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Enrichment of Arsenic in Surface Water, Stream Sediments and Soils in Tibet

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Abstract

Groundwater in sedimentary deposits in China, Southern, and Southeast Asia down gradient from the Tibetan plateau contain elevated As concentrations on a regional scale. To ascertain the possibility of source region As enrichment, samples of water (n=86), stream sediment (n=77) and soil (n=73) were collected from the Singe Tsangpo (upstream of the Indus River), Yarlung Tsangpo (upstream of the Brahmaputra River) and other drainage basins in Tibet in June of 2008. The average arsenic concentration in stream waters, sediments and soils was 58 ± 70 $\mu\text{g/L}$ (n=39, range 2-252 $\mu\text{g/L}$), 42 ± 40 mg/kg (n=37, range 12-227 mg/kg), and 44 ± 27 mg/kg (n=28, range 12-84 mg/kg) respectively for the Singe Tsangpo and was 11 ± 17 $\mu\text{g/L}$ (n=30, range 2-83 $\mu\text{g/L}$), 28 ± 11 mg/kg (n=28, range 2-61 mg/kg), and 30 ± 34 mg/kg (n=21, range 6-173 mg/kg) respectively for the Yarlung Tsangpo. A dug well contained 195 $\mu\text{g/L}$ of As. In addition to elevated As levels in surface and shallow groundwater of Tibet, hot spring and alkaline salt lake waters displayed very high As levels, reaching a maximum value of 5,985 $\mu\text{g/L}$ and 10,626 $\mu\text{g/L}$ As, respectively. The positive correlation between [As] and [Na]+[K] in stream waters indicates that these surface water arsenic enrichments are linked to the hot springs and/or salt lakes. Further, 24% of As in stream sediment is reductively leachable, with bulk As displaying a positive correlation with stream water As, suggesting sorption from stream water. In contrast, the fraction of reductively leachable As is negligible for soils and several rock samples, suggesting that As in them are associated with unweathered minerals. Whether the pronounced As anomaly found in Tibet affects the sedimentary As content in deltas downstream or not requires further study.

Keywords

Arsenic; Tibet; geothermal; surface water; groundwater; soil; sediment

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1. Introduction

Occurrence of elevated groundwater As ($> 10 \mu\text{g/L}$ As, WHO drinking water guideline value) has been reported in many countries on all continents except for Antarctica (Ravenscroft et al., 2009). In most aquifers, As is geogenic (Smedley and Kinniburgh, 2002). Population exposed to unsafe levels of As ($> 10 \mu\text{g/L}$) in drinking water in eight countries of South Asia, but especially in Bangladesh and India (Chakraborti et al., 2002), was estimated to be as high as 100 million (Mukherjee et al., 2006). In Bangladesh alone, one in 17 adult deaths are attributable to As exposure, and in turn, the premature deaths reduces the Gross Domestic Product (Flanagan et al., 2012).

With an average upper crustal abundance of 4.8 mg/kg (Rudnick and Gao, 2003), As is by no means a scarce element and is highly toxic in its inorganic forms. Dissolution of 1 mg/kg of solid phase As can enrich the groundwater to $\sim 8000 \mu\text{g/L}$ As for a porosity of 25%. Such a simple calculation illustrates that the As content of the solid phase do not necessarily need to be elevated to cause As concentrations in water to exceed $10 \mu\text{g/L}$. In other words, basic principles of earth science would predict that groundwater could contain $> 10 \mu\text{g/L}$ As at many locations. Arsenic concentrations $> 10 \mu\text{g/L}$ are not found in groundwater everywhere because As partitioning between the solid and liquid phase is dependent on the thermodynamic state of the aquifer system, especially the oxidation and reduction potential because groundwater tends to have circum-neutral pH values. It is rare to observe $> 10 \mu\text{g/L}$ dissolved As in natural waters such as surface water bodies that contain dissolved oxygen, except in the cases of acid-mine drainages with low pH water. Under oxic conditions, solid surfaces are usually coated with enough Fe-oxyhydroxides that adsorb most of the available As onto its surface, limiting the amount of As that can enter the water. This As, however, is more mobilizable than that trapped in the crystalline lattice of an unweathered mineral. Reducing environment stimulates mobilization of the As on Fe oxyhydroxides from the solid phase to solution. This process can be microbially (Islam et al., 2004) and chemically mediated (Mladenov et al., 2010). Therefore, one usually finds elevated As concentrations, frequently as As(III), in anoxic groundwater that is enriched in dissolved Fe (Korte and Fernando, 1991) and depleted in dissolved sulfate (Zheng et al., 2004). Reviews on the occurrence of As in groundwater suggest that most major sedimentary aquifers with elevated As levels display this type of chemistry (Smedley and Kinniburgh, 2002). While far from perfect, this first-order explanation of the As release mechanism in groundwater, the so-called Fe-oxides reductive dissolution hypothesis, has been invoked for a range of aquatic environments: groundwaters (Nickson et al., 2000; Zheng et al., 2004) and various lakes (Aggett and Kriegman, 1988) and marine pore waters (Sullivan and Aller, 1996). The oxidation of As-containing sulfides (Schreiber et al., 2000) results in As enrichment in groundwater, but those waters are usually enriched in dissolved sulfate and are acidic.

Although the geological sources are well recognized to be associated with the widespread occurrence of As in groundwater, the influence of source region As enrichment on As occurrence in sedimentary aquifer down gradient has only been tentatively assessed (Pfeifer et al., 2004). This may have to do with the fact that solid phase As is generally abundant enough and is not regarded as a limiting factor for a specific aquifer at small spatial scale ($< 100 \text{ m}$). However, this view may be incorrect when As enrichment is of basin scale ($> 100 \text{ km}$) because the inventory of aquifer As is then substantial. For the Ganges-Brahmaputra Delta, glaciers have been proposed to accelerate transport of arsenic (Saunders et al., 2005) from the source regions of the Himalayan mountains where it occurs as As-bearing minerals in rocks that may have to do with As originally enriched in oceanic ferro-manganous sediments in the palaeo-Tethys (Stanger, 2005). Groundwater from the deltaic plains in Cambodia (Buschmann et al., 2007; Polya et al., 2005) and Vietnam (Berg et al., 2001) of the Southeast Asian deltas, and the corresponding upstream locations in Yunnan and

Sichuan Provinces of the southwestern China (Yu et al., 2007), along with sedimentary basins in Xinjiang of the northwestern China exhibits considerable As enrichment. The sediment of these As-containing aquifers are all supplied by rivers draining the Tibetan plateau. Although these basins or deltas in Asia formed under a variety of tectonic settings, including foreland basin, back-arc basin and by rifting (Hsu, 1989), a common characteristic is that rapid subsidence related to the orogeny contributed to deposition of thick sequences of sediments (Zheng, 2007) that presumably has not been well flushed by groundwater. However, whether these sediments originally contain elevated As concentration has not been assessed.

There are limited evidence that easily weathered, As-rich, ultramafic rocks (e.g., serpentinites) are located in the suture zones of the Himalaya mountains from which the unconsolidated sediment may have been derived (Guillot and Charlet, 2007; Hattori and Guillot, 2003). Favorable partitioning into fluid phases during subduction enriches volatile elements, such as As, to serpentinites (Hattori et al., 2005), resulting in several orders of magnitude higher As concentrations relative to the composition of the mantle (Ryan et al., 1996; Savov et al., 2002). This partitioning to fluid phases during high-temperature water-rock interactions also manifests itself as elevated As concentrations in hydrothermal waters (Webster and Nordstrom, 2003). Such speculation on a source of As in rock-forming minerals other than sulfides does not imply that the two are mutually exclusive. Serpentinites often co-exist with ore-grade sulfide minerals (Ni, Cu, etc.) for mining (Nickel and Thornber, 1977) in the same rock body known as ophiolite. Arsenic concentration in two surface water samples from Singe Tsangpo and its upstream tributary were reported to be 59 µg/L and 144 µg/L, respectively (Tian et al., 2002). Average arsenic concentration of Tibetan soil was also reported to be 18.7 mg/kg (n=205) (Zhang et al., 2002), considerably higher than the commonly cited background value of approximately 10 mg/kg of As for soil (Tanake, 1988). The elevated arsenic concentration in surface water and soils in this remote area are unlikely due to anthropogenic pollution.

