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Geochemical Characteristics of Arsenic in Sediments and Surface Water in Pinpet Deposit, Southern Shan State, Myanmar

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Abstract

Myanmar has great potential in a variety of metal and mineral resources, many of which have been poorly explored. The Pinpet deposit is the second-largest iron (Fe) deposit in Myanmar, located in the Shan Plateau, the eastern part of Myanmar. The Pinpet deposit was studied by several authors (eg., Svanholm:1951, Bender:1983) and identified as limestone replacement type, lateritic type, iron oxide-copper-gold (IOCG) type, respectively. The previously unpublished report indicated that arsenic contents in some limonite ores are significantly high (up to 0.25 wt.%). The mine operations have been suspended since 2017, due to the contamination of heavy metals and hazardous elements into the surrounding aquatic environment and associated public concern. A scientific investigation of the source and degree of contamination in the stream near the deposit has not yet been conducted. Geochemical characteristics of sediments, after acid digestion, show no significant difference in the all sediments samples, also low contents of hazardous elements (As, Cu, Zn, U) in the sediment samples from (DM) and Nan-tank-pauk stream (S5 and S8), although arsenic the content of DM is slightly higher (92 mg/kg) than in S5 and S8. Sequential extraction of As shows that F9 fraction (associated with organic matter and secondary sulfides), and F10 fraction (residual) are the dominant phases in the S8 sample. The other two sediment samples (DM and S5) have F6 (co-precipitate with crystalline Fe, Al, and Mn hydroxides) as a significant As-bearing phase in addition to fractions F9 and F10. Labile fractions (F1- soluble by distilled water and F2- exchangeable and loosely adsorbed) fractions were very low (< 0.2%) in all the sediment samples. The geochemical analyses of major elements in surface water in a stream flowing near the Pinpet deposit show that the surface water samples were dominated by calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) ions, controlled by limestone bedrock in the study area. The dissolved trace elements (As-0.001 ppm) are in low concentrations, below the WHO standard as well as the proposed national drinking water quality standards in Myanmar. Arsenic concentration in the sediments is similar to those in uncontaminated sediments, although some sediment in the tailings dam was probably transported to the middle reaches of the stream. However, As in these sediments is mostly bounded in insoluble fractions. The surface water and sediment in a stream flowing near the Pinpet deposit indicate that no significant past and present contaminations of metals into the aquatic environments. Therefore, it is unlikely that As at Pinpet will be released into the aquatic environment by interacting with water during ore beneficiation processes.

Keywords: Arsenic, Environmental impact, Pinpet mine, Sequential extraction

မျက်နှာပြင်ရေနှင့်အနည်အနှစ်များထဲရှိ အာဆင်းနစ်၏ ဘူမိဓာတုဆိုင်ရာ သွင်ပြင်လက္ခဏာများ၊ ပင်းပက်သံသတ္တုသိုက်၊ ရှမ်းပြည်နယ်တောင်ပိုင်း၊ မြန်မာနိုင်ငံ

