島根大学地球資源環境学研究報告　35, 1～6 ページ（2016 年 12 月）
Geoscience Rept. Shimane Univ., 35, p.1～6（2016）

Article

Geochemical examination of gold mining waste at Nzunguni in central Tanzania

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Abstract

Waste of gold mining at Nzunguni, central Tanzania was analyzed by X-ray fluorescence analysis (XRF) using the press powder method to evaluate environmental impact to the surrounding area. Gold (Aurum) occurred within quartz vein (reef) in the host granitic rock, which was separated by crushing the quartz vein and concentrated by gravity separation process on the slope. Mercury (Hg) was used for more concentration, but this process was not common in this site. Samples were collected at the gravity separation site, which were light yellowish gray silt. Aurum was detected in all 11 samples, even though only by qualitative analysis. This is because Au bearing standard powder was not obtained yet. Mercury was not detected for two samples which were treated with Hg at the site. Copper concentrations show variation from 500 to 1200 ppm suggesting relation of Au or Au bearing minerals. High Fe_2O_3 concentrations (10-19 wt%) in waste materials may be mainly derived from secondary formed iron oxide in cracks of quartz veins. Zn, Pb, Cr, Ni and V did not show high concentrations indicating absence of heavy minerals in the veins. Stream sediments did not show deviation of both Cu and Hg, suggesting negligible effects of contamination from the smelting process.

Keywords: geochemistry, gold mining, waste, mercury, Tanzania

Introduction

Mining industries are important economic factors that contribute to the level of livelihood, however, they also have significant environmental effects (Ikingura *et al*., 1997). Human exposure to mercury (Hg) in artisanal gold mining of the world can harm human health condition and its risk is well known (Kristensen *et al*., 2014). Emission of Hg into the air has become a global issue even though the activities are small-scale gold mining industries in developing countries (Lacerda, 2003). The Minamata convention in 2013 stipulated action for reduction and feasible elimination of Hg use in artisanal gold mining (Spiegel *et al*., 2015). In Tanzania, 0.5-1.5 million small-scale artisanal gold minings have been operated and gold-extracting chemicals and their waste disposal were reported to have caused severe hazard to humans and surrounding areas (Bose-O'Reilly *et al*., 2010; Taylor *et al*., 2005; Van Straaten, 2000; Charles *et al*., 2014). The present study described geochemical compositions of waste materials of the mining site to evaluate their potential environmental impact. In addition soil, stream sediments and host rock compositions were analyzed for comparison and evaluation of back ground level of heavy metals.

Study Area

Small-scale artisanal gold mining is common in Tanzania, especially in southwest of Lake Victoria (Fig. 1). Other activities are scattered in western and central Tanzania (Fig. 1). This study focused on the Nzunguni artisanal mining site located 12 km east of Dodoma, central Tanzania (Fig. 1). The central part of Tanzania is mainly characterized by a flat geography with some rocky hills. Dodoman area forms smooth hills and ridges. Geologically the area belongs to the Tanzania shield composed of migmatites and granitic complexes of Archaean age (Williams, 1936; Wade *et al*., 1938; Fozzard, 1962a, b). The Dodoman gneisses (2500 Ma) and the post-Nyanzian intrusive granites (1870 Ma) have been described (Wendt, 1972; Bell and Dodson, 1981).

Barth *et al*. (1996) has reported the geology of the Nzunguni mining and described the geology and mineralogy of the site

