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Geochemical Characteristics of Wuyang Siliceous Rocks in the Southern Margin of North China Craton and its Constraint on the Formation Environment of BIF of Tieshanmiao Formation

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Abstract: Precambrian banded iron formation (BIF) is one of the most important mineral resources in China, mostly abundant in the North China Craton (NCC) with relatively less common in South China. Since the BIF and siliceous rocks both originated from chemical deposition, the syngenetic BIF and Siliceous rocks can help evaluate their environment of formation. We examine here the mineralogy and geochemistry of siliceous rocks associated with the Tieshanmiao Formation BIF, aiming to decipher the conditions of formation of both BIF and Siliceous rocks in the Wuyang area in the NCC. Analysis of the geochemical characteristics of whole rock shows that the SiO_2 content of the siliceous rock ranges from 90.11% to 94.85% and is relatively high overall. Trace element contents of Ba and U are also high, the Ba/Sr ratio ranges from 3.89 to 25.28 and the U/Th ratio ranges from 0.09 to 0.20. Finally, the ΣREE value of rare earth elements ranges from 57.03 ppm to 152.59 ppm, and these indexes all indicate that siliceous rock resulted from hydrothermal deposition. Plots of Al_2O_3-SiO_2, SiO_2/(K_2O+Na_2O)-MnO_2/TiO_2 and Mn-10×(Cu+Co+Ni)-Fe in discrimination diagrams also verify this interpretation. However, both the MgO content, ranging from 0.16 to 0.32, and the Fe/Ti ratio, ranging from 2.50 to 9.72, suggest that terrigenous material was added during the depositional process. Major and trace element parameters of siliceous rock, such as the Al/(A1+Fe+Mn) ratio (from 0.81 to 0.93), MnO/TiO_2 (from 0.00 to 0.17), Al/(Al+Fe) (from 0.82 to 0.93), Sc/Th ratio (from 0.21 to 0.50), U/Th (from 0.09 to 0.20), $(La/Yb)_N$ (from 0.83 to 3.04), and the $(La/Ce)_N$ (from 0.01 to 0.02) all imply that the siliceous rock formed in a continental margin. In addition, the Sr/Ba ratio from 0.08 to 0.26, the δCe value from 0.31 to 0.90, and the δEu value from 0.14 to 0.58, all indicate that the siliceous rock was formed at a relatively deeper water depth and under weak hydrodynamic conditions. Siliceous rock and BIF formed in the same geological setting, with the SiO_2/(K_2O+Na_2O) ratio of siliceous rock ranging from 28.61 to 47.43, the SiO_2/Al_2O_3 ratio from 16.53 to 32.37, and the SiO_2/MgO ratio from 287.28 to 592.81, which are all in agreement with chemical deposition associated with volcanic eruptions. The Al_2O_3/TiO_2 ratio from 37.82 to 50.30 indicates that the magma source of siliceous rock was of slightly intermediate composition. During the Late Archean in the Wuyang area, the high concentration and high purity SiO_2 quickly precipitated from hydrothermal fluids to finally result in the accumulation of siliceous rock in a marginal sea, while the input corresponding to iron formation components was deposited to form iron formation layers, and limestone was only the product formed during the deposition intervals of siliceous rock and iron formations. In this study, the synsedimentary siliceous rocks of BIF act as a new way to provide direct evidence to understand the formation environment of BIF due to its high geochemical stability.

Key words: siliceous rock, banded iron formation, geochemistry, Tieshanmiao Formation, Wuyang area

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1 Introduction

As one of the most important iron ore types, the Banded Iron Formations (BIFs) have contributed to academic focuses for a long time. The uncertainty for geological setting of deposition belongs to one of the hot academic topics for BIFs, which has led to a lot of studies on the host rocks of BIF ore deposits (Zhang et al., 2012; Dai et al., 2017; Wang et al., 2017; Zhao et al., 2016). In the previous studies on formation environment of BIF, the BIFs mainly developed along stable continental margins and in shallow sea settings belonging to craton marginal basins, while in China they are usually closely associated with island-arc settings (Haugaard et al., 2013; Thurston et al., 2012; Yang et al., 2012; Zhang et al., 2012). However, these evidence for formation environment of BIFs came from geochemical tracing of middle-high grade metamorphic rocks (Dai et al., 2012; Huang et al., 2013), interring from protolith reconstruction (Xiang et al., 2012) and inference from depositional scale related to geological evolution (Trendall, 2002), and whose accuracy can be affected more or less by the stability of geochemical compositon or indirection of their method. In fact, the formation environment of BIFs can be covered by some rocks of synchrotron with stable geochemical composition, which have been proved by the siliceous rock from the Zankan iron deposit in West Kunlun in China (Li et al., 2016). So, the rocks of synchrotron with stable geochemical composition can act as direct evidence to expose the formation curcumstance, and the occurred siliceous rocks of synchrotron with BIFs would possibly become the fortunate one.

The siliceous rocks attract interests in many ore deposit for its strong capabilities in tracing geological setting. The sedimentary rocks attract many researches due to its recording on geological setting (Chen et al., 2019). Acting as one of the most significant sedimentary rocks, the siliceous rock could well trace the tectonic environment since they are widely distributed in relatively extensional tectonic settings or at plate margins (Chen et al., 1997; Fang et al., 2003; Lin et al., 1998; Qi and Li, 1997; Xue, 1997; Zhang et al., 2006; Zhou et al., 2008; Zhu et al., 2005; Li et al., 2012a, 2014b, 2019). Frequently, siliceous rocks are closely related to base metal mineralization (Feng et al., 2002; Jiang et al., 1992; Liang et al., 2009; Lü et al., 2004; Qi et al., 2002; Li et al., 2015). A siliceous rock may recrystallize with time through evolution (Lynne et al., 2005; Murray et al., 1992; Li et al., 2009a, 2011; Zhou et al., 2006), with concomitant increase in both the order and crystalline degrees of the siliceous system (Li et al., 2010, 2011; Li, 2012). With the gradual improvement in the crystallinity degree of SiO_2-group minerals in a siliceous system, the amorphous substance opal ($SiO_2.nH_2O$) and cryptocrystalline chalcedony ($SiO_2.2H_2O$), which are poor crystalline degrees in the early stages), will be converted into crystalline quartz to form a siliceous rock. Although a siliceous rock undergoes recrystallization, it exhibits a strong resistance to transformation and high geochemical stability due to its compact and hard characteristics, and it is widely used to trace origins, formation environment, etc. (Audley-Charles, 1965; Murray et al., 1990; Zhou, 1990; Liu et al., 1997, 1998, 1999; Li et al., 2009b; He et al., 2009). Thus, the siliceous rocks become keys to understand many ore deposits including gold deposit (Zhang and Li, 2004), copper deposit (Xue et al., 2000), lead-zinc deposit (Li et al. 2009), pyrite deposit (Wang et al., 1996), iron deposit (Li et al., 2016), etc.

In the Wuyang area, the contact between siliceous rock and iron ore layers provides important evidence for the formation environment of BIFs. In China, the BIFs are most widely distributed in the North China Craton (NCC) (Li et al., 2012b; 2012c; 2014c; Yang et al., 2012; Zhang et al., 2012), which can undoubtedly reflect the geological evolutionary processes of the Precambrian earth. The Wuyang iron ore is one of the typical BIF deposits that formed along the southern margin of the NCC between 2.7 -2.5Ga (Tu, et al., 1981), and its chemical sedimentary origin was verified by whole-rock geochemical studies (Lan et al., 2013). Furthermore, its microfiber characteristics revealed that volcanic activities occurred during the process of sedimentation (Li et al., 2014a, 2019). Although whole rock geochemical tracing of the ceiling, floor, and internal volcanic strata may reveal the tectonic setting of BIF (Zhang et al., 2012; Haugaard et al., 2013), the surrounding rocks in the Wuyang area underwent intensive amphibolite facies metamorphism, thus making extremely difficult to restore the protolith and determine the formation environment (Li et al., 2013b). Therefore, the formation environment of BIF in the Wuyang area is still a puzzle, which seriously restricts our understanding on the genesis of the deposits. However, a suite of quartz-albite- and siliceous rock, with a thickness of greater than 400 m, developed at the bottom of the Tieshanmiao Formation BIF in the Wuyang area, are associated with the iron ore layer and characterized by a high geochemical stability (Liu et al., 1998; Li et al., 2013a, 2014b). In light of the information mentioned above, this study aims to describe the formation environment of the Tieshanmiao Formation in Wuyang area with its siliceous rocks, which can also give direct eviende to understand the original formation of the coexisting BIF in the Tieshanmiao Formation. What's more, this study also introduces a new perspective to expose the formation of BIFs all over the world.

2 Geological Setting and Samples

2.1 Regional geological setting

More and more attentions have been paid to the NCC due to its complex evolution history (Shi et al., 2019). The NCC is one of the most significant areas for the development of BIFs (Shen, 1998), with several ore deposits mainly located in the Anshan - Benxi, Miyun - Jidong, Wutai - Lvliang, Wuyang - Huoqiu, and Luxi areas (Fig. 1) (Zhang et al., 2012b). These BIFs have a close relationship with late Archean basic magmatic rocks, which subsequently metamorphosed and occuring as widely distributed greenstone belts (Zhai, 2011). Previous studies showed that the formation of the BIF ore deposits in the NCC is largely concentrated in the late Neoarchean era (approximately 2.52 to 2.60 Ga) (Zhang et al., 2012b).

