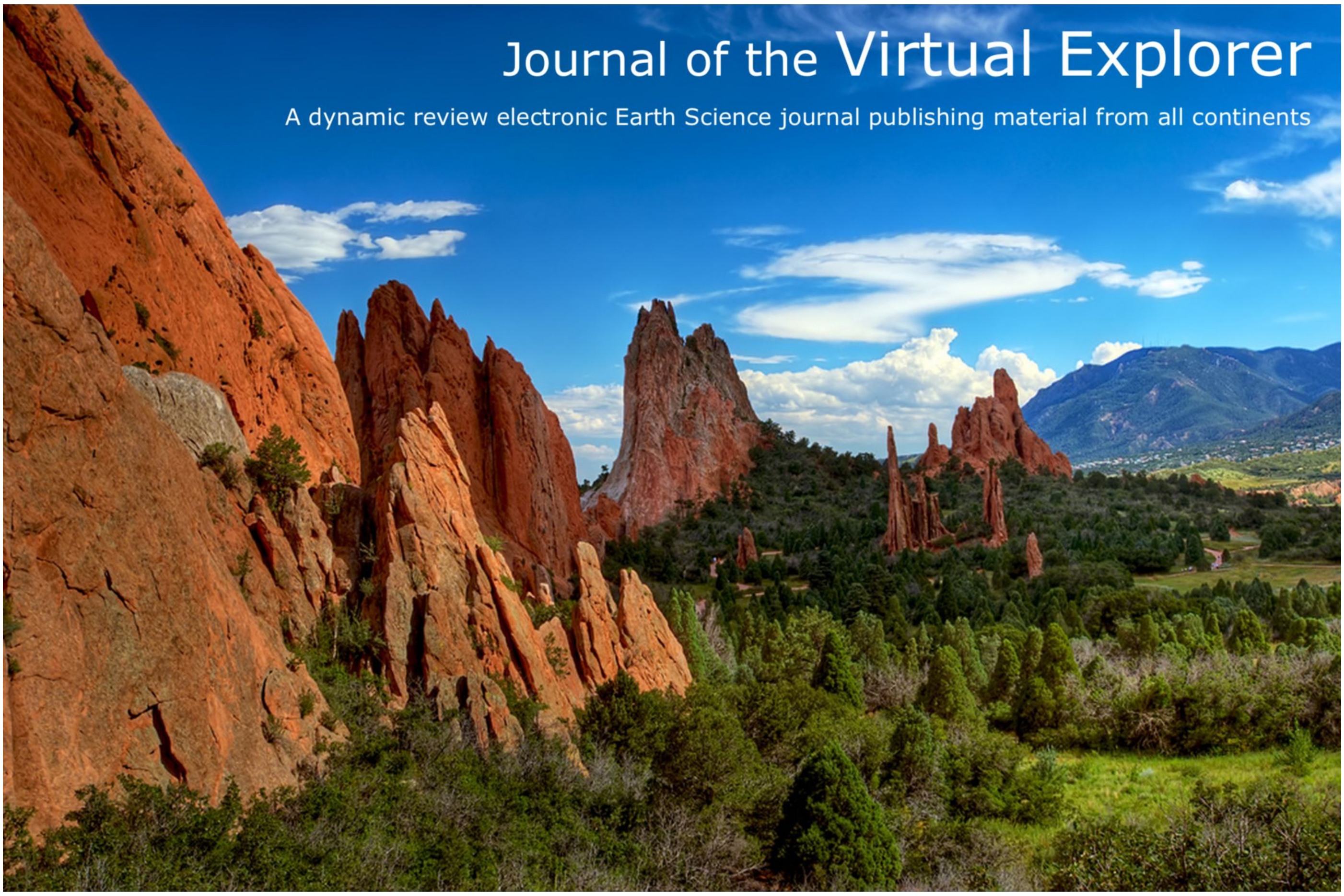


# The Carboniferous tropical paleo-latitude of the Hida Marginal Belt (SW Japan) from pedologic evidence in metapelites

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# The Carboniferous tropical paleo-latitude of the Hida Marginal Belt (SW Japan) from pedologic evidence in metapelites

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**Abstract:** Petrology and geochemistry of chloritoid-bearing Al-rich metapelites in the Carboniferous Shimozaisho Group (Hida Marginal Belt, Central Japan) reveal the abundance of metamorphic sericite and less quartz than in non-Al-rich metapelites. This indicates that quartz was consumed during a metamorphic reaction as well as the contribution of Si-free aluminous minerals in detritus derived from highly weathered soil. The high CIA (Chemical Index of Alteration) values and high $TiO_2$ contents (up to 2.05 wt. %) in the Shimozaisho metaclasts are comparable to those of modern tropical soils and suggest that tropical climate may have controlled the intense weathering of their protolith source. The volcaniclastic layers that prevail in the Carboniferous formations that overlie thick limestone beds in the Hida Terrane suggest that a stable land surface evolved into the unstable tectonic setting that triggered the detritus supply and mixing of its highly weathered and non-weathered materials. Al-rich metaclastic rock series in Hida Marginal Belt with protolith originating from Late Paleozoic shelf deposits commonly have formed at tropical climate conditions.

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## Introduction

Al-rich metapelites traditionally play important roles in determination of the metamorphic zones (e.g. Eskola 1915; Thompson, 1957) because of their temperature-sensitive Al-rich minerals such as chloritoid. However, the source of the Al-rich content is still a matter of debate. Some authors have demonstrated that the Al-rich metapelite originated from paleosoil (e.g. Liou and Chen, 1978; Sharma, 1979; Barrientos and Selverstone, 1987). Others have suggested that the protolith of Al-rich pelites consists of soil-derived detritus (e.g. Iwao, 1978; Kawamura *et al.*, 1985; Franceschelli *et al.*, 1998). More advanced understanding of the chemical reactions in weathering has produced a vast body of paleoclimatic literature based on paleosoil chemistry (e.g. Nesbitt and Young, 1982; Retallack, 2001). In this study, we attempt to evaluate the soil-derived materials in metaclastic rocks by applying an analysis of metamorphic reactions to provenance analysis in order to understand weathering and metamorphic processes for Al-rich pelites.

