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Tension vein arrays in progressive strain: complex but predictable architecture, and major hosts of ore deposits

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Abstract

Most en échelon vein arrays are extensional and can be termed tension vein arrays (TVAs). TVAs in major fault and shear zones (FSZs) are subject to progressive deformation. This deforms the initial TVA (whose geometry is well documented in the literature), via discrete stages; first into progressively more complex architecture, involving folding of the tension veins, then into progressively more simple architecture, ultimately forming pipes. During this progression the TVA axis (new definition) rotates within the shear plane from normal, to parallel, to the displacement vector. The deforming TVA axis has simpler geometry than the complex tension veins, and it can be employed to precisely track the deformation state of the FSZ, its displacement vector, and shear sense, through all the strain stages. Five structural–metasomatic stages are defined by discrete steps in the strain evolution.

TVAs are difficult to recognise, and are under-recognised, in ore systems for a number of inherent geological reasons. Orebodies founded on dilation form parallel to the TVA axis, which is also parallel to dilational jogs in the parent FSZ. Orebodies formed early in the FSZ history are normal to the displacement vector, and in progressive shear rotate with the TVA axis toward the displacement vector; orebodies formed late in the FSZ history overprint apparently complex to 'chaotic' vein stockwork, which nevertheless has analysable geometry. TVA-hosted orebodies are not necessarily parallel to the displacement vector of the host FSZ, but occupy elongate orientations over a 90° range within the FSZ. Large orebodies are favourably developed in TVAs in unfoliated FSZs (type 1 shear zones), which may form fluid 'superhighways'. Type 1 shear zones form in predictable circumstances involving particularly host rocktype and crustal position. Strike-slip FSZs possess a downdip TVA axis and are especially able to tap deep crustal fluid.

TVA-hosted orebodies form a major deposit style. Exploration requires careful analysis of the prospect geometry at an early stage, and recognition of the multi-faceted TVA architecture. The relationship between the parent shear zone or fault (including fault veins) and the component tension veins is complex, and search strategies depend critically on the strain stage, the type of host FSZ, and the type of exposure. Deciphering the architecture of TVAs involves a combination of vector (orientational) parameters and scalar (angular relationship) parameters. This permits ready analysis in oriented rock (outcrop and oriented drillcore) and in unoriented rock (unoriented drillcore, mine dumps and float).

Keywords: Extension fractures; Fracture patterns; Veins; Faults; Shear zones; Progressive strain; Kinematic analysis; Fluid flow; Ore deposits

1. Introduction

Arrays of en échelon fractures and veins (tension gash arrays) are a well-known feature accompanying faults and shear zones (FSZs). However their role as a major ore host in FSZs is not so well recorded, for a number of inherent geological reasons. The under-recognition of en échelon vein arrays stems from both geological and cognitive factors: the greater complexity of en échelon vein arrays than hitherto documented in progressive non-plane strain, and the poor exposure of arrays in many drilled mineral exploration environments in contrast to the classically exposed arrays studied in the literature. This paper examines two aspects of en échelon vein arrays: their evolving geometry in progressive strain and their hosting of ore deposits.

En échelon arrays of fractures and veins have been ascribed to several mechanisms, which ultimately fall into two end-member categories (Smith, 1996a; Srivastava, 2000): extensional fracturing (Ramsay, 1980; Segall and Pollard, 1983; Nicholson and Pollard, 1985; Rothery, 1988)

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or mechanisms involving shear fracturing (faulting) (Hancock, 1972; Beach, 1975; Engelder, 1987; Smith, 1996a,b). Most en échelon fracture/vein arrays can be ascribed to extensional fracturing (Smith, 1996a). This category of en échelon vein arrays can be termed tension vein arrays (TVAs). Distinction between TVAs and fault-related arrays is possible on morphological grounds (e.g. Srivastava, 2000). The present analysis is confined to TVAs.

Previous studies of TVAs have been confined to plane strain. They document the evolution of veins via cylindrical rotation and fracture propagation, to the stage where veins are 'badly oriented' for accommodating further extension, and new veins develop (Ramsay and Huber, 1983). However natural TVAs evolve with increasing shear strain, into non-plane strain and non-cylindrical rotation of veins. This paper documents five architectural stages of TVA evolution; the first two have been the subject of previous studies and the last three represent the progressive non-plane shear strain phases. The geometric components of a TVA bear a specific relationship to the kinematic components of shear direction and shear sense in the host FSZ, and the relationship changes through the five evolutionary stages. Kinematic analysis can employ the relationship change to gauge the third kinematic component, the relative magnitude of shear strain. TVAs are a powerful, and the most commonly available, tool for the analysis of FSZ displacement and shear strain.

TVA-hosted ore deposits are localised at specific sites within the evolving TVA architecture, and have shapes and orientations that change dramatically through the five strain stages. This includes a 90° change in orientation of the orebody and ore shoots, from a low-strain to a high-strain FSZ. Independently of strain magnitude, large ore deposits tend to be developed in a favourable specific TVA type. Understanding the evolution of TVAs is critical to successful exploration for TVA deposits.

2. Evolution of TVAs in progressive strain

A TVA is a dynamic entity whose architecture changes, dramatically, as its parent FSZ progresses through increasing strain from low- to ultra-high-strain. Initially a TVA comprises planar tension veins, at a particular vein array angle (Smith, 1995 and earlier workers) to the host FSZ, and the initial TVA axis develops normal to the shear direction in plane strain (Hancock, 1985; analogous to the stress-axes relationship underlying the P–T axes method of Turner (1953) and Stauder (1962)) (Fig. 1). The TVA axis L_T is defined by five distinct but parallel linear elements in the TVA (Fig. 1 and Table 1): (a) the line of intersection of tension veins and the parent FSZ, L_p; (b) the line of intersection of old and younger tension veins, L_v; (c) the axes of folded veins, L_f; (d) the axis of any coherent (linear) bulges in veins, L_b; and (e) the tipline of veins where these are regular (that is, several colinear), L_i. The axis of jogs in

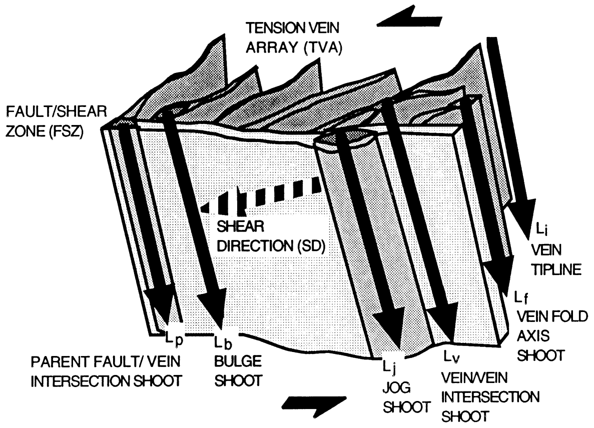

Fig. 1. Fundamental architectural elements of a TVA, shown in their initial orientation (prior to any rotation during progressive strain).

the fault plane, L_j, is commonly also parallel to the TVA axis, which is the direction of maximum dilation during FSZ movement.

