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Geochemical Features of Pelitic Gneiss in the Lhenice Shear Zone (Moldanubian Zone of the Southern Bohemian Massif)

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Abstract

Whole rock chemical analysis was carried out for sillimanite-cordierite-biotite-garnet (Sil-Crd-Bt-Grt) gneisses at Ktiš in the Lhenice shear zone of the southern Bohemian Massif, Czech Republic, in order to consider the origin of this rock. The Sil-Crd-Bt-Grt gneiss shows a variety of lithotype mainly controlled by modal amount and grain size of main constituent minerals, resulting in the wide chemical variation of SiO₂ content even in one outcrop from mafic composition (48.5 wt%) of a melanocratic layer with coarse-grained Grt to felsic composition (76.9 wt%) of a leucocratic vein. Petrology of the Sil-Crd-Bt-Grt gneiss and common occurrence of the leucosome in the outcrop suggest that the study rock suffered the partial melting during the exhumation stage. Available geochemical data suggest that leucocratic lithotypes with SiO₂ contents from 70.3 to 76.9 wt% were formed by the partial melting of the protolith and melanocratic types with SiO₂ contents from 48.5 to 60.6 wt%, which include the main lithotype, were the residue. Therefore, leucocratic/melanocratic layer intercalations with SiO₂ contents from 57.0 to 65.0 wt% would most likely represent the chemical composition of the protolith of Ktiš gneiss. Several lines of chemical features of the leucocratic/melanocratic layer intercalation suggest that the protolith would be a mixture of greywacke and pelite with moderate aluminum saturation index (ASI) value and is characterized by extreme high Fe₂O₃ compared with continental and trench fill sediments.

Keywords: whole rock, Bohemian Massif, Lhenice shear zone, Protolith

ボヘミア山塊南部 Lhenice shear zone に産する 泥質片麻岩の全岩化学組成

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1. Introduction

Partial melting of crustal rocks is one of the main mechanisms of production of granitoid magmas. The presence of even a small amount of distributed partial melt can have a profound effect on the bulk rheological properties of crustal section rock (e.g. Rosenberg and Handy, 2005). Anatexis, leucogranite and leucosome generation are demonstrated to play a significant role in crustal differentiation (e.g. Brown, 1994). Therefore, the geochemical study of anatectic high-grade metamorphic rocks is important for understanding partial melting process and formation of the continental crust.

Partial melting of crustal rocks has been extensively investigated low- to mid-pressure conditions, in the stability field of sillimanite, but studies of these rocks at higher-pressure conditions are relatively few. Felsic granulites in the southern part of the Bohemian Massif (Gföhl Unit, Moldanubian Zone; Fig. 1) contain high-pressure and high-temperature mineral assemblages such as garnet + ternary feldspar + kyanite, and their geochemistry mostly corresponds to peraluminous fractionated granitic rocks. Therefore, the protolith of felsic granulites was considered as rhyolites or granites formed at lower-pressure conditions (Fiala et al., 1987; Vellmer 1992; Janoušek et al., 2004)

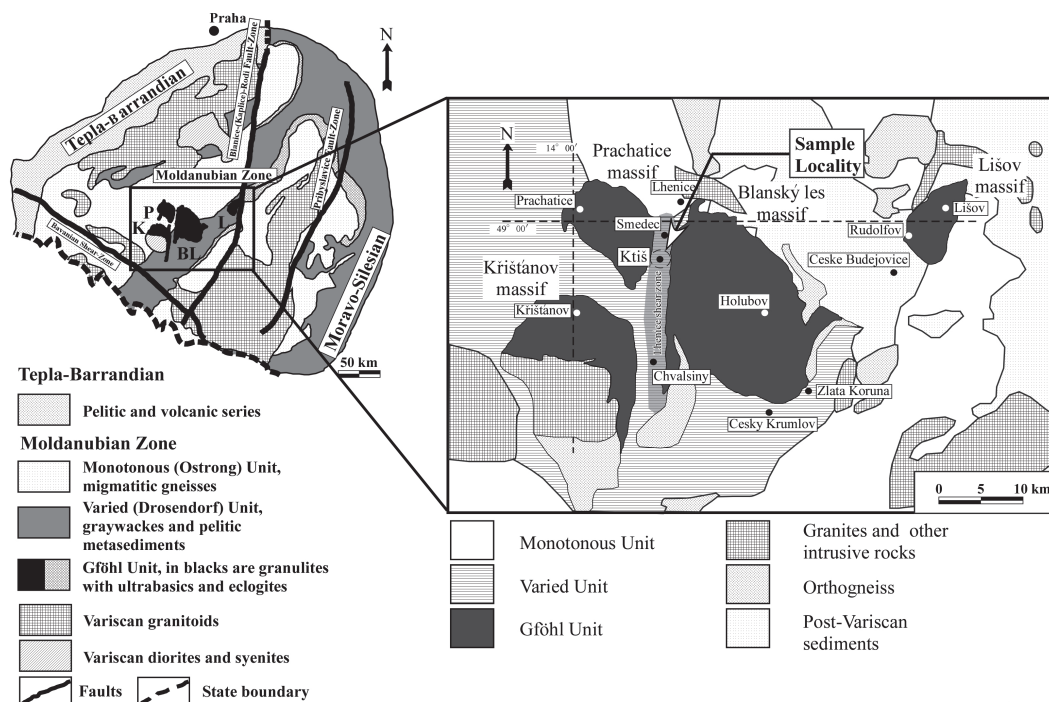


Figure 1. Geological sketch map of the Variscan orogenic belt in the Bohemian Massif (after Svojtka et al. 2002, Kobayashi et al. 2011), and a simplified geological map of southern Bohemia. The sample locality, Ktiš, is located in the Lhenice shear zone, developed between the Blanský les and Prachatice granulite body. P = Prachatice; K = Křišťanov; BL = Blanský les; L = Lišov.

or at higher-pressure conditions (Jakeš, 1997; Kotková and Harley, 1999).

