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# The Tam Ky-Phuoc Son Shear Zone in central Vietnam: Tectonic and metallogenic implications

Hai Thanh Tran [a,*], Khin Zaw [b], Jacqueline A. Halpin [b], Takayuki Manaka [b], Sebastien Meffre [b], Chun-Kit Lai [b], Youjin Lee [b], Hai Van Le [c], Sang Dinh [b]

[a] Department of Geology, Hanoi University of Mining and Geology, Hanoi, Viet Nam
[b] CODES ARC Centre of Excellence in Ore Deposits, University of Tasmania, Private Bag 126, Hobart, Tasmania 7001, Australia
[c] Olympus Pacific Minerals Inc., Da Nang, Viet Nam

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ABSTRACT

The Tam Ky-Phuoc Son Shear Zone (TKPSSZ) is one of the most pronounced crustal structures in central Vietnam and juxtaposes high-grade rocks of the Kontum Massif against lower grade rocks of the Truong Son Fold Belt. An internal zone comprises highly strained rocks, including ultramafic–mafic tectonites, bounded by mylonitic zones that straddle tens to hundreds of kilometers. An external zone comprises mainly high-grade metamorphic complexes (southern flank), and weakly metamorphosed siliciclastic and carbonate rocks with subordinate greenstone (northern flank). Detailed structural analysis reveals that the shear zone is a multi-deformed terrane: $D_1$ produced a regional high grade schistosity and mylonitization; $D_2$ generated regional northwest–southeast trending fold arrays and brittle–ductile shear zones; $D_3$ locally produced northeast-trending folds; brittle faulting occurred during $D_4$–$D_5$. U–Pb dating of zircon and monazite suggests that $D_1$ involved metamorphism and felsic magmatism at ca. 430 Ma, recording part of a regional collisional orogeny. Monazite and titanite growth at ca. 250–240 Ma in basement rocks is synchronous with widespread syn- to post-$D_2$ magmatism between ca. 260 and 245 Ma suggesting a second major collisional event during the Indosinian Orogeny. $D_3$ may have occurred as part of (or soon after) this Permo-Triassic event. Deformation during post-collisional stages, perhaps in response to extrusion/wedging and oroclinal rotation of terranes, led to post-$D_3$ structures ($D_4$–$D_5$). The E–W trending TKPSSZ is here shown to be a continuation of the N–S trending Po Ko Shear Zone (PKSZ). Most of the significant lode gold occurrences in central Vietnam occur along this TKPSSZ–PKSZ structure and are associated with, and controlled by, $D_1$ ductile to ductile–brittle high-strain zones. Mineralized later-stage structures support remobilization and reconcentration of ore during subsequent events at ca. 240 Ma (Re–Os molybdenite age). The TKPSSZ–PKSZ $D_1$ structure likely represents part of a paleosuture zone, marking the closure of an ancient ocean basin through terrane assembly in the Early Paleozoic.



## 1. Introduction

In central Indochina, an extensive zone of shear-bounded, mélange-style exotic blocks of heterogeneous composition, including ophiolite-type mafic–ultramafic blocks and arc-type volcanic assemblages, has been termed the Tam Ky-Phuoc Son Shear (or Suture) Zone (TKPSSZ, Nguyen and Tran, 1992; Nguyen, 2001; Quynh et al., 2004; Lepvrier et al., 2004). The shear zone generally trends east–west, from the East Sea (or South China Sea), near Tam Ky in the east, and extends more than 100 km to Phuoc Son district, near the Vietnam–Laos international border in the west, where it is transected by a series of complex cross faults and folds (Fig. 1). West of Phuoc Son, the shear zone appears to trend into and across the Laos border but surface exposure is not clearly defined. This zone forms the margin of the Kontum Massif, central Vietnam, where it separates the generally high-grade metamorphic rocks of the, probably Precambrian, Kontum Massif in the south against the lower grade Early Paleozoic sedimentary rocks in the north (Fig. 1). Along the TKPSSZ, numerous gold occurrences of various sizes have been identified, some of which comprise important economic gold deposits, which have long been explored and/or mined.

Structural interpretation from recent investigations along the TKPSSZ (Tran et al., 2008, 2009) indicates that this shear zone is characterized by thermotectonic reworking. Most of the rocks were stretched, flattened, isoclinally folded and extensively mylonitized, forming of an up to tens of km thick high-strain zone. The ductile fabrics were successively refolded and faulted by later deformational events. The repeated folding and fracturing led to complex geometry and surface expression of the shear zone.