Increasing strain in ductile and brittle/ductile FSZs produces rotation/folding of the TVA toward the shear direction (Fig. 2) analogous to the general rotation of rock markers toward the maximum extension direction (Sorby, 1853, 1856; March, 1932; Bryant and Reed, 1969; Borradaile, 1972; Roberts and Sanderson, 1974) and the shear direction in thrusting (Hobbs et al., 1976, pp. 286–287). All the TVA elements are folded, bent or rotated; these comprise the veins (with rotated vein centres relative to the constant tip propagation direction as in Ramsay (1980)), the inter-vein bridges (Nicholson and Pollard, 1985) and the TVA axis L_T. In general, non-plane strain veins undergo complex folding in three-dimensions, but L_T experiences a simpler change: L_T rotates later than the early vein rotation, and it remains within the FSZ plane. We can thus simplify the complex evolving architecture into four stages of progressive rotation of L_T (Fig. 2): (1) L_T normal to shear direction and veins planar; (2) L_T normal to shear direction and veins rotated with a folded shape; (3) L_T

Table 1
Structural elements of a tension vein array (TVA)

Planar	
FSZ	Fault or shear zone (type 1, 2 or 3)
SZ	Shear zone (type 1, 2 or 3)
F	Fault
TVA	Tension vein array
V_t	Tension vein
Linear	
SD	Shear direction (displacement vector)
L_e	Elongation lineation, mineral lineation (colinear), parallel to SD
L_T	TVA axis, defined by any of the following five elements:
L_v	Vein/vein intersection line
L_p	Vein/parent fault/foliation intersection line
L_f	Fold axis of (sigmoidally) folded tension vein
L_b	Axis of coherent bulge in tension vein
L_i	Distal tipline of tension vein
L_j	Axis of dilational jog

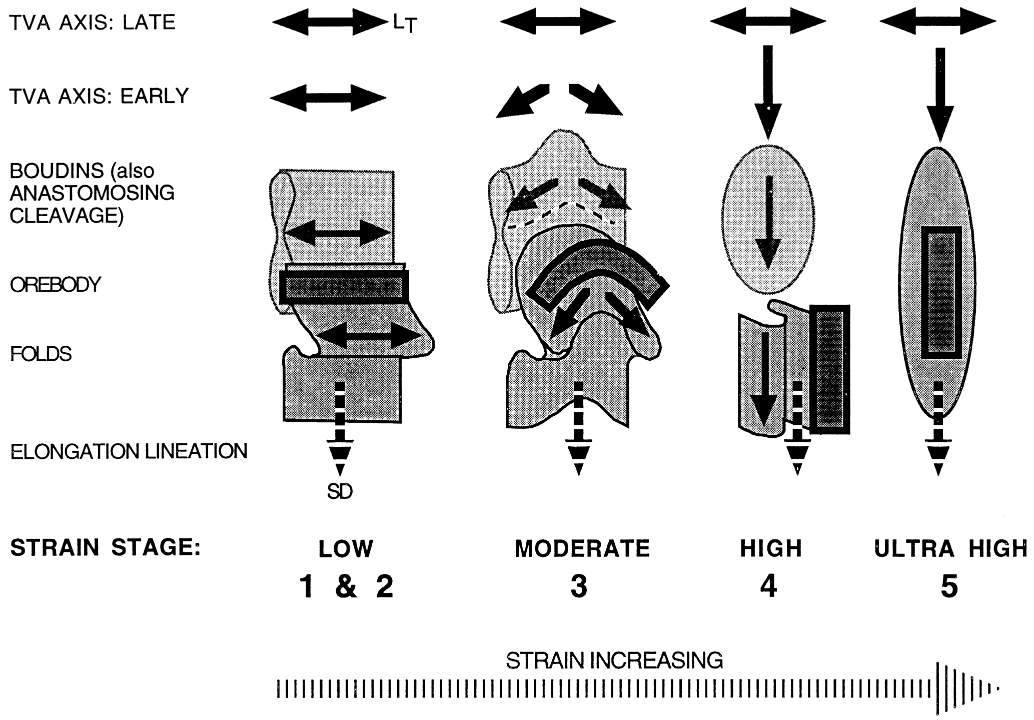

Fig. 2. Relationships within the shear plane of an FSZ (longitudinal section), between its linear elements, as strain increases from stage 1 to stage 5 (left to right). Each element (with its orientation shown as an arrow) rotates toward the elongation lineation.

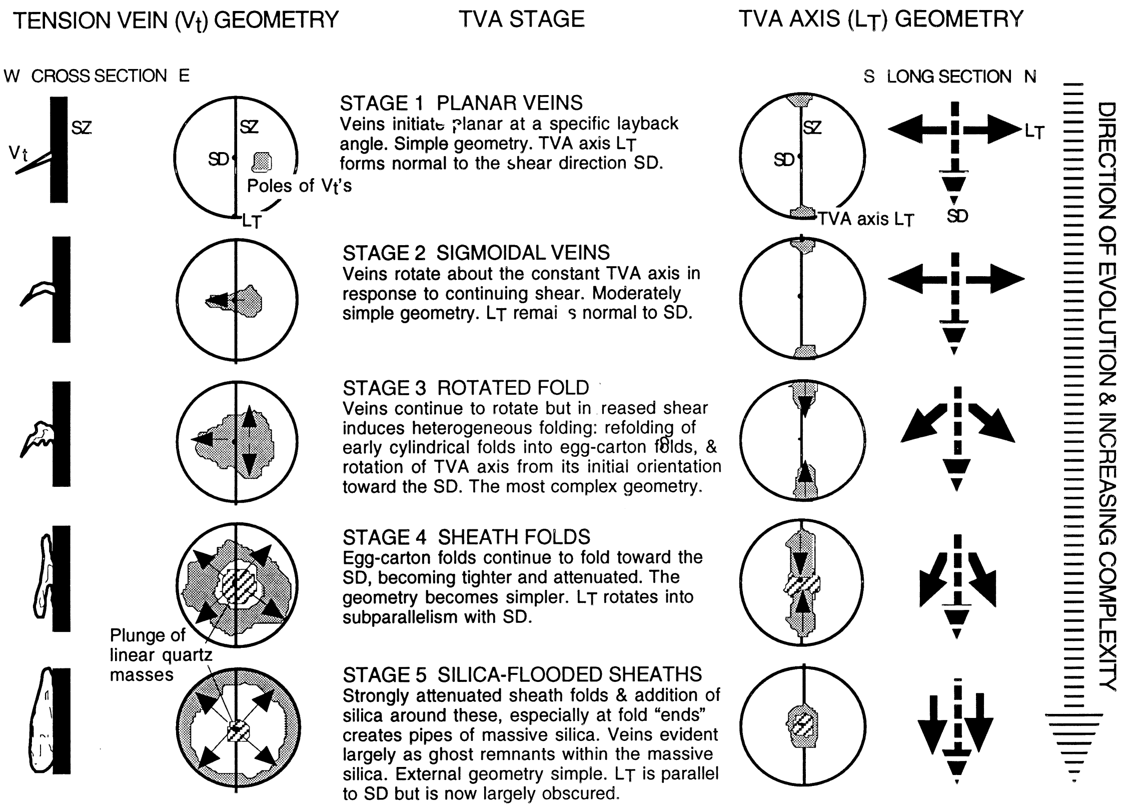

Fig. 3. The five stages of geometric–metasomatic evolution of a TVA with progressive strain (downward). Tension vein shape (cross-section on left) and TVA axis orientation (longitudinal section in plane of FSZ on right). Arrows in the stereonets indicate rotation of veins (left) and of TVA axis (right).

oblique to shear direction; and (4) L_T parallel to shear direction. The corresponding fold geometry (Fig. 3) comprises (1) one-dimensional sheeted vein stockwork, (2) two-dimensional cylindrically (sigmoidally) curved stockwork, (3) three-dimensional (egg-carton) folded stockwork, and (4) a simple one-dimensional array of sheath folded veins in mylonites. The four structural stages have diagnostic orientational relationships between foliation, tension veins, fold axes, and elongation (mineral) lineation. The egg-carton stockwork produced by the progressive rotation of veins within the shear plane is distinguished from other mechanisms that involve overprinting, by the non-folded (planar) nature of the foliation (where present) or axial plane of the folded veins. The metasomatic evolution (the fluid filling the veins), which accompanies this structural evolution, commonly has a fifth stage wherein the TVA is flooded with replacive material in the vein walls (Fig. 3). The replacive material is most commonly silica or carbonate. TVAs thus evolve through a one-, two-, and three-dimensional stockwork (Laing, 2002b), then in the most deformed stage they revert to a simple one-dimensional pipe, which may be massive silica.

