Kupol, E. Russia; Kelian, Indonesia).

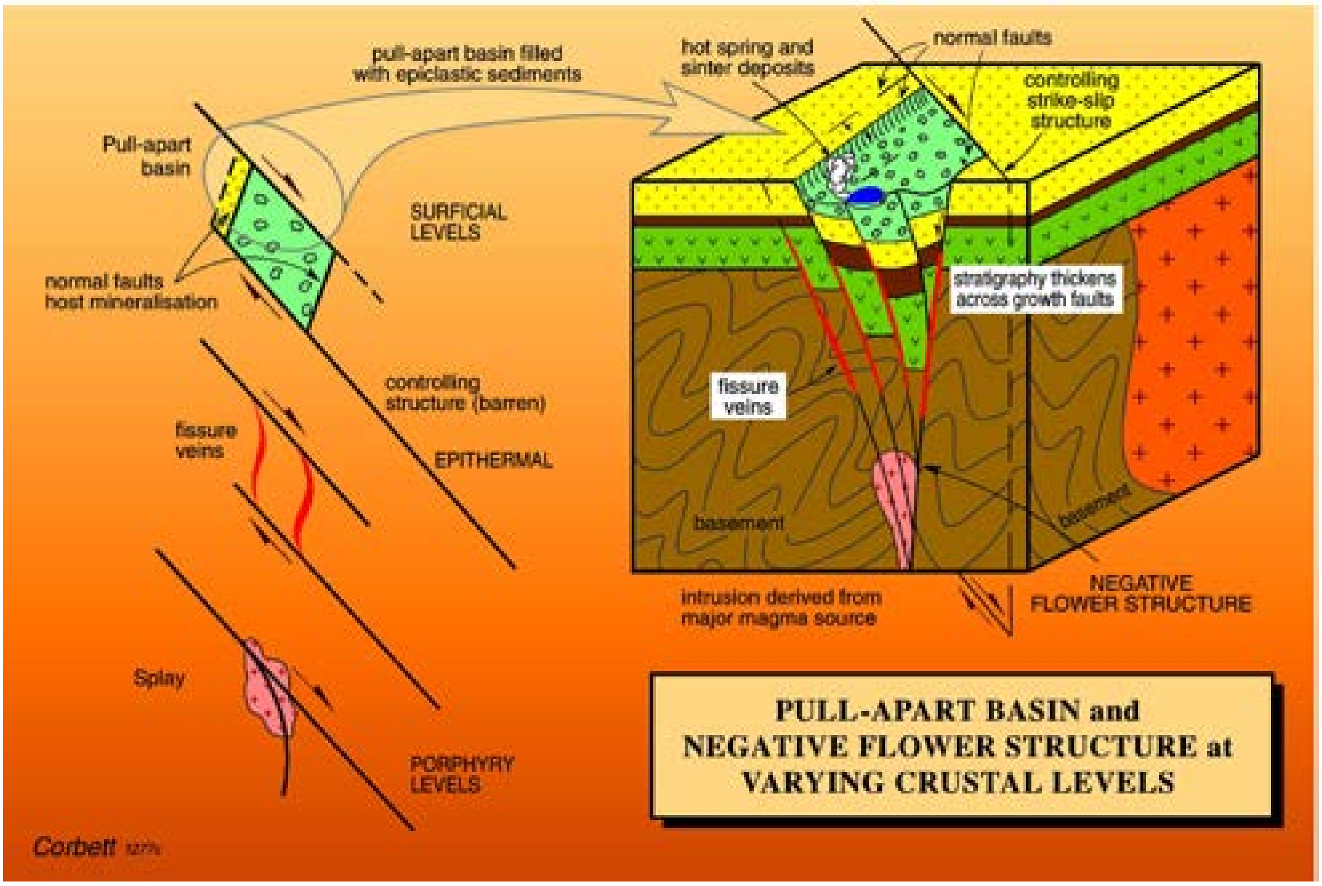


Figure 3.17 *Illustration of a negative flower structure as described herein.*

3.2.2.2 Fault jogs

Fault jogs (Sibson, 1987) represent dilatant cross-overs, of the strike-slip fault movement from one structure to another in a segmented fault or corridor of fractures, typically involving the development of subsidiary dilatant cross-over or link fractures between the strike-slip faults, termed controlling structures (figures 3.16-18). These dilatant features are also termed releasing bends (McClay and Moody, 1995), and fault jogs are most easily identified as rhomboidal pull-apart basins in poorly eroded terrains (Crowell, 1974; Sylvester, 1988; Price and Cosgrove, 1990), while restraining bends represent anti-dilatant jogs. The array of link or cross-over fractures are progressively dilated by the continued strike-slip movement on the controlling structures with associated down-drop as normal faults or fill of open space by hydrothermal minerals within tension fractures to form mineralised fissure veins or lodes. The controlling strike-slip structures are generally not mineralised whereas most dilation and hence mineralisation is recognised on the link structures which extend to depth as part of the negative flower structure. Continued strike-slip movement on the controlling structures provides internal rotation and increased dilation of the link structures or step-overs as mineralised tension veins (below, sections 3.2.2.5 & 3.2.2.5.3).

3.2.2.1.1 A modern analogy of a fault jog

is apparent as the cross-over in strike-slip movement between segments of a fault activated during a 7.2 magnitude earthquake at Dasht-e Baÿaz, Iran in 1968 (figure 3.19), delineated in an analysis of air photo linears (Tchalenko and Ambraseys, 1970). The EW trending strike-slip structures, labelled as controlling structures in figure 3.19, are linked by the subsidiary fractures which in an ore system would be expected to progressively open during appropriate strike-slip movement on the controlling structures, in order to develop as mineralised tension veins. Here, sinistral movement has dilated the second order fractures (figures 3.16-19, whereas dextral movement would provide compression on those fractures (figure 3.42) within a restraining bend. In ore systems hot pressurised hydrothermal fluids rising rapidly up the open fractures would be expected to cool and boil to deposit minerals on the fracture margins or breccia clasts. Repeated opening associated with earthquake activity over geological time, would promote polyphasal mineral deposition as banded veins which might host high grade precious metal mineralisation. Many epithermal veins appear to grow inwards (figure 1.11 A). Offsets of cultural features in the Dasht-e Baÿaz example provide a sense of displacement of only 4.5m, for a fault jog (step over) which is almost 2 km long and 1 km wide, between segments in a structure identified over an 80 km strike distance (figure 3.19, Tchalenko and Ambraseys, 1970). Such small movements are typical of faults which host mineralisation as excessive strike-slip movement on the controlling faults may dismember veins. Note in figure 3.19, formation of the subsidiary fractures was initiated at angles of about 45° at the intersection with the controlling structures, and the dilatant fractures bend to higher angles in the central portions during progressive strike-slip movement, as discussed below (sections 3.2.2.5 & 3.2.2.5.3).

Figure 3.18 *Small scale fault jogs evident as fill of dilatant fractures formed by strike-slip movement on the controlling structures, marble pavement, Spain.*

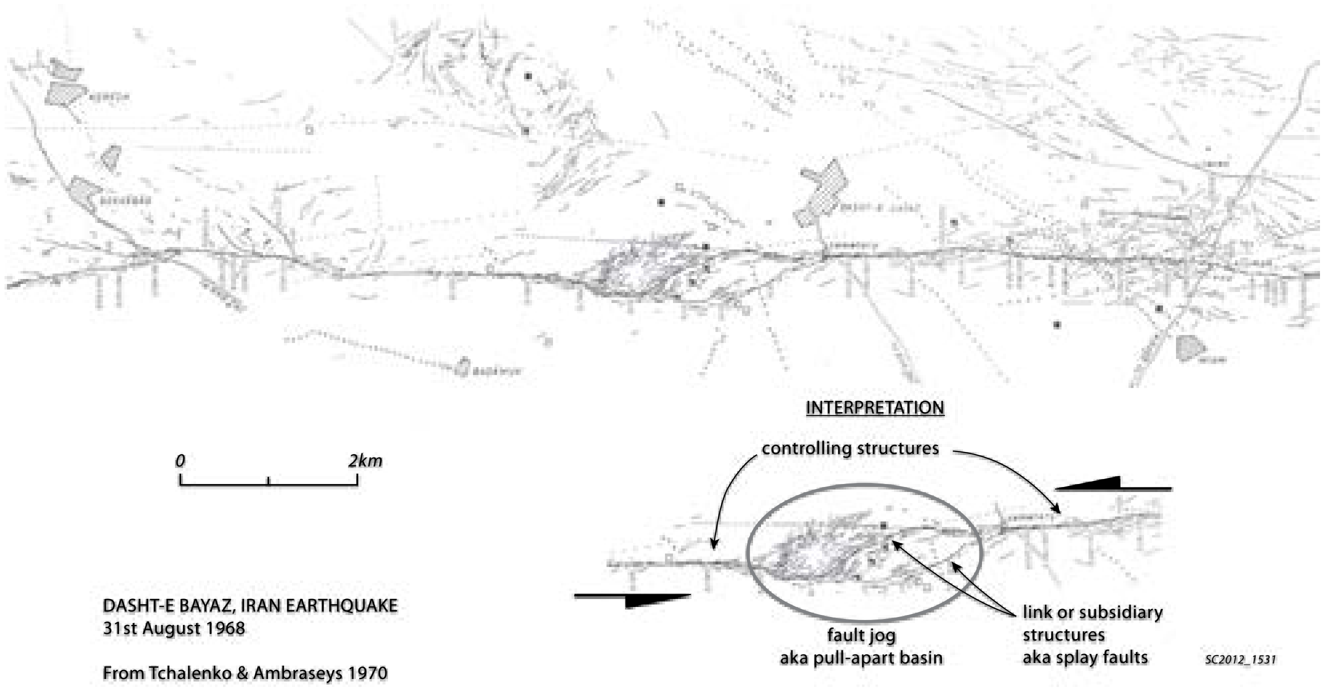


Figure 3.19 *Analysis of fractures associated with an earthquake at Dasht-e Bayaz, Iran, 31 August 1968 from Tchalenko and Ambraseys (1970), showing a fault jog which hosts dilatant subsidiary fractures developed where strike-slip movement has crossed from one controlling structure to another.*

3.2.2.2.2 At the Thames district, New Zealand, a regional scale fault jog hosts the Thames 1.4 M oz goldfield, Ohio Creek porphyry and Lookout Rocks barren shoulder of advanced argillic alteration (Merchant, 1986; Corbett and Leach, 1998). Regional-scale dextral movement in New Zealand, which is most apparent on the Apline fault in the South Island, continues northward to Mio-Pliocene Coromandel Peninsular, discernible from the orientation of vein fabrics (Waihi and Golden Cross below). By contrast orthogonal extension is currently apparent at the Taupo Volcanic Zone. The Hauraki fault, which defines the contact between the Coromandel Peninsular and the Hauraki graben displays a side step in the Thames district and so forms a 10 x 20 km dilatant fault jog under the influence of the regional scale dextral movement (figure 3.20; Corbett and Leach, 1998). The many quartz-sulphide lodes which link the Ohio Creek porphyry to the Thames goldfield are therefore interpreted to have developed as tension veins and display increased rotation in the vicinity of the Thames bonanza goldfield. It has been suggested (Corbett and Leach, 1998) ore fluids derived from a magmatic source in the vicinity of the Ohio Creek porphyry migrated SW along the dilatant quartz-sulphide reefs to deposit bonanza Au by mixing with meteoric waters at the intersection with NS fractures at Thames. The early miners traced the SW-NE lodes, obtaining only low grade Au grades (as typical of low sulphidation quartz-sulphide Au + Cu mineralisation), in order to identify the intersection the NS structures termed flinties from the chalcedony-pyrite fill (Fraser, 1910), which localised bonanza grade Au mineralisation (typical of low sulphidation epithermal quartz Au style). Ore shoot formation related to down-drop at the Sons of Freedom reef is shown in figure 3.30 D

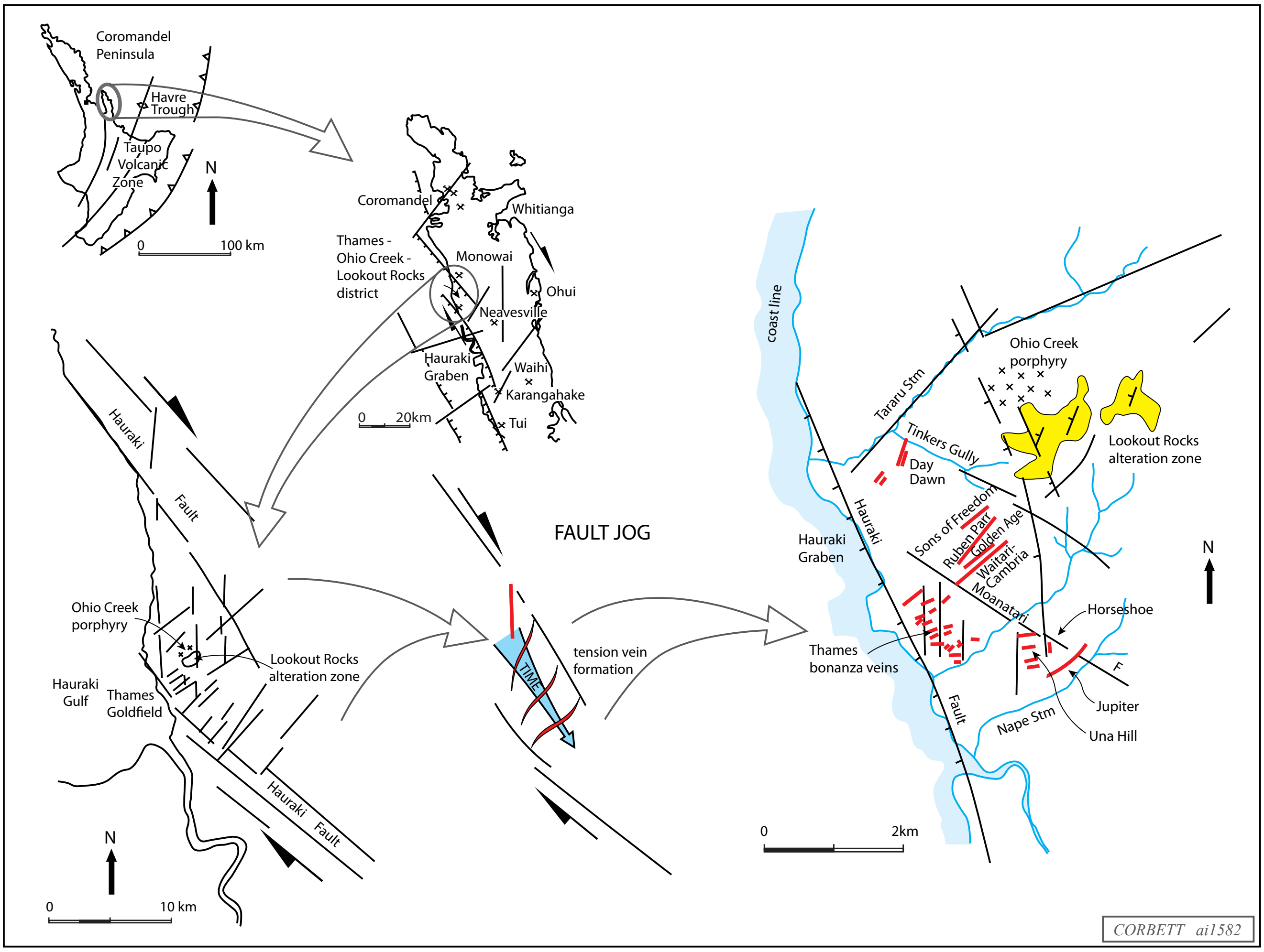


Figure 3.20 *The Thames-Lookout Rocks district, New Zealand showing development of a regional scale fault jog in the Hauraki fault and development the quartz-sulphide tension vein lodes which link the Ohio Creek porphyry and Thames goldfield.*

3.2.2.2.3 The Umuna lode at the Misima gold mine, in Milne Bay Provence of eastern Papua New Guinea in the recent period of exploitation from 1990 to 2004 produced 3.7 M oz Au. The Misima goldfield was discovered in 1889 and produced an estimated 200,000 oz Au to 1911. In the mine area, controlling structures of the WNW structural grain of Milne Bay have undergone a component of dextral strike-slip movement, resulting in the development of the Umuna Lode as a link structure mined over a distance of 2 km. The dilatant setting has provided normal fault movement on Umuna Lode, which is characterised by open space fill vein textures along with banding formed by repeated activation of the controlling faults. Although deeply oxidised, mineralisation is of a typical carbonate-base metal style Au mineralisation consistent with the MnO stain (figure 3.21; Corbett and Leach, 1998 and references therein). Gold grades no doubt display a strong component of supergene enrichment in oxide zone ores.

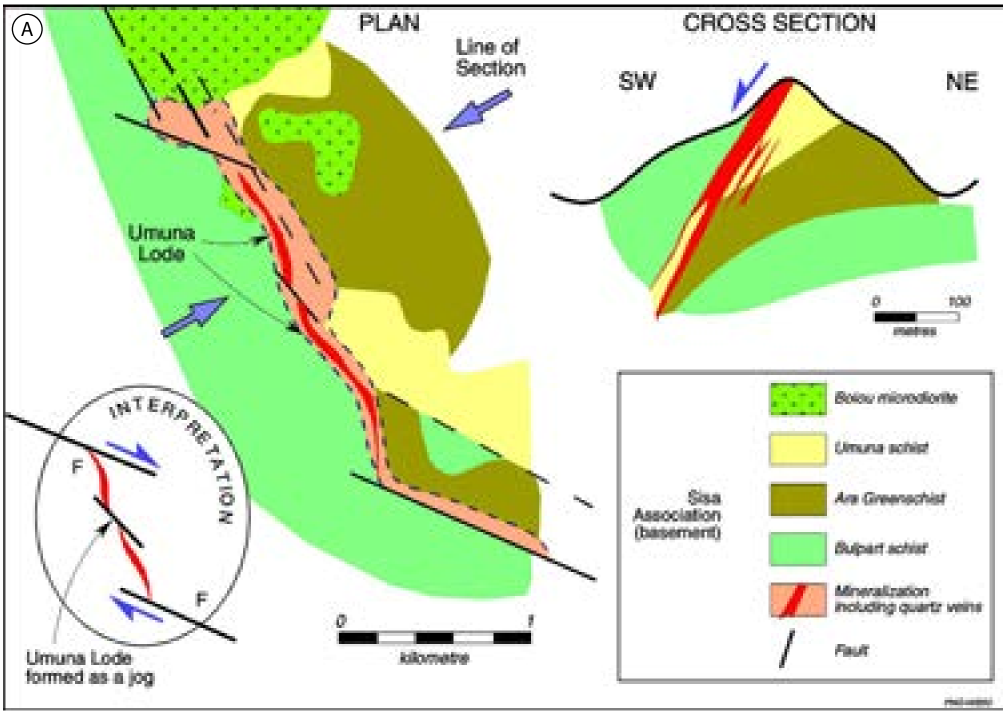


Figure 3.21 *The Umuna Lode, Misima gold mine, Papua New Guinea.*
A - *Graphic illustrates the development of the lode as a 2 km long link structure constrained between controlling structures with a dextral sense of movement.*
B - *Open pit mine aligned along the lode in 1990 at the early stage of development.*
C - *Banded quartz-MnO oxidised ore.*

3.2.2.2.4 Cracow goldfield, SE Queensland, Australia, produced about 850,000 oz Au mainly from the Golden Plateau area to 1992 (Worsley and Golding, 1990) although current mining and exploration are focused upon low sulphidation chalcedony-ginguro style veins about 2 km west in the Klondyke area (Creenaune et al., 2003). Competent Early Permian Camboon Andesite hosts many gold-bearing quartz veins including the arc-parallel Golden Mile and White Hope trends which are interpreted (Corbett and Leach, 1998) to have undergone a component of sinistral strike-slip movement to form the 700 m long Golden Plateau link structure (figure 3.22). At the time of discovery in 1875, much of this vein system, was obscured by the Cretaceous Precipice Sandstone (figure 3.22). Banded veins attest to repeated fault activity although the high fineness, high Au grade chlorite breccia ores (of the epithermal quartz Au style; section 7.2.1.3) are best developed within steep pitching ore shoots (Brooks, 1971) at the intersections with NS structures (Corbett and Leach, 1998). These ores are of a more magmatic character than the banded chalcedony ginguro veins which dominate at Klondyke (figure 7.5).

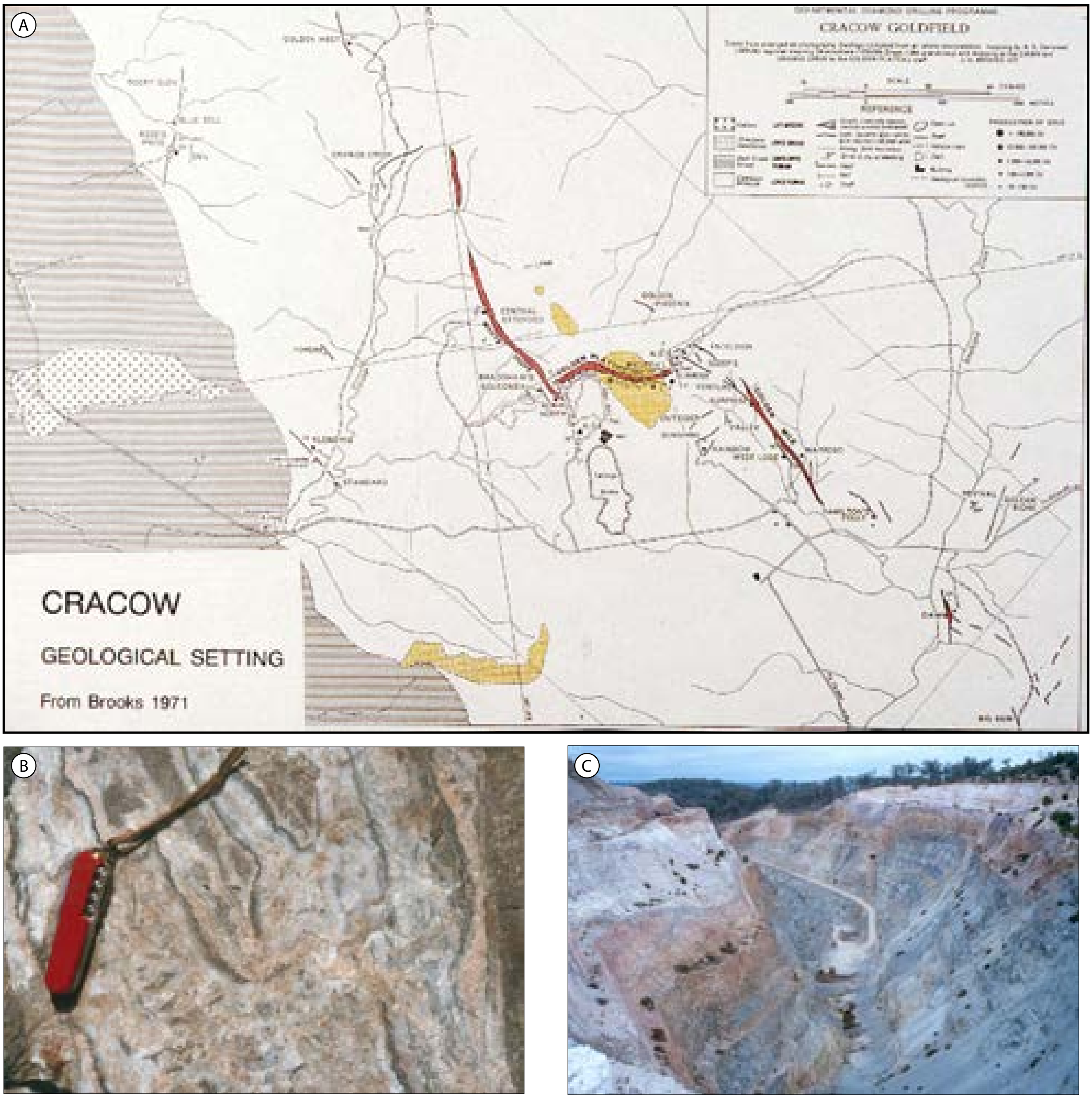


Figure 3.22 *Golden plateau, Link structure, Cracow goldfield, SE Queensland.*
A - *Plan illustrates the Golden Plateau link structure formed by interpreted sinistral strike-slip movement on the two controlling structures which host numerous small gold showings (from Brooks, 1971).*
B - *Banded quartz adularia vein/breccia from Golden Plateau.*
C - *View showing Precipice Sandstone cover.*

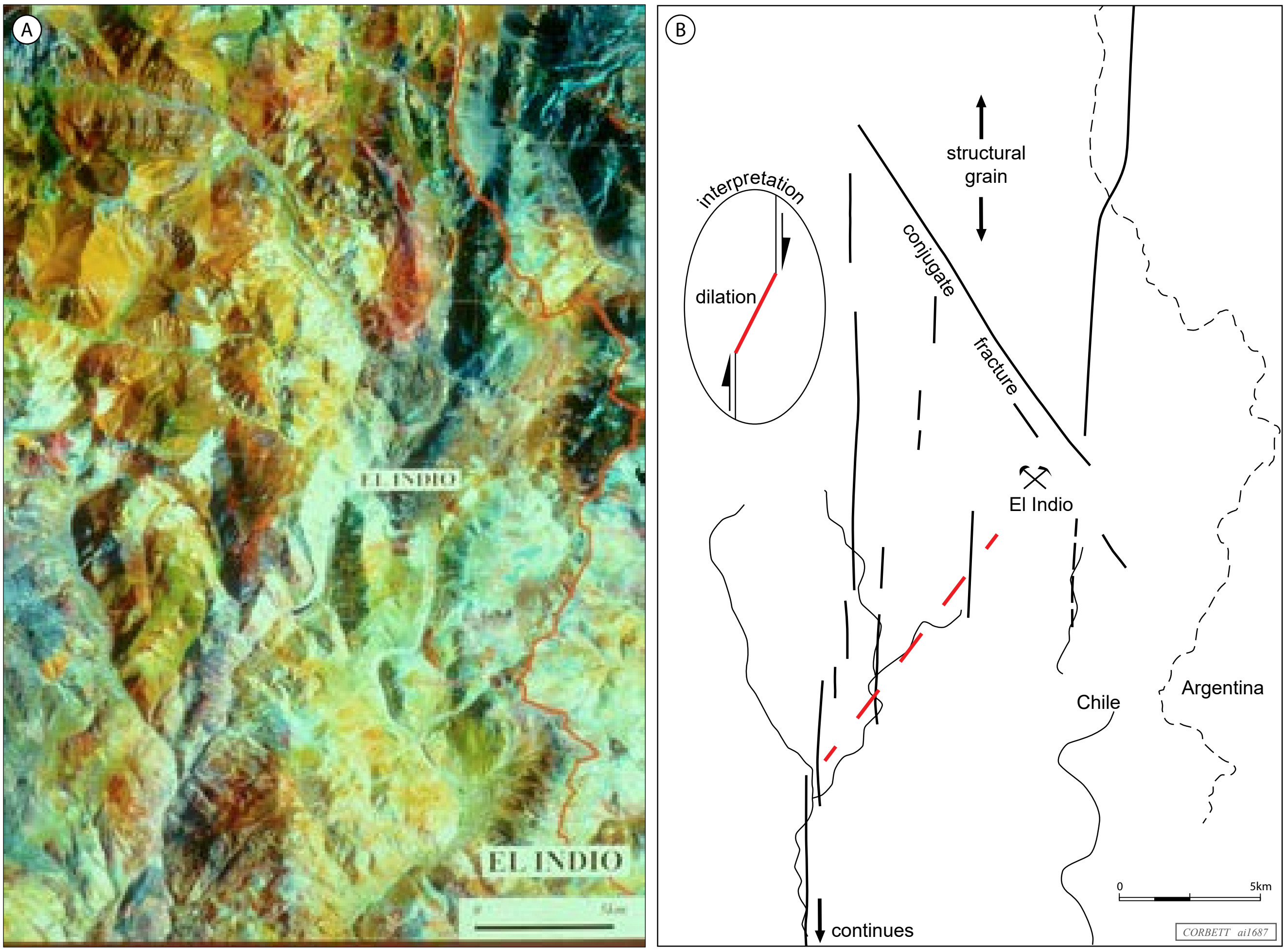


Figure 3.23 *Localisation of El Indio within a regional scale cross over of dextral fault movement.*
A - *Remote sensing image in which major structures are apparent as drainage anomalies.*
B - *Line diagram showing the dilatant link zone formed by the transfer of dextral strike-slip movement from the NE to SW major structures.*