Some metaclastic rocks originating from Carboniferous rocks in Japan yield index minerals such as staurolite, chloritoid and aluminosilicate minerals (e.g. Seki, 1955; Asami, 1979; Hiroi, 1983; Okuyama-Kusunose, 1994; Sakashima *et al.*, 1999), which imply Al-rich bulk compositions. To understand age constraint of characteristic bulk composition, we described the petrographical and geochemical features of the metaclastic rocks of the Shimozaisho Group in the Itoshiro area, Gifu Prefecture, Japan. We then evaluate the Al-enrichment process and the degree of weathering of the source rocks, provenance of the protolith and tectonic background causing the detrital supply.

## Geological outline

Al-rich metaclastic rocks in Carboniferous deposits occur in five areas in Japan (Fig. 1; Seki, 1955; 1957; Asami, 1979; Hiroi, 1983; Sakashima *et al.*, 1999).

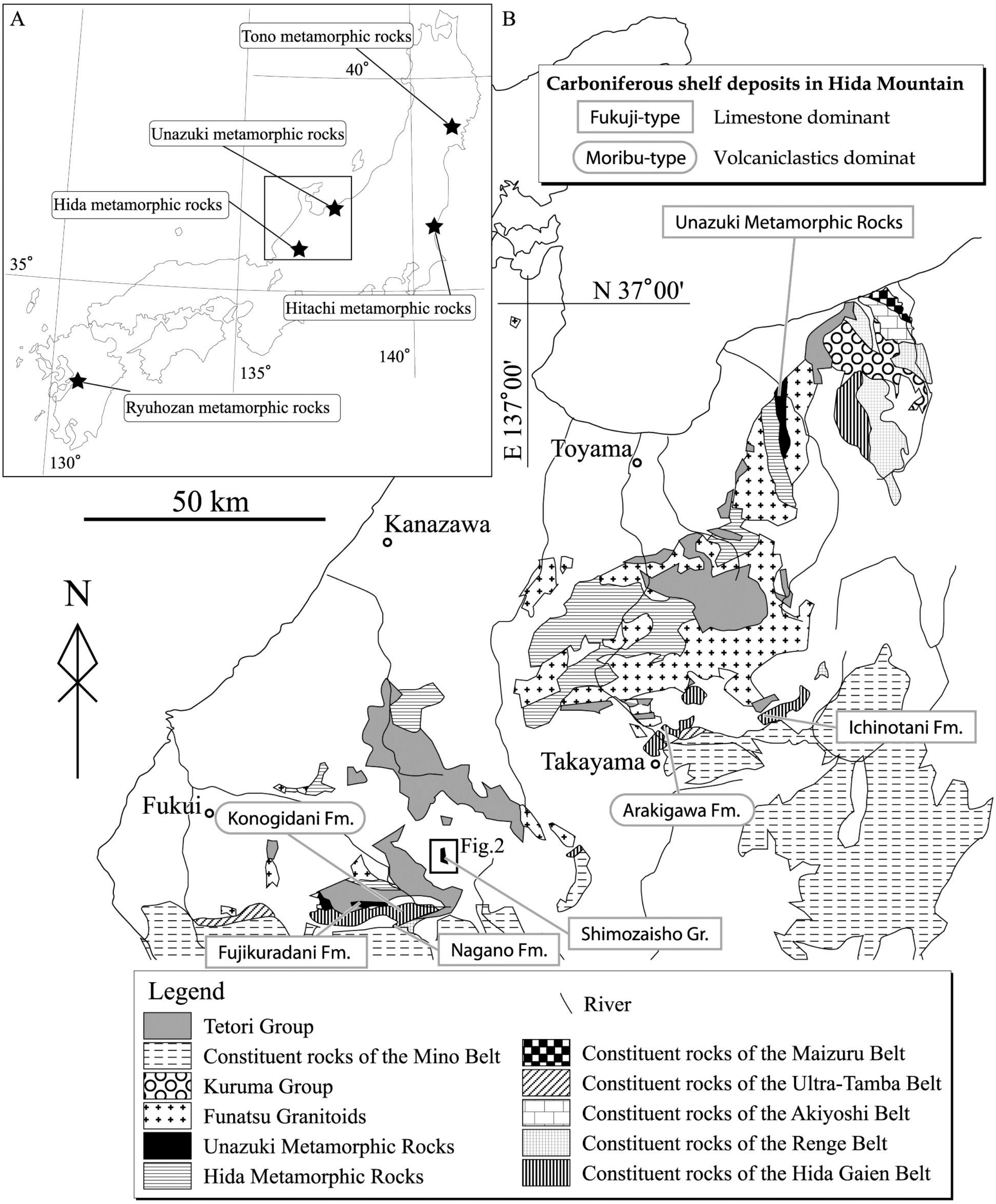
While their deposition took place during the Carboniferous, their metamorphic ages are of ca. 240 Ma or ca. 100 Ma (Ueda *et al.*, 1969; Yamaguchi and Yanai, 1970; Sugiyama, 1972; Hiroi, 1978; Kawamura *et al.*, 1985; Suzuki and Adachi 1994; Sakashima *et al.*, 1999). The Tono metamorphic rocks also partly include Permian protolith (Yoshida *et al.*, 1994).

Paleo-Mesozoic systems in the Hida Mountains consist of eight geological units from northwest to southeast (Fig. 1C; Tsukada *et al.*, 2004): (1) Hida Metamorphic Rocks are a series of low-*P* polymetamorphic rocks. (2) Unazuki Metamorphic Rocks are a series of ca. 240 Ma medium-*P* metamorphic rocks, which include Al-rich metapelites. (3) Hida Marginal (Gaien) Belt is composed of Paleozoic shelf sediments. (4) Renge Belt is composed of Ordovician ophiolite and Carboniferous high-*P* metamorphic rocks. (5) Akiyoshi accretionary complex shows a limestone-dominated facies with Permian accrecionary age. (6) Maizuru Belt is considered as arc-back arc system. (7) Ultra-Tanba accretionary complex shows a deficient limestone facies with Permian accretionary age. (8) Mino accretionary complex is a series of Jurassic accretionary complex.