ဒေါက်တာကျော်ဇေယျ၊ ဘူမိဗေဒအရာရှိ
ဘူမိဗေဒလေ့လာရေးနှင့်ဓာတ်သတ္တုရှာဖွေရေးဦးစီးဌာန

စာတမ်းအကျဉ်း

မြန်မာနိုင်ငံသည်သတ္တုနှင့် တွင်းထွက်သံယံဇာတအရင်းအမြစ် အမျိုးမျိုးအတွက် ကြီးမားသော အလားအလာများစွာရှိသော်လည်း တူးဖော်ထုတ်လုပ်မှုတွင် လိုအပ်ချက်များရှိပါ သည်။ ၎င်းတို့အနက် ရှမ်းပြည်နယ်(တောင်ပိုင်း) တွင်တည်ရှိသော ပင်းပက်သံသတ္တုသိုက်သည် ဒုတိယ အကြီးဆုံး သံသတ္တုသိုက်တစ်ခုဖြစ်ပါသည်။ ယခင်လေ့လာခဲ့သော မှတ်တမ်းများ အရ ပင်းပက် သတ္တုသိုက်ရှိ လီမိုနိုက်ဇုံ ထဲတွင် အာဆင်းနစ် ၀.၂၅ ရာခိုင်နှုန်း ခန့် ပါဝင်ကြောင်း မှတ်တမ်းများ ရှိသော်လည်း သတ္တုမိုင်းပတ်ဝန်းကျင်ရှိ ရေထုထဲတွင် အဆိပ်အတောက် ဖြစ်စေနိုင်သောသတ္တု ဓာတ်များ ပါဝင်နေမှုရှိမရှိကို သုတေသနပြု ဆောင်ရွက်ထားခြင်းမရှိပေ။ အနည်အနှစ်များရှိ အဆိပ် အတောက်ဖြစ်စေနိုင်သော သတ္တုဓာတ်များပါဝင်မှုအား သိရှိနိုင်ရန်အတွက် အက်စစ်ဖြင့် အလုံစုံခြေဖျက်သောနည်းစဉ် (Acid digestion method) ဖြင့် ဓာတ်ခွဲ စမ်းသပ်ရာတွင် ပင်းပက် သံသတ္တုမိုင်းဇရိယာအတွင်းတည်ရှိသောအနည်စစ် ရေစုကန်(DM)ရှိအနည်နှစ်တွင် အာဆင်းနစ် ပါဝင်မှုမှာ (92 mg/kg)ဖြစ်ပြီး ပင်းပက်သတ္တုမိုင်း၏ အရှေ့ဘက်တွင်စီးဆင်းနေသော နမ့်တက် ပေါက်ချောင်းထဲရှိ အနည်နှစ်(S5, S8) တွင်ပါဝင်သော အာဆင်း နစ်တန်ဖိုးထက် အနည်းငယ် ပိုမိုလျက်ရှိပါသည်။ အဆင့်လိုက် ချေဖျက်ခြင်းနည်းစဉ် (Sequential extraction)ဖြင့် ဓာတ်ခွဲ စမ်းသပ်ရာတွင် ၎င်းအာဆင်းနစ်သည် သဘာဝဒဏ်ကြောင့် ပြိုကွဲပျက်စီးလွယ်သော ဓာတု ဆိုင်ရာတွဲစပ်မှုအပိုင်း(Labile Fraction)ထဲ၌ ၀.၂ရာခိုင်နှုန်းအောက်သာ ပါဝင်နေကြောင်း တွေ့ရှိ ရပါ သည်။ ပင်းပက်သတ္တုဇုံ အနီးစီးဆင်း နေသော ချောင်းရေမျက်နှာပြင်ထဲရှိ အဓိက ဒြပ်စင် များ၏ ဘူမိဓာတုဆိုင်ရာ အခြေအနေများ ကို ဆန်းစစ်ရာတွင် ကယ်လဆီယမ်၊ မဂ္ဂနီစီယမ်တို့ ပေါများစွာပါဝင်ခြင်း၊ ကာဗွန်နိတ်ကြွယ်ရေ အမျိုးအစားဖြစ်ပေါ်နေခြင်းတို့တွေ့ရှိရပါသည်။ ထိုသို့ ဖြစ်ပေါ်ရခြင်းမှာ နမ့်တက်ပေါက်ချောင်း စီးဆင်သော အောက်ခံကျောက် အမျိုးအစား

(ထုံးကျောက်)၏ နှီးနှောဆက်နွယ်မှုမှာ အဓိက ကျသောအချက်ဖြစ်ကြောင်း တွေ့ရှိရပါသည်။ ၎င်းချောင်းရေထဲတွင် အာဆင်းနစ်ပါဝင်မှုမှာလည်း 0.001 ppm သာဖြစ်ခြင်းကြောင့် ကမ္ဘာ့ ကျန်းမာရေး အဖွဲ့မှ သတ်မှတ်ထားသော လက်ခံနိုင်သည့် အာဆင်နစ်ပါဝင်မှု၊ မြန်မာနိုင်ငံမှ သတ်မှတ်ထားသော သောက်သုံးရေထဲတွင် အာဆင်း နစ်ပါဝင်မှု၏ လက်ခံနိုင်သော ပမာဏ တန်ဘိုး 0.01 ppm ထက်များစွာ လျော့နည်းလျက် ရှိကြောင်း လေ့လာတွေ့ရှိ ရပါသည်။ သတ္တုဧရိယ ပတ်ဝန်းကျင်ရှိအနည်နှစ်များထဲတွင်ပါဝင်သောအာဆင်းနစ်၏တန်ဘိုးမှာလည်း အဆိပ်တောက် မဖြစ်နိုင်သော အနည်နှစ်များ၏ အာဆင်းနစ် တန်ဘိုးကဲ့သို့ ဖြစ်ပေါ်နေခြင်း၊ ဟီမဟိုက်ဧရိယ အတွင်းမှ အာဆင်းနစ်သတ္တုဓာတ်များ လွှတ်ထွက်နိုင်မှု အခွင့်အလမ်း နည်းပါခြင်းတို့ကြောင့် ပင်းပက်သံသတ္တုမိုင်းအနီးရှိ ချောင်း ရေမျက်နှာပြင်သည် ယခင်အချိန်မှ ယခုအချိန်ထိ အာဆင်း နစ်ကြောင့် အဆိပ်အတောက် ဖြစ်ပေါ်နေခြင်း မရှိသေးပါ။ ပင်းပက်သံသတ္တုသိုက် အနီးရှိ ချောင်းရေနှင့် အနည်းအနစ်များကို သုတေသနပြု ဓာတ်ခွဲစမ်းသပ်ချက်အရ သံသတ္တုရိုင်း သန့်စင်ရန် လိုအပ်သောရေအတွက် သဘာဝရေ အမျိုးအစားကိုသာ အသုံးပြုပါက ပတ်ဝန်းကျင် ရေထုထဲသို့ အာဆင်းနစ် ထွက်ပေါ်ပါဝင်မှုမှာ ဖြစ်နိုင်ခြေ လွန်စွာနည်းပါးလျက်ရှိပါကြောင်း လေ့လာ တွေ့ရှိ ရပါ သည်။