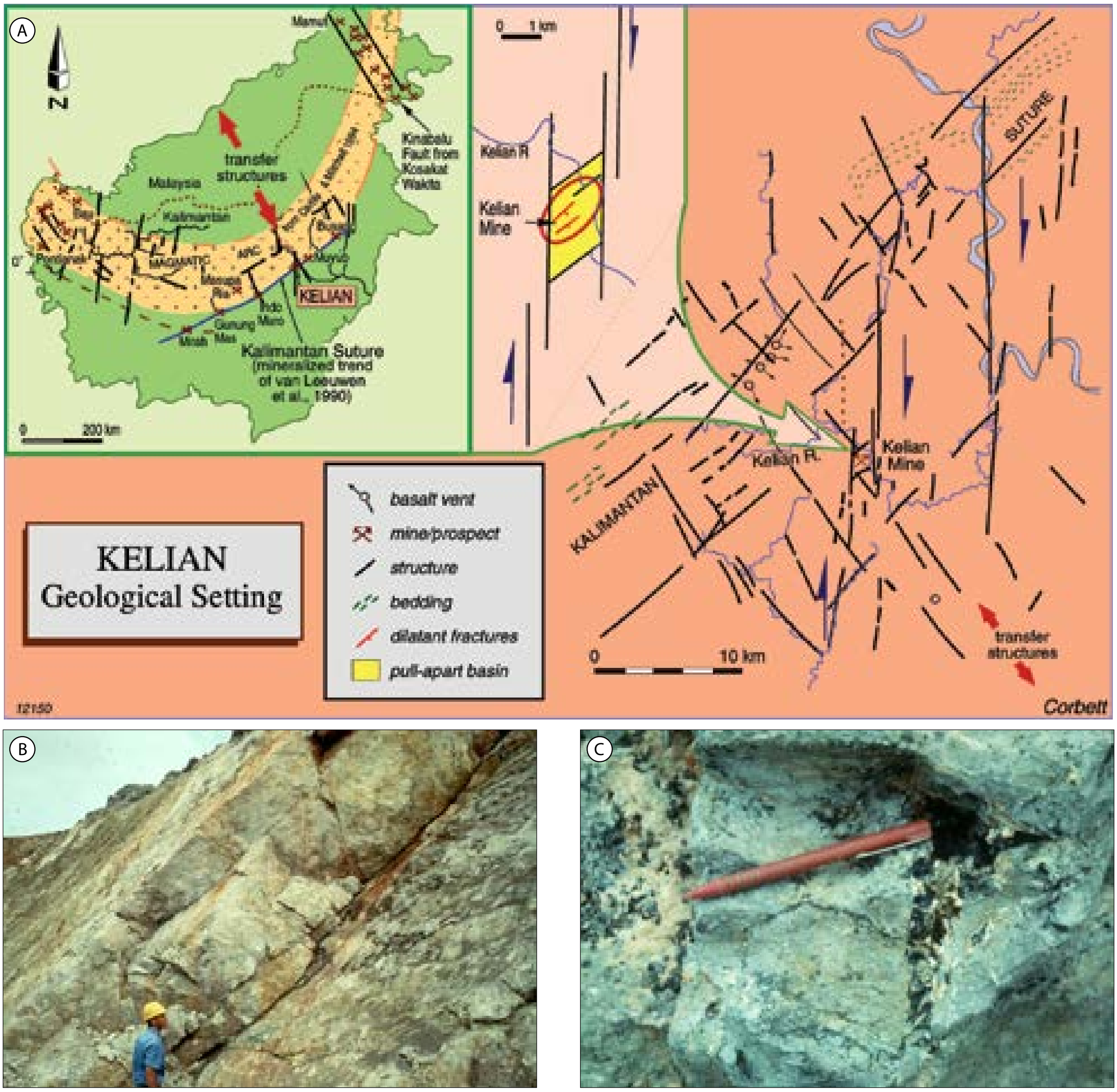
3.2.2.2.5 The El Indio Au district, Chile, is localised within a regional scale cross over between arc-parallel structures interpreted to have exhibited a dextral strike-slip sense of movement in order to trigger ore formation, discernible in the kinematics of individual ore zones (figure 3.28). Repeated movement led to the development of banded veins (figure 3.13 D) and floating clast breccias are indicative of the dilatant ore environment (figure 3.28 D). The El Indio mine hosts ore within a sigmoidal loop (Caddy in Jannas et al., 2000) apparent as a fault flexure which hosts early banded pyrite-enargite veins and later quartz-gold veins, while the individual ore shoots at the Viento vein to the east also occur within flexures formed by the same dextral sense of movement (figure 1.13 & 3.28)

.3.2.2.3 Pull-apart basins

Pull-apart basins are recognised as rhomboidal down-dropped blocks formed by normal fault movement on the rhomboid short dimension normal faults, dilated by strike-slip activation of the controlling structures which host the rhomboid long limbs and do not display any down-drop (figures 3.16 & 17). Ratios between the long and short axes of pull-apart basins vary from 2 to 5: 1 (Aydin and Nur, 1982 in Price and Cosgrove, 1992, p. 142). Pull-apart basins are commonly grouped along country scale transcurrent or strike slip-structures such as the San Andreas fault (Crowell, 1974), Sumatran fault (Pudjowalujo, 1990) and Philippine fault (figure 3.39). Importantly, vein mineralisation is only likely to be localised within the short limb faults of the rhomboid which display dilatant down-drop and activation as growth faults, whereas the long limb strike-slip faults tend not to be dilated and mineralised. Multiple mineralised growth faults are common in many pull-apart basins (Gympie goldfield, Australia; Corbett and Leach, 1998) and structures with more dilation display both greater growth fault down-drop and better later vein development. Consequently, exploration targets might emerge within steeper portions of growth faults, from stratigraphic analyses of volcanic successions.

Pull-apart basins are commonly discernible at the surface by recognition of the rhomboidal shape of fault bounded basins filled by epiclastic sedimentary rocks in which rapid syn-deformational down-drop might be evidenced by common disconformities (figure 3.24 D). However, the epiclastic sediments which fill pull-apart basins are generally incompetent and may restrict vein formation. At Kelian (below) these rocks have been rendered competent by silicification, whereas at the Way Linggo district (below) dilatant veins are developed in the footwall competent basement rocks. The controlling structures are likely to be aligned within the structural grain of the district, whereas the link structures will be initiated at 45° and rotate to higher angles where best mineralised (figure 3.19 & below).

3.2.2.3.1 The Kelian Au mine, Kalimantan, Indonesia, lies within a pull-apart basin formed at a cross-over in the dextral movement on two conjugate NS fault elements localised within the NW trending Kalimantan Suture fracture corridor which hosts several mines (figure 3.24; van Leeuwen et al., 1990; Corbett and Leach, 1998). This sense of movement suggests the basin and mineralisation developed during orthogonal convergence. The mine lies in the NW corner of the interpreted pull-apart basin evidenced by fill of epiclastic rocks, overlying a basement shale sequence, and constrained by the NE trending Burung normal fault and adjacent West Prampus strike-slip structure (figure 3.24A). Spectacular disconformaties in the epiclastic sequence testify to the substantial and rapid down-drop within the pull-apart basin (figure 3.24 E). Andesite domes (lacoliths) and a felsic diatreme-flow dome complex, have been emplaced into the pull-apart basin followed by sheeted vein and breccia mineralisation aligned in the (Burang Fault) dilatant direction of the pull-apart basin (figure 3.24). The permeable epiclastic rocks



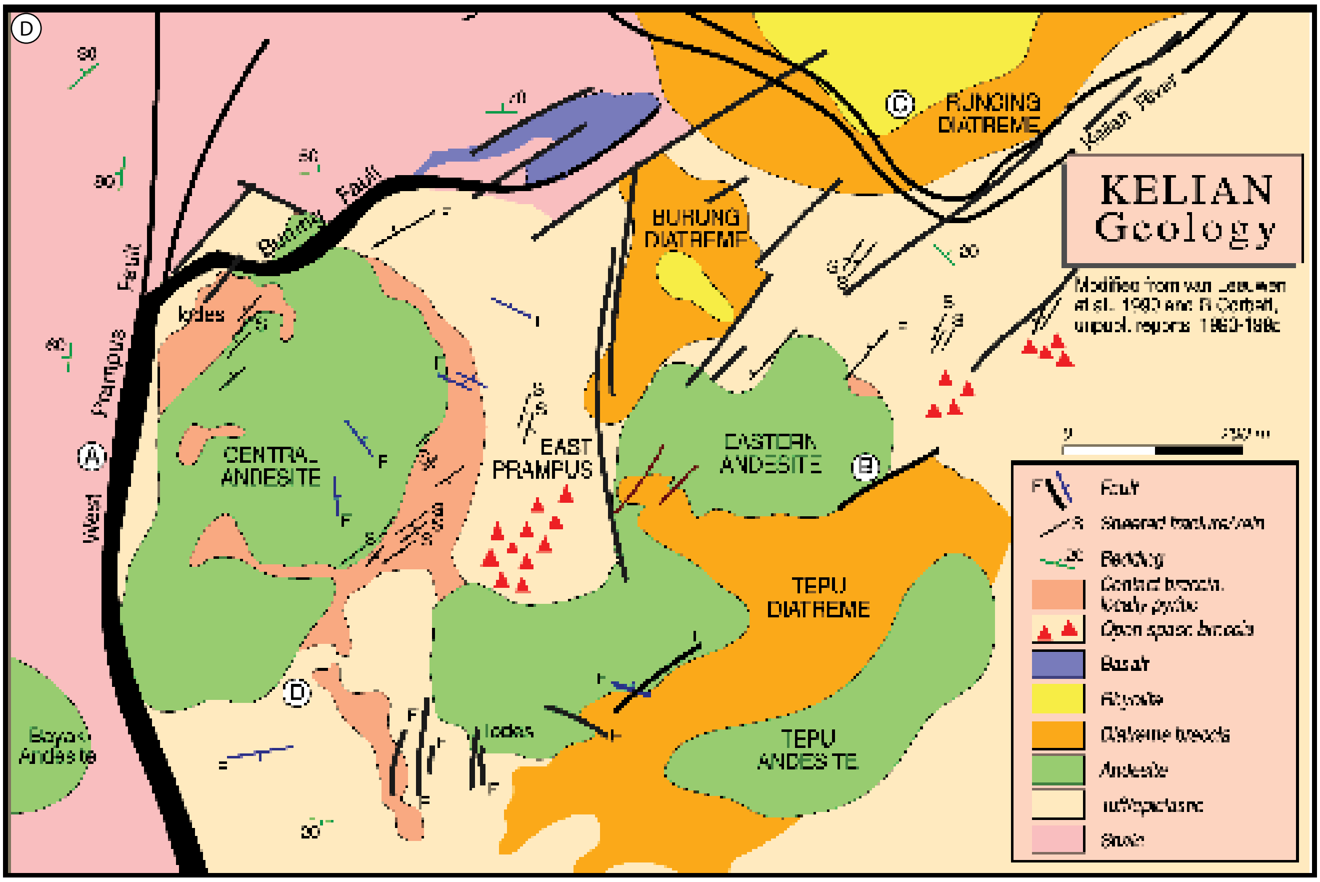
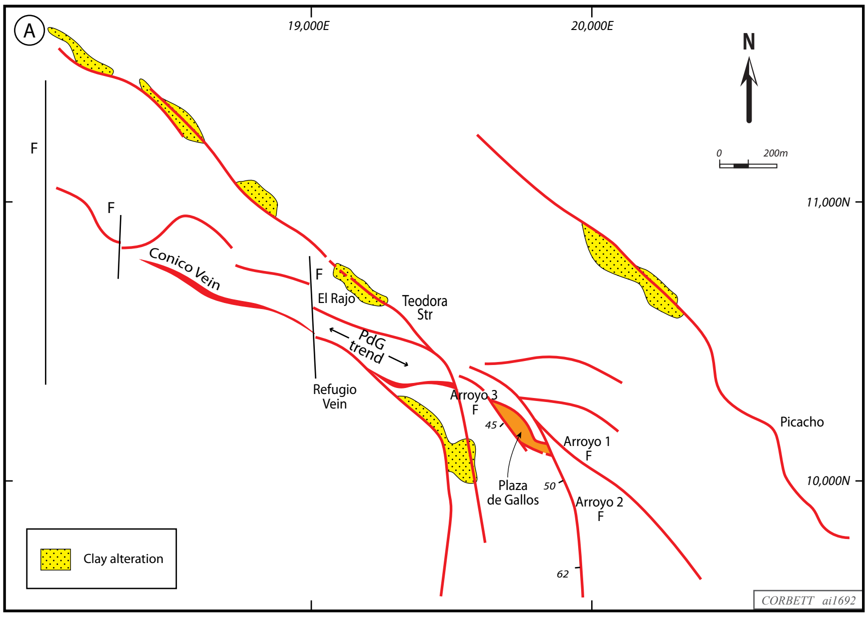
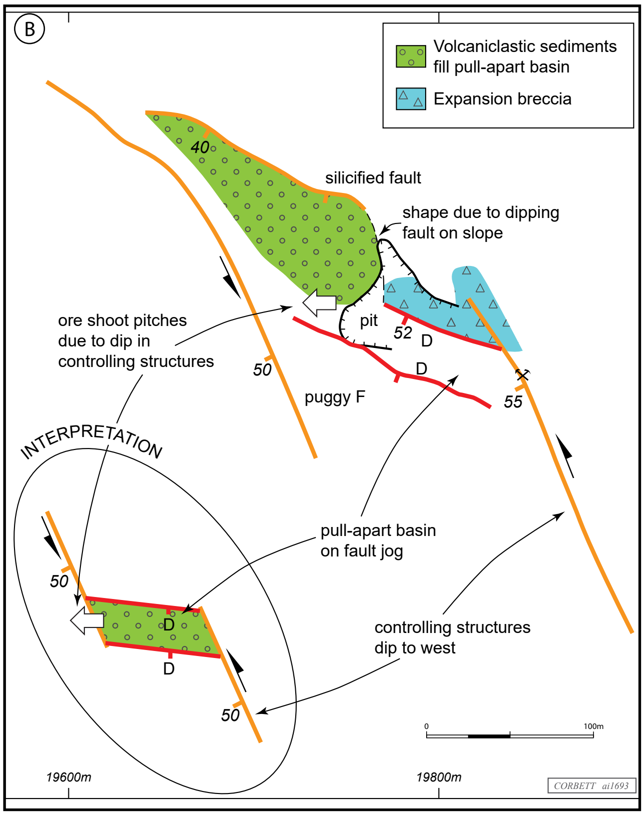


***Figure 3.24** The Kelian pull-apart basin hosted, low sulphidation epithermal carbonate-base metal Au deposit.*
A - *Setting within a compressional magmatic arc which provides a dextral sense of movement to the NS conjugate fracture.*
B - *Sheeted quartz-pyrite Au veins.*
C - *Carbonate-base metal breccia mineralisation formed by increased dilation of the sheeted veins. Figures from Corbett and Leach, 1998 and references therein.*
D - *Mine area in the NW corner of the pull-apart basin showing the Burung normal and West Prampus strike-slip faults, andesite domes, diatreme-flow dome complex and sheeted veins grading to breccias with increased deformation.*
E - *Disconformities in the epiclastic sediments.*

were readily silicified to facilitate the formation of fracture-controlled mineralisation, whereas the shale basement and diatreme breccia rocks which underwent ductile deformation did not fracture and so are barren. Continued strike-slip movement created increased dilation on sheeted fractures with quartz-sulphide Au mineralisation (figure 3.24 B) and so facilitated the transition to open space breccias with higher Au grade carbonate-base metal Au mineralisation (figure 3.24 C; section 7.2.1.2).

3.2.2.3.2 The Ocampo, low sulphidation polymetallic Ag-Au deposit lies in Sierra Madre region of northern Mexico, characterised by extensional tectonism on parallel listric faults (figure 3.25 A). While vein mineralisation typically occurs in the steeper portions of listric faults, the Plaza de Gallos pitching ore shoot is developed within a fault jog localised by an offset between two fault segments with a component of strike-slip fault movement derived from the curvature of the listric fault system (figure 3.25 B). The fault jog link structures have been activated as normal growth faults to result in development a localised pull-apart basin (figure 3.25 C).





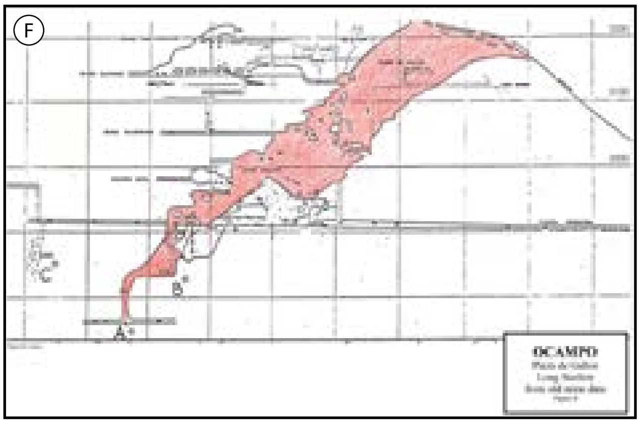


Figure 3.25 *The development of the Plaza de Gallos ore shoot within a pull-apart basin at Ocampo, Mexico.*
A - *Map of the listric faults (by Hall Stewart) showing location of the Plaza de Gallos ore shoot.*
B - *Detail of the pull-apart basin and ore shoot.*
C - *Surface exposure of the pull-apart basin showing thickening of volcanic units across the growth faults (person in the bottom right for scale).*
D - *Drill core through the ore shoot showing the dilatant character of the mineralisation.*
E - *Faults which control the ore shoot underground.*
F - *Ore shoot from old mine data.*

3.2.2.3.3 The Way Linggo district in the Lampung district in SW Sumatra hosts some of the many pull-apart basins developed along the dextral strike-slip Sumatran fault system, developed in response to collision between the northward moving Indo-Australian plate with the Eurasian plate (Hall, 2002 and references therein). The Way Linggo low sulphidation epithermal Au project is localised by a NNW trending link structure developed as the cross over of dextral strike-slip movement between elements of the Trans Sumatran Fault System, which also facilitated development of the pull-apart basins (figure 3.26).

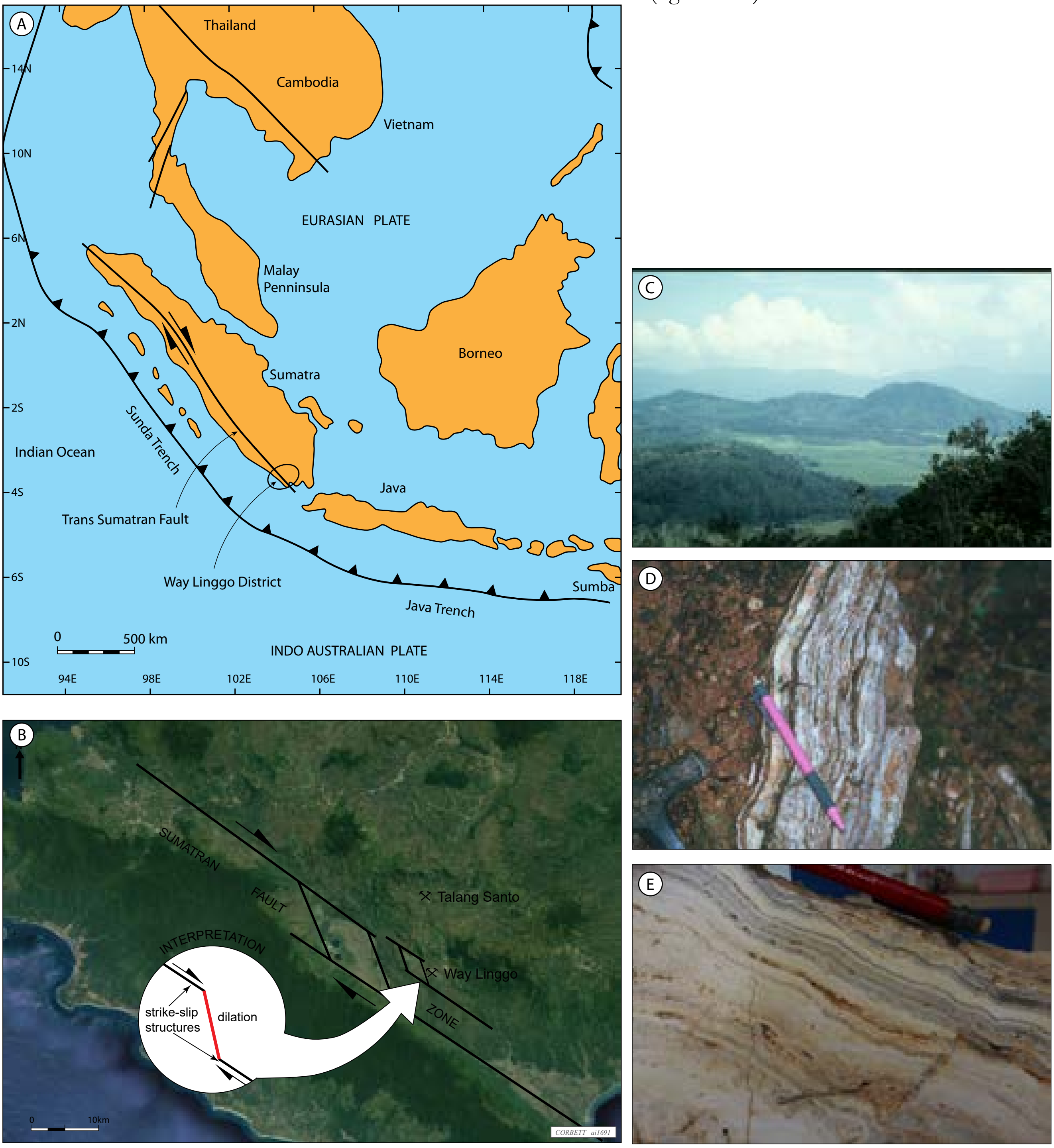


***Figure 3.26** The Way Linggo district hosts low sulphidation epithermal Au veins within the dilatant fractures formed in a several pull-apart basin terrain associated with dextral movement on the Sumatran Fault system.*
A - *Tectonic setting of the Way Linggo district.*
B - *Remote sensing image with an overlay of structure.*
C - *View of pull-apart basin about 1993.*
D - *Way Linggo banded low temperature opal-bearing vein identified during exploration about 1993.*
E - *Banded chalcedony-ginguro ore mined in the 2011-17 era.*

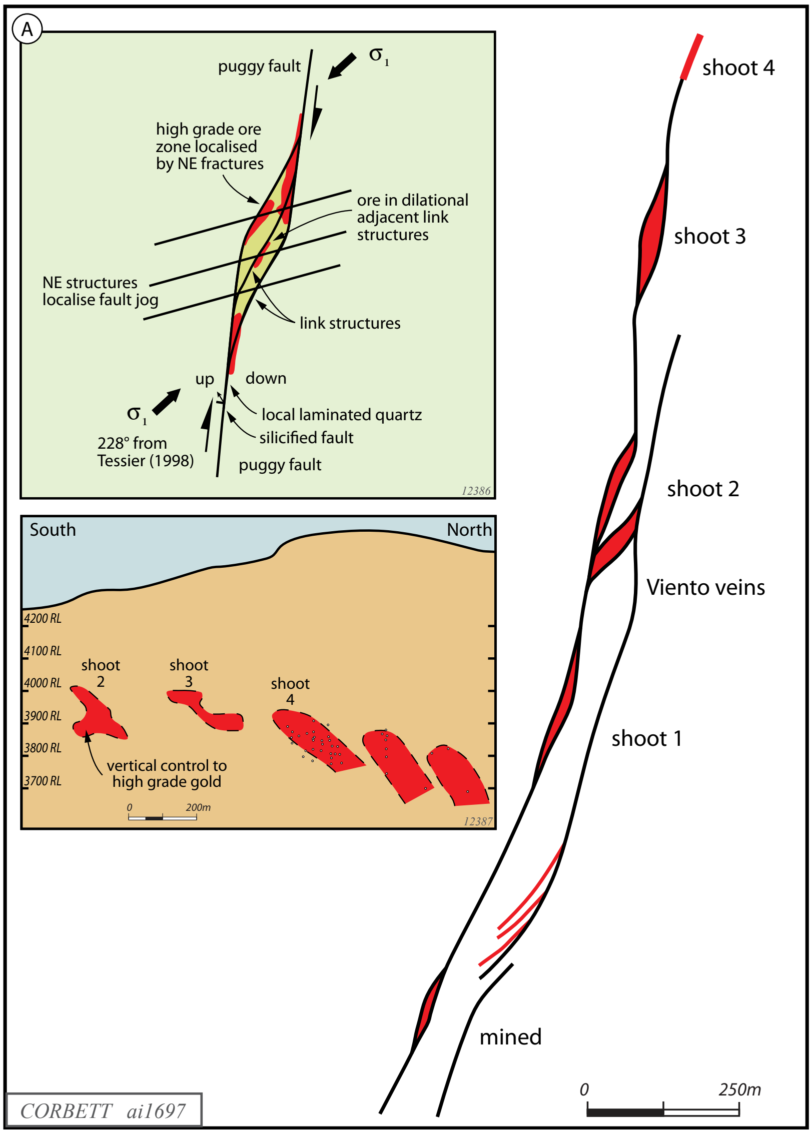
3.2.2.4 Flexures

Flexures are defined above as dilatant bends formed at a side-step (pertubation) within throughgoing strike-slip structures (figure 3.16, 3.27 & 3.28) and may be grouped along individual structures as settings for ore shoot formation, and so have long been recognised as are a setting for high precious metal grade vein mineralisation (fig 92, McKinstry, 1948). Repeated activation of movement on the strike-slip structures provide banded high grade veins (figure 3.29 C) or open space breccias (figure 3.28). The throughgoing fractures may include steep dipping portions of listric faults, and flexures are recognised in the central vertical portion of negative flower structures where down-drop is common on these structures. In purely strike-slip structures flexure-hosted ore shoots pitch vertically in the plane of the fault (figures 3.7) but the pitch varies if an oblique fault movement is combined with normal or reverse movement (section 3.2.4). As discussed above dilatant fractures join the tails of arrows which illustrate the movement direction on faults, whereas compressional restraining bends which join the arrow heads are likely to develop as reverse of thrust faults (figure 3.16).