Orebodies that develop in the FSZ have a relationship with the TVA axis which depends on the timing of ore deposition during the shearing event (Fig. 4). Orebodies form parallel to the TVA axis because it is the locus of dilation (open space) and fracture intersection, and its early cylindricity creates strong permeability along the TVA axis. Early orebodies formed parallel to the TVA axis, and to any folds in the FSZ, rotate during the continuing strain together with these early elements. Late orebodies form parallel to the TVA axis, and overprint the earlier rotated TVA axis and folded veins. Deposits that appear to be complex stockworks ('chaotic/random stockworks') can be resolved into their component ore-depositing events by determining the timing of veins, via timing their TVA axis.

The widespread occurrence of veins in shear zones (sub)parallel to the cleavage, is difficult to explain in a simple bulk strain ellipsoid model in which the cleavage is parallel to the maximum compressive plane; it is commonly ascribed to either a later strain regime dilating earlier cleavage, or overpressuring fluid conditions (e.g. Phillips et al., 1998, p. 134). The present analysis suggests that in a proportion of cases the (sub)parallelism of veins and cleavage is due to the rotation of early tension veins towards or into the cleavage during a single progressive strain event. In some studied cases this is confirmed by a continuum of uniform-style veins with orientations varying from tension veins oblique to cleavage to veins essentially parallel to cleavage.

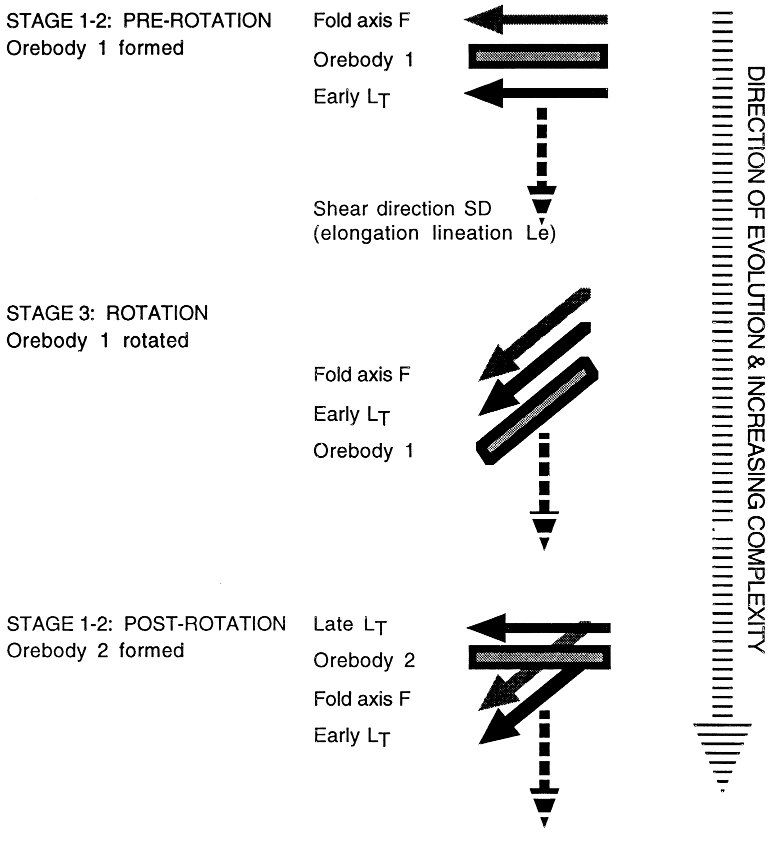

Fig. 4. The relationships between TVA axes (early and late), fold axis, and orebody orientation, for an early-formed orebody (top) and later-formed orebody (bottom). The later orebody forms in infinitesimal strain stage 1 despite the finite strain stage of the FSZ being at least stage 3. Longitudinal section in plane of FSZ.

3. TVAs in fault displacement analysis

The five structural/metasomatic stages of TVA evolution provide a diagnostic guide to the strain state of the FSZ, and the expected geometry and orientation of ore deposits in the FSZ (Fig. 2). The diagnostic TVA axis L_T is manifest pervasively throughout the TVA via its five forms L_p, L_v, L_f, L_b and L_i, and is readily measured in outcrop and particularly in drillcore. A detailed recipe for kinematic and strain analysis, based on the structural elements present, is provided in Table 2. Discrimination between early and later tension veins provides more detailed constraint on the strain and displacement history, and on the timing of ore deposition (Fig. 4). Some of the diagnostic architectural parameters are non-vectorial and can be measured in non-oriented rock such as unoriented drillcore. Two examples of these scalar diagnostic parameters follow:

(a) The linear versus non-linear nature of L_T is determined from the angle in FSZ cleavage, between L_T and the shear direction manifest as an elongation lineation; this is a scalar, measured in the cleavage plane with a protractor.
(b) The colinearity of measured L_T is a pattern, which can be determined in unoriented drillcore by docking a length of drillcore (say 5–10 m), scribing an arbitrary bottom-of-hole line on the drillcore, and measuring the orientation of 10–20 veins in a drillcore orienting frame or via the α/β method; their poles form a great circle stereographic distribution where they are colinear, and the pole of the great circle represents the TVA axis.

Some of the diagnostic parameters (vector and scalar) require a significant size of exposure; for example, the vein array angle and its derived shear sense. This parameter can be analysed in drillcore, but requires a statistical approach to the small vein segments provided by drillcore.

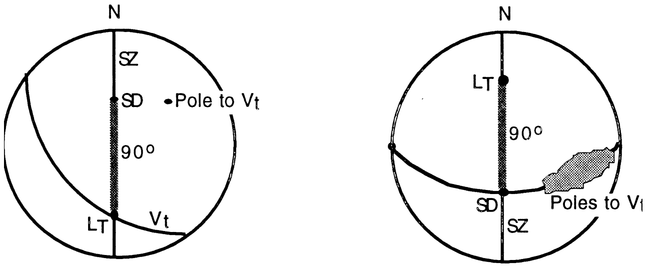

Fig. 5. Calculation of shear direction (displacement vector) for a stage 1 or 2 TVA, by measuring the TVA axis L_T, thence 90° rotation in the shear plane (shear zone SZ) to the shear direction (SD). Construction for planar tension veins on left, sigmoidally folded tension veins on right.