Geochemical Characteristics of Arsenic in Sediments and Surface Water in Pinpet Deposit, Southern Shan State, Myanmar

1. Introduction

Myanmar has many types of mineral deposits such as tin-tungsten, antimony, lead-zinc-silver, nickel-copper-gold, iron-manganese as well as gem and industrial mineral deposits (e.g., barite, fluorite, gypsum, coal, etc.,). Despite Myanmar has the potential endowment, many deposits have not been discovered and poorly explored due to decades of isolation, lack of funds, and technical know-how. However, the iron (Fe) ore deposit at Mt. Pinpet has been known since 1951, and the exploration of the deposit was started in the year 1954. Initially, the stages of exploration were carried out by pitting and trenching, later followed by diamond drilling and geomagnetic survey. The first attempts to explore the mine were made in 1961 but stalled in 1962 after Burma's (Myanmar) first military coup. This was followed by geological work that was performed in 1982. A second attempt followed the 1991 cease-fire agreement. After that, the activities were stalled again, this time, however, due to the lack of funds. In 2004, Russia and the Italian company started to develop the Pinpet Fe deposit and to build up an ore processing plant and mined by an open-pit method. The deposit size is 4.02 km × 0.80 km × 90 m which consists of the estimated reserve of 10 million tons of hematite (56.4 %Fe) and 70 million tons of limonite (42.6 %Fe). The ore bodies are composed solely of oxide ores: limonite ore (mainly goethite) and hematite ore. Arsenic contents in some ore zones are high, up to 0.25 wt.% (Krupp-Rohstoff, 1962). In 2017, the mine was temporarily suspended because of lack of economic viability and possible contamination of heavy metals and hazardous elements, such as arsenic (As), copper (Cu), and zinc (Zn) into the surrounding aquatic environments, due to public concerns about the effects of mining activities. However, an appropriate scientific study has never been carried out to investigate heavy metal and hazardous elements concentration in the stream and ores in this area. The minerals and ores are chemically stable under in situ geological conditions, but when excavated and exposed to the atmosphere, the solid phase becomes chemical unstable (Younger and Wolkersdorfer, 2004). The anthropogenic sources of heavy metals are constituted mainly by mining activities and too much use of fertilizer for agricultural land (Khan *et al.*, 2013). Anthropogenic activity is the major cause of arsenic pollution in the environment. During iron ore beneficiation, liquid wastes are degradation to the water quality since iron ores consist of an excessive amount of harmful trace metals such as As, Cu, Pb, Ni, etc., and may generate leachate when acid mine runoff is introduced and may result in pollution of water bodies within and surrounding of the mine area.

Water can be easily contaminated in different ways, among them mining is one of the major activities causing water pollution and threatens the quality of surface water and groundwater. Water pollution is caused by mining activities carried out nearby due to overburden dumps, surface impoundments, mine water, acid mine drainage, tailing ponds, etc. (Singh *et al.*, 2013). Even tailing from the mineral processing plants affect the surface and groundwater quality. River or streams flowing close to the mining area can be contaminated continuously from the point as well as a non-point source. Various studies have demonstrated that concentrations of metals in river sediments can be sensitive indicators of the overall

contamination in the aquatic systems (Bellucci *et al*., 2002) and represents a useful tool for the identification of anthropogenic contamination sources (Bidhendi *et al*., 2007). Metal ions in sediments are partitioned between the different phases present, i.e. organic matter, oxyhydroxides of iron, aluminum, and manganese, phyllosilicate minerals, carbonates, and sulfides. (Fuentes *et al*., 2008). So, we followed a modified sequential extraction method for arsenic fraction to predict the future of arsenic in solid and transport to the surface water. Sequential extraction can be used to determine the speciation and concentration of trace elements in the solid matrix.

