



Geometry, kinematics and regional significance of faulting and related lamprophyric intrusion in the mineralised zone at the Pu Sam Cap complex, Northwest Vietnam

Findlay R.H.

VietOz Minerals Pty Ltd, 141b Gordons Hill Road, Lindisfarne, Tasmania, Australia 7015

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ABSTRACT

The alkali volcanics and intrusive rocks, dated at around 35-33Ma, are cut by mineralised northeast and east trending faults showing predominant evidence for strike slip. Mineralisation includes haematite-Au-Cu and is accompanied by iron-rich alteration of the volcanic rocks. Detailed assessment of the geometry of the fault system at Pu Sam Cap suggests that the faults formed as a Riedel shear system during left-lateral slip within the Song Hong-Song Chay shear zone and the numerous contemporaneous northwest trending faults to the south; the northeast trending faults are interpreted as dextral “book-end” faults between major northwest trending faults enclosing the Pu Sam Cap massif. As mineralisation is hosted within these faults and is also associated with lamprophyric dykes it confirms a thermal event younger than the alkaline volcanics and syenitic intrusives at Pu Sam Cap, suggesting a hidden, young porphyry system. The age of faulting, and thus the maximum age for this young intrusive event, is attributed to the 23-21Ma period of late-stage left-lateral strike-slip motion across northwest Vietnam.

Keywords: Mineralisation; lamprophyric dykes; syenitic intrusives; strike-slip fault.

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1. Introduction

Northern Vietnam lies across the modern plate boundary zone, the Song Hong-Song Chay Shear Zone (Figure 1) and related faults to the south, between the South China craton and the Indochina block. This shear zone extends into China where it is known as the Ailao Shan-Red River Shear Zone and across which there has been between 300km and possibly 700km left-lateral strike-slip displacement (Tapponier et al.1990; Leloup et al. 1995) that spanned the period 35-5Ma (Scharer et al., 1994; Zhang and Scharer 1996; Leloup et al., 2001; Giley et al., 2003;

Searle 2006) and which may continue today, as indicated by seismic studies across this region (Khuong The Hung, 2010).

Since the work of Tapponier et al. (1990) and Leloup et al. (1995), studies in northern Vietnam and westwards into Yunnan and Tibet have continued to focus on this structure (Figure 1, Figure 2) to the near-complete exclusion of the other related structures mapped previously elsewhere by staff of the Vietnamese Geological Survey (Findlay and Trinh 1997, Lepvrier et al., 1997), which indicate that much of Vietnam north of Da Nang (Figure 1) is broad plate-boundary zone of distributed strain involving numerous faults comparable to those along the western sea-

*Corresponding author, Email: rhfindlay44@gmail.com

board of the USA, in New Zealand and in Papua New Guinea.



Figure 1. SR Viet Nam and location of Pu Sam Cap

Such broader, regional considerations are important not only for understanding processes along strike-slip plate boundaries but are very important in respect both of geohazards and the minerals economy, the latter often depending on faults controlling sites of high-grade epithermal and mesothermal mineralisation related ultimately to interactions at plate boundaries. This paper therefore presents new data discussing the kinematics and timing of faulting from mined fault zones in the artisanal mining areas of Pu Sam Cap (Figure 3, 4, 5) an alkaline volcanic/intrusive complex that south of the Song Hong-Song Chay Shear Zone has been held under an exploration licence since 2005 by Triple Plate Junction Ltd (TPJ). The paper also forms a contribution to previous palaeostress studies in northern Vietnam.

The present study formed part of a consultancy to TPJ, and was carried out with assis-

tance from the company's staff, in particular geologists Messrs M Farmer, Do Quang Huy and Nguyen Tam.

2. Geological setting

Figures 2, 3, 4 and 5 show the Pu Sam Cap area in its regional setting within a major sinistral shear belt cutting all pre-Oligocene rocks in northern Vietnam. Although the major locus of strain is that between the Song Chay and Song Hong (Red River) Faults (Figure 1), the region south of this high-strain zone is heavily faulted by northwest trending faults related to the shear zone bounded by the Song Chay and Song Hong Faults. Modern seismic data confirm that this broad region remains dominated by sinistral strike-slip motion (Khuong The Hung 2010).

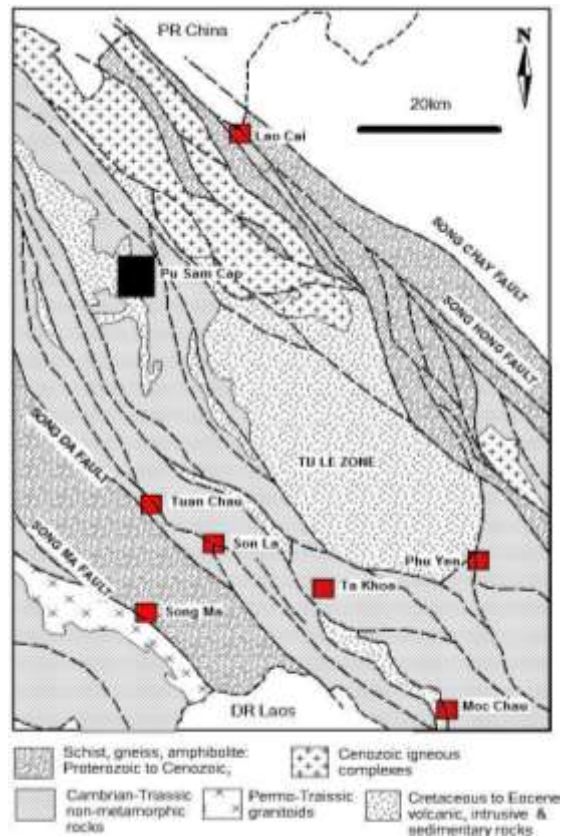


Figure 2. Regional geology, simplified, of northwestern Vietnam to show study area and Song Hong-Song Chay Shear Zone. Derived from Vietnamese Geological Survey 1:250 000 geological maps and LANDSAT imagery

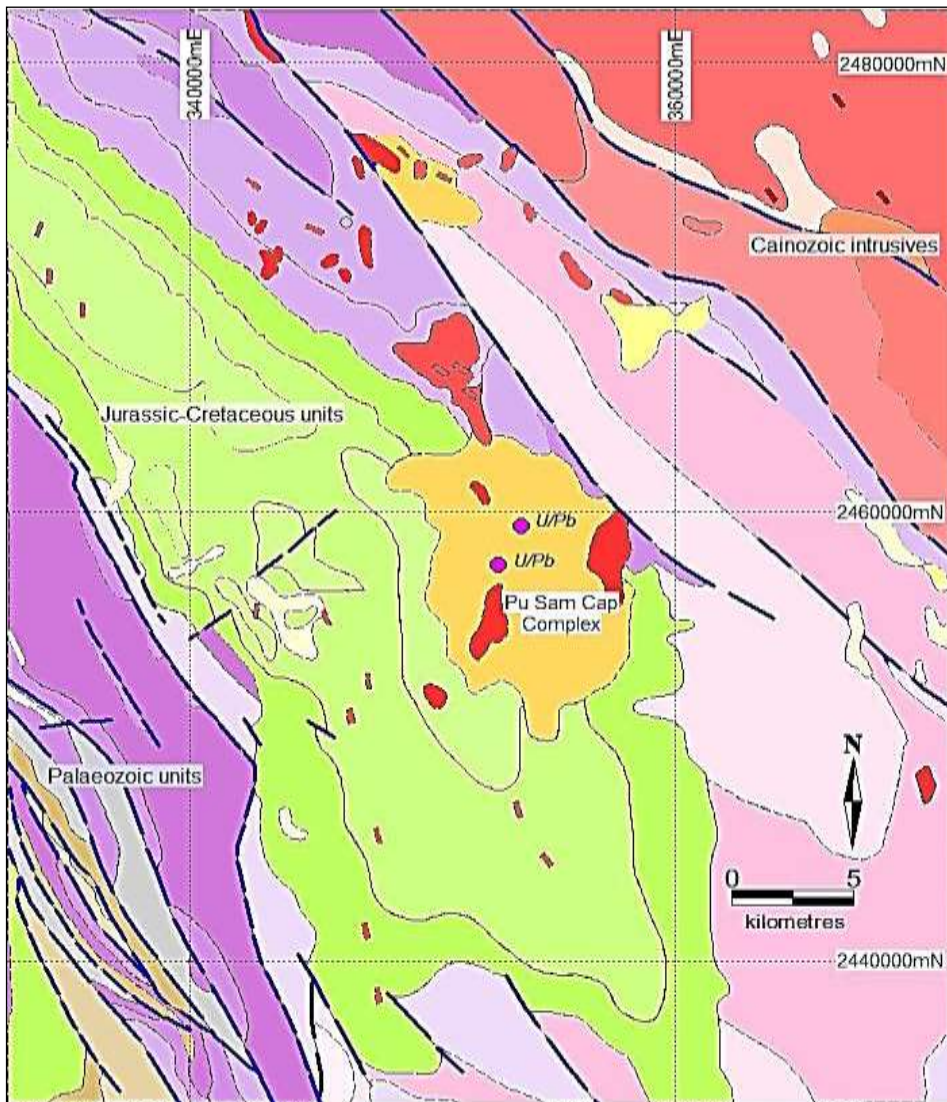


Figure 3. Regional geology, Pu Sam Cap. Locations for U/Pb zircon ages (Nguyen Thi Bich Thuy 2016) are shown as magenta-coloured solid circles. Geology from 1:250 000 Vietnamese Geological Survey maps

The Pu Sam Cap Complex forms a large, mountainous, alkaline intrusive and extrusive system which has been dated at 35Ma through U/Pb zircon dating by Nguyen Thi Bich Thuy (2016). It lies southwest of the alkali granites of the Eocene Phan Xi Pan massif and on the western side of the northwest-trending Tu Le alkali volcanic zone, and constitutes a complex of alkaline volcanic and intrusive rocks which forms part of a 30-40Ma

(Chung et al., 1997; Searle 2006; Nguyen Thi Bich Thuy 2016) alkaline intrusive-extrusive system extending from Vietnam through Yunnan to Tibet.

