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A preliminary study of the sedimentary petrography of coarse clastic deposits in the Da Nang-Khe Sanh shear zone, central Vietnam

Kohki YOSHIDA[1] and Masaru SUGAWARA[2]

[1]*Department of Geology, Faculty of Science, Shinshu University, Matsumoto 390-8621, JAPAN*
[2]*Graduate School of Technology and Science, Shinshu University, Matsumoto 390-8621, JAPAN*
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Abstract

The ductile deformation belt in the Da Nang-Khe Sanh shear zone is the one of the NW-trending fault zone developing in the central Vietnam. This belt mainly comprises undeformed Jurassic sedimentary rocks, granite, gneissose metamorphic rocks, serpentine, and schistose rocks originated from the Paleozoic with extensive faulting. The A Lin Formation comprising undeformed conglomerate, sandstone, andesite, felsic tuff, and tuffaceous mudstone is distributed in the Da Nang-Khe Sanh shear zone and is designated to the Upper Permian formation. Its distribution is narrow and restricted to the NNW-trending shear zone, wherein the sedimentary mode is considered as a fault-bounded basin fill.

The preliminary study of the clastic composition of the A Lin Formation reveals the derivation from volcanic and metamorphic terranes comprising andesite, rhyolite, psamitic schist, quartz mica schist and mylonite. This suggests that the provenance of the A Lin Formation is correlated to the metamorphic rocks contiguous to the depositional basin. The petrographic characteristics of the metamorphic rock fragments in the sandstone are consistent with the gneissose granitic complex, which is adjacent to the basin and was dated as early Triassic with subordinate Jurassic-Cretaceous metamorphic age.

These results lead to the inference that the A Lin Formation was deposited following the early Triassic metamorphic event. The deposition might be correlatable to the Jurassic-Cretaceous tectonic movement, i.e., andesitic volcanism and reactivation of the shear zone. Although sufficient information on post-collisional crustal deformation of the Indochina Block

during Mesozoic is not available, sedimentation in the NW-trending fault zone leading to the A Lin Formation provides significant information for a crustal deformation the in post-collisional stage.

Preface

Recent geochronological studies on metamorphic and plutonic rocks in Vietnam have indicated the occurrence of a thermotectonic event in the Permo-Triassic age around central Vietnam and in the Indochina Block (Nam, 1998 ; Nam et al., 2001, Lepvrier et al., 1997 ; Lan et al., 2003). These ages are considered to represent granulite to amphibolite facies metamorphism, correlatable to the initiation of the Indochinian Orogeny (Lepvrier et al., 1997). Although the Indochinian Orogeny is regarded as a result of the collision between the Indochina and South China blocks (Lepvrier et al., 1997), the location of the boundary zone between the two blocks and the duration of the orogenic period have been contentious. Many researchers, such as Bunopas and Vella (1983) have speculated or assumed the Song Ma Fault in northern Vietnam as a boundary zone or boundary fault between the two blocks mentioned above. However, some researchers have deduced that the northern boundary of the Indochina Block is located in the region around central Vietnam, such as the Da Nang-A Luoi-Khe Sanh Fault or the Son Ca Fault (Nguyen Dinh Hoe and Rangin, 1999 ; Findlay, 1999) and the Paleozoic rocks in northern Vietnam belong to the South China Block. Owing to Rangin et al.'s (1995) indication of the rearrangement of the Paleozoic terranes in northern and central Vietnam by the Cenozoic reactivation of the fault system, the actual situation of the Indochinian Orogeny is still controversial. The activation history of the faults in the northern part of central Vietnam, such as the Da Nang-Khe Sanh Fault and the Song Ma Fault, is regarded as a key aspect in deciphering the tectonic development of Southeast Asia following the collision between the two blocks.

The tectonic significance of the NW-trending fault zone in central Vietnam (Fig. 1-A), along the southern margin of the Truong Son Block, has been discussed in some literatures (Rangin et al., 1995 ; Lepvrier et al., 1997). Although the precise location and striking trend of the fault zone vary across the literatures, the formation is considered to be accompanied with ductile deformation and thermal tectonic events such as metamorphism and igneous activity (Lepvrier et al., 1997 ; Nagy et al., 2000). The ductile deformation belt in the Da Nang-Khe Sanh shear zone, mainly comprises granite, gneissose metamorphic rocks, ultramafic rocks, and deformed and undeformed sedimentary rocks with extensive faulting. The radiometric ages of metamorphic rocks in this deformation belt are concentrated in the late Permian to early Triassic periods, however, the subordinate Cretaceous and Tertiary reactivation ages (Lepvrier et al., 1997 ; Nam, 1998) are considered to be significant with regard to the Mesozoic and Cenozoic reactivation of the deformation belt. In particular, the undeformed