Among these BIFs, the Wuyang iron ore is located at the southern margin of the NCC (Fig. 2a), and belongs to the Lushan-Wuyang-Huoqiu-(Xincai) sedimentary metamorphic iron ore metallogenic belt (Yang et al., 2012). The mining area is situated in the Northwest Lushan Beizi-Xipingshan anticlinorium structure. The ore-bearing formation is found in the Late Archean Taihua Group that formed between 2.45–2.60 Ga (Liu and Yang, 2017; Liu et al., 2018). The strata of Taihua Group are mainly concealed underground, whith scattered outcrops mainly composed of Late Archean gneiss. The ore-bearing formation is divided from bottom to top into two Formations, which are named Zhaoanzhuang Formation and Tieshanmiao Formation (Figure 2b). The Zhaoanzhuang Formation is dominated by amphibolites and gneisses (Wen and Wang, 2005), while the Tieshanmiao Formation is mainly composed of amphibolite, gneisses and marbles (Wang, 2006). Accordingly, the iron ores may be classified into two types, i.e. the Zhaoanzhuang type (Ore strata A and B, from bottom to top) and the Tieshanmiao type (Ore strata C and D, from bottom to top). The former type includes the following ore deposits: Zhaoanzhuang, Wangdaoxing, Xiacao, Yuzhuang, Lianggang, Miaozhuang, Zengzhuang, Chenchang, etc., while the latter is represented by the following ore deposits: Tiegukeng, Tieshanmiao, Shimenkuo, Hewan, Gangmiaoliu, Jingshansi, Lenggang, Xiaohanzhuang, Yaozhuang, Qianlu, Wanglou, etc.

The bedrock strata distributed in the Wuyang area mostly include regional metamorphic rocks of the Neoarchean Taihua Group (containing iron ore) and basalt -andesite porphyries of the Xiong'er Group, quartzite, sandstone, conglomerate and shale of the Mesoproterozoic Ruyang Group, tillite of Sinian, limestone of Cambrian, and sediments of Quaternary (Fig. 2a). The folds axial directions in the mining area trend NE60–90° and SE100–110°, with three anticlines and three synclines that jointly form anticlinoria basically developed in the Taihua Group. Faults are made up of larger-scale NW- and smaller-scale, nearly SN-trending faults, most of them distributed along the outer margin of the industrial deposits. Magmatism in the region is relatively strong and closely associated with the Neoarchean iron ore-bearing metamorphic rocks. It is reflected by the intrusion of a large syenite body in Yanshanian and by sporadic outcrops near the deposits and south of the mining area. Additionally, up to several meters to tens of meters thick and NNE-trending granitic dyke swarms, offset the orebodies and display clear, and without any alteration phenomena, contacts to the surrounding rocks.

2.2 Sample collection and petrological characteristics

Pure siliceous- and quartz-albite-bearing siliceous rocks occuar mainly in the Tieshanmiao Formation, especially concentrate in some ore sections, e.g. Jingshansi, Biandanshan, Xiaofoshan, Libazhuang, Shanmenggang and Shangmiao, with a total thickness of more than 400 m. Generally, the siliceous rock formation is composed of quartz, while in some areas siliceous rocks also contain a certain amount (less than 5 vol%) of feldspar. The studied siliceous rocks were sampled from the Shangmiao and Shanmenggang areas of the Jingshansi Mine. The sampling strata are in conformable contact with the iron ore layer, which displays a well-defined banded structure (Fig. 3a, b). The siliceous rock strata trend from SN to NW and SE, are steep dipping, e.g. between 61° and 71°, with highly variable dip direction. Siliceous rock specimens are compact and hard, and mostly white to grey

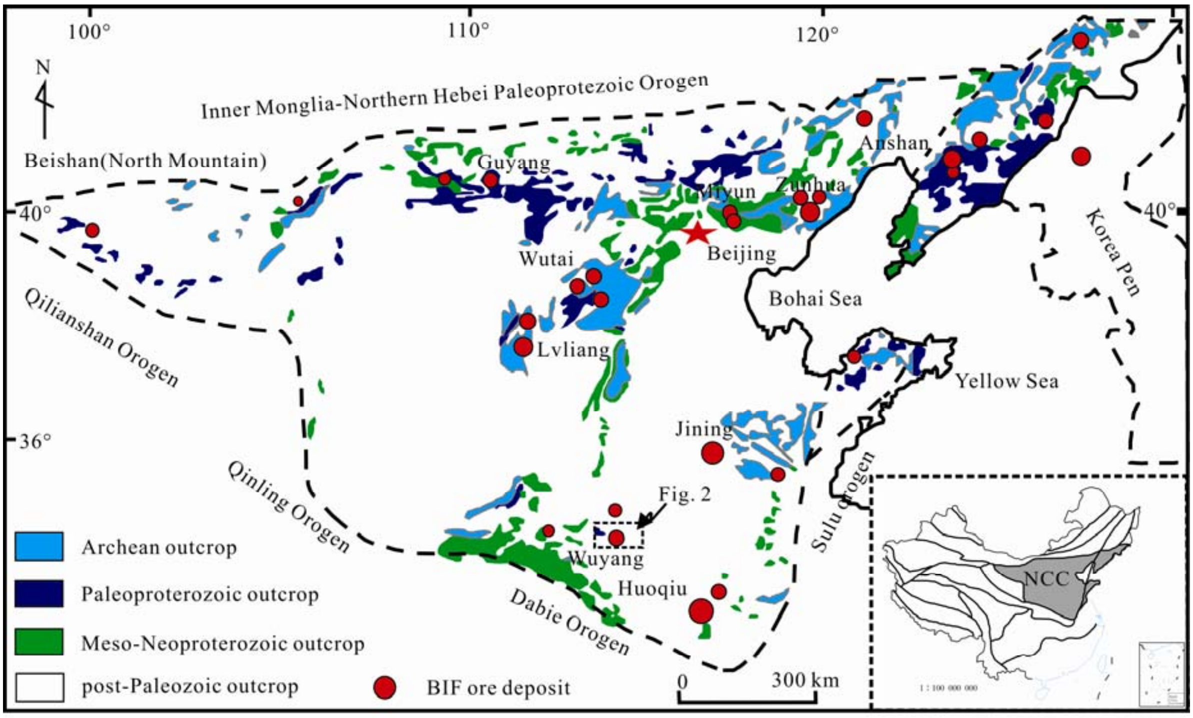

Fig. 1. Geological sketch of the NCC with its location in tectonic setting of China (Zhang et al., 2012b; China basemap after China National Bureau of Surveying and Mapping Geographical Information).

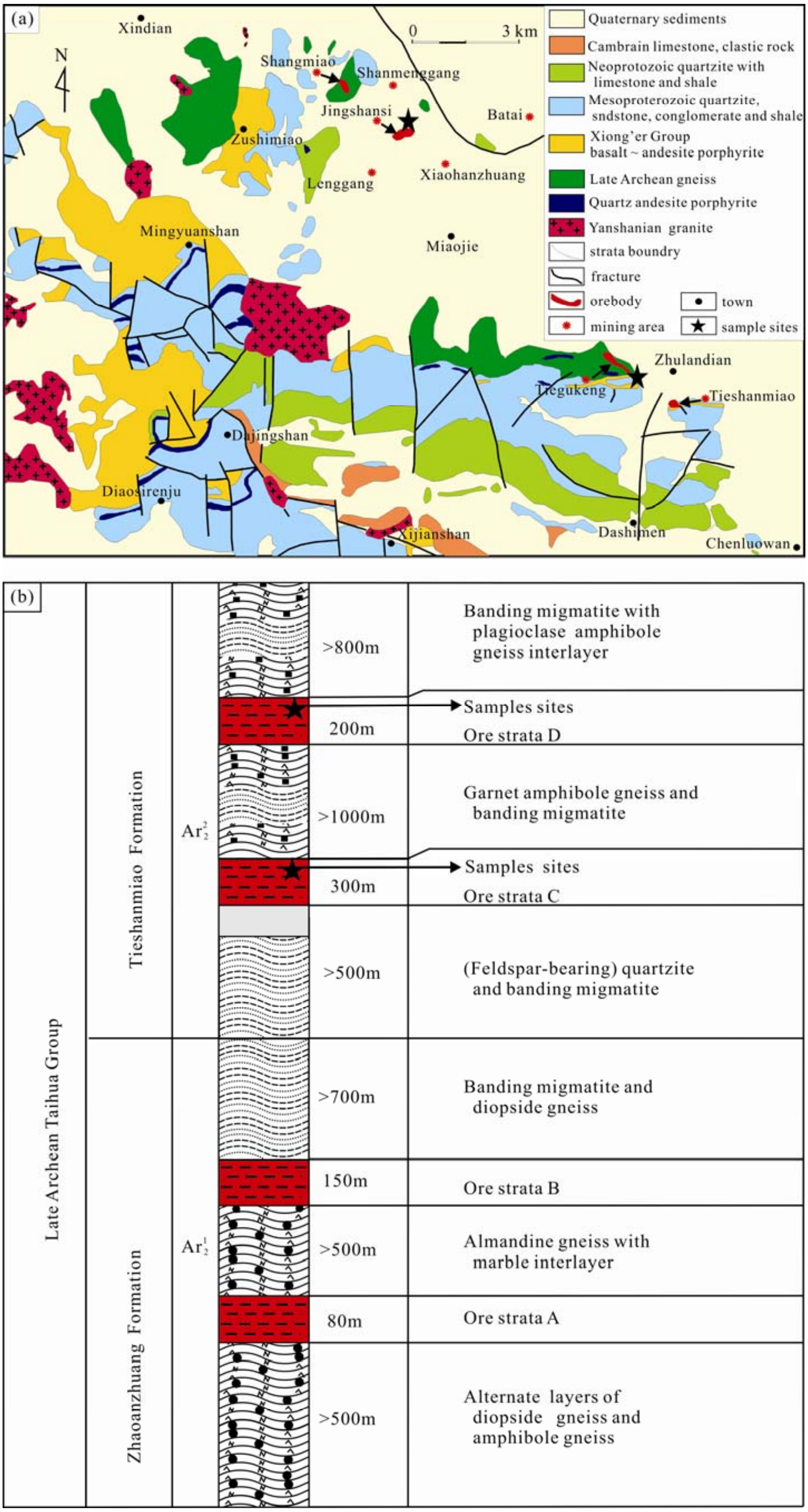

Fig. 2. Geological sketch map (a) and sketch stratigraphic column (b) of the Wuyang area (after Li et al., 2014a).