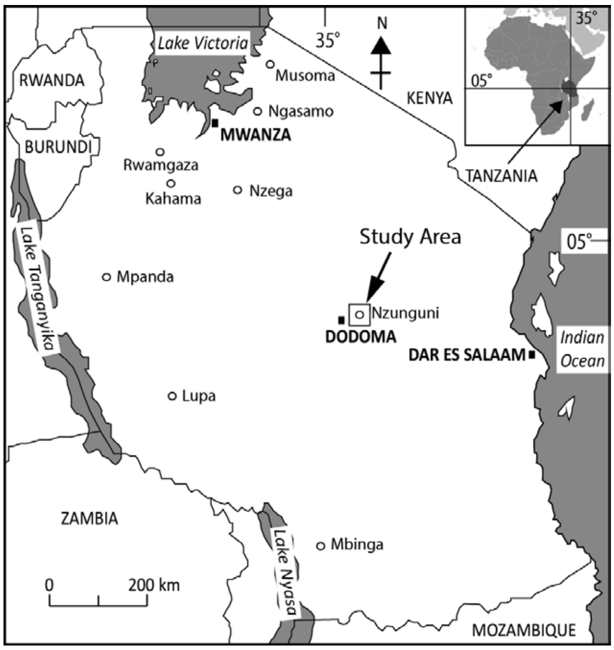

Fig. 1 Map of the Nzunguni gold mining site (Madengi Hill) in Tanzania, showing the study area. Other gold mining sites are also indicated in this map.

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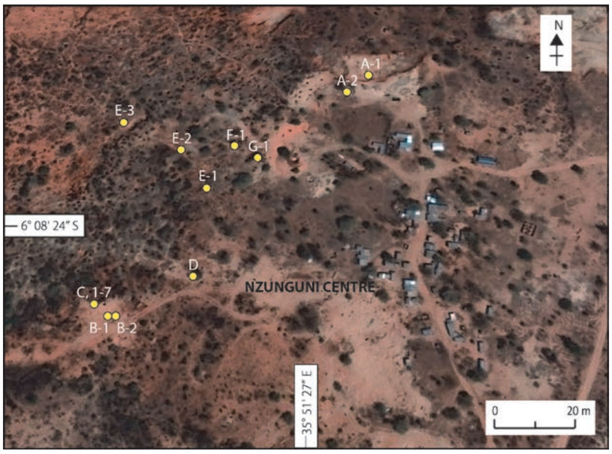

Fig. 2 Map showing features of the Nzunguni gold mining site in central Tanzania and sampling sites (map used from Google image).

as follows: Beginning of Madengi Hill artisanal gold mining (Fig. 2) was recorded in 1932 after the discovery of eluvial and alluvial placers. The "gold rush" came to Madengi Hill, where 10,000 people inhabited in early 1990th. After decline of production of gold, the local name "Nzunguni" was settled at this hill. According to Barth *et al*. (1996), 6,000 people were living.

The geology of the gold prospect comprised mainly of granite and "schistose quartz-sericite schist" (mylonitic schists), accompanied by some roof pendant of green metadolerite. The granite shows gray color and is coarse-grained with dark clots consisting of hornblende, biotite, sillimanite and sphene. Rocks bearing gold mineralization were sheared, crushed and saucerization with trend of NE-SW dipping 60°NW. The shear zone was stained with iron and manganese oxides. Gold and auriferous rocks occurred within quartz veins (reef). For this small-scale artisanal mining, shafts were commonly constructed to approach to underground ore materials (Fig. 3).

Native gold appears as sharp-edged to elongated grains, usually 50-400 mm in size (Barth *et al*., 1996). Following description was given by Barth *et al*. (1996). Assay of samples yielded gold of 2.3 g/t in average (the highest values ranging 23-55 g/t). Paragenetic ore mineral is galena embedded in a quartz matrix. Microprobe analysis showed silver contents of 3-20 % (average of 42 grains) and an outlier value of 59 % Ag, copper values were constant at about 0.2 %. The grade of the crude ore is 150 g/t (average of 3 bulk samples); 33 g/t were produced from single mineral aggregates of hematite; a sample of metadolerite from the waste dump yielded 27 g/t.