In the Hida Mountains, Carboniferous shelf deposits belong to the Hida Marginal Belt and their metamorphic equivalents belong to the Unazuki Metamorphic Rocks and possibly a part of Hida Metamorphic Rocks (Tsukada *et al.*, 2003; Kamikubo and Takeuchi, in press). These consist of two types (Tsukada, 2003; Tsukada *et al.*, 2004). One is the dominantly carbonatic rocks Fukuji-Type that includes the Shimozaisho Group, Ichinotani Formation, Fujikuradani Formation, Nagano Formation and Unazuki Metamorphic Rocks. The other is the volcaniclastic dominated rocks Moribu-Type including the Arakigawa and Konogidani Formations. The limestone dominated type rocks commonly include Al-rich horizons and mafic volcaniclastic layers (Kawai, 1956; Igo, 1956; 1961).

Amidst the Fukuji-type rocks, the Shimozaisho Group, studied herein, correlates with the low-grade part of the Unazuki metamorphic rocks, and forms part of the Unazuki Belt (Hiroi, 1981).

Figure 1. Index map of the Japanese islands showing occurrences of Paleozoic chloritoid-bearing metamorphic rocks.

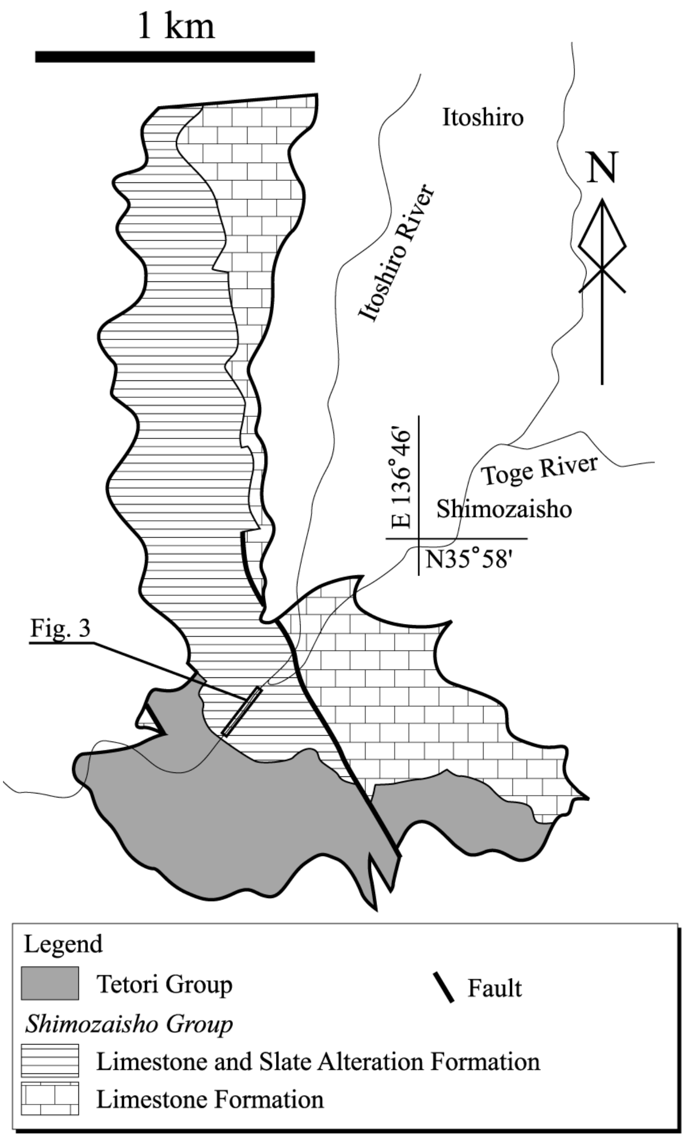



(A) Location of Carboniferous-origin Al-rich clastic rocks in Japan (stars). (B) Distribution of Mesozoic and Paleozoic rocks in the Hida mountains region (after Niwa *et al.*, 2002; Takeuchi *et al.*, 2004; Tsukada *et al.*, 2004; Maki, 2006). Cretaceous volcanic rocks are omitted. Gr. = group, Fm.= Formation.

## Shimozaisho Group

The Shimozaisho Group is Carboniferous in age (Konishi, 1954, Kawai, 1959), and consists of the Limestone Formation and the Limestone and Slate Formation, in ascending order (Konishi, 1954; Fig. 2). The Shimozaisho Group is unconformably overlain by the Cretaceous Tetori Group and Tertiary volcanic rocks (Maeda, 1957).

Figure 2. Geological map of Paleo-Mesozoic systems in the Shimozaisho area (after Konishi, 1954; Maeda, 1957)




The base of the Shimozaisho Group is not exposed. The Shimozaisho Limestone Formation yields Late Carboniferous fusulinid fossils (Konishi, 1954). Low-grade metamorphism of unknown age has affected these rocks, changing limestones into marbles and Fe-/Al-rich deposits into chloritoid-bearing metapelites.

The Limestone and Slate Formation is composed of metaclastic rocks with intercalated meta-mafic tuffs, and marbles (Fig. 3).

Chloritoid occurs as porphyroblasts in some metaclastic layers. Relict sedimentary structures such as cross lamination and normal grading are observed in metaclastic layers (Fig. 4A).

Marbles are composed of carbonate clasts including bioclasts and partly show normal grading. Crinoids are observable in recrystallized limestones. Meta-mafic tuffs are composed of chlorite, clay minerals and opaque minerals, partly including hematite. Metamorphic minerals in meta-mafic tuffs include chlorite and hornblende.

## Petrography of metaclastic rocks

### *General features of the Shimozaisho metaclastic rocks*

Protolith texture and detrital grains are preserved in metaclastic rocks of the Shimozaisho Group (Figs. 4A; 4B). The protoliths are fine-grained to very coarse-grained lithic wackes or arenites containing detrital felsic volcanic fragments, quartz and plagioclase. Detrital grains are sized 0.2-1.5 mm. Most quartz grains show undulatory extinction. Plagioclase grains are mostly converted to aggregates of sericite and deficient calcite. Felsic volcanic fragments exhibit felsitic texture. Felsic volcanic fragments have suffered mostly sericitization or merely chloritization.