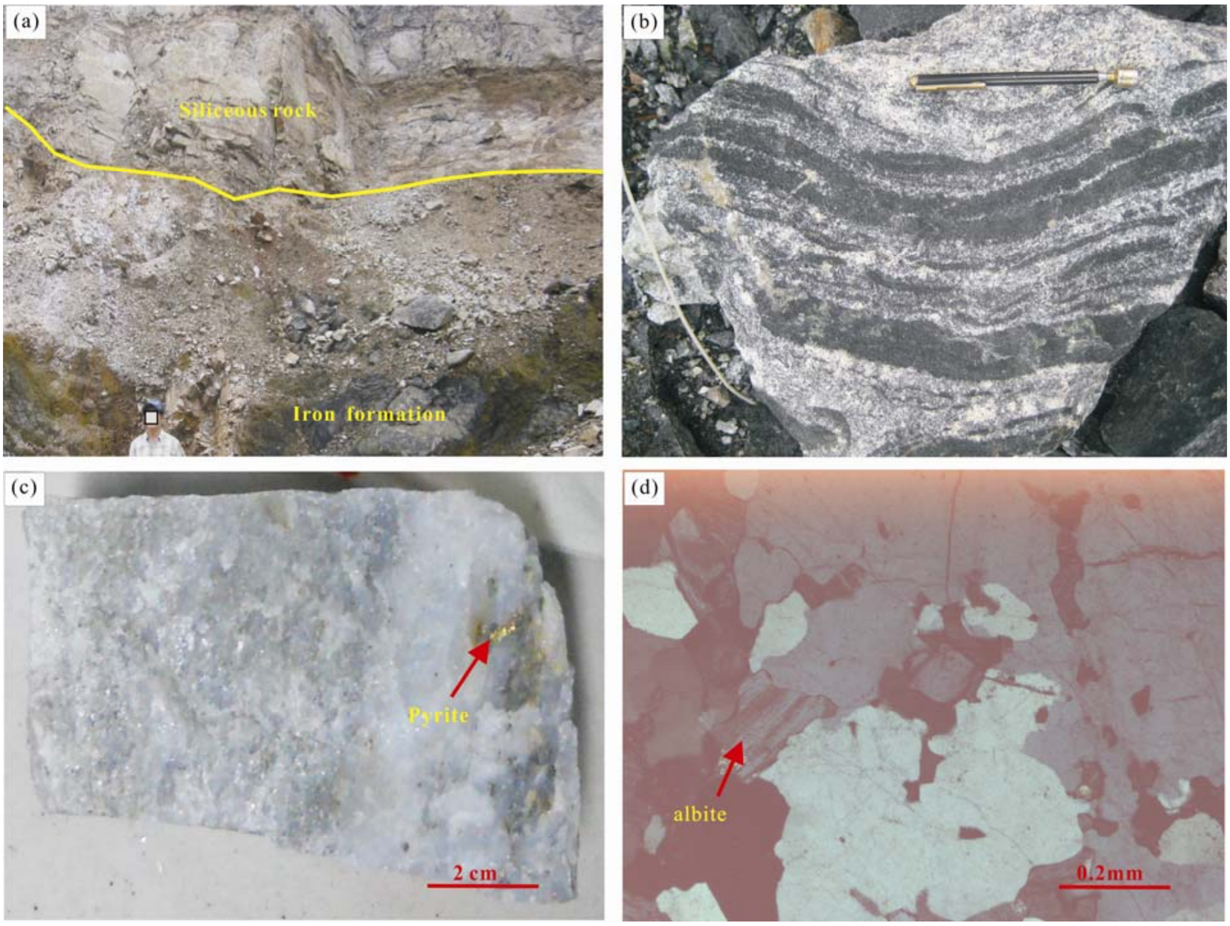

Fig. 3. The field outcrop, samples and microscope photographs of siliceous rocks.
(a) Outcrop of Shangangmiao mining area, the siliceous rock is conformable with the iron formation; (b) iron formation where the layers of ore can be seen; (c) hand specimens of siliceous rock; (d) microphotograph of siliceous rocks where quartz and albite are present (crossed polarized nicols).

(Fig. 3c), while plagioclase-richer specimens are significantly whiter. Pyrite may accompany quartz in the rock (Fig. 3c). The samples collected for this study are basically pure siliceous rocks, the major mineral observed with a polarizing microscope is quartz (Fig. 3d), occasionally a small percentage of albite also occur.

The studied pyroxene-magnetite BIFs are grey-black, with alternating white and black micro-bands (Fig. 4a). Microscopically (Fig. 4b–d), their major components include pyroxene (mainly clinopyroxene), quartz and magnetite within two styles of micro-bands. The first style of micro-band is mainly composed of fine-grained quartz with minor amounts of pyroxene and magnetite (Fig. 4b). The second type of micro-bands consists of magnetite and pyroxene (Fig. 4c), with magnetite present either inside or at the edges of the pyroxene bands. Very minor isolated quartz grains are also observed within the pyroxene-magnetite micro-bands (Fig. 4b). There are alternative appearances for these two types of micro-bands (Fig. 4b, d). Magnetite in the quartz micro-bands is extremely rare or absent, as opposed to its abundance in the pyroxene-magnetite micro-bands where it occurs in disseminated form and grain sizes ranging from tens to hundreds μm (Fig. 4c–d).

3 Sample Preparation and Analyses

Sample preparation was completed in the Guangdong Provincial Key Lab of Geological Processes and Mineral Resource Survey. The rock samples are composed of siliceous rock and BIF. Fresh siliceous rock samples were selected and divided into two groups: one group for thin sections and the other for geochemistry after cleaning, drying and crushing up to 200 mesh according to standard procedure. The thin sections, including siliceous rock and BIF, and powder samples of siliceous rock were prepared for optical analysis and for geochemical study respectively.

Analyses of major, trace, and rare earth elements were carried out in the Guangdong Provincial Key Lab of Geological Processes and Mineral Resource Survey. X-ray fluorescence spectroscopy (XRF, instrument model: Shimadzu XRF-1700/1500) was employed to analyse major elements. Trace and rare earth elements were analyzed with Inductively Coupled Plasma Mass Spectrometer (ICP-MS, instrument model: X2) manufactured by American Thermo Inc. The main analytical procedure with ICP-MS is as follows: (1) 50±1 mg of a powder sample is weighed and put in Teflon crucible; (2) the sample was moistened using 1–2 drops of

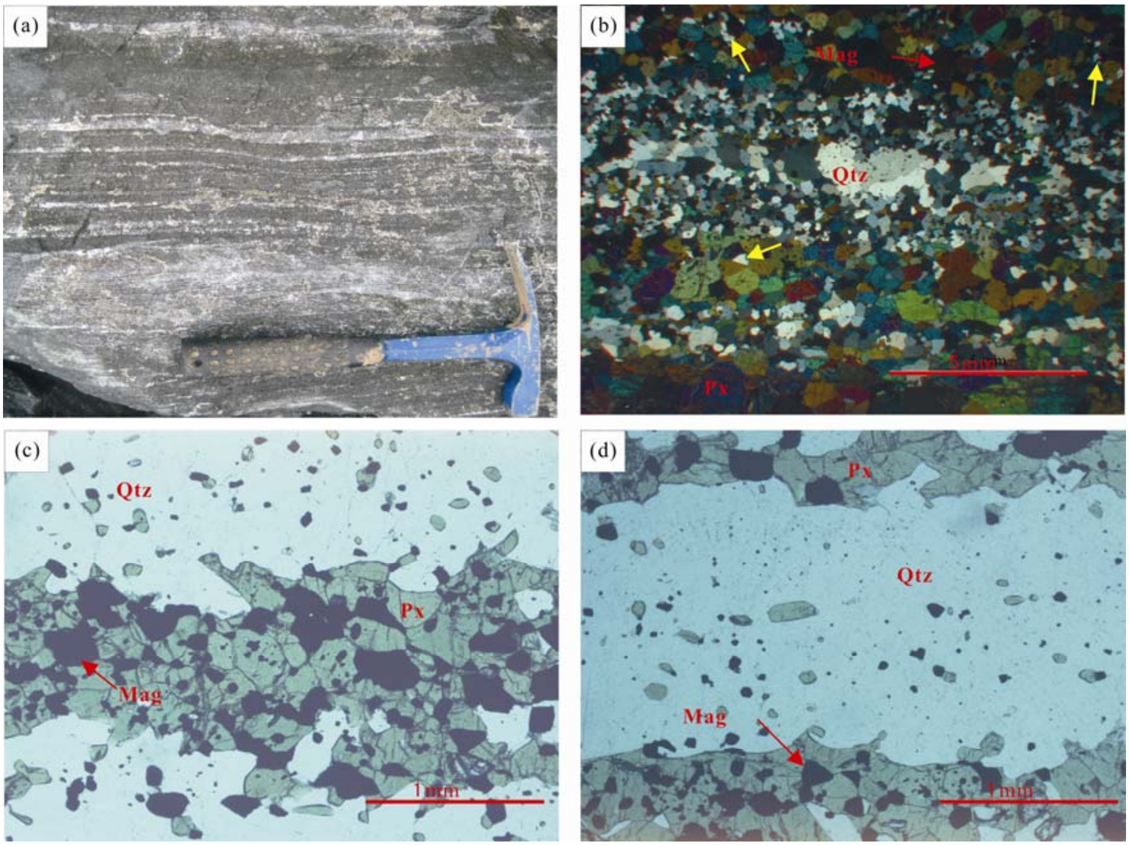

Fig. 4. Samples and microphotographs of pyroxene-magnetite BIF of the Wuyang area.
(a) Samples in the field; (b) microphotograph of BIF, yellow arrows point at isolated quartz particles (cross polarized nicols); (c) microphotograph of BIF (plain polarized nicols); (d) microphotograph of BIF (plain polarized nicols); Mag-magnetite, Qtz-Quartz, Px-Pyroxene).

high purity water, then 1mL HNO_3 and 1mL HF are added in sequence; (3) Teflon crucible was placed in a steel sleeve, and after it was tightened, it was placed in an oven to heat at 190°C for 48 h; (4) the Teflon crucible was dried on an electric hot plate (115°C) after being cooled and opened, and then dried again after 1 mL HNO_3 was added (ensuring no liquid remains on the wall of the Teflon crucible); (5) 3 mL 30% HNO_3 was added to the Teflon crucible, then put in the steel sleeve again, tightened, and placed in an oven to heat at 190°C for 12 h; (6) the solution was transferred to polyethylene plastic bottle; 2% HNO_3 was used to dilute up to about 100 g (the corresponding dilution factor was 2000); and finally it was sealed and preserved for standby.