Extraction and Processing in mining site

The Nzunguni gold mining is a typical small-scale mining, for the hoisting system at shaft has been adopted for taking out of ore material. Two people were holding hands on rotating by applying a force (Fig. 3). Due to the manual operation of the shaft, the potential depth of safety was limited within 30 m. After removing wood fragments and roots, quartz veins (Fig. 4A) were packed into bags for temporary storage (Fig. 4B). Crushing ore material on the hard rocks by steel made hammers was usually done by women (Fig. 4B). Crushing was observed at three sites where it was engaged in same manner in 2015. After crushing and drying, materials are fed into ball mill grinder using tungsten carbide balls (Fig. 4B) to process them into finer powder (Fig. 4C). The next stage was gravity separation carried out by hydraulic washing on wood made slope about 45 degrees and followed by more gentle slope, both of which were covered by straw mat (Fig. 4D). Heavy material presumably yielding gold was retained on the mat (Fig. 4E). Aurum amalgamation using mercury and panning to refine gold was partly conducted at the site C in Fig. 2. For sluicing process, demand of water is significant due to scarcity on the hill sites and the related dry climate. For this reason, grit chamber system was settled for separation of water and solid material (waste) (Fig. 4F). The wall of the grit chamber was coated by clay material for protection from water leakage (Fig. 4F).

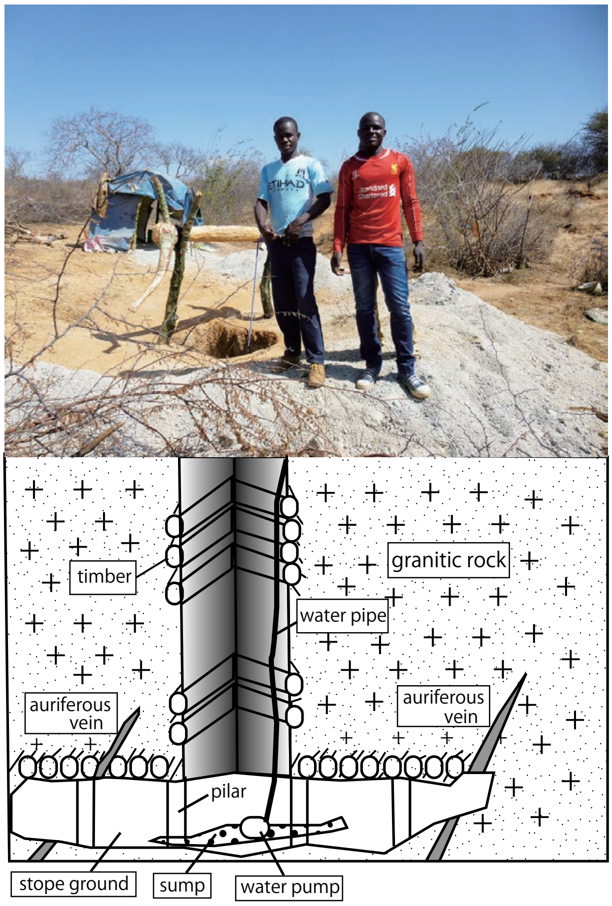

Fig. 3 Photo and sketch indicating shaft for excavation of gold and auriferous ore bearing material at Nzunguni gold mining (Madengi Hill) in central Tanzania. Shaft was constructed vertically and the soft walls were protected by timbers. Stope ground was formed underground of which was supported by timber pillars and to drain the sump (water pit) by water pump. White material around the shaft is drained weathered rocks.

Fig. 4 Photos showing the gold mining processes at Nzunguni (Madengi Hill) in central Tanzania. A; Quartz vein (reef) presumably yielding gold material attained by iron oxide. B; Manual crushing of gold and auriferous mineral bearing quartz vein by steel hammer. C; Powdered material after crushing and grinding by ball mill. D; Concentration of gold and auriferous material by hydraulic separation process. E; Concentration of waste after hydraulic separation. F; Separation of water and solid material (waste) by grit chamber system (see sketch in Fig. 5.)