Explorationists should be aware that in many vein systems all the meaningful mineralisation is restricted to flexure-hosted ore shoots, while the intervening vein portions may be essentially barren or sub-economic (figure 3.29 A). Consequently, careful geological mapping is required in order to design drill programmes to correctly evaluate the flexures. This may necessitate not using traditional grid arrays.

3.2.2.4.1 The Viento veins in the El Indio district of Chile host a series of moderate pitching ore shoots, which detailed geological mapping (Corbett, unpubl. report., 2000) demonstrated are localised by flexures in a throughgoing structure with a dextral component of strike-slip movement (figure 3.28). Cross-structures are interpreted to account for the setting of each dilatant flexure by development of step-overs in the main structure, dilated by the continued dextral strike-slip movement. Within each flexure, link structures facilitated the rise of magmatic fluids and therefore host bonanza Au grades (figure 3.28 A), locally as sulphide matrix fluidised breccias (figure 1.13 B). Entry of meteoric waters drawn into the dilatant flexures no doubt contributed towards the development of quartz in-fill expansion breccias, including floating clast breccias (figure 3.28 B & C), a characteristic feature of dilatant structural environments, (section 4.4.7.5). Quartz-gold breccias (figure 1.13 B, C & D) were therefore derived from progressive mixing of the south to north migrating evolved magmatic ore fluid with increased ground waters (sections 1.2.2.4 & 7.5). The flexure shape evidences the dextral sense of movement and the northerly pitch of the ore shoots is derived from a combination of this dextral strike-slip and west block up movement, discernible from slickensides (figure 3.28). The presence of abundant quartz is indicative of transition along strike from high to lower sulphidation epithermal mineralisation (section 1.2.2.4).

***Figure 3.27** Small scale flexures.*
A - *Banded open space filled flexure within a quartz vein, with an offset of an earlier vein to show the sinistral direction of movement, from the La Arena region of Central Peru.*
B - *Calcite vein in a marble pavement, Spain.*



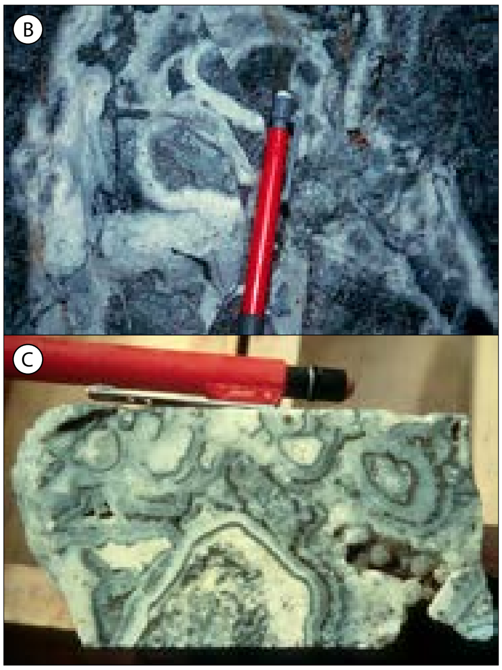


Figure 3.28 *Flexures in the Viento vein El Indio district (figure 3.22), Chile.*
A - *The Viento vein system, from figure 1.13, showing a series of flexures which account for the moderately north pitching ore shoots in long section. A detailed model in plan view, derived from the mapping multiple of flexures, illustrates the distribution of high grade Au mineralisation in relation to the link structures, while slickensides provide an indication of the sense of movement (from Corbett, unpubl. report, 2000).*
B & C - *Quartz-sulphide fill floating clast breccias illustrate the pronounced extension within the flexures, in underground exposure (B) and drill core (C), and locally take on the appearance of floating clast breccias (section 4.4.7.5).*

3.2.2.4.2 At Vera Nancy, in the Pajingo Mining District of North Queensland Australia, steep pitching ore shoots viewed in long section are localised along a major NW trending structure, described as a regional scale rift (figure 3.29; Butler, 2004; Hoschke and Sextan, 2005). Although younger sandstone cover obscures the structure at the surface, underground mapping has demonstrated that each ore shoot lies within a flexure where the structure deviates from NW toward EW, locally apparent on geophysical data (Simms, 2000). Indeed other ore systems in that district (Scott Lode, Anne, Cindy) are also hosted by EW vein portions (see Mustard et al., 2005). In long section the ore zones bottom at a shallow SE pitching zone (figure 3.29), possibly due to a combination of the flattening of the host structure (as a listric fault) at the base of the ore zone, and the confinement of mineralisation to a competent portion of the east dipping Mt Janet Andesite host rock. There may also be dilation due to a component of refraction of the major structure upon entering the competent host (section 3.2.1.3), although Mustard et al., (2005) suggest structural complexities restrict definition of the stratigraphy. Simms (2000) interpreted the veins to dip steeply within the ore shoots also apparent on the data of Mustard et al. (2005). It is common for several factors to contribute towards the development of ore shoots (section 3.2.4).

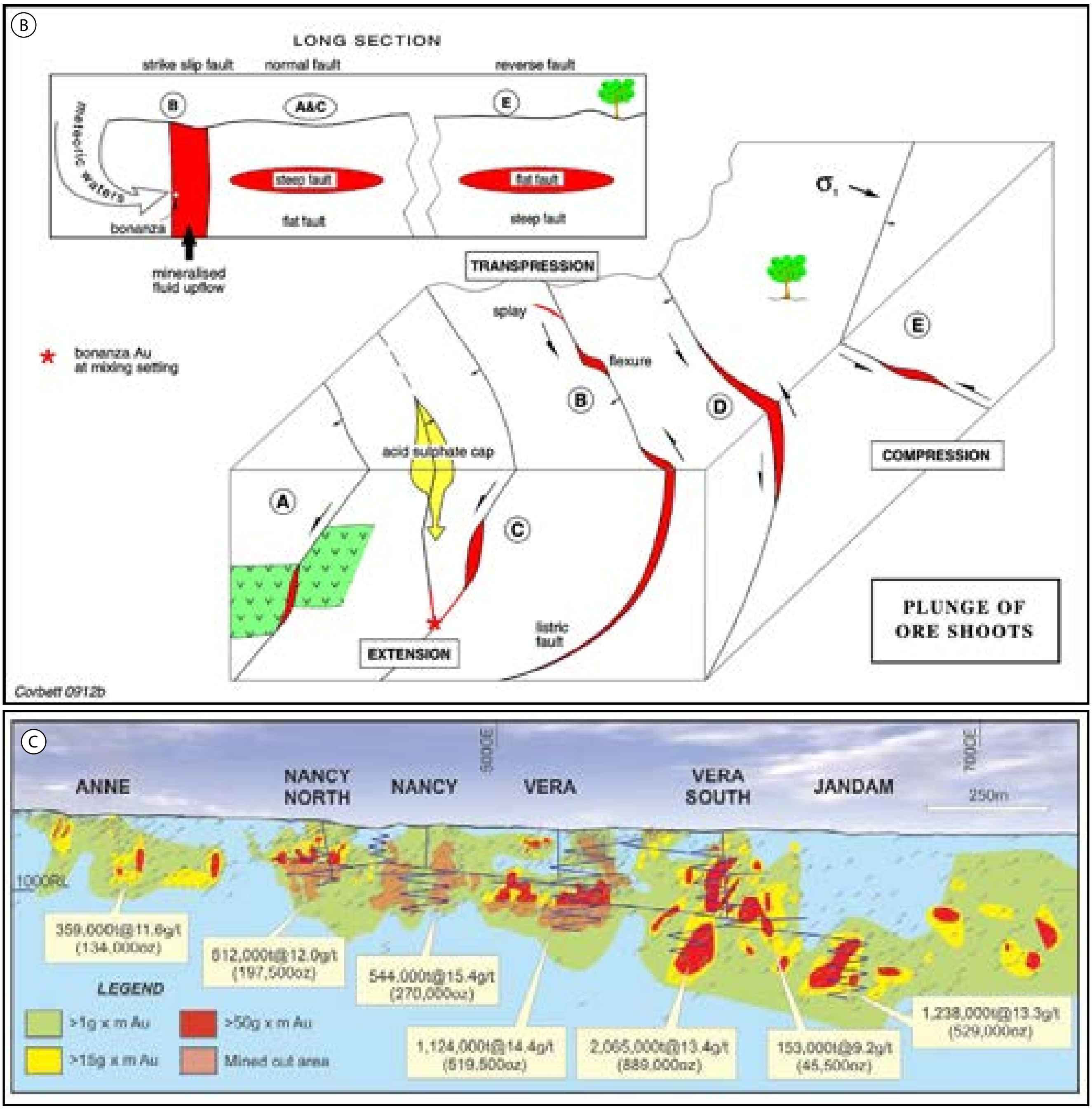


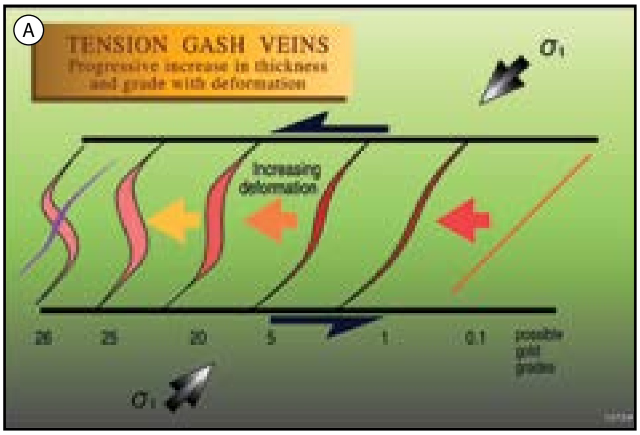
Figure 3.29 *Flexure-hosted ore shoot mineralisation at Vera Nancy, Australia.*
A - *Vera Nancy banded epithermal quartz vein mineralisation formed by the repeated activation of the strike-slip structural setting.*
B - *Model for the development of steep pitching flexure-related ore shoots (from Corbett, 2012).*
C - *Long section illustrating the steep pitch on ore shoots and the manner in which drill holes between ore shoots are barren (from Hoschke and Sextan, 2005).*

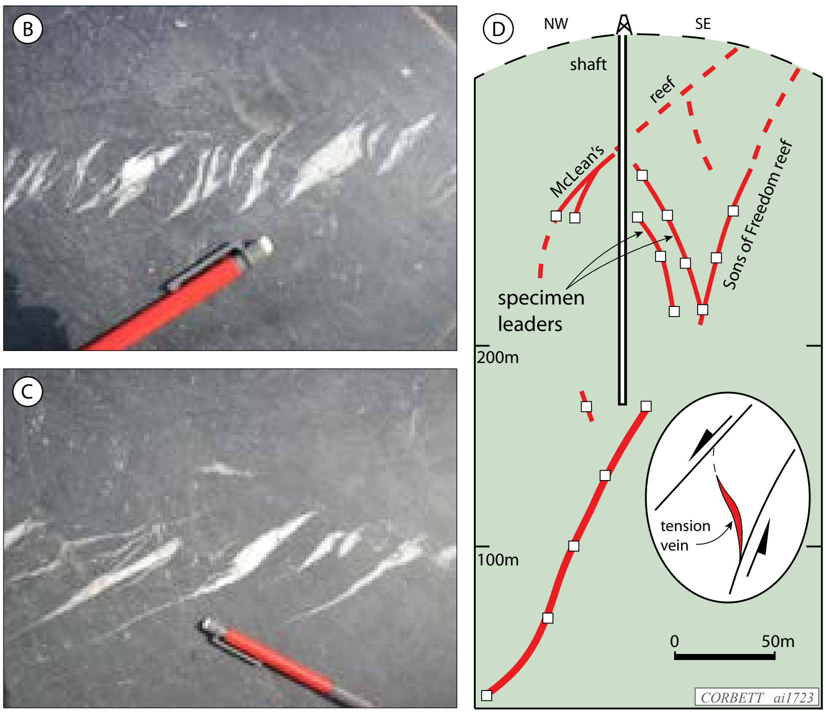
The **exploration implication** is that the host structure between the ore shoots may exhibit only very low grade mineralisation varying to essentially barren, and so it is important to plan drill programs to attempt to intersect the flexures and not rely on grid drilling.

3.2.2.5 Tension veins

Tension or extension fractures develop by the application of a shear component to a brittle rock and these fractures transition to veins as the open space becomes filled by hydrothermal minerals. While clusters of tension veins are commonly grouped as en echelon vein arrays, this terminology might also include many other variably termed dilatant fractures and veins such as link structures, cross overs developed within fault jogs, fissure veins and larger lodes, localised in a negative flower structure setting between the near surficial pull-apart basin and a deeper splay fault (figure 3.17). McKinstry (1948) also notes an association with horse tail (splay) faults which places tension veins in the central portion of negative flower structures (figures 3.17). Therefore tension veins represent an important site of epithermal vein mineralisation development and local normal fault activity.

Tension vein geometry is apparent from analyses of modern analogies (figure 3.19) and exposures from outcrop (figure 3.27) to mine (figures 1.13) and district (3.19, & 3.22) scale. Tension veins develop as fractures initiated at angles in the order of 45° (see Price and Cosgrove, 1990) to the controlling strike-slip structures, and progressively widen as tension gash rotates in response to continued movement on the controlling strike-slip structures (figure 3.30). The wider gash continues to fill with hydrothermal minerals to form a tension vein. At an angle of just past 90° to the controlling structures, the rotated portion of the existing tension gash vein becomes anti-dilational and a new vein initiates in the vicinity of 45° to the controlling structures and the process continues. Importantly, the wider reoriented tension veins host higher precious metal grades in addition to the greater amounts of vein material and so commonly represent ore shoots.





At the Thames goldfield, New Zealand (figure 3.20), large scale tension veins within the Thames fault jog become better mineralised in association with the change in orientation which results from continued dextral strike-slip movement on the NNW trending fault jog controlling structures. While the NNE trending tension veins, which host mines such as the Day Dawn, take on a wider and higher Au grade character as they are reoriented to the NE to host mines such as the Sons of Freedom, best mineralised veins trend EW in the vicinity of the Thames Bonanza Goldfield (figures 3.20). The fluid flow model proposed by Corbett and Leach (1998) suggested magmatic ore fluids migrated from the vicinity of the Ohio Creek porphyry-Lookout rocks alteration zone, towards the SW along the dilated NE tension veins, which host low Au grade quartz-sulphide Au mineralisation. Bonanza Au was deposited within EW veins at the Thames Bonanza Goldfield aided mixing of pregnant ore fluids with meteoric waters which collapsed down the NS trending flinty cross structures (section 7.5.4). Normal fault down-drop on the NE trending tension veins resulted in the development of intervening second order tension veins discernible in cross section (figure 3.30 D). These bonanza grade ore shoots, termed 'specimen leaders' (figure 3.30 D), were described by Fraser (1910) as "richly gold-bearing ... highly pyritised quartzose veinstone".

3.2.2.5.1 The Waihi Mine, New Zealand, provides a good example of a set of mineralised tension veins (figure 3.31). The Coromandel Peninsula of New Zealand displays dextral strike-slip movement on regional NS structures (figure 3.20), such that throughout the district better Au mineralisation (including ore shoots) is recognised in association with the progressive reorientation of veins as from NNE to NE, and on to near EW orientations which localise high Au grade ore shoots. This is the same pattern as at Thames (above). At Waihi several tension veins up to 1 km long, which are constrained between NS trending

Figure 3.30 *Tension veins.*
A - *Develop by the fill of progressively reoriented tension gash fractures during strike-slip movement on the controlling structures to form veins which are wider and host higher precious metal grades.*
B & C - *Tension veins in marble pavement, Spain. The vein above the pen top in A displays the theoretical form.*
D - *A cross section through Sons of Freedom reef, Thames goldfield, New Zealand (figure 3.20) illustrates the development of bonanza Au grade specimen leaders (veins) as tension veins by a component of normal fault movement on the larger scale veins, modified from Fraser (1910).*

dextral strike-slip faults, include the principle Martha vein normal fault and overlying Royal, Empire and numerous smaller hanging wall veins, which dip back towards the principle vein (figure 3.31; Corbett and Leach, 1998; Braithwaite et al., 2006 and references therein each). Well banded veins developed by regular opening of this dilatant structural setting controlled by regional scale fault movement and regular deposition of ore and gangue minerals from rapidly cooling and boiling hydrothermal fluids. Veins in the more dilatant settings, such as the near EW oriented Martha vein, tend to host more banded quartz (chalcedony) deposited from circulating meteoric waters and veins (Union, Amaranth, Gladstone and Favona) extend for about 3.5-4 km SE in the hanging wall of the Martha normal fault (figure 3.31) towards the Waihi Basin described (Bromley and Braithwaite, 1991) as a possible collapse caldera. The Martha structure might therefore represent a regional scale listric fault with extension to the SE related to the down drop at the Waihi caldera, from where the ore fluids may have been derived. have speculated the Martha structure might represent a regional scale listric fault with extension to the SE related to the down drop at the Waihi caldera, from where the ore fluids may have been derived.

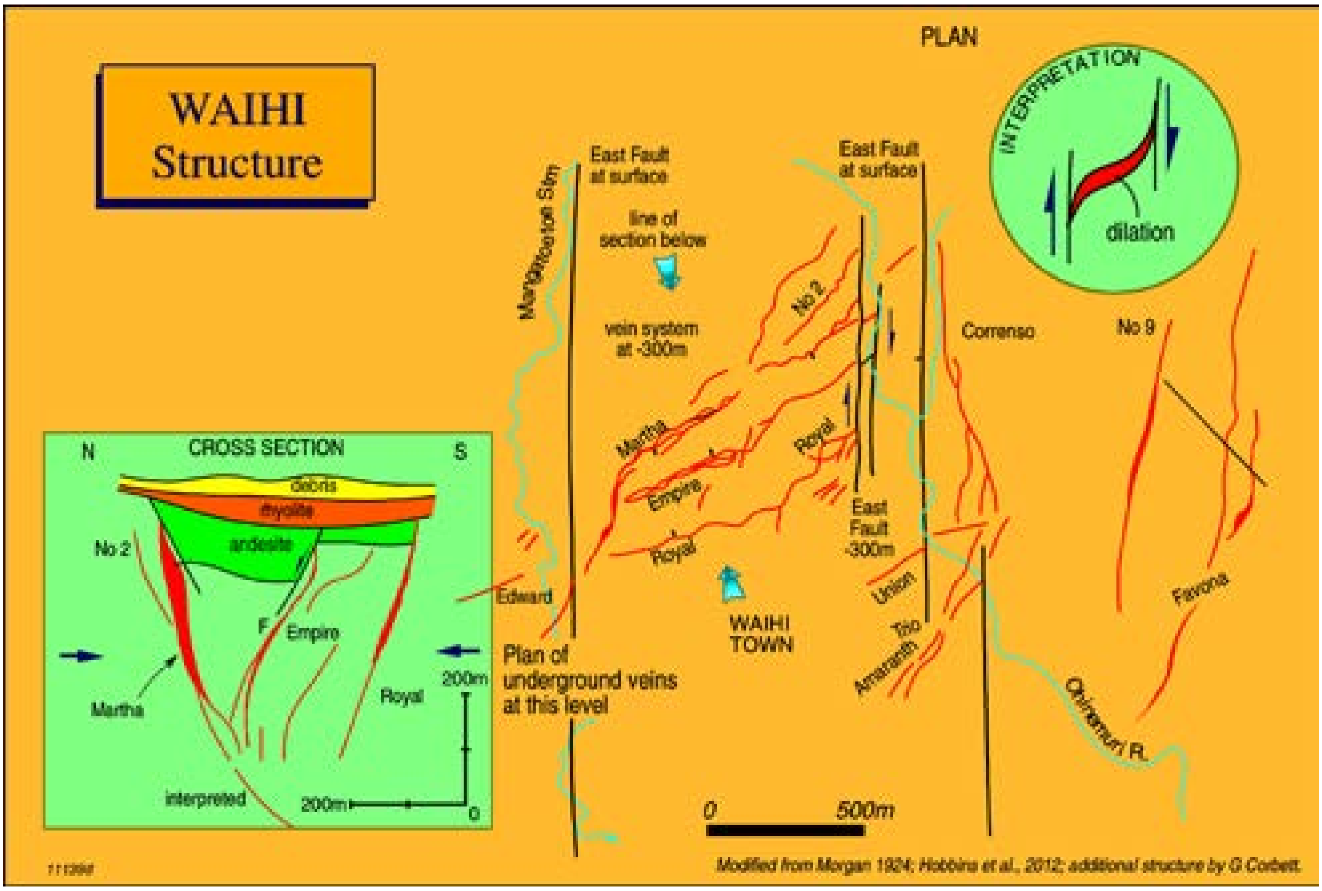


***Figure 3.31** Structure of the Waihi mine New Zealand (modified from Corbett and Leach, 1998 and references therein) showing NS controlling structures recognised from air photo interpretation and mapped in underground workings, while the cross section shows development of the tension veins as a listric fault (Martha Vein) and hanging wall splays (Empire and Royal Veins). The Correnso veins are oriented in a much less dilatant setting than the main NE portion of the Martha vein.*

sulphides as the evolved ginguro bands. Veins in the less dilatant NNE orientations such as the base metal sulphide-rich veins at Corenso (Hobbins et al., 2012), described by Singh (2015) as carbonate-base metal Au style, contain less banded quartz. (See discussion in section 7.1.2). Eruption breccias with low temperature clay alteration cap the nearby Favona veins (Torckler et al., 2006) described in section 4.4.6.3.1. Note in figure 3.31 how the andesite thickens on the down-drop side to the normal fault which hosts the Martha vein in figure 3.31 indicating this structure displayed some activation as a growth fault. A series of steep dipping

3.2.2.5.2 The Golden Cross mine, New Zealand, exploited one of several tension fissure veins and overlying stockwork veins. Early miners discovered the outcropping NNE to NE tension veins (Hippo, Taranaki and Golden Cross) developed by interpreted (Corbett and Leach, 1998) dextral movement on NS structural elements of the Coromandel Peninsular, recognised throughout the Hauraki Goldfield. The blind Empire Vein was discovered in the mid 1980’s during exploration of the stockwork veins adjacent to the west (figure 2.23). Recent interpretation of steep east dipping bedding in the Waipupu Formation host-rock andesite, (below the flat dipping post-mineral Whakamoehau andesite of Simpson et al., 2001, previously termed Omahine andesite by Corbett and Leach, 1998), led Begbie et al. (2007) to suggest the Empire Vein originally dipped east and the now flat-lying stockwork veins on the eastern side developed as steep dipping hanging wall splay faults. Post-mineral normal fault are offset by Steep-dipping bedding-plane faults. If this post-mineral clockwise rotation in the order of about 70° is removed, then the Golden Cross fissure vein might have dipped in the order of 65° east and the stockwork veins steep west (approx. 82°).

3.2.2.5.3 Exploration of tension veins requires some care in the design of drill programs. As described above, in the formation of tension veins, fractures initiate at approximately 45° to the controlling strike-slip structure within competent host rock, and progressively widen as they rotate in response to continued movement on the controlling strike-slip structures (figure 3.30). In addition to greater width, the re-oriented veins display high precious metal contents, although a new tension vein develops at an angle just past 90o to the controlling structures. Some larger scale tension veins host steep pitching ore shoots in conditions of purely strike-slip deformation. The end result of this process commonly represents a set of tension veins in which the highest Au grade and widest veins (potential ore shoots) are normal to the orientation of the controlling structures and commonly including the structured grain of the district (figures 3.30 & 3.32). Any negative flower structure (fault jog or pull-apart basin) style soil geochemical anomaly is likely to be elongate along the direction of the controlling structures, which commonly lie within the structural grain of the district. There is a natural tendency to drill across the

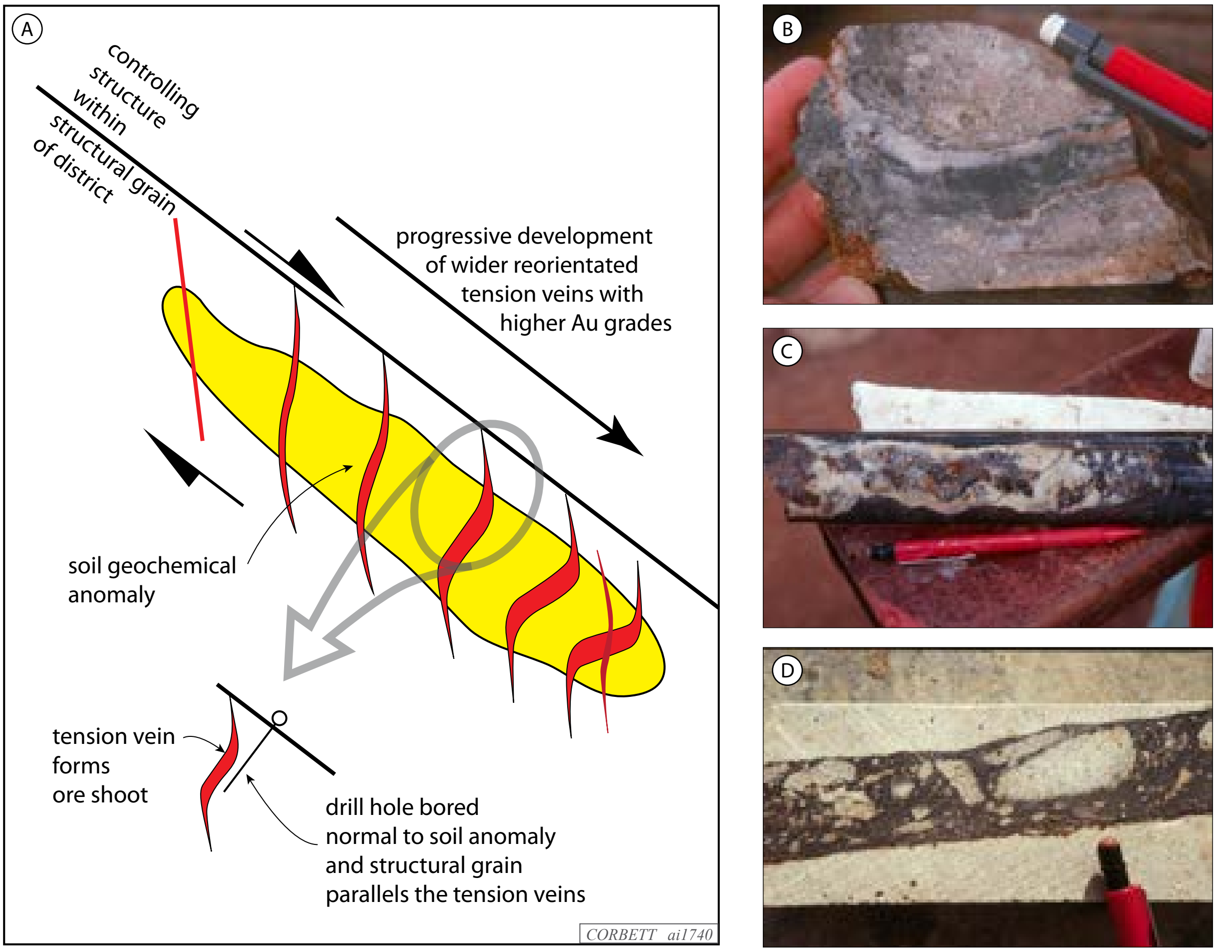


***Figure 3.32** Tension vein mineralisation and drill direction.*
A - *Tension veins rotate during progressive strike-slip deformation to host wider and higher precious metal grade central portions at 90° to the controlling. Vertical drill holes would not intersect the veins. Some of the drill holes bored across the structural grain and elongation of the soil anomaly trend would be parallel the tension veins might bore down veins and give high results while others might not intersect veins. The resulting irregular grade x thickness pattern might be difficult to interpret.*
B - *High grade vein sub-parallel to a drill hole (1.64 m down hole @ 61.4 g/t Au & 4100 g/t Ag).*
C - *Mineralised vein parallel to the core axis that influenced a resource determination.*
D - *Fluidised breccia intersected parallel to the core axis.*

structural grain of the district and any elongate soil geochemical anomaly. However, in this case some drill holes may bore along (down) the highest grade veins (normal to the structural grain) and yield long drill intersections of high Au-Ag grade mineralisation (figure 3.32), yet other barren drill holes might lie between veins, and so the overall drill program might provide irregular results which are difficult to interpret. The intercept of a drill hole bored down a narrow vein will make a much greater contribution towards the resource than is justified, locally with dire consequences for resource estimates (figure 3.32). There are other explanations for core parallel veins.