### *Shimozaisho Al- or Fe-rich metaclastic rocks*

Metamorphic chloritoid, sericite and anatase are observed in the Shimozaisho Al-rich metaclastic rocks that also contain detrital grains as pseudomorphs. Metamorphic minerals overprint the protolith texture. Felsic volcanic fragments have reaction rims composed of sericite (Fig. 4D). Plagioclase grains also show reaction texture (Fig. 4E). Chloritoid porphyroblasts overgrow the sedimentary texture and the detrital quartz and ilmenite (Fig. 4F). Prismatic anatase grains occur parallel to the pressure solution cleavage (Fig. 4G). Chloritoids are prismatic crystal with size changing from 0.05 x 0.30 mm to 0.75 x 2.00 mm. The grain size of chloritoid is almost constant in hand specimen.

Two types of chloritoid-bearing metapelites are classified on the basis of megascopic observations. Type 1 rocks are white to dark-gray with indistinguishable detrital grains. Type 2 rocks are dark-gray with distinguishable detrital grains. Type 1 rocks have matrix composed of abundant sericite with no chlorite. Quartz in the matrix decreases in inverse proportion to the amount of sericite present, to the extent where quartz is absent. These rocks contain fewer detrital quartz grains than the chloritoid-free rocks. Detrital grains are poorly preserved and converted into sericite. Outlines of detrital grains are blurred. Type 2 rocks have matrix composed of abundant chlorite and lesser sericite. Detrital grains are mostly preserved and show partial replacement by chlorites.

Figure 3. Outcrop-map of the Shimozaisho Limestone and Slate Alteration Formation, and locations of analyzed samples.

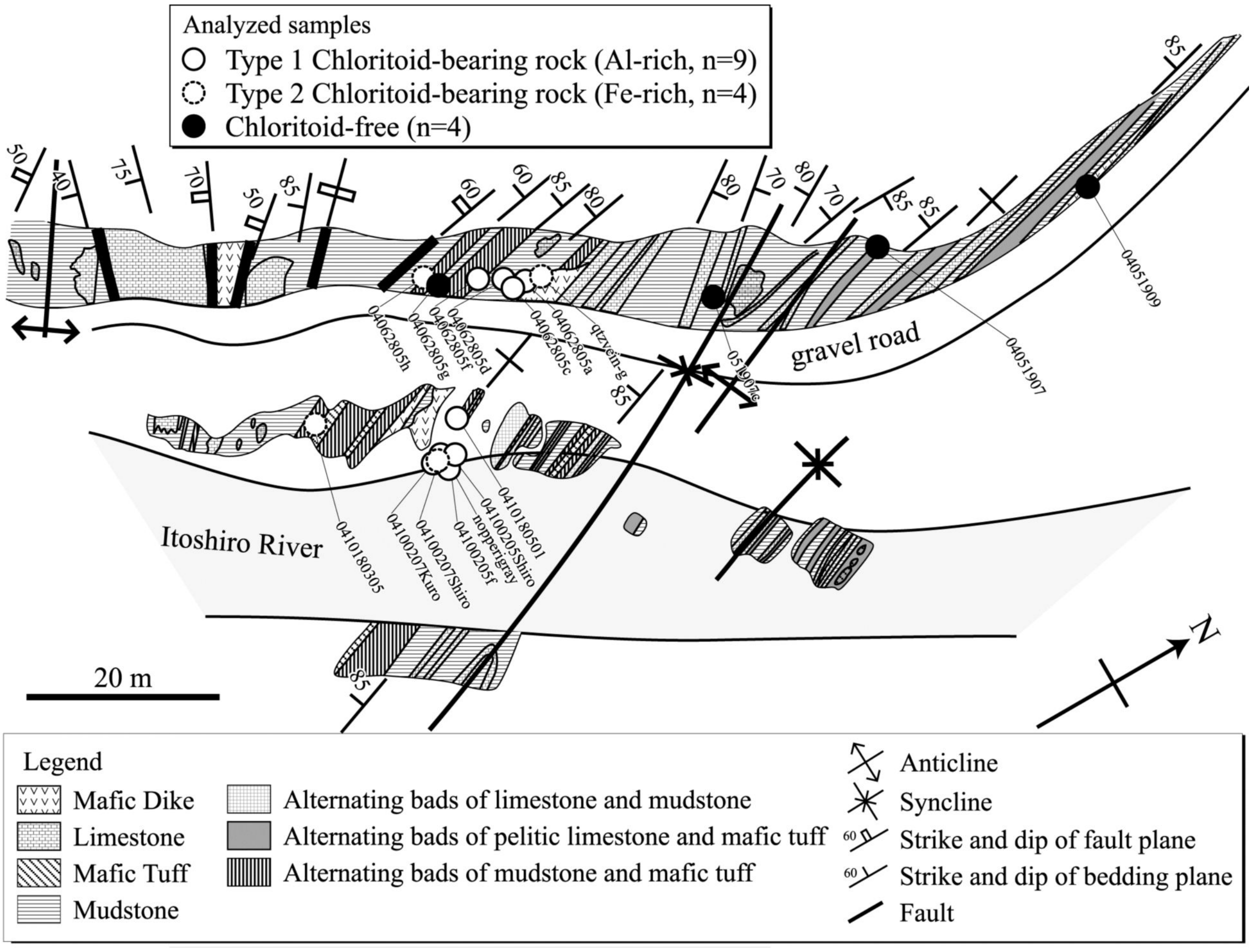
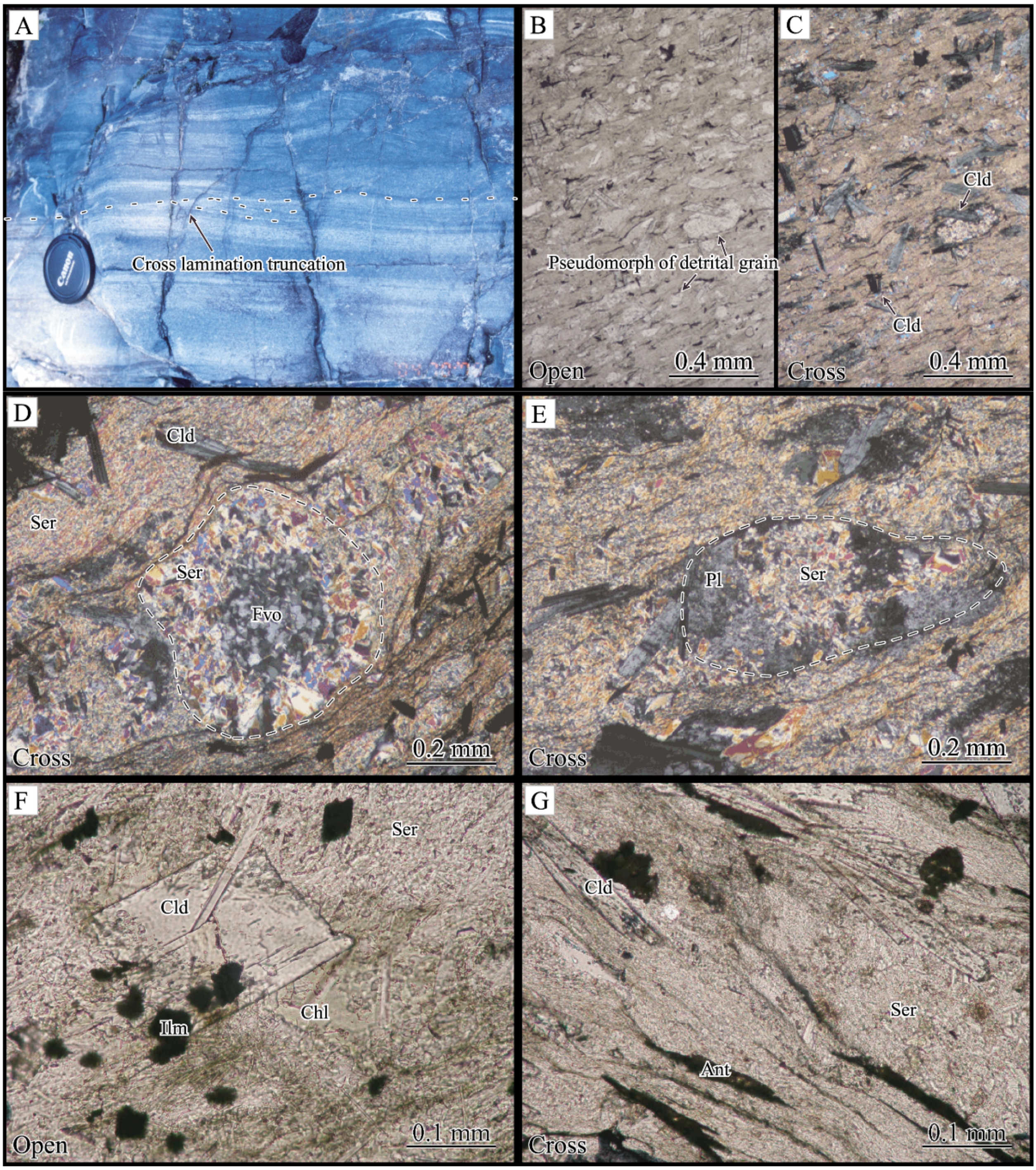