Sampling Methods

Samples of soil, stream sediment and waste of about 100 g each were collected at the Nzunguni area (Fig. 2). Two soil samples were taken close to the mining pit (Fig. 2). The soil samples may represent the background geochemical compositions of the area. In addition three stream sediment samples were taken directly from river that runs out of Nzunguni mine site (Fig. 2). Eleven samples were taken from waste materials left behind at the site after extraction of gold and auriferous minerals (Fig. 2). Among them seven samples were collected at the site C (Fig. 2), and the locality of each was indicated in Fig. 5. This figure indicates system of gravity separation and grit chambers from right to left. Granite samples were taken as a representative of the host rock.

Samples were imported with permission of Soil Plant Protection, the Ministry of Agriculture, Forestry and Fisheries, Japan on 20th August, 2015.

Sample Preparation and Analytical procedure

Approximately one-third of each sample was transferred to Pyrex beakers, covered with aluminum foil to protect from contamination, and dried in an oven at 160˚C for 48 hours. Once

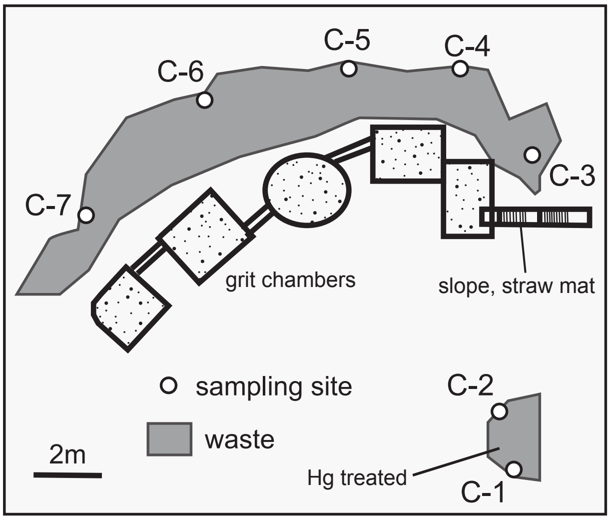

Fig. 5 Map showing structure of grit chambers and distribution of waste after extraction of gold and auriferous minerals of site C (Fig. 2) at Nzunguni gold mining (Madengi Hill) in central Tanzania.

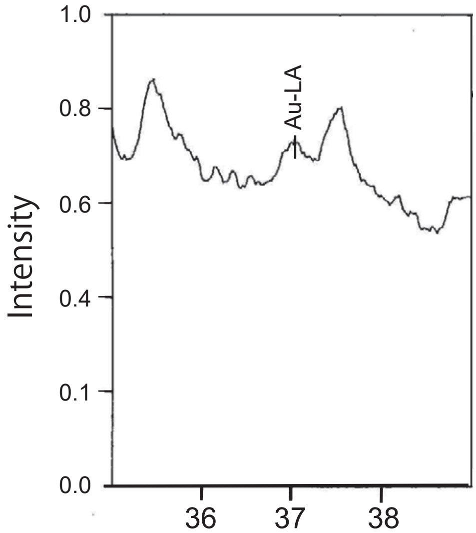

Fig. 6 Example of XRF qualitative analysis of aurum peak, detected at $2\theta = 36.96^\circ$ from waste sample (A-1) from Nzunguni gold mining (Madengi Hill) in central Tanzania.

dried, sub-samples of the soil were crushed in an Automatic Agate Mortar and Pestle grinder to produce a powder sample. Then, the pressed powder pellets were prepared by pressing the powdered sample into 30 mm diameter vinyl chloride rings, using a force of 200 kN for about 60 s in an automatic pellet press (E-30.M Maekawa Co., Ltd.).

Abundances of selected major elements (TiO_2, Fe_2O_3* (total iron expressed as Fe_2O_3), MnO, CaO and P_2O_5 wt%) and the trace elements As, Pb, Zn, Cu, Ni, Cr, V, Sr, Y, Nb, Zr, Th, Sc, TS (total sulfur), F, Br, I in ppm were determined by using X-ray fluorescence analysis (XRF; Rigaku RIX-2000) in the Department of Geoscience, Shimane University. Gold (Au) was analyzed and detected by the XRF but was not quantified. The XRF analyses were performed following the method of Ogasawara (1987). Average errors for all elements are less than ± 10% relative. Analytical results for GSJ standard JSL-1 were acceptable compared to the proposed values by Imai *et al*. (1996). Analytical results of samples are given in Table 1.