This study aims to investigate the extent of arsenic enrichment in surface water, stream sediment and soil samples from the headwater regions of Tibet where groundwater enrichment has been noted in flood plains down gradient in South Asia. The study areas encompass the Singe Tsangpo flowing west towards the Indus River in Pakistan and the Yarlung Tsangpo flowing east to the Brahmaputra River in Bangladesh (Fig 1). River, lake, hot spring and dug well waters were analyzed for arsenic, major cations and anions. Chemical compositions, including As concentration determined by total digestion of reductive leaching, of stream sediment and soils samples were assayed. The source of As in stream water and sediment, and the implication for down gradient As enrichment in aquifer, are discussed.

2. Materials and Methods

2.1. Study area

The study area (28.6°-32.6°N, 79.5°-91.2°E) is located in southwestern Tibet (Fig.1) along the Indus-Yarlung Tsangpo Suture Zone, which is the tectonic boundary between the uplifted Himalaya mountain ranges and the interior plateau of Tibet (Yin, 2006).

2.2. Sampling and Field Measurement

In June 2008, water (n=86), stream sediments (n=77), soil (n=73) and rock (n=58) samples were collected from a total of 92 locations in the Singe Tsangpo (also known as Shiquan River), Yarlung Tsangpo and other drainage basins in Tibet. The locations were numbered sequentially from 1 to 92. For example, a set of samples collected from site 1 were named as TW-1 for water, TD-1 for stream sediment, TS-1 for soil, and TR-1 for rock. The stream

sediment samples were collected from nearly the exact locations where the water samples were collected but the top soils and rock samples are within a short walking distance depending on availability of the soil profile and the outcrop.

A total of 81 water samples from stream (n=69), salt lake (n=7), freshwater lake (n=2), hot spring (n=2) and dug well (n=1, depth 2 m) were collected from the Singe Tsangpo and the Yarlung Tsangpo drainage basins (Table 1). Five water samples were from other basins. The locations of the sampling were primarily determined by accessibility, with efforts made to cover a range of tributaries and to span over one thousand km distance. The GPS location was recorded by a handheld device (Garmin eTrex Vista C). pH was tested using pH paper. Dissolved oxygen, temperature and conductivity were measured using a multi-probe (HACH sensION 156) after daily calibration. Three aliquots of water sample were collected at each sampling location. One was unfiltered for alkalinity titration. Two others were filtered through 0.45 μm membrane filter on site. One of which was used for anion analysis and the other was acidified to 1% HNO_3 (trace metal grade) for cation and As analyses. All the water samples were stored in polyethylene bottles that had been pre-cleaned with de-ionized water and kept at 4 $^{\circ}\text{C}$.

The sediment and soil samples were air-dried and finely grounded and passed through a 0.150 mm sieve. Rock samples were crushed, grounded and passed through a 0.075 mm sieve.

2.3. Laboratory Analysis

2.3.1. Chemical analyses of water—Alkalinity of the water samples were measured by titration with 0.1M HCl at the State Key Lab of Environmental Geochemistry (SKLEG) Institute of Geochemistry, Chinese Academy of Sciences. Anions including F^- , Cl^- , SO_4^{2-} , PO_4^{3-} , NO_3^- , NO_2^- and Br^- were analyzed by ion chromatography (IC, DIONEX DX500) at Queens College, City University of New York (CUNY) following EPA method 300. Major cations including K^+ , Na^+ , Ca^{2+} and Mg^{2+} in water were measured by Flame Atomic Absorption Spectroscopy (FAAS, PE5100PC). Arsenic was measured by hydride generation-Atomic Fluorescence Spectroscopy (AFS-920) following a procedure described by Qin et al. (2010). Arsenic in samples was first reduced by a mixed solution of concentrated hydrochloric acid (HCl), 5% thiourea (H_2NCSNH_2) and 5% ascorbic acid ($\text{C}_6\text{H}_8\text{O}_6$) for 30 min. Hydride generation from the reduced sample was achieved through 1% KBH_4 in 0.2% NaOH before analysis by AFS under optimized instrumental conditions. Other trace elements were measured by inductively coupled plasma-mass spectrometry (ICP-MS, Micromass Platform ICP) at SKLEG. Quality assurance and control were performed using certified external standard solutions, internal standards and replicate sample measurements during the analysis. External standard solutions for As, Na, K, Mg and Ca were prepared from GBW(E)080622, GBW(E)080552, GBW(E)080553, GBW(E)080554 and GBW(E)080555 (GB stands for National Standard obtained from Certified Reference Material Center, China), respectively.

2.3.2. Chemical analyses of solids—The major and trace elements of all solid samples as powder (soil, sediment and rock) were first measured using a handheld X-ray fluorescence spectrometer (XRF, INNOV-X ALPHA-6500R) at CUNY. For As, an USGS-SDO-1 with a certified value of 68.5 ± 8.6 mg/kg yielded an average value of 59 ± 2 (n=5) whereas NIST (National Institute of Standard and Technology, USA) SRM 2781 with 7.82 ± 0.28 mg/kg and NIST SRM 2586 with 8.7 ± 1.5 mg/kg As were both not detectable (<10 mg/kg). In addition, a subset of solid samples were digested using high purity concentrated HClO_4 -HF- HNO_3 (Fisher Optima) by microwave oven digestion at CUNY. Briefly, to about 100 mg samples, 2mL HF, 2mL HClO_4 , and 7mL HNO_3 were added into

the Teflon container. The digestion was for 35 min following the manufacturer recommended temperature protocol for soil until it was completely dissolved. The samples were brought to dryness to expel HF residual in the sample on a hot plate, and then re-dissolved in 10 mL 1% HNO₃ for measurement. NIST SRM 2709 was included in each batch of digestion for the quality assurance. Major and trace elements of the digested samples were determined by ICP-MS (Perkin-Elmer Dynamic Reaction Cell) at the Environmental Sciences Analytical Center, Brooklyn College, CUNY. Arsenic concentration of the digest was quantified using hydride generation-AFS at SKLEG following a method similar to that described above. The method can quantify As content of soil and plant standard reference materials with a 92% or better accuracy, and can achieve a recovery of spiked As of 102%-104% (Qin et al., 2010). Quality assurance and control were performed using certified standards, internal standards and replicate sample measurements used during the analysis. NIST standards SRM-1643e and SRM 2709 with a certified As concentration of 60.45 $\pm$ 0.72 μ g/L and SRM 2709 of 17.7 $\pm$ 0.8 mg/kg were also used to monitor the analytical accuracy. The mean value of As was 58.3 $\pm$ 1.7 μ g/L (n=6) for SRM-1643e and 16.2 $\pm$ 5.9 mg/kg (n=10) for SRM 2709 total digest, respectively. The precision and accuracy of elements measured by AAS, AFS, IC, ICP-MS are usually 10% or better except for the total digest of NIST SRM 2709 because one of the Teflon vessels used for digestion the NIST SRM 2709 unfortunately developed a leak.

2.3.3. Reductive leaching of rock, soil and sediment—A subset of solid samples enriched in As (n=20) was subjected to reductive leaching to evaluate As that are adsorbed to ferro-manganesian oxides or carbonate minerals following a procedure described by Chester and Hughes (1967). About 0.5 g of rock, soil or sediment sample was weighed to a centrifuge tube. These samples, along with blanks, were combined with 5 mL of 1M hydroxylamine hydrochloride in 25% acetic acid. The resulting mixture was shaken at room temperature for 4 hours on a shaker. Samples were then centrifuged at 3500 rpm for 10 minutes and supernatants were collected for As analysis by hydride generation-AFS at SKLEG following similar procedure described above.

3. Results

3.1. Chemistry of Water

The average values of As concentrations in water in the order from high to low are: hot spring (4914 $\pm$ 1515 μ g/L, n=2) > lake (1733 $\pm$ 3446 μ g/L, n=9) > dug well (195 μ g/L, n=1) > stream (36 $\pm$ 57 μ g/L, n=74). Stream waters from the Singe Tsangpo drainage contain more As (58 $\pm$ 70 μ g/L, n=39, range 2 – 252 μ g/L, Table 1) than those of the Yarlung Tsangbo drainage (11 $\pm$ 17 μ g/L, n=30, range 2- 83 μ g/L, Table 1). More than 50% of stream water from the Singe Tsangpo drainage display [As] > 50 μ g/L (Fig. 2), whereas only 3% of stream water samples from Yarlung Tsangpo contain > 50 μ g/L As (Fig. 2). Compared to the WHO drinking water guideline value of 10 μ g/L As, 23% and 64% waters from Yarlung Tsangpo and Singe Tsangpo are above it. The average concentration of arsenic in the upstream stretch of Yarlung Tsangpo River west of Lazi (where TW-7 is located at 29°05'22.5"N 87°37'33.2"E, elevation 4019m, Fig. 1), is 45 $\pm$ 27 μ g/L (n=4, Fig. 1), higher than the value of 6 $\pm$ 6 μ g/L (n=26) downstream.