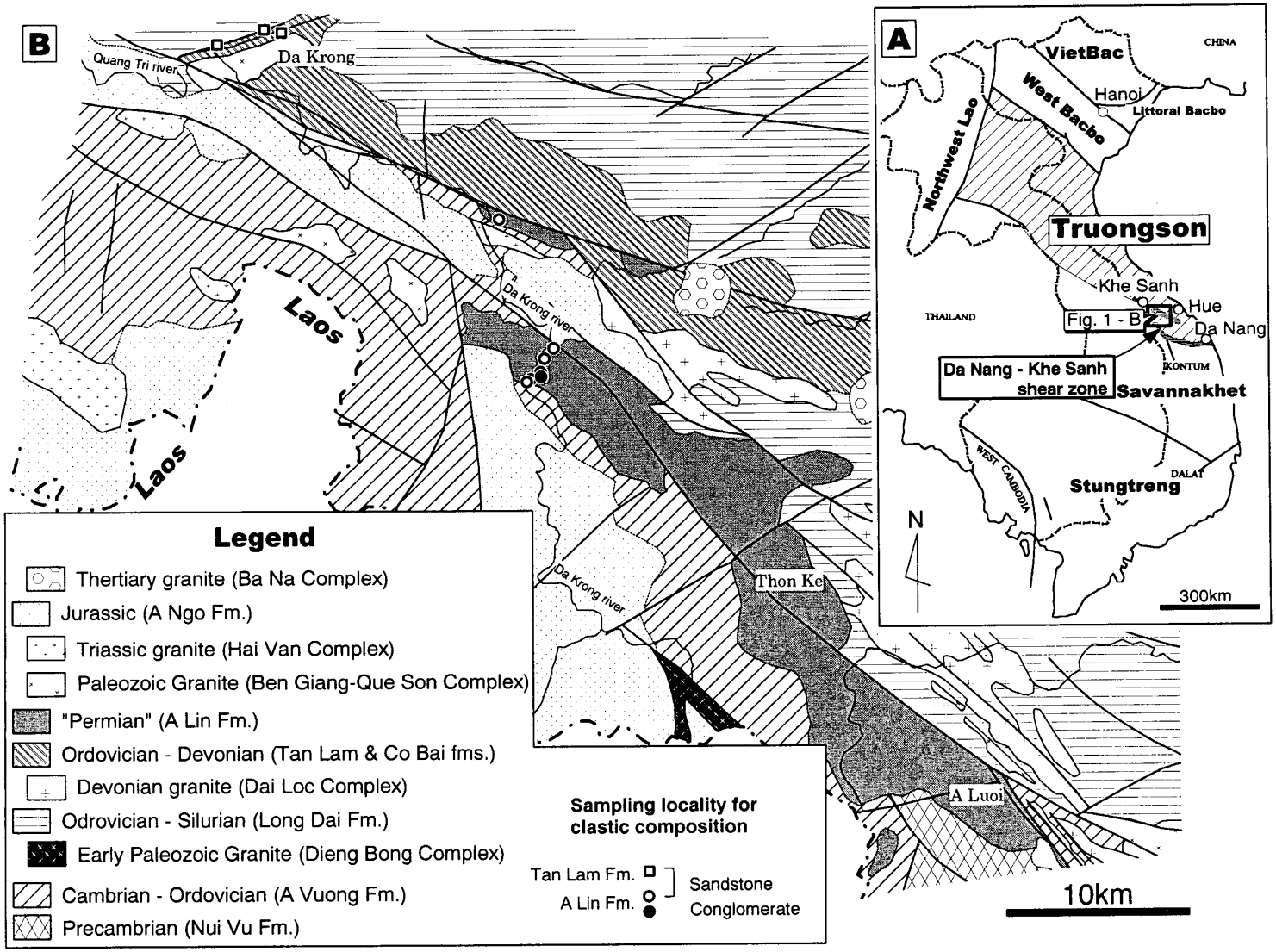

Fig. 1 A : Index map of the studied area in central Vietnam. The Da Nang-Khe Sanh shear zone (Lepvrier et al., 1997) is also shown.
B : The geological map simplified from Phan Cu Tien (1991). The localities of the sandstone specimens are also shown.

"Upper Permian" sedimentary rocks, referred to as the A Lin Formation, are distributed as a narrow basin fill in the deformation belt. Thus, the A Lin Formation might be deposited during either the initial fault movement or the subsequent to reactivation phase. This report undertakes a preliminary study for the sedimentary petrography in order to clarify the relationship between the deposition of the A Lin Formation and the movement of the deformation belt.

The field data in this paper were gathered from one route along the Da Krong and A Luoi areas, along the Da Nang-Khe Sanh shear zone. Excursions were taken from Hue to the Da Krong and the A Luoi areas to view the important lithology comprising the geology in those regions.

Geological setting

The classical tectonic divisions of Vietnam, comprising Viet Bac, west Bacbo, littoral Bacbo, northeastern Lao, Truong Son, Savannakhet, Stungtreng, and West Cambodia, from north to south, have been frequently cited (e. g. Phan Cu Tien and Dickins, 1994). In this division, the Truong Son Block is regarded as a Paleozoic fold belt because of the development of a thick sequence ranging from the Precambrian to the Permian ages.