2. Location, Climate, Vegetation, and Land Use

The study area is situated at Pinpet range, about 11 km southeast of Taunggyi Township, southern Shan State, Myanmar, (Fig 1). Physio-graphically it has a conspicuous land feature, which can be divided into two portions such as lowland area and mountainous terrain. The study area lies in a humid subtropical climate in which monsoon starts from June to the middle of November. The dry season is from March to the beginning of June. Annual rainfall is about an average of 1540 mm/yr. The carbonated rock area, usually present in very rugged terrain with steep slopes covered by fairly dense forest. The siltstone and shale areas have fairly vegetative and forest covers. Soil covered areas are good for cultivation and low-lying areas are cultivated for rice, crop, corn, tea leaf plant, peanut, and vegetable garden. The study area includes not only the mine area (Pinpet Fe ore zone) but also cultivated areas in the eastern part of the ore zone. The Nan-tank-pauk stream pass-through from north to south in the eastern part (Hopong valley). The farmlands have been developed mainly along the Nan-tank-pauk stream and cultivated by using traditional methods, which utilize available natural resources (such as animal waste) combined with a synthetic chemical such as fertilizers and pesticides. Small villages, in which populations are ~7,000 people in total, are also located along the Nan-tank-pauk stream. Most villagers who are farmers and breeders living near Mt.Pinpet are of the Pa'O ethnic group with Shans and Indians people also living in the area (Pa-O Youth Organization, 2009).

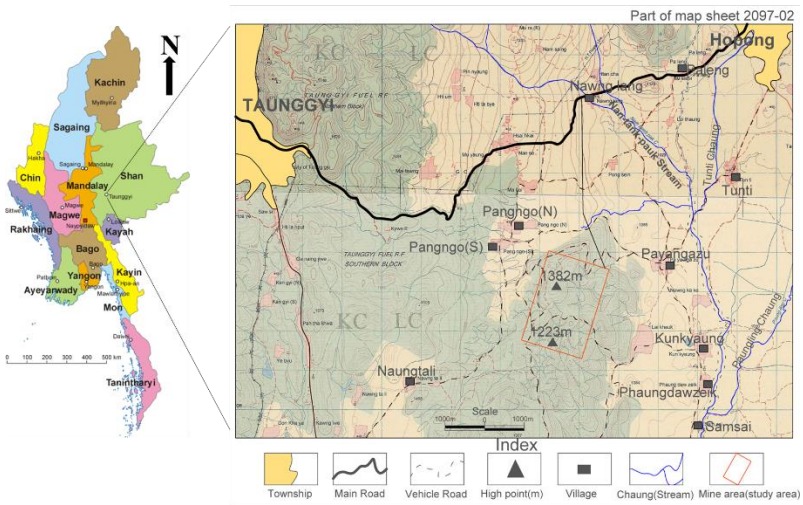

Figure 1. Location map of the study area (modified after DGSE, 2015).

3. Geology of the Study Area

The study area is located in the Shan Plateau, the eastern part of Myanmar consists of Cambrian-Ordovician sedimentary sequences with localized Ordovician volcanic rocks and volcaniclastics unconformably overlain by thick Middle-Upper Permian limestone sequences (Aye Ko Aung, 2012). The regional geological map of Taunggyi is shown in Fig. 2. In the east of the study area, lower Paleozoic rocks are exposed such as Ordovician age of Lokepyin Formation, Wunbye Formation, Nan on Formation, Silurian age of Linwe Formation, Wabya Formation, Carboniferous age of shale, pebbly schist, sand-shale intercalation limestone, Premian age of Thitsipin limestone and Nwabangyi Dolomite Formation. The western and northern parts comprised of Ordovician, Silurian, Permian to Triassic age carbonate rock sequence. The Nwabangyi dolomite formation is well exposed in Taunggyi- Hopong road section. In the east of the study area, Hopong plain is remarkable as a low-lying area. This plain is trending N-S and extending to the south. West of the study area has a remarkable Heho plain and Pintaya range composed of Ordovician, Silurian, Devonian, and Permian ages rock sequences.