Recently, precursor high-pressure metamorphic conditions, i.e., > 1.5 GPa at 700°C , and partial melting evidence around 800°C at < 0.8 GPa were identified from sillimanite-cordierite-biotite-garnet (Sil-Crd-Bt-Grt) gneisses cropped out at Ktiš in the Lhenice shear zone, located between Branský les and Prachatice granulite massifs in southern Bohemian Massif (Fig. 1; Kobayashi et al., 2011). The Lhenice shear zone has been considered to belong to the Varied or Monotonous Units in spite of the scarce geological evidence (Rajlich et al., 1986). The new findings of Kobayashi et al. (2011) awakened an argument on the origin of the Lhenice shear zone. To arriving at a goal of this argument, we need more comprehensive understanding for the constituents of the Lhenice shear zone. In this report, we describe the major elements whole rock chemical characteristic of Sil-Crd-Bt-Grt gneisses and discuss its origin.

Mineral abbreviations are after Kretz (1983).

2. Geological setting

The Bohemian Massif represents a relic of the Variscan orogenic belt in Central Europe. Tectonically the Bohemian Massif is subdivided into two units; Moldanubian zone in the south and Saxothuringian in the north-western part. Metamorphic rocks in the Moldanubian Zone of the Bohemian Massif belong to three tectonic units, which are Varied, Monotonous and overlying Gföhl Units, accompanied by numerous Variscan granitoids intrusion (Dudek and Fediuková, 1974; Fediuková, 1989; Franke, 1989; Fuchs, 1990; Matte et al., 1990; Fiala et al., 1995; Medaris et al., 1995; O'Brien and Vrána 1995; Medaris et al., 1998; Klápová, 1998; Konopásek et al., 2001; Massonne and O'Brien, 2003; Tropper et al., 2005; Schulmann et al., 2005; Faryad et al., 2010) (Fig. 1). The Varied Unit is composed of metasedimentary rocks intercalated with amphibolites, quartzites, marbles and calc silicates. The Monotonous Unit consists of paragneisses intercalated with orthogneiss bodies. The lower part of the Monotonous Unit is characterized by a thick sequence of amphibolites and metagabbros (Racek et al., 2006) and locally containing eclogites (O'Brien and Vrána, 1995). The Varied and Monotonous Units generally exhibit medium-pressure (MP) and low-pressure (LP) mineral assemblages, respectively (Fuchs, 1971; Tollmann, 1982; Matte et al., 1990). The Gföhl Unit consists of two tectonic units; upper high-pressure (HP) granulite series and lower migmatitic gneisses unit associated with garnet and spinel peridotites, eclogites, pyroxenites, orthogneisses, paragneisses, amphibolites, calcsilicate gneisses and metagabbros (Fuchs and Matura, 1976; Pin and Vielzeuf, 1983; Urban, 1992; Carswell and O'Brien, 1993; Fiala et al., 1995; Faryad et al., 2010).

The studied sillimanite-cordierite-biotite-garnet (Sil-Crd-Bt-Grt) gneiss is cropped out in an abandoned quarry at Ktiš ($48^{\circ} 55' 40\text{N}$, $14^{\circ} 08' 37\text{E}$) in the Lhenice shear zone located between Branský les and Prachatice massif of the Gföhl unit (Fig 1). Main foliation of the gneiss strikes N40W

and dips 38S. Granitic vein is also found in the center of the outcrop about 1.5 m width.

2.1 P-T conditions of Varied and Monotonous Unit and Lhenice shear zone

Rajlich et al. (1986) invoked that the Lhenice shear zone has been suffered amphibolite facies metamorphism of which grade is almost identical to the peak pressure-temperature (P-T) conditions of the Varied and Monotonous Unit; about 0.5–0.9 GPa and 700–840°C in the Lower Austria (Petrakakis, 1986; Büttner and Kruhl, 1997; Tropper et al., 2006). The prograde metamorphic evolution of the Monotonous unit is documented by inclusions of staurolite (Linner, 1994), kyanite (Ky), garnet (Grt) and biotite (Bt) in plagioclase (Pl). Staurolite (St) and Ky were considered as relics of prograde stage (Linner, 1994). P-T conditions of the prograde stage were estimated as 0.5–1.1 GPa and 534–555°C based on Grt-Bt geothermometer and the coexistence of Bt, Ky, St and Grt (Büttner and Kruhl, 1997). Retrograde P-T conditions are estimated as 0.12–0.22 GPa and 420–460°C based on phengite geobarometer and muscovite-biotite geothermometer (Büttner and Kruhl, 1997).

However, Kobayashi et al. (2011) inferred that the Sil-Crd-Bt-Grt gneiss at Ktiš recorded multiple equilibrium stages, based on the mode of the occurrence of constituent minerals and the zoning pattern of Grt. Furthermore, they proposed the following developing history of the host rock, such as, a prograde stage defined by the assemblage of grossular (Grs)-rich and phosphorus (P)-poor Grt core (Grs_{27}) + Pl (anorthite (An_{11-15})) under 1.5–2.3 GPa at 700–900°C (Stage 1), a subsequent Grt-rim forming stage represented by Grs-poor and P-rich garnet (Grs_5) + Pl (An_{12-19}) + alminosilicate (Ky/Sil) at 730–830°C and 1.0–1.3 GPa (Stage 2), and a following decompression stage by the P-poor outermost rim of Grt (Grs_2) + Sil + Crd \pm spinel (Spl) at 740–850°C and 0.6–0.8 GPa (Stage 3) accompanying with the partial melting of the host rock (Fig. 9 of Kobayashi et al. 2011)

3. Lithotype and petrology

The main lithology of Sil-Crd-Bt-Grt gneiss is a melanocratic type with fine-grained Grt (0.1–1.0 mm in diameter) accompanying with patchy or lens-shape leucosome, up to 10 cm long, suggesting partial melting. Hereafter, we call this part as “fine-grained melanocratic part”, which mainly consists of Bt, Grt, K-feldspar (Kfs), Crd and Sil with subordinate amounts of Pl and quartz (Qtz) (Fig 2a). Intercalation of melanocratic and leucocratic layers with coarse-grained Grt (3.0–5.0 mm in diameter) partly developed in the fine-grained melanocratic part (Fig 2b-c). The matrix mineral assemblages in this intercalation are identical with those of the main lithology. Leucocratic layer (a few tenth cm in width) with fine-grained Grt is locally developed (Fig 2d) in the outcrop. It is bi-mineralic, mainly composed of Qtz and Kfs, with subordinate amounts of Bt, Grt, Sil and Pl.