In addition to displaying thousands of μ g/L As, Na⁺ is the dominating major cation for two hot spring water samples (Table 1). The hot spring from Jiushi, Mapam Yumco in Singe Tsangpo drainage basin was Na⁺/HCO₃⁻-Cl⁻-SO₄²⁻ type (Fig.3) with a pH of 7.5. The hot spring from Yangbajain in Yarlung Tsangpo drainage basin was Na⁺/Cl⁻-SO₄²⁻ type with a pH of 8.2 (The charge is not balanced for this sample because Mg datum was missing). Both samples contained also substantial Br⁻ and NO₃⁻ (data not shown).

Concentration of As of salt lake water displayed the widest range from 40 to 10,626 $\mu\text{g/L}$ ($n=7$, Table 1), averaging 2,181 $\mu\text{g/L}$. Five of the 7 lake waters have pH value of about 9. Salt lake waters are of $\text{Na}^+ - \text{K}^+/\text{Cl}^- - \text{SO}_4^{2-}$ or $\text{Na}^+ - \text{K}^+/\text{HCO}_3^- - \text{CO}_3^{2-}$ type. Five salt lake water samples are charge balanced within 25% are used for water type classification (Fig. 3).

The stream water, freshwater lakes and well water in Yarlung Tsangpo and Singe Tsangpo drainages are of neutral pH, and of $\text{Ca}^{2+} - \text{Mg}^{2+}/\text{HCO}_3^- - \text{CO}_3^{2-}$ types based on samples with acceptable charge balanced within 25%. Sixty nine out of 86 samples have charge balance within 25%. The charge imbalance is in part due to titration of not-filtered stream water, some of which contain suspended particles with calcite, resulting in excess alkalinity. Stream waters with higher As concentrations ($> 50 \mu\text{g/L}$) contains higher proportions of $\text{Na}^+ - \text{K}^+$ and $\text{Cl}^- - \text{SO}_4^{2-}$ ions (Fig. 3).

3.2. Arsenic in stream sediments, soils and rocks

The average values or value of As concentrations of stream sediment samples in the order from high to low are: hot spring (219 mg/kg , $n=1$) $>$ salt and freshwater lakes ($77 \pm 60 \text{ mg/kg}$, $n=7$) $>$ Singe Tsangpo drainage ($42 \pm 40 \text{ mg/kg}$, $n=37$) $>$ Yarlung Tsangpo drainage ($28 \pm 11 \text{ mg/kg}$, $n=28$). Concentration data used for calculations are a combination of XRF and total digestion results for both sediment and soil samples (Table 2), whenever possible the total digestion data are used instead of the XRF data. This is because the XRF has higher detection limit, excluding the sample below detection would result in a slightly higher average value. For instance, Yarlung Tsangpo stream sediment average As concentration is $29 \pm 7 \text{ mg/kg}$ ($n=23$) based on XRF data only.

The distribution of As in the soils of the drainages are similar to that of the stream sediments (Fig. 4). The soils from the Singe Tsangpo drainage displayed higher average concentrations of As of $44 \pm 27 \text{ mg/kg}$ ($n=28$) than $30 \pm 34 \text{ mg/kg}$ ($n=21$) of the Yarlung Tsangpo drainage. The only soil sample from a hot spring (T57 Yangbajain) contains 36 mg/kg As. Concentrations of As in soil samples from salt and freshwater lakes averaged $74 \pm 85 \text{ mg/kg}$ ($n=6$), ranging from 24 mg/kg to 246 mg/kg with the maximum being a soil from a fresh water lake site.

Reductive leaching of As of soils and rocks yielded negligible amounts of As (Table 2). In contrast, the fraction of reductive leachable As in stream sediments ranged from 3% to 36%, averaging 24%. All stream sediments leached were from the Singe Tsangpo drainage.

4. Discussion

4.1. Enrichment of As in stream water and sediments

The enrichment of As in stream waters of both drainages are pronounced in these remote areas with little anthropogenic influence. These enrichments are likely linked to other high As waters, i.e. hot spring and alkaline lake waters, in Tibet. Supporting this interpretation is a linear correlation between concentrations of As and $\text{Na} + \text{K}$ content (Fig. 5). Assuming that As is sourced from a high As end member, either the hot springs or the salt lakes, dilution by low As stream flow in the summer presumably dominated by snow melt (Ge et al., 2008) could explain the As enrichment observed in the stream. However, it is worth noting that most of stream water samples containing As fall below this conservative dilution line (Fig. 5), suggesting that either there is an additional source of $\text{Na} + \text{K}$ to the stream water relative to As or that As has been removed from stream water. Because concentrations of As in stream water and sediments also display a positive although weak correlation (Fig. 6), it is likely that As has been sorbed onto stream sediments, resulting in this deficiency relative to $\text{Na} + \text{K}$ content in the water.

Continental geothermal water (Webster and Nordstrom, 2003) often enriched in arsenic and have been shown to elevate downstream surface water arsenic concentration in many hydrothermally active regions but are especially well demonstrated for the Waikato River, New Zealand and rivers down streams of Yellowstone, USA. An early review of As concentrations in geothermal fluids reported a range from less than 0.1 to nearly 50 mg/L, where Cl concentrations varied from 100 to 100,000 mg/L (Ballantyne and Moore, 1988). Although As concentration is not correlated with that of chloride in all geothermal fields, there is a correlation between As and electrical conductivity for geothermal waters at Yangbajing geothermal field in Tibet (Guo et al., 2008) where shallow geothermal fluids contain about 3 mg/L As and are of Na-Cl type. Geothermal As from Yellowstone National Park waters is generally 0.1 to 3 mg/L (Planer-Friedrich et al., 2006), but one sample was found to contain 14.6 mg/L. Yellowstone's thermal outflows contribute high As concentrations (10-370 µg/L) to the Madison and Missouri Rivers in Montana and Wyoming (Nimick et al., 1998). Although As concentration is controlled by sorption in oxic aqueous environment, dissolved As is found to be transported largely conservatively in the Gibbon, Firehole, Madison and upper Missouri Rivers downstream from its Yellowstone source for at least 310 km (McCleskey et al., 2010; Nimick et al., 1998; Nordstrom et al., 2010). This conservative transport has been hypothesized to occur because of silica deposition on river sediments that inhibit sorption (McCleskey et al., 2010). This pattern is partly explained by processes active in lakes along the drainage, where the average concentrations in the sediment tend to be between 10 to 100 mg/kg (Nimick et al., 1998). Concentrations of As display seasonal changes in Waikato River, New Zealand, which are typically lower in winter at about 15 µg/L and reaches maximum of ~ 60 µg/L in summer, even when factors such as dilution have been taken into account (McLaren and Kim, 1995). However, this seasonal pattern can reverse depending on the distance from Lake Taupo and the upmost stretch of the river that receive a number of geothermal inputs (Wilson and Webster-Brown, 2009). Winter As concentration minima are caused by the dilution of geothermal fluids during the wetter winter months, in combination with increased adsorption of As onto Fe-oxide-rich suspended particulate matter, which is more prevalent in winter (Webster-Brown and Lane, 2005) and with the highest As concentrations of 190 mg/kg (Wilson and Webster-Brown, 2009). Stream sediments are also enriched in As, frequently exceeding 100 mg/kg and reaching a maximum of 383 mg/kg (Wilson and Webster-Brown, 2009).