The southern marginal zone of the Truong Son Block contacts the northern margin of the Kontum Massif comprising the Precambrian metamorphic core of the Indochina Block. This marginal zone comprises a fault zone with NW-trending in the west, EW-trending on the east. The fault zone with ductile deformation, which consists of mainly gneissose granite and schistose meta-sedimentary rocks with ultramafic rocks, has been traced from Khe Sanh, through A Luoi, to Da Nang, fringing the northern margin of the Kontum Massif. The sedimentary sequence in the area comprises the Precambrian Nui Vu Formation, the Cambrian-Ordovician A Vuong Formation, the Ordovician-Devonian Tan Lam and Co Bai formations, the Carboniferous-Permian Cam Lo Formation, the "Upper Permian" A Lin Formation, and the Jurassic A Ngo Formation in stratigraphically ascending order (Nguyen Van Trang, 1996 ; Fig. 1-B). Clastic and volcanic rocks are dominant from the Precambrian to the Devonian, whereas continental limestone prevails in the upper Devonian-Permian systems, with the exception of the A Lin Formation. A distinct unconformity is traced below the Lower Devonian system (Nguyen Van Trang, 1996). The Jurassic sequence is predominated by reddish clastic rocks with minor limestone and volcaniclastic rocks. The Paleozoic sequence in the deformation belt has suffered regional and thermal metamorphisms. Granitic rocks are chronostratigraphically correlated from the Late Carboniferous and Late Permian-Early Triassic (Nguyen Van Trang, 1996).

The pre-Jurassic rocks including the Lower Paleozoic are faulted by the NW-trending fault system (Nguyen Van Trang, 1996), which indicates that the fault system

was active after the Jurassic period (Rangin et al., 1995).

Regional geology and field observations

The Paleozoic strata are deformed to various degrees in the deformation belt and intense deformation has locally obscured the protolith. However, its sedimentary nature can be commonly distinguished. On the other hand, the Paleozoic sequence out of the deformation belt and Mesozoic sequence have undergone either slight or nor deformation. Nguyen Van Trang (1996) describes the details and characteristics of the A Lin Formation as follows: the A Lin Formation, which has been designated to the Upper Permian, is approximately 700 m thick and consists of altered andesite, andesitic tuff, tuffaceous mudstone, conglomerate and sandstone. The lithology is characteristic of contemporaneous sedimentation with subaerial volcanism.

The distribution is limited along the deformation belt and is fault-contacted with the Paleozoic and the Jurassic strata (Nguyen Van Trang, 1996). It is implied that this formation unconformably overlies the Cambrian and the Siluro-Devonian, and is in turn unconformably overlain by the Jurassic (Nguyen Van Trang, 1996). The formation is non-fossiliferous in this area ; however, it has been reported that Permian fusulinids has been found from the western prolongation in the Khang Khay area of the Lao territory (Nguyen Van Trang, 1996).

We investigated the Da Nang-Khe Sanh shear zone from Da Krong to the north of A Luoi along the Da Krong River. The altered andesite, sandstone and the conglomerate of the A Lin Formation crop out on the road-side along the Da Krong River.

The conglomerate is composed of subrounded and subangular pebbles and cobbles that have a reddish sandstone matrix. The clasts in the conglomerate are characterized by the amount of volcanic rocks accompanying the gneissose granite. The rhyolitic to basaltic volcanic clasts are not metamorphosed. Several felsic tuff clasts exhibit eutaxitic texture. The metamorphic clasts mainly comprise quartzofeldspathic gneis-

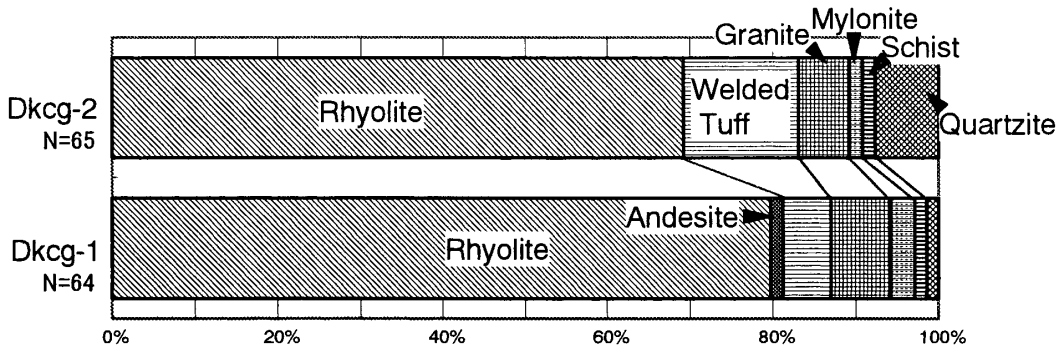

Fig. 2 The composition of the clasts of the conglomerate at two conglomeratic layers among the outcrops of the A Lin Formation in Fig. 1. N denotes the number of counted pebbles. Rhyolitic clasts distinctly predominated with clasts of welded tuff and metamorphic rocks.

ses. Quartzite clasts are rarely found. The composition of the clasts indicates the predominance of rhyolitic volcanic and volcaniclastic rocks (Fig. 2).