Bt is the main matrix forming phase and defines the main foliation with or without Sil. It also occurs as an inclusion in Grt. Sil occurs both as an inclusion phase in Grt and as a matrix phase. Ky

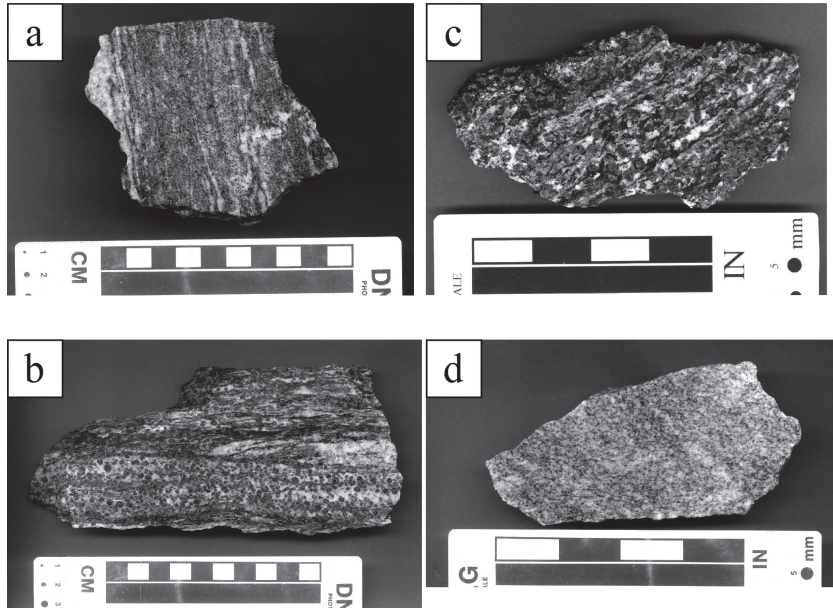


Figure 2. Photographs of Sil-Crd-Bt-Grt gneisses. (a) Melanocratic part with fine-grained garnet (0.1–1.0 mm) with leucosome. (b) Leucocratic/melanocratic layer intercalation with coarse-grained (3.0–5.0 mm) garnet. (c) Melanocratic layer with coarse-grained (3.0–5.0 mm) garnet. (d) Fine-grained (0.1–1.0 mm) leucocratic layer.

is identified only as an inclusion phase in the rim of Grt. The studied rocks contain scarce amount of Pl, although Pl occurs both as inclusion in Grt and as the matrix phase. Kfs occurs both as the inclusion phase in Grt and as the matrix phase. Kfs in the melanocratic layer with coarse-grained Grt commonly shows perthitic texture. Crd occurs only in the matrix both as the isolated grain and as a reaction corona surrounding Grt. The occurrence of Spl is limited only in the Crd corona and in Qtz inclusion in Grt. The Grt shows bimodal grain size; coarse-grained (3.0–5.0 mm in diameter) and fine-grained (0.1–1.0 mm in diameter). Some coarse-grained (> 3.0 mm) Grts show chemical heterogeneity both in major and minor elements; Grs-content is homogeneous and high ($X_{\text{grs}} = 0.27$) in an apparent core of the grain and continuously decreases towards the rim ($X_{\text{grs}} = 0.02$). However, pyrope (Prp)-content shows an inverse pattern against Grs-content, i.e., Prp content is low and constant ($X_{\text{prp}} = 0.03$) in the core and gradually increases towards the rim (up to $X_{\text{prp}} = 0.28$). The outline of Grs and Prp content contours show symmetrical hexagonal shapes. Phosphorous (P)-content is almost below the detection limit of EPMA in the apparent core but it is high at the margin of the grain with local development of P-poor outermost rim. The outline of P-poor core shows a hexagonal shape, similar to that of Grs and Prp content contours. There is a discordance between the position of the outermost edge of P-poor core and of the outermost edge of the apparent core determined by “high Grs ($= 0.27$)-content.

4. Modal composition

We determined the modal compositions for all lithotypes of Sil-Crd-Bt-Grt gneisses by the point-counting method. For getting an average mode of the gneiss, counting transects were set perpendicular to the gneissosity and more than 15,000 points were counted.

Average modal composition of the fine-grained melanocratic part shows following value; Qtz (34.6%), Kfs (23.6%), Grt (21.3%), Bt (14.3%), Crd (3.0%) and Sil (2.1%) and others (0.9%). Average modal composition of the leucocratic/melanocratic layer intercalations with coarse-grained Grt shows following value; Qtz (39.5%), Kfs (24.4%), Bt (15.2%), Grt (12.3%), Sil (5.0%) and Crd (2.7%) and others (0.9%). These modal data show that Qtz, Kfs, Grt and Bt occupy about 80 percent of the studied rocks. Crd, Pl, Sil, graphite and rare greenish spinel (hercynite) also occur in the matrix.

In contrast, melanocratic layer with coarse-grained Grt mainly composed of Kfs (31.7%), Bt (28.2%) and Grt (33.4%). Modal amount of Pl is scarce (up to 1.5%). Fine-grained leucocratic layer, however, is bi-modal composition that mainly composed of Qtz and Kfs.

5. Whole-rock composition

5.1 Analytical Method

Whole-rock major element compositions were determined using X-ray fluorescence spectrometer at Kyoto University (Rigaku SIMULTANEOUS 3550). The analytical procedure followed that of Goto and Tatsumi (1994, 1996). A 1:10 ratio of powdered rock sample (0.4g) and anhydrous lithium borate flux (4.0g) were weighed into a Pt crucible and fused at 1200°C to prepare a glass bead sample. Utilizing these glass bead samples, major element contents have been determined on eleven samples as follows; three samples of the main lithotype, i.e., fine-grained melanocratic part, two of leucocratic/melanocratic layer intercalation with coarse-grained Grt, three of leucocratic layer with fine-grained Grt, one of melanocratic layer with coarse-grained Grt, one Crd-bearing leucocratic patch and one leucocratic vein (KT421).