At Mt Kasi, Fiji, a series of tension veins lie at high angles to the structural grain and an elongate early open pit (Corbett and Taylor, 1994). The initial drill test across the grain and open pit yielded highly irregular results such as those described above (figure 3.32). Subsequent geological mapping by Geoff Taylor recognised the importance of the tension veins and planned better a oriented drill test, and eventual mine development proceeded some years later.

The **exploration implication** is that explorationists should carefully monitor the angle of veins to the core axis in conjunction with the metal distribution in drill results as:

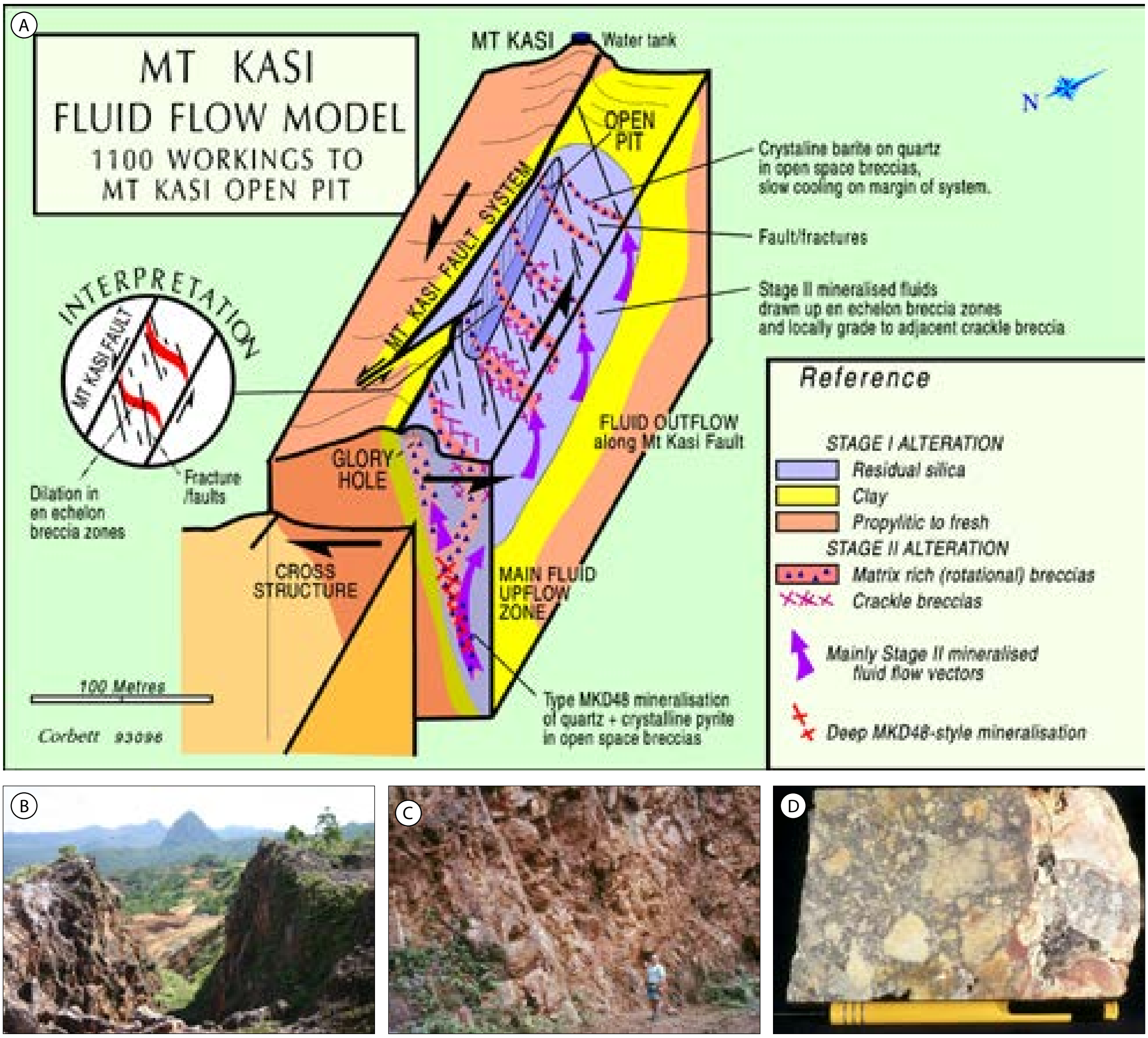


__Figure 3.33__ Tension vein mineralisation and drill direction, Mt Kasi, Fiji.
A - *Sketch (from Corbett and Taylor, 1994) illustrates the development of tension veins at a high angle to the elongation of the old open pit, soil anomaly and structural grain of the district which an early unsuccessful drill program bored directly across.*
B - *Looking long the old open pit and the structural grain with the Waidamudamu dome in the background.*
C - *Fractures and tension veins at a high angle to the open pit wall, Geoff Taylor for scale.*
D - *Detail of the mineralised tension vein breccias in drill core.*

- Irregular grade x thickness distribution combined with veins at a low angle to core axis should prompt a review of the geological model to test for the scenario described above and initiate a possible change in drill direction.
- Resource estimates might be biased by drill intercepts which have bored down veins.
- Documentation of drill results should provide an indication of the true vein thickness or sufficient information on the context to allow the reader to evaluate the results.

fault movement on the parallel fractures, in order to develop mineralised tension veins at high angles to the controlling faults and commonly parallel to the drill core axis. Consequently, irregular Au grades may occur outside the main ore envelope of the normal fault-hosted fissure vein (figure 3.34).

The **exploration implication** of this model explains the presence of locally elevated Au grades within small core-parallel stockwork veins which, during resource

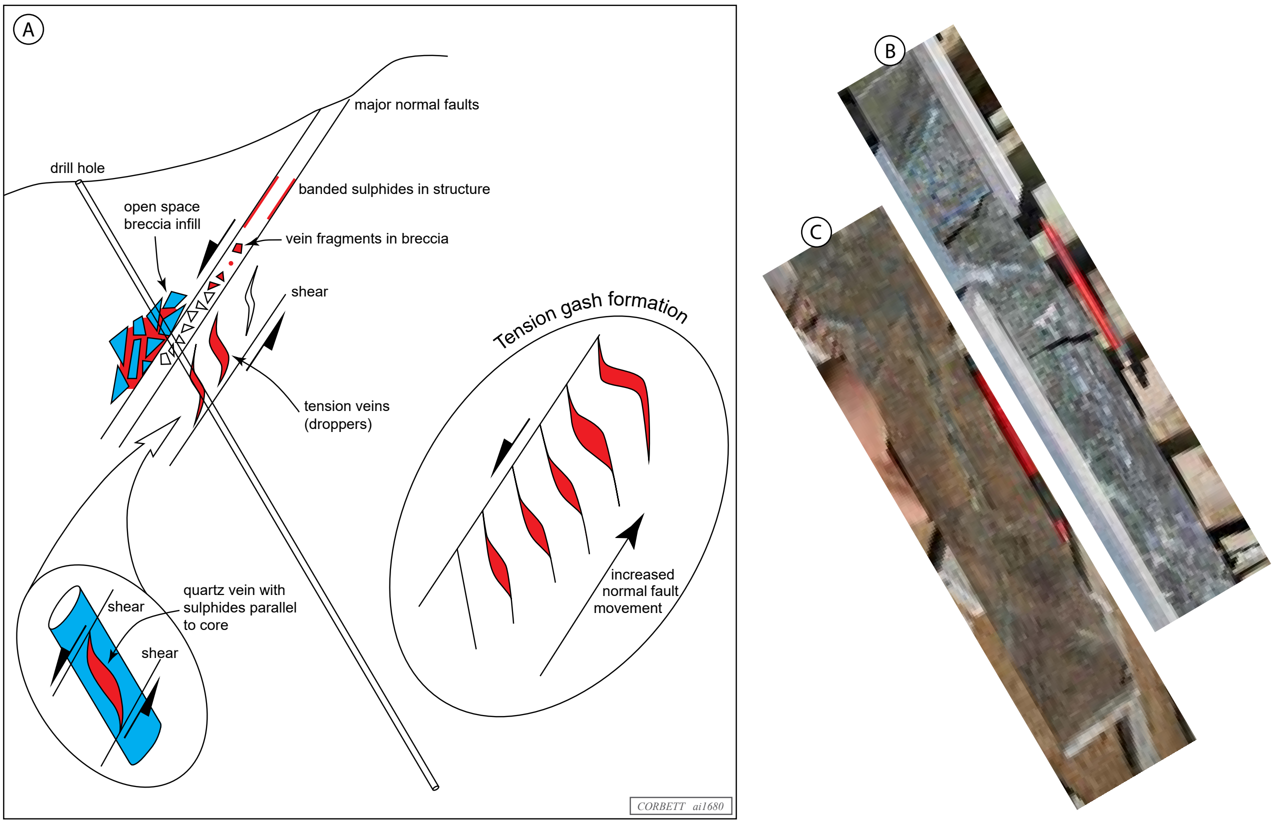


Figure 3.34 *Sigmoid veins aligned along the drill core axis and constrained by small scale shears, are common marginal to veins developed within normal faults.*
A - *Graphic to illustrate the relationships discussed herein*
B - *Core-parallel sigmoidal tension vein limited by shears, Palmarejo, Mexico.*
C - *Core-parallel sigmoidal tension vein limited by shears, Drake goldfield, Australia.*

3.2.2.5.4 Tension veins and normal faults

The drill cores obtained by the drill tests of many epithermal vein systems bored from the hanging wall towards dipping veins commonly host small scale sigmoid-shaped tension veins with long axes aligned parallel to the core axes and constrained between barren shears at moderate angles to the core axis (figure 3.34). Orientation of the drill core consistent with the original drill hole demonstrates these tension veins have developed by activation of fractures, as mini-normal faults, parallel to the main normal fault which hosts the epithermal vein system under investigation. Tension fractures have become reoriented and dilated by continued normal calculations, must be taken into account as not part of the main fissure vein but as a marginal stockwork. Elsewhere the recognition of these veins supports any interpretation of normal fault movement on the main structure.

3.2.2.6 Splay faults

Splay faults represent the deepest crustal level element of dilatant negative flower structures present as link structures or cross overs which facilitate the change in strike-slip movement from one structural element to another, in the development of fault jogs (figure 3.17). Multiple splay arrays are termed horse tail faults (figure 3.35) and splay or horsetail faults may mark the termination of strike-slip fault systems (figure

Figure 3.35 Horsetail fault array as the termination of this structure, El Indio, Chile.

3.16). At this deep dilatant environment splay faults localise porphyry intrusions, particularly as stock-like apophyses to larger deeply buried magmatic source rocks. Sheeted veins which transport ore fluids from the magmatic source into the overlying stock are aligned along the dilatant splay fault orientation. Prior to the classification of porphyry deposits, Lindgren (1933), Bateman (1950), McKinstry (1948) all describe horsetail faults as mineralised fissure veins mostly citing the example of Butte, Montana, as a clearly dilatant mineralised vein array. Splay faults therefore participate in the creation of the space required for porphyry emplacement within essentially compressional magmatic arcs and later mineralisation of the stock drawing fluids from the deeper magmatic source.

3.2.2.6.1 The Chuquicamata porphyry lies within a continuous zone of mineralisation up to 22 km long from Radomiro Tomic in the north and the Toki cluster in the south as shown in recent mapping (Rivera et al., 2012). The Chuquicamata porphyry is localised at the intersection of NS trending Falla Oeste (West Fault), as a local element of the Domeyko fault corridor, and splay faults discernible as the NNE Zaragoza and NE Estanques Blancos faults and parallel mineralised veins (Boric et al., 1990; Lindsay, 1997; Lindsay et al., 1995), and so the term horsetail may be appropriate (figures 3.2 & 3.36). The West Fault cannot easily be traced north of Chuquicamata suggesting it might terminate at this point, and movement could cross to another structure further east. If so, then the splay faults would represent link or cross over structures. Localisation by the porphyry by such a splay would suggest there has been a component of dextral movement on the Domeyko fault structural corridor at the time of mineralisation which contrasts with the expected reverse movement for most of the history on the West Fault and a speculated sinistral movement suggested by Rivera et al. (2012). The Chuquicamata Porphyry is cut at

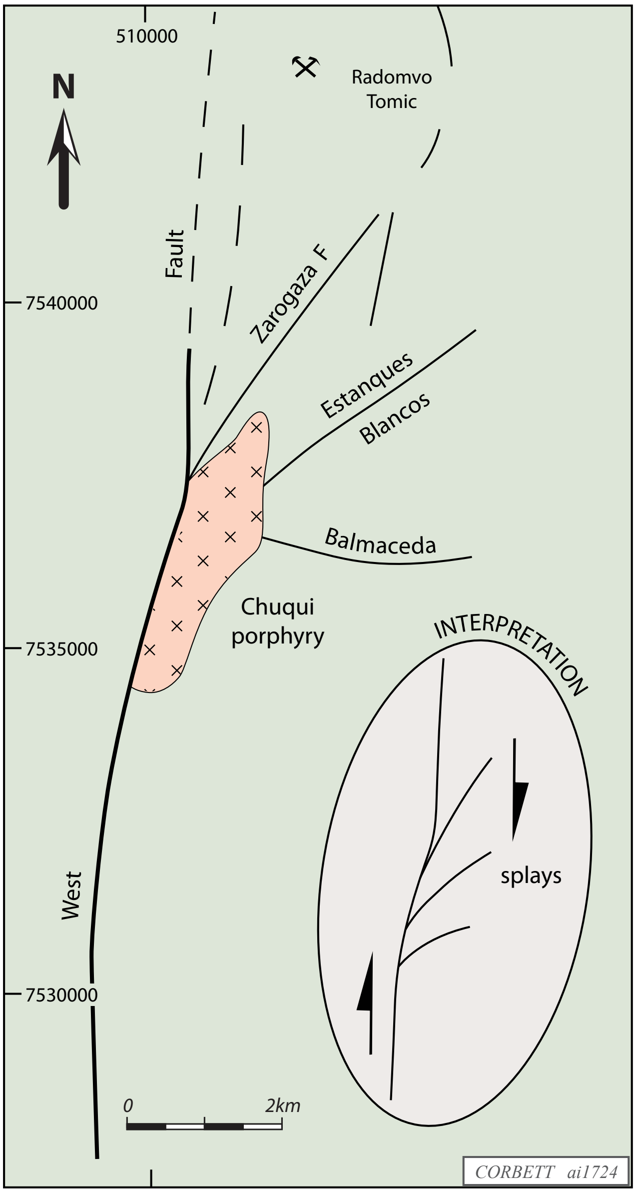


Figure 3.36 Structural setting of Chuquicamata within the Domeyko fault corridor shown in figure 3.2, here localised at the intersection of the West Fault and splay faults such as the Zarogaza and Estanques Blancos faults, from Boric et al., 1990; Lindsay, 1997; Rivera et al., 2012.

the western margin by probably post-mineral reverse movement on the West Fault which places Palaeozoic-Triassic metamorphic rocks against Calama Formation Eocene-Oligocene gravels on the eastern side (Rivera et al., (2012).

3.2.2.6.2 The La Escondida porphyry system (including Zaldivar and Escondida Norte) lies within an NE trending link structure interpreted (Corbett, unpubl data, 1998) between NS tending segments of the Domeyko Fault Corridor (figures 3.2 & 3.37). That study further suggested a component of dextral strike-slip on the Domeyko corridor dilated this NE link structure in order to trigger porphyry emplacement and mineralisation. NE trending mineralised intrusions and faults are consistent with

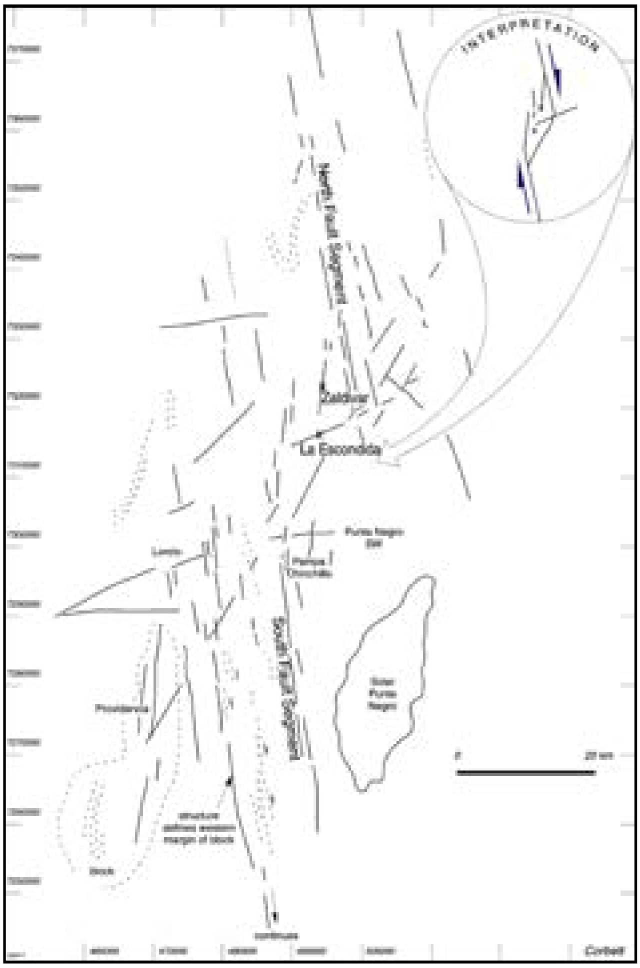
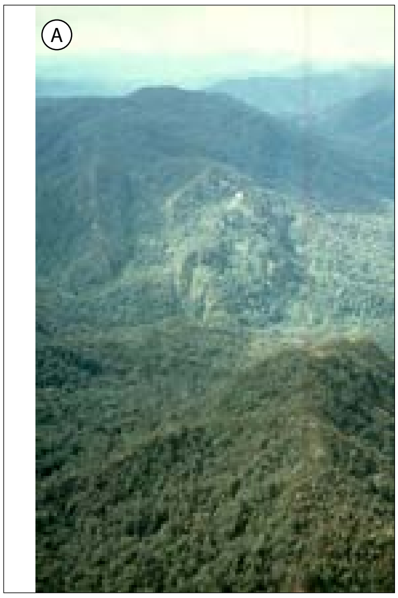
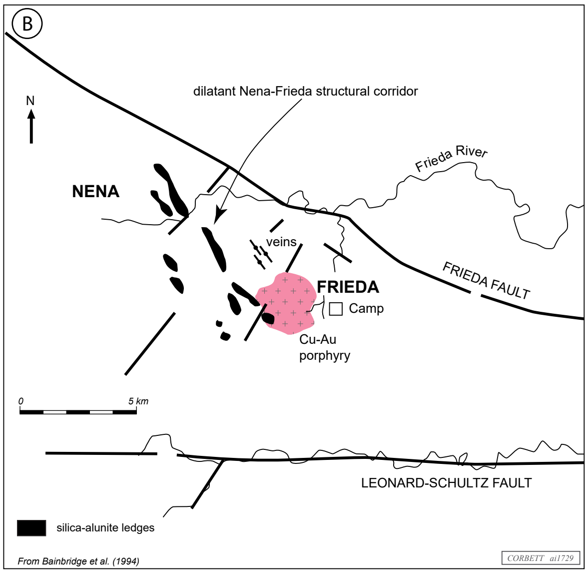


***Figure 3.37** Interpretation of remote sensing data which places La Escondida within a link structure in the Domeyko Fault Corridor.*

the suggestion by Herve et al (2012) the La Escondida Porphyry emplacement and mineralisation took place under conditions of dextral strike-slip movement on the Domeyko Corridor. The setting of the La Escondida district in a link structure could give the impression that the corridor of NS Domeyko faults terminate there (figure 3.37). Folklore in the region is that the porphyry deposits occur close to terminations of structural elements of the Domeyko Corridor, which is consistent with the localisation of intrusions within the link structures between the main NS structural elements, including splay faults.

3.2.2.6.3. The Frieda porphyry Cu-Au district, which also hosts the Nena high sulphidation epithermal Au-Cu deposit, is localised in a major splay in the regional scale Fiak-Leonard Schultz Fault system (figure 3.38) which suggests porphyry-epithermal mineralisation developed in response to a dextral sense of movement





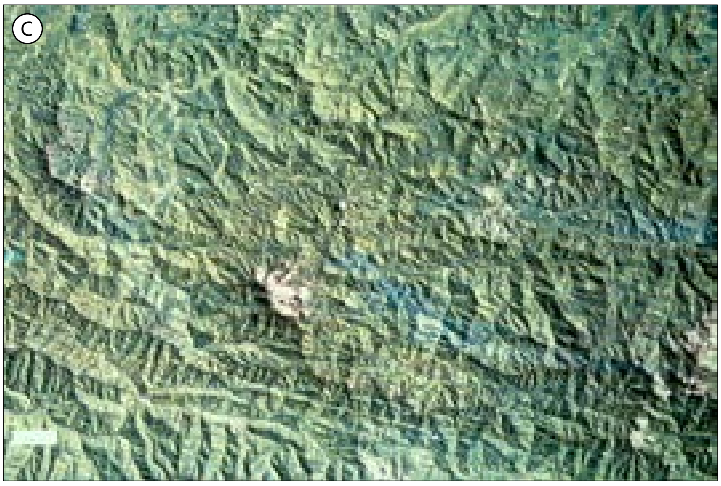


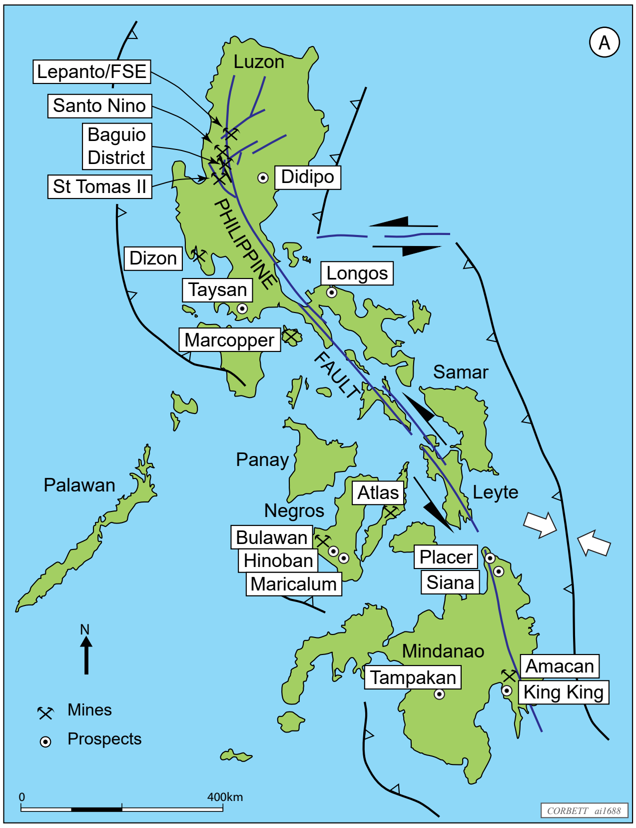
***Figure 3.38** Frieda-Nena localised by a splay in the Fiak-Leonard Schultz fault, Papua New Guinea and development of the dilatant Frieda-Nena structural corridor. See figure 3.4 for location.*

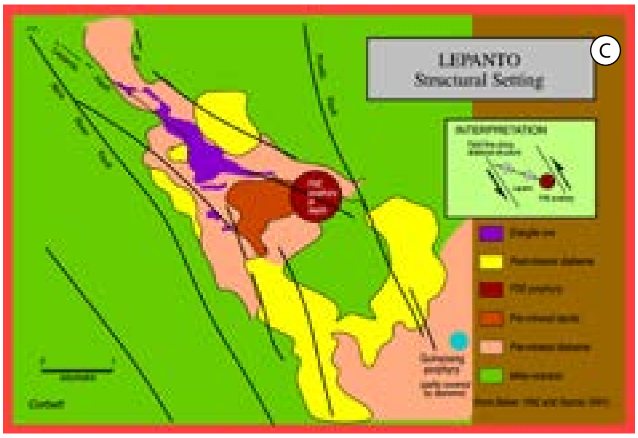
A - *View of the Frieda-Nena structural corridor looking NW towards Nena. See figure 2.31 view of Frieda-Nena structural corridor looking SE.*

B - *Interpretation of the Frieda structural elements.*

C - *Side looking radar image for the Frieda region.*

on that structure (Bainbridge et al., 1994; Corbett and Leach, 1998). In these conditions the elongate Frieda-Nena structural corridor has developed as a dilatant structure related to the splay fault and dextral movement on the Fiak-Leonard Schultz Fault system. It is dominated by numerous silica-alunite ledges including the Debom barren shoulder (section 2.2.4.2.2), developed adjacent to the Horse Ivaal porphyry and the Nena high sulphidation epithermal Au-Cu deposit (figure 3.38).