The thick-bedded or massive sandstone is greenish red in color and is medium-to fine-grained. It occasionally included mudstone rip-up clasts. The reddish color of the rocks indicates the deposition in subaerial environments as the processing of the oxidation of ferric material in the sediments. The sequence, comprising thick-bedded sandstone and conglomerate that shows upward fining and thinning, is interpreted as fluvial channel fill sediments. Reddish tuffaceous mudstones including pseudomorph of glass shards, such as pumice, bubble-wall, and bubble-wall junction, are frequently found in the several localities.

The ductile deformation and metamorphic recrystallization are not been distinguished in the rocks of the A Lin Formation, moreover, thermal recrystallization and alternation by contact metamorphism are not apparent in the outcrops.

Sandstone petrography

Samples for provenance analysis were collected mainly from the A Lin Formation and Siluro-Devonian Tan Lam Formation exposed on the road side along the Da

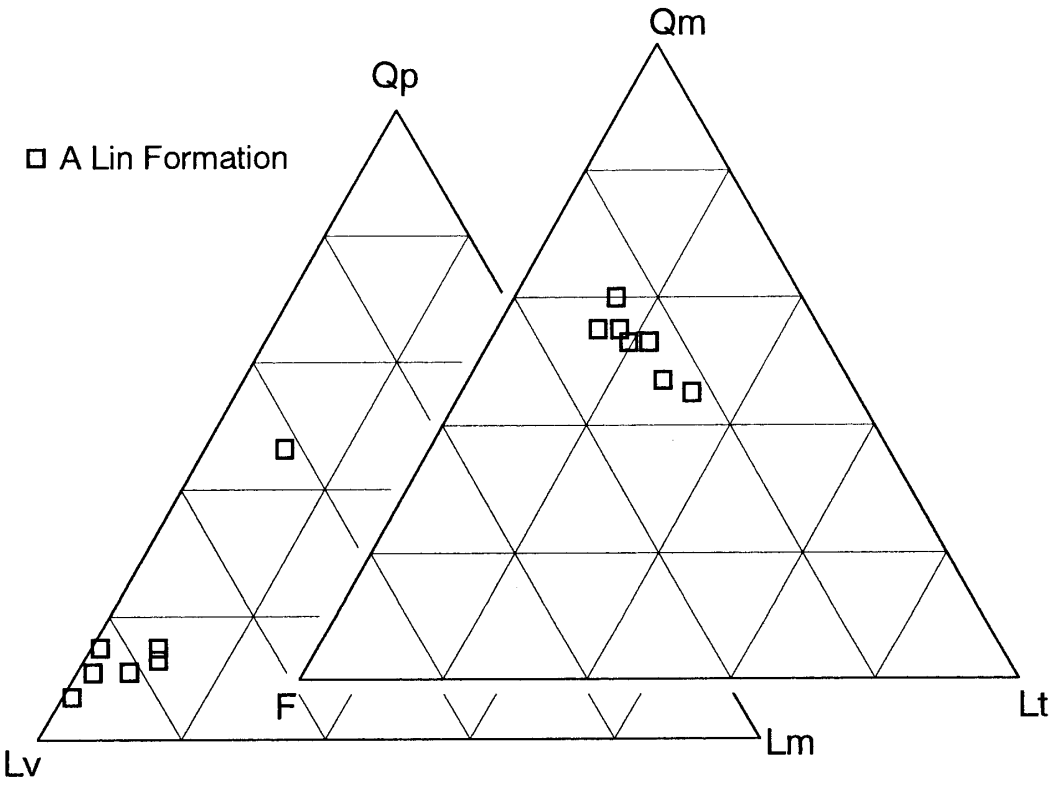

Fig. 3 Modal composition of the sandstone in the A Lin Formation. The diagrams show quartzose and a predominance of volcanic lithic fragments in the composition. Qm : monocrystalline quartz, F : total feldspar, Lt : total lithic fragments, Qp : polycrystalline quartz, Lv : lithic volcanic fragments, Lm : metamorphic lithic fragments.

Krong and the Quang Tri rivers. Seven teen sandstone samples, mainly medium-grained, were collected for a modal count of composition.

The modal count was performed for 7 samples obtained from the A Lin Formation using the Gazzi-Dickinson method (Dickinson, 1985), and by following the procedure outlined by Dickinson and Suczek (1979). However, point counting for samples collected from the Tan Lam Formation was not undertaken, owing to the strong deformation which prevented the quantitative analysis by petrography. Each section was stained in order to distinguish potassium feldspar. On each thin section of the A Lin Formation, 500 grains were counted, and the data were plotted on ternary diagrams (Fig. 3).