5.2 Result

The result is summarized in Table 1.

All data are plot in SiO₂-variation diagrams (Figs. 3 and 4) along with the data of representative continental sediments, such as averages of phyllites (50 samples) and mica schists (103 samples) data of Poldervaart (1955), North American Shale Composition = NASC (Gromet et al., 1984), Post Archaean Australian Shale = PAAS, Upper Continental Crust = UCC (Taylor and McLennan, 1985), and Bulk Continental Crust = BCC (Rudnik and Fountain, 1995), trench fill sediments representing

Table 1. Whole-rock chemistry of Grt-Bt-Sil-Crd gneiss from Ktiš area. Total Fe as Fe₂O₃.

Sample No	KT301	KT302	KT307M	KT416	KT311	KT305	KT308	KT309	KT421M	KT307L	KT421L
Rock type	Fine-grained melanocratic part	Fine-grained melanocratic part	Fine-grained melanocratic part	Leucocratic/mela nocratic layer intercalates with coarse-grained garnet	Leucocratic/mela nocratic layer intercalates with coarse-grained garnet	Melanocratic layer with coarse-grained garnet	Leucocratic layer with the fine- grained garnet	Leucocratic layer with the fine- grained garnet	Leucocratic layer with the fine- grained garnet	Cordierite- bearing leucocratic patches	Leucocratic vein
(wt%)											
SiO ₂	59.1	60.6	59.5	57.0	65.0	48.5	71.3	72.8	72.7	70.3	76.9
TiO ₂	0.6	1.2	1.4	0.9	0.8	1.1	0.5	0.5	0.6	0.4	0.2
Al ₂ O ₃	14.8	19.4	19.7	16.3	14.2	20.4	12.4	13.0	11.9	15.9	12.5
Fe ₂ O ₃	17.2	9.7	9.7	15.2	11.5	17.1	8.2	4.7	7.3	2.7	2.1
MnO	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0
MgO	3.6	2.7	2.9	3.7	2.7	4.4	1.7	1.2	1.6	0.8	0.4
CaO	0.6	0.4	0.4	0.7	0.8	1.2	0.7	0.7	0.7	0.4	0.9
Na ₂ O	0.5	0.5	1.1	1.7	2.4	2.9	2.6	3.3	2.4	2.0	4.0
K ₂ O	3.5	5.0	4.7	3.9	2.7	4.8	2.3	2.9	2.5	7.0	2.7
P ₂ O ₅	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1
total	100.1	99.5	99.7	99.7	100.3	100.5	99.9	99.4	99.8	99.6	99.7
A/CNK	3.2	3.3	3.2	2.6	2.4	2.3	2.2	1.9	2.2	1.7	1.7
Na ₂ O/K ₂ O	0.13	0.11	0.24	0.44	0.89	0.60	1.14	1.15	0.94	0.29	1.47
ClA	72.5	73.7	72.0	66.2	62.8	62.7	60.2	56.8	60.4	57.7	53.2
ClW	89.1	92.6	88.4	79.9	72.2	74.6	68.6	65.9	70.0	79.4	60.7