The volcanic rocks overlie unconformably and are also faulted against Cretaceous redbeds (siltstones, sandstones and conglomerates) and the unconformably underlying Palaeozoic units, which had been deformed during the Indosinian Orogeny. Findlay and

Trinh (1997) has demonstrated that 80km to the southeast, in the Song Da tectonic zone, the deformed pre-Indosinian units overthrust the Cretaceous red-bed series to form part of a complex Tertiary fold-thrust system, and that

this deformation, together with widespread strike-slip faulting, is likely to have been related to that which occurred during the major sinistral strike-slip displacement across the Song Hong-Song Chay Shear Zone.

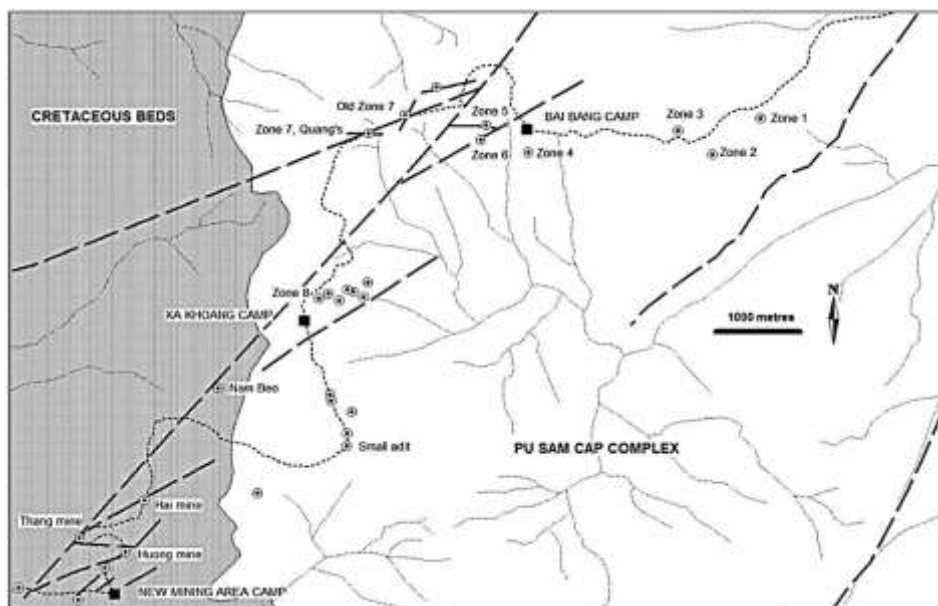


Figure 4. Study area showing mined areas (circle with dot in centre), mapped faults (heavy broken lines), tracks (dotted lines), drainage (very fine dotted lines) and camps

The study area lies within the west-central part of the Pu Sam Cap Complex and extends over an area of some 77sq km, bounded to the east and west by regional-scale faulting (Figures 2 and 3). It is an area where numerous local artisanal miners have excavated narrow adits along mineralised faults and whose diggings for gold have provided access to many of the structures studied. The mineralisation consists of a haematite-specularite-copper sulphides-galena-gold-silver vein carbonate assemblage hosted in an alkaline volcanic-intrusive system including syenitic intrusives and lamprophyric/lamproitic dykes. According to TPJ's geologists, mineralisation may have been multiphase, but in the artisanal mines visited there is a clear spatial association between specularite and the mined gold.

The Geological Survey of Vietnam has carried 1:50,000 mapping across the complex and has studied the mineralisation and alteration. The Geological Survey's work demonstrated extensive argillic alteration hosting much of the mineralisation including gold (see also Khuong The Hung, 2010), and also identified a number of eastnortheast-trending zones of mineralisation as long as 1.5km crossed by northwest-trending zones that may be related to late faulting. Most artisanal workings occur in a 4km by 1.5km zone following the mapped alteration. This study confirms that the artisanal workings are controlled by dominantly strike-slip faults following northeast, eastnortheast and easterly trends.

As recognised by staff of TPJ the majority of the volcanic rocks in the study area consist

of massive alkaline volcanic breccias intruded by small stocks of syenite and syenite porphyry, which were intruded in two phases. A third phase of intrusion produced lamprophyre dykes, some of which are associated intimately with Au mineralisation. In the south-central part of the complex, a broad zone of iron-rich alteration extends some 5 kilometres to the eastnortheast with a width in excess of 1kilometre. Most of the known mineralisation occurs within this zone. In this zone, east-northeast to northeast-trending faults traverse

the complex and control both alteration and mineralisation.

The study area (Figure 4) and adjacent areas show unequivocal evidence for young, rapid uplift. The valleys are commonly deeply incised and show relics of older erosion levels perched on ridges; the hillsides are over-steepened, indicating no equilibrium between uplift and erosion rates; and in the Phan Xi Pan area, mountain slopes rise abruptly and approach the vertical. These general considerations confirm very rapid, young, regional uplift.

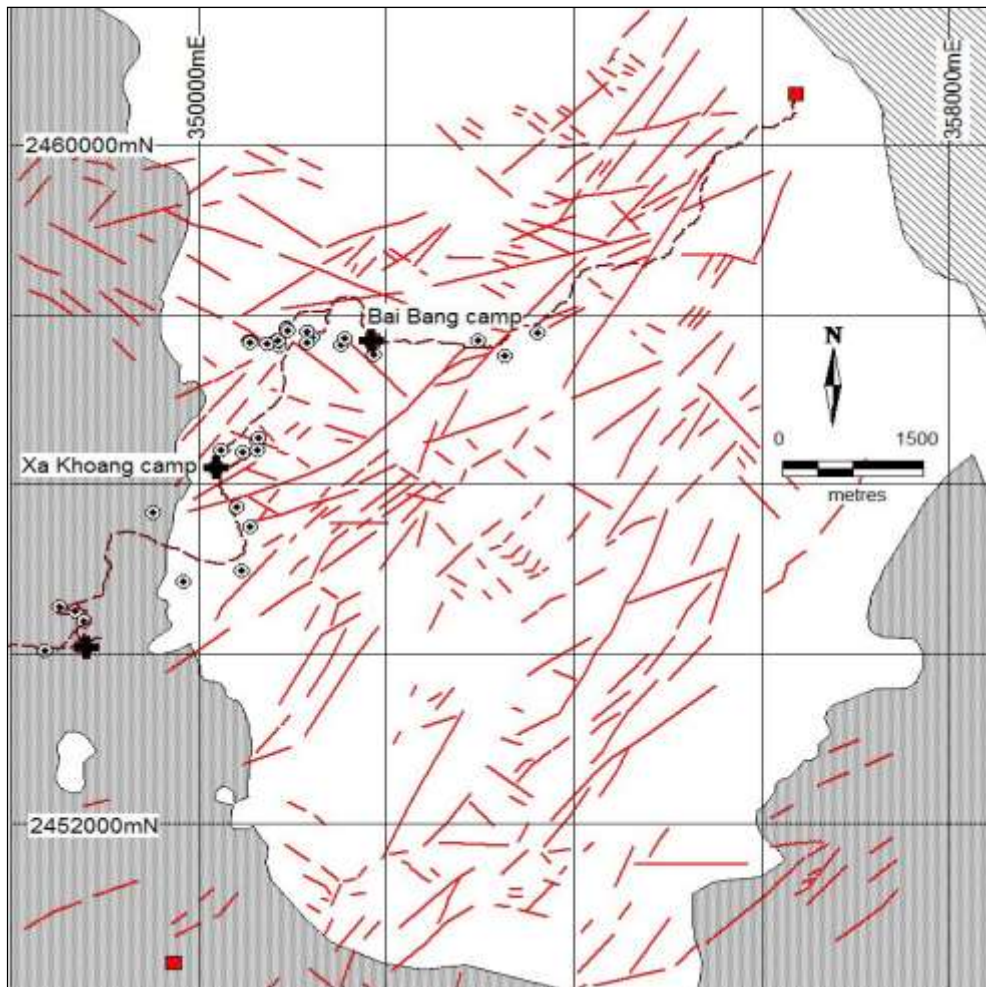


Figure 5. Topographic lineaments from Quickbird satellite imagery. Red lines, lineaments. Grey stipple, Cretaceous sedimentary rocks. White, Pu Sam Cap Complex. Diagonal cross-hatch, Palaeozoic-Mesozoic rocks

3. Structural geology

3.1. General comments

Satellite imagery shows that the Pu Sam Cap Complex is crossed by prominent north-east-trending topographic lineaments (Figure 5) which in some cases are followed by magnetic lineaments evident in the aerial aeromagnetic survey flown at a spacing of 100m by TPJ (M. Farmer, pers. com. 2007). In addition, local mapping by TPJ's staff between Bai Bang camp and the New Mining area (Figure 4) has confirmed that the predominant faults trend northeast and roughly east-west. Overall, my study confirms that least one major fault (Thanh Mine Fault) can be expected to extend northeast from the Thanh Mine in the New Mining area, through Nam Beo and towards the Bai Bang area, where it joins one of the northeast trending magnetic lineaments, and that other faults trend eastnortheast and east. This pattern and that of the topographic lineaments are both consistent with the Riedel shear pattern (Cloos 1928; Riedel 1929) for a strike-slip fault array.