Results and Discussion

Waste samples show lower concentrations of As, Pb, Zn and Ni (Table 1). Contents of Cu show higher values than other heavy metals ranging from 500 ppm to 1200 ppm (Table 1). This indicates the existence of Cu bearing minerals and their relation to auriferous minerals. Arsenopyrite (FeAsS) is often accompanied in the auriferous mineral matrix (Keshavarzi *et al*., 2012), and this chemical species may also become a toxic matter for human (Charles *et al*., 2014). However, present results show quite low contents of As of less than 5 ppm (Table 1). This indicates absence of As bearing minerals in Nzunguni mining site. Thus hazard by arsenite reported from other mining sites in Tanzania (Charles *et al*., 2014; Kassenga and Mato, 2008) may not be the case. Contents of V and Cr show some variation (Table 1), and may occur as heavy minerals. Yttrium, Nb, Zr and Th have lower contents excluding two samples with higher Zr contents (C-2 = 270 ppm and C-5 = 117 ppm in Table 1). Fluorine contents vary among samples, but TS contents show quite lower levels. TiO_2, MnO and CaO contents vary among samples but do not show considerable deviation. Fe_2O_3 concentrations show quite high values ranging from 7.99 wt% to 19.84 wt% in Table 1, suggesting derivation from iron oxide stained quartz veins (indicated in Fig. 4a and b) and additional contamination from crushing hammer and ball mill machine (Fig. 4b).

Concerning to results of stream sediments, significant high values of Cu, Zn and Pb were not observed. Sample E-3 has considerably high Zr content (1042 ppm) and relatively high Th (217 ppm), Cr (228 ppm) and V (244 ppm) contents compared to other samples. This may be related to sorting effects within the stream during wet season. Granite sample does not show peculiar results (Table 1), but lower Nb (2 ppm) for continental granite may reflect subduction related magmatism. Looking at Nb contents of waste, soil and stream sediments in Table 1, all values are below 10 ppm which can support this consideration. Although material derived from the source rocks do not always show the same concentrations of Nb, considerable low Nb contents could suggest depletion at the source.

Qualitative analysis of XRF, aurum peak was detected at $2\theta = 36.96^\circ$ for waste samples (Fig. 6), excluding one sample (C-7) indicated in Table 1. This indicates the possibility of recovery of aurum from the waste, and such technology could be developed. Tow samples of waste (C-1 and C-2) were treated with Hg at the site (Fig. 5), but Hg peak was not detected by qualitative analysis. This indicated Hg recovery

Table 1 Geochemical analysis (XRF) of waste, soil stream sediments and rock samples from Nzunguni gold mining (Madengi Hill) in central Tanzania. det; Au peak detected of qualitative analysis. Blank; not detected.