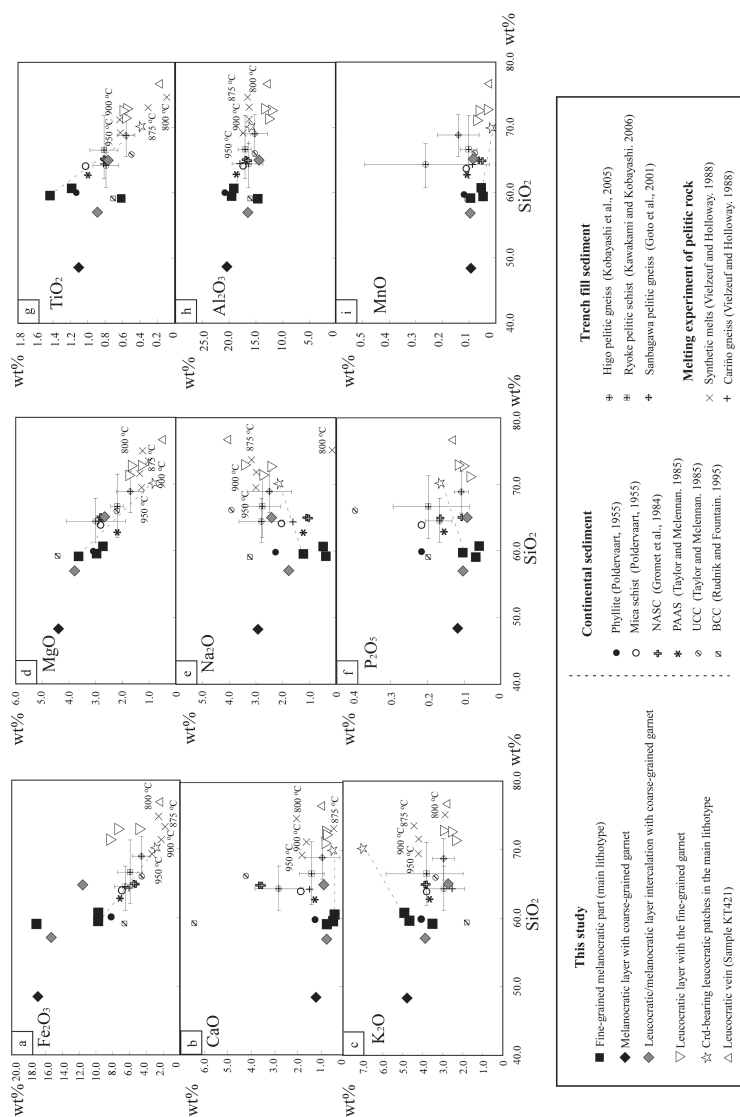


Figure 3. Comparison of whole-rock major-element compositions of Kfs-Sil-Crd-Bt-Grt gneisses with synthetic granitic melts and continental/trench fill sediments; Synthetic melts are from Vielzeuf and Holloway (1988), obtained from partial melting experiment of Carlini gneiss at conditions of 0.8 GPa and 800 °C, 1.0 GPa and 875, 900 and 950 °C, respectively. Typical composition of phyllite and mica schist from Poldervaart (1955), NASC = North American Shale Composition (Gromet et al., 1984), PAAS = Post Archaean Australian Shale, UCC = Upper Continental Crust (Taylor and McLennan, 1985) and BCC = Bulk Continental Crust (Rudnik and Fountain, 1995) are also shown. Average bulk composition of pelitic gneiss from Higo metamorphic terrane (Kobayashi et al., 2005), pelitic schist from Ryoke metamorphic belt (Kawakami and Kobayashi, 2006) and pelitic schist from Sanbagawa metamorphic belt (Goto et al., 2001) are plotted for comparison. (a) Fe_2O_3 - SiO_2 plot. (b) CaO - SiO_2 plot. (c) K_2O - SiO_2 plot. (d) MgO - SiO_2 plot. (e) Na_2O - SiO_2 plot. (f) P_2O_5 - SiO_2 plot. (g) TiO_2 - SiO_2 plot. (h) Al_2O_3 - SiO_2 plot. (i) MnO - SiO_2 plot.

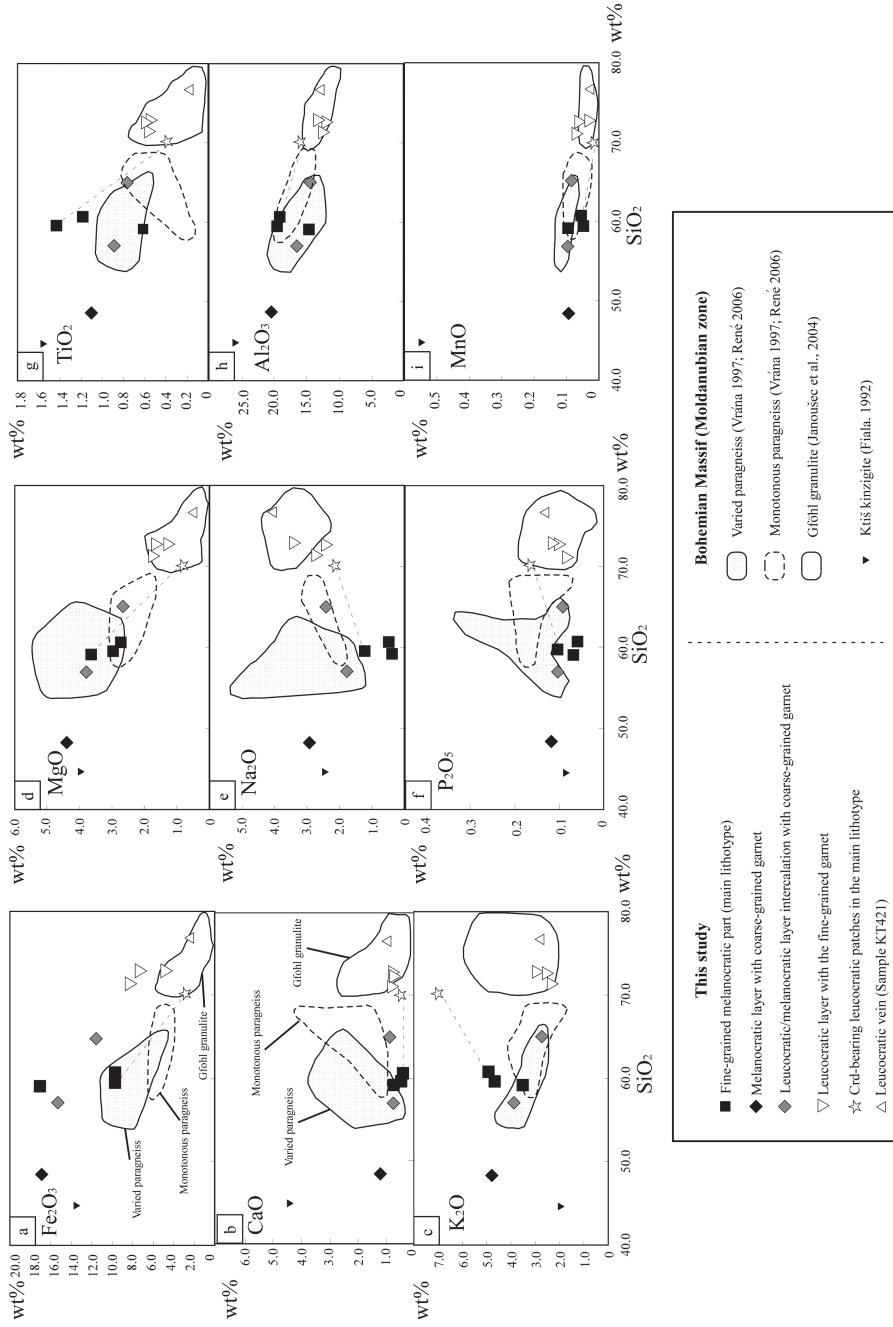


Figure 4. Comparison of whole-rock major-element compositions of Ktiš Sil-Crd-Bt-Grt gneisses with paragneisses from Monotonous and Varied Unit (Vrána, 1997; René, 2006) and Gřohl granulites (Janoušek, 2004). Ktiš kinzigite data from Fiala (1992) is also plot. (a) Fe_2O_3 - SiO_2 plot. (b) CaO - SiO_2 plot. (c) K_2O - SiO_2 plot. (d) MgO - SiO_2 plot. (e) Na_2O - SiO_2 plot. (f) P_2O_5 - SiO_2 plot. (g) TiO_2 - SiO_2 plot. (h) Al_2O_3 - SiO_2 plot. (i) MnO - SiO_2 plot.

the accretionary setting such as average compositions of pelitic gneiss from Higo metamorphic terrane (Kobayashi et al., 2005), pelitic schists from the Ryoke metamorphic belt in Aoyama area (Kawakami and Kobayashi, 2006) and pelitic schists from Sanbagawa metamorphic belt in shikoku (Goto et al., 2001) and of granitic melt compositions obtained from melting experiments of Vielzeuf and Holloway (1988) in figure 3 and the compositional range of paragneisses from Monotonous and Varied Unit (Vrána, 1997; René, 2006) and of Gföhl granulites (Janoušek, 2004) and Ktiš kinzigite data from Fiala (1992) in figure 4.