Figure 4. Photograph (A) and photomicrographs (B-G) of the Shimozaisho Al-rich metaclastic rocks.




(A): Cross lamination. (B): Preserved sandstone texture (wacke) and overprinting metamorphic minerals. Pressure solution cleavages are well developed. Open polarized light. (C): Cross polarized light of photomicrograph (B). (D): Reaction texture showing sericite replacing felsic volcanic fragment. Dotted line indicates original shape of detrital felsic volcanic fragment. (E): Reaction texture showing sericite replacing plagioclase. Dotted line indicates original shape of the detrital plagioclase. (F): Metamorphic chloritoid overprinting ilmenite. (G): Metamorphic anatase occurring parallel to the cleavage.

Abbreviations: Fvo = felsic volcanic fragments, Pl = plagioclase, Ilm = ilmenite, Cld = chloritoid, Ser = sericite, Ant = anatase.

## Bulk chemistry

Major element compositions of 19 whole-rock samples the metaclastic rocks were determined using a Shimadzu SXF-1200 XRF spectrometer at Nagoya University in June 2005. The results are presented in Table 1 with CIA (Chemical Index of Alteration) values (Nesbitt and Young, 1984). Localities of analyzed samples are shown in Fig. 3.

Figure Table 1. Bulk chemistry of the Shimozaisho metaclastic rocks

Table 1. Bulk chemistry of the Shimozaisho metaclastic rocks.