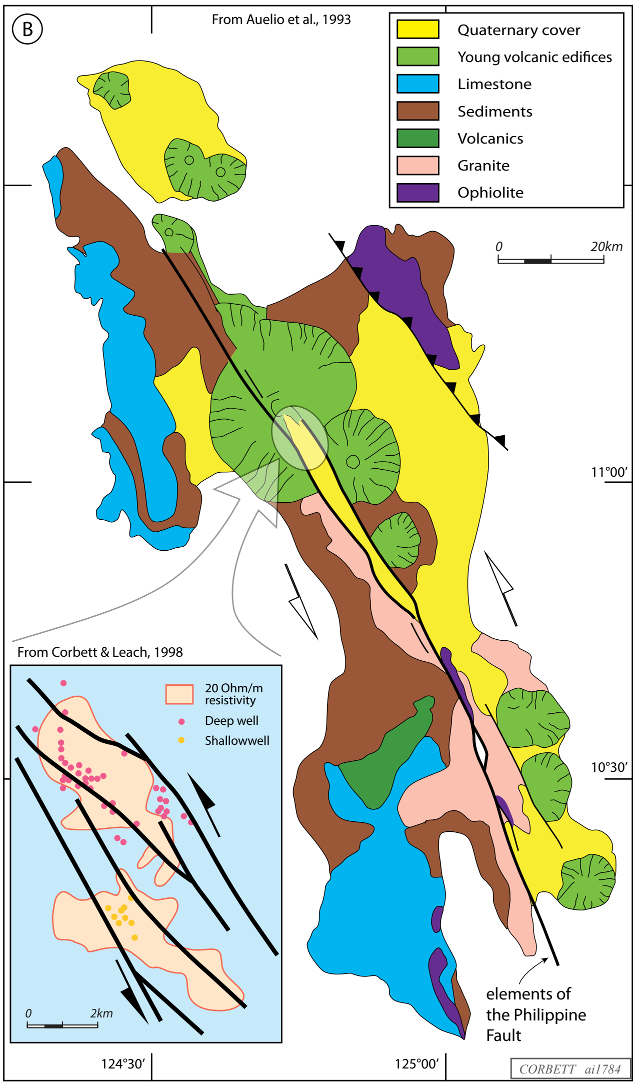


Figure 3.39 *Splay faults along the Philippine Fault localise ore systems.*
A - *The Philippine fault and location of some Philippine ore systems.*
B - *Geological interpretation showing the setting of the Tongonan geothermal field on the island of Leyte, from Corbett and Leach, 1998, hosted within in a fault jog in the Philippine Fault where splay faults, which localise greatest fluid flow in geothermal wells at depth, are similar to mineralised fissure veins. Geological map from Auelio et al. (1993).*
C - *The buried Far South East porphyry is localised at the intersection of the Lepanto splay fault and elements of the sinistral Philippine fault, while the Lepanto high sulphidation epithermal Au-Cu mineralisation, also projected to the surface, is located at the intersection of the dilatant Lepanto fault and a diatreme margin (from Corbett and Leach, 1998 and references therein).*
D - *Philippine strike-slip fault adjacent to the Tongonan geothermal field in a non-dilatant portion of the structure.*
E - *The dilatant surficial pull-apart basin formed between in two segments of the Philippine Fault which hosts the Tongonan geothermal field as a site of intrusion-related geothermal activity.*

3.2.2.5.4 The Philippine Fault transects the Philippine islands with a consistent sense of sinistral strike-slip displacement derived from the plate tectonic setting and evidenced in many ore systems throughout the country. In northern Luzon the generally NNW trending Philippine Fault breaks up into several NS trending segments which would be expected to display the same sinistral sense of movement. The Far South East porphyry is localised where a splay fault diverges from one of the Philippine Fault segments (figure 3.39). The Lepanto high sulphidation epithermal deposit lies at the intersection of the splay fault and a diatreme breccia pipe (section 4.4.5), and displays a fluid evolution trend consistent with models that ore fluids were bled from the Far South East environment at depth (Corbett and Leach, 1998 and references therein). The Didipio porphyry district in Northern Luzon is constrained by NS trending fault segments formed parallel to the Philippine Fault. Here the Dinkidi porphyry hosts NW trending sheeted veins developed as tension veins in response to sinistral movement on those NS structures (Corbett, unpubl. reports; Garrett, 1996). The sheeted veins not only host mineralisation but are interpreted to have bled ore fluids from the magmatic source at depth to a higher crustal level of mineral deposition in cooler conditions. On the island of Leyte the intrusion-related Tongonan commercial geothermal field is located within a fault jog, discernible as a surficial pull-apart basin, developed as a cross-over between segments of the sinistral Philippine Fault (figure 3.39; Corbett and Leach, 1998). Highest (intrusion-related) geothermal fluid flow in 1-2 km deep drill holes is associated close to splay faults which might therefore be analogous to mineralised epithermal fissure veins developed as part of a negative flower structure below the surficial pull-apart basin.

There is an **exploration implication** in the recognition that splay faults or link structures formed within structural corridors with oblique senses of movement represent sites for the localisation of porphyry Cu-Au intrusions or epithermal veins. Once the sense of strike-slip movement is estimated on such a corridor of individual structures, defined use of geological mapping, remote sensing or magnetic imagery, an inspection for cross overs could easily identify exploration targets. Link structures in one orientation will be dilatant releasing bends (figure 3.16) and in the other orientation represent anti-dilational restraining bends.

3.2.3 Orthogonal compression

Orthogonal compression not a common setting for mineralisation, despite the overall compressional nature of subduction-related magmatic arcs which host epithermal vein deposits and porphyry intrusions. Several settings for the development of mineralised veins and ore shoots include steep dipping structures normal to the structural grain and parallel to compression, conjugate fractures and arc-parallel reverse faults or thrusts. Reverse faults host flat pitching ore shoots best within flatter dipping fault portions (figure 3.7), described below.

3.2.3.1 Arc-normal veins

In settings of orthogonal compression veins may develop parallel to the direction of principle stress and hence normal to the arc (figure 3.7) as steep dipping fissure veins. Movement on conjugate fractures which are common these settings during orthogonal compression (section 3.1.3) may promote the development of ore shoots by rotation of the arc normal fractures as tension veins (figure 3.40)

3.2.3.1.1 The El Guanaco high sulphidation epithermal gold deposit in northern Chile hosts both structurally controlled feeder structures, within competent andesites, and larger bodies of lithologically controlled mineralisation, within fiamme tuffs (section 8.4.1.7). The ore system occurs as a several km long, roughly EW-ENE trending, steep dipping, structural corridor of veins, formed at a very high angle to the NS trending structural grain of the district, and constrained between both conjugate fractures and reverse faults developed as part of the structural grain (figure 3.40). Limited components of strike-slip movement during orthogonal compression on the NE-SW and NW-SE trending conjugate fractures discernible on remote sensing imagery, have locally deformed and dilated the EW veins to result in the development of steep pitching ore shoots within flexures (figure 3.40). See also Cerro Vanguardie (below).

3.2.3.2 Conjugate fractures

Conjugate factures described above develop at variable angles to the orientation of compression from the order of 30° in epithermal-porphyry terrains to as much as much as 60° in deeply eroded crustal levels such as the Pontides of NE Turkey (section 3.1.3). Although these structures are interpreted to have formed in response to orthogonal compression, transient relaxation or changes in the orientation of compression may trigger their involvement in ore formation. It is common for one of the conjugate fractures to become more dominant. The

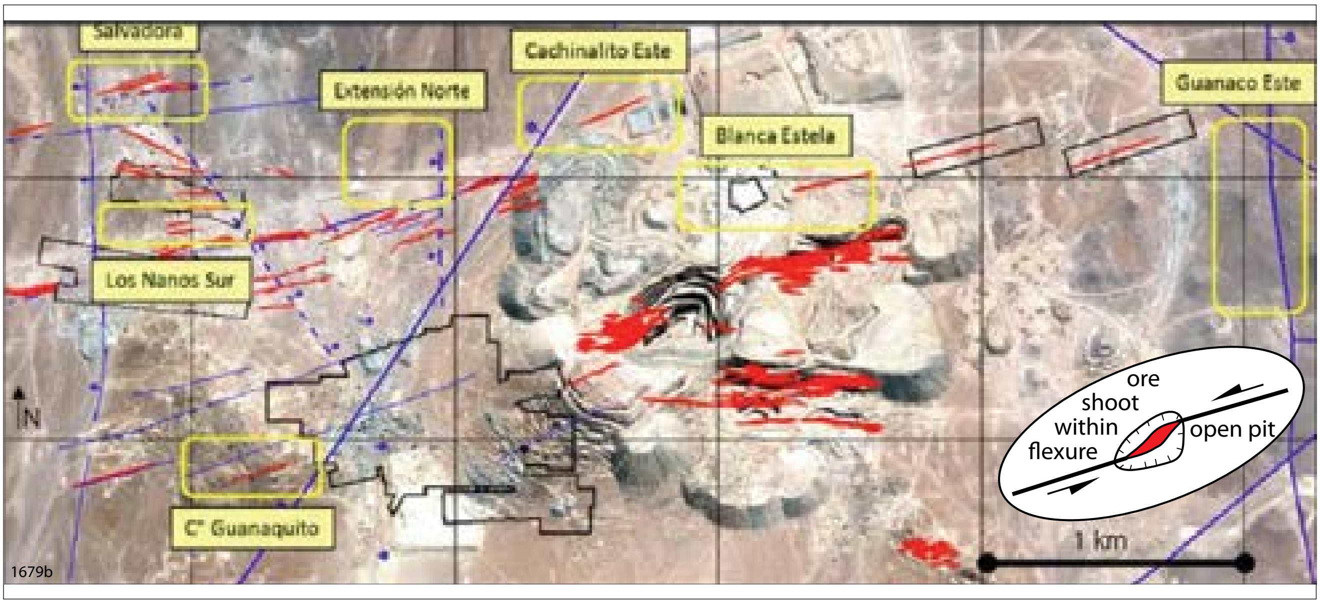


Figure 3.40 *Structure of the El Guanaco high sulphidation epithermal Au deposit, Chile for which lithologies, alteration and mineralisation are shown in section 8.4.1.7, as an aerial image with superimposed veins, from www.australgold.com.au.*

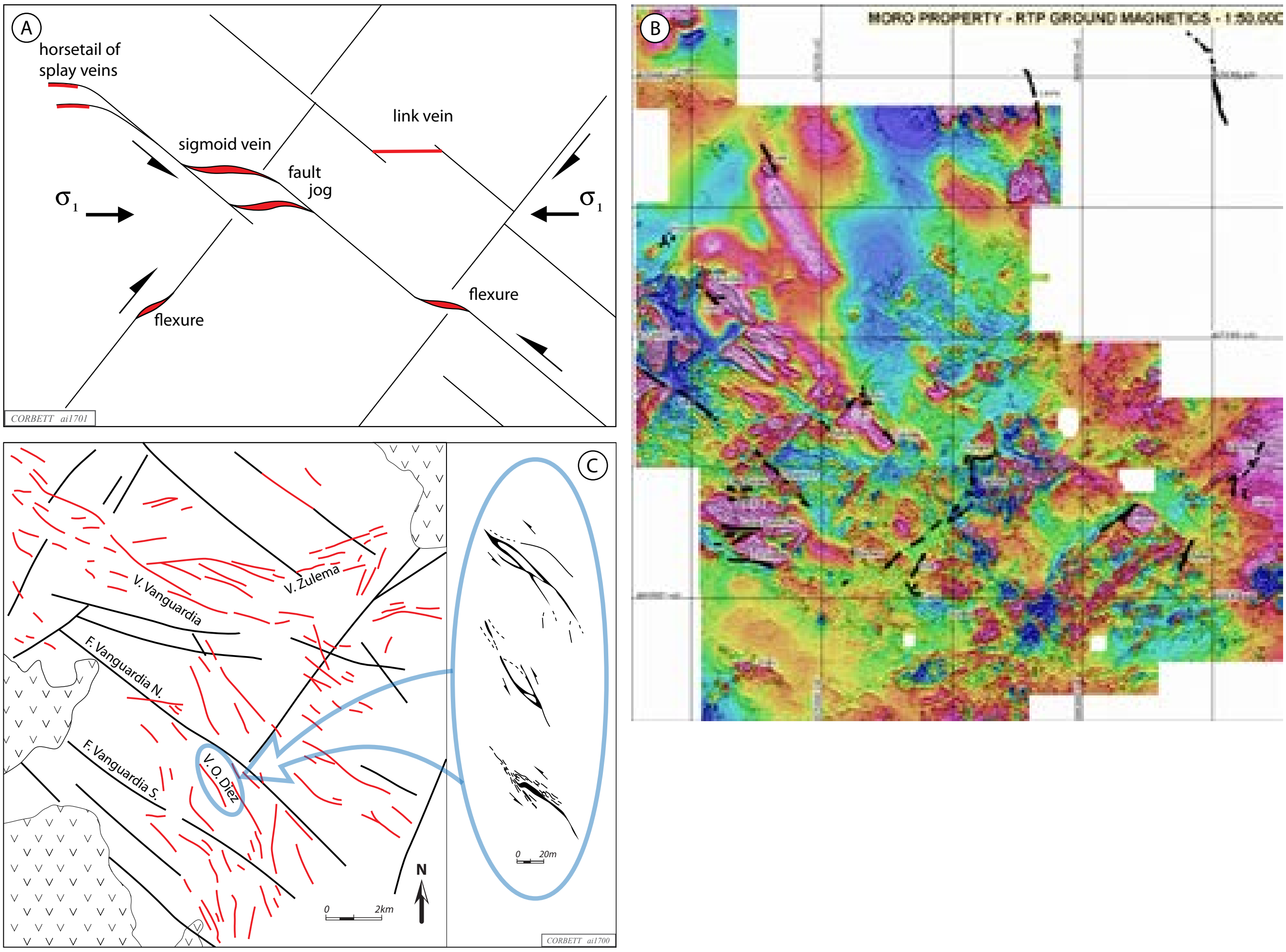


Figure 3.41 *Mineralised veins and ore shoots related to conjugate fractures.*
A - *Model based upon conjugate fractures in the Deseado Massif of Argentine Patagonia features NW dominant over NE conjugate fractures, each with components of strike-slip deformation during EW orthogonal compression. Dilatant veins include: EW link structures developed between NW fracture/veins and splay veins, flexures sigmoid loops, which feature the progression to wider veins with higher metal grades as veins rotate (from NW to WNW and EW) during progressive deformation.*
B - *Magnetic data for Cerro Moro which illustrates the NW-SE and NE-SW conjugate fractures along with many prospects along with the most prospective EW trending Escondida vein group in the bottom left (from Perkins and Williams, 2007).*
C - *Ore shoot formation at Veta Osvaldo Diez, Cerro Vanguadia, (from Zubia et al. 1999).*

development of mineralisation under conditions of orthogonal compression is considered here.

3.2.3.2.1 The Deseado Massif, Argentine Patagonia, which lies in a back arc setting within Argentine Patagonia, is cut by prominent conjugate fractures interpreted to have developed in response to orthogonal compression (section 3.1.3; figure 3.5). Many mines and exploration projects feature mineralised veins hosted by the within NE-SW and NW-SE conjugate fractures which are clearly discernible on remote sensing or magnetic imagery (Cerro Vanguadia, Zubia, et al., 1999; Cerro Moro, Perkins and Williams, 2007; Cerro Negro, Shatwell et al., 2011; San Jose [aka Juevos Verde], Dietrich et al., 2012; Cap Oeste, Bow, 2012). Activation of the conjugate fractures, with only small components of strike-slip movement, in response to orthogonal compression, has facilitated the formation of dilatant sites which host ore shoots characterised by wider and higher metal grade vein portions. Dilatant sites formed by strike-slip movement on the NW fractures in response to orthogonal compression include EW link structures locally developed within jogs to between fault segments and including splay veins and flexures developed as dilatant bends in throughgoing veins (figure 3.41 A). Sigmoidal shapes develop as veins grade to wider forms with higher metal grades as the angular relationship to the master fault increases (figure 3.41 A). At Cerro Vanguadia ore shoots with wider veins and higher Au grades are discernible as dilatant flexures within the throughgoing veins (figure 3.41 C). Many ore systems also feature a change kinematic conditions to NE extension discussed below (section 3.5.2).

3.2.3.3 Restraining bends and thrust-related mineralisation.

Whereas figure 3.16 illustrates dilatant second order structures, compression results if the second order structures are oriented at 90° those fractures, or if there is the opposite movement on the controlling strike-slip structures. In that case, restraining bends develop at compressional flexures, while folds and domes are common within anti-dilational jogs, locally developed as positive flower structures prospected as oil traps (figure 3.42). Reverse faults which take up compressional movement locally host vein mineralisation, within ore shoots that are most prevalent in the flatter dipping portions, which might therefore be blind at the surface and pitch flatly in the plane of the fault (figure 3.7). Combinations of reverse and strike-slip movement provide an inclined pitch to ore shoots.

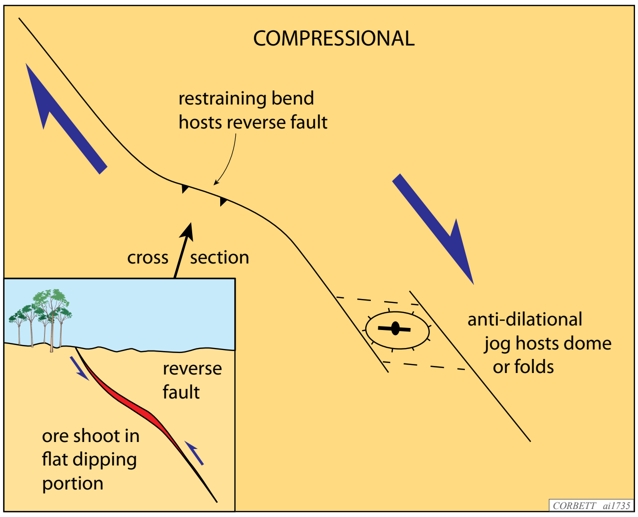


Figure 3.42 *Second order compressional structures formed in a setting of oblique fault movement, showing development of an ore shoot in a flatter dipping portion of a reverse fault developed in a restraining bend.*

3.2.3.3.1 At Kencana, Gosowong, Indonesia, slickensides formed normal to the dip of the fault, which hosts vein mineralisation, indicate movement has been either orthogonal dip-slip or reverse. Comparison of the dip angles of the host structure and Au content (as gram-metres) indicates best mineralisation occurs in the flatter dipping fault portions contoured in figure 3.43. Consequently, the Kencana mineralisation is interpreted to have developed within a reverse fault. The 90° divergence in strike between the mineralised Kencana reverse structures to the Gosowong extensional listric fault is consistent with these two divergent ore systems having formed in the same kinematic environment. Whereas ore shoots have been identified in the flatter dipping portions of the Kencana reverse faults, Gosowong vein ore shoots are hosted by the steep dipping fault portion (figure 3.43). The Kencana veins, which are blind at the surface were identified during step out drilling from the Gosowong vein (Richards et al., 2005).

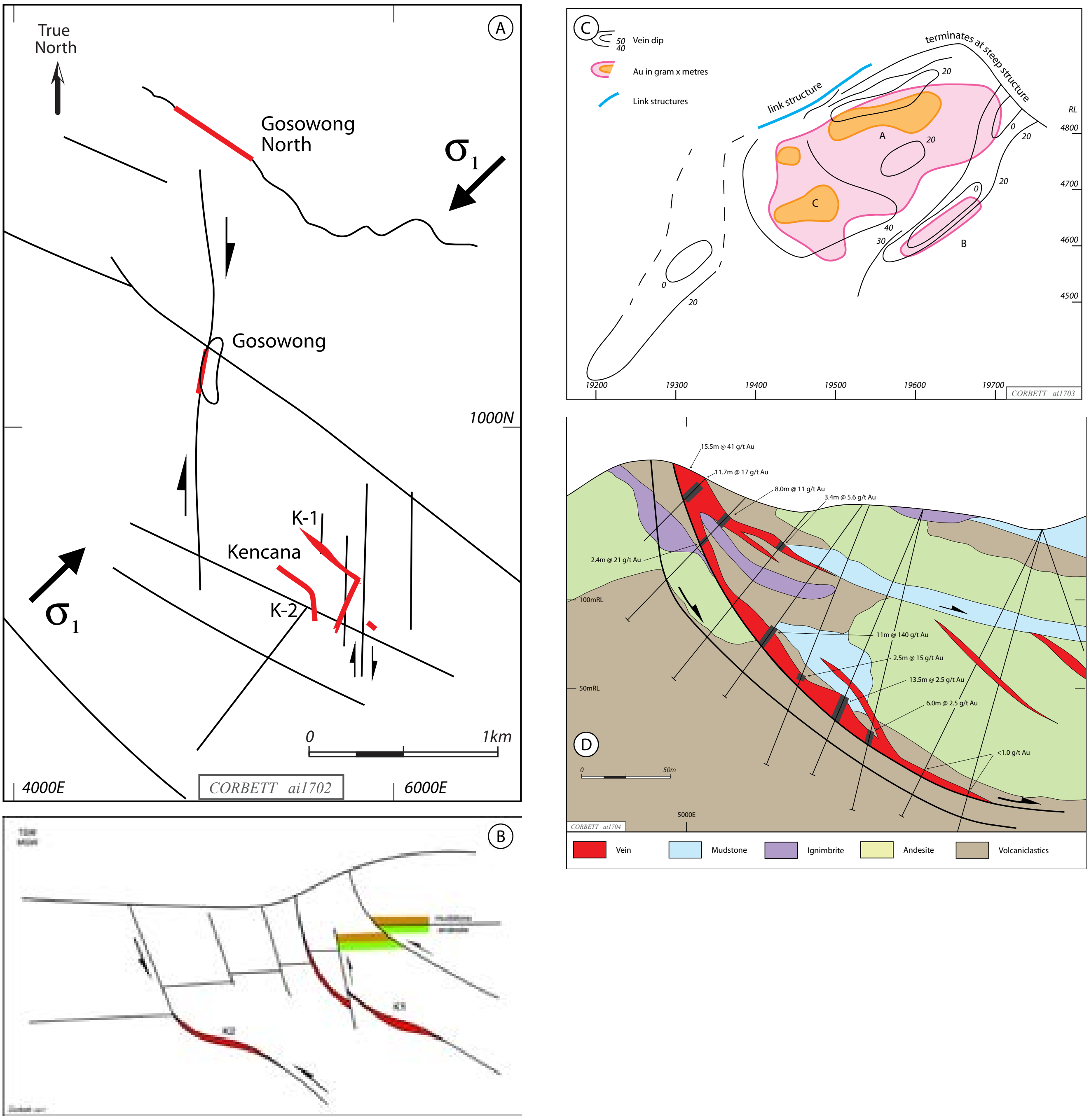


Figure 3.43 *Kencana ore zone, Gosowong Project, Indonesia.*
A - *East Gosowong district in which the Kencana thrust lies at 90° to the Gosowong extensional listric fault and so both are related to SW-NE compression, from Richards et al., 2005.*
B - *Cross section of the Kencana veins, from Richards, et al., 2005 and updated in Corbett, unpubl. report, 2007.*
C - Long section for the Kencana K2 structure showing the close correlation between flat dipping portions of the thrust and higher grade mineralisation in gram metres, from Corbett, unpubl. report, 2007.
D - *Gosowong listric vein formed in the same kinematic regime but at 90° to Kencana, graphic redrawn from Richards, et al., 2005.*

3.2.3.3.2 The Talang Santo mine in the Way Linggo District, South Sumatra hosts banded chalcedony-ginguro Au-Ag vein mineralisation within a compressional structural setting (figures 3.26 & 3.42). Throughout west Sumatra dextral movement on the NW trending Trans Sumatran Fault System derived from the NS collision of the Indo-Australian and Eurasian plates (section 3.2.2) resulted in the development of roughly NS trending dilatant fractures. However, at Talang Santo the NW structural grain of the district progressively changes to WNW and then east-west orientation, and in that configuration the EW fractures can no longer accommodate dextral movement apparent on the NW structures (figures 3.26 & 3.42). Rather, EW trending banded veins developed within reverse faults and host steep pitching ore shoots at the intersections with steep dipping splay faults (figure 3.42). Close to these intersections the generally NW trending splay faults are dilated as NS trending flexures, which are also aligned within the NS compression.

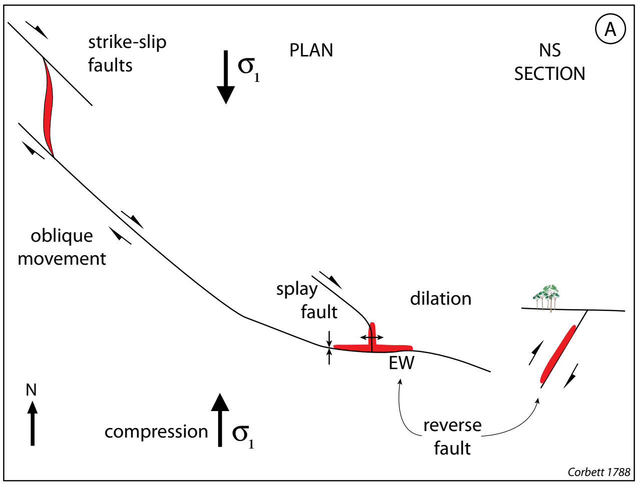


***Figure 3.44** Talang Santo*
A - *Structural setting of the Talang Santo vein in red as plan and cross section views.*
B - *Talang Santo banded chalcedony ginguro Au-Ag epithermal vein mineralisation in the underground workings.*

3.2.4 Ore shoot orientation

Ore shoots which host best ore within many epithermal vein systems vary in orientation from steep where hosted by flexures activated by components of strike-slip deformation, to flat within the steeper dipping portions of listric faults or flatter portions of moderate dipping reverse faults or thrusts (figure 3.7). Combinations of dip-slip and strike-slip fault movement (commonly in listric faults) provide inclined ore shoots, just as ore shoots delineated as structural intersections also display highly variable orientations. Other ore shoots develop at structural intersections which represent settings of Au deposition by fluid mixing (section 7.5.4) or at the intersections of structures with breccia pipe margins (Lepanto, Philippines) or other settings.

Consequently, ore shoots, which commonly display pencil-like forms (see McKinstry, 1948 for examples), are often considered with respect to the controlling structure. Linear features such as ore shoots define a pitch (rake in Bateman, 1950) as the angle between the shoot and a horizontal line on the controlling fault (Lindgren, 1933), whereas plunge is the angle between the linear feature and the horizontal (Price and Cosgrove, 1990), but not within the plane of the controlling fault (figure 3.45). The orientation of ore shoots is typically considered with respect to the host vein/fault in long section where the term pitch is most appropriate (figure 3.45), although drill intercepts may be projected from an inclined fault onto a vertical plane.

3.3.4.1 At Palmarejo, Mexico, best ore lies within ore shoots localised at the intersection of competent host rocks such as andesite and silicified sandstone with several structural settings in association with the corridor of NW structures. The Rosario clavo formed at the intersection of the La Prieta and La Blanca veins, while flexures host the 76 and 108 clavos (figure 4.46 A). The Guadalupe mineralisation lies in a fault jog 6 km along strike to the SE (figure 4.46 B). Here, ore shoots are interpreted to have formed by combinations of dip-slip movement on listric faults and a strike-slip component. The intersection of host structures with competent rock types (silicified sandstone and underlying andesite) also provides a sub horizontal character or limits to ore shoots. Some shoots (76) are characterised a combination of west block down listric fault dip-slip and sinistral strike-slip movement to provide south pitching ore shoots.