Tan Lam Formation

The sandstones of the Tan Lam Formation originally comprise closely packed grains including lithic arenite, feldspathic arenite, and wacke (Fig. 4-A). Carbonate mineral that originated from metamorphic recrystallization is commonly included in the sandstone. The shape of its grains varies from subrounded to rounded, and the composition mainly comprises quartz and feldspar with volcanic rock fragments. The quartz grains are prevalent and commonly subrounded or rounded, the feldspar grains are subrounded and rich in albite, which is probably altered from plagioclase by metamorphism. Although the volcanic rock fragments are observed to have cryptocrystalline texture, the other textures in it cannot be distinguished. The primary matrix, which was originally clayey, may have later been altered to chlorite and sericite with carbonate. In contrast, the monotonous volcanic sandstone comprises andesitic volcanic fragments with plagioclase and clinopyroxene grains. However, intense metamorphic and diagenetic changes obscure the original characteristics.

Ductile deformation structures developed in the Da Krong area are distinctly observed as a foliation on the outcrop. These deformations are demonstrated by elongated quartz grains, mica-fish and pressure shadow under the microscope. The penetration of softer grains such as glassy volcanic fragments by quartz and feldspar grains are common in these rocks. Slight mutual penetration of quartz, feldspar and volcanic grains is also present to an extent.

A Lin Formation

The sandstone of the A Lin Formation is poorly sorted, quartz-rich lithic wacke and comprises quartz, feldspar, volcanic and metamorphic rock fragments with a reddish tuffaceous matrix (Fig. 4-B). The grain shapes are angular-subangular. The quartz content in flame work grains ranges from 45% to 60%. Quartz grains are typically euhedral, but angular polycrystalline quartz grains such as "ribbon quartz" are common (Fig. 4-C). The percentage of feldspar grains ranges from 23 to 31. The