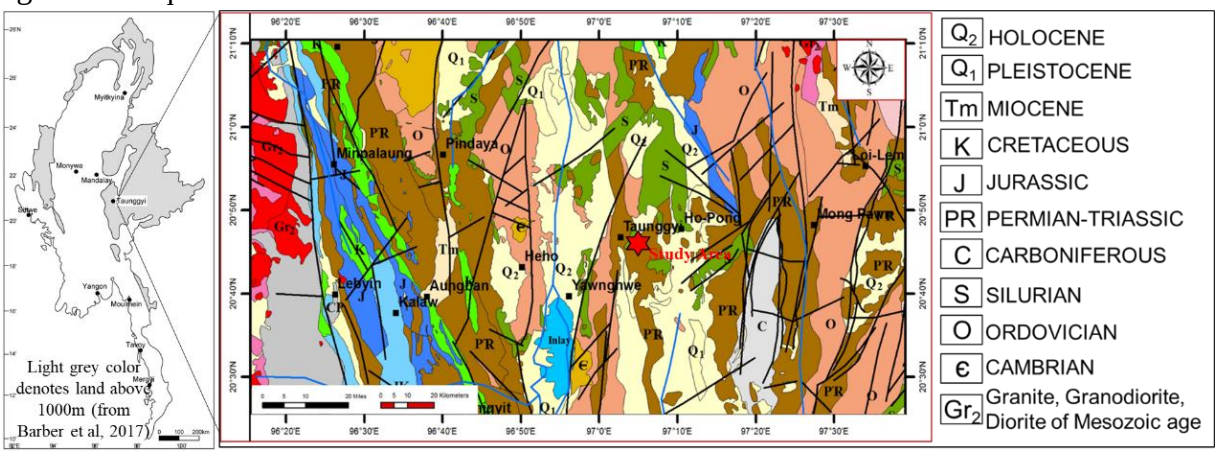

Figure 2. Regional Geological Map of Taunggyi Area (DGSE, 2015).

Surrounding the study area are the two major regional faults, such as the Kyaukkyan fault and the Htam-Sang fault. They are general trends from north to south direction. Kyaukkyan fault is one of the prominent seismotectonic features (Win Swe & Win Naing, 2008; Soe Min *et al*., 2016). It is extending in the nearly north-south direction and small lineament, branching of cross fault in E-W direction. The two parallel faults roughly trend NE-SW direction and fault scarps sporadically occur along the fault valley (Hopong valley). This structure appears to be largely important in controlling the Pinpet Fe ore zone since the mineralized zone occurs between the two faults and may have been considered as an elevated fault block. WNW-ESE trending diagonal minor faults are also found in the mineralized shear zone associated with hematite ore zones.

4. Sampling and Analytical Methods

4.1 Collected samples

Sampling locations were selected based on different land-use patterns. The sediment samples (DM, S5, S8) were obtained by shoveling sediments at 0 – 10 cm depth in the stream beds also tailing dam (DM) in the mine area which is stored in polyethylene bags. Eight

water samples (S1-S8) were collected from different locations (upstream and downstream) of the Nan-tank-pauk stream including two water samples from two tributaries: one flowing in the residential area of the mining town (TS1) and another flowing in the main ore zone (TS2; Fig. 3). The water samples were collected from different locations in two seasons, the wet season (during November 2017) and the dry season (during April-May, 2019). Tributary samples were obtained only during the wet season because tributaries contained no water during the dry season. Water was sampled using a plastic bucket and disposable cups and then filtered using 0.20 µm PTFE membranes in the field. They were filled in 50 ml polypropylene bottles sealed with Teflon tape and acidified with 1 vol% HNO_3; ultrapure grade, Kanto Chemicals, Tokyo, Japan) for cation concentration analysis. The samples were transported to Environmental Geology Laboratory, Hokkaido University, Japan. The liquid samples were stored in a refrigerator kept at ~4°C until they were analyzed.