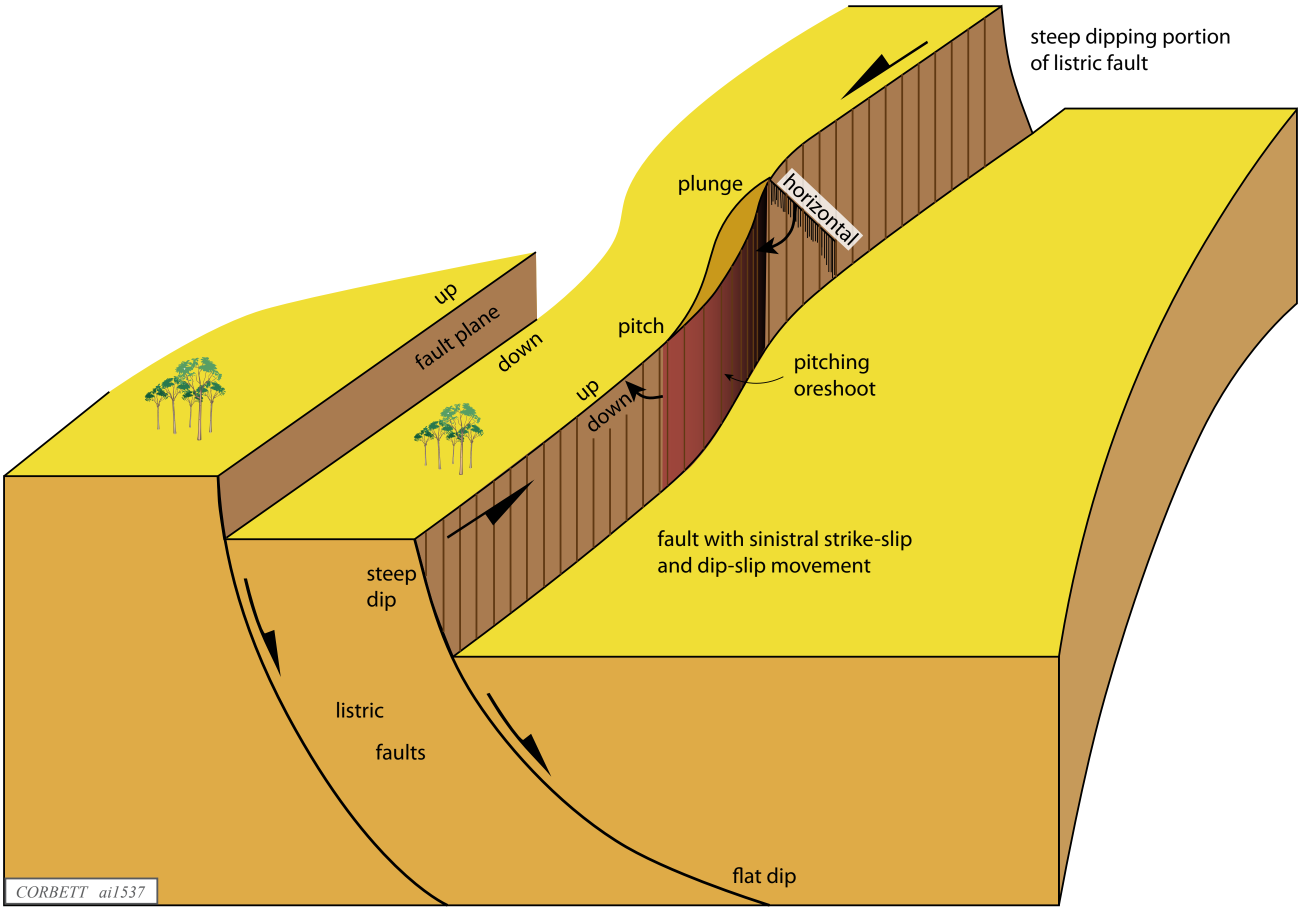
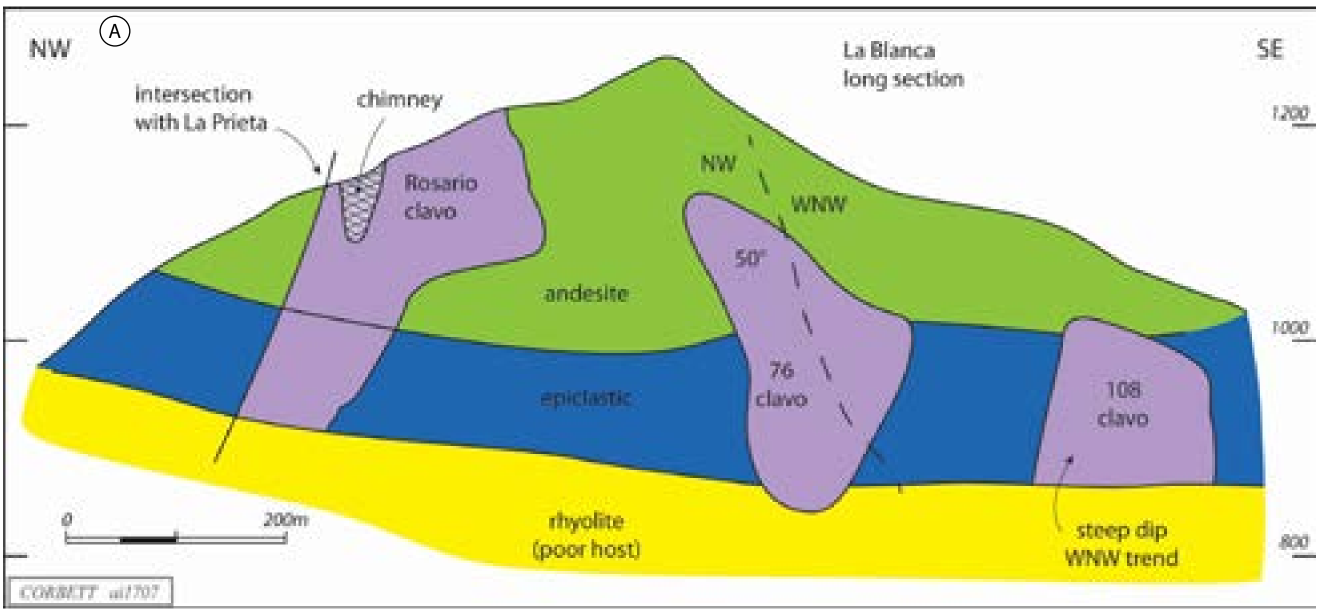
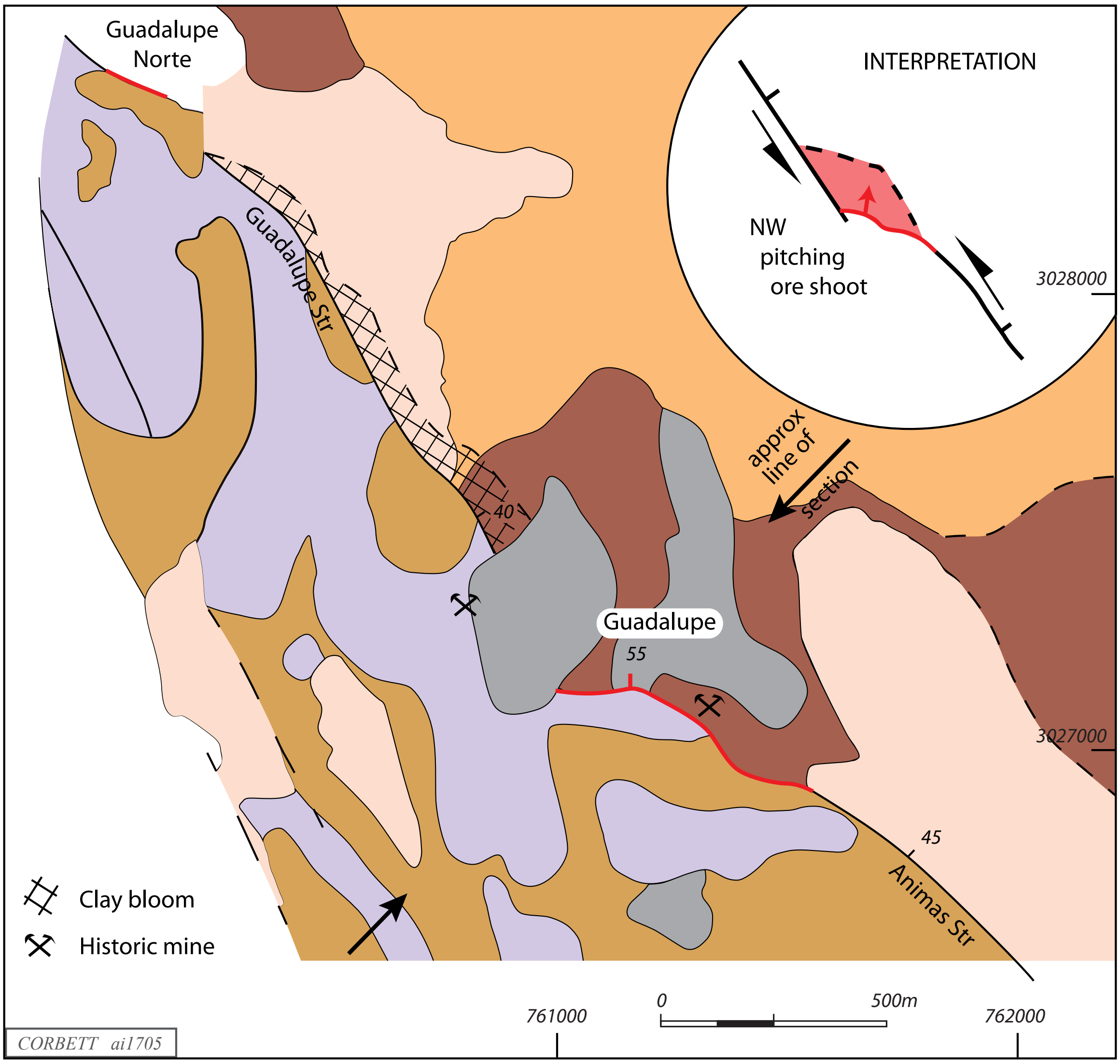


Figure 3.45 *The orientation of an ore shoot formed in the steep dipping portion of a listric fault by the combination of strike-slip and dip-slip movement showing the position of pitch and plunge.*



(B)



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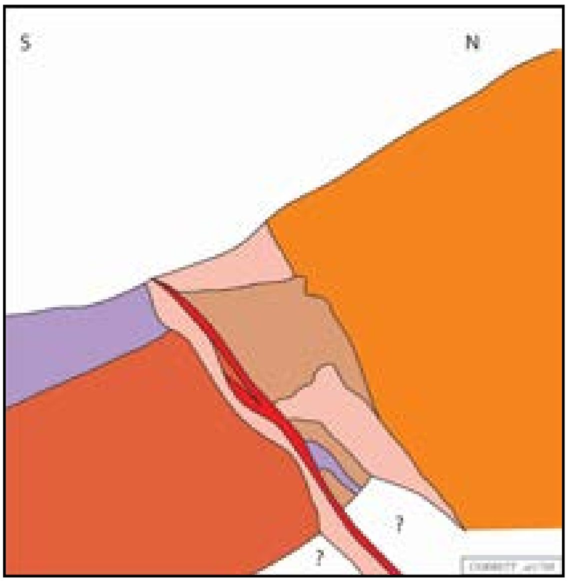


Figure 3.46 *Structural control to ore shoots at Palmarejo, Mexico including Guadalupe, see figure 3.10 D for map of Palmarejo and legend*
A - *Palmarejo long section showing ore shoots localised at a structural intersection (Rosario fault intersection) or 76 and 108 flexures, with competent andesite or silicified sandstone.*
B - *Geological map of the Guadalupe zone at Palmarejo showing the localisation of mineralisation within link structures.*
C - *Guadalupe cross section showing mineralisation and normal fault movement apparent from the offset of the bedded basalt.*

3.2.4.2 The Viento vein at the El Indio Mine, Chile, hosts pitching ore shoots within the host structure (Corbett, unpubl. reports, 2000; Heberlein, 2008). Geological mapping sought to define the controls to shoot formation (figure 3.28) within the Viento Vein system, which parallels the more significant El Indio Veins. The NNE trending regional structures which localise the El Indio district lie within a regional scale link structure developed between the southern termination of a NS structure to the east with the northern termination of a NS structure to the west (figure 3.23), activated by an interpreted transient component of dextral movement on the regional NS structures. Underground mapping at the Viento vein demonstrated that each ore shoot is localised within a NE trending flexure in the NNE controlling structure localised at the intersection with NE cross-structures (figure 3.28). The pitching ore shoots are interpreted to have formed by a combination of dip-slip (down on the east) and dextral strike-slip movement supported by slickensides (figure 3.28). Mapping of the main El Indio veins by Stan Caddy (Jannas et al., 1999) had already demonstrated the El Indio mineralisation is developed within a sigmoidal loop formed by a component of dextral movement on the NNE link structures.

3.2.5 Collapse and flat dipping structures

In addition to compressional settings above (section 3.2.3.3), flat dipping ore shoots also form as a result of collapse and reactivation of bedding planes locally as bedding plane shears.

3.2.5.1 The Emperor gold mine, Fiji, is localised at the intersection between a Tavua collapse caldera margin and an EW regional structure which terminates as a set of NW trending dilatant splay faults within a fault jog environment. These dilatant splay faults display normal fault movement to facilitate subsidence of the bedded submarine basalts adjacent to the caldera as a series of blocks (figure 3.47). In this environment some bedding planes within bedded basalts have become dilated and host flatmake mineralised structures with variable shallow dips. This model (Corbett, unpubl. data) further suggests the steep dipping dilatant NW shears (e.g, Brewster, Prince of Wales and Crown) are have acted as mineralised feeder structures for the flat-dipping mineralised flatmakes.

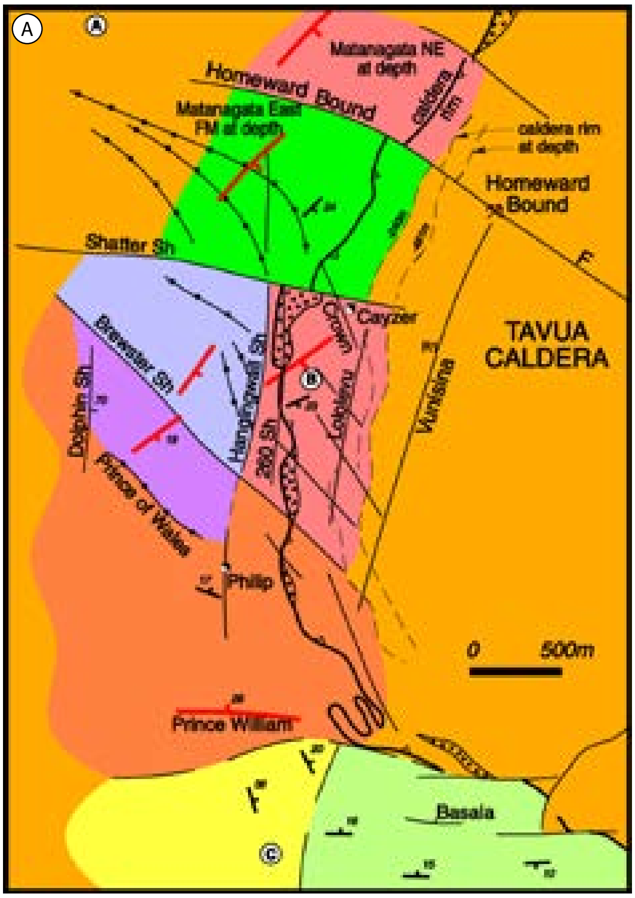
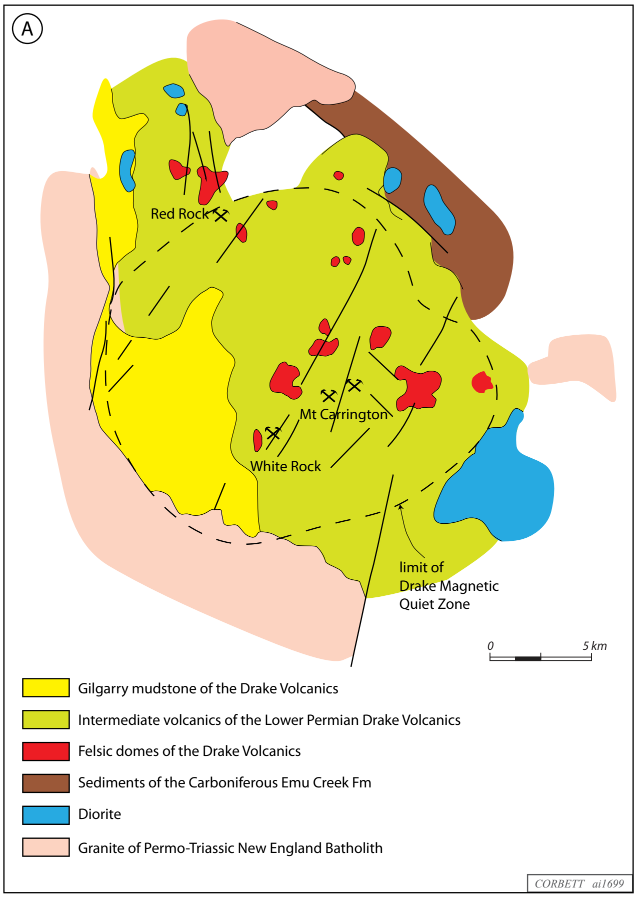


***Figure 3.47** Development of ore hosting flatmakes at the Emperor gold mine, Fiji.*
A - *Structure of the mine area with different colours to distinguish collapsed blocks within the wall rocks adjacent to the Tavua caldera and flatmakes shown in red.*
D - *Flatmake in the mine workings.*

3.2.5.2 In the Drake Volcanics of eastern Australia, geological mapping by Grace Cumming has defined a 20 km diameter collapse caldera with resurgent domes within an area of subdued magnetic response termed the Drake Quiet Zone (Cumming et al., 2013). Collapse associated with the caldera resulted in activation of bedding planes within the adjacent volcanic sequence to form bedding plane shears which host carbonate-base metal style Au-Ag lodes such as at the Red Rock Mine (figure 3.48). In some cases disseminated mineralisation grades away from the shears into permeable wall rocks. Normal fault movement on the shears during collapse facilitated the formation of intervening steep dipping tension gash veins which contain abundant quartz in addition to carbonate-base metal Au-Ag mineralisation (figure 3.48). The banded tension gash veins display sigmoid shapes, terminating in the shears which facilitated their formation and have commonly been intersected at low angles to the drill core axis (figure 3.34). High level felsic domes are interpreted to have been related to the magmatic source for mineralisation and host best Ag-Au grades.



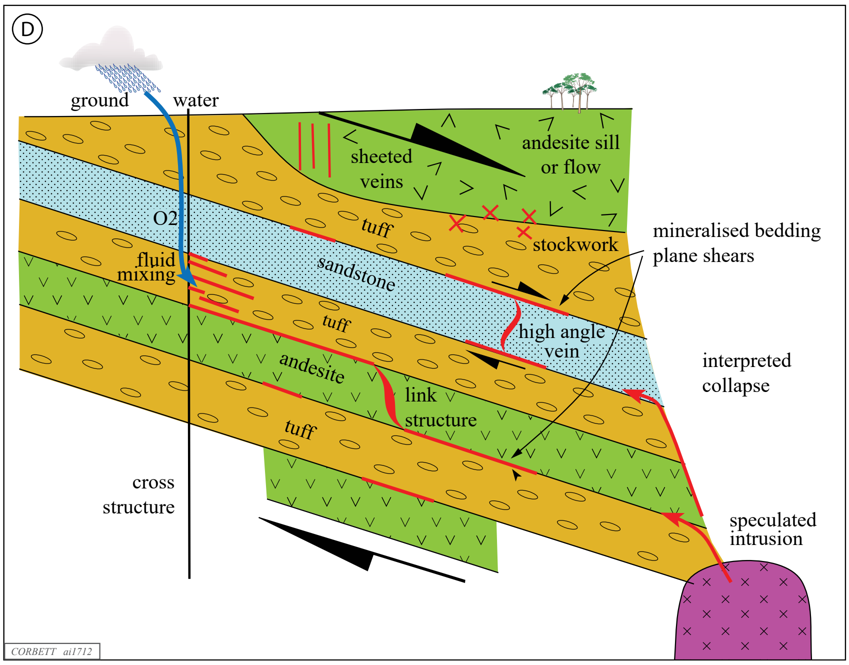


Figure 3.48 *Mineralised bedding plane shears at the Drake Caldera.*
A - *Caldera collapse structure with locally mineralised resurgent felsite domes, from Cumming unpubl reports and Cumming et al. (2013).*
B - *Red Rock mine showing mineralised bedding plane.*
C - *Mineralised bedding plane shear, Hampton workings, 5.1 g/t Au.*
D - Conceptual model for development of bedding plane shear and tension vein (figure 3.34) mineralisation, from Corbett, unpubl. report and Cumming et al. (2013).

3.2.5.3 At the Ladolam gold mine, Lihir Island, Papua New Guinea, described above (section 3.2.1.1), unroofing during seaward sector collapse of an andesitic stratovolcano provided a trigger for mineralisation, best developed within the listric faults which facilitated collapse of the volcanic edifice (figure 3.11). Sub-horizontal ore zones (Lienetz and Coastal) prospected early in the exploration history are now interpreted (Corbett, 2005b) to have been localised within flat dipping portions of listric faults, whereas better quality mineralisation was later identified in the sub-vertical Minifie structure developed as a steep-dipping portion of a listric fault close to the caldera boundary (figure 3.11).

3.2.5.4 Flat-moderate dipping bedding planes may be reactivated within folded rock sequences during compression within magmatic arcs and host stockwork vein mineralisation which extends into the wall rock (Kelian, Indonesia and Cowal, Australia, Corbett, pers. observ.).

3.3 STRUCTURES ASSOCIATED WITH PORPHYRY DEPOSITS

Porphyry stockwork and sheeted quartz-sulphide veins which host and locally transport most Cu-Au-Mo mineralisation represent the main structures associated with porphyry Cu-Au deposits, commonly developed within stocks or vertically attenuated spine-like intrusions, which overlie buried more major magmatic sources of metals and volatiles, and locally extend into the adjacent wall rocks (see section 5). The dilatant settings which localise porphyry intrusions influence vein orientations which are considered (Corbett and Leach, 1998) in order to:

- Understand the 3 dimensional form of the porphyry intrusion to guide drill tests and resource determinations.
- Develop exploration models to explore for porphyry intrusions in any district.

3.3.1 Some definitions

Stockwork veins comprise multi-directional vein arrays with either no preferred orientation, or with multiple directions derived from the intersection of conjugate, orthogonal or other vein orientations, either developed as one event or the result of multiple overprinting events, the latter locally related to repeated porphyry emplacement (figure 3. 49 A & B).

Sheeted veins form as arrays of parallel veins which reflect the stress conditions active at the time of vein development, and as dilatant features, facilitate the transport of ore fluids some distance from the magmatic source at depth to higher crustal levels where mineral deposition takes place either within intrusive stocks (figure 3.49 C) or wall rocks (figure 3.49 F). Sheeted veins may display a polyphasal character (figure 3.49 D).

Laminated veins host mineral (quartz, magnetite) bands separated by linear zones of weakness which may be reactivated and host later sulphides, locally apparent as crack-seal textures (figure 3.49 E).

Wallrock porphyry Cu-Au deposits host metals within the wall rocks away from any obvious intrusion source and are typically characterised by dilatant sheeted vein arrays which have facilitated metal transport (figures 3.16, 3.49 E & F). Most porphyry deposits feature some continuation of mineralisation from intrusions into the adjacent wall rocks.

Isotropic wall rocks or intrusions exhibit no preferred grain as a control to vein formation, whereas anisotropic wall rocks may contain a cleavage or volcanic/sedimentary layering as a control to fracture/vein formation. In some volcanic sequences only the competent lavas host wallrock porphyry veins, while incompetent intervening lapilli tuffs and breccias do not fracture to facilitate vein formation, especially if these permeable rocks become clay altered. Breccia pipe environments are commonly associated with concentric veins (below).

Stress characteristics which control porphyry emplacement are provided by the analyses of vein directions, assuming the two are relatively coeval, as orthogonal compression-extension or oblique convergence, while vein directions are also influenced by the crustal level in the porphyry system under consideration and host rock characteristics (Heinrich and Titley, 1982; Titley, 1990; Corbett and Leach, 1998).

Concentric structures such as ring dykes, sheeted cone fractures, or veins, may develop as circular arrays of fractures within the wall rocks overlying the outside of a buried intrusion or breccia pipe. These fracture patterns are interpreted (Phillips 1973, 1974) to have developed in response to the upward force of retrograde boiling and may be enhanced by collapse following evacuation of volatiles from the top of a magma chamber (section 4.4.4.1). Mineralised concentric, locally sheeted fracture-veins are well developed in breccia pipes with interpreted significant components of collapse (section 4.4.4.6), and locally kink around pipe margins (Kidston, Australia; figure 4.17).

Radial veins and lodes are common within wall rocks outboard of the upward projection of source intrusions in settings of dominantly upward intrusion emplacement without significant collapse (figure 3.51 & 3.52; Cargo, Eastern Australia; San Juan, Safford District, Arizona, Heidrick and Titley, 1982).

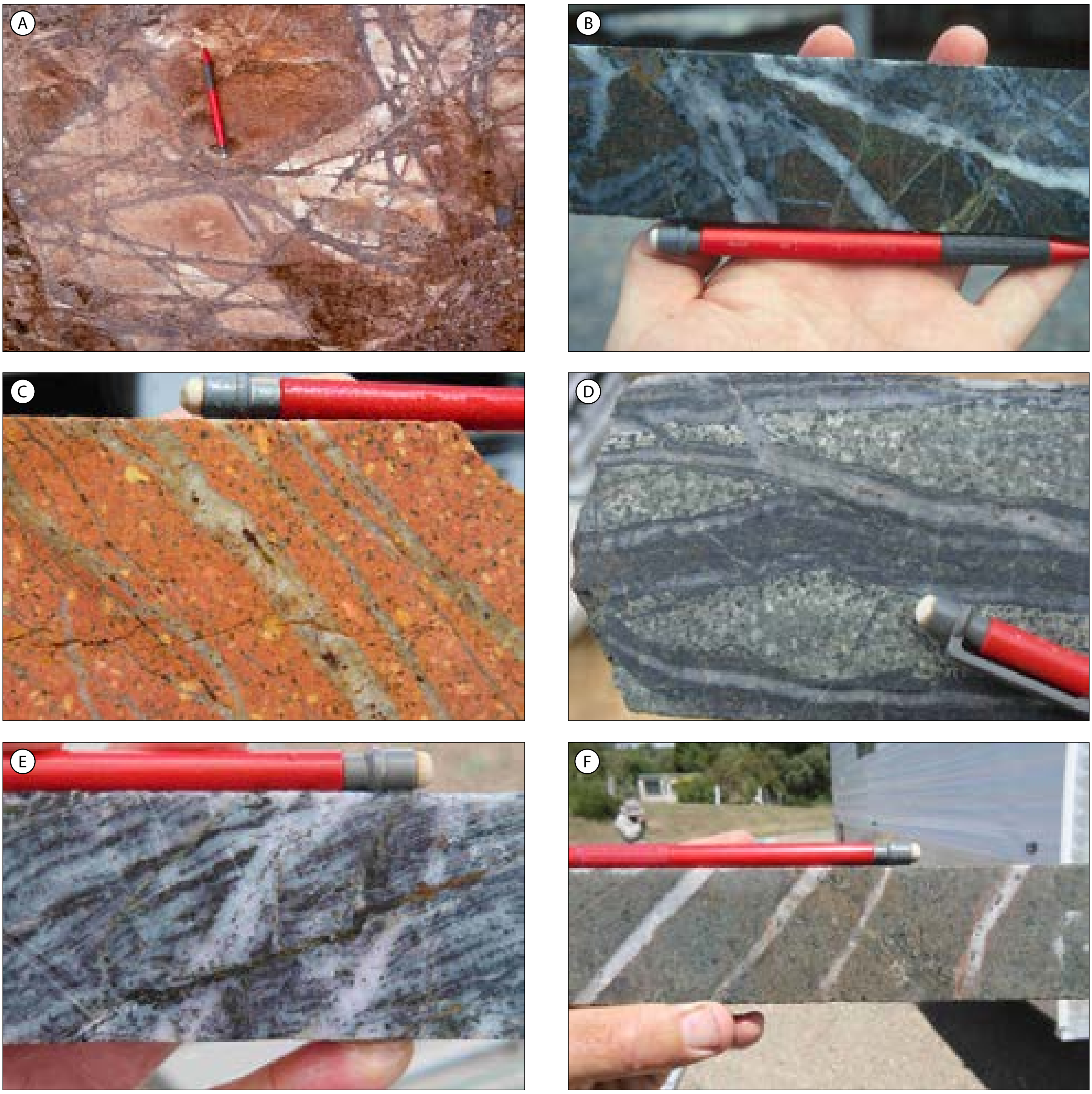


Figure 3.49 *Porphyry quartz-sulphide vein styles.*
A - *Multi-directional stockwork quartz veins derived from one event, La Granja, Peru.*
B - *Multi-directional stockwork quartz veins derived from 4 vein events associated with multiple intrusion emplacement, Ridgeway, Australia.*
C - *Sheeted porphyry AB veins, Goonumbla, Australia.*
D - *Sheeted porphyry M cut by B veins, Namosi, Fiji.*
E - *Laminated quartz-magnetite vein with bornite on the crack partings and cut by a B and then later C which exploit to re-opened crack-seal partings, discussed in section 5, Ridgeway, Australia.*
F - *Sheeted wallrock porphyry A veins within volcaniclastic host rocks, Cadia East, Australia.*

3.3.2 Porphyry vein formation

Porphyry vein orientation are influenced by a number of factors which vary according to:

- Mainly the stress pattern active at the time of quartz vein formation, typically at failure of an overpressurised carapace. These patterns might be distinguished as:
    - Vertical (and no doubt some lateral) compression stress.
    - Localised collapse.
    - Orthogonal extension.
    - Transpression.
- Time as the stress patterns vary, especially as triggers for mineralisation.
- Crustal level from within or above an intrusion.
- Host rock competency.