In light of the above, it is likely that the basin scale enrichment of stream water As in Tibet is attributable to As from widespread geothermal activities that supply a superlative amount of As. The Indus-Yarlung Tsangpo Suture Zone has abundant hydrothermal activities, with over 600 hot springs from Tibetan plateau (Zhao et al., 2002; Zhou and Qin, 1991). Previous studies also identified high As concentrations in the hot springs of Tibet (Zhang et al., 1982), with a maximum As concentration of 125.6 mg/L, the highest reported for continental geothermal water. These waters are also found to be superlatively enriched in incompatible elements such as B, Li, Rb and Cs, and are thought to have resulted from melting of thick sedimentary sequences beneath the Tibetan plateau (Zhang et al., 1982). The locations of hot springs are not random and are result of both uplifting and erosions that create steep geothermal gradients to drive intense shallow hydrothermal circulation (Koons and Craw, 1991). Hot springs are primarily found in two kinds of tectonic-geomorphic settings. The majority of Himalayan hot springs in Nepal are found along major incised valleys, in zones of steep river reaches and rapid fluvial down cutting (Bhattarai, 1980). These hot springs from deeply incised river gorges cross the Main Central Thrust along steep stream reaches are found to represent substantial heat transfer by this fluid flow to extract a large fraction of the tectonically advected heat (Derry et al., 2009). Thus, the superlative As enrichment in Himalayan hot springs are not surprising.

At present the reasons for the enrichment of As in alkaline salt lakes in Tibet and elsewhere are not well understood. It is possible that geothermal As is the ultimate source although that evaporation based on excess deuterium was invoked to explain As enrichment up to 1,200 µg/L of Dajiacuo and 504 µg/L of Dawa little lake, both are closed basin lakes (Tian et al., 2002). Significant concentrations of dissolved inorganic As have been found in the waters of a number of lakes located in the Nevada and California (Oremland et al., 2004), with the highest concentrations of arsenic occurring in hypersaline, closed basin soda lakes such as Walker Lake (975 µg/L), Big Soda Lake (1500 µg/L), Mono Lake (15,000 µg/L) and Searles Lake (225,000 µg/L). The Tibetan lakes with high As concentrations certainly share common chemical characteristics with the soda lakes in western USA. However, it is also known that geothermal activities in Sierra Nevada mountains have resulted in elevated stream water As concentration (Wilkie and Hering, 1998) and thus may contribute to As in soda lakes.

4.2. Enrichment of Arsenic in the Upper Crust of the Indus-Tsangpo Suture Zone

A recent assessment of continental crust composition has yielded recommended As abundance values of 4.8 mg/kg, 3.1 mg/kg and 0.2 mg/kg for the upper, middle and lower crusts, respectively, with the bulk continental crustal value of 2.5 mg/kg (Rudnick and Gao, 2003). The higher bulk continental crustal value of 2.5 mg/kg recommended by Rudnick and Gao (2003) as compared to the earlier estimate of ~ 2 mg/kg is because that the earlier estimates did not include the As enriched sedimentary reservoir in the upper crust. Rudnick and Gao (2003) suggest that these new estimates can be considered as representative of the upper crust to within 30% uncertainty. However, they also note that the small uncertainty undoubtedly reflect the fact that there have been few independent estimates made of the upper crust composition for As, with few measurements of As in loess available. In addition, glacially derived loess is subject to less weathering effects compared to shales and thus providing a better upper crustal estimate for the aqueous mobile As (Rudnick and Gao, 2003). The degree of weathering in loess, as measured by the “chemical index of alteration” (CIA = molar $\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$), is small relative to that seen in shales. Furthermore, the weathering induced fractionation in loess has been recognized as an ancient feature inherited from the glacially eroded bedrocks that had previously experienced sedimentary differentiation.

Concentrations of As found by a survey consisted of 250 surface soils (A horizon) and 156 subsurface soils (B and/or C horizon) were from 205 representative pedons in the Tibetan Plateau were comparable between A and C horizons, and averaged about 20 mg/kg for soils derived from sandstone, shale, limestone, glacial deposits, alluvial sediments and lake deposits with a lower average value of 14.7 mg/kg for soils derived from igneous rocks (Zhang et al., 2002). Compared to these Tibetan soils, soils from Singe Tsangpo and Yarlung Tsangpo drainages are even more elevated in As concentrations, suggesting that they may have been influenced by processes other than weathering.

Another large scale geochemical survey in northern Pakistan covering 100,000 km² area also found concentrations of As ranging from < 0.5 mg/kg to 683 mg/kg with a median value of 8.5 mg/kg (n=4260) using panned concentrate and <200 mm fraction (minus 80 mesh) samples (Halfpenny and Mazzuchelli, 1999). The survey encompasses the collision zone between the Eurasian and the Indian plates, and an intervening Cretaceous–Tertiary island arc system (the Kohistan and Ladakh arcs). These three main tectonic crustal units are separated by two major thrust faults, the Northern Suture Zone (NSZ) and the Main Mantle Thrust (MMT), which are zones of shearing up to 4 km wide that incorporate oceanic ophiolitic volcanics and alpine serpentinite intrusions where As enriched rocks have been reported (Hattori and Guillot, 2003). This area is characterized by extreme topographic relief, extending from the Karakoram Mountain Range, which includes peak elevations over

8000 m, to the Indus River valley. Taken together, the evidence suggest that regional upper crustal anomaly of As exists in the Himalayans.

4.3. Implications for As transport downstream

The correlation between As in stream water and sediment in Tibet further implies that a common source of As for both dissolved and particulate phases, suggesting that hot spring may be a more important source of As to downstream areas than previously thought, especially considering the numerous hot springs along the major river incisions cross the Himalayan ranges (Derry et al., 2009). The Himalayan orogeny has 5 periods (Le Fort, 1996): the prelude known as the Andean-type evolution of the northern margin of Tethys during the closure of the oceans that produced the Trans Himalaya-Karakoram ranges and the South Tianshan Mountain Belt, followed by the accretion of Euroasia plate colliding with the Indian plate between 55-50 Ma B.P., and then, a series of crustal thickening and thrust faulting. Intense uplifting began ~ 50 Ma B.P. This has provided a sediment source that formed the largest terrestrial foreland basin west of the Himalaya, depositing at locations where the subsidence rate is high, and is currently active in the Ganges-Brahmaputra Delta (Burban et al., 1996). Using U-Pb age distribution of detrital zircons, it has been demonstrated that foreland sediments located South of the Himalaya mountains may have been deposited by a transverse river which had not traveled for a great distance along the Himalayan front, with sediment supplied by Gangdese batholith north of the Himalaya on the Tibetan side starting from about 10 Ma before present (Cina et al., 2009).

Further research is much needed to ascertain whether As enriched sediment or As-enriched primary minerals are transported downstream, and if so, whether it has any linkage to groundwater As enrichment. It has been suggested that principal As-bearing minerals in the arsenic-containing shallow aquifer of Bangladesh were derived from multiple sources including heavy minerals, primarily from ophiolitic belts in the Indus-Tsangpo suture in the northeastern Himalayan and Indo-Burman Mountain ranges (Uddin et al., 2011). Concentrations of As were found to range from 10 to 50 mg/kg in biotite, accounting for 3 to 50% of the As in bulk sediment of Pleistocene and Holocene strata respectively (Seddique et al., 2008). Sediment from the Indus River display As concentration ranging from 0.17 to 7.5 mg/kg with an average value of only 1.7 mg/kg (Tariq et al., 1996). Suspended particulate matter sampled from dozens of locations from the Ganges, Brahmaputra, and Meghna Rivers in Bangladesh displayed values of As from 4 mg/kg to 5.5 mg/kg (Chowdhury et al., 2003; Tareq et al., 2003). If more data confirm the sediment As in downstream rivers, it would imply sediment derived from other sources low in As content have diluted As in sediments from the upstream source such as those found in the Singe Tsangpo and Yarlung Tsangpo.

5. Conclusions

Pronounced enrichment of arsenic in the surficial environment and upper crust of Tibet is observed. The enrichment of As in stream water and sediments in the Singe Tsangpo and the upper Yarlung Tsangpo drainages is mostly likely linked to superlative As enrichment of geothermal waters, emitted from hot springs located along major incised valleys, in zones of steep river reaches and rapid fluvial down cutting. The alkaline salt lakes are also enriched in As although the sources of As are not well understood. Despite evidence for sediment input from the Tibetan side of Himalayan mountains by rivers traversing the ranges to the South Asia side of the Himalayan, the implications of regional scale As enrichment along the Indus-Tsangpo Suture zones to occurrence of elevated groundwater As in downstream areas require further research.