* Corresponding author. Tel.: +84 4 3838 4048.
*E-mail address:* tranthanhhai.geo@humg.edu.vn (H.T. Tran).

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All of the major gold occurrences along this major crustal structure appear to be shear zone-hosted, lode-type and closely associated with, or controlled by, the brittle–ductile to ductile shear zones which are part of the main TKPSSZ (Nguyen, 1996; Banks et al., 2004; Borisenko et al., 2006). Despite this intimate relationship with ore deposits, the nature and origin of this shear zone are not well understood and age constraints for the host rocks and the timing of mineralization are scarce. Some workers suggest that the TKPSSZ juxtaposes two continental blocks to form Indochina (e.g., Lepvrier et al., 2004) whereas others argue that this zone is an intracontinental structure that formed during an orogenic event (i.e. Indosinian Orogeny; e.g. Gatinsky and Hutchison, 1987). In this paper, we review previous limited geological investigations and present the results of our recent work on the structural and geochronological history of the TKPSSZ, regional implications, as well as its relationship to gold metallogeny.

## 2. Regional geological setting

The central Indochina area comprises a 'core' block, generally known as the Kontum Massif (part of the Truong Son Fold Belt), of dominantly high-grade para- and ortho-gneissic rocks, which are intruded by numerous magmatic complexes of varying age and origin. Low-grade and unmetamorphosed sedimentary rocks are rare within the Kontum Massif but extensively cover much of the northern and western part of central Indochina (Fig. 1a). Metamorphic conditions reach high-*T*/ultrahigh-*P* (~900 °C at ~40 kbar) overprinted by high-*T* to ultrahigh-*T*/med- to high-*P* (up to ~1000 °C at 11–12 kbar) in the core zone (Kannack and Ngoc Linh complexes: Nam et al., 2001; Nakano et al., 2007; Osanai et al., 2008) and peak conditions are ~700–750 °C at ~6–8 kbar along the western and northern margins of the massif (Kham Duc Complex: Osanai et al., 2008; Usuki et al., 2009). These metamorphic assemblages delineate a clockwise *P*–*T* evolution and are interpreted to represent differing crustal levels during orogenesis (Osanai et al., 2008). Although early geological maps in Vietnam considered rocks of the Kontum Massif to be Archean to Proterozoic in age, recent geochronology demonstrates the prevalence of Ordo-Silurian (i.e. 'Caledonian') and Permo-Triassic (i.e. 'Indosinian') ages (e.g. Carter et al., 2001; Nagy et al., 2001; Nam et al., 2001; Lan et al., 2003; Lepvrier et al., 2004; Maluski et al., 2005; Nakano et al., 2007; Roger et al., 2007; Nakano et al., 2008) and detrital zircon ages suggest that protoliths of the basement metasedimentary rocks were derived from Gondwana continental margin and deposited during the Neoproterozoic–Early Paleozoic (Usuki et al., 2009; Burret et al., 2014–in this issue). While these studies demonstrate that the central part of Vietnam and adjacent areas in Indochina underwent two major thermotectonic events during the Ordo-Silurian and Permo-Triassic, their regional significance is debated. The latter event is widely known as the Indosinian Orogeny (Fromaget, 1937), traditionally interpreted as recording the amalgamation of the Indochina and South China blocks (e.g. Lepvrier et al., 2004; Hutchison, 2007; Lepvrier et al., 2008; Nakano et al., 2008; Osanai et al., 2008), but which has also been attributed to far-field stresses associated with the docking of Sibumasu with Indochina (Carter and Clift, 2008). The Ordo-Silurian event in Indochina has been interpreted either as related to arc magmatism (Nagy et al., 2001), extension within Gondwana (Carter et al., 2001) or continental collision (Usuki et al., 2009).