TVAs provide two of the three displacement components of their parent FSZ: direction, and sense, of displacement. The displacement direction is most readily determined from the initial L_T with its perpendicular relation to the displacement direction (Figs. 1, 2 and 5) (analogous to stress analysis via the P–T axes method of Stauder (1962)). Where measurement of an L_T population shows a non-linear distribution, the initial L_T may be identified from the symmetrical centre of the L_T population. The sense of displacement is determined from the vein array angle (Fig. 6, with extra detail in Ramsay and Huber (1983) and Laing (2002a)). TVAs do not provide the third kinematic component, displacement distance. However, the strain state (Figs. 2 and 3) yields a qualitative measure of the degree of movement across the FSZ. The expression of a TVA in a map (or underground wall) provides an initial guide to its kinematics (Fig. 7), with the proviso that a two-dimensional exposure may provide misleading information (Smith, 1995) and requires careful interpretation.

TVAs are a most effective structural tool for analysing the kinematics and relative strain of FSZs. TVAs are

Table 2
Primary measurement of TVA elements from rock exposure. The recipe commences with the ingredients (left-hand column) and proceeds to the right, via measurement and stereographic plotting, to the elucidated TVA element (right-hand column). Note the multiple, equivalent ways of determining the principal TVA elements; SZ or F and L_T

Present in exposure	Measure	Plot (stereographic)	Element
One vein, planar	Dip of vein	Pole to vein	V_t
Two veins, planar, not intersecting	Dip of veins	Two poles–great circle–pole = L_v	$V_t(1)$, $V_t(2)$ and L_v (calculated)
Two veins, planar, intersecting	Dip of veins	Two poles–great circle–pole = L_v	$V_t(1)$, $V_t(2)$ and L_v (calculated)
	Plunge of intersection	Plunge of intersection	L_v (measured)
One vein, planar	Plunge of vein tipline	Plunge of vein tipline	L_i (measured)
One vein, folded or bulging	Plunge of fold or bulge	Plunge of fold or bulge	L_f or L_b (measured)
One vein plus fault/SZ foliation	Dip of vein, dip of foliation	Two poles–great circle–pole = L_p	V_t, S_p and L_p (calculated)
	Plunge of intersection	Plunge of intersection	L_p (measured)
Foliation or fault	Dip of foliation or fault	Pole to foliation or fault	SZ or F
Foliation/fault plus fibres or mineral lineation or slickensides	Dip of foliation/fault, pitch or plunge of elongation lineation	Pole to foliation	SZ or F
		Plunge of elongation lineation	L_e
External boundaries of shear zone, fault zone or TVA corridor	Dip of boundaries	Pole to boundaries = S_p	F, SZ or TVA

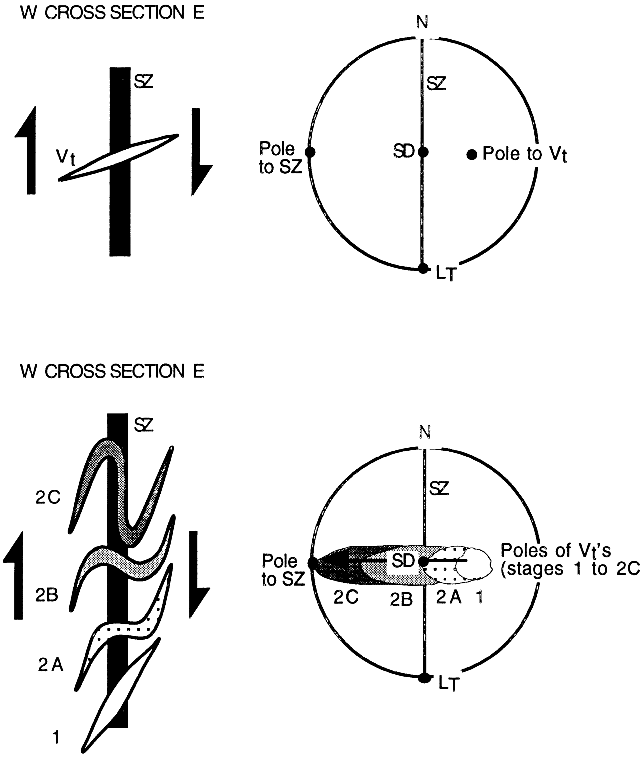

Fig. 6. Calculation of shear sense, by measuring tension veins and determining vein array angle from the asymmetry of poles across the FSZ. Planar tension veins at top, sigmoidally folded tension veins beneath. The sense of shear is the rotation from the pole of the (late) planar vein through the obtuse angle to the pole of the FSZ (measured in the lower hemisphere). The example given in both cases is pure dip-slip, W-block-up.

significantly more common in FSZs than indicated in the literature (including FSZ-hosted ore deposit descriptions) as discussed below. Elongation lineations (mainly mineral fibres in faults and mineral lineation in shear zones) may be as widespread as TVAs, and delineate the displacement vector, but commonly fail to provide the sense of movement because mineral lineation is symmetric and mineral fibres are commonly too fine to observe the diagnostic imbricate fabric. Ductile shear zone textures (asymmetric porphyroclasts, etc.) are prone to the same difficulty, and are not so widely developed across the spectrum of faults and shear zones. Marker units are the principal tool for determining displacement distance, which is provided by neither TVAs nor elongation lineation, but they are less commonly available than the internal FSZ structures such as TVAs and elongation lineation, especially in high-strain terranes such as the Yilgarn.

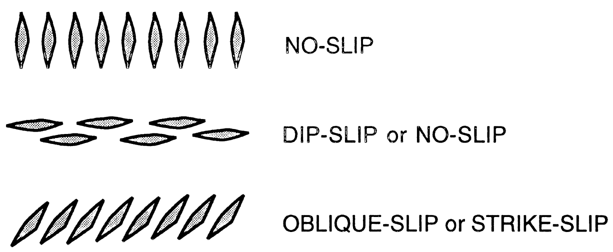

Fig. 7. Guide to the kinematics of a TVA from its mapped pattern of veins. View normal to the FSZ. This pattern is replicated for a vertical or obliquely oriented exposure (for example underground walls) by appropriate modification of the interpreted slip direction.

4. The systematic under-recognition of TVAs

The West Australian Yilgarn is renowned for its FSZ gold deposits (Eisenlohr et al., 1989; Hammond and Nisbet, 1992; Passchier, 1992; Swager, 1997; Vearncombe, 1998), yet few are described as related to TVAs (for example in comprehensive volumes such as Hughes (1990) and Berkman and Mackenzie (1998)). The author's 20 deposit consultancies in the Yilgarn include 10 TVA-related deposits, and 110 world-wide consultancies include 27 TVA-related deposits (Laing, unpublished reports). That is, between 25 and 50% of the (mostly gold) deposits are interpreted as occurring in or related to a TVA. The under-recognition of TVA deposits is inherently due to their complex structural/metasomatic architecture, which tends to obscure the underlying coherence of the TVA, and their occurrence in ore deposits with poor to zero exposure, commonly limited to drillcore with maximum vein 'outcrop' measured in centimetres:

1. A TVA is similar to a shear-fracture array, and in some cases difficult to distinguish.
2. The fractures/veins of a TVA may be reactivated as faults in later deformation.
3. A TVA is not a single structural feature, it is a specific suite of structures—veins ± faults ± foliation ± shear zone boundary ± folds—in a specific geometric relationship to each other. In poorly exposed ore deposits, the 'wood' is less visible than the 'trees'.
4. TVAs occur generally at a scale larger than the mesoscopic arrays which feature prominently in published photographs. Their diagnostic architecture (e.g. folded veins, parallel vein tips, array of parallel L_T axes) may only be evident at decametre scale. Tension veins commonly have a high aspect ratio (length:width) of the order of 100–1000, which means that the characteristic tension vein wedge shape and termination distal from the parent structure may be present, but inscrutable without large exposures.
5. TVAs may be associated with faults, or shear zones, or with neither, in a TVA-only shear zone (see below).
6. Tension veins are infill structures, they commonly comprise multiple infill stages, and they may contain complex infill combinations of comb-textured minerals, fibrous minerals, and breccia.
7. A TVA commonly consists of older and younger veins in a spectrum of progressive deformation.