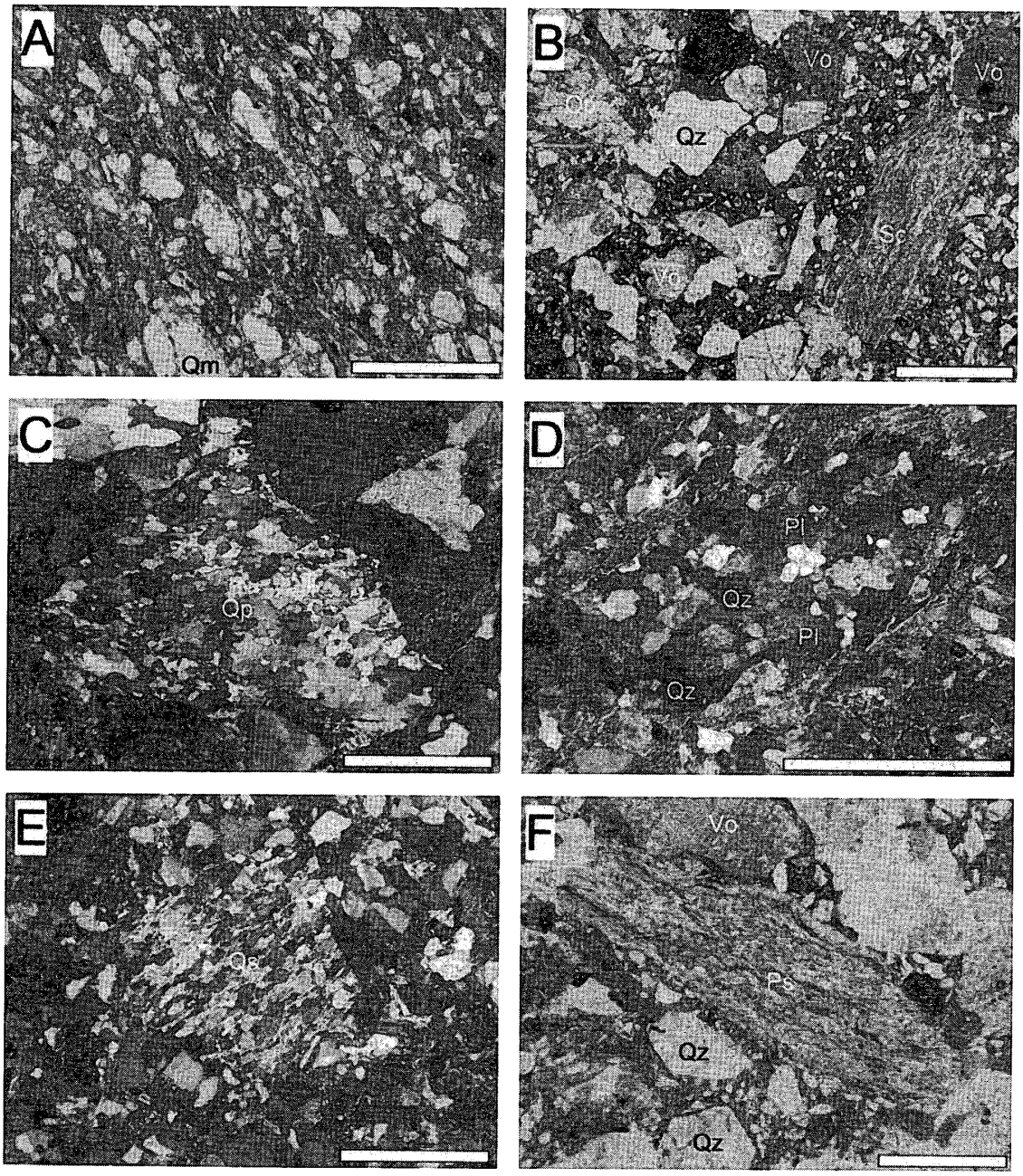

Fig. 4 Photomicrograph of the sandstone and rock fragments in the sandstone. A : schistose sandstone with distinct foliation that originated from calcareous sandstone of the Tan Lam Formation. It should be noted that the elongated quartz grains, mica-fish, and pressure shadow in the sandstone using plane polarized light. B : poorly sorting, quartzo-lithic sandstone of the A Lin Formation. Matrix comprises the red material of iron oxide. Vo denotes volcanic rock fragments, Sc denotes schistose clast, and Qm denotes monocrystalline quartz. C : polycrystalline quartz grain (Qp), comprising micro-quartz grains with sutured structure, derived from mylonite. D : felsic holocrystalline metamorphic rock fragments showing granoblastic texture, implying the high -grade nature of the metamorphic rock. Qz denotes quartz, and Pl denotes plagioclase. E : quartz-muscovite schist grain (Qs), indicating the derivation from siliceous metamorphic rock. F : phyllite grain (Ps) with distinct foliation. Note the coexistence of the quartz and the phyllite grains that should be undurable, showing the sediment supply from adjacent area. In all, scale bar = 0.5mm.

potassium feldspar grains are typically weathered and subrounded and frequently observed despite its low ratio. In contrast, several grains of plagioclase were angular and unweathered. Sedimentary clasts such as shale, slate and phyllite (Fig. 4-F) are present. The volcanic lithic fragments make up a low percentage in flame work grains, and mainly include the clasts of rhyolite and rhyolitic tuff accompanied by andesitic and basaltic clasts. Metamorphic rock fragments are commonly observed and the shapes of them are mostly angular. They comprise quartz-mica schist (Fig. 4-E), and granulites with a granoblastic texture (Fig. 4-D).

Sandstone geochemistry

On the geochemical analysis, a total of 10 sandstone samples were crushed and finely powdered in an agate swing mill. As part of the preparation for major elements, fusion beads made from pre-ignited rock powder were fused with lithium metaborate flux in a ratio of 1 : 2 following the procedure of Miyake et al. (1996). These were then analyzed by X-ray fluorescence spectrometry (XRF) using a Philips PW1400 spectrometer with an Rh anode tube at the Faulty of Science, Shinshu University.

Sandstones from the A Lin Formation show a characteristically high amount of Al_2O_3, Na_2O and K_2O, however, a simple distinction cannot be made for the Tan Lam Formation. Bhatia (1983) has developed a discriminator of tectonic setting that uses SiO_2 contents and a K_2O/Na_2O ration for sandstone. Using this classification, the A Lin Formation shows the deposition in the active continental margin setting (ACM). On the other hand, the sandstone of the Tan Lam Formation varies in composition and is plotted in the passive margin (PM) and the boundary area between volcanic island arc (ARC) and ACM. However, considerable amount of carbonate by metamorphic recrystallization included in the sandstone may distort the original composition. The discrimination of tectonic setting using this diagram with SiO_2 wt% as an ordinary axis is not completely evident.

The discriminate analysis proposed by Kroonenberg (1994) is one approach to determine the intensity of chemical weathering using geochemical data. This diagram uses $SiO_2/20$, Na_2O+K_2O, and $TFeO+MgO+TiO_2$ in a tri-angular diagram. As a result, the sandstone of the A Lin Formation displays a felsic nature and a low chemical maturity than that of the Tan Lam Formation, which exhibits diverse origin and relatively high chemical maturity.