Major crustal structures within the central part of Indochina include the TKPSSZ and the Po Ko Shear (or Fault) Zone (PKSZ), which contain abundant shear-bounded allochthonous assemblages, including probable ophiolitic rocks, and have been interpreted by some workers as sites of ocean closure during the assembly of microcontinental blocks (e.g., Nguyen and Tran, 1992; Lepvrier et al., 1997; Van et al., 2001; Lepvrier et al., 2004, 2008). The TKPSSZ lies along the northern margin of the Kontum Block, whereas the PKSZ forms its western flank (Lepvrier et al., 2004, 2008). Both zones separate the highly metamorphosed (granulite facies) rocks of the Kontum Massif against the lower grade early Paleozoic sedimentary successions of the rest of the Truong Son Fold Belt (Fig. 1). Numerous gold deposits have been identified along these shear zones and therefore they are considered important structural controls for gold mineralization in this region (see below).

Given the different interpretations of the significance of the TKPSSZ and PKSZ (i.e. suture zones vs. intraplate shear zones), the genetic relationship of the Kontum Massif to the wider Truong Son Fold Belt is controversial. Many workers consider the Kontum Massif and Truong Son Fold Belt to represent parts of the same terrane involved in Indosinian collisional orogenesis (e.g., Nakano et al., 2008; Osanai et al., 2008; Nakano et al., 2010). However, the presence of lithotectonic markers including exotic blocks of differing compositions, age and origins, from remnants of oceanic crust to arc-type intrusive and extrusive rocks that are interleaved with sedimentary sequences and high-grade metamorphic rocks along the walls of extensively highly strained zones strongly supports a paleosuture setting for these major crustal structures. Considering structural and geochronological data collected recently in these areas, Lepvrier et al. (2004, 2008) suggested a model involving oceanic subduction along the PKSZ during the Permo-Triassic. With the emerging significance of the Ordo-Silurian thermotectonism in Vietnam (e.g. Carter et al., 2001; Roger et al., 2007) and throughout SE China (e.g. Li et al., 2010 and the references therein), a Paleozoic collision between continental fragments has also been discussed, at least along the Song Ma suture zone between Indochina and South China (e.g. Carter and Clift, 2008; Usuki et al., 2009).

## 3. General structural features

The TKPSSZ is a complexly deformed domain, which can be separated into internal and external regions. The internal part of the TKPSSZ extends tens of km across strike and is represented by numerous highly-strained exotic blocks with variable composition, size, age and origin (Nguyen Van Trang, 1986; Nguyen, 2001). These include strongly dismembered, sheared and serpentinized ultramafic to plagiogranite blocks which form part of the Hiep Duc Complex (or 'ophiolite', Tran, 2009a). These bodies are scattered hundreds of km along strike and are considered to be remnants of ancient oceanic crust (Nguyen, 2001; Izokh et al., 2006; Fig. 1a,b). They are surrounded by metasedimentary rocks and locally felsic orthogneiss (Trinh, 2009a, 2009b), which, in many places, are severely deformed to form km-thick mylonite zones. The external parts of the TKPSSZ are variable in composition and degree of deformation. The northern portion of the external zone comprises predominately dismembered and shear-bounded units of interpreted Late Proterozoic to Early Paleozoic greenstone (Nui Vu Formation) and weakly metamorphosed Early Paleozoic rocks comprising mainly of sericite, chlorite and graphite schist and carbonate rocks (A Vuong Formation; Nguyen Van Trang, 1986; Pham and Tran, 2009; Fig. 1a). These rocks are unconformably overlain by early Triassic volcanogenic assemblages and late Triassic fluvial to lacustrine gray molasse deposits comprising conglomerate, sandstone and coal-bearing successions, which form part of the Nong Son Basin (Nguyen Van Trang, 1986; Fig. 1a). Along the southern flank of the TKPSSZ, thick assemblages of primarily medium-*P*, high-grade metamorphic rocks, including garnet–kyanite–sillimanite-bearing schist and gneiss (Phan, 1991; Usuki et al., 2004; Nakano et al., 2007; Osanai et al., 2008; Usuki et al., 2009), interlayered with amphibolite, calc-silicate, and quartzite that comprise the Kham Duc Complex (Nguyen Van Trang, 1986; Trinh, 2009a) are extensively exposed (Fig. 1a).

Both sides of the TKPSSZ are intruded by numerous magmatic bodies of variable composition, from mafic and intermediate to felsic compositions and include plutons and pegmatitic dykes and sills. The age of these intrusive rocks ranges from the Silurian to the Triassic (e.g., Carter et al., 2001; Nagy et al., 2001; Lepvrier et al., 2004; Trinh, 2009b; Fig. 1a). Many of the Silurian–Devonian intrusive complexes have also undergone several ductile deformation and