At Pu Sam Cap, faulting is predominantly oblique strike-slip with most slickenlines plunging very shallowly. The slickenlines consist primarily of generally grooves and ridges and finer scratch lineations; slickenlines formed of quartz, chlorite and calcite fibres are extremely rare; and some mineralised surfaces show slickenlines whereas others do not. There is evidence in some instances that the fault-controlled chalcopyrite-haematite-specularite, and presumably contemporaneous gold, mineralisation has been cut by subsequent slip on the fault hosting the mineralisation.

Some faults carried dip-slip lineations and in one notable instance, the adit visited ("small adit") in the Xa Khoanh area, carried a large number of moderately steep to steeply dipping faults of a wide range of strike, all of which carried dip-slip lineations and markings

consistent with normal slip (Figure 6). These slickenlines overprint strike-slip slickenlines. As the adit penetrated a very steep hill-slope, I consider this clearly post-mineralisation dip-slip motion to have been caused by gravity-driven down-slope creep of the rocks forming the slope.

The following section examines in detail the mesoscopic faulting in adits and outcrops between Bai Bang camp and the New Mining area in order to assess the style and movement history of faulting so as to develop an understanding of the kinematics of faulting in the Pu Sam Cap area.



Figure 6. Dip-slip slickenlines on mineralised surface in fault through "small adit", Xa Khoanh area. Dip slip slickenlines overprint faint oblique-slip slickenlines plunging to left of picture at about 20°

3.2. Method

My approach depends on the now well-established empirical observation that mesoscopic fault arrays tend to mimic the geometries of the main faults around them (e.g. Tchalenko 1970) and that faults and tensional fractures in any one fault system tend to form predictable geometrical arrays. Although anisotropies such as pre-existing fractures and bedding (and indeed topography), will influence the orientation of subsequent faults, in the Bai Bang to Xa Khoanh region the rocks are predominantly massive, well-indurated volcanic breccias in which the only major lithological anisotropy is created by lamprophyre dykes. The Cretaceous beds of the New

Mining area are well-bedded sandstone and siltstones with some conglomeratic intervals and therefore contain numerous bedding plane anisotropies that could influence the orientation of faults. However, where seen by me, the Cretaceous beds dips shallowly and are cut at a very high angle by the steeply dipping faults, and thus the effect of the bedding anisotropy appears to have been minimised. It is accepted that gravitational loading can affect the orientation of faults during faulting; this aspect cannot be quantified and may well lead to non-ideality, primarily of the dip, of the faults studied.

The analysis depends also on the empirical observation that the intersection of kinematically related faults defines the orientation of the intermediate stress axis (σ_2) during faulting. This implies tectonic stress in only two orthogonal directions at the time of rupture, the maximum (σ_1) and minimum (σ_3) stress directions, which lie in a plane (the movement plane or M-plane) orthogonal to σ_2 . The consequence of this geometry is that poles to related faults will plot along a great circle girdle, which defines the M-plane, in the equal-area stereographic net, and thus, ideally, unique fault systems should produce specific and recognisable fingerprints in the stereographic net.

Palaeostress analysis, commonly based on slickenline orientation and slip-sense, is now a thoroughly established technique for analysing the kinematics of faulting. As part of such an analysis, it is essential to determine the slip-sense (direction of movement) of the faults measured and although ideally only six faults showing their slip-sense are needed to define the stress tensor, the results are more convincing when a larger population of faults of known slip-sense are available.

In the present study it proved difficult to determine the slip-senses of many of the faults studied as they did not demonstrate convincingly features by which slip-sense could be determined unequivocally. Thus in many instances where the faults were clearly parts of local strike-slip arrays I determined the probable local-slip sense by consideration of the

faults' geometrical relations following the well-established Riedel shear model (Cloos 1928, and Riedel 1929) for strike-slip systems. This paper therefore focuses on the geometrical relations between faults and thus predicts the probable kinematics of the faulting at Pu Sam Cap, and discusses this in relation to recent geochronology at Pu Sam Cap, development of mineralisation and the known motion along the Indochina-South China plate boundary that is marked by the Song Hong-Song Chay Shear Zone.

All structural measurements are True North; measurements were made with a Freiberg compass-clinometer; all stereographic nets are equal-area southern hemisphere projections. All stereonets were plotted by hand on paper for analysis; I have used Georient by R. Holcombe for the purpose of display.

3.2.1. Local geometries of faulting

Bai Bang: Zone 5 to Zone 7 areas

This region (Figure 7) is dominated by steeply dipping faults mapped by TPJ staff and this author as following northeast, eastnortheast trends and easterly trends. Faulting was studied at Zone 5, Zone 6 and Zone 7; I was assisted by Messrs Farmer and Nguyen Tam (geologists employed by TPJ Ltd) in collecting measurements from Zone 5 and Zone 6.

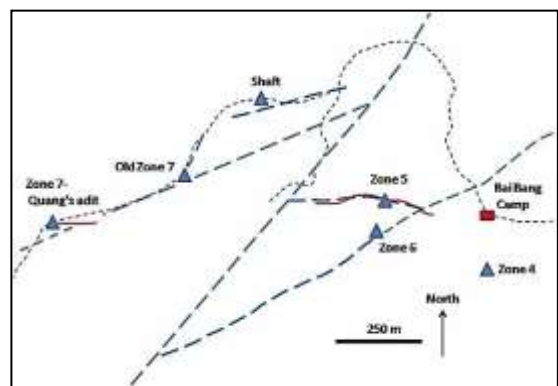


Figure 7. Bai Bang to Zone 7 mining area. Broken blue lines show mapped major fault zones, the red line at Zone 5 tracks the mined out adit, the black broken line marks the walking track

Zone 5. The prominent Zone 5 region, which occupies a deep east-west trending gully, contains at its western end a major artisanal mine (Hung's Adit), together with other less prominent adits. The section visited in Hung's Adit has been mined out but it included possibly two closely spaced, narrow lenses of mineralisation joined by a fracture system. At the western, blocked, end of Hung's Adit, horizontal slickenlines are readily evident on a fault dipping about 60° to 150-160° (060-070° strike). Detailed surveying of Hung's Adit by TPJ staff (Figure 8) shows that it consists of variably trending, linked sections consistent with narrow zones of east-west T shears linked by R and R' shears.

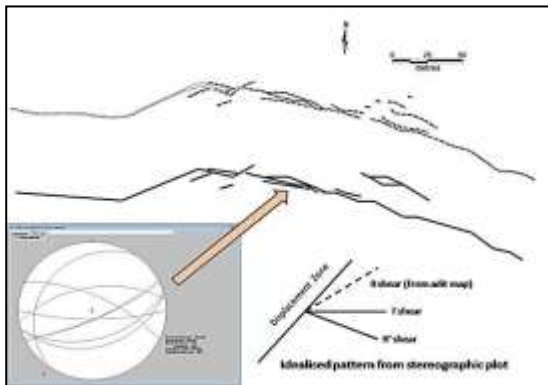


Figure 8. Faults (broken lines, top) in Zone 5 as mapped by TPJ's geologists. Solid lines below show interpretation of fault pattern. The inset stereographic plot shows the orientation of faults measured by the author in Hung's adit

Both in the gully of Zone 5 and also in Hung's Adit, dip-slip, probably normal, slickenlines are present on faults of the 060-070° trend (Figure 8). This would be consistent with the interpretation of these structures as extensional T-shears and could explain the wide zone of mined-out mineralisation here.

Plots of 77 mesoscopic faults from throughout Zone 5 fall along a shallowly dipping great circle (M-plane) whose pole plung-

es steeply west-northwest (Figure 9, top left and right), indicative of the predominance of strike-slip in this general area. When all the measured Zone 5 faults are considered, the rose diagram shows a simple pattern consistent with strike-slip faulting with σ_2 (β in Figure 9) plunging steeply northwest and some faults falling in the appropriate position for their interpretation as T-shears. The northeast-trending mesoscopic faults follow the trend of the main faults mapped by TPJ's staff across the mined area of Pu Sam Cap. These northeast-trending mesoscopic faults are interpreted therefore as representing the main displacement zone. The geometry shown in Figure 9 is thus consistent with dextral strike-slip faulting on the major faults trending northeast.