4 Results

4.1 Major elements

Major element analyses in the Wuyang siliceous rocks and their relevant geochemical indexes can be seen in Tables 1 and 2, and the results suggest the following genetical aspects:

(1) Generally, the studied siliceous rock exhibit characteristics of both hydrothermal and non-hydrothermal origin, as most of the geochemical indexes differed from the characteristics of typical hydrothermal sedimentary origins: the SiO_2 content of the siliceous rock ranges between 90.11 and 94.85%, with a relatively high mean of 91.89%. The Si/Al ratio ranges from 14.57 to 21.34, with a mean of 19.30, which is lower than the Si/Al ratio of pure siliceous rock (80-1400; Murray et al., 1992). The content of MgO ranges from 0.16 to 0.32%, with a mean of 0.22%, which is much higher than the MgO content of hydrothermal sedimentary rock. The later has been strongly depleted in the modern mid-ocean ridge's hydrothermal system and its content is zero in the East Pacific Rise's 350 ^{o}C thermal water (Sugisaki and Kinoshita, 1982). The Fe/Ti ratio of typical hydrothermal sediment in the modern ocean is higher than 20 and the (Fe+Mn)/Ti ratio is higher than 20±5 (Rona, 1988). In this study, the Fe/Ti ratio is between 2.50 and 9.72 with a mean of 5.29, the (Fe+Mn)/Ti ratio is between 2.59 and 9.94 with a mean of 5.41, and both ratios are lower than those of typical hydrothermal sediment as described above. The Al/(A1+Fe+Mn) ratio may indicate the degree of hydrothermal sediment content. In this study, the Al/(A1+Fe+Mn) ratio of siliceous rock ranges between 0.81 and 0.93 with a mean of 0.88, which is slightly higher than that of siliceous rock of typical hydrothermal origin (Bostrom and Peterson, 1969). Nevertheless, as shown in the Al_2O_3-SiO_2 and SiO_2/(K_2O+Na_2O)-MnO_2/TiO_2 discrimination diagrams (Fig. 5a–b), all data plot in the hydrothermal field, which suggests that this siliceous rock is of hydrothermal origin, e.g. it represents a hydrothermal

Table 1 Results for major elements (wt%) of siliceous rocks from the Wuyang area

sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3(T)	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
WY001	94.85	0.06	2.93	0.50	0.01	0.16	0.11	0.55	1.45	0.02	0.26	100.90
WY002	91.65	0.09	4.06	0.43	0.01	0.26	0.10	0.75	1.74	0.01	0.44	99.54
WY003	91.93	0.11	4.16	0.45	0.01	0.32	0.11	0.36	1.85	0.01	0.64	99.95
WY004	90.11	0.14	5.45	0.30	0.01	0.24	0.08	0.70	2.45	0.01	0.66	100.15
WY005	92.74	0.10	3.83	0.48	0.01	0.19	0.10	0.93	1.28	0.02	0.32	100.00
WY006	90.93	0.11	5.17	0.35	0.01	0.24	0.12	1.12	1.68	0.02	0.46	100.21
WY007	91.19	0.10	5.03	0.34	0.00	0.16	0.14	1.50	1.62	0.02	0.30	100.40
WY008	91.68	0.09	4.23	0.50	0.01	0.17	0.14	1.62	0.82	0.01	0.44	99.71
average	91.89	0.10	4.36	0.42	0.01	0.22	0.11	0.94	1.61	0.02	0.44	100.11

Table 2 Characteristic indexes of major elements for siliceous rocks from the Wuyang area

sample	Si/Al	MnO/TiO_2	K_2O/Na_2O	$SiO_2/(K_2O+N_2O)$	Al_2O_3/TiO_2	SiO_2/Al_2O_3	$Al_2O_3/(100-SiO_2)$	SiO_2/MgO	Al/(Fe+Al+Mn)	Al/(Al+Fe)	Fe/Ti	(Fe+Mn)/Ti
WY001	28.54	0.17	2.64	47.43	48.83	32.37	0.57	592.81	0.81	0.82	9.72	9.94
WY002	19.90	0.11	2.32	36.81	45.11	22.57	0.49	352.50	0.87	0.88	5.57	5.72
WY003	19.48	0.09	5.14	41.60	37.82	22.10	0.52	287.28	0.87	0.87	4.77	4.89
WY004	14.57	0.07	3.50	28.61	38.93	16.53	0.55	375.46	0.93	0.93	2.50	2.59
WY005	21.34	0.10	1.38	41.96	38.30	24.21	0.53	488.11	0.86	0.86	5.60	5.73
WY006	15.50	0.09	1.50	32.48	47.00	17.59	0.57	378.88	0.92	0.92	3.71	3.83
WY007	15.98	0.00	1.08	29.23	50.30	18.13	0.57	569.94	0.92	0.92	3.97	3.97
WY008	19.11	0.11	0.51	37.57	47.00	21.67	0.51	539.29	0.86	0.86	6.48	6.62
average	19.30	0.09	2.26	36.96	44.16	21.90	0.54	448.03	0.88	0.88	5.29	5.41

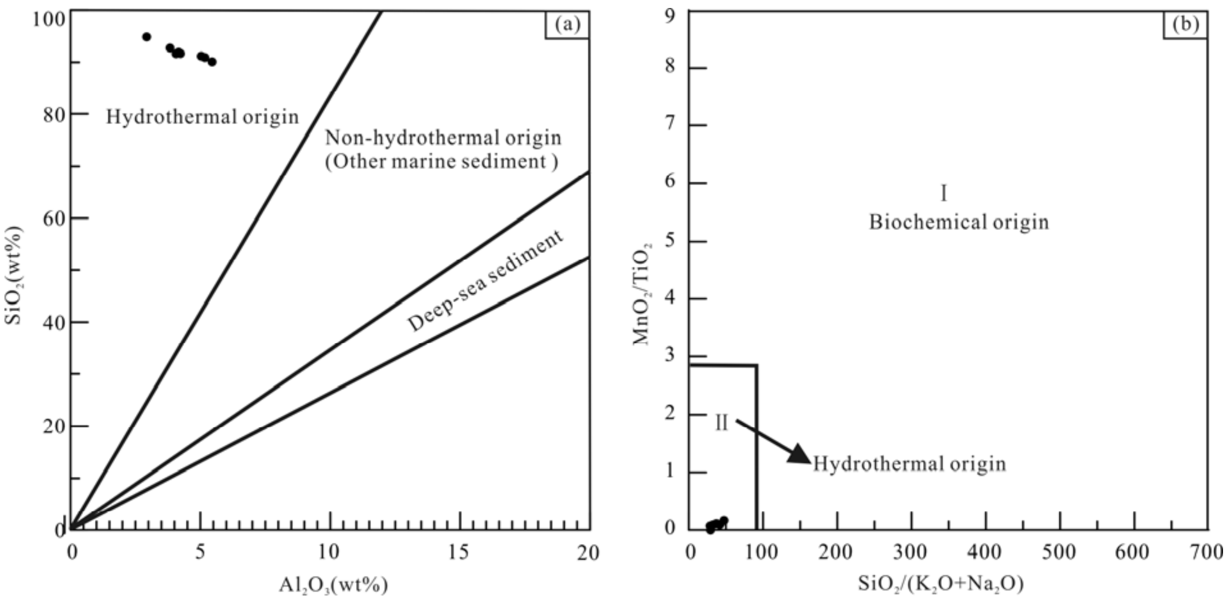

Fig. 5. (a) SiO_2–Al_2O_3 and (b) MnO_2/TiO_2–$SiO_2/(K_2O+Na_2O)$ discrimination diagrams demonstrating the origin of the siliceous rocks from Wuyang area (after Murray, 1994).

sediment that was once deposited in the primary sedimentary system. The major element characteristics mentioned above indicate that the siliceous rock in the study area were subjected to both hydrothermal and non-hydrothermal sedimentary material input, with the main discrimination indicators being inconsistent with the characteristics of typical hydrothermal sedimentary siliceous rock and suggesting that a large amount of terrigenous matter was deposited during the sedimentary process.