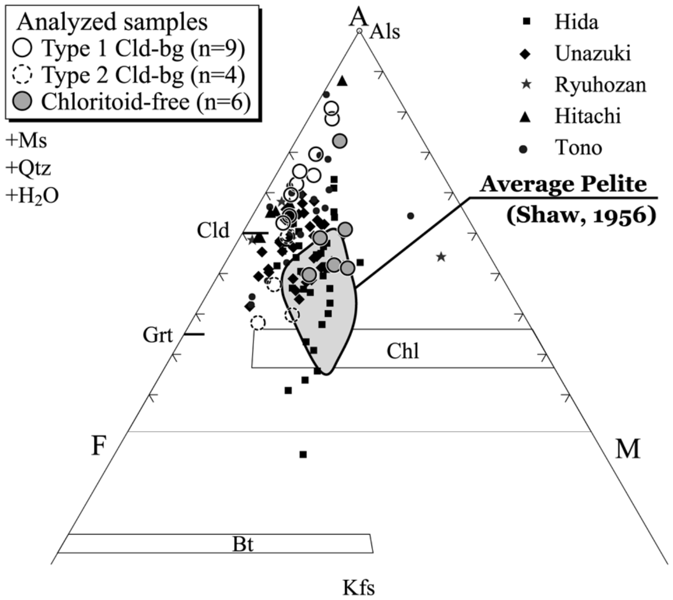
| Sample No. (wt.%) | 04100205f Type 1 | 04100207Kuro Type 1 | 04100207Shiro Type 1 | 0410180501 Type 1 | 04062805a Type 1 | 04062805f Type 1 | 04062805c Type 1 | 04062805d Type 1 | nopperigrey Type 1 | 04100205Shiro Type 2 | 0410180305 Type 2 | 062805h Type 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 50.94 | 52.67 | 51.49 | 45.70 | 43.30 | 51.51 | 61.65 | 60.41 | 58.36 | 48.77 | 53.94 | 47.58 |
| $TiO_2$ | 1.59 | 1.24 | 1.21 | 2.05 | 1.62 | 1.50 | 1.31 | 1.51 | 1.26 | 1.47 | 0.92 | 1.08 |
| $Al_2O_3$ | 29.77 | 27.66 | 28.50 | 28.63 | 36.91 | 28.41 | 23.28 | 23.33 | 24.88 | 21.54 | 22.70 | 14.88 |
| $Fe_2O_3$* | 7.06 | 9.23 | 7.50 | 9.80 | 3.99 | 9.21 | 3.42 | 6.00 | 4.60 | 20.31 | 13.66 | 23.98 |
| MgO | 0.55 | 0.87 | 0.79 | 0.85 | 0.47 | 0.75 | 0.53 | 0.89 | 0.57 | 2.70 | 1.69 | 3.01 |
| MnO | 0.16 | 0.09 | 0.08 | 0.20 | 0.09 | 0.19 | 0.08 | 0.11 | 0.08 | 0.18 | 0.21 | 0.25 |
| CaO | 0.62 | 0.26 | 0.18 | 1.11 | 1.14 | 0.54 | 2.35 | 0.71 | 1.12 | 0.19 | 0.48 | 0.93 |
| $Na_2O$ | 2.32 | 1.18 | 1.17 | 1.15 | 3.74 | 1.88 | 1.54 | 1.97 | 1.88 | 0.21 | 0.88 | 0.62 |
| K2O | 3.22 | 3.83 | 4.61 | 1.51 | 3.29 | 2.65 | 0.92 | 1.76 | 2.59 | 0.77 | 0.63 | 0.19 |
| $P_2O_5$ | 0.03 | 0.03 | 0.03 | 0.02 | 0.06 | 0.05 | 0.03 | 0.02 | 0.03 | 0.09 | 0.10 | 0.28 |
| Total | 96.27 | 97.06 | 95.54 | 91.01 | 94.61 | 96.70 | 95.11 | 96.70 | 95.35 | 96.23 | 95.21 | 92.80 |
| CIA value | 78.08 | 81.00 | 79.90 | 83.89 | 76.02 | 80.63 | 75.07 | 78.50 | 75.99 | 94.27 | 89.15 | 86.88 |

| Sample No. (wt.%) | qtzvein-g Type 2 | 04051907 Cld-free | 051907 Cld-free | 051907c Cld-free | 04051909 Cld-free | 04062805g Cld-free | cld-z-hasai-g Cld-free | L2** Average Pelite | L10** Average Pelite | L12** Average Pelite | L29** Average Pelite |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 48.95 | 57.69 | 73.16 | 67.99 | 64.65 | 61.13 | 56.26 | 58.14 | 67.25 | 62.44 | 58.56 |
| $TiO_2$ | 0.48 | 0.61 | 0.56 | 0.62 | 0.63 | 1.24 | 0.83 | 0.65 | 0.97 | 1.04 | 1.10 |
| $Al_2O_3$ | 15.94 | 16.74 | 12.56 | 14.17 | 17.44 | 22.63 | 16.93 | 21.00 | 16.42 | 21.29 | 22.30 |
| $Fe_2O_3$* | 20.35 | 10.85 | 4.89 | 4.88 | 6.97 | 3.10 | 9.24 | 7.35 | 6.53 | 3.94 | 8.74 |
| MgO | 4.30 | 3.77 | 2.09 | 1.93 | 1.67 | 0.83 | 2.36 | 0.06 | 0.02 | 0.08 | 0.07 |
| MnO | 0.21 | 0.16 | 0.06 | 0.07 | 0.04 | 0.05 | 0.14 | 3.41 | 1.05 | 1.25 | 1.87 |
| CaO | 0.31 | 3.91 | 1.67 | 3.18 | 0.61 | 2.45 | 3.57 | 0.32 | 0.05 | 1.00 | 0.18 |
| $Na_2O$ | 0.44 | 2.25 | 1.11 | 1.66 | 0.47 | 0.92 | 2.85 | 1.10 | 0.79 | 2.58 | 0.93 |
| K2O | 0.24 | 0.08 | 1.45 | 0.91 | 2.80 | 2.06 | 0.13 | 3.85 | 2.81 | 4.01 | 2.88 |
| $P_2O_5$ | 0.08 | 0.09 | 0.12 | 0.16 | 0.01 | 0.01 | 0.19 | 0.00 | 0.07 | 0.18 | 0.15 |
| Total | 91.29 | 96.16 | 97.65 | 95.56 | 95.28 | 94.42 | 92.49 | 95.88 | 95.96 | 97.81 | 96.78 |
| CIA value | 92.16 | 61.05 | 67.15 | 60.86 | 78.10 | 73.47 | 60.91 | 76.20 | 79.38 | 68.10 | 82.85 |

Cld = chloritoid
*Total iron as $Fe_2O_3$.
** Cited from Shaw (1956)

The Shimozaisho metaclastic rocks are characterized by enrichment in $Al_2O_3$ or $Fe_2O_3$ compared to average pelite (Shaw, 1956; Fig. 5). Type 1 and type 2 rocks are richer in Al and Fe, respectively, than chloritoid-free metapelites. Maximum content of $TiO_2$ is 2.05 wt.%. Other metaclastic rocks originating from Carboniferous protoliths also plot in the cover Al or Fe rich area in the AFM diagram (Fig. 5). Chloritoid-bearing samples have much higher CIA values than chloritoid-free samples.