Overprinting relationships between veins, some planar, some folded, produce a deceptively complex stockwork in which vein sets may be erroneously classified as distinct events.

8. The folded tension veins of stages 2–4 are commonly mistaken as an event older than the genetically related faults or foliation, which are axial planar to the folds (classed as 'veins predating the shear zone').
9. The geometry of classic sigmoidally folded, and intersecting early/later tension veins, only appears cleanly in an exposure viewed along the TVA axis L_T. Other views produce an apparently chaotic, folded stockwork, particularly in drillcore.
10. In the later stages of TVA evolution, the folding of the veins may distort or destroy the original vein array angle, and sufficient rotation can produce an angle which is the reverse of the initial geometry.
11. Increasing strain in a shear zone converts the original simple TVA sheeted stockwork, progressively into a simply folded stockwork, a complexly folded stockwork, and then simple sheath folds. TVAs are a structural 'chameleon'.
12. Metasomatism during TVA development can produce a selvedged TVA, with a more complex architecture than a simple infill vein TVA. The selvedge may pervade the entire TVA, and it may obliterate the veins themselves. A TVA may become a siliceous pipe. Large orebodies (e.g. Marvel Loch; Laing, unpublished report to Sons of Gwalia Ltd) are commonly accompanied by such alteration.

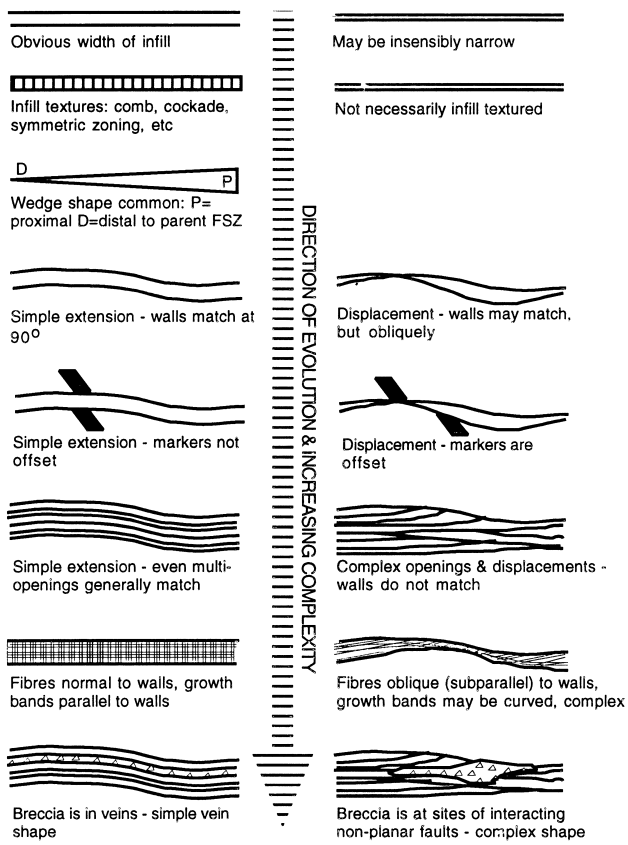

Fig. 8. Morphological guide to distinguishing tension veins and faults.

5. Diagnosing a TVA and determining its parent structure geometry

A TVA is diagnosed in two steps: identification of tension veins, and confirmation that they are part of a TVA. Tension vein diagnosis is necessary, but not sufficient, for diagnosing a TVA, because tension veins may be formed in scenarios other than a TVA. Tension veins are identified morphologically (Rickard and Rixon, 1983; Smith, 1995, 1996a,b; Fig. 8) and an absence of displacement of marker units across the veins. In ore deposits earlier veins provide useful marker units. A TVA is subsequently identified on several rigorous architectural criteria. Firstly a number of potential TVA axes are measured on the vein array, as detailed in Table 2; only a small population (5–20) is required. The distribution permits the diagnosis of a TVA.

Where the proposed TVA axis is distributed within the plane of the proposed parent FSZ, this is a necessary, and almost sufficient, condition to prove a TVA. The parent structure may be any combination of fault/shear zone and/or the TVA itself, which defines the corridor of shearing. The stockwork might not be related to the FSZ, but alternative strain scenarios involve a coincidental parallelism between the non-TVA stockwork and the FSZ. The vein distribution may be either a point maximum or a spread, according to the FSZ strain stage (respectively, stages 1–2 or 5, versus 3–4).

A distribution of the proposed TVA axis outside the plane of the proposed parent FSZ is sufficient to disprove a TVA. The stockwork cannot be related as a TVA to the FSZ.

Many TVAs occur in regional FSZs with histories of multiple internal deformations. In these FSZs it may not be clear which parent structure is associated with a particular identified TVA. In poorly exposed terrains the parent structure, being large, may be unclear despite mesoscopic

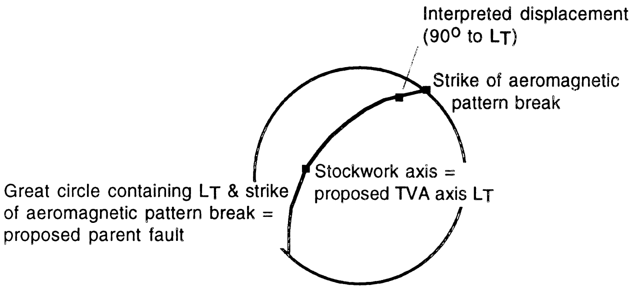

Fig. 9. An example of the determination of the orientation of the parent structure of a TVA, from the TVA axis and the strike of a candidate structure (in this case a regional aeromagnetic pattern break). The fault displacement vector can also be derived, as the line 90° removed around the parent structure from the TVA axis.

evidence of a coherent apparent TVA. In both these situations the diagnostic procedure can be implemented in reverse, to help identify the parent structure of a vein array that internally contains all the necessary characteristics of a TVA. In this scenario the apparent TVA axis, measured as the stockwork axis (as above), must lie within the (as yet unknown) plane of the parent FSZ. In the example of Fig. 9, a proposed TVA axis measured in drillcore was correlated with an aeromagnetic pattern break striking NE, to identify a candidate parent fault dipping 50°NW. This was independently supported by the concurrently-interpreted strike-slip displacement (the vector 90° removed from L_T within the plane of the fault, as in Fig. 5) which was consistent with independent regional data.

6. Ore deposits in TVAs

6.1. Deposit environment

TVA-hosted ore deposits occur in all geological environments containing FSZs. These include, in particular, fold-belts, crustal-scale shear zones, and epithermal, mesothermal, and porphyry ore environments. The principal, but not sole, commodities comprise gold, silver and base metals.

6.2. Architecture—where is the deposit orientationally?

Ore deposits hosted by TVAs take a variety of forms. These reflect the geometry of the FSZ strain stage (Fig. 2). Deposits in general comprise a combination of vein infill (invariably) and replacive selvedge enclosing the TVA (in a proportion of deposits). Linear ore deposits and ore shoots are characteristic (Figs. 1 and 2): vein/fault intersections, vein/vein intersections, the hinges of sigmoidal veins, and breccia and/or replacive pipes in dilational jogs. These shoots are overwhelmingly parallel to the TVA axis L_T. From this it follows that low-strain deposits are normal to the shear direction, medium-strain deposits are oblique to the shear direction, and high-strain deposits are parallel to the shear direction.