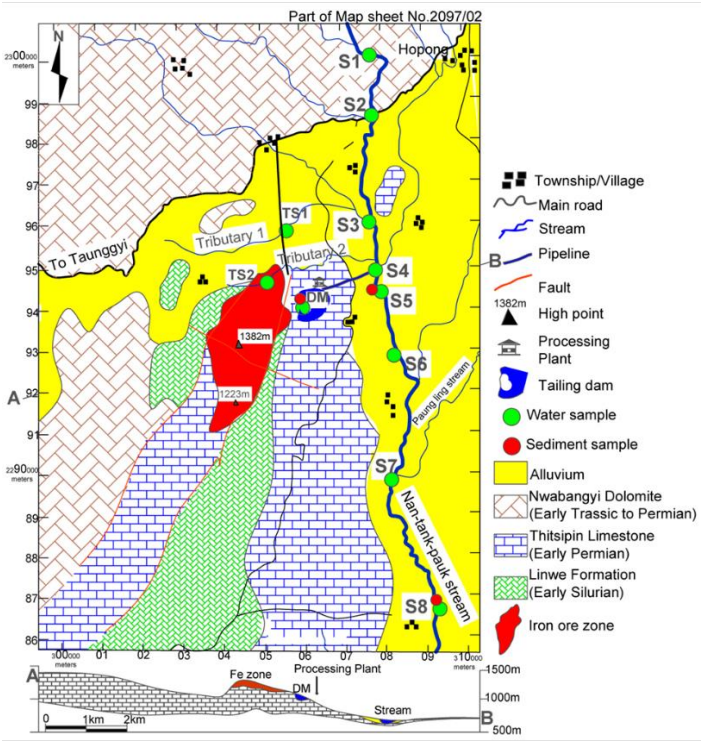

Figure 3. Water and sediment samples location map of the study area.

4.2 Analytical methods

Sediment samples were dried at room temperature and pulverized using a Multi-Beads Shocker (PV1001(S), Yasui Kikai) and sieved through a 53 µm stainless steel sieve. Bulk concentrations of heavy metals (e.g. As, Cu, Zn) in the sediment samples were determined by total digestion of 0.4 g of each sample by 15 ml of a 3:1 mixture of HNO_3 (ultrapure grade; Kanto Chemicals) and HF (TAMAPURE AA-100, Tama Chemicals) at up to 180°C for 15 min using a microwave assistant digestion system (ETHOS, Milestone), and analyzed by ICP-mass spectrometry (ICP-MS; iCap Qc, Thermo Scientific) after diluting the solutions by a factor of 10,000. Standard solutions were prepared using Anion mixture standard solution I (FUJIFILM Wako Pure Chemical), ICP multi-element standard solution IV (Merck), and Indium standard solution (Kanto Chemical). Water samples were diluted by a factor of 5 and analyzed for major- and trace- metal concentrations measured using

inductively coupled plasma-atomic emission spectroscopy (ICP-AES; ICPE-9000, Shimadzu) and ICP-mass spectrometry (ICP-MS; iCap Qc, Thermo Scientific).

Sequential extraction of As from the sediment samples was conducted using a modified method by Javed *et al*., 2013. Arsenic was extracted from sediment samples using various acids, such as sodium acetate, sodium dihydrogen phosphate, ammonium oxalate, Ti-citrate-EDTA-bicarbonate, hydrogen fluorite, nitric acid, and hydrogen peroxide. The protocols were divided into 10 steps (first fraction (F1) to tenth fraction (F10)); F1: soluble by distilled water; F2: exchangeable and loosely adsorbed; F3: strongly adsorbed; F4: carbonate bounded; F5: co-precipitated with amorphous Fe, Al, Mn oxyhydroxides; F6: co-precipitated with crystalline Fe, Al, Mn oxyhydroxides; F7: associated with As oxide and silicate clays; F8: co-precipitated with pyrite and amorphous orpiment; F9: associated with organic matter and secondary sulfides; and F10: residual.

5. Results

Arsenic in sediment samples showed that F9 fraction (associated with organic matter and secondary sulfides), and F10 fraction (residual) are the dominant phases in the S8 sample, which has the lowest As concentrations of the sediment samples (Fig. 4a). The other two sediment samples (DM and S5) have F6 (co-precipitate with crystalline Fe, Al, and Mn hydroxides) as a significant As-bearing phase in addition to fractions F9 and F10. Metals associated with a residual fraction (F10) are stable and are not soluble under normal environmental conditions. Soluble and exchangeable fractions represent highly bioavailable metals by virtue of metal adsorption when relates to changes in water ionic composition that may affect the adsorption-desorption process and mobility of metals (Fuentes *et al*., 2008). This fraction is of great importance because metals in this fraction can be toxic to aquatic organisms (Davutluoglu *et al*., 2011). But in the study area, labile fractions (F1- soluble by distilled water and F2- exchangeable and loosely adsorbed) fractions were very low (< 0.2%) in all the sediment samples.

After acid digestion by ICP–MS analysis shows no significant difference in the all sediments samples, also low contents of hazardous elements (As, Cu, Zn, U) in the sediment samples from (DM) and Nan-tank-pauk stream (S5 and S8), although arsenic the content of DM is slightly higher (92 mg/kg) than in S5 and S8 (Table. 1; Fig. 4b).