(2) The Wuyang area siliceous rock formed in a continental margin. In siliceous rocks, the elements Al and Ti usually reflect the degree of terrigenous matter input (Bostrom and Peterson, 1969), while involvement of hydrothermal water is often characterized by Fe and Mn enrichment (Murray, 1994). According to the different formation environments of siliceous rock, the Al/(A1+Fe+Mn) ratio displays a decreasing trend from 0.619 in continental margins, through 0.319 in ocean basins and islands to 0.00819 in mid-ocean ridges, related to the increasing influence of hydrothermal water from the continental margin to a mid-ocean ridge (Baltuck, 1982). The Al/(Al+Fe+Mn) ratio of siliceous rock in the study area varies between 0.81 and 0.93 with a mean of 0.88, which is closer to that of the siliceous rock formed in the continental margin. Siliceous sediments in continental margins are characterized by MnO/TiO_2 ratio of less than 0.5 (Adachi et al., 1986), and this agrees with the MnO/TiO_2 ratio obtained in the study, which ranges between 0.00 and 0.17 with a mean of 0.09. Previous research

found that the average Al/(Al+Fe) ratio of siliceous rock in mid-oceanic ridges is 0.12 and the average in continental margins is 0.6 (Sugisaki and Kinoshita, 1982). In this study, the Al/(Al+Fe) ratio of siliceous rock is between 0.82 and 0.93 with a mean of 0.88, which is basically consistent with the characteristics of siliceous rock formed in continental margins. The conclusion that the siliceous rock in the study area were formed in a continental margin, coincides with the previous finding that terrigenous matter was deposited during the sedimentary process.

(3) Siliceous rock is closely related to volcanism. Previous research has shown that siliceous rock formed by normal biochemical reaction is characterized by K_2O/Na_2O >>1 and siliceous rock associated with seafloor volcanism is characterized by K_2O/Na_2O <1 (Sugisaki and Kinoshita, 1982). In this study, the K_2O/Na_2O ratio of siliceous rock varies from 0.51 to 5.14, with a mean of 2.26, which is higher than that of siliceous rock associated with seafloor volcanism, and clearly deviates from that of siliceous rock formed by normal biochemical reaction. In addition, the $SiO_2/(K_2O+Na_2O)$, SiO_2/Al_2O_3 and SiO_2/MgO ratios reflect different formation mechanisms of siliceous rock (Tang and Zeng, 1990; Zhang, 1989). In this study, the $SiO_2/(K_2O+Na_2O)$ ratio ranges from 28.61 to 47.43 with a mean of 36.96, which is in complete agreement with that of a siliceous rock deposited through chemical sedimentation in association with volcanic eruptions (Tang and Zeng, 1990). The SiO_2/Al_2O_3 ratio ranges from 16.53 to 32.37 with a mean of 21.90, and agrees with that of the siliceous rock related to magmatism (SiO_2/Al_2O_3 <13.7 (Zhang, 1989)). On the contrary, the SiO_2/MgO ratio varies between 287.28 and 592.81 with a mean of 448.03, thus clearly deviating from that of a siliceous rock of typical chemical sedimentation associated with volcanic eruptions (Zhang, 1989). Finally, the Al_2O_3/TiO_2 ratio of siliceous rock is in the range from 37.82 to 50.30 with a mean of 44.16, consistent with their near intermediate magmatic source region (Al_2O_3/TiO_2=17–50 (Girty et al., 1996)). The above geochemical data indicate a close relationship between the studied siliceous rocks with intermediate magmatism probably in an island arc environment.

4.2 Trace elements

Trace element data for the studied siliceous rocks are presented in Table 3, and lead to the following results:

(1) The siliceous rock displays typical characteristics of hydrothermal sedimentary origin. Their Ba content ranges from 27.74 to 352.20 ppm, with a mean of 122.33 ppm, e.g. values between those of MORB (12.00 ppm) (Sun, 1980) and continental crust (707.00 ppm) (Weaver and Tarney, 1984); the U content ranges from 0.39 to 1.46 ppm, with a mean of 0.42 ppm, and is also between MORB (0.10 ppm) and continental crust (1.30 ppm). The relatively high Ba and U content is consistent with a hydrothermal sedimentation (Marchig et al., 1982). The Ba/Sr ratio of modern hydrothermal water is > 1 resulted through the contribution of seafloor hydrothermal fluid (Peter and Scott, 1988). The Ba/Sr ratio of siliceous rock in this study ranges from 3.89 to 25.28, with a mean of 9.12, of typical hydrothermal origin. It is well known that normal deep sea sediment may adsorb a large amount of Th from seawater due to its slow sedimentation rate, resulting the a higher Th than U in the sediment; on the opposite, hydrothermal sediment due to its faster sedimentary rate is relatively rich in U and low in Th (i.e. U/Th<1) (Girty et al., 1996). The U/Th ratio of the studied siliceous rocks ranges from 0.09 to 0.20, with a mean of 0.14, consistent with ratios of hydrothermal sediments. In the Mn-10×(Cu+Co+Ni)-Fe discrimination diagram (Fig. 6) the siliceous rock plot near the hydrothermal sedimentary field, in agreement with the results above.

(2) The studied siliceous rock formed in a continental margin. It was previously suggested that selected trace elements in siliceous rock, e.g. Zr, Nb, Hf, Ta and Th, may be indicative for an origin from terrigenous materials (Yasuhiro et al., 2002). Siliceous rocks are considered to be originated from continental margins when the U/Th ratio is lower than 0.26 and the Sc/Th ratio is between 100

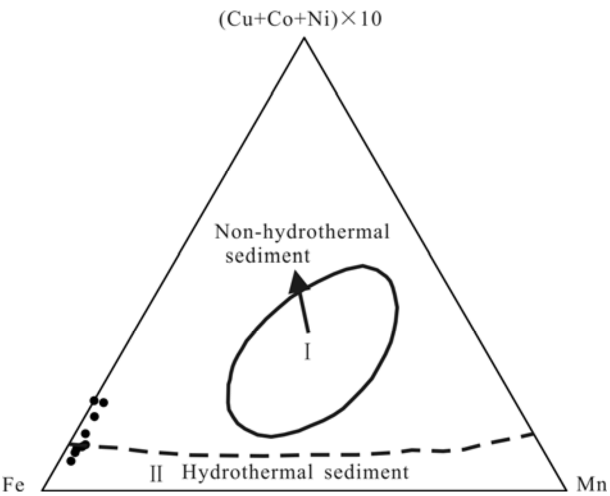

Fig. 6. (Cu+Co+Ni)×10–Fe–Mn discrimination diagram of siliceous rock from Wuyang area (after Rona, 1978).

Table 3 Results of trace element analysis (ppm) of siliceous rocks from the Wuyang area

sample	Sc	V	Co	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Nb	Cs	Ba	Hf	Ta	Pb	Th	U
WY001	1.25	5.70	3.99	58.39	7.70	5.34	2.89	28.63	8.24	2.75	146.60	0.48	0.49	99.44	3.76	0.03	4.07	5.57	0.51
WY002	1.85	8.32	3.73	66.18	4.65	14.91	4.10	43.48	15.46	2.22	52.32	1.96	0.69	102.50	1.38	0.17	7.39	4.03	0.39
WY003	1.30	9.82	2.55	17.15	3.03	12.68	6.47	76.57	13.93	9.27	199.70	6.87	0.75	352.20	4.80	0.70	7.81	6.22	1.08
WY004	1.51	12.79	2.05	19.53	3.13	17.61	6.05	76.50	15.55	2.69	119.70	2.53	1.22	137.80	2.95	0.25	8.44	4.21	0.61
WY005	2.12	8.31	3.33	23.84	4.63	11.76	4.76	34.35	13.81	6.17	153.70	1.94	0.59	67.93	3.96	0.22	8.76	7.47	1.46
WY006	2.12	9.51	2.42	21.88	3.00	15.04	6.39	51.22	15.81	5.47	104.80	2.50	0.92	100.60	2.79	0.26	7.60	4.20	0.53
WY007	1.33	8.85	2.68	52.65	3.76	74.44	5.39	35.18	18.46	3.62	113.80	3.99	0.55	90.42	2.73	0.46	11.83	4.98	0.57
WY008	1.64	7.32	3.32	21.55	11.35	14.56	4.91	16.04	7.13	3.40	80.14	1.83	0.39	27.74	1.98	0.17	6.49	4.20	0.63
average	1.64	8.83	3.01	35.15	5.16	20.79	5.12	45.25	13.55	4.45	121.35	2.76	0.70	122.33	3.04	0.28	7.80	5.11	0.72

and 1.0 (Girty et al., 1996). In this study, the Sc/Th ratio of siliceous rock ranges from 0.21 to 0.50, with a mean of 0.34; the U/Th ratio varies from 0.09 and 0.20, with a mean of 0.14; both values indicating a formation of the studied siliceous rock in a continental margin (Girty et al., 1996). On the Ti-V, and Ti/V-V/Y discrimination diagrams (Fig. 7a–b) the Wuyang area siliceous rock plot in and/or close to continental margin environments.

(3) The studied siliceous rock was formed in an anoxic environment under weak hydrodynamic conditions. Selected trace elements, e.g. V, Ni, Cr and Co, are closely related to redox conditions (Yarincik et al., 2000). According to previous autohrs V/Cr ratio >2 and Ni/Co ratio >4, are indicative of anoxic sedimentary environments, with lower values suggestive of oxygenated conditions. Our data indicate that Ni/Co ratio of siliceous rock ranges from 6.73 to 19.63, with a mean of 11.37, consistent with an anoxic fluid state. Moreover, Sr/Ba ratios <1, usually reflect deep sea or stagnant neritic environments for siliceous rocks (Sun et al., 1993). The fact that the Sr/Ba ratio in the studied samples varies between 0.08 and 0.26 with a mean of 0.15, suggests that their deposition took place under weak hydrodynamic conditions.