Discussion

Provenance and tectonic setting of the A Lin Formation

The petrographic study reveals that quartzo-lithic detritus is predominant in the sandstone of the A Lin Formation. Although volcanic rock fragments are prevalent, metamorphic fragments and polycrystalline quartz are also commonly found in terms

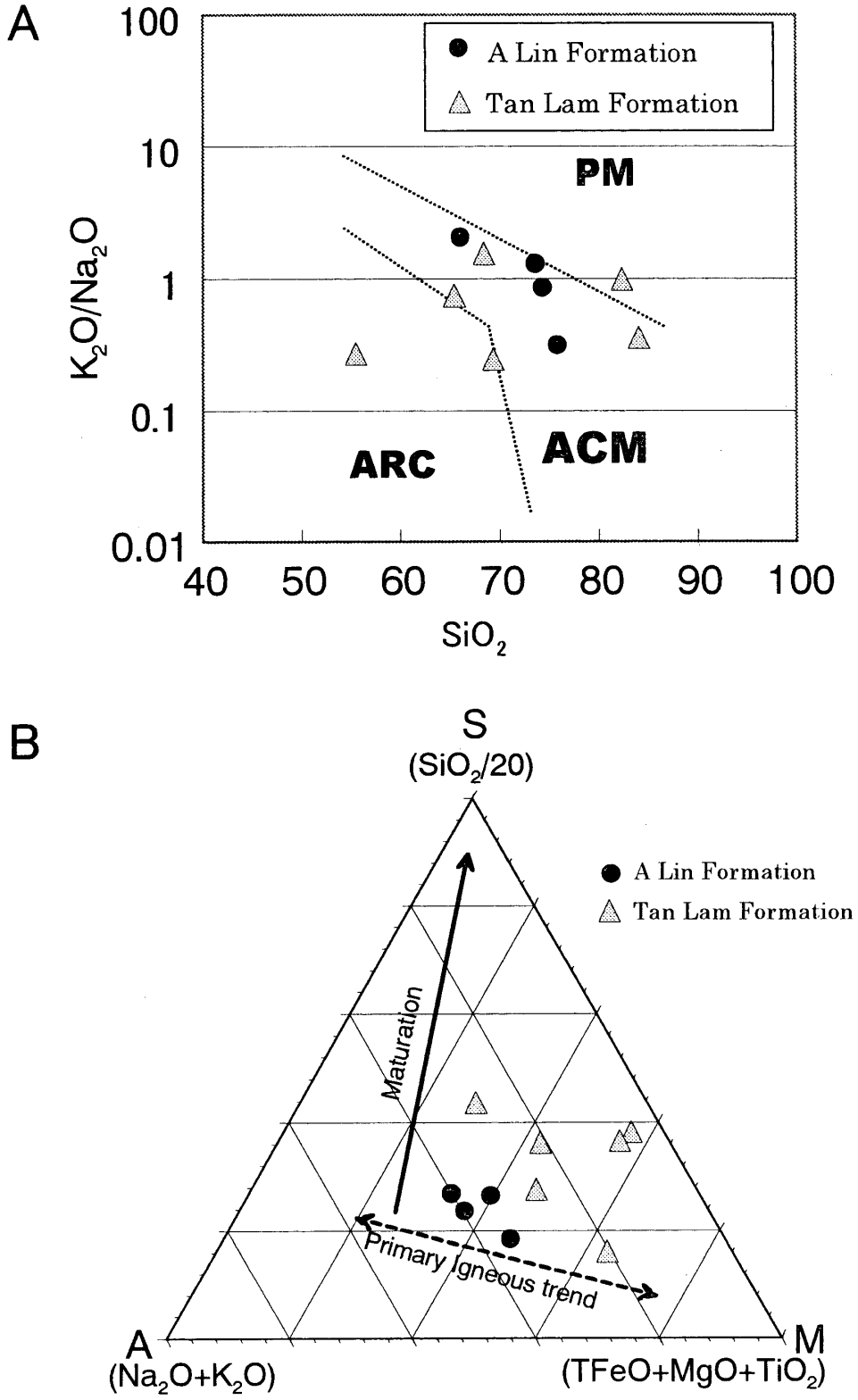

Fig. 5 Tectonic discrimination diagram from geochemistry. A: SiO_2 versus K_2O/Na_2O diagram based on Bhatia (1983). ARC=island arc, ACM=active continental margin, PM=passive margin. B: $SiO_2/20-Na_2O+K_2O-TFeO+MgO+TiO_2$ diagram based on Kroonenberg (1994).

of composition. The predominance of the rhyolitic clasts in the conglomerate and a large amount of volcanic fragments in the sandstone suggest the deposition under contemporaneous volcanic activity. Metamorphic rock fragments such as granulite and quartz mica schist grains are commonly observed in the sandstone, which suggests derivation from metamorphic terrane despite highly volcanic activity. In addition, sedimentary and metamorphic rock fragments that should exhibit low durability, such as pelitic schist, are still angular in shape and coexist with quartz grain, which is considered to be most resistant. This suggests the derivation from adjacent hinterland with a short traveling distance. The polycrystalline and mylonitic quartzes including "ribbon quartz" are considered to have originated from quartz-rich metamorphic rocks such as quartz mylonite or granitic mylonite distributed around the basin.