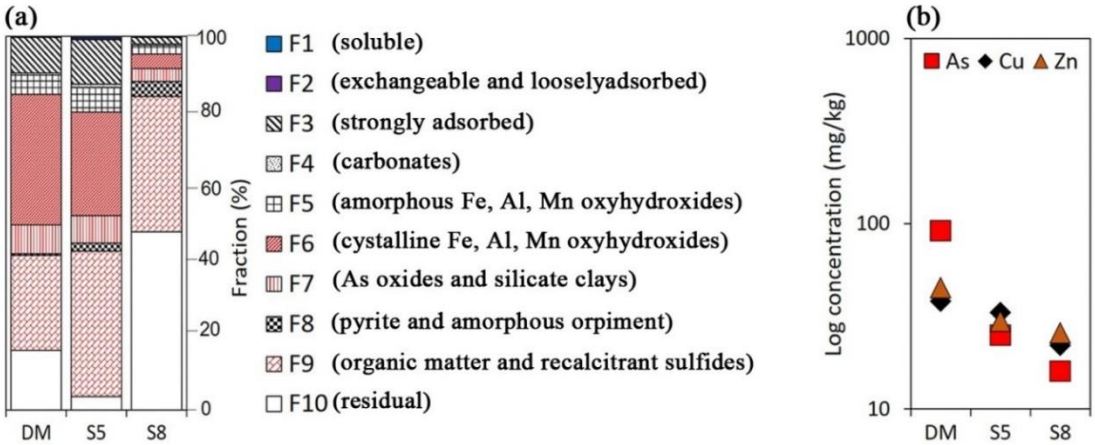

Figure 4. Results of sequential extraction and variations in Cu, Zn, and As concentrations in sediment samples (a) ICP-MS analysis after acid digestion (b).

Table 1. Bulk chemical compositions (trace- elements) of sediment samples.

Sample	Cu mg/kg	Zn mg/kg	As mg/kg	Pb mg/kg	U mg/kg
DM	38	34	92	45	14
S5	33	37	25	30	13
S8	22	35	16	26	13

Results of traces elements analyses for water samples show that concentrations of metal and hazardous elements were all lower than 4 µg/L, except for Fe, which was 36.3 µg/L in the tailings dam in the dry season. Other elements detected by ICP-MS analysis include Mn, Fe, Cu, Zn, As, Pb, and U (Table. 2). Zinc was detectable in the Nan-tank-pauk stream only in the wet season, and its concentration tended to decrease in the downstream direction (Fig. 5a), which may have been caused by automobile exhausts from the nearby main road (e.g., Akhter & Madany, 1993; Al-Khashman, 2004). In the wet season, concentrations of other elements (As, Cu, and Fe) were fairly uniform along the stream even below the mining area. Iron concentrations in the Nan-tank-pauk stream were ~6 to ~11 µg/L. Arsenic, Cu, and Fe concentrations were lower in the tailings dam and the two tributaries than in the Nan-tank-pauk stream. However, during the dry season, their concentrations in the Nan-tank-pauk stream tended to gradually increase in the downstream direction, although the maximum concentrations were <3 µg/L for As and Cu, and <30 µg/L for Fe (Fig. 5b). Concentrations of these elements were higher in the tailings dam than in the Nan-tank-pauk stream. Uranium was only detectable in the dry season, whose concentrations were ~0.2 µg/L.

Most metal concentrations were higher in the dry than in the wet season and increased in the downstream direction in the Nan-tank-pauk stream. However, the increases were gradual starting from S3 or S4, suggesting that the increase was caused by multiple sources and not a point source such as the mine site. We suggest that the increases in Fe and As concentrations are geogenic and attributable to an increased amount of fine (<0.2 µm) Fe-bearing particulates from eroded materials or dust. Previous studies (e.g., Smedley & Kinniburgh, 2002; Campbell & Nordstrom, 2014) have shown that As is strongly associated with Fe oxides in the natural environment. All of the measured heavy metals (such as As, Cu, Zn, etc.,) concentrations were also below the WHO standards as well as national quality standards for drinking water proposed by the Ministry of Health and Sports of Myanmar (e.g., 1.0, 0.05, 3.0, and 2.0 mg/L for Fe, As, Zn, and Cu, respectively).