Low-strain deposits occupy a simple sheeted vein stockwork with planar or cylindrically curved veins (Victoria (Claveria et al., 1999), Cadia, Golden Mile, Binduli, Ora Banda, Bartons, Transvaal, Emerald Reward, Hadleigh Castle, Soapspar; Laing, unpublished company reports). Medium-strain deposits occupy a folded, overprinting, stockwork, which nevertheless contain a specific line, L_T, colinear in each vein (Waihi (Sibson, 1987), Golden Cross (Corbett and Leach, 1998), Bendigo, Stawell, Sunrise Dam (Figs. 10 and 11), Mount Marion (Figs. 10 and 11), Eloise, Tunkillia, Union Reefs, Orient Well; Laing, unpublished company reports). High-strain deposits occupy complex folded stockwork with no common fold axis (Yilgarn Star; Laing, unpublished company report). Ultra-high-strain deposits occupy simple pipes parallel to the elongation lineation (Marvel Loch; Laing, unpublished company report).

6.3. Localisation along the host FSZ—where is the deposit spatially?

The internal architecture of a TVA deposit may be more readily determined than the controls on its localisation along the parent FSZ. TVAs form along their parent FSZ, but may wax and wane along its length according to various factors, as follows (see also Caine et al., 1996; Fig. 1) (example in Fig. 12):

(a) lithological (competency) changes along the FSZ;
(b) variations in pore fluid conditions (pressure, flux, composition);
(c) bends, which cause stress and strain variations; dilational jogs commonly host a TVA;
(d) the ends (tips) of the parent structure tend to localise TVAs (Zhang et al., 2001); these fault-tip TVAs may be developed domainally along the FSZ as discussed in detail by Kim et al. (2003).
(e) intersections with other FSZs.

The variations in TVA intensity, measured as vein density, vein intersection density, and/or total dilation, may be gradual and/or minor, or they may be sharp. Sharply increased TVA intensity tends to produce ore deposits (and ore shoots within a deposit) with pipe geometry. The pipe is elongate parallel to the TVA axis. In a low-strain FSZ the pipe is normal to the shear (elongation) direction (Fig. 12), and in a high-strain FSZ the pipe is (sub)parallel to the shear direction. The reason for a localised TVA along an FSZ may not be obvious, especially in a complex geological environment. Determining ore controls in a TVA ore deposit is a two-step process: (i) determine that a TVA hosts the ore, via TVA analysis, and (ii) determine the reason(s) for the localisation of the host TVA along the parent structure, by searching for controls of the kind listed above, via mapping of the fault zone, its TVA, and its wallrock types.

6.4. Large to world-class ore deposits

Shear zones may contain a TVA without accompanying faults or foliation. These are termed type 1 FSZs (Fig. 13). They form via a strain partitioning mechanism described as kinematic control on fracturing (Mandl, 1988; Smith and Durney, 1992; Smith, 1993). FSZs may transform into TVAs via lateral strain partitioning; as may faults laterally transform into foliated ductile shear zones. A transitional type of TVA comprises tension veins linked by shear fractures (Peacock and Sanderson, 1995). In type 1 FSZs the host rock deforms by combined ductile strain of the host grain aggregate, and brittle fracture with extensional

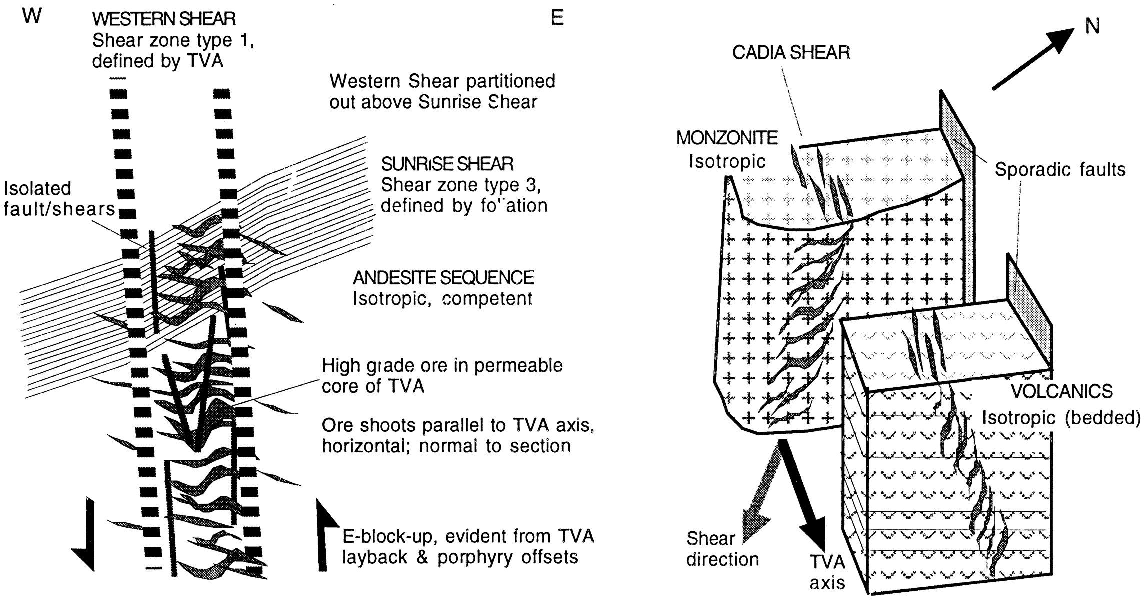

Fig. 10. Two world-class ore deposits in type 1 shear zones: Sunrise Dam (cross-section on left) and Cadia (block diagram on right). The ore in both consists dominantly of infill in the tension veins, with lesser resource in narrow selvedge around the veins. The principal infill niche (see Laing, 2002a) at Sunrise Dam has ultra-high niche grade (thousands of grammes per tonne) while Cadia has low niche grade.

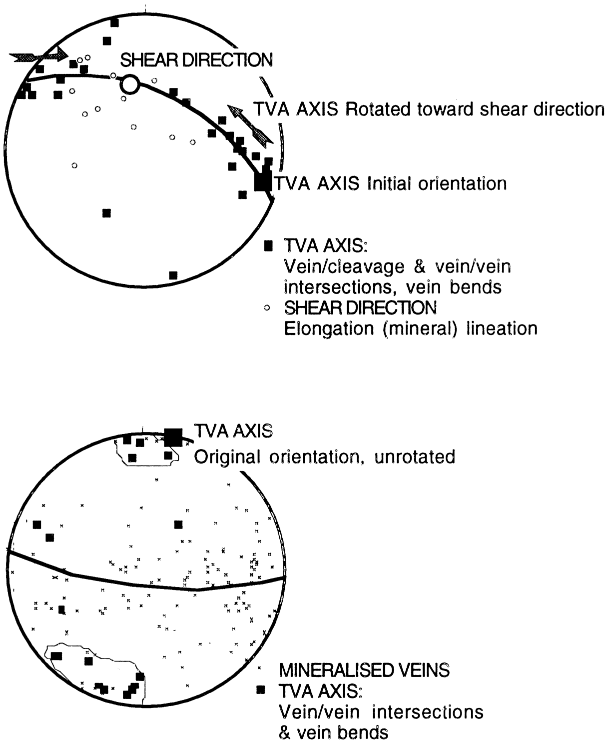

Fig. 11. Orientation diagrams for TVA structures at Mount Marion (on top) and Sunrise Dam (beneath). Mount Marion is a stage 3 (medium-strain) oblique slip TVA with the TVA axis rotated halfway to the shear direction, while Sunrise Dam is a stage 2 (low-strain) dip-slip TVA, with mild rotation of the TVA, evident in a small spread of veins away from the girdle, and a small spread of L_T.