The **evolution of mineralised porphyry veins** is interpreted to include a paragenetic sequence of events characterised as:

3.3.2.1 Initial emplacement of a stock or spine-like intrusive body of molten magma results in the development of a chilled margin to the inward cooling intrusion and formation of adjacent hornfels developed as contact metamorphosed wall rocks, which together combine to act as a seal to constrain volatiles within the intrusion carapace (figure 3.50 A).

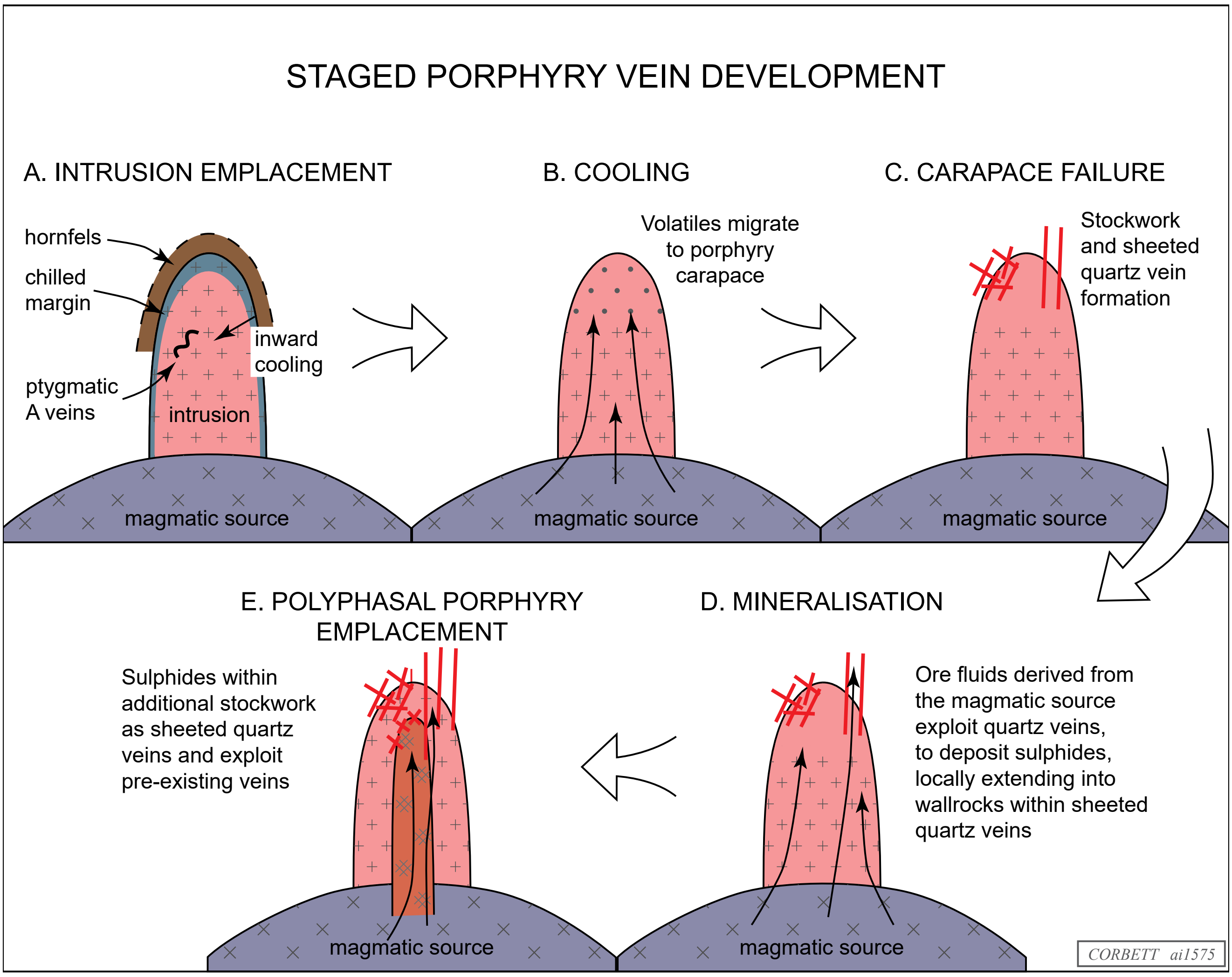


Figure 3.50 *Stages in the development of mineralised porphyry quartz veins discussed herein.*

3.3.2.2 Cooling of the molten spine-like intrusion features separation of the solid and volatile components as hot pressurised fluids (water and gases) rise and gather towards the carapace of the vertically attenuated intrusion. The sealed carapace traps the rising fluids from not only the spine-like intrusion, but also derived from the cooling magmatic source at depth, causing the uppermost portion of the intrusion to become over-pressurised (figure 3.50 B). The magma source at depth and possibly the core of the intrusion have not solidified at this stage.

3.3.2.3 Failure of the over pressurised carapace is described in the model of retrograde boiling (Phillips, 1973), to take place when the volatile fluid pressure exceeds the lithostatic (confining) pressure and tensile strength of the confining rock. However, more recent field studies (Corbett and Leach, 1998) suggest external structural processes may also initiate failure of the carapace. The regional structure which has localised a porphyry intrusion might be expected to feature repeated movement and so crack the brittle over pressurised carapace. Failure of the carapace results in a dramatic drop in fluid pressure which promotes quartz deposition (figure 3.50 C) developed as veins fill fractures locally dilated by the stress regime active at that time. Pressure exerts the prime control to silica solubility (Corbett and Leach, 1998). Thus, vein orientations may be used to estimate the stress prevailing at the time of carapace failure, essentially porphyry emplacement. It is also possible to estimate the sense of movement on any controlling major structure during vein development.

3.3.2.4 Cu-Au mineral deposition no doubt began with initial depressurisation and quartz vein formation as early linear A veins host sulphide mineralisation (section 5.2.4.1). However, Corbett and Leach (1998) point out much of the Cu-Au mineralisation in many porphyry deposits has been introduced following initial quartz vein formation, at a lower temperature. Textures in the discussion of porphyry mineralisation herein (sections 5.2.4 & 5.2.5) illustrate the common parallelism of quartz and sulphide veins as the latter exploit central vein terminations (B veins), or laminations within banded quartz-magnetite (M veins), as an indication that the same stress regime responsible for quartz vein development has been active to facilitate later sulphide introduction (figures 5.16, 5.19 & 5.20), although sulphide (as C veins) may also cross-cut quartz veins (figures 5.21 & 5.22). A significant proportion of the later sulphides are derived from the progressively cooling magma source at depth and utilised the dilatant structures, originally exploited by quartz, to rise to higher crustal levels of ore deposition (figure 3.50 D). The laminated nature of many barren (figure 5.15) and mineralised M veins (figure 5.16) supports repeated activation of the same dilatant structural setting to promote quartz, magnetite and later sulphide deposition. The later variable sulphide introduction provides an explanation for the presence of barren quartz-magnetite (M) veins particularly in the cores of some porphyry intusions (section 5.2.4.2).

Most economic porphyry Cu-Au deposits are characterised by the presence of many individual porphyry intrusions, each with several overprinting vein styles which may introduce additional mineralisation along with overprinting hydrothermal alteration (sections 5.2.4 & 5.2.5).

In summary, several stages in the development of quartz-sulphide porphyry veins feature quartz deposition in response to pressure drop upon failure of an over pressurised intrusion carapace and evolution of ore fluids from a magmatic source at depth using the same dilatant fracture system. Earlier dilatant quartz veins may be reactivated and exploited by later sulphide mineralisation which may either parallel earlier events, or fracture and cross-cut pre-existing brittle quartz veins, including as C veins (figure 3.50 E).

The **exploration implication** is that this process of repeated porphyry emplacement and mineralisation may upgrade a sub-economic single-event porphyry deposits to form an economic ore systems.

3.3.3 Porphyry vein orientations

Porphyry vein orientations are controlled by several factors dominated by the stress regime active at the time of carapace failure and quartz vein formation, which generally also facilitated sulphide introduction. Several variations in stress regime and hence vein configuration recognised in porphyry deposits (figure 3.51) include:

3.3.3.1 Forceful upward intrusion emplacement without other stresses or host rock anisotropy, in which a pronounced vertical σ_1, results in the development of radial fractures (Phillips, 1974) grading from the intrusion into the adjacent and overlying wall rocks. These fractures which may be exploited by porphyry style quartz-sulphide veins as recognised at San Juan, Arizona or thicker D vein style lodes such as at Cargo, eastern Australia (figures 3.51 A & 3.52).

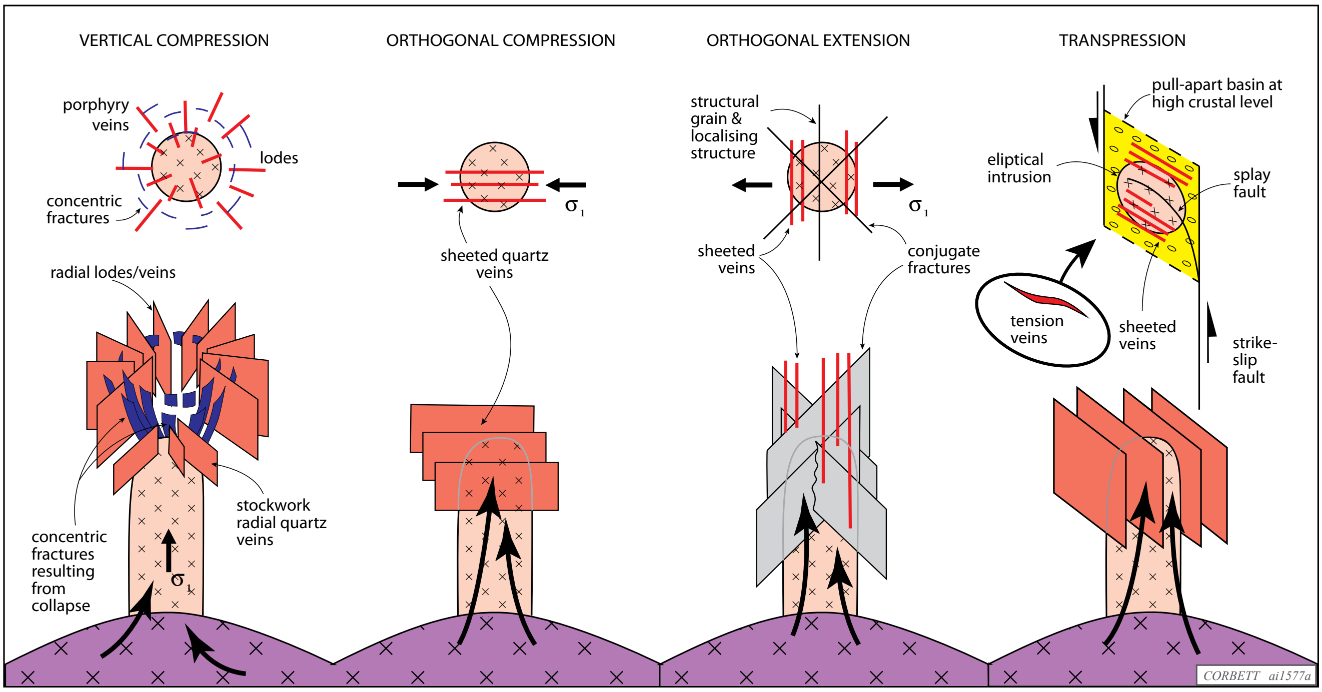


__Figure 3.51__ Different quartz vein configurations formed in varying structural settings. The sheeted veins in the transpressional setting may rise above the porphyry environment to form wallrock porphyry deposits.

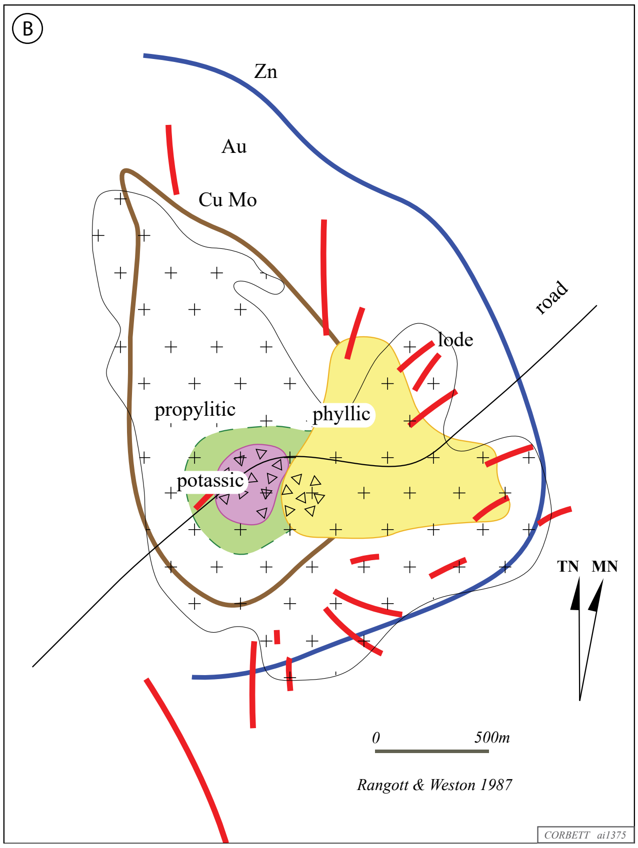


***Figure 3.52** Fracture/veins overlying forcefully vertically emplaced intrusions.*
A - *Radial and concentric fractures formed marginal to the upper portions of a porphyry intrusion, at San Juan, Arizona (from Heidrick and Titley, 1982).*
B - *Lodes which radiate from a breccia at the Cargo prospect, eastern Australia (from Rangott and Weston, 1987 unpublished).*
C - *Radial fractures at the Cargo porphyry prospect which contain sulphide lodes and later andesite dykes.*

3.3.3.1.1 A component of collapse, most commonly recognised in association with breccia pipes, and also many intrusions, follows intrusion emplacement and degassing. Caldera ring dyke complexes develop following collapse of some major magma sources such as the Permo-Carboniferous Lochaber and Bagstow Ring Dyke Complexes south of Kidston in NE Australia (Branch, 1966). Concentric quartz veins rim porphyry intrusions such as at San Juan, Arizona (figure 3.52), here forming a stockwork with the intersecting radial fractures, or kink as straight segments around the margins of breccia pipes such as at Kidston (figure 4.16).

3.3.3.2 Oblique convergence (transpression) provides a common control to porphyry mineralisation in settings where a component of strike-slip movement on throughgoing structures has localised the porphyry intrusion, typically within splay faults, while mineralisation is hosted within dilatant structures varying from lodes to sheeted porphyry veins, which parallel the splay faults (figure 3.51 D).

The Chuquicamata porphyry deposit, Chile, is localised by intersection of NE-trending splay faults, and the NS-trending Falla Oeste (West Fault) of the Domeyko Fault System, such that porphyry veins, sericite alteration and Mo distribution form roughly NE trending horsetail arrays (Lindsay, 1997; Lindsay et al., 1995). At Didipio, Philippines, NW trending sheeted veins within the spine-like Dinkidi porphyry developed in response to sinistral movement on the NS controlling structures, governed by the regional sinistral transpression, apparent on the Philippine and associated faults (figure 3.53; Corbett unpubl. report, 1995 in Garrett, 1996).

There is an **exploration implication** that the dilatant sheeted veins are interpreted to not only host sulphide mineralisation, but to have participated in the bleeding of ore fluids from the magmatic source at depth, to a higher crustal level where mineral deposition occurs in cooler conditions. Consequently, parallel sets of overprinting sheeted veins may host elevated metal grades, discernible as high grade Au in bornite-bearing M veins (figure 3.49 D) and must be tested with correctly oriented bore holes. The activation of sheeted veins is discussed further in the context of triggers for mineralisation, below.

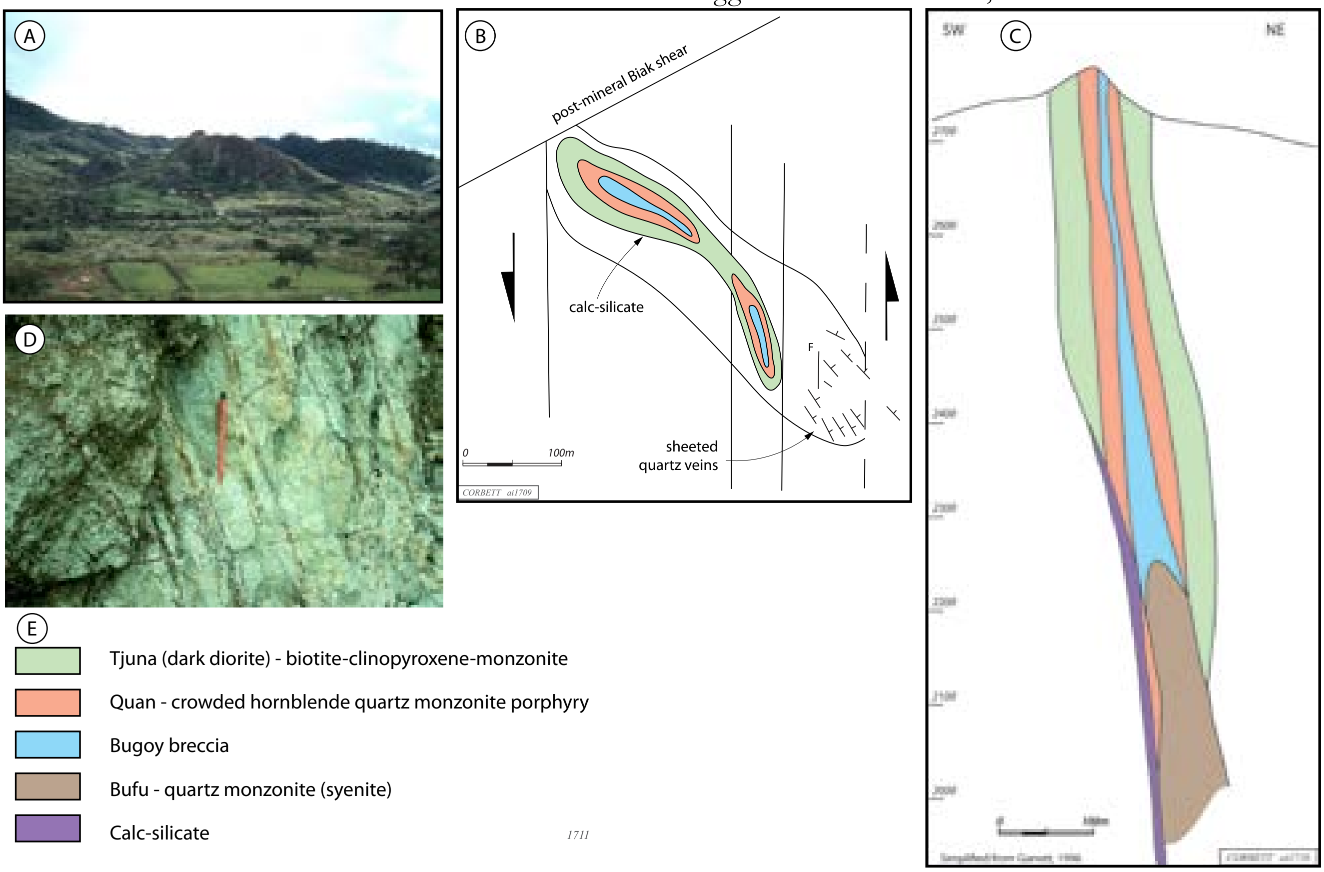


Figure 3.53 *Sheeted veins developed by oblique convergence, Dinkidi, Philippines.*
A - *The Dinkidi intrusion at Didipio, Philippines also shown as part of a wider angle view in figure 2.27 E which includes the marginal barren shoulders of alteration.*
B - *Plan view of the Dinkidi intrusion and NS faults which, by a component of strike-slip movement, facilitated the development of tensional sheeted veins.*
C - *Spine-like polyphasal porphyry intrusion, redrawn from Garrett (1996).*
D - *Sheeted quartz veins in outcrop.*
E - *Legend*

3.3.3.1 The Browns Creek skarn is localised by the NS structural grain of the district which defines the contact between the Carcoar Granodiorite and a limestone (metamorphosed to marble) unit within the Blayney Volcanics (section 6.2.4). While some (post-mineral) fault slices of Au-Cu skarn trend NS, most Au production was from a set of NW trending en echelon skarn bodies constrained between the NS faults (figure 6.17). Highest Au grades, locally greater than 100 g/t Au are associated with the wollastonite-bornite dominant skarn, while Au grades with a 15 g/t head grade were mined where NW trending sheeted quartz veins transect the skarn. The model proposed (Corbett, unpubl. report, 1997) suggested sinistral strike-slip movement on the NS structural grain provided the dilatant structural environment for skarn and higher Au grade sheeted quartz vein development (figure 3.54). A component of post-mineral dextral fault movement has dismembered some skarns as fault slices.

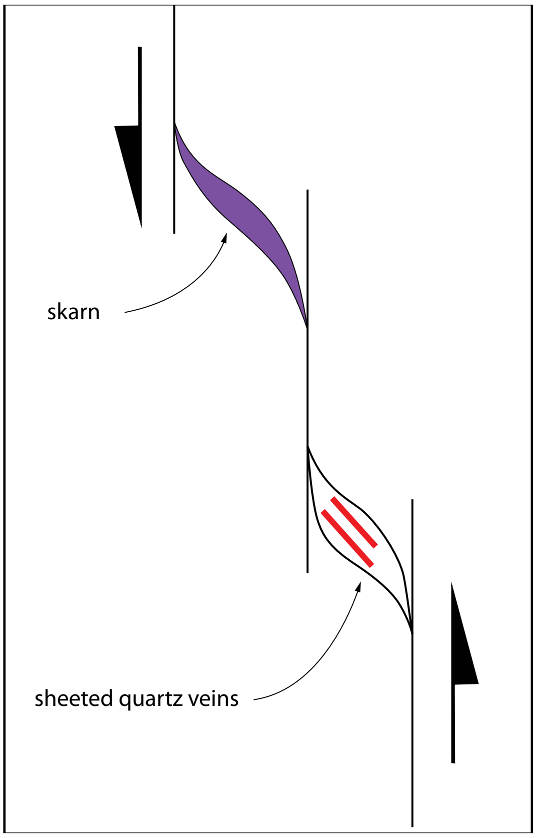


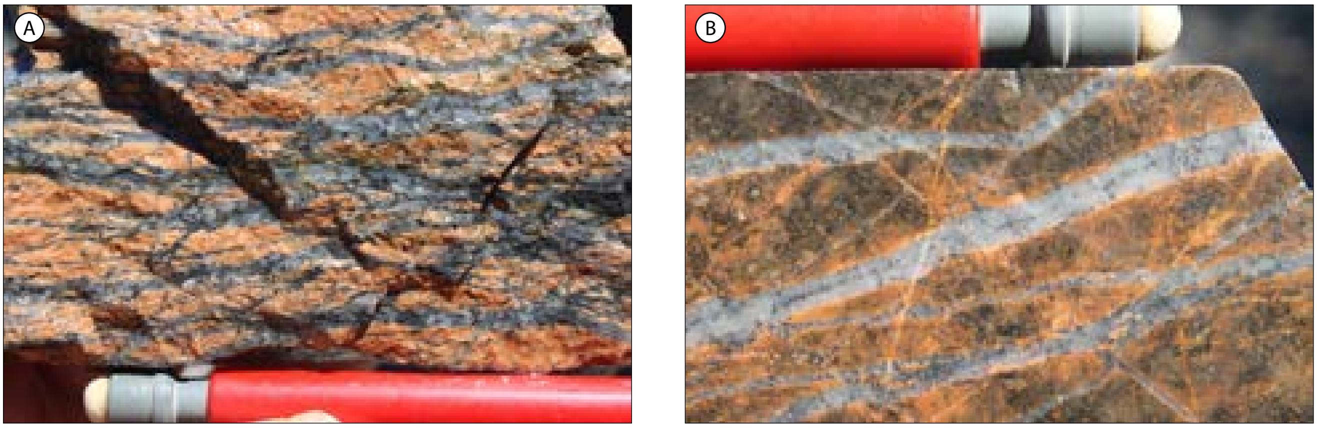
Figure 3.54 *Structural control to the Browns Creek Au skarn using data in figure 6.17.*

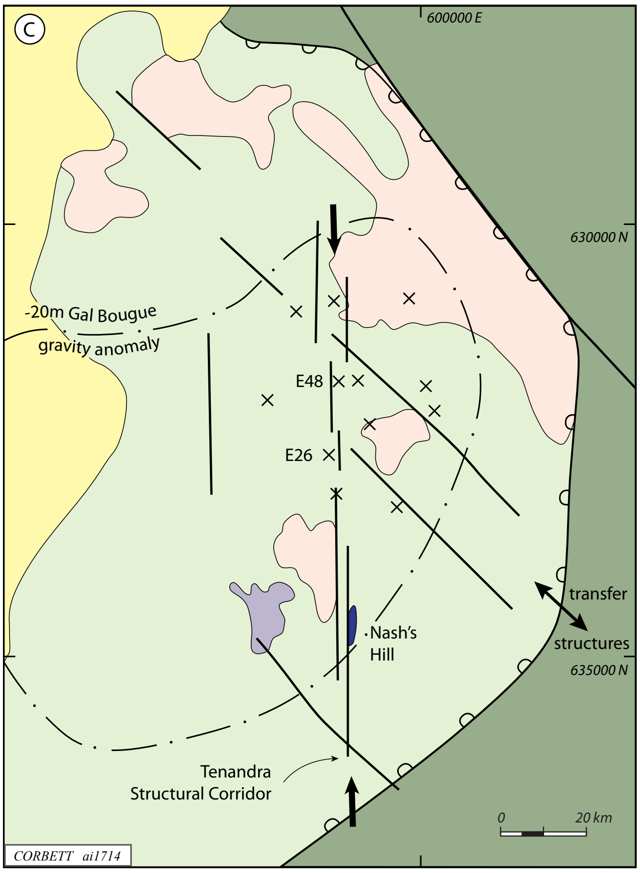
3.3.3.3 Orthogonal extension

may provide for the development of both sheeted (figure 3.51; Goonumbla, Eastern Australia), or stockwork quartz veins, the latter formed either by the exploitation of pre-existing conjugate fractures (Batu Hijau, Indonesia, figure **), intersections of a principle fracture direction and an orthogonal set (Golpu, Papua New Guinea, figure 5.14), or other vein configurations.