Figure 5. AFM diagram for metaclastic rocks originating from Carboniferous and Permian, shelf sediments in Japan

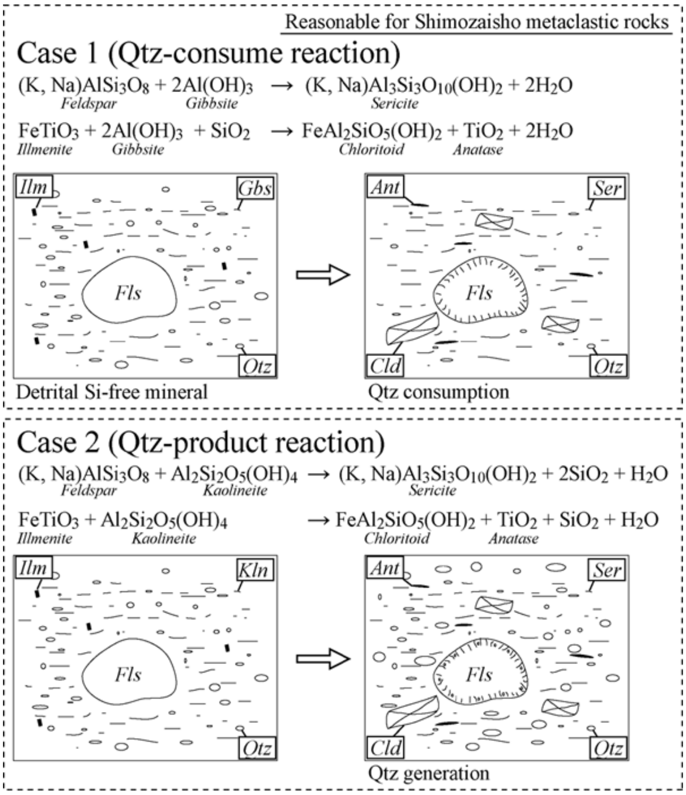



(compiled from Onuki, 1960; Asami, 1979; Asami and Adachi, 1979; Kano, 1980; Okuyama, 1980; Hiroi, 1983; 1984; Naito, 1993; Sakashima *et al.*, 1995; Kim and Ishiwatari, 1997).

## Metamorphic reactions

In order to clarify the protolith characteristics, we considered conventional metamorphic reactions. Bulk chemistry of detrital sediments is primarily controlled by the composition of the source (e.g., Bhatia, 1983). $Al_2O_3$ or $Fe_2O_3$* contents of the Shimozaisho Group are relatively high compared to the average pelite of Shaw (1956) (Table 1). The Al- or Fe-rich composition is probably related to weathering processes (hydrolysis, oxidation, hydration, salinization) on the provenance (Retallack, 2001). The chemical compositions of the Al-rich metaclastic rocks of the Shimozaisho Group are comparable with pyrophyllite-muscovite rock of lateritic soil parentage from Central India (Sharma, 1979). However, the protoliths of the Al-rich metaclastic rocks in the Shimozaisho Group were not soils. The presence of detrital grains and sedimentary structures obviously indicate that the protolith was formed as a result of transport and redeposition deposition of detritus, which may have been derived from weathered soil. To evaluate soil component on the provenance, we attempt to identify the detrital minerals derived from the weathered soils adopting conventional metamorphic reactions as described below (Fig. 6).

Figure 6. Major sericite and chloritoid forming metamorphic reactions in the Al- and Fe-rich pelitic rocks




Our study shows that the Shimozaisho metaclastic rocks contain no metamorphic quartz, indicating that detrital Al-free minerals were abundant in the protolith (Case 1 is reasonable). Abbreviations: Qtz = quartz, Cld = chloritoid, Ser = sericite, Fls = feldspar, Gib = gibbsite, Kln = kaolinite, Ilm = ilmenite, Ant = anatase.

Feldspar + Gibbsite = Sericite + 2 $H_2O$ (1)

Ilmenite + 2Gibbsite + Quartz = Chloritoid + Anatase + 2 $H_2O$ (2)

We use Al-containing minerals, because the Al contents in this system is related to the amount of feldspar destroyed during weathering, which is prevailing in most types of rocks (Nesbitt and Young, 1982).

Reaction rims surrounding detrital feldspar and felsic volcanic fragment are composed of dominant sericite and no quartz (Figs. 4E, 4F) suggesting that the feldspar consumption reaction generates only sericite and no quartz (reaction (1)). The matrix is composed mainly of sericite and lesser amount of quartz (Figs. 4B, 4C, 4D, 4E) suggesting that the quartz consumption reaction (2) occurred. Occurrences of Ti-minerals suggest that ilmenite is a pre-metamorphic mineral and that anatase is a metamorphic mineral (Figs. 4F, 4G). This indicates that anatase was formed from breakdown of detrital ilmenite (reaction

(2)). These observations suggest that Si-free minerals such as gibbsite were present in the protolith of the Al-rich metaclastic rocks and negate the possibility of contribution of Si-bearing minerals, such as kaolinite and halloysite, to the metamorphic reaction (Fig. 6).

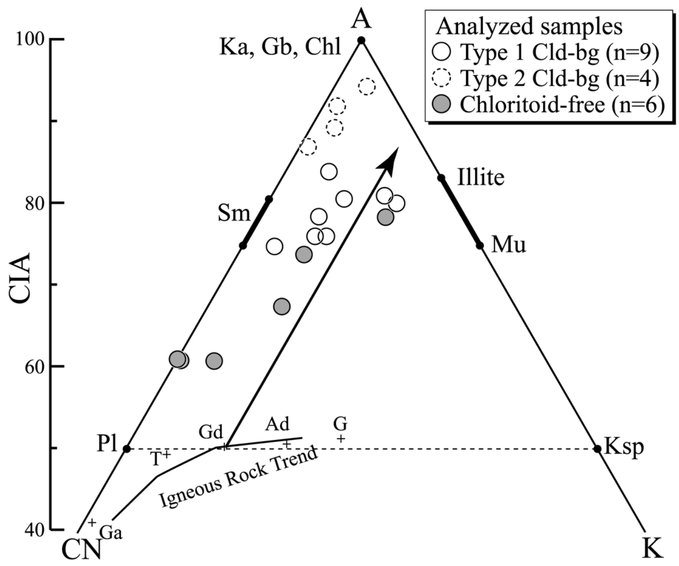
## Provenance

Detrital grains, including quartz, plagioclase and felsic volcanic fragments indicate felsic volcanic and plutonic rocks in provenance of the Shimozaisho meta-clastic rocks. In addition to these felsic igneous fragments, highly weathered rocks and mafic rocks should be in their provenance due to the following reasons.