4.3 Rare earth elements

The rare earth elements content of the analyzed siliceous rocks is shown in Table 4, and the results are described below:

(1) The protolith of the studied rocks was mainly a hydrothermal sediment influenced by terrigenous materials. In general, the REE concentration in sediments is mainly controlled by three sources, namely (a) terrigenous materials, (b) seawater and (c) seafloor volcanic hydrothermal materials (Murray et al., 1991); in siliceous rocks the REE are mainly derived from seawater, and subordinately from terrestrial sources and from seafloor pyroclastics (Ding and Zhong, 1995). The ΣREE of siliceous rock in this study ranges from 57.03 ppm to 152.59 ppm, with a mean of 86.78 ppm, and this overall agree with values of hydrothermal sedimentary siliceous rock, which are usually lower than 200 ppm (Murray et al., 1991; Fu, 2007). In figure 8a, the REY (e.g. REE+Y) patterns normalized by PAAS (Post-Archean-Australian-Shale, after Mclennan, 1989) are relatively much steeper, which obviously deviates from the characteristics of hydrothermal sediment (Li et al., 2012a) and the BIF ores (Lan et al., 2013). The samples overall exhibit negative Eu anomalies and very week Ce anomalies (Fig. 8a), which clearly differ from siliceous rock from hydrothermal sediment. Slightly positive Eu anomalies and no obvious Eu anomaly exhibited by several samples (Fig. 8b). In summary, the ΣREE values of siliceous rocks in the study area agree with their characterization as siliceous rock resulting from hydrothermal sediments, but their REY distribution curves obviously reflect the input and involvement of terrigenous materials in the sedimentary process.

(2) The studied siliceous rock was formed in a continental margin. According to Murray (1994) and Murray et al. (1990) the $(La/Yb)_N$ values of siliceous rocks gradually decrease from continental margins (1.1–1.4), abyssal basins (0.70) to mid-ocean ridges (0.3), which indicates a non-obvious differentiation between light and heavy rare earth elements in continental margins, as opposed to a LREE depletion and HREE enrichment in mid-ocean ridges. The $(La/Yb)_N$ values of the Wuyang area siliceous rock range from 0.83 to 3.04, with a mean of 1.52, and the the $(La/Ce)_N$ values vary from 0.01 to 0.02, with a mean of 0.01, close to those of siliceous rock from continental margin (Murray, 1994). The δCe value in modern oceans varies from 0.29 in mid-ocean ridges, 0.55 in abyssal basins to 0.90–1.30 in continental marginal sedimentary environments, which implies that the depletion of Ce gradually decreases from mid-ocean ridges to continental margins (Murray et al., 1990). In this study, δCe value of siliceous rock ranges from 0.31 to 0.90 e.g. values between those for continental margins and abyssal basins, with a mean of 0.49, which is more consistent with an abyssal basin environment. The δEu

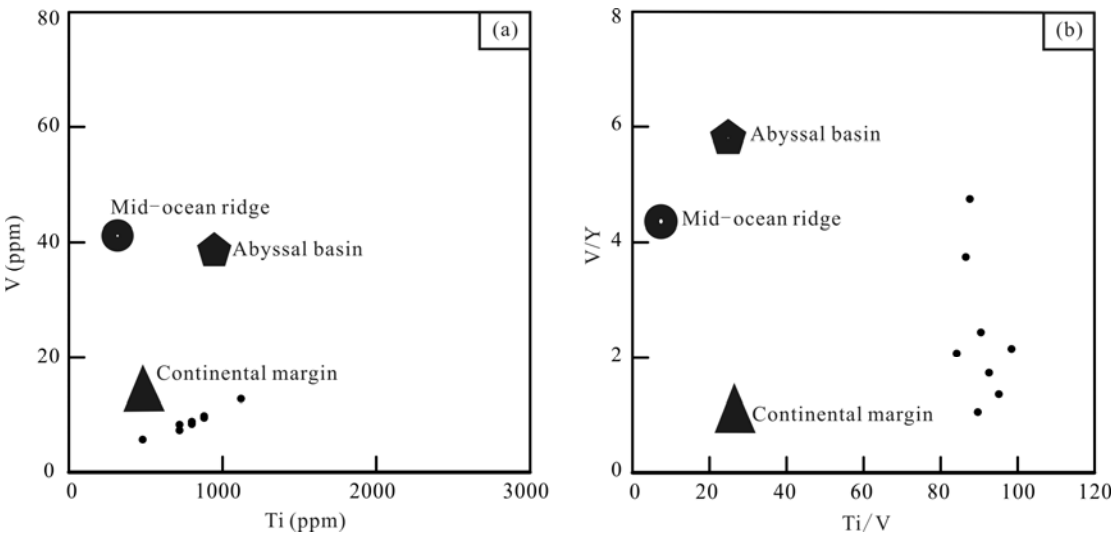

Fig. 7. (a) V-Ti and (b) V/Y-Ti/V discrimination diagrams demonstrating the formation environment for siliceous rocks from the Wuyang area (after Murray et al., 1992).

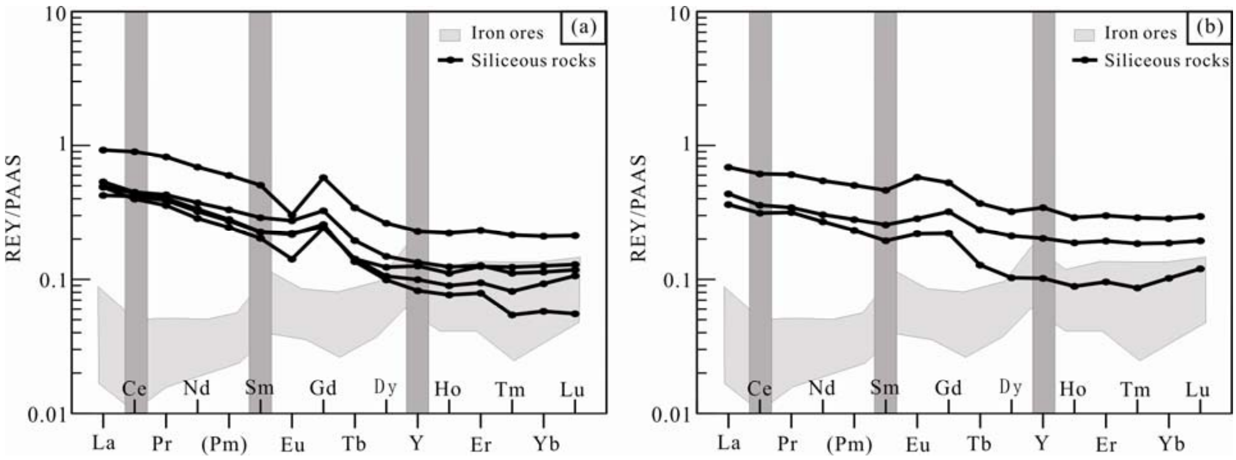

Fig. 8. PAAS (Post-Archean-Australian-Shale) normalized REY Patterns for siliceous rocks and BIF ores from the Wuyang area (data for PAAS is from McLenenan,1989, and BIF ores are from Lan et al., 2013).

value of siliceous rock decreases from 1.35 at mid-ocean ridges to 1.02 at 75 km away from mid-ocean ridges (Murray et al., 1991). The δEu value of siliceous rock in the study area ranges from 0.14 to 0.58, with a mean of 0.28, close to characteristics of a continental margin distal from mid-ocean ridges. It is suggested here that the siliceous rock in the study area likely formed in a continental margin, possibly in a deeper water environment as indicated by the δCe values.

5 Discussion

5.1 Geochemical implication on the origin of siliceous rock in the Wuyang area

The geochemical data presented here show that the siliceous rocks in the Wuyang area are geochemically stable with consistent data overall, as expressed by a high correspondence between major, trace and rare earth elements data to each other, thus preserving their primary sedimentary geochemical characteristics.

Generally, the studied siliceous rock exhibits a hydrothermal origin, however, deviation of some geochemical indexes implies the involvement of terrestrial material into the sedimentary process. Although the Si/Al ratio is lower than that of pure siliceous rock (Murray et al., 1992), their SiO_2 content with values from 90.11% to 94.85%, are very close to the standard material. The high values of Ba and U, as well as the Ba/Sr- and U/Th ratios ranging from 3.89 to 25.28 and from 0.09 to 0.20, respectively, agree with a hydrothermal sedimentary origin (Girty et al., 1996; Marchig et al., 1982; Peter and Scott, 1988). Their ΣREE values ranges from 57.03 ppm to 152.59 ppm, suggesting their initial deposition as a hydrothermal sedimentary siliceous rock (Murray et al., 1991). Discrimination diagrams (e.g. Al_2O_3 vs SiO_2, SiO_2/(K_2O+Na_2O) vs MnO_2/TiO_2 and Mn-10×(Cu+Co+Ni) vs Fe) also support a hydrothermal origin for the siliceous rocks at Wuyang area. On the other hand, other geochemical parameters like their MgO content (0.16 to 0.32%), Fe/Ti ratio (2.50 to 9.72), (Fe+Mn)/Ti ratio (2.59 to 9.94) and the Al/(Al+Fe+Mn) ratio (0.81 to 0.93), and the REE normalized pattern with negative Eu anomalies, deviate to some extent from the characteristics of typical hydrothermal sedimentary siliceous rock (Bostrom and Peterson, 1969; Rona, 1988; Sugisaki and Kinoshita, 1982). It is suggested that these deviations reflect a terrestrial non-hydrothermal sedimentary involvement in the primary sedimentation process. Since the argillaceous minerals act as the easy carriers of REE (Murray et al., 1991), the terrestrial material would certainly affect the geochemical characteristics of the sedimentary system. Due to the involvement of argillaceous minerals, the sediments are usually high in REE and low in SiO_2 content (Girty et al., 1996). Involvement of terrestrial materials may explain not only the deviation of the REE patterns between the studied siliceous rocks and a hydrothermal sediment but also the Si/Al ratio of the former. Usually, under ambient temperature conditions, terrigenous dissolved SiO_2 is difficult to precipitate due to its low solubility (Feng and Liu, 2001; Liu and Zheng, 1991), and even if low concentrations of SiO_2 are maintained over a long time or quickly precipitate under an extreme condition, it is difficult to form extremely pure and large-scale SiO_2 sedimentary systems (Li et al., 2012a; 2013). Therefore, only a hydrothermal origin can best explain the hundreds of meters thick layer of siliceous rock that developed in the study area. We prefer here a scenario where the supply of the studied siliceous rock included two pathways, a hydrothermal and a non-hydrothermal, with the main source of materials being of hydrothermal origin and with partial terrestrial material being involved in the sedimentary process.