3.3.3.3.1 In the Goonumbla district, eastern Australia (figure 3.55 A), strongly vertically attenuated spine-like quartz monzonite porphyry intrusions are linked to a batholitic larger magmatic source of equigranular quartz biotite monzonite at depth (Heithersay et al., 1990) although it contains xenoliths of earlier and deeper diorite. Several of these intrusions and the Nash's Hill barren shoulder of advanced argillic alteration are aligned along the NNW-NS trending Tenandra structural corridor which locally forms a shoulder-like batholith margin (Corbett and Leach unpubl. report, 1995). Sheeted quartz veins from the E26 porphyry (figure 3.55 B) occur as a 340° set which overprints 240° and 290° conjugate veins (Harris and Holcombe, 2014). Similarly, the E48 ore body on the same structure is dominated by roughly NS trending sheeted quartz-sulphide veins (figure 3.55 C). A major contributor to the development of the Goonumbla ore systems has been the reactivation of high temperature sheeted quartz veins formed in the 600-800° C range as dilatant brittle fractures for the later transport of cooler ore fluids in the 200-400° C range, from the magmatic source at depth into the spine-like intrusions (Corbett and Leach, unpubl. report, 1995). The bornite-rich ore is Au rich and is locally enhanced in the presence of sericite overprint on potassic alteration, including quartz-albite.

Metal grades of the Au-rich bornite ore is locally enhanced in the presence of sericite overprint on potassic alteration, including quartz-albite (see also Owens et al., in press; Quigley et al., 2017). The consistent NS sheeted quartz vein orientation is interpreted to result from the trigger for vein development, and mineralisation, provided by EW extension on the regional NS structural grain derived from transient relaxation of subduction-related EW compression.





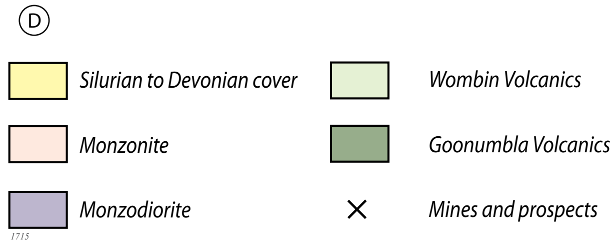


Figure 3.55 *Sheeted quartz vein formation at the Goonumbla district, Eastern Australia.*
A - *Sheeted quartz veins from the E26 porphyry in hand specimen.*
B - *Sheeted quartz veins showing bornite mineralisation from E48 porphyry.*
C - *Geological setting of the E 26 and E48 porphyry systems, from Owens et al., in press; and Corbett and Leach, unpubl. report, 1995.*
D - *Legend*

3.3.3.4 Orthogonal compression, may promote the formation of veins parallel to the direction of principle stress (figure 3.51).

3.3.3.4.1 The Cadia Valley, Eastern Australia, includes the Cadia Hill and Cadia East wallrock porphyry sheeted veins and the Ridgeway vertically attenuated spine-like porphyry, each with sheeted and laminated veins aligned along the WNW trend of the arc-normal Lachlan Transverse Zone (Wilson et al., 2007 and references therein). A prominent magnetic anomaly is associated with the elongation of the interpreted buried magmatic source for mineralisation (Newcrest Mining Staff, 1996), along with magnetite skarn deposits. Only Ridgeway displays overprinting intrusion and vein relationships to form local stockwork veins where the NW veins

Figure 3.56 *Cadia East wallrock porphyry.*
A - *Sheeted A type quartz veins with auriferous pyrite and Mo and K-feldspar alteration selvages.*
B - *Down-drop on veins-hosting fractures within the wall rock.*

overprint minor radial veins (figure 3.51). However, the vertically attenuated nature of the sheeted veins at the wallrock porphyry deposits, to well over 1000m at Cadia East (Wilson et al., 2007), is indicative of a strongly dilatant structural setting which hosts Au-Mo wallrock porphyry mineralisation (figure 3.56) Some structural elements of the Lachlan Transverse Zone at Ridgeway and Cadia East represent early growth faults reactivated to host lodes and quartz vein packages, similar to that recognised in pull-apart basin scenarios (figure 3.17), with down-drop indicative of extension normal to the Lachlan Transverse structures.

3.3.3.4.2 Thrust fault control is not as common in porphyry-epithermal deposits as would be expected in compressional magmatic arcs (above). Packages of shallow dipping quartz veins are locally recognised within dilatant flatter dipping portions of moderate dipping thrust faults (figure 3.57 A). Typical economic porphyry deposits develop as a result of the migration of ore fluids from the magmatic source at depth to the mineralised intrusion apophysis, best in association with steep dipping dilatant sheeted veins. Consequently, thrust controlled porphyry mineralisation will be limited by the quality of any connection between the magmatic source and setting of the sheeted quartz veins. Shallow dipping sheeted veins may also form by decompression of batholitic magma bodies during uplift and erosion (figure 3.57 D & E, Rawbelle, Eastern Australia, Corbett et al., 2009).

***Figure 3.57** Flat dipping porphyry quartz veins.*
***A** - Thrust-hosted alteration zone, Ortiga, Argentina.*
***B** - Flat dipping thrust with alteration and quartz veins, Hinoba-an, Philippines.*
***C** - Flat dipping sheeted veins from B above.*
***D** - Flat dipping batholith-hosted fracture/veins in outcrop, Rawbelle, eastern Australia, from Corbett et al., 2009.*
***E** - Flat dipping batholith-hosted fractures with alteration selvages drill core from D above.*

3.4 TRIGGERS FOR MINERALISATION

Triggers initiate the rapid and forceful emplacement of intrusions and fluids responsible for vein and breccia mineralisation which were formerly constrained within fertile magma source rocks at depth during compression, and these dynamic events contribute towards the development of elevated metal grades (Corbett and Leach, 1998). The formation of quality mineralisation might therefore be promoted by changes in the geological environment such as:

- Rapid depressurisation as:
    - Sector collapse of volcanic edifices.
    - Thrust erosion.
    - Rapid uplift and erosion of the magmatic arc.
- Transient changes in the nature of convergence
    - From orthogonal compression to components of oblique deformation.
    - Relaxation of orthogonal convergence, typically manifest as a change from compression to extension.

Tectonic triggers may also responsible for changes in the nature of magmatism, including from intermediate to felsic magmatism, commonly synchronous with the onset of epithermal mineralisation (Coromandel Peninsula, New Zealand; Japan; Far Eastern Russia), locally overprinting deeper level epithermal (Porgera, Papua New Guinea) on porphyry intrusions (Bilimoia, Papua New Guinea). However, an age gap is likely in other instances where porphyry and epithermal alteration and mineralisation are recognised at the same exploration projects (Woodlark Is. and Misima Is., Papua New Guinea).

3.4.1 Rapid depressurisation

3.4.1.1 Sector collapse such as that recognised as the 1980 Mt St Helens failure of a portion of a volcanic edifice (figure 3.11) may provide sufficient unroofing to depressurise the rising high level magma and promote an explosive volcanic eruption as well as brecciation and degassing of a buried magma source at greater depth. At the Ladolam ore body, Lihir Is., Papua New Guinea, the Luise volcanic edifice, established over the last 1 m.y. of the 3 m.y. period of island building, underwent seaward sector collapse at about 100,000 years ago (Wallace et al., 1983). The youthful trace of the collapsed detritus derived from the volcanic edifice failure is easily recognised within Luise Harbor on the offshore seismic data on (figure 3.11). Similar listric faults to those which participated in the Mt St Helens sector collapse have been identified in drill ore and open pit exposures at the Ladolam Gold Mine (Corbett et al., 2001; Corbett, 2005b). The listric faults at Ladolam slid along the anhydrite matrix brecciated at the top of a monzonite porphyry intrusion to facilitate rapid unroofing and then these same structures hosted later epithermal mineralisation (figure 3.11), best developed in the steeper-dipping portions of the listric faults portions (section 3.2.1.1). Consequently, at Ladolam, while porphyry intrusions were emplaced during volcanism, sector collapse triggered the change from subeconomic porphyry to economic epithermal Au mineralisation derived from the deeper magmatic source.

3.4.1.2 Thrust erosion has been proposed to account for distribution and timing of Au mineralisation at Porgera and Mt Kare, Papua New Guinea (Corbett, 2005b). The Waruwari open pit carbonate-base metal Au mineralisation is closely associated with augite hornblende diorite intrusions of the Porgera Intrusion Complex formed at a deep crustal level and characterised by dark Fe-rich high temperature sphalerite and local pyrrhotite at the Jez Lode (figure 3.12; section 7.2.1.24.1; Corbett et al., 1995 and references therein). The overprinting epithermal quartz Au style quartz-gold-roscoelite bonanza grade Au mineralisation is best developed within Porgera Zone VII of the Romane Fault and was mainly mined underground, although it extends into Waruwari open pit. It formed at a low temperature and shallow crustal level and is associated with post-carbonate-base metal mineralisation felsite intrusions (figure 3.12; Corbett et al., 1995; Corbett and Leach, 1998). Although there must be at least 600 m vertical distance between the crustal level of formation of the two intrusion and mineralisation events, they are dated at roughly the same age (Ronacher et al., 2002) and much the same age as the similar Mt Kare mineralisation, at about 6.0 m.y. (Richards and Ledlie, 1993). Mt Kare is located about 17 km from Porgera down plunge in the direction of thrust movement in the fold-thrust deformation of the Papua New Guinea Highlands (figure 3.58 A). While Au mineralisation at Mt Kare is of a similar carbonate-base metal Au and quartz-Au-roscoelite style as Porgera and hosted within essentially similar Chim Formation sediments, there are fewer intrusions and the ore zones are less distinct. Detailed drilling at Mt Kare (figure 3.58 E) demonstrated mineralisation bottomed in a flat lying fault (Corbett, unpubl. reports 1996-7; Corbett, 2005b) which separates the upper mineralised sequence from a lower very incompetent unaltered brown shale. Thrust erosion is speculated (Corbett, 2005b) to have removed a substantial body of rock (at least 600 m vertically) from above the active Porgera system to initiate a change from mafic to felsic magmatism and deep to shallow epithermal Au mineralisation, and the

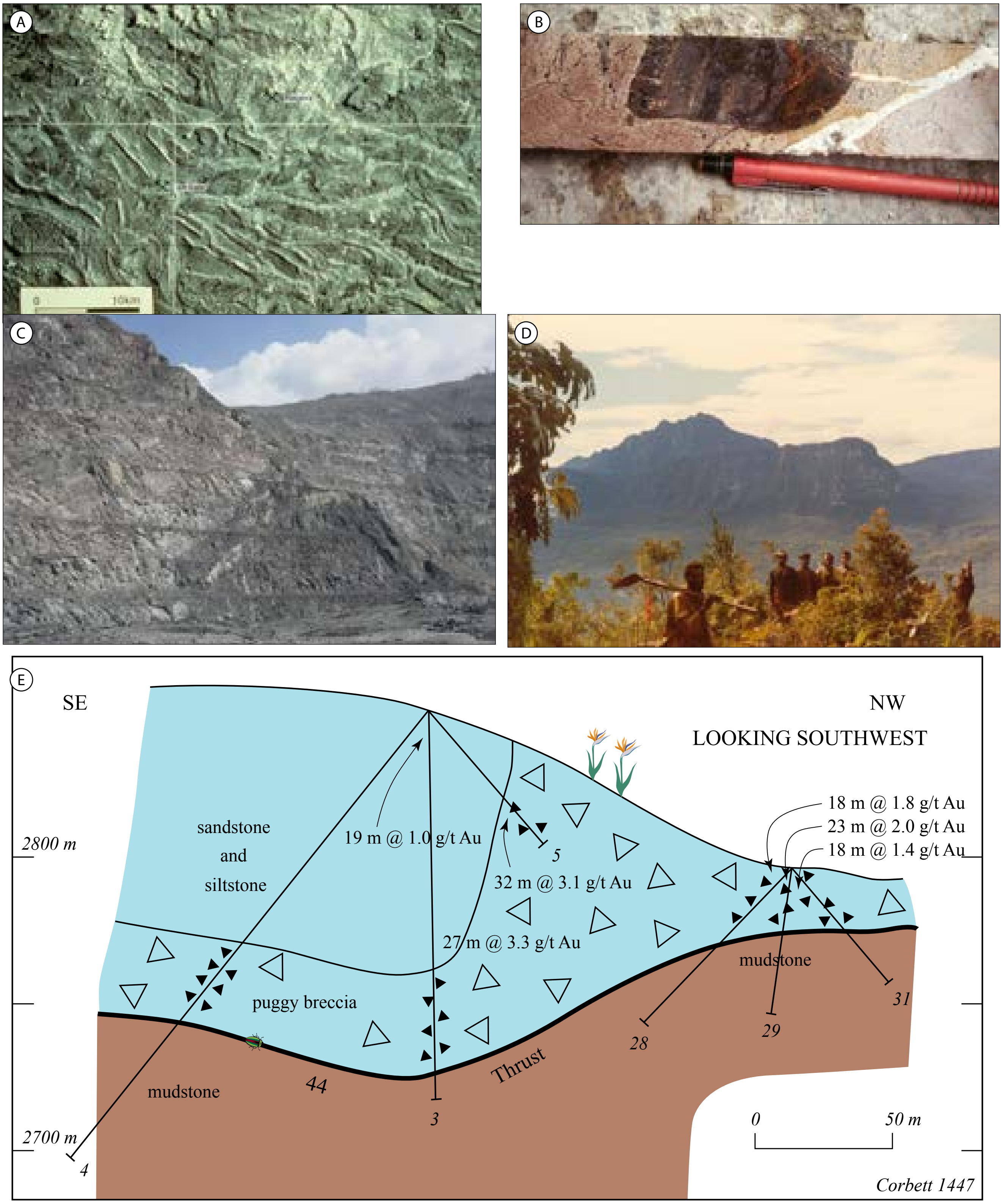


Figure 3.58. Thrust erosion of the top of speculated to now occur as Mt Kare.
A - *Slide looking Radar image shows Porgera within a coincident topographic and magnetic circular interpreted (Corbett et al., 1995) to reflect a buried intrusion source for the outcropping stocks at Waruawri (figure 3.13).*
B - *Felsite dyke with clast of an earlier carbonate-base metal vein.*
C - *Thrust in the Waruwari open pit.*
D - *Double thickness of Dari Limestone at Mts. Paim and Kajende, from Waruwari, 1980.*
E - *Mt Kare cross-section.*
F - *Coarse grained augite hornblende diorite from a stock within in the early Waruwari open pit mine.*

thrust-off top of Porgera occurs down-plunge at Mt Kare. The Dari Limestone which overlies the Chim Formation caps the eastern portion of Mt Kare but is absent from Porgera, although a thrusted double thickness of limestone crops out a few km south of Porgera at Mt Paim and Mt Kajende (figure 3.58 D) and between Porgera and Mt Kare.

3.4.1.3 Rapid uplift and erosion may unroof a magma source in order to promote intrusion emplacement locally capped by magmatic hydrothermal breccias. Skewes and co-workers suggest in Central Chile in the late Miocene, major porphyry-related breccia events resulted from late stage rapid uplift and erosion due to the flattening of the subduction angle (Skewes and Stern, 1994; Skewes et al., 2003).

The Ok Tedi Porphyry Cu-Au in Papua New Guinea is interpreted (above) to have been emplaced in conditions of rapid uplift and erosion (section 5.1.7), in a terrain characterised by substantial lateral (65 mm/y) and vertical movement at a collisional plate boundary (figure 3.4). The spatially dominant intrusions, Sydney monzodiorite and Fubian monzonite porphyries are of 2.6 and 1.1-1.2 Ma respectively in age, with the latter forming the main host to mineralisation (Page, 1975; Rush and Seegers, 1990), yet this porphyry is well exposed by erosion. Assuming a depth of emplacement of 1-2 km to the top of the porphyry now exposed by erosion, then even the wet tropics rate of 1-2 km per million years or 1 m per 1,000 years represents a high rate of erosion. Rather, is assumed many porphyry intrusions are emplaced into settings of rapid uplift and erosion. Similarly, elsewhere in Papua New Guinea younger epithermal deposits occur in proximity to porphyry intrusions (Bilimoia, Woodlark Is., Misima Is.) in response to rapid uplift and erosion.

The Copper Hill, Cu-Au porphyry deposit in Eastern Australia (Hayward et al. (2015) interpret progressive syn-mineral uplift and erosion accounts for overprinting events of mineralisation and alteration emplaced at progressively shallower crustal levels as: NW trending low grade Cu-Au mineral associated with tonalite intrusion, followed by EW trending laminated and sheeted quartz veins associated with microdiorite intrusion, higher crustal level carbonate-base metal Au mineralisation typically within the same EW trending veins, overprinted by late stage low temperature laumontite + gypsum veins.

3.4.2 Transient changes in the nature of convergence

As suggested above, vein kinematics provide an indication of the tectonic conditions under which porphyry and epithermal deposits were formed and so are commonly consistent with regional scale trends. In the Philippines many NW veins or breccia are constrained between NS sinistral strike-slip structures related to sinistral movement on the Philippine Fault (Lepanto & Dinkidi in Luzon or others in Mindanao). Similarly, NE trending epithermal veins in the Coromandel Peninsular, New Zealand are associated with country-scale dextral oblique plate movement, well developed at Thames (figure 3.20) and Waihi (figure 3.31).

By contrast, elsewhere analyses of ore deposit veins suggests many deposits formed in kinematic conditions contrary to the expected regional kinematics active in that region at that time and these discrepancies may be consistent for many ore deposits throughout districts across geological time. Consequently, working in the SW Pacific rim Corbett and Leach (1998) proposed a model that transient, and locally multiple, changes from orthogonal to oblique convergence, active for only a brief period of time, facilitated the development of dilatant structural sites in which ore formation took place, but as only brief events that are not readily apparent in other aspects of the geological record. The change in the nature of convergence has provided a trigger for magma and ore fluids constrained at depth in conditions of orthogonal convergence to be forcefully emplaced into the dilatant structural sites. Intrusions may include polyphasal spine-like porphyry bodies. Importantly, this model has the potential to resolve the space problem associated with the emplacement of porphyry intrusions within compressional magmatic arcs. The forceful emplacement contributes towards the development of porphyritic textures and rapid cooling of ore fluids to promote the development of elevated metal grades. The link zones developed within cross-structures as individual dilatant sites, locally present as negative flower structures (figure 3.17) grading vertically from surficial pull-apart basins downwards to fissure fractures (which host epithermal veins) and splay faults (which localise porphyry intrusions). Repeated fault activation and multiple fluid flow forms banded epithermal veins.

In <u>conclusion</u>, transient changes in the nature of convergence provide triggers to facilitate the rapid emplacement of magma and ore fluids within dilatant structural sites, to high crustal levels where rapid cooling promotes metal deposition. This model developed in the SW Pacific rim (Corbett and Leach, 1998) has since been found to apply to ore formation in other magmatic arcs.

3.4.2.1 Transient changes from orthogonal to oblique compression

The activation of conjugate-like cross structures provides dilatant sites which host ore during transient changes in convergence commonly recognised as changes from orthogonal compression to oblique convergence (Corbett and Leach, 1998; Corbett, 2012). Many ore systems appear to be localised by the intersection of a cross structure with major structural corridors such as arc-parallel sutures or terrain boundaries. For instance, the La Escondida porphyry Cu appears to be localised within the Domeyko Fault System by the intersection of a NW conjugate fracture (figures 3.2 & 3.37) and the Kelian epithermal Au deposit lies at the intersection of a Kalimantan Suture and a NS structure, which facilitated formation of a pull-apart basin (figure 3.24). Intersections of NS cross structures with the Lachlan Transverse Zone no doubt also play a role in the localisation of the individual Cadia Valley porphyry-related deposits.

A model proposed (Corbett and Leach, 1998) to account for the general NW trend of many ore systems constrained between structures of the NS structural grain in the Lachlan Orogen of eastern Australia, utilised a transient change from orthogonal to sinistral oblique compression (figure 3.59). In many cases the major structures may also represent arc-parallel terrain boundaries or sutures, locally present at corridors of individual structural elements such as fractures, faults or shears, with a reverse sense of movement during orthogonal compression. It is possible, in response to orthogonal compression, for a major arc-parallel structure to be offset by the cross-structures which then form link zones between segments of the major structure, or elements of a structural corridor, apparent at perturbations in throughgoing fractures (figure 3.59 A & B). Later transient changes to sinistral oblique convergence may reactivate the major structure or structural elements with a strike-slip sense of movement (figure 3.59 C). Correctly oriented perturbations may act as link zones to facilitate the transfer of strike-slip movement between elements of the structural corridor and become dilated in that process (figure 3.579C; section 3.2.2). Dilatant sites such as these represent

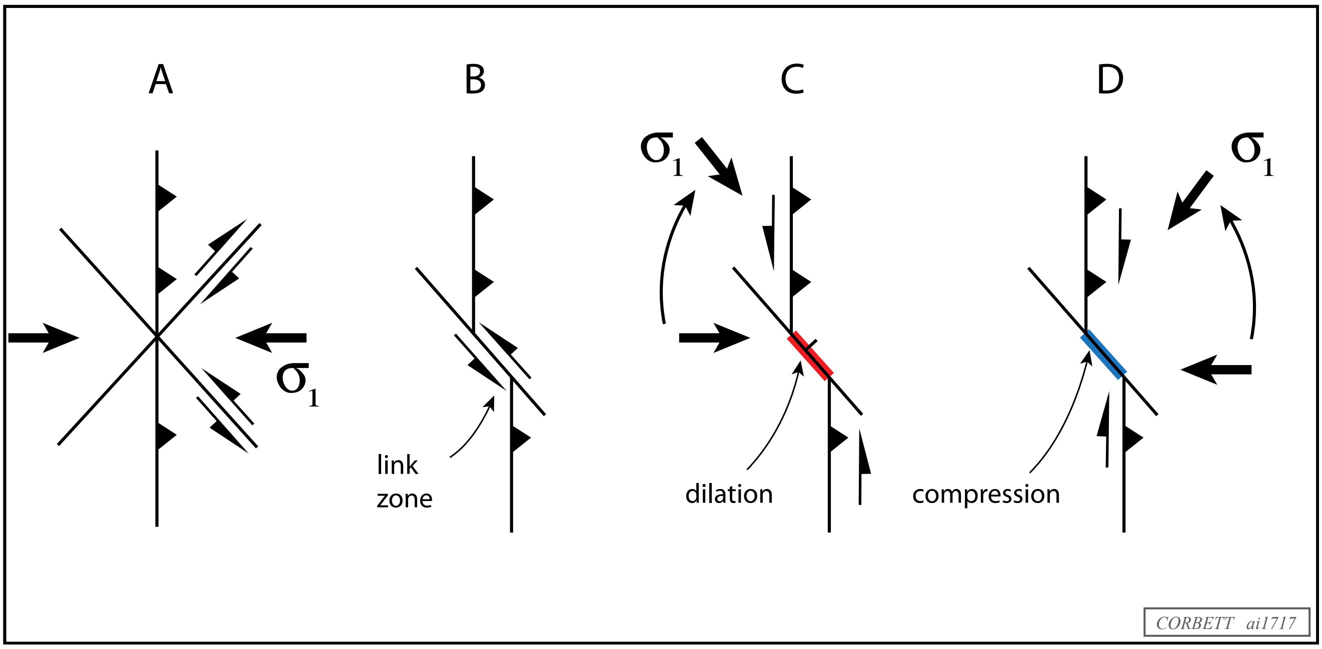


Figure 3.59 *Formation of dilatant ore-hosting sites by the activation of cross structures during transient changes in the nature of convergence.*

A – *Typical structural scenario characterised by a major structure, here an arc-parallel terrain boundary with a reverse sense of movement, and conjugate-style cross structures in conditions of arc subduction-related compression.*

B – *Offset of the major structure by cross fracture and development of a link zone during compression.*

C – *Transient change to oblique convergence, here suitably oriented to facilitate reactivation of the former reverse faults and strike-slip structures and development of a dilatant site in the link zone suitable of hosting porphyry or vein emplacement.*

D – *Non-suitably oriented convergence results in the development of anti-dilatant sites which might be manifest as folds, domes or thrusts with lesser potential to host mineralisation than C.*

common settings for the forceful emplacement of porphyry intrusions and development of structurally controlled epithermal veins. Alternatively, other link structures, including those developed by relaxation of convergence, may be oriented in a anti-dilatant or compressional orientations as sites of dome or thrust fault formation (figure 3.59 D), the latter only locally associated associated with lesser ore formation (section 3.2.3.3).

3.4.2.1.1 In the Lachlan Orogen, Eastern Australia many ore systems (figure 3.3) were interpreted (Corbett and Leach, 1998) to have formed in conditions of sinistral movement on the roughly NS structural grain of the district (Mineral Hill, Sofala, Cowal, the entire Cobar district in the data of Glen, 1987; Browns Creek, skarn-sheeted veins; all the deposits along the Gilmore suture such as Gidgingung, Adelong; West Wyalong, etc). This sinistral sense of movement continues north in the Lachlan Origin of Queensland (Gympie goldfield; Corbett and Leach, 1998 and elsewhere in that region) and is also recognised as alternating events in Triassic sedimentary basins (Babaahmadi et al., 2015). Most reconstructions suggest the arc displayed an overall orthogonal character in the Ordovician (Glen, 2013 and references therein; pers commum, 2013), although potential for sinistral convergence is included in the recent model of Cayley (2015). Nevertheless, the difficultly of any estimates for the conditions of formation of such old and subsequently deformed arcs cannot be overlooked. The transient change from orthogonal compression to sinistral transpression was provided as the trigger for the onset of mineralisation, repeatedly active over geological time (Corbett and Leach, 1998).

3.4.2.1.2 In Chile, dextral movement on the Domeyko Fault system (figure 3.2), evidenced by the splay fault and parallel veins is interpreted to account for development of the Chuquicamata porphyry and also localisation of the giant La Escondida porphyry within a link structure between individual fault elements (figures 3.36 & 3.37). As the Domeyko Fault system is widely regarded as a terrain boundary with a reverse sense of movement, transient dextral sense of movement may have provided a trigger to initiate porphyry emplacement and mineralisation. Furthermore, the El Peñon low sulphidation epithermal deposit and La Coipa and El Indio high sulphidation epithermal deposits (figure 3.23) are also to have developed in response to episodes of dextral transpression on the NS structural grain of the district. Thus in Chile, repeated changes from orthogonal compression, to dextral transpression, are interpreted herein to have provided triggers for porphyry and epithermal ore formation. The West Fault (Falla Oeste) formed as part of the Domeyko Fault System, displays complex movement over time and space, as some workers (Dilles et al., 1997; Tomlinson and Blanco, 1997) record sinistral sense of movement at Chuquicamata and El Abra, although ore bodies such as MM are unlikely to be faulted off portions of Chuquicamata.

More on this topic to come.