veining. The dominance of brittle deformation over ductile deformation in type 1 shear zones renders them less likely to progress to strain stages 3–4, and preserves a coaxial stockwork with a concomitant anisotropic high permeability parallel to the TVA axis. Type 1 shear zones may be expected to be mostly small-displacement structures. Vein opening may be relatively prolonged as there is no shear across the fractures. Vein density may be abnormally high because vein dilatancy is the principal manner of accommodating the far-field strain. The TVA is unusually dilatant and permeable, and it remains so if it has a prolonged history and a resultant high vein density. Type 1 shear zones may form metasomatic 'super highways'. This conclusion is supported by the findings of Caine et al. (1996) that damage zones around faults possess permeability several orders of magnitude greater than the fault core, and form the principal conduit in fault zones.

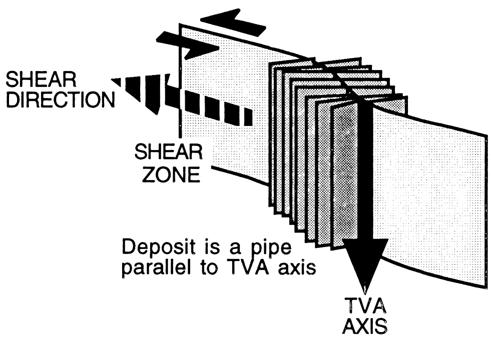

Fig. 12. Geometry of a TVA-hosted ore deposit or shoot, at a bend (antidilational jog in this case) in the parent FSZ. The TVA extends substantially further along the TVA axis than in the other dimensions. Hence an orebody or shoot hosted by an individual vein or by the TVA has its long axis parallel to the TVA axis.

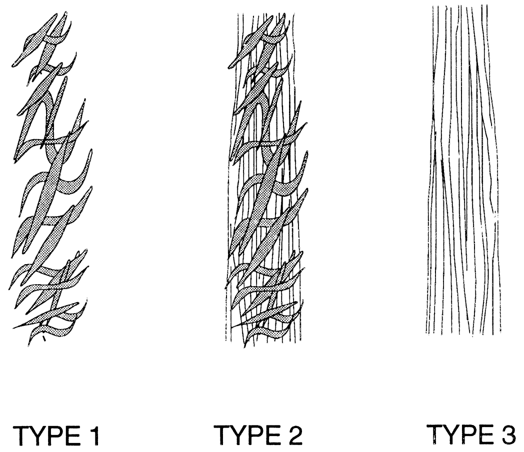

Fig. 13. The three fundamental types of brittle and/or ductile shear zone (excluding cataclastic shear zones). In types 2 and 3 the foliation may be parallel or oblique to the zone boundaries.

Type 1 shear zones tend to occur in isotropic rocks, low in phyllosilicate content, in the brittle/ductile crustal regime at relatively shallow crustal levels. Typical host regimes are porphyry/epithermal, granitoid, and sedimentary basinal environments. An important type 1 TVA also occurs in deeper regimes, in isotropic competent 'islands' within ductile shear zones. The Yilgarn contains many such examples, in TVA stockworks in felsic porphyry (Binduli, New Celebration), competent dolerite (Paddington), and BIF lozenges in regional shear zones.

World-class TVA deposits in type 1 FSZs include Sunrise Dam Au (WA), Cadia Cu + Au (NSW) deposits (Figs. 10 and 11), Waihi Au (New Zealand) and Victoria Au (Philippines). Sunrise Dam (6 million ounces Au; Gold Gazette, 2002) occupies subvertical type 1 dip-slip shear zones beneath an earlier shallow-dipping type 3 shear zone (Newton et al., 2002). High grade ore, to several percent gold per metre, lies in dilatant breccia vein infill in the type 1 conduits, and lower grade, at around 2–8 g/t, in alteration selvedge in the trapsite formed by the large type 3 shear zone (Laing, 1999). The host rock is mostly isotropic andesites and BIFs. Cadia (18.7 million ounces Au, 2.45 million tonnes Cu; Newcrest Mining Limited, 2001) consists of five laterally subjacent deposits within a subvertical type 1 shear zone (Laing, 2000). The ore lies in narrow tension veins (infill and selvedge) within isotropic monzonitic stocks and andesites. Waihi (6.4 million ounces Au) lies in an en échelon vein array, which has been interpreted alternatively as a shear-fracture array (Braithwaite and Faure, 2002) and as a TVA (Sibson, 1987), which is a type 1 FSZ in andesite flows and volcaniclastics. Victoria Au deposit (Claveria et al., 1999) contains in excess of 2.3 million ounces (Cuison et al., 1998) in a TVA in a type 1 FSZ hosted by dacite volcanics and porphyries.

Strike-slip FSZs have a down-dip TVA axis. This facilitates deep crustal tapping, and the direct liberation of large fluid volumes with high fluid fluxes to the upper crust, and to the surface in epithermal environments. The known propensity of regional strike-slip faults (e.g. Philippines Fault) to host large epithermal Au and porphyry deposits, is ascribed partly to the strong channelling capacity of their vertical TVA axis.

6.5. Exploration in FSZs and TVAs

Exploration of FSZs requires detailed understanding of the geometry of their contained TVA. The complex, but predictable, architecture of the TVA has several unusual features that require careful exploration design, particularly in light of the varying scale of the TVA architectural elements.

The predicted TVA-hosted ore deposit architecture critically depends on the strain state of the host FSZ, and drilling strategies and directions need to change accordingly (possibly dramatically). Documentation of ore controls in the literature on FSZ deposits focuses almost exclusively on the displacement vector, but most deposits and shoots in FSZs are controlled by the TVA axis. TVA analysis yields the TVA axis and the strain state, which control the orebody elongation and the direction of internal shoots. The principal

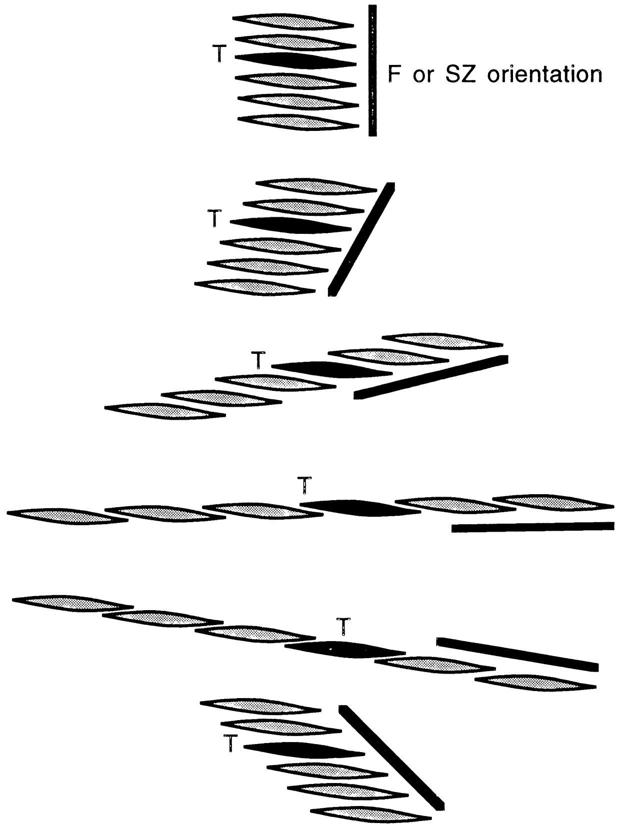

Fig. 14. The range of geometries of a TVA with variation in the shear sense and the vein array angle, showing possible scenarios for the extensions of faults and TVAs, away from a single exposed tension vein (T). For a given exposed tension vein (black), the host TVA may have any of the depicted shapes. The black line indicates the orientation of the parent fault or shear zone; this is the direction in which to explore along the TVA for more veins. There is a 180° arc of possible search directions. Should an initially-located tension vein be erroneously classified as a fault vein (or vice versa) the search direction will be incorrect.

shoot direction, parallel to the TVA axis, changes from normal, to parallel, to the displacement vector as the strain state progresses.