The Al/(A1+Fe+Mn)-, MnO/TiO_2-, and the Al/(Al+Fe) ratios of the siliceous rock at Wuyang area (e.g. 0.81 to 0.93, 0.00 to 0.17 and 0.82 to 0.93 respectively), are highly consistent with those of continental marginal chert (Adachi et al., 1986; Baltuck, 1982; Sugisaki and Kinoshita, 1982). Parameters such as Sc/Th- and U/Th ratios 0.21 to 0.50 and 0.09 to 0.20 respectively), and the $(La/Yb)_N$ and $(La/Ce)_N$ values (0.83 to 3.04 and 0.01 to 0.02 respectively) also reassemble to those from continental marginal cherts in accordance to Girty et al. (1996) and (Murray (1994), Murray et al. (1990). The δCe and δEu indices generally are not in contradiction to marginal characteristics, and they likely indicate a deep-water formation environment of siliceous rock: the δCe value (0.31 to 0.90; mean 0.49), and δEu value (0.14 to 0.58, mean 0.28) are more consistent with an abyssal basin away from the mid-ocean ridge (Murray et al., 1990; Murray et al., 1992; Li et al., 2014b). A deep sea or stagnant neritic environment and weak hydrodynamic conditions are also consistent with the Sr/Ba ratio which is lower than 1 (0.08 and 0.26; e.g. Sun et al., 1993). A formation of the siliceous rock in a continental margin at deep water and weak hydrodynamic conditions is the most plausible scenario.

The seawater was layered with oxidation-reduction quality. According to the $(Pr/Pr^*)sn$-$Ce/Ce^*)sn$ discrimination diagram (Bau and Dulski, 1996), the siliceous rock samples in the study area have negative Ce anomalies, suggesting that their formation environment was aerobic (Fig. 9). This phenomenon quite agrees with both the negative Eu anomalies in the REE distribution curve of siliceous rock and the geochemical characteristics of BIF ore in the Tieshanmiao Formation of Wuyang area (Lan et al., 2013). However, there also exist positive and no anomaly of La_{sn} and Ce_{sn} in Figure 9. Already, Lan et al. (2013) proposed a mixed model of layered seawater, where the later was divided into oxygen-containing- and oxygen deficit layers. Differences on oxidation-reduction quality of layered seawater, was possibly contributed by the widely distributed episodic volcanic activities (Li et al., 2014a). This model can well explain the coexisting positive and no anomaly of La_{sn} and Ce_{sn} for both siliceous rocks and BIF, which were contributed by seawater with different oxidation-reduction quality of different layers. In addition, the previous study proposed the oxidation-reduction quality of seawater changed due to the volcanoes with their volcanic ejecta (Zhao, 1993), which contributed to the alternative bands of the BIF (Li et al.,

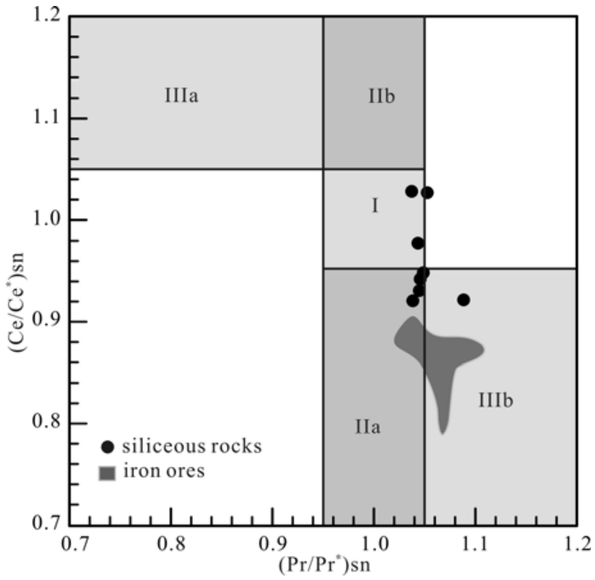

Fig. 9. $(Pr/Pr^*)sn$-$Ce/Ce^*)sn$ discrimination diagram for siliceous rocks and iron ores from the Wuyang area.
After Bau and Dulski, 1996; I-no anomaly of La_{sn} and Ce_{sn}; II_a- positive La_{sn} anomaly and no anomaly of Ce_{sn}; II_b- negative Lasn anomaly and no Ce_{sn} anomaly; III_a-positive Ce_{sn} anomaly; III_b- negative Ce_{sn} anomaly.

2014a). Thus, the sedimentary process of siliceous rock was accompanied by gradual changes of depth of seawater and spasmicspasmodic volcanic activities, which contribute to the different oxidation-reduction quality of seawater during the hydrothermal sedimentation including BIF and siliceous rocks.

5.2 Implications for the formation of the Wuyang BIF

The Wuyang area experienced extensive metamorphism. The most common host rocks in the study area are migmatite, gneiss and marble, and the metamorphic degree of these rocks can be up to amphibolites facies. Geochemistry of siliceous rock (e.g. $SiO_2/(K_2O+Na_2O)$-, SiO_2/Al_2O_3 and the SiO_2/MgO ratios which range from 28.61 to 47.43, 16.53 to 32.37, and 287.28 to 592.81, respectively) show that the chemical sedimentary siliceous rock was associated with volcanic eruptions in a marginal sea (e.g. Tang and Zeng, 1990; Zhang, 1989), that also controlled the development of Tieshanmiao Formation BIF. On the basis of Al_2O_3/TiO_2 ratio (e.g. 37.82 to 50.30), an intermediate magma was indicated for the source (Girty et al., 1996), most probably an island arc, which is also compatible with the proposed depositional environment of BIF in NCC (Zhang et al., 2012).

In the Taihua Group of the Wuyang area, with an exception of BIF in association with the marble interlayers at the Zhaoanzhuang Formation (Fig. 2b), marble is also frequently developed in BIF in the Jingshansi mining area (Fig. 10a) and Tieshanmiao mining area (Fig. 10b). Field investigations suggest that the thickness of these laminated marbles is constant along strike and that the marbles are in conformable contact with the iron ore layer, and do not penetrate into cracks of the ore beds. These layers are clearly unrelated to carbonate veins (or dykes) formed by late hydrothermal fluid circulation. Under the microscope, a quartz-magnetite BIF also contains plenty of carbonate minerals that promote the growth of magnetite particles (Li et al., 2013b). According to geological and petrological data the marble could be the metamorphic product of a stable neritic facies limestone, which further implies a stable neritic facies environment during the sedimentation period. Based on the conformable contact between marble and iron ore (strata C and D, Fig. 10a, and particularly the development of marble interlayers in the iron formation, both iron formation and marble likely formed under the same sedimentation process. The carbonate strata were formed in the gaps between different continuous quick voluminous deposition of iron formations.

According to geochemical results for siliceous rock, the Tieshanmiao Formation siliceous rock formed in a sea basin of continental margin under relatively weak hydrodynamic conditions. Similarly, the formation environment of the iron formation was stable neritic facies associated closely with magmatic arc, most likely back-arc basin, which is in accordance with a weak hydrodynamic marginal sea. In light of the above, both BIF and siliceous rock from the Tieshanmiao Formation formed in the same geotectonic setting, and the fundamental factor leading to the differences in lithology and ore-bearing character is the difference in the composition of the source during the

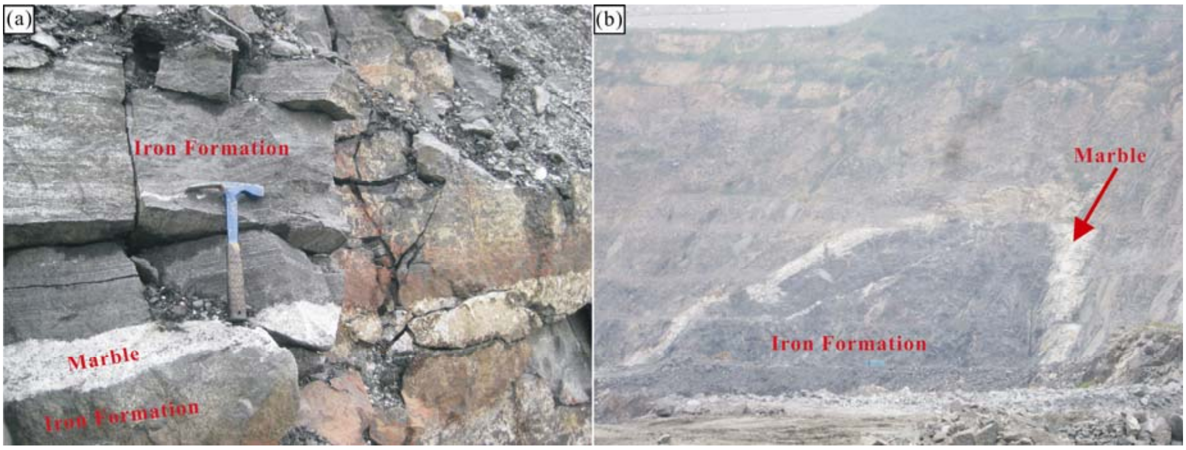

Fig. 10. The outcrops of BIF strata and marbles interlayers in the Wuyang area.
(a) Jingshansi area; (b) Tieshanmiao area.

sedimentation process. During the original deposition from a hydrothermal system, the hydrothermal sediments, composed of silica and magnetite, had higher concentrations and purity than the normal marine sediments (eg. carbonate minerals, clay minerals and metallic minerals). Thus, the depositional rate of silica was much higher than of the other sediments, which contributes to the siliceous rocks with higher concentrations and purity. Similarly, the hydrothermal silica, magnetite and volcanic ash deposited to form the BIF, whose alternative banded contributed by the discontinuity of deposition for magnetite and volcanic ash (Li et al., 2014a). According to Li et al. (2012), both the siliceous rock and BIF formed in extensional settings, and that this sedimentary system was the product of stratified water mixing. Hydrothermal deposition came to an end due to changes of the tectonic setting, and hence mainly carbonate mineral were deposited in the depositional gaps to form limestone.