In contrast, the sandstone of the Siluro-Devonian Tan Lam Formation comprises calcareous quartz-rich sandstone including minor metamorphic fragments. Although only present in low concentrations, monogenic andesitic volcanic sandstone can be distinguished. Therefore, the clastic material of the sandstone is considered to have been derived from quartzose provenance as well as subordinate metamorphic rocks. Since, andesitic volcanic sandstone exhibits andesitic volcanic activity, the sedimentary basin of the Tan Lam Formation is inferred to be in relatively stable environment, wherein it is affected by temporal arc volcanism, i. e., continental setting with arc volcanism.

The geochemical data are roughly consistent with the petrographic interpretation, although the geochemical provenance indicators are mixed. Generally, the chemical weathering degree is low in the A Lin Formation, suggesting that the origin of the clastic material differs from that of the Tan Lam Formation, and the depositional environment is situated under a large sedimentary supply that does not undergo weathering. However, since the evidence is limited, several samples have not been discriminated from the Tan Lam Formation by geochemistry.

Regional implication

Nguyen Dinh Hoe and Rangin (1999) demonstrated that the Paleozoic sequence in Dong Ha near the A Luoi area consists of the Ordovician-Silurian volcanic arc sequence and Upper Devonian-Permian continental limestone lacking the Precambrian metamorphic terrane. Great stratigraphic discordance has been traced below the Devonian sub-continental red beds. The above-mentioned description of the geological circumstance of this area during the Siluro-Devonian period is consistent with the tectonic setting inferred from sandstone petrography showing continental-continental marginal setting without the exhumation of large metamorphic masses.

On the other hand, although the A Lin Formation is composed of undeformed strata and is designated to the Upper Permian, it is cut by numerous NW-trending

faults cutting the mylonitic gneiss dating to the earliest Triassic period as shown by Lepvrier et al. (1997). The distributional mode of the A Lin Formation is narrow and is restricted by the NW-striking fault, thus suggesting the following two possibilities :

(a) The A Lin Formation is considered as the Upper Permian formation and its distribution was rearranged by the NW-striking fault after the Jurassic period. However, this possibility should not be taken into consideration, because the depositional age is extremely close to its own metamorphic age assuming that the major metamorphic events occurred in the latest Permian-earliest Triassic period on the lines of Lepvrier et al. (1997) and Nam (1998). It should be noted that the metamorphic clasts eroded from the place where they had been uplifted and exposed at the surface of the crust after they reached their peak metamorphic condition. In addition, the Triassic ages recently reported from the metamorphic complex in the Kontum Massif (Nam et al., 2001) which was previously regarded as the Precambrian age by previous researchers (e.g. Hutchinson, 1989), are suggestive of the possibility that the major metamorphic events in central Vietnam occurs in the Indochinian age.

(b) The A Lin Formation is not Permian and is deposited in an unspecified period when the NW-striking fault was active. The A Lin Formation has not suffered from severe deformation and recrystallization with slaty cleavage or schistosity, which is in contrast with the severely foliated lithology of the Tan Lam Formation in the Da Krong sector. The formation of the deformation belt is claimed to be a result of the strike-slip-related deformation accompanied with high-grade metamorphism in the earliest Triassic age (Lepvrier et al., 1997). The narrow distribution of the A Lin Formation is indicative of sedimentation in a fault-controlled restricted basin, such as a strike-slip basin in an extensional tectonic setting. Therefore, the formation of the depositional basin constrained by a boundary fault might be correlatable to the reactivation stage of the deformation belt, which occurred in the Jurassic and Cretaceous periods, as suggested by overlapping ages (Lepvrier et al., 1997). It is also important to note that Nam et al. (2001) reported the Cretaceous age (116 Ma) for andesite, obtained from approximately 30 km north of A Luoi, where the A Lin Formation is distributed.

The existence of andesitic volcanic rocks and the significant amount of andesitic -rhyolitic volcanic and pyroclastic material in the coarse clastic rocks of the A Lin Formation suggest a sedimentation under considerable subaerial volcanism. However the origin of this sedimentation has not exactly been identified. Considering that the A Lin Formation is of the Jurassic or Cretaceous ages, the upper Jurassic-Cretaceous acidic volcanic rocks of the Dalat sector in southern Vietnam (Phan Cu Tien, 1991) may be correlatable to the A Lin Formation. Sedimentation leading to the A Lin Formation is evidenced in central Vietnam to be related to crustal deformation accompanied by acidic volcanism in a post-collisional environment.

It has been established that the Cenozoic crustal deformation of the Southeast Asia, including the Indochina Block, is related to the Indo-Himalayan collision tectonics such as extrusion or escape tectonics, or the linking of the South China Sea opening (Tapponier et al., 1982, 1986). However, the late Mesozoic crustal movement of Indochina is still unclear with the exception of the Cretaceous-Jurassic radiometric ages in the Da Nang-Khe Sanh and the Son Ca shear zones (Lepvrier et al., 1997 ; Nam et al., 2001). Although our data do not permit an age-determination of the A Lin Formation, the sedimentation in the shear zone is considered to be an evidence of fault activation during the post-collisional stage.

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