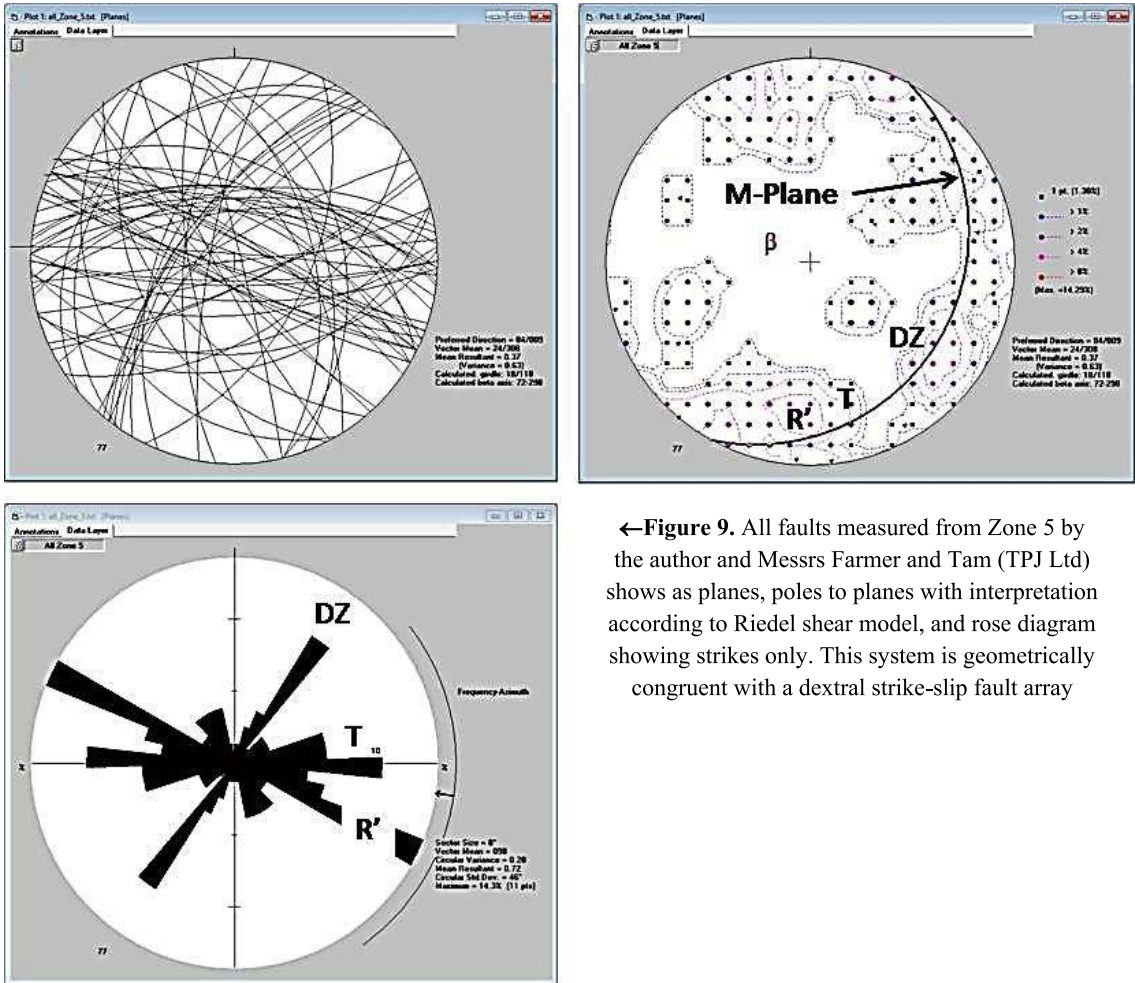
Zone 6 lies on the hillside on the southern side of the Zone 5 gully. There are a number of prominent mined faults here, the majority of which carry strike-slip scratch striations and grooves. The main fault here strikes northeast, dipping at 62° to 330°, and is marked by a pug carrying pyrite with some quartz, and as it is followed by the local artisanal mines it forms a mineralised trend. This trend is that of the aeromagnetic lineaments and the trend of the major faults mapped by TPJ staff across the region.

Figure 10 presents the orientations of mesoscopic faults in Zone 6. According to the shallow plunge of the striations on some of the faults and the common intersection points of all the faults, σ_2 plunges steeply northwest, consistent with previous observations of strike-slip movement.

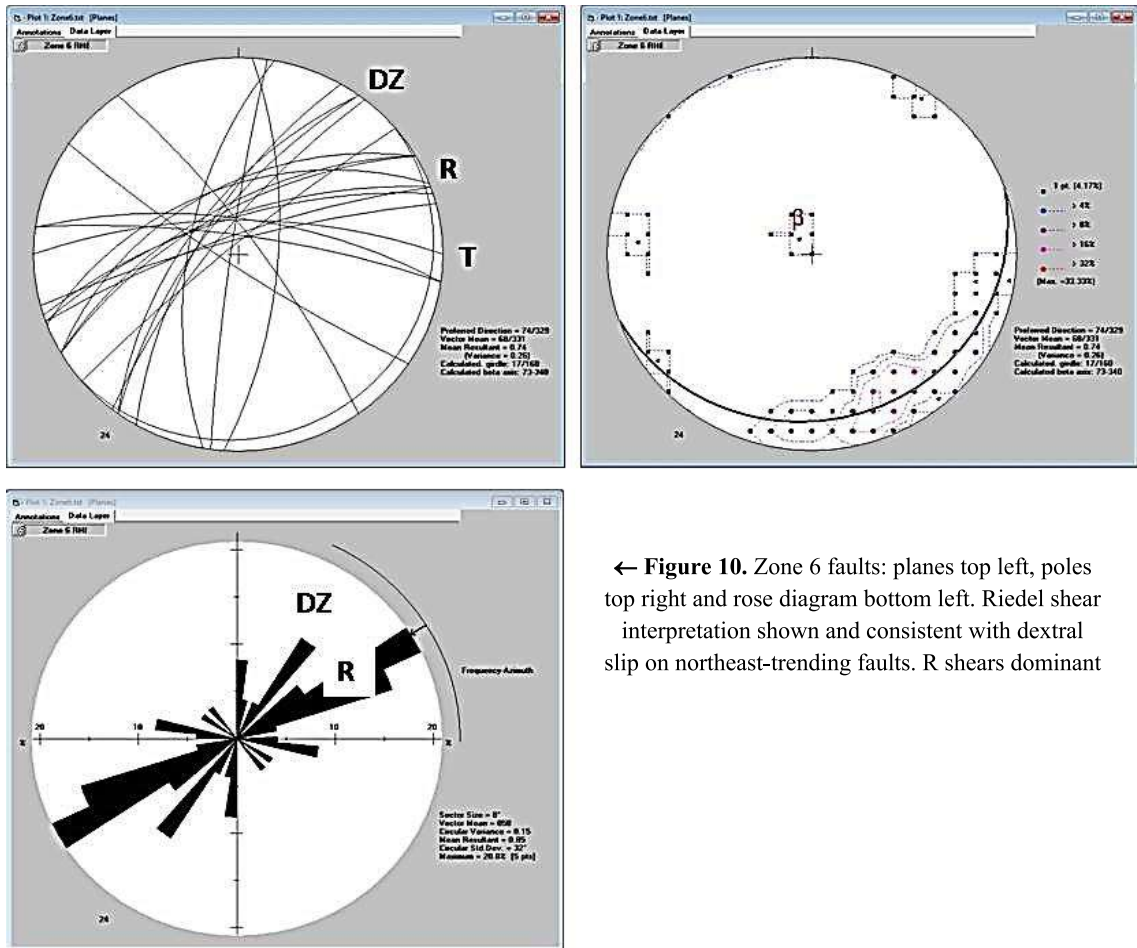
Two of the mesoscopic northeast-trending faults carried lunate Riedel fractures and small steps indicative of dextral slip and the geometry of the faults is consistent with a dextral Riedel shear system with the T shears striking

090°-110°. One of these strike-slip faults cuts into a lamprophyric dyke (itself apparently bounded by a northeast-trending fault carrying

gold; M. Farmer, TPJ, pers. com. 2007) thus suggesting the likelihood of continuation of dextral slip after mineralisation.



←Figure 9. All faults measured from Zone 5 by the author and Messrs Farmer and Tam (TPJ Ltd) shows as planes, poles to planes with interpretation according to Riedel shear model, and rose diagram showing strikes only. This system is geometrically congruent with a dextral strike-slip fault array

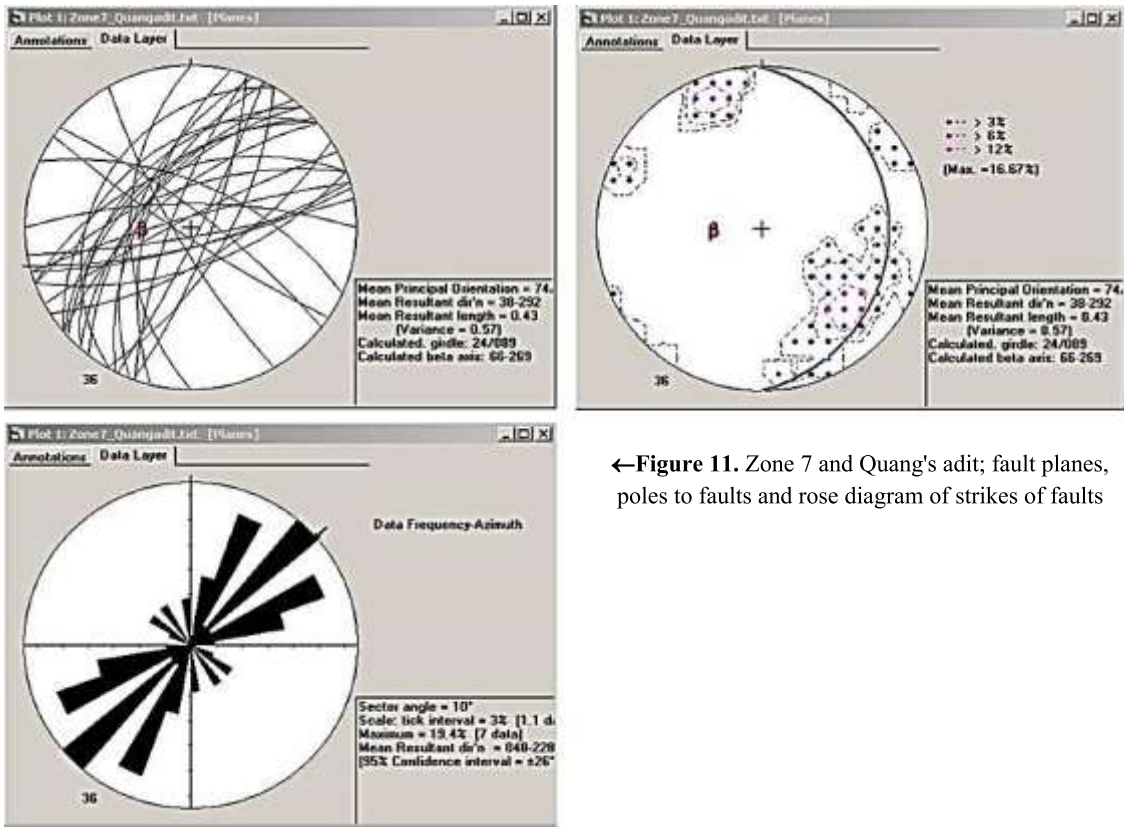


← **Figure 10.** Zone 6 faults: planes top left, poles top right and rose diagram bottom left. Riedel shear interpretation shown and consistent with dextral slip on northeast-trending faults. R shears dominant