6. Discussions and conclusion

6.1 What is the protolith of Ktiš gneiss: Comparison with synthetic melts and representative crustal rocks in Harker diagrams.

The SiO₂ contents of Sil-Crd-Bt-Grt gneiss at Ktiš in the Lhenice shear zone show an extremely wide variety from mafic (48.5 wt% of a melanocratic layer with coarse-grained Grt) to felsic composition (76.9 wt% of a leucocratic vein, KT421) (Table 1) collected from even in the narrow outcrop. Following elements, Fe₂O₃, MgO, TiO₂, Al₂O₃ and MnO for all rock types show a negative correlation with SiO₂ (Figs. 3a, d, g, h, i). Such trend could form by the fractional crystallization process from the mafic rocks. However, this idea is unlikely, as other major elements such as CaO, Na₂O and K₂O did not show a clear correlation with SiO₂ (Figs. 3b, c, e) and as graphite, common in sedimentary rocks, is identified as metamorphic minerals in the study gneiss.

According to the field observation, the developments of patchy or lens-shape leucosome are distinct, suggesting the partial melting was taken place. Crd-bearing leucocratic patches show three-dimensionally closed shapes and do not connect to veins or shear zones. This observation suggests that the Crd-bearing leucocratic patch is frozen acidic melts originated by the *in situ* melting of the host rock, although we cannot deny the possibility of an external melt origin, as some leucocratic veins cut through the main foliation of the fine-grained melanocratic part (main lithotype).

SiO₂ contents of the leucocratic lithotypes (i.e., leucocratic layer with fine-grained Grt, Crd-bearing leucocratic patch and leucocratic vein) have a limited compositional range between 70.3 and 76.9 wt% (Figs. 3 and 4) and are greater than those of the other lithotypes, i.e., from 48.5 and 65.0 wt% for fine-grained melanocratic part, melanocratic layer with coarse-grained Grt and leucocratic/melanocratic layer intercalation with coarse-grained Grt.

Synthetic melt compositions shown in figure 3 were obtained by the melting experiments of Cariño para-gneisses at following P-T conditions; 800°C and 0.8 GPa, and 875, 900 and 950°C at 1.0 GPa (Vielzeuf and Holloway, 1988). We selected those data, as the experimented P-T conditions are almost equivalent to inferred P-T conditions of melting timing of the study rock (Kobayashi et al., 2011). The SiO₂ compositions of the leucocratic lithotypes in this study are similar to SiO₂

compositions of abovementioned synthetic melts at 875–900°C and 1.0 GPa. Furthermore, the compositional range of the leucocratic lithotypes mostly overlaps with those of Gföhl granulite (Fig. 4). Geochemical feature of Gföhl granulites mostly corresponds to peraluminous fractionated granitic rocks. Therefore, the Gföhl granulites was considered to be as metamorphic equivalents of rhyolites or granites (Fiala et al., 1987; Vellmer 1992; Jakeš, 1997; Kotková and Harley, 1999; Janoušek et al., 2004;). These facts suggest that the leucocratic lithotypes represent acidic partial melts.

If we assume the melting process was took place in nearly closed system, i.e., *in situ* melting, the residue of the melt and the original protolith should have less siliceous compositions than the leucocratic types. Actually, the SiO₂ contents of the melanocratic layers or the leucocratic/melanocratic layer intercalation with coarse-grained Grt range from 48.5 to 65.0 wt%. Therefore, the melanocratic layers or the leucocratic/melanocratic layer intercalation with coarse-grained Grt is the candidate of the protolith. Furthermore, a linear correlation will be expected among the partial melt, residue and the protolith in their major element compositions in the closed system. As mentioned before, all analyzed samples show a distinct negative correlation between SiO₂ against Fe₂O₃/MgO/Al₂O₃. Average SiO₂ content of the leucocratic/melanocratic layer intercalation with coarse-grained Grt (61.0wt%) is higher than those of the melanocratic layers (56.9 wt% for 4 rocks, or 59.7 wt% for only fine-grained melanocratic part, Table 1). Therefore, the melanocratic layers could be the residue and the leucocratic/melanocratic layer intercalation with coarse-grained Grt may represent or be near the chemical composition of the protolith.

Actually, the compositions of leucocratic/melanocratic layer intercalation with coarse-grained Grt are best fit to the composition range of paragneisses in the Monotonous and Varied Unit (Fig. 4), although their Fe₂O₃ contents are significantly higher than those of paragneisses in Monotonous and Varied Unit. There is no explicit way to determine the protolith composition, which suffered partial melting process, either *in situ* melting or melt infiltration from outside, we propose a working hypotheses that the protolith of Sil-Crd-Bt-Grt gneiss at Ktiš was a paragneiss with similar composition with those of Monotonous and Varied Unit.

Melanocratic layer with coarse-grained Grt (sample KT305) shows a slight different lithology, being rich in biotite and garnet, and thus, it is treated separately, and has a similar bulk composition of Ktiš kinzigite of Fiala (1992) except for CaO, K₂O and MnO. K₂O content of sample KT305 is richer than those of Ktiš kinzigite, whereas CaO and MnO content of sample KT305 are poorer than the Ktiš kinzigite (Fig. 4). Such variation could form by the melt extraction from the host rock during the decompression stage (Stage 3) and/or metamorphic segregation represented by the development of coarse-grained Grs-rich Grt at prograde higher-pressure stage (Stage 1). The wide scattering of bulk data of melanocratic part with coarse/fine-grained Grt may suggest there is a difficulty to reconstruct the residue composition also.