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Highlights

Pronounced enrichment of As found in water, sediment and soil from Tibet

Geothermal As enriches stream water and sediments in the Singe and Yarlung Tsangpos

Superlative enrichment of As in alkaline salt lakes requires further study

Fig. 1. Arsenic concentrations in the water, soil and sediment and of Yarlung Tsangpo (right panels) Singe Tsangpo (left panels) drainages, superimposed on digital elevation maps. Locations of salt lakes and hot springs sampled by this study are indicated by rectangles and triangles, respectively. The locations of hot springs from previous studies by Zhang et al. (1982) and Zhao et al. (2002) are indicated by the hot spring symbols. The Indus and Brahmaputra river drainages are shown in the top panel.

Fig. 2.
Histogram of As concentration in various types of water from Tibet

Fig. 3. Piper diagrams for water from Tibet. The colors indicate As concentration range for each water sample. The symbols indicate various types of water. Water samples with cation and anion charge difference exceeding $\pm 25\%$ were excluded.

Fig. 4.
Histogram of arsenic concentrations in the Tibetan stream sediments and soils.

Fig. 5. Correlation between [As] and [K+Na] in water samples from Tibet. Both axes used log scale.

Fig.6.
Correlation between As concentrations of stream water and sediment.

Chemical Composition of Water

Table 1

Sample	Location	Latitude N	Longitude E	Elevation m	pH	DO mg/L	EC µS/cm	T °C	As µg/L	HCO ₃ ⁻ mg/L	CO ₃ ²⁻ mg/L	Cl ⁻ mg/L	SO ₄ ²⁻ mg/L	NO ₃ ⁻ mg/L	Anion meq/L	K ⁺ mg/L	Na ⁺ mg/L	Ca ²⁺ mg/L	Mg ²⁺ mg/L	Cation meq/L
Yarlung Tsangpo (Y.T.)																				
TW-1	Y.T., Quxu	29°21'05.4"	90°43'54.3"	3587	7	12.02	200	19.1	8.6	109.2		6.5	29.0	0.32	2.6	3.9	11.3	31.1	6.0	2.6
TW-2	Y.T., Nyemo	29°20'15.2"	90°16'06.0"	3665	7	12.45	199	18.1	12.3	116.5		5.5	28.9	0.19	2.7	4.0	11.3	30.1	6.0	2.6
TW-3	Y.T., branch at Rinbung	29°17'35.1"	89°47'55.6"	3745	7	13.25	329	14.6	2.9	239.2		28.4	102.9	0.05	6.9	6.2	17.5	54.8	8.5	4.4
TW-4	Y.T., branch at Jeding	29°12'45.4"	88°22'09.7"	3896	7	8.69	108	11.9	2.3	115.3		10.2	45.4	0.61	3.1	2.6	8.2	35.7	6.5	2.7
TW-7	Y.T., branch at Lhaze	29°05'22.5"	87°37'33.2"	4019	7	13.33	168	13.2	2.7	99.5		0.5	50.8	0.38	2.7	2.2	4.5	32.4	7.5	2.5
TW-9	Y.T., branch at 14 Road	29°30'21.9"	86°27'53.7"	4657	7	11.40	166	12.0	83.2	92.7		3.4	39.6	0.13	2.4	3.7	13.6	28.2	4.5	2.5
TW-10	Y.T., Saga	29°19'12.1"	85°13'22.7"	4473	7	11.40	207	11.6	37.1			7.8	42.5	0.19	1.1	5.1	13.2	38.6	7.0	3.2
TW-11	Y.T., branch at Zhongba	29°42'42.5"	84°04'10.9"	4574	7	10.16	195	14.8	20.2	142.2		9.7	12.2	0.20	2.9	4.8	11.9	34.6	6.0	2.9
TW-12	Y.T., upstream at Zhongba	29°45'40.7"	83°56'28.1"	4587	7	12.75	131	15.6	37.7	90.9		4.2	13.5	0.03	1.9	4.4	7.6	21.6	4.7	1.9
TW-66	Y.T., at Xigaze	29°19'09.4"	88°51'00.8"	3842	7	9.96	159	15.0	11.7	105.6		5.6	38.7	0.09	2.7	3.2	7.7	29.9	5.2	2.3
TW-67	Nianchu River(N.R.), at Xigaze	29°15'58.9"	88°53'55.0"	3836	7	11.63	271	14.5	5.7	166.0		4.1	67.3	0.24	4.2	3.4	9.6	49.8	11.5	3.9
TW-68	N.R., branch at Xigaze	29°13'16.9"	88°53'54.7"	3866	7	8.36	269	16.9	4.2	216.6		2.5	38.8	0.24	4.4	2.2	10.5	47.7	11.3	3.8
TW-69	N.R., branch at Xialushi	29°09'26.9"	89°00'03.7"	3880	7	11.66	187	17.3	3.6	91.5		0.8	51.7	0.09	2.6	1.6	5.1	36.0	5.8	2.5
TW-70	N.R., branch at Qionggrang	29°10'07.8"	89°03'23.7"	3867	7	8.53	250	20.6	3.0	119.6		0.5	57.2	0.31	3.2	1.4	5.1	39.2	12.1	3.2
TW-71	N.R., 6.28km to Bainang	29°09'23.5"	89°14'07.1"	3885	7	12.44	274	13.8	3.5	153.2		3.5	86.7	0.39	4.4	3.4	9.1	50.5	11.6	4.0
TW-72	N.R., branch at Bainang	29°05'12.1"	89°16'50.7"	3913	7	8.15	347	18.9	3.4	173.9		17.5	69.4	0.55	4.8	6.5	14.7	52.0	8.4	4.1
TW-73	N.R., branch at Zijin	28°56'40.0"	89°32'41.9"	3992	7	12.14	325	15.1	3.8	189.8		7.2	68.3	0.48	4.7	4.4	12.3	62.7	12.3	4.8
TW-74	N.R., branch at Nanni,	28°50'16.7"	89°39'10.6"	4055	7	8.78	280	18.0	4.1	156.8		7.0	65.3	0.32	4.1	4.9	10.8	54.5	10.1	4.2
TW-75	N.R., branch at east Shaogang	28°40'52.6"	89°38'37.8"	4142	7	12.76	309	14.8	4.9	139.7		8.3	93.4	0.21	4.5	6.0	11.3	61.1	10.6	4.6
TW-76	N.R., branch at west Shaogang	28°41'22.9"	89°37'57.2"	4160	7	9.43	258	15.2	3.5	141.6		4.1	67.1	0.86	3.8	2.7	8.6	52.6	10.1	3.9
TW-77	N.R., at Gyangze Bridge	28°54'23.9"	89°35'59.1"	4018	7	5.93	295	16.7	3.4	152.5		3.4	90.4	0.44	4.5	3.3	8.2	50.3	12.2	4.0
TW-78	N.R., branch at Dazi	29°04'11.2"	89°26'22.6"	3940	7	7.38	269	23.2	2.8	189.8		1.5	53.5	0.40	4.3	2.3	7.3	45.6	7.6	3.3
TW-79	N.R., branch at Gyangze	28°54'24.6"	89°37'00.1"	4034	7	8.70	323	20.9	4.5	126.3		1.4	102.1	0.20	4.2	3.1	7.4	48.0	13.3	3.9
TW-80	N.R., at Yuxi	28°50'29.3"	89°46'07.3"	4116	7	10.32	252	10.8	3.8	143.4		1.0	121.4	0.37	4.9	2.1	5.6	34.0	9.8	2.8
TW-81	N.R., branch at Longma	28°51'40.1"	89°56'32.3"	4308	7	14.13	276	11.0	6.7	109.8		0.3	121.0	0.32	4.3	1.9	7.2	63.7	8.9	4.3
TW-82	N.R., upstream at Relong	28°49'34.0"	90°02'49.7"	4444	7	9.98	255	10.7	4.7	107.4		0.2	127.0	0.18	4.4	3.5	3.9	62.1	7.7	4.0
TW-84	Lasha River(L.R.), downstream	29°27'58.1"	90°55'45.9"	3624	7	9.48	96	14.7	4.6	67.1		1.7	16.5	0.16	1.5	2.3	4.3	16.7	3.3	1.4