Zone 7 and Quang's adit. The mesoscopic fault array in this region is consistent with regional strike-slip faulting with σ_2 close to that for Zone 5 and Zone 6 (Figure 11). The majority of the faults in this area strike northeast, northnortheast and eastnortheast. The latter two sets are readily interpreted as Riedel R and P shears about a northeast-trending displacement zone. The mesoscopic geometry within a narrow, mineralised fault crossing one part of the roof of Quang's adit (Figure 12) clearly indicates dextral slip along this fault; the

orientation of this fault, relative to that of the northeast-trending faults, is consistent with its interpretation as a dextral P shear.

As mapped by TPJ's staff, the mineralised Quang's adit runs overall towards about 095° (Figure 7) consistent with its interpretation as an extensional T shear in a dextral strike-slip fault system. Mineralisation in the adit consists of haematite-specularite and lesser chalcocopyrite with invisible gold extracted by the artisanal miners from the fault-controlled mineralised veins.



←Figure 11. Zone 7 and Quang's adit; fault planes, poles to faults and rose diagram of strikes of faults



Figure 12. View up-dip into adit's roof showing fault crossing Quang's adit at 116m from the entrance. The fault dips 72° to 120°. When projected into the floor of the adit and viewed down-dip, this fault shows a dextral strike-slip movement-sense

3.2.2. Xa Khoanh area: Zone Than and adits to south

The Xa Khoanh area (Figure 13) has been

less well-developed by artisanal miners, although there are several apparently abandoned adits and shafts in this area, together with one worked mine in the south known to TPJ staff as the “small adit”.

The orientations of all mesoscopic faults from these localities are shown in Figure 14, which shows the same constancy of pattern as do faults in the previous localities. Here, the region appears dominated by structures following the general northeasterly trend of the major topographic and aeromagnetic lineaments, together with generally east-trending faults. The geometrical arrangement of mesoscopic faults can be interpreted as mimicking a major northeast trending displacement zone together with a set of R' shears and a set of north- and south-dipping extensional T shears. The shallow dip of the M-plane in-

icates strike-slip faulting. One east-dipping fault is known, though its sense of slip is not; as its strike is close to orthogonal to that of the T-shears, conceivably it would be a reverse fault.

This geometrical interpretation is consistent geometrically with a dextral strike slip system.

Three adits south of the Xa Khoang camp provide useful detail. These adits are found at my GPS waypoints POI006 (103.548600°E/22.199500°N), POI007 (103.548667°E/22.199233°N) and GPS waypoint POI 016 (the mined “small adit”; 103.549600°E/22.196233°N), south of the Xa Khoang exploration camp (Figure 13).

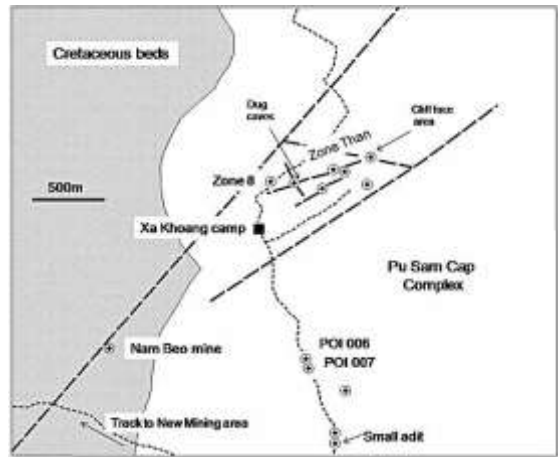
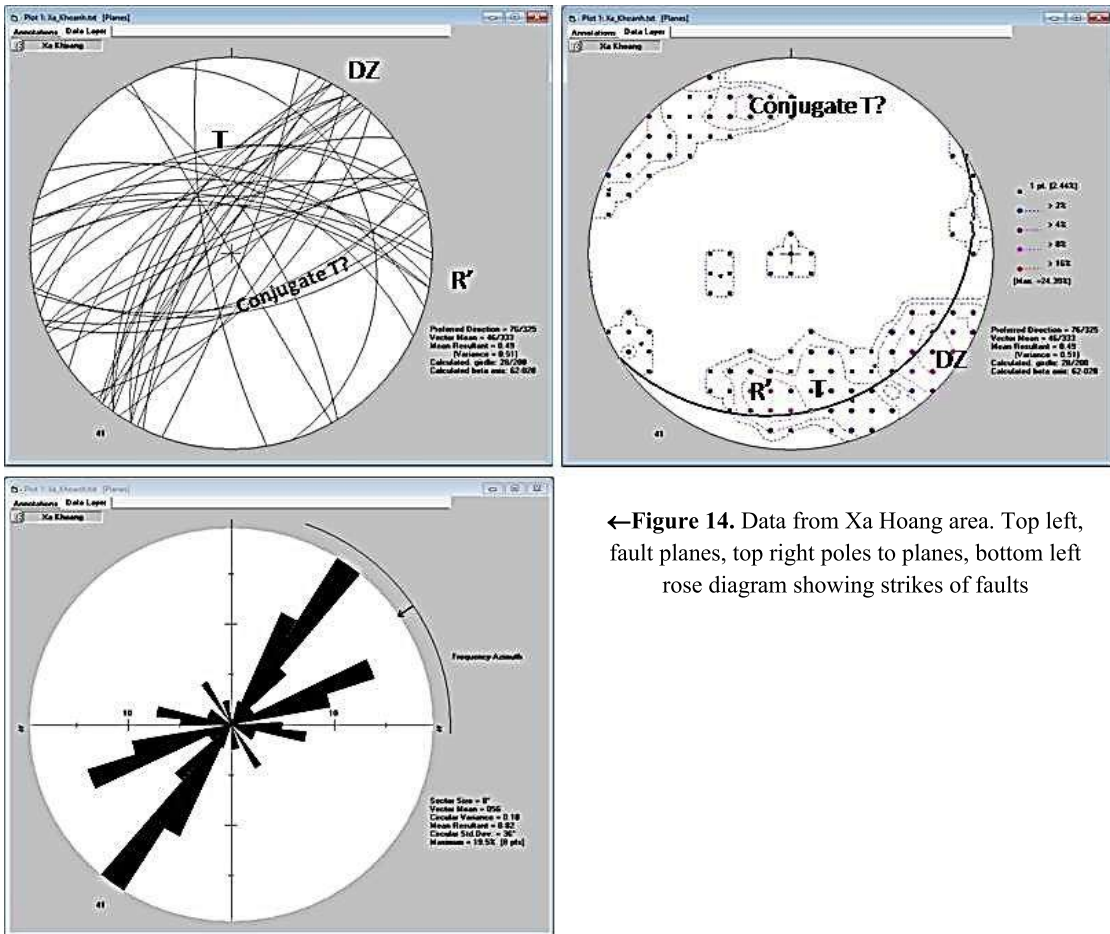


Figure 13. Xa Hoang area. Broken heavy black lines are faults; the dotted black line is the walking track. Mines and diggings are shown by the circles with a central diamond



←Figure 14. Data from Xa Hoang area. Top left, fault planes, top right poles to planes, bottom left rose diagram showing strikes of faults

The adits at POI 006 and POI 007 display northeast-trending faults that are accompanied by what are clearly east-trending conjugate tension fractures (Figure 15), which form a conjugate set of extensional faults consistent geometrically with dextral shear along the northeast-trending faults. The north-dipping tension fracture at POI 007 (Figure 15, bottom) forms the mined haematite-specularite vein and the mineralisation here would have occurred early, during formation of T shears in the initial stage of the faulting.