6.2 What is the protolith of Ktiš gneiss: Comparison with synthetic melts and representative crustal rocks in A-CN-K/A-CNK-FM diagrams.

The aluminum saturation index [$ASI = Al_2O_3 / (CaO + Na_2O + K_2O) = A/CNK$ in Table 1] (Zen, 1986) of leucocratic lithotypes range from 1.7 to 2.2 and of studied Ktiš samples except for leucocratic lithotypes range from 2.2 to 3.3).

Following indices were proposed for evaluating the weathering degree of sediments; e.g. the chemical index of alteration [$CIA = (Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O)) \times 100$] (Nesbitt and Young, 1982), the chemical index of weathering [$CIW = (Al_2O_3 / (Al_2O_3 + CaO + Na_2O)) \times 100$] (Harnois, 1988). 100 of CIA is regarded as highly altered, which is applicable for rock/sediments mainly composed of kaolinite and/or chlorite, and 70 to 75 for average shales (Nesbitt and Young, 1982). CIA value of >50 is regarded as non-altered value (Nesbitt and Young, 1982). Taylor and McLennan (1985) reported a CIA value of 85 to 100 for residual clays, e.g. laterite.

We regard the leucocratic/melanocratic layer intercalation with coarse-grained Grt as the most probable protolith of Ktiš gneiss in the previous section. Those samples show CIA values of 62.8 to 66.2 (Table 1), which are slightly lower CIA value than those of average shales ($CIA = 70$ to 75) (Nesbitt and Young, 1982). Harnois (1988) reported that fresh basaltic and granitic rocks show CIW values of 32 to 76, and 81 to 99 for strongly weathered residues. The leucocratic/melanocratic layer intercalation with coarse-grained Grt show CIW values of 72.2 to 79.9, which indicate middle weathering grade of the original sedimentary protolith (Table 1).

Nesbitt and Young (1984) and Nesbitt et al. (1996) proposed the ternary diagrams Al_2O_3 -($CaO + Na_2O$)- K_2O [the A-CN-K] and Al_2O_3 -($CaO + Na_2O + K_2O$)- $Fe_2O_3 + MgO$ [the A-CNK-FM], to deduce weathering trends. Bulk compositions of sands are plotted close to the feldspar field in A-CN-K and A-CNK-FM diagram (Nesbitt et al., 1996). The muds have higher Al_2O_3 values on A-CN-K diagram and have higher $Fe_2O_3 + MgO$ values on A-CNK-FM diagram than the sands (Nesbitt et al., 1996). Applying ternary diagrams of A-CN-K and A-CNK-FM (Nesbitt and Young, 1984; Nesbitt et al., 1996), the leucocratic/melanocratic layer with coarse-grained Grt show relatively low $CaO + Na_2O$ and high $Fe_2O_3 + MgO$ ratio and plot in mud region (Fig. 5). The fine-grained melanocratic part (main lithotype) plotted lowest $CaO + Na_2O$ region in A-CN-K diagram (Fig. 5).

The leucocratic lithotypes except for Crd-bearing leucocratic patch are similar to synthetic melts at 875–900°C and 1.0 GPa of Vielzeuf and Holloway (1988) in A-CNK-FM diagram. However, the leucocratic layer with fine-grained Grt shows higher $Fe_2O_3 + MgO$ ratio than those of synthetic melts, and plotted in mud field of the diagram, which can be caused by a large amount of Grt in this lithotype. Although we do not have data to distinguish the origin of those garnets either metamorphic origin or melt origin at present, so there remains as a future work.

Furthermore, clastic type of sedimentary protolith can be checked using the classification diagram of Wimmenauer (1984), which is based on the K_2O/Na_2O and SiO_2/Al_2O_3 ratios. These ratios reflect