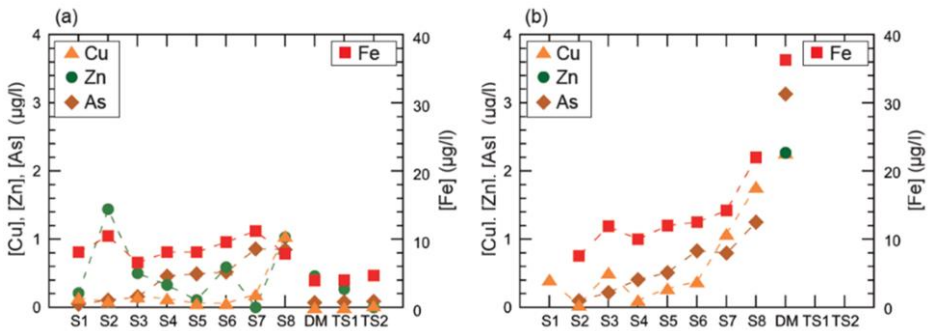

Figure 5. Variations in dissolved Cu, Zn, and As concentrations (left axis) and Fe concentration (right axis) in the downstream direction (S1 to S8) in waters of the Nan-tank-pauk stream, and in the tailings dam (DM) and two tributaries (TS1 and TS2), in the (a) wet (2017) and (b) dry (2019) seasons.

Table 2. Trace-element (Unit: µg/l) concentrations in Pinpet water samples and WHO drinking water standards (2004).

Sample	Mn	Fe	Cu	Zn	As	Pb	U	Mn	Fe	Cu	Zn	As	Pb	U
Nov. 2017 – wet season								Apr. to May 2019 – dry season						
S1	0.58	8.11	0.14	0.21	0.05	B.D	B.D	B.D	B.D	2.41	B.D	B.D	B.D	0.19
S2	5.62	10.5	0.09	1.44	0.11	B.D	B.D	65.4	7.55	0.04	B.D	0.10	B.D	0.17
S3	5.11	6.59	0.16	0.50	0.16	B.D	B.D	43.5	11.9	0.51	B.D	0.22	B.D	0.17
S4	8.97	8.10	0.13	0.33	0.46	B.D	B.D	116	10.0	0.11	B.D	0.41	B.D	0.18
S5	8.61	8.11	0.06	0.11	0.49	B.D	B.D	74.9	12.0	0.28	B.D	0.51	B.D	0.18
S6	7.83	9.61	0.06	B.D	0.52	B.D	B.D	18.6	12.5	0.38	B.D	0.83	B.D	0.19
S7	6.72	11.2	0.19	B.D	0.86	0.07	B.D	5.97	14.2	1.08	B.D	0.80	B.D	0.24
S8	5.52	7.89	1.05	B.D	0.85	0.01	B.D	7.27	22.0	1.77	B.D	1.25	B.D	0.24
DM	0.73	3.96	0.10	0.46	0.79	B.D	B.D	B.D	36.3	2.27	B.D	3.13	B.D	0.23
TS1	0.82	3.99	0.80	0.27	0.13	B.D	B.D	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A
TS2	1.66	4.68	0.03	B.D	0.32	B.D	B.D	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A
WHO (2004)	400	-	2000	-	10	10	15							

N.A.: samples were not available in the dry season

B.D.: below the detection limit

6. Conclusions

All heavy metal and hazardous element concentrations are within the WHO standards for drinking water. Although Fe and As concentrations in the dry season increased in the downstream direction to 36 and 3.1 µg/L, respectively, these increases are inferred to be attributable to a geogenic source, namely the transportation of fine Fe-bearing particulates from eroded materials or dust. Transportation of very fine particulates through the tailings dam could have delivered Fe and As into sediment of sample S5, which has a higher As concentration than downstream sediment (sample S8). Because As is also hosted in Fe hydroxides, it could be further concentrated during ore beneficiation.

Bulk chemical compositions of sampled sediments in the Nan-tank-pauk stream indicate no significant past contamination by hazardous elements. Arsenic, Zn, and Cu concentrations in the sediments are similar to those in uncontaminated sediments, although some sediments in the tailings dam were probably transported to the middle reaches of the Nan-tank-pauk stream.

Sequential extraction for sediments of sample S5, which is close to the mine site and tailings dam, shows that ~50% of As is associated with strongly adsorbed or amorphous or crystalline Fe, Al, and Mn oxyhydroxides. The As host phase fraction pattern of S5 (sediments at S5 were transported from the tailings dam) is similar to that of sediments from the tailing dam (DM), but different from that of sediments from the most downstream site (S8), which is ~10 km from the mine site. Furthermore, because most fractions of As in sediments were found in labile fractions (insoluble phases) were very low (< 0.2%), the chemical impacts of sediment-hosted As on the surrounding environment are likely to be minimal. Additionally, no significant contamination of surface water caused by mining activity or hematite and limonite ore beneficiation processes was found in the wet or dry seasons.

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