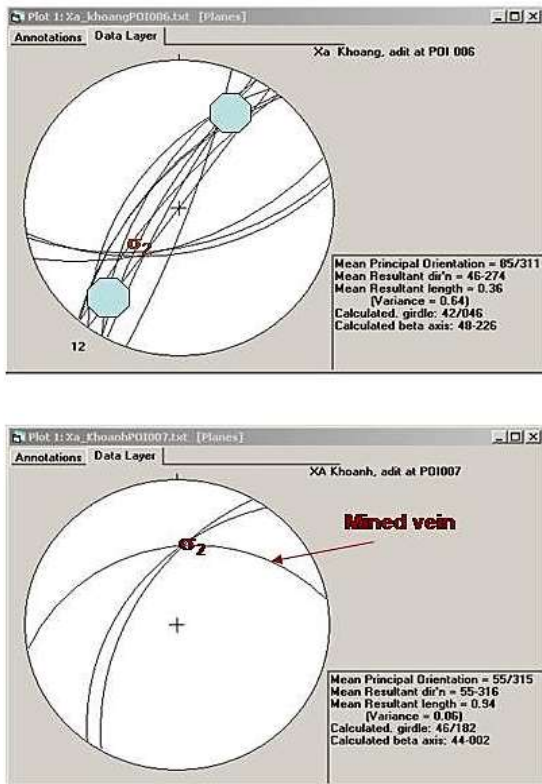


Figure 15. Top, faults in adit at POI 006. Bottom faults in adit at POI 007. The blue hexagons show general orientation of slickenlines. The two figures indicate that the tension gashes form a conjugate set of extensional faults, as has been recognised elsewhere

Evidence for multiple faulting is seen in the “small adit” at GPS waypoint POI 016 (103.549600°E/22.196233°N). The first event is recognised as the fault A (Figure 16), which

contains a 15cm-thick, haematite-specularite zone dipping 60° to 324°. This fault strikes parallel to other mineralised fractures in a prospect pit about 150m north and to the main known northeast-trending faults in the region.

Fault A is cut at 21m from the entrance of the “small adit” by the main mined zone (fault B, Figure 16) which contains faulted 2-3cm-thick lenses haematite-specularite and consists of a 30-50cm-thick fault zone striking between 100-120° and dipping about 60° north-northeast (3 measurements within this fault zone).

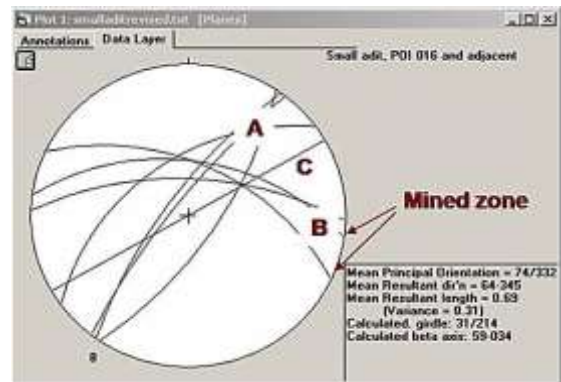


Figure 16. Data from the small adit

As viewed in the roof of the adit (Figure 17), fault B displays a series of asymmetric boudins and offsets of pre-existing haematitic lenses. When viewed up-dip in the roof of the adit the geometry of these features shows an apparent sinistral slip-sense; when viewed conventionally down dip this translates into dextral shear. That is, this fault, which is of an orientation appropriate for it to be regarded as a sinistral R’ shear in the dextral system is incongruent to such dextral shear. As this fault deforms a pre-existing series of lensoidal mineralised fractures following approximately the 120° trend, it is taken as indicating late re-activation of what was a formerly congruent and mineralised R’ sinistral shear.



Figure 17. Mineralisation and faults in roof of small adit. View up dip. The haematitic veins are cut by apparently sinistral faulting (dextral when viewed down dip). This fault zone is Fault B in Figure 16. Note: 030° is the magnetic bearing (declination to true north is just over 1° to the west)

3.2.3. New Mining Area

The geometries of all faults measured here are given in (Figure 18).

The major fault found here occurs at the Thanh Mine (Fault A in Figure 18) where it is marked by a 4m-thick zone of brecciation in Cretaceous sandstone and conglomerate horizons. This very steep fault strikes directly to the Nam Beo mine and thence into the Bai Bang area. There is no quartz veining associated with this fault and the fault breccia does not appear to be heavily indurated but rather simply consists of smashed rock with clay filling the interstices between clasts. The material extracted from the mine is dominated by haematite-specularite and contains also chalcopyrite and malachite. The mined haematite-specularite-gold vein lies at the hanging wall contact with the fault breccia and at the surface is about 15-20cm thick. TPJ geologists have mapped a lamprophyre dyke adjacent to the mineralised and altered zone at this location; the dyke follows the fault's trend and therefore may be related to mineralisation.

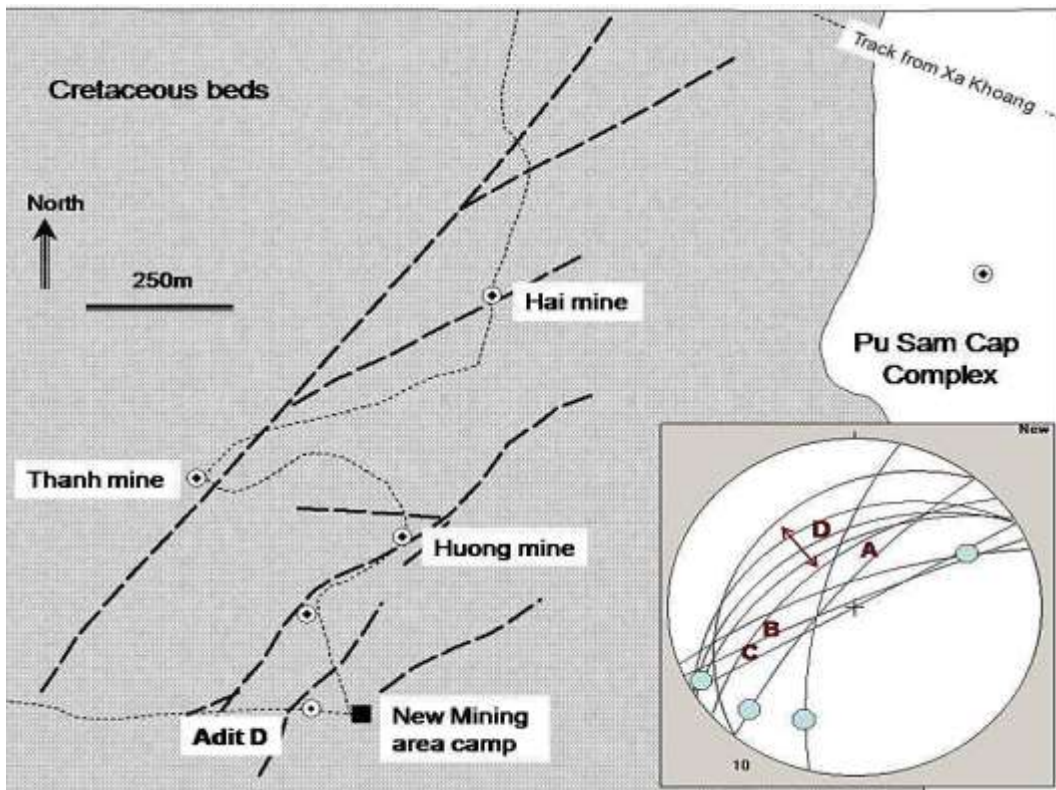


Figure 18. New Mining area. Legend as previous Figures

The Hai Mine (Figure 18) contains a major fault breccia about 3-4m thick (fault B in Figure 18) which trends to 060° and thus may be an R shear related to the Thanh Mine Fault. As with the Thanh Mine fault, the Hai Mine fault is again completely lacking in quartz and also contains loose clay in the matrix.

The Huong Mine, which hosts Fault C (Figure 18) similarly follows an unsealed quartz-free fault breccia following a trend a similar to that at the Hai Mine.

The adit marked as (D) in Figure 18 crosses a series of mineralised faults dipping between 70° and 45° to the northwest (unmarked faults in the stereo-net, Figure 18) before meeting at a distance of 53m down the adit the main fault-controlled ore zone, which dips 60° to 328°. This ore-zone is between 1m and 2m thick and contains haematite-specularite, chalcopryrite, chalcocite and malachite and follows the contact between the Cretaceous sediments and a lamprophyre dyke, thus suggesting again that late-stage lamprophyric intrusion is important.

4. Discussions

4.1. General geometry and regional relationship of mesoscopic faults

The poles to the 187 mesoscopic faults measured (Figure 19) plot on a shallowly dipping great circle girdle (Figure 19 and Figure 20). This confirms a simple fault system whose σ_2 plunges 64° to 314°; that is, Figure 20 confirms that the faulting between Bai Bang camp and the New Mining area is oblique-slip with a predominant strike-slip component, as clearly confirmed by the large number of shallowly (30° to horizontally plunging) slickenlines encountered on the faults.

Figure 21 shows the strikes of all faults; the dips of most faults ranges between 60° and vertical (Figure 19). This geometry is readily interpreted as that of a dextral strike-slip system, wherein the majority of the northeast-

trending faults follow the main displacement zones across Pu Sam Cap. Those faults trending 60-70° are interpreted as R shears, the faults trending 90° are the T shears and those faults trending about 110-115° are the R' shears. In this system, the tensional faults (T shears) on the 90° trend would be the most likely to carry productive mineralisation, as may be exemplified by the prolific artisanal mining along the east-trending Zone 5 gully at Bai Bang. Unless the array represents a transpressional strike-slip fault system, the R shears in particular are also likely to have extensional jogs along them and thus would also be exploration targets.