5.3 Formation circumstance of BIF

The formation age of BIF displays a long-time span. In the published paper, BIF is widely distributed in the world, with a long and a huge scale (Bekker et al., 2010). In geological history, the main formation age of BIF begins at ~3.8 Ga and ends in 0.7–0.8 Ga, whose concentration ages are between 3.5 Ga and 1.9 Ga (Huston and Logan, 2004). The peak development period of BIF is 2.7–1.9 Ga (Klein, 2005; Bekker et al., 2010), which can be witnessed by the largest two BIFs of the world in Western Australia region and Transvaal area of South Africa with formation age ~2.5 Ga (Wu et al., 2012). In rough division, the formation age of BIF can be divided into two stages, whose first stage is 3.8~1.6Ga and is closely related to the global hypoxia (Zhai et al., 1990) with formation age shows three mineralization peaks of 2.8–2.7 Ga, 2.5–2.4 Ga, 1.9–1.8 Ga (Huston et al., 2004). The second stage is late Proterozoic (Klein, 2005), and has an excellent coupling relationship with snowball events during this period (Babinski et al., 2013). So, the formation age 2.45–2.60 Ga (Liu and Yang, 2017; Liu et al., 2018) seems to be no clear debate, and is quite agree with the other BIFs in NCC with similar geological setting.

In the previous studies, varies of methods are used to learn the formation environment BIF, such as geochemical tracing of middle-high grade metamorphic rocks (Dai et al., 2012; Huang et al., 2013), interring from protolith reconstruction (Xiang et al., 2012) and inference from depositional scale related to geological evolution (Trendall, 2002). So far, studies have approved that the original deposition circumstance for BIFs were continental margin, island arc, back arc basin, intracontinental rift and other geological background (Gross, 1980; Klein, 2005; Zhang et al., 2012). Since the siliceous rock, with high geochemical stability, is introduced in studying formation environment, the BIF from Zankan area are confirmed to be formed in sea basin of continental margin (Li et al., 2016). In this study, the Wuyang seliceous rocks also deposited in sea basin of continental margin, and undoubtly support the synsedimentary BIF of Tieshanmiao Formation was formed in a sea basin of continental margin. In addition, there is coincidence of era for formation of BIFs and major geological events (Fig. 11) (Zhai and Santosh, 2013). The major geological events are composed of rapid growth of the crust (Rasmussen et al., 2012), plate subduction (Dobson & Brodholt, 2005), mantle plume activities (Barley et al., 1998; Konhauser et al., 2002, 2009) and meteorite impact events (Slack et al., 2009) and other major geological events. In fact, these geological events display different degrees of coupling relationship, whose majority all have a common tectonic stress field of tension. In terms of the confirmed formation environment of BIFs, all the geological setting, such as continental margin, island arc, back arc basin and intracontinental rift, show a tectonic stress field of tension, although some of them are quite different from each other. Thus, the BIF belongs to the product of a tectonic stress field of tension, and can be well supported by the formation environment of continental margin of both siliceous rocks and BIF in Tieshanmiao Formation from this study.

6 Conclusions

(1) The siliceous rock in the Wuyang area resulted from hydrothermal deposition with additional imput from

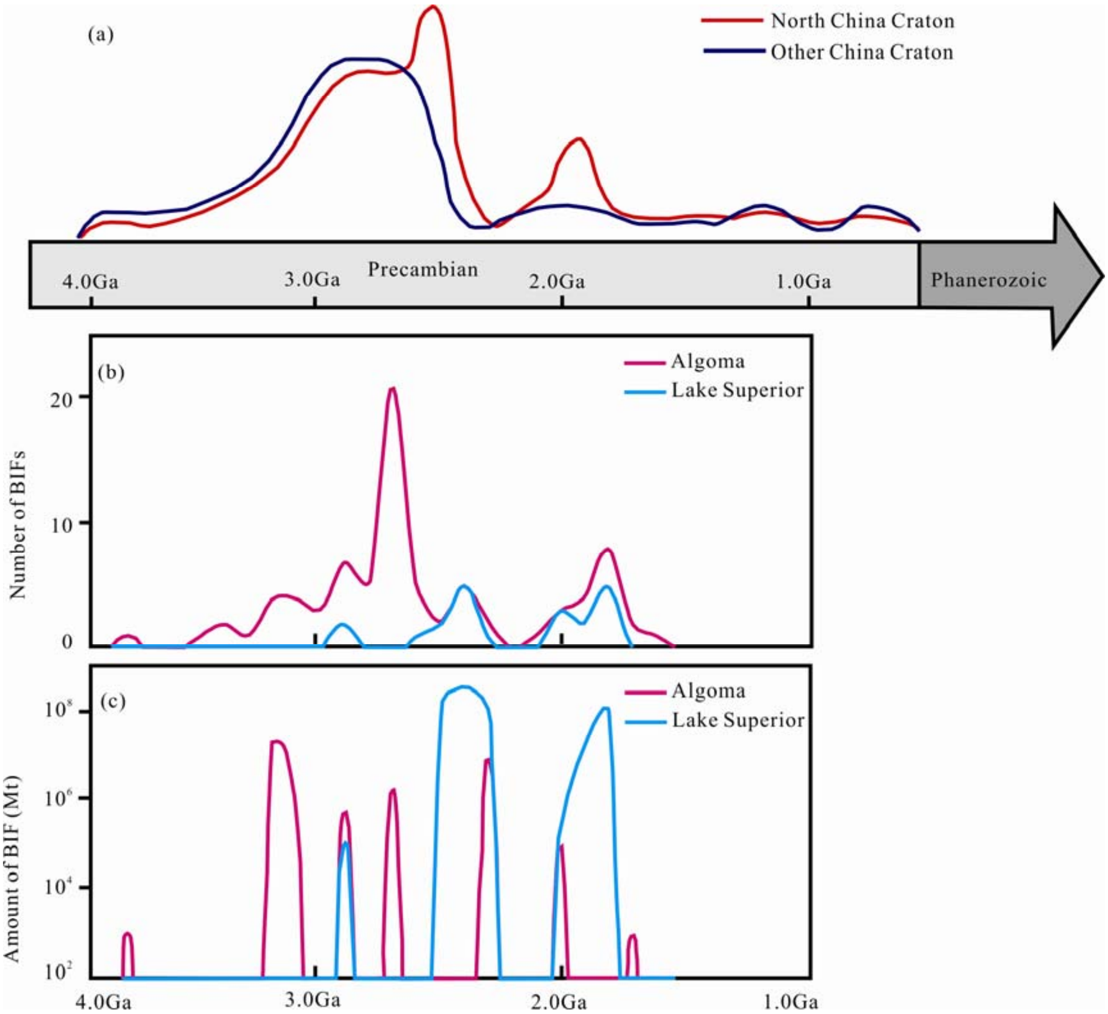

Fig. 11. Crustal proliferation and BIF development rules.
(a) Crustal accretion (Zhai and Santosh, 2013); (b) number of global BIF deposits (Huston and Logan, 2004); (c) global reserves of BIF minerals (Logan, 2004).

terrigenous material. A hydrothermal origin is suggested by their SiO_2 content which ranges from 90.11% to 94.85% and is relatively high overall, the high contents of Ba and U, the Ba/Sr and U/Th ratios which ranges from 3.89 to 25.28 and from 0.09 to 0.20 respectively and the ΣREE value ranges from 57.03 ppm to 152.59 ppm. Plots of Al_2O_3-SiO_2, $SiO_2/(K_2O+Na_2O)$-MnO_2/TiO_2 and Mn-10×(Cu+Co+Ni)-Fe in discrimination diagrams also verify this interpretation. Both the MgO content, ranging from 0.16 to 0.32, and the Fe/Ti ratio, ranging from 2.50 to 9.72, suggest that terrigenous material was added during the depositional process.

(2) The siliceous rock was formed in a continental margin under weak hydrodynamic conditions. Major-, trace- and rare earth element ratios such as Al/(A1+Fe+Mn) from 0.81 to 0.93, MnO/TiO_2 from 0.00 to 0.17, Al/(Al+Fe) from 0.82 to 0.93, Sc/Th from 0.21 to 0.50, U/Th from 0.09 to 0.20, $(La/Yb)_N$ from 0.83 to 3.04, and $(La/Ce)_N$ from 0.01 to 0.02, imply that the siliceous rock formed in a continental margin. In addition, the Sr/Ba ratio of siliceous rock (from 0.08 to 0.26), the δCe value (from 0.31 to 0.90), and the δEu value (from 0.14 to 0.58), all indicate that the water depth of siliceous rock formation was relatively high and the hydrodynamic conditions weak.

(3) Siliceous rock and BIF formed in the same geological setting, the magma source of siliceous rock was a slightly intermediate magma. The $SiO_2/(K_2O+Na_2O)$ ratio of siliceous rock from 28.61 to 47.43, the SiO_2/Al_2O_3 ratio from 16.53 to 32.37, the Al_2O_3/TiO_2 ratio from 37.82 to 50.30 and the SiO_2/MgO ratio from 287.28 to 592.81, are all in agreement with chemical deposition associated with volcanic eruptions. The high concentration and high purity SiO_2 quickly precipitated from the hydrothermal fluids to finally formed the accumulation of siliceous rock in a marginal sea, while the input corresponding to iron formation components was deposited to form iron formation layers, with limestone being only the product formed during the deposition intervals of siliceous rock and iron formations.

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