The en échelon geometry means that a tension vein lode extends in a direction different from repeats of the lode or a deposit comprising multiple veins (Fig. 14). Similarly, a tension vein lode has a different trend from a deposit comprising the TVA alteration selvedge. Exploration of an initially 'single vein lode' deposit needs to take into account the possibility that it is part of a larger TVA, by searching for repeats which do not lie on the prolongation of the known lode. The correct search direction vitally depends on the vein array angle between the lode vein and the host FSZ. The lode repeat can be anywhere within a 360° arc of the known vein. TVA analysis identifies the correct quadrant for exploration.

Each vein in a developing exploration program needs to be classified as a fault, a tension vein, or a reactivated fault/tension vein. A fault vein lode and a tension vein lode extend in different orientations; the former along its length, the latter across its length in a multi-directional TVA scenario (Fig. 14). The fundamental relationship between a parent fault and a tension vein is shown in Fig. 15. The geometry of tension veins across a parent fault may be categorised into three cases: throughgoing tension vein, faulted tension vein, and asymmetric tension vein, and each case requires a different targeting strategy for vein extensions.

Tension veins may laterally change thickness dramatically, because of their (sigmoidal) shape, and also because they are commonly wedge-shaped, with a sharp truncation at their thick end against the 'proximal' parent FSZ, thinning to the 'distal' vein tip. Drilling strategies in a TVA require careful derivation of the interpretation

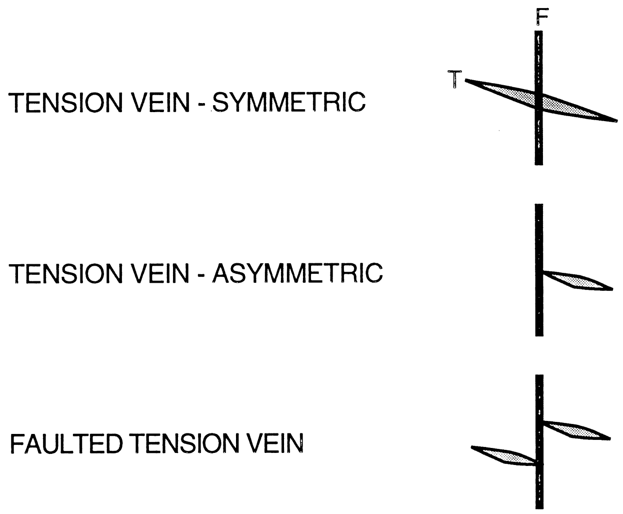

Fig. 15. The three possible across-fault relationships between a tension vein and a parent fault. A tension vein may span the parent structure or it may extend only on one side. Tension veins may be faulted by their parent fault during the FSZ deformation. Each scenario requires a different exploration strategy.

template (Laing, 2002a) early in the program to permit the correct (or the most real) correlation between drill intercepts.

The surface footprint of a TVA deposit changes dramatically according to the FSZ shear direction. Dip-slip FSZs produce subhorizontal deposits with a long footprint but possibly little depth extent; strike-slip FSZs have a small footprint but a considerable potential depth extent. Dip-slip deposits may not outcrop, but rapidly make resource at shallow depth; strike-slip deposits are likely to outcrop but in a small area. Because TVA deposits are built on dilation, they commonly attain high grade and correspondingly small volume.

TVA-hosted deposits require vigilant exploration informed by detailed knowledge of the host TVA architecture.

6.6. Resource definition

TVA deposits have historically been classed generally as stockwork-hosted, sheeted vein, or vein-hosted deposits. Sheeted vein TVA deposits are likely to occur in low-strain FSZs. Stockwork-hosted TVA deposits are likely to occur in medium to high-strain FSZs. Within this variety of styles, their variography is generally strongly anisotropic, which provides a clue to their origin in a TVA. The variography potentially also provides a guide to their TVA strain-stage classification, hence the relative strain state, by relating the variographic axes to the TVA axis and the elongation lineation. There is currently no information on the relationship between variography and TVA architecture. It might be expected that the axis of maximum range (resource continuity) would be generally parallel to the TVA axis.

7. Summary

Each vein in an exploration program needs initially to be classified as a fault, a tension vein, or a reactivated fault/tension vein. TVAs contain a linear axis, which tracks the strain state, and can be employed to determine the principal kinematic components of the parent FSZ. Establishing the presence and architecture of a TVA (TVA analysis) can be completed on minimal information, using a combination of scalar and vector rock data. The presence of a TVA is identified via the orientational pattern of TVA axial elements (colinear, coplanar or neither), which is a scalar. Measurement of this pattern can be on large pieces of unoriented rock: mine dumps, talus debris, glacial moraine, or a single unoriented drillhole (provided the core is dockable). The orientation of the TVA elements is a vector, which requires (only a small) in-situ rock sample: a small number of veins in outcrop, a costean, or a single oriented interval of drillcore. Oriented drillcore permits a full TVA analysis and identification of the kinematic and strain states.

TVAs in ore systems and ore deposits are under-recognised for a number of inherent geological reasons. TVA-hosted ore deposits have widely varying architectures, and a large part of the variation reflects the evolutionary stages of the TVA from low to ultra-high-strain. The TVA axis marks the primary long axis of the ore deposit and ore shoots. As strain increases, the deposit and shoot elongation direction changes systematically, from normal, through oblique, to parallel, to the displacement vector. As strain increases TVA-hosted deposits tend to become increasingly dominated by alteration, which further obscures an increasingly complex strain architecture. However, at highest strain, TVA-hosted ore deposits revert to a simple pipe architecture at 90° to the original deposit long axis. FSZ-hosted ore deposits parallel to the elongation (mineral) lineation should be carefully investigated for fossil low-strain enclaves, which may reveal a complex evolutionary history. In TVA environments, repeats of lodes or shoots occur removed from the prolongation of the known lode or shoots. The complex history and architecture of TVA-hosted deposits means that the success of exploration will be in proportion to the knowledge of the TVA architecture.

Type 1 FSZs, comprising a TVA without faults or foliated shear zones, are anomalously permeable, long-lived fluid conduits which tend to host large ore deposits in a range of major metallogenic environments. Strike-slip FSZs with their subvertical TVA axis form particularly effective vertical conduits for deep-sourced fluids.

TVA analysis permits the recognition of a TVA and its parent structure, the prediction of orebody location and geometry within the TVA architecture, the design of exploration and drilling programs to locate these orebodies, and the focussing of exploration toward large TVA-hosted orebodies.

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