The Si-free Al-mineral in the protolith of the Shimozaisho meta-clastic rocks should be detritus of weathering products which were mostly derived from feldspar through the weathering hydration process. Gibbsite is generated at low activity of aqueous $SiO_2$ and low $^{a}K^{+}/^{a}H^{+}$ activity ratios (Aagaard *et al.*, 1983). In other words, the source of the protolith was located in a humid and well-drained surface (Barshad, 1966). In tropical climates, hydration removes most of the Si from soils because of high humidity (Retallack, 2001). Thus, the presence of detrital gibbsite, as main soil derived detritus in the Carboniferous Shimozaisho Group, suggests that the provenance was located in a tropical climate zone (Fig. 8). In addition, high $TiO_2$ content also suggests a provenance from highly weathered soil because high $TiO_2$ contents are frequent in intensely weathered modern tropical soils (e.g., Brazilian soil contains 2.3 wt.% $TiO_2$; Cornu *et al.*, 1999), whereas in average soils the $TiO_2$ content is 0.35 wt.% (Pendias and Pendias, 1984).

Source rocks of the Shimozaisho metapelites are shown in the A-CN-K diagram (Fig. 7).

Figure 7. A-CN-K diagram.



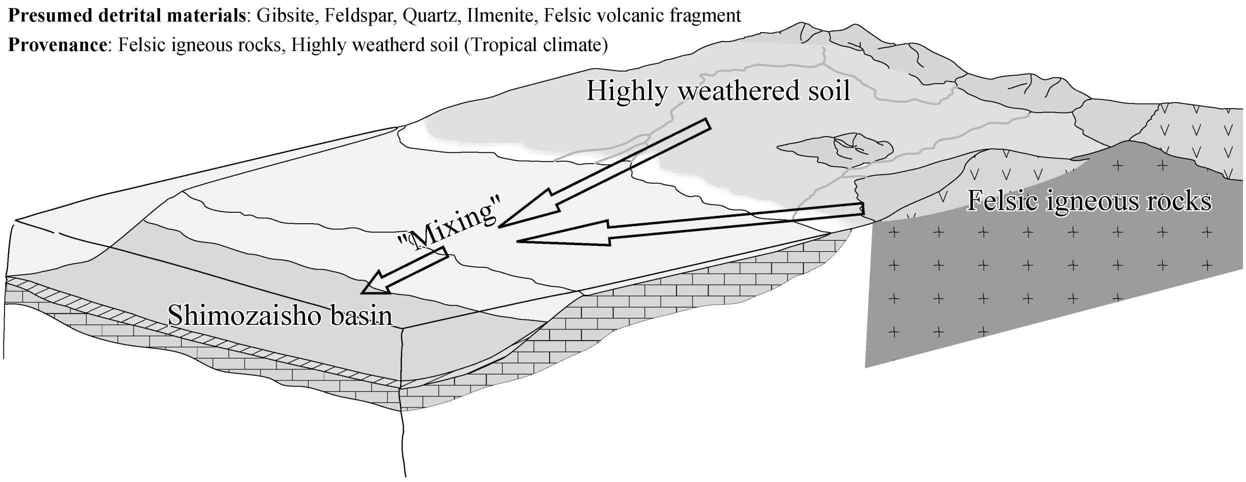

Arrow indicate ideal weathering trend. Cross symbols shows average igneous rocks (Nesbitt and Young, 1984). Abbreviations: Ad = Adamellite, G = Granite, Ga = Gabbro, Gd = Granodiorite, Cld = Chloritoid, Pl = Plagioclase, Ksp = K-feldspar, Sm = Smectite, Mu = Muscovite, Ka = Kaolinite, Gb = Gibbsite, Chl = Chlorite, T = Tonalite.

On the A-CN-K diagram, ideal weathering trend (Nesbitt and Young, 1984) suggests that chemical compositions of the Shimozaisho meta-clastic rocks are comparable with ideally weathered rocks originated from mafic to felsic rocks. Abundant sericite in the matrix of type 1 rocks suggests their potassium-rich rock origin and relevant felsic rocks in their provenance. Chlorite as major component of type 2 rock matrix suggests their iron- and magnesium-rich rock origin and relevant mafic rocks in their provenance.

## Sedimentary mixing forcing Al-rich metapelites chemistry

In the previous section we suggested that source rocks for Shimozaisho pelite included highly weathered soils (suggested by presumed detrital gibbsite), felsic igneous rock (indicated by detrital volcanic fragments, quartz and feldspar) and mafic rocks (suggested by chemical composition) (Fig. 8).

Figure 8. Schematic block diagram




Schematic block diagram illustrating the suggested provenance of the detrital materials in the Carboniferous Shimozaisho Group with source in a tropical climate zone. Not to scale.

In addition to this, we emphasize two implications concerning the Shimozaisho meta-clastic rocks: mixing of weathered and non-weathered materials during sedimentary process; and wide variation in source rock types including felsic and mafic rocks with highly weathered soil. A key to the understanding of the mechanism of complex detritus supply for the Shimozaisho basin is intercalating volcaniclastic layers.

Carboniferous shelf deposits in the Hida Mountains commonly include volcaniclastic layers. These indicate that the sedimentary basins were not far from volcanic activities.

The suggested provenance of the Al-rich horizons from highly weathered materials implies a stable surface - whereas the volcanic horizons suggest an active surface. This necessitates a change in tectonic setting from presumably passive margin to active margin. In support of this assumption is the occurrence of the Al-rich horizons, characteristically towards the base of the pelitic sequence overlying thick limestone beds in the Unazuki Metamorphic Rocks (Hiroi, 1978). In this case, the mixing of highly weathered and non-weathered materials and the supply of both detritus to Carboniferous basins was caused by volcanic activity and/or associated tectonic uplifting. We here mention that the wide distribution of Japanese Carboniferous Al-rich metaclastic rocks might be result of regional-scale detrital supply of intense weathered materials, which was caused by the change in tectonic setting. Interpretation of the petrology and geochemistry of metapelites in the Carboniferous Shimozaisho Group of the Hida Marginal Belt, Central Japan as the result of a mixed tropical pedogenesis of the protolith sheds light on simultaneous tectonic activity and paleolatitude of this Gondwana derived terrane.

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