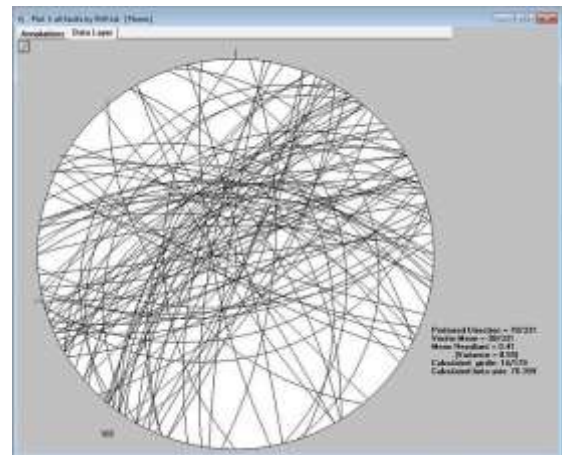


Figure 19. Planes of all faults measured

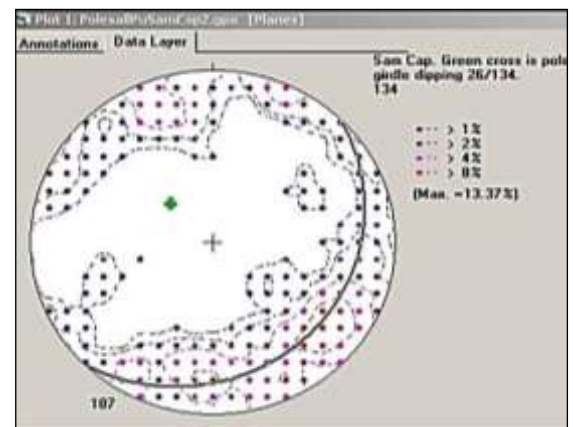


Figure 20. Poles to all faults measured

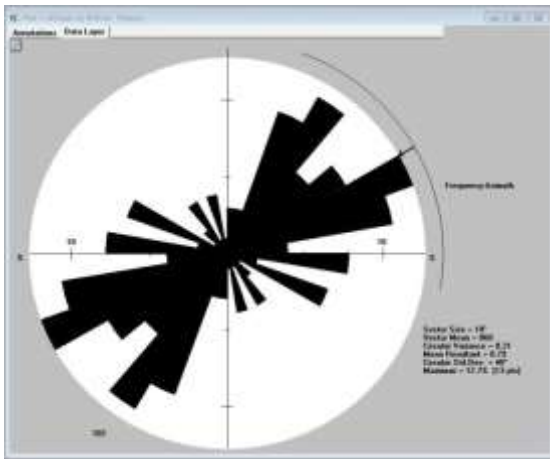


Figure 21. Rose diagram to show strikes of all faults measured Compare lineament map, Figure 5

Palaeostress analysis by Phan Trong Trinh et al., 1994 (Figure 23) shows an east-west trending compression direction across northern Vietnam during Miocene times, which is

similar to results derived from modern seismic motion studies (Khuong The Hung 2010) for the broad region encompassing Pu Sam Cap. This provides support for the conclusion arrived at herein that the extensional structures at Pu Sam Cap follow an east-west trend. The compression direction reported by Phan Trong Trinh et al. (1994) is certainly in accord with the recorded sinistral strike-slip motion on the Song Hong-Song Chay Shear Zone.

Satellite imagery (Figure 22) and mapping by the Geological Survey of Vietnam confirms that the Pu Sam Cap massif lies between two very long northwest-trending faults, themselves within a broad zone of similar long faults following a strike of the 320-330°. These faults are parallel to subparallel to the Song Hong-Song Chay Shear Zone, and thus may be assumed to be related kinematically to this shear zone.

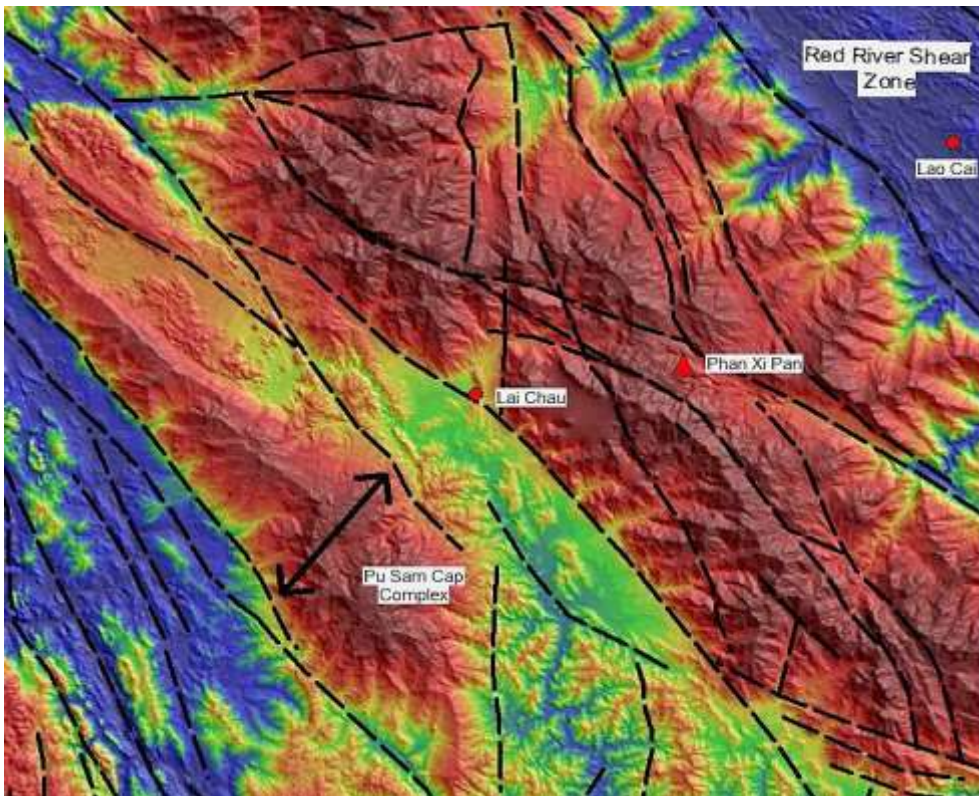


Figure 22. LANDSAT image northwestern Vietnam showing major faults. Double-ended arrow shows trend of main faults across Pu Sam Cap

The geometrical relationship between the faulting at Pu Sam Cap and the steeply dipping northwest-trending faults, including the Song Hong and Song Chay Faults, is shown (Figure 23). The main northeast-trending dextral faults at Pu Sam Cap show a strike of 80° away in the clockwise sense from that of the Song Hong-Song Chay Shear Zone; through construction of an idealised Riedel shear array for the Song Hong-Song Chay Shear Zone it can be seen readily that the ideal tensional fractures (T-shears) would trend between 090° and 105° and that the ideal P' shears would trend between about 025° and 035° . That is, the dextral faults trending northnortheast to

northeast can be interpreted readily as P' (not R' or P) shears related to left-lateral slip across the Song Hong-Song Chay Shear Zone and those other strike-slip faults of similar northwesterly orientation.

These P' shears are also in the ideal position for them to have acted as "domino" or "book-end" faults between the northwest-trending faults that form the northeastern and southwestern boundaries of the general area of the Pu Sam Cap Complex. In this context the deep incision and over-steepening of the hillsides within the complex could be indicators of rapid uplift during transpressional strike-slip deformation (Figure 24).

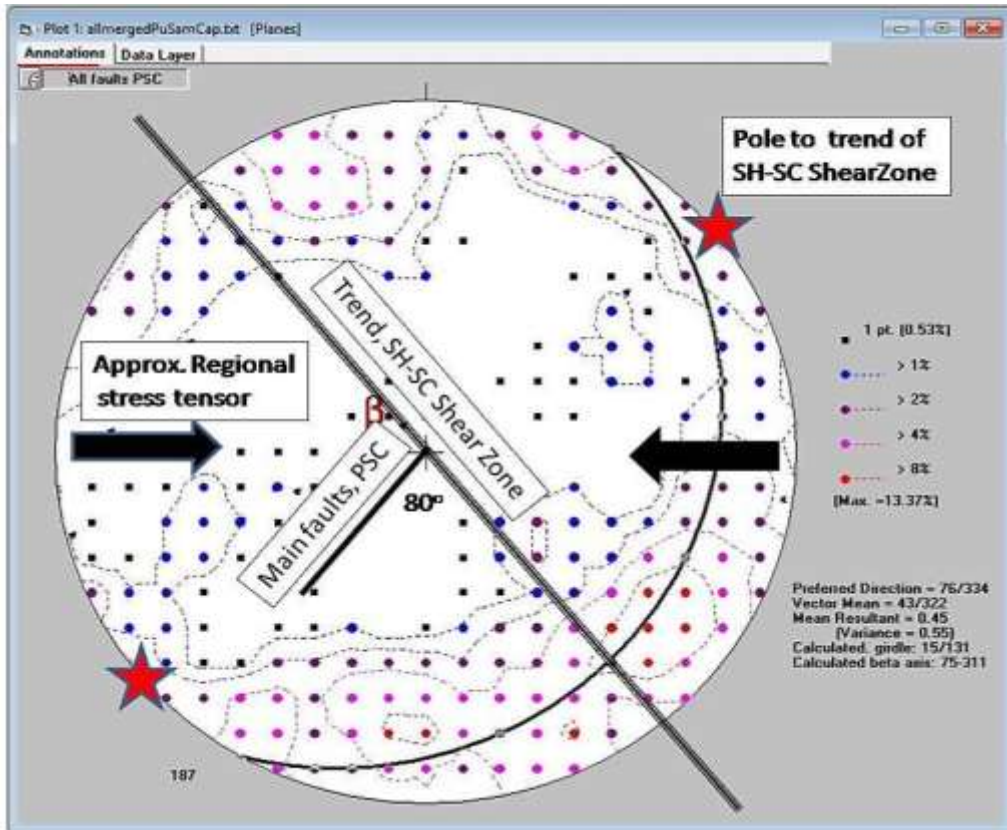


Figure 23. Stereographic plot of poles to all faults with strike of Song Hong-Song Chay Shear Zone and strike of main faults, Pu Sam Cap superimposed. Strike of approximate regional compressive stress tensor derived from Phan Trong Trinh et al., 1994