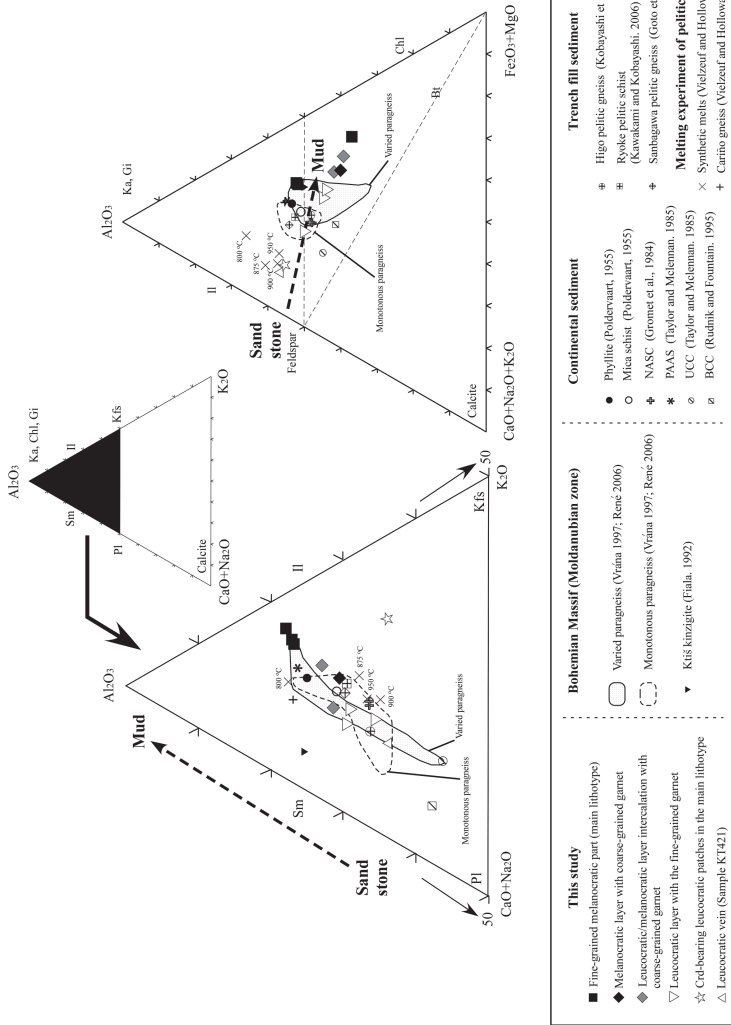


Figure 5. Comparison of Al_2O_3 -($\text{CaO} + \text{Na}_2\text{O}$)- K_2O and Al_2O_3 -($\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}$)- $\text{Fe}_2\text{O}_3 + \text{MgO}$ contents of Kfs Sil-Crd-Bt-Grt gneisses with other representative samples. Synthetic melts are from Vielzeuf and Holloway (1988), obtained from partial melting experiment of Carino gneiss at conditions of 0.8 GPa and 800 °C, 1.0 GPa and 875, 900 and 950 °C, respectively. Typical composition of phyllite and mica schist from Poldervaart (1955), NASC = North American Shale Composition (Gromet et al., 1984), PAAS = Post Archaean Australian Shale, UCC = Upper Continental Crust (Taylor and McLennan, 1985) and BCC = Bulk Continental Crust (Rudnik and Fountain, 1995) are also shown. Bulk composition of paragneiss from Monotonous and Varied Unit (Vrána, 1997; René, 2006) and that of Gföhl granulites (Janoušek, 2004), Kfs kinzigite data from Fiala (1992). Average bulk composition of pelitic gneiss from Higo metamorphic terrane (Kobayashi et al., 2005), pelitic schist from Ryoke metamorphic belt (Kawakami and Kobayashi, 2006) and pelitic schist from Sanbagawa metamorphic belt (Goto et al., 2001) are plotted for comparison. Ka = kaolinite; Chl = chlorite; Gi = gibbsite; Sm = smectite; Il = illite; Pl = plagioclase; Kfs = K-feldspar; Bt = biotite.

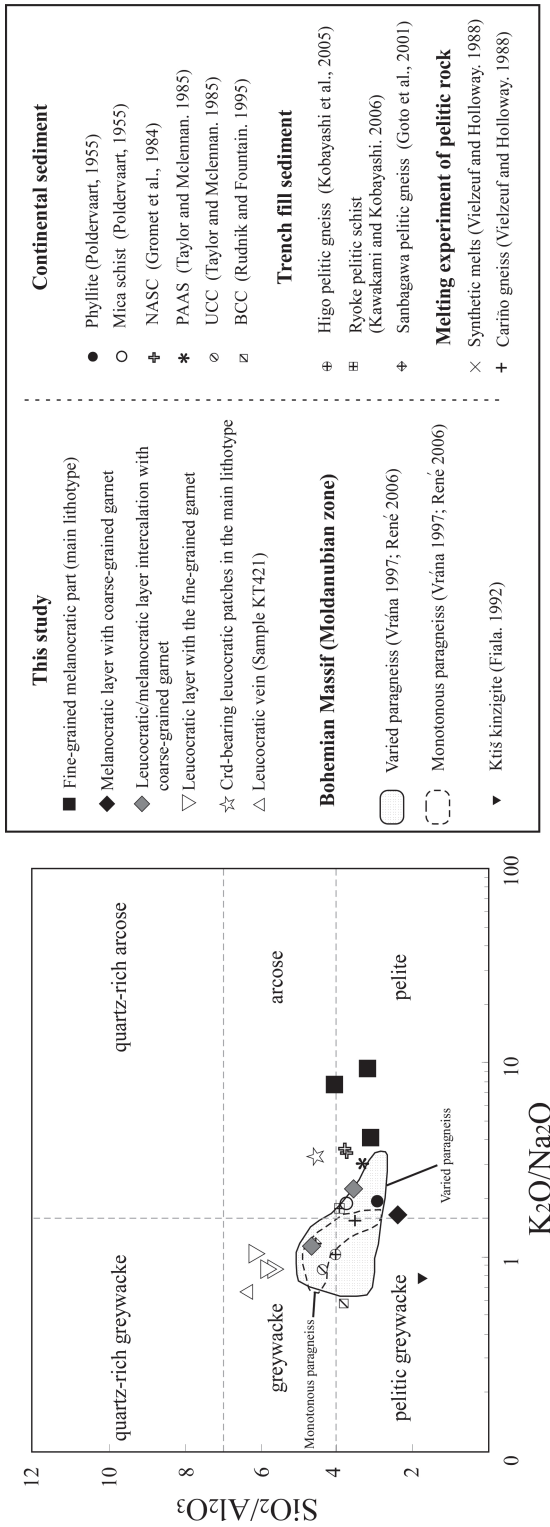


Figure 6. Comparison of $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio in classification diagram of Wimmenauer (1984) among Křiš Sil-Crd-Bt-Grt gneisses and other representative samples. Typical composition of phyllite and mica schist from Poldervaart (1955), NASC = North American Shale Composition (Gromet et al., 1984), PAAS = Post Archean Australian Shale, UCC = Upper Continental Crust (Taylor and McLennan, 1985) and BCC = Bulk Continental Crust (Rudnik and Fountain, 1995) are also shown. Bulk composition of paragneiss from Monotonous and Varied Unit (Vrána, 1997; René, 2006) and that of Gföhl granulites (Janoušek, 2004). Křiš kinzigite data from Fiala (1992). Carino gneiss data from Vielzeuf and Holloway (1988). Average bulk composition of pelitic gneiss from Higo metamorphic terrane (Kobayashi et al., 2005), pelitic schist from Ryoke metamorphic belt (Kawakami and Kobayashi, 2006) and pelitic schist from Sanbagawa metamorphic belt (Goto et al., 2001) are plotted for comparison.

mainly the relative amount of feldspar, quartz and clay minerals in the sedimentary protolith (Fig. 6). Applying the geochemical classification plot of K_2O/Na_2O versus SiO_2/Al_2O_3 (Wimmenauer, 1984), Moldanubian paragneisses are plotted in the fields of greywake, pelitic greywake and pelite. In contrast, data of the leucocratic/melanocratic layer intercalation with coarse-grained Grt are plotted in greywake-pelite region (Fig. 6). Therefore, the studied Ktiš sample may be derived from a mixture of mud and greywacke with moderate ASI value and extreme high Fe_2O_3 .

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