Sample	Location	Latitude N	Longitude E	Elevation m	pH	DO mg/L	EC µS/cm	T °C	As µg/L	HCO ₃ ⁻ mg/L	CO ₃ ²⁻ mg/L	Cl ⁻ mg/L	SO ₄ ²⁻ mg/L	NO ₃ ⁻ mg/L	Anion meq/L	K ⁺ mg/L	Na ⁺ mg/L	Ca ²⁺ mg/L	Mg ²⁺ mg/L	Cation meq/L
TW-85	L.R., branch at Doilungdeqen	29°57'45.4"	90°43'05.5"	3978	7	13.75	73	14.4	2.2	47.6		0.7	13.7	0.33	1.1	1.4	2.1	14.2	1.7	1.0
TW-86	L.R., Duilongqu,	30°00'35.5"	90°38'33.3"	4032	7	10.82	70	13.0	29.8	45.2		1.8	31.0	0.12	1.4	3.5	8.3	12.3	1.4	1.2
TW-88	L.R., Duilongqu,	30°08'14.8"	90°32'40.6"	4356	7	13.43	91	12.5	2.0	54.3		10.8	9.0	0.17	1.4	6.9	9.9	12.8	1.4	1.4
Singe Tsangpo (S.T.)																				
TW-17	Gar Tsangpo (G.T.),upstream	31°27'52.0"	80°28'34.0"	4618	7	11.31	52	8.9	5.9	34.2		1.3	11.1	0.16	0.8	1.2	3.2	10.6	2.3	0.9
TW-18	G.T., at 1170km of 219 Road	31°39'33.4"	80°19'06.2"	4471	7	10.08	109	11.7	11.5	82.4		3.6	25.0	0.18	2.0	2.4	7.0	15.0	7.2	1.7
TW-19	G.T.,branch at Naburu	31°53'57.3"	80°09'19.6"	4401	7	15.47	117	9.7	6.1	75.7		1.2	32.1	0.22	1.9	2.9	4.1	26.1	3.2	1.8
TW-20	G.T.,at 219 Road cross it	32°00'47.6"	80°06'40.6"	4327	7	10.23	117	11.8	17.7	89.7		5.0	25.6	0.24	2.1	2.6	7.6	18.0	5.9	1.8
TW-21	G.T., branch at Shazidaban	32°16'35.7"	80°02'26.1"	4370	7	12.90	150	13.6	5.6			5.0	32.5	0.12	0.8	2.4	3.3	31.2	4.9	2.2
TW-22	S.T., ditch at south of Gar	32°25'36.2"	80°02'02.9"	4280	7	8.85	154	17.9	160.0	170.8		7.8	29.1	2.54	3.7	4.8	14.4	30.4	4.8	2.7
TW-23	G.T.,downstream at Luma	32°24'18.4"	79°45'02.3"	4238	7	16.50	83	9.6	17.1	111.1		2.6	12.8	0.17	2.2	2.8	7.4	15.7	4.1	1.5
TW-24	S.T., at Xaxigang	32°33'15.6"	79°38'07.2"	4232	7	9.31	149	14.5	23.6	105.6		6.6	21.6	0.25	2.4	4.0	10.4	20.0	6.4	2.1
TW-25	S.T., downstream of Gar	32°27'49.7"	79°58'31.0"	4264	7	14.88	294	14.4	129.5			18.0	54.0	0.11	1.6	8.9	25.2	38.0	11.1	4.1
TW-26	S.T., branch from Zoco	32°26'09.2"	80°12'07.8"	4383	7	9.80	193	15.6	187.9	117.2		8.7	28.0	0.19	2.8	4.3	22.0	30.4	4.5	3.0
TW-27	S.T., subbranch from Zoco	32°24'29.1"	80°14'19.6"	4422	7	14.24	153	13.8	4.7	81.2		2.0	43.4	0.45	2.3	1.8	2.9	31.0	4.8	2.1
TW-28	S.T., branch at Langjiu	32°21'46.3"	80°21'20.5"	4496	7	10.26	179	15.3	178.7	115.3		6.1	22.2	0.11	2.5	4.9	13.2	29.6	4.3	2.5
TW-30	S.T., branch from Zoco	32°17'51.6"	80°26'38.0"	4582	7	13.62	111	11.4	12.5	88.5		1.6	17.1	0.10	1.9	1.8	4.7	24.2	3.3	1.7
TW-31	S.T., branch from Zoco	32°12'50.4"	80°26'00.9"	4695	7	10.12	119	10.0	6.8	108.0		2.2	11.6	0.02	2.1	2.8	8.8	24.2	5.4	2.1
TW-33	S.T., ditch at south of Gar	32°29'22.2"	80°05'25.0"	4298	7	16.32	240	12.6	54.4	170.8		15.0	30.8		3.9	6.7	20.7	31.1	10.9	3.5
TW-34	S.T., at Gar county	32°30'18.2"	80°06'56.8"	4294	7	15.18	243	14.0	41.0	182.4		16.0	31.2	0.11	4.1	7.1	21.9	31.2	11.6	3.7
TW-35	S.T., at Gar reservior	32°30'50.9"	80°08'41.3"	4300	7	7.50	262	15.7	35.8	176.3		13.1	27.3	0.12	3.8	7.3	21.9	30.1	11.6	3.6
TW-36	S.T., branch of Gar reservior	32°34'46.2"	80°11'51.9"	4389	7	13.96	124	12.4	3.2	119.6		5.9	17.5	0.01	2.5	3.0	3.5	23.7	5.7	1.9
TW-37	S.T., branch at 70km to Gegyai	32°35'02.7"	80°23'57.1"	4428	7	6.89	119	24.0	2.7	82.4		4.8	6.4		1.6	2.3	2.0	18.2	3.7	1.4
TW-38	S.T., branch at 62km to Gegyai	32°33'04.0"	80°28'55.4"	4389	7	9.00	395	18.5	3.7	295.9		25.7	62.2	0.60	6.9	6.7	26.1	28.5	30.4	5.2
TW-39	S.T., at downstream of Gegyai	32°32'44.5"	80°29'41.8"	4385	7	10.14	225	18.5	76.7			9.8	26.5	0.07	0.8	6.2	16.7	29.6	5.9	2.8
TW-40	S.T. at downstream of Gegyai	32°32'36.6"	80°41'27.1"	4426	7	10.13	225	17.7	78.5	150.7		8.5	25.3	0.09	3.2	6.3	17.3	30.7	6.0	2.9
TW-41	S.T., branch at 26km to Gegyai	32°26'23.8"	80°51'04.9"	4463	7	5.82	239	18.7	56.7	162.3		14.7	30.3	0.02	3.7	8.4	17.7	31.7	5.9	3.0
TW-42	S.T., at downstream of Gegyai	32°23'44.0"	81°04'34.3"	4509	7	25.80	178	15.5	62.4	125.1		5.2	17.2	0.07	2.6	5.1	13.2	28.8	5.1	2.6
TW-43	S.T., at upstream of Gegyai	32°21'03.8"	81°10'46.2"	4537	7	13.90	164	9.6	148.8	131.2		6.2	23.0	0.05	2.8	5.8	15.0	27.3	4.8	2.6
TW-44	S.T., at Bongha reservior	32°08'29.8"	81°16'56.0"	4629	7	8.63	173	15.0	150.4	111.1		6.1	23.9	0.07	2.5	5.6	12.7	25.0	4.4	2.3
TW-45	S.T., branch at Lergar	32°10'44.7"	81°17'00.4"	4608	7	12.73	151	14.0	3.7	136.7		3.5	5.0	0.09	2.4	4.1	9.0	28.0	4.8	2.3