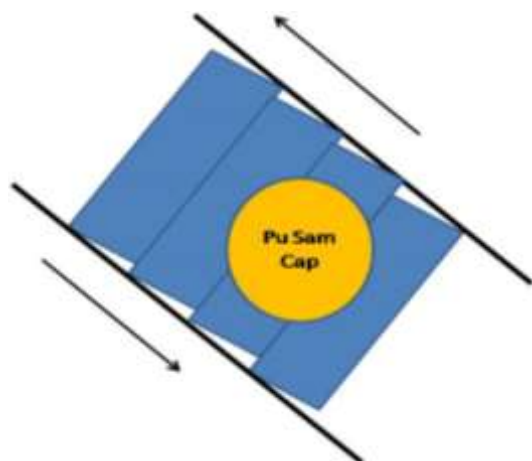


Figure 24. Model for Pu Sam Cap dextral faults as Riedel P' shears acting as “domino” or “book-end” faults between the two northwesterly trending faults bounding the Pu Sam cap area

4.2. Age of fault-hosted mineralisation at Pu Sam Cap

Published dating of the Pu Sam Cap Complex is limited solely to two hornblende-porphphy syenite bodies dated by the U/Pb LA-ICPMS method at of 35-33Ma (Nguyen Thi Bich Thuy, 2016). The thermal event involved with production of syenite at Pu Sam Cap clearly coincides with the 35.2 \pm 0.4Ma U/Pb titanite age for crystallisation of the alkaline granite of the Phan Xi Pan massif (Zhang and Scharer, 1999). These ages fall in the 50-30Ma age-range (Chung et al., 2005) for the regional thermal event that produced alkaline, mantle-derived, volcanic and intrusive rocks across much of the Qiangtang and Kunlun terranes of northern Tibet and the Yangtze-South China block, which includes part of northern Vietnam.

At Pu Sam Cap, TPJ's geologists recognised dykes and possible stocks of biotite-rich lamprophyre as being the youngest intrusives in the volcano-intrusive stratigraphy; these have not been dated. One lamprophyre dyke (TPJ geologist M. Farmer pers. com. 2007) at Zone 6 has gold at its margin and is cut by the major mineralised fault, thus suggesting a

close relationship between lamprophyric intrusion, mineralisation and faulting. Lamprophyric breccia also occurs in mine dumps in Zone 7 and thus it seems that the mineralisation here could also be related to lamprophyric intrusion. TPJ's geologists have mapped a lamprophyric stock adjacent to the Zone 5 mineralisation; and, in the New Mining area, TPJ's geologists mapped a lamprophyre dyke along the alteration and mineralisation zone at the Thang mine, as well as lamprophyre and syenite dykes following the fault-controlled trends of mineralisation at the Huong and Hai mines.

Therefore, at Pu Sam Cap, faulting, intrusion of alkaline dykes (and in particular lamprophyric bodies) and mineralisation could well have been penecontemporaneous with faulting; and both faulting and the lamprophyric bodies clearly post-date formation of the alkalic volcanic rocks, which are intruded by and therefore older than the two hornblende syenite bodies dated at 35-33Ma (Nguyen Thi Bich Thuy, 2016).

However, the lamprophyric dykes at Pu Sam Cap have not been dated, although they are the youngest intrusives known.

Elsewhere in northwestern Vietnam the ^{39}Ar - ^{40}Ar method has been used to date lamproitic intrusion and these ages range from 40Ma to 26Ma. Whilst this age-range encompasses the two 35-33Ma U/Pb zircon ages obtained from Pu Sam Cap, it does not adequately constrain the age of the younger but undated lamprophyres at Pu Sam Cap, which certainly follow fracture systems cutting the 33-35my-old and older rocks of the Pu Sam Cap Complex. In the Lai Chau-Laizhou region, Yan Yi Sing et al., 2013 confirm that here also, intrusion of lamprophyre dykes occurred after the regional 35-33y-old alkaline magmatic event.

Pei-Ling, et al., 1998 report $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 25-21Ma for cooling in the predominantly high-grade metamorphic rocks of Day Nui Con Voi massif between the Song Hong and

Song Chay Faults and conclude that they define a cooling span of 27-17Ma for the Ailao Shan-Red River Shear Zone (Song Hong-Song Chay Shear Zone). The rocks dated were gneiss, amphibolite, pegmatite and leucogranite, the latter two rock-types forming dykes both cross-cutting and parallel with the foliation in the metamorphic rocks.

U-Pb monazite, allanite and zircon ages of 26.0 \pm 0.2 Ma and 23.7 \pm 1.7 Ma are known (Nagy et al., 2000) from granite melts in the core of the Bu Kang domes, southwest of the Song Hong-Song Chay Shear Zone and extending westward into Laos (Jolivet et al., 1999). These ages confirm an Oligocene-early Miocene high-temperature event synchronous with leucogranites along the Ailao Shan-Diancang Shan sectors of the Ailao Shan-Red River Shear Zone (Scharer et al. 1990, 1994; Zhang and Scharer 1999).

Viola and Anczkiewicz (2008) review previous $^{40}\text{Ar}/^{39}\text{Ar}$ and fission-track dating in northwestern Vietnam and provide further fission-track analyses across the Phan Xi Pan-Day Nui Con Voi region. They conclude that the kinematics of this region and thus of the Ailao Shan-Red River Shear zone are more complex than previously supposed. Importantly for the present study, Viola and Anczkiewicz (2008) note that two of their samples adjacent to the large-scale sinistral Riedel shears within the Phan Xi Pan region (Figure 2) yielded apatite and zircon fission-track ages ranging between 23Ma and 20Ma. Given the clear geomorphological evidence for rapid uplift, these exhumation ages serve to date closely the age of shear-heating related to this fault, which is one of the arrays of generally northwest-trending faults encompassing Pu Sam Cap. The corollary is that on the northwest-trending faults adjacent to Pu Sam Cap, and which are arguably related to the Song Hong-Song Chay Shear Zone, sinistral transcurrent slip was active between 23Ma and 20Ma.

Viola and Anczkiewicz's (2008) work supports the considerations of Searle (2006 and 2010) who used published U-Th-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of granites along the shear zone to argue that timing of left-lateral ductile shearing along the Song Hong-Song Chay Shear Zone lay between the age of the earlier deformed leucogranites (31.9-24.2 Ma) and the later crosscutting dykes (21.7 Ma). Searle (2006) argued that initiation of the Ailao Shan-Red River fault system may have been no earlier than about 21Ma.

Cao et al., 2010, through Up/Pb dating of granite dykes intruding the high-grade metamorphic Diancang metamorphic complex within the Chinese sector of the Ailao Shan-Red River Shear Zone, argue that left-lateral shearing had ended by 21Ma when rapid brittle deformation commenced to initiate exhumation of the Diancang complex.

It follows from the above that the faulting at Pu Sam Cap is likely at its oldest to be no older than 23-21Ma, which is 14my younger than the age of the alkaline magmatic event that produced both the dated late Eocene syenitic intrusives and what must be, at their youngest, the penecontemporaneous and likely related alkaline volcanics at Pu Sam Cap, as well as the related late Eocene intrusives and volcanics known along this broad zone of alkali magmatism between northern Vietnam and Tibet.

Therefore, the lamprophyres and attendant mineralisation and hydrothermal alteration at Pu Sam Cap not only attest to a regionally significant but as yet poorly known, or ignored, regional latest Oligocene-earliest Miocene thermal event within northwestern Vietnam and which includes granitic intrusion at the Bu Kang dome and within the Day Nui Con Voi Massif, but would also serve to provide constraints on transcurrent faulting in northwest Vietnam.

5. Conclusions

At Pu Sam Cap the system of auriferous haematite-specularite veining follows steeply dipping (60-90°) strike-slip faults and tensional fractures characterised by Riedel shear geometry in a northeast-trending corridor several kilometres wide. Within this corridor, the faults' slickenlines generally plunge between 30° and horizontally.

Based primarily on structural geometry, the northeast-striking faults at Pu Sam Cap developed as dextral strike-slip P' shears acting as a "book-end" fault system enabling local rigid-block rotation during regional sinistral transcurrent faulting related to sinistral slip along the Song Hong-Song Chay Shear Zone.

At Pu Sam Cap, the alteration and mineralisation are considerably younger than the exposed 35-33Ma syenitic intrusives and associated volcanic rocks. Rather, mineralisation and probably related intrusion of lamprophyre dykes are attributed to a regional, latest Oligocene-earliest Miocene thermal event that also involved intrusion of granitoids, contemporaneously to penecontemporaneously with transcurrent slip on adjacent northwest trending faults, followed rapidly by regional uplift and exhumation, dated by zircon and apatite fission track studies, in the period between 23-20Ma. In respect of mineralisation at Pu Sam Cap, this could well demand deep and concealed, mineralised alkaline intrusive bodies some 14my younger than those at the surface and which represent part of a very poorly known, younger, regional thermal event and intrusive system.

Post-mineralisation normal dip-slip faulting is present and is attributed to gravitational collapse of the over-steepened slopes.

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