	Trace elements (ppm)																			Major elements (wt%)					
sample	As	Pb	Zn	Cu	Ni	Cr	V	Sr	Y	Nb	Zr	Th	Sc	Au	TS	F	Br	I	Cl	TiO_2	Fe_2O_3	MnO	CaO	P_2O_5	remarks
A-1	3	9	103	1214	135	217	354	40	16	5	49	26	9	det	352	206	2			0.42	19.38	0.11	0.77	0.05	waste
A-2	4	13	66	1157	58	255	259	105	19	6	75	19	9	det	426	45	2			0.61	16.11	0.12	0.94	0.06	waste
B-1	3	12	63	1127	92	162	224	73	11	4	66	20	3	det	427	27	3			0.27	15.10	0.08	0.86	0.06	waste
B-2	3	12	100	1207	124	136	330	45	15	5	49	26	9	det	340	89	2			0.45	19.84	0.11	0.83	0.05	waste
C-1	2	10	27	728	36	193	128	72	8	4	80	11	3	det	367	27	2	17		0.29	7.03	0.04	0.87	0.04	waste (Hg treated)
C-2	2	15	45	491	29	212	147	232	17	6	270	12	8	det	342	168	2	14		0.72	5.78	0.08	1.14	0.09	waste (Hg treated)
C-3	3	10	53	1013	60	122	171	98	12	4	65	14	4	det	394	104	2	4		0.32	10.49	0.06	0.80	0.04	waste
C-4	2	12	54	913	66	105	177	73	11	4	75	10	5	det	344	57	2	5		0.39	10.53	0.07	0.87	0.04	waste
C-5	3	18	71	570	43	146	159	175	19	6	117	14	9	det	381	120	3	8		0.66	7.99	0.08	1.12	0.06	waste
C-6	2	15	92	1028	75	179	246	137	22	7	87	15	13	det	389	89	3			0.74	13.23	0.10	1.05	0.06	waste
C-7	3	18	86	970	74	231	255	90	19	6	78	16	10		463	165	4			0.60	14.88	0.11	0.96	0.05	waste
D	1	25	20	13	2	30	15	362	14	2	112	9	2		298	89	2	35		0.22	1.16	0.01	2.12	0.07	weathered granite
E-1	2	21	19	7	14	45	49	290	15	3	85	5	5		304	89	2	30		0.21	2.39	0.04	2.03	0.02	stream sed
E-2	2	23	28	10	15	54	85	371	16	3	108	20	8		321	73	2	17		0.32	3.60	0.06	2.75	0.03	stream sed
E-3	4	19	24	11	11	228	244	298	18		1042	217	8		326	183	2			0.43	9.86	0.06	2.49	0.03	stream sed
G-1	2	24	45	33	45	89	127	354	22	5	129	18	13		333	441	3	17		0.59	5.87	0.08	2.24	0.04	soil
F-1	4	27	16	16	8	37	38	307	16	2	85	7	4		308	89	2	25		0.12	1.87	0.03	1.65	0.02	soil

was mostly completed and if any, quite lower level of Hg might be included in the waste.

Acknowledgements

The authors gratefully acknowledge Shimane University for support the field research in Tanzania. Thanks are Tanzania Government and Soil Plant Protection, Ministry of Agriculture, Forestry and Fisheries, Japan for export and import permissions of the soil samples. The authors appreciate Mr. Juma Ally of Geological Survey of Tanzania for his help and assistance during field work. Constructive comments and review by editor were useful.

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(Received: Oct. 01, 2017, Accepted: Dec. 19, 2017)

（要　旨）

石賀裕明・Paschal Justin Magai・Miguta Faustine Ngulimi，2016．タンザニア中央部のズグニにおける金鉱山の廃棄物の地球化学的検討．島根大学地球資源環境学研究報告，35，1-6.

タンザニア中央部のズグニにおける金鉱山の周辺環境への影響を評価するため，廃棄物について，XRF による粉末プレス法により分析した．金および金を含む鉱物は母岩に含まれる石英脈中に産出し，この石英脈は粉砕され，斜面において比重選鉱により分離される．さらに金を濃縮するために水銀が用いられるが，この鉱山ではこの作業はまれであった．試料は比重選鉱場で採取したが，それらは淡黄灰色シルトであった．定性分析ではあるが，10 試料で金が検出された．この分析を行ったのは，金の標準試料がまだ準備されていないためである．水銀による処理が行われた，2 試料について検討したが，水銀は検出されなかった．銅の含有量は，500 から 1200 ppm と変化に富むが，これらは金を含む鉱物に伴われると考えられる．高い Fe_2O_3 含有量（10-19 wt%）は，主に石英脈の割れ目に 2 次的に生じた酸化鉄による．亜鉛，鉛，クロム，ニッケルとバナジウムは低濃度であり，これらを含む重鉱物が石英脈に伴われないことを示す．鉱山流域の堆積物の銅と水銀については異常値を示さず，精錬による影響が低いことを示す.