Sample	Location	Latitude N	Longitude E	Elevation m	pH	DO mg/L	EC µS/cm	T °C	As µg/L	HCO ₃ ⁻ mg/L	CO ₃ ²⁻ mg/L	Cl ⁻ mg/L	SO ₄ ²⁻ mg/L	NO ₃ ⁻ mg/L	Anion meq/L	K ⁺ mg/L	Na ⁺ mg/L	Ca ²⁺ mg/L	Mg ²⁺ mg/L	Cation meq/L
TW-47	S.T., upstream at Nagnozu	31°48'21.7"	81°48'13.9"	4765	7	9.85	167	6.5	252.2	145.2		11.7	17.5	0.16	3.1	5.1	17.1	22.1	6.0	2.5
TW-48	S.T., upstream at Ruojiaole	31°43'57.9"	81°45'55.8"	4810	7	22.10	176	15.8	77.3	139.7		5.1	15.1	0.10	2.8	4.7	10.1	22.4	7.7	2.3
TW-49	S.T., upstream branch at Lago	31°32'53.1"	81°47'17.7"	5021	7	8.27	86	13.0	3.1	62.9		0.8	13.9	0.19	1.3	2.3	2.9	17.0	2.5	1.2
TW-50	S.T., upstream branch at Lago	31°27'32.7"	81°38'40.7"	5215	7	13.26	61	12.1	2.7	64.1		1.4	2.5	0.14	1.1	2.8	4.7	12.0	1.7	1.0
TW-51	S.T., upstream branch at Keliba	31°23'47.8"	81°30'54.5"	5096	7	7.68	109	13.3	20.7	71.4		2.0	12.5	0.17	1.5	3.9	9.2	20.3	4.0	1.8
TW-52	S.T., branch at Laquhe Bridge	31°24'20.7"	81°28'17.4"	5075	7	12.97	52	12.2	2.4	41.5		0.5	9.4	0.14	0.9	1.8	1.7	10.8	1.4	0.8
TW-53	S.T., branch at Saize Bridge	31°25'45.8"	81°25'18.3"	5045	7	10.76	60	10.4	3.1	51.3		0.4	12.2	0.17	1.1	1.4	1.1	13.7	1.8	0.9
TW-54	S.T., subbranch at Keliba	31°27'45.3"	81°21'02.9"	4997	7	13.42	107	9.5	4.0	72.6		0.5	32.9	0.00	1.9	1.6	1.4	23.7	4.1	1.6
TW-55	S.T., branch at Niremubuduhe	31°28'36.1"	81°16'15.6"	4971	7	9.80	54	9.0	61.7	47.0		1.2	6.8	0.04	0.9	1.8	4.4	12.5	1.5	1.0
TW-56	S.T., subbranch at Meibuhe	31°46'17.1"	81°06'15.0"	4809	7	16.78	100	3.5	234.1	95.2		3.0	13.4	0.04	1.9	3.0	9.4	24.5	3.6	2.0
TW-57	S.T., upstream at Remajiang	31°44'33.0"	81°09'42.7"	4790	7	11.70	76	7.9	47.9	76.9		1.4	13.1	0.10	1.6	2.4	5.8	14.2	2.4	1.2
TW-58	S.T., upstream at Mangla	31°52'21.0"	81°13'23.7"	4734	9	11.70	94	9.8	82.0			2.4	15.7	0.09	0.4	2.8	7.9	19.5	2.9	1.6
Hot Spring																				
TW-87	4# well of Yangbajain	30°5'11.09"	90°32'17.0"	4300	8	5.01	1547	boiled	3843.0	25.0		820.0	597.0	431.90	42.9	95.1	456.4	4.0	0.0	22.5
TW-14	Jiushi beside Mapam Yumco	30°46'00.9"	81°21'46.9"	4598	8	2.50	3310	boiled	5985.0	1690.8		611.2	238.2	0.19	49.9	78.2	1052.3	16.7	2.3	48.8
Freshwater lake																				
TW-13	Mapam Yumco	30°45'06.7"	81°22'27.7"	4575	7	15.66	483	21.1	305.6	233.1		22.1	39.6	0.09	5.3	6.8	50.1	19.1	30.1	5.8
TW-83	Yangzuoyongcuo	29°01'19.2"	90°23'56.0"	4509	7	13.69	283	15.9	20.6	98.2		1.5	115.0	0.10	4.0	4.5	6.9	54.8	9.9	4.0
Salt lake																				
TW-8	Langcuo	29°12'44.3"	87°22'59.3"	4296	7	9.82	2190	18.6	39.7	712.7	705.7	173.8	22.8	0.00	40.6	33.4	800.2	4.7	76.9	42.2
TW-59	Nierco in Gegyai	32°14'56.6"	82°12'40.8"	4422	8	0.00	14490	16.1	769.0	570.5	140.4	545.1	16527.0	1.45	373.7	790.3	2755.2	228	3534	442.3
TW-60	Biruzeco in Gegyai	32°11'2.78"	83°29'59.6"		9				10626.0	866.4	1195.0	7561.8	12898.0		536.1	1076	9868	12.5	1134	550.6
TW-61	Dongco in Gerze	32°09'40.5"	84°41'57.3"	4398	9	0.01	55900	15.1	713.9	505.2	1405.0	13665.0	37566.0	5.64	1223.3	6223	27103	25.8	2401	1536.9
TW-62	saml Dawaco in Coqen	31°13'51.5"	85°04'52.2"	4636	9	9.87	4470	25.1	259.7	202.0	873.7	23.0	45.0	0.09	34.0	149.4	1276.1	16.7	295.7	84.5
TW-64	Garingco in Coqen	30°27'26.0"	85°12'07.5"	4859	9	11.85	3710	15.9	60.8	435.7	1002.0	650.6	433.3		67.9	130.8	1377.6	10.6	37.6	66.9
TW-65	Daggyaico in Saga	29°56'01.8"	85°42'48.5"	5160	9				2800.0	634.6	760.9	193.8	859.4		59.1	88.0	1232.6	10.6	45.6	60.1
Groundwater																				
TW-46	well, at Xungba	32°02'25.9"	81°55'24.2"	4595	7	9.85	215	3.7	194.5	162.3		22.7	21.5	0.14	3.8	6.2	30.5	37.1	6.9	3.9
Others																				
TW-15	Langqin Tsangpo, at Moince	31°08'41.8"	80°53'57.1"	4626	7	14.03	55	5.4	4.9	37.2					0.6	0.9	3.4	12.5	2.3	1.0
TW-16	Langqin Tsangpo, at Moince	31°10'55.6"	80°45'27.5"	4418	7	11.31	95	9.5	7.1	79.9		0.6	10.3	0.19	1.5	2.0	7.6	18.5	4.0	1.6

Sample	Location	Latitude N	Longitude E	Elevation m	pH	DO mg/L	EC µS/cm	T °C	As µg/L	HCO ₃ ⁻ mg/L	CO ₃ ²⁻ mg/L	Cl ⁻ mg/L	SO ₄ ²⁻ mg/L	NO ₃ ⁻ mg/L	Anion meq/L	K ⁺ mg/L	Na ⁺ mg/L	Ca ²⁺ mg/L	Mg ²⁺ mg/L	Cation meq/L
TW-63	Cuoqin Tsangpo,	30°57'37.3"	85°07'28.0"	4679	7	9.14	128	14.8	5.7	65.3		32.4	91.2	2.34	3.9	3.9	9.6	21.6	3.7	1.9
TW-89	Nagqu River, upstream at Ando	32°17'01.7"	91°42'45.7"	4720	7	9.13	425	8.8	5.9	248.9		20.7	153.0	0.31	7.9	8.2	33.3	79.1	27.3	7.9

Arsenic Concentrations in Stream Sediments, Soils and Selected Rocks

Site	Latitude	Longitude	Elevation	Sediment			Soil			Rock					
				As mg/kg	Description		As mg/kg	Description		As mg/kg	Description				
Yarlung Tsangpo (Y.T.)															
T1	29°21'05.4"	90°43'54.3"	3587	30	Silty										
T2	29°20'15.2"	90°16'06.0"	3665	30	Silty				6.0	Sandy soil					
T3	29°17'35.1"	89°47'55.6"	3745	36	Clayey				25	Clay soil					
T4	29°12'45.4"	88°22'09.7"	3896	28	Muddy				21	Yellow soil					
T5	29°08'48.6"	88°09'41.7"	4082						ND	Purple soil					
T7	29°05'22.5"	87°37'33.2"	4019	35	Silty				28	Yellow soil	37	46.3	0.02	Phyllite with amnochrysos	
T9	29°30'21.9"	86°27'53.7"	4657	50	Muddy	61.1			24	Meadow soil					
T10-1	29°19'12.1"	85°13'22.7"	4473	35	Silty				28	Diluvial soil					
T11	29°42'42.5"	84°04'10.9"	4574	29	Silty										
T12	29°45'40.7"	83°56'28.1"	4587	22	Silty	38.1			ND	Diluvial soil					
T66	29°19'09.4"	88°51'00.8"	3842	26	Silty				ND	Colluvial soil					
T67	29°15'58.9"	88°53'55.0"	3836	24	Silty										
T68	29°13'16.9"	88°53'54.7"	3866	ND	Muddy	16.4									
T69	29°09'26.9"	89°00'03.7"	3880	36	Muddy				ND	Sandy soil					
T70	29°10'07.8"	89°03'23.7"	3867	24	Muddy				30	Yellow soil					
T71	29°09'23.5"	89°14'07.1"	3885	26	Muddy				17	Colluvial soil					
T72	29°05'12.1"	89°16'50.7"	3913	21	Muddy										
T73	28°56'40.0"	89°32'41.9"	3992	34	Silty										
T74	28°50'16.7"	89°39'10.6"	4055	30	Silty				173	Colluvial soil	36	48.2	0.10	Shale	
T75	28°40'52.6"	89°38'37.8"	4142	ND	Silty	23.0			ND	Sandy soil					
T76	28°41'22.9"	89°37'57.2"	4160	20	Silty				48	Colluvial soil					
T78	29°04'11.2"	89°26'22.6"	3940	21	Silty				ND	Black soil					
T79	28°54'24.6"	89°37'00.1"	4034	20	Silty										
T80	28°50'29.3"	89°46'07.3"	4116	ND	Silty	33.8			ND	Colluvial soil					
T81	28°51'40.1"	89°56'32.3"	4308	ND	Silty	21.8			32	Colluvial soil					
T82	28°49'34.0"	90°02'49.7"	4444	38	Silty				26	Colluvial soil					

Site	Latitude	Longitude	Elevation				Sediment				Soil				Rock			
			N	E	m		XRF	As mg/kg	Digest	Leach	AFS	Description	XRF	As mg/kg	Digest	Leach	AFS	Description
T84	29°27'58.1"	90°55'45.9"			3624		34					Silty						
T85	29°57'45.4"	90°43'05.5"			3978		36		7.8			Silty	ND		14.5			Purple soil
T86	30°00'35.5"	90°38'33.3"			4032								28		18.4			Red soil
T88	30°08'14.8"	90°32'40.6"			4356		ND		1.5			Sandy						
T20	32°00'47.6"	80°06'40.6"			4327		36					Silty	25		36.0			Yellow soil
T21	32°16'35.7"	80°02'26.1"			4370		12					Sandy	39					Yellow soil
T22	32°25'36.2"	80°02'02.9"			4280		38					Silty	79					Clayey
T23	32°24'18.4"	79°45'02.3"			4238		34					Silty						
T24	32°33'15.6"	79°38'07.2"			4232		ND		17.9			Sandy						
T25	32°27'49.7"	79°58'31.0"			4264		38			1.3		Silty	38					Diluvial soil
T26	32°26'09.2"	80°12'07.8"			4383		54			18.5		Silty	ND		17.3			Red soil
T27-1	32°24'29.1"	80°14'19.6"			4422		ND		12.2			Silty	32					Yellow soil
T27-2																		
T28	32°21'46.3"	80°21'20.5"			4496		50			16.6		Silty	65					Yellow soil
T29	32°22'04.9"	80°23'16.1"			4520								35					Grey soil
T30	32°17'51.6"	80°26'38.0"			4582		57					Silty						
T31	32°12'50.4"	80°26'00.9"			4695		36					Silty	96					Yellow soil
T32	32°23'36.0"	80°15'15.4"			4447								ND		21.7			Colluvial soil
T34	32°30'18.2"	80°06'56.8"			4294		48			6.3		Silty						
T35	32°30'50.9"	80°08'41.3"			4300		22					Sandy	50					Yellow soil
T36	32°34'46.2"	80°11'51.9"			4389		21					Sandy	ND		18.3			Sandy soil
T37	32°35'02.7"	80°23'57.1"			4428		20					Sandy						
T38	32°33'04.0"	80°28'55.4"			4389		21					Sandy	30					Colluvial soil
T39	32°32'44.5"	80°29'41.8"			4385		80			23.9		Silty						
T40-1	32°32'36.6"	80°41'27.1"			4426		41					Silty	ND		21.9			Colluvial soil
T40-2																		
T40-3																		
T41-1	32°26'23.8"	80°51'04.9"			4463		29					Muddy	55					Colluvial soil
T41-2																		

Site	Latitude	Longitude	Elevation m	Sediment			Soil			Rock		
				As mg/kg	Description		As mg/kg	Description		As mg/kg	Description	
	N	E		XRF	Digest	Leach	AFS	XRF	Digest	Leach	AFS	XRF
T42	32°23'44.0"	81°04'34.3"	4509	21				93	118.9	3.43	Colluvial soil	
T43	32°21'03.8"	81°10'46.2"	4537	33			4.1	54			Diluvial soil	
T44	32°08'29.8"	81°16'56.0"	4629	18				33			Diluvial soil	
T45	32°10'44.7"	81°17'00.4"	4608	ND		13.7						
T47-1	31°48'21.7"	81°48'13.9"	4765	91	Muddy		32.5	ND	27.6		Silty soil	ND
T47-3										20.5	Basalt	
T48	31°43'57.9"	81°45'55.8"	4810	47	Muddy		4.0					
T49	31°32'53.1"	81°47'17.7"	5021	ND	Silty	20.9		78			Colluvial soil	
T50	31°27'32.7"	81°38'40.7"	5215	ND	Muddy	16.7		17			Silty soil	
T51	31°23'47.8"	81°30'54.5"	5096	21	Muddy			22			Silty soil	
T52	31°24'20.7"	81°28'17.4"	5075	20	Sandy	24.7						
T53	31°25'45.8"	81°25'18.3"	5045	25	Silty			79	1.31		Diluvial soil	
T54	31°27'45.3"	81°21'02.9"	4997	67	Silty			42	68.6		Colluvial soil	
T55	31°28'36.1"	81°16'15.6"	4971	30	Silty							
T56	31°46'17.1"	81°06'15.0"	4809	225	Silty	227.1	78.0					
T57	31°44'33.0"	81°09'42.7"	4790					36	36.5		Colluvial soil	
T58	31°52'21.0"	81°13'23.7"	4734	139	Silty	42.3		ND	15.8		Silty soil	
Hot Spring												
T87	30°5'11.09"	90°32'17.0"	4300					36			Clayey soil	
T14	30°46'00.9"	81°21'46.9"	4598		muddy	218.9						
Freshwater lake												
T13	30°45'06.7"	81°22'27.7"	4575	73	Grey silty	66.8		46			Grey soil	
T83	29°01'19.2"	90°23'56.0"	4509	75	Grey silty	75.2		139	245.5	0.63	Colluvial soil	
Salt Lake												
T8-1	29°12'44.3"	87°22'59.3"	4296	26	Black silty	33.6		47			Yellow soil	28
T8-2										34.4	Greenyellow shale	
T59	32°14'56.6"	82°12'40.8"	4422	66	Grey silty							
T61	32°09'40.5"	84°41'57.3"	4398	97	Grey silty			47			Colluvial soil	
T62	31°13'51.5"	85°04'52.2"	4636	ND	Black silty	6.5		24			Sandy soil	

Site	Latitude	Longitude	Elevation	Sediment			Soil			Rock						
				XRF	As mg/kg Digest Leach	Description	XRF	As mg/kg Digest Leach	Description	XRF	As mg/kg Digest Leach	Description				
T64	30°27'26.0"	85°12'07.5"	4859													
T65	29°56'01.8"	85°42'48.5"	5160	196		Grey silty	ND	34.8	Colluvial soil							
Groundwater																
T46	32°02'25.9"	81°55'24.2"	4595				60		Diluvial soil							
Others																
T15	31°08'41.8"	80°53'57.1"	4626				36		Yellow soil							
T16	31°10'55.6"	80°45'27.5"	4418	18	12.2	Yellow silty	84		Diluvial soil							
T63	30°57'37.3"	85°07'28.0"	4679	25		Muddy	25		Colluvial soil							
T89	32°17'01.7"	91°42'45.7"	4720	ND	20.6	Silty	29		Red soil							
T90-1*	32°18'09.4"	91°44'07.1"	4736				49		Red soil 170-185cm							
T90-3							96	0.04	130-150cm							
T91	32°18'08.0"	91°44'06.6"	4723				36		Red soil							
T92	31°25'28.0"	91°58'49.0"	4486	106		Muddy	18		Silty soil							

ND = not detected, < 10 mg/kg