Remote Sensing and Field Survey for Mojos Remains Excavation

Susumu Ogawa*, Kohta Imai*, and Naoki Okada*

Key words : archaeology, Bolivia, ASTER, JERS1

1. Introduction

Analysis for the Mojos Project in August, 2005, was reported using satellite data, the field survey, soil tests and X-ray diffraction. The satellite data were Landsat ETM, ASTER, and JERS1/SAR for land cover classification and identification for the objects. The objective remains were *Loma* (hill), artificial reservoirs, agricultural fields, and circles. The field surveys were carried out by the total station. The results were plotted on the GIS software to make contour maps and bird's-eye views. Soil tests were soil size analysis for samples at digging areas. X-ray diffractions were carried out for iron pieces, beads, and earthenware dug.

2. Method

2-1. Study Area

Bolivia has three times area as much as Japan, constituting the Andes Mountains with more than 4000-m height on the west and tropical low lands with 1000-km^2 wide area on the east. The Mojos Plains extend on the north of the low lands in the Amazon watershed. This study covers satellite data analysis and the field survey for *loma*, artificial reservoirs, agricultural fields, and circles. Figure 1 shows Trinidad and *Loma Pancho Román*, where the excavation research was carried out in this study.

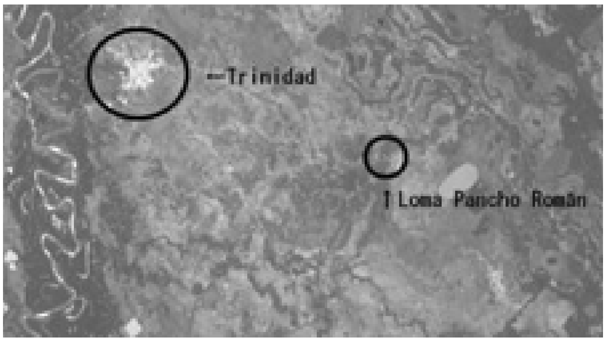

Figure 1 Trinidad and Loma Pancho Román, Bolivia

2-2. Used Satellite Data

Used satellite data were Landsat ETM, ASTER, and JERS1/SAR for land cover classification and the identification of the objects. The objective remains were the *loma*, artificial reservoirs, agricultural fields, and circles. First, the satellite data for the artificial reservoirs were ASTER/VNIR in an L1A product shot on September 8 in 2001 and Landsat/ETM+ with 30-m resolution shot on September 19 in 2001, downloaded from the home page of Maryland University. The center site is at 14.8 degrees on the south latitude and 64.3 degrees on the west longitude. The Landsat scene is on the path of 232 and the row of 70. Next, the satellite data for terraplén (causeway) were JERS1/SAR with the center site of 13.46 degrees on the south latitude and 63.28 degrees on the west longitude, and on the path of 416 and the row of 323. The other satellite used for the remains are listed in Table 1.

2-3. Analysis for Satellite Data

Images for the artificial reservoirs were abstracted from ASTER. First, noises in the original image were deleted with a linear smoothing filter keeping the edge components. Next, the differential operator, Laplacian 8 filter, was used for enhancing the edge in

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Table 1 Used Satellite Data

Satellite	Senser	PATH/ROW	Acquired Date	Remarks
ASTER	VNIR	231/194	2002/07/13	
		231/194	2003/02/22	
		232/193	2001/08/27	
		232/193	2002/12/27	
		232/195	2001/04/12	
		232/195	2001/08/27	
		232/196	2001/04/19	
		232/196	2005/04/07	
ASTER	DEM	232/195	2001/08/27	
		232/196	2005/04/07	
		232/196	2002/12/27	
JERS/1	SAR	414/330	1997/06/26	
		414/331	1997/06/26	
		415/322	1997/03/31	
		415/323	1997/05/14	
		415/323	1997/03/31	
		416/323	1997/06/28	
		417/322	1997/06/29	
		417/323	1997/04/02	
		417/323	1997/06/29	
		417/325	1996/05/29	
		417/326	1996/05/29	
		418/323	1997/05/17	
		418/325	1996/05/30	
		418/326	1996/05/30	
		419/324	1997/07/01	
		419/325	1996/05/31	
		419/325	1997/07/01	
		419/326	1996/05/31	
		420/325	1996/06/01	
		420/326	1996/06/01	
JERS/1	VNIR	415/322	1994/08/13	
		415/323	1994/08/13	
		416/322	1994/08/14	
		416/323	1994/08/14	
		416/323	1994/08/14	
		416/323	1993/04/17	
		418/322	1994/08/16	
		418/323	1994/08/16	

the image. Finally, the digitizing process for the image was carried out to abstract the artificial reservoirs.

1:25000 maps for the remains were produced from Landsat and ASTER images. The images were geometrically corrected and added with parallels of latitude and meridians for the maps.

2-4. Field Survey

The field surveys were carried out for the *loma* and its surrounding, agricultural fields, and the circle with the total station measurement. The artificial reservoir was measured in depth with a measure pole from the boat. The *loma* was measured with a grid of 10-m intervals. The watercourses surrounding the *loma* were measured in longitudinal and cross sections. The agricultural fields were measured in the longitudinal and cross sections with the area of 50m by 50m. The circle was measured along the perimeter with 10-m intervals. The artificial reservoir was also measured in depth with 10-m intervals. These results were summarized as figures.

2-5. Three-dimensional Images from the Field Survey Data

The field survey data were indicated as contour maps with GIS software, ArcMap. The interpolation method was used with a spline curve. The contour

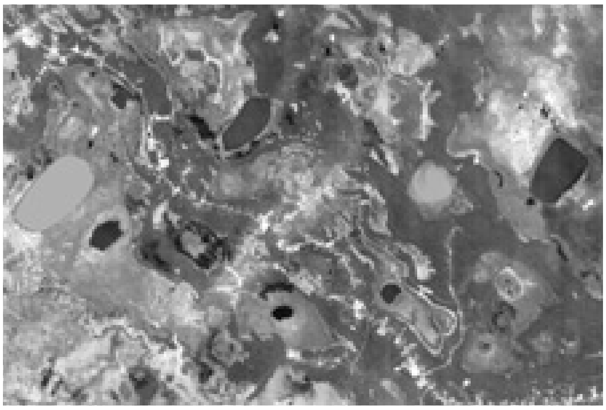

Figure 2 Original mage of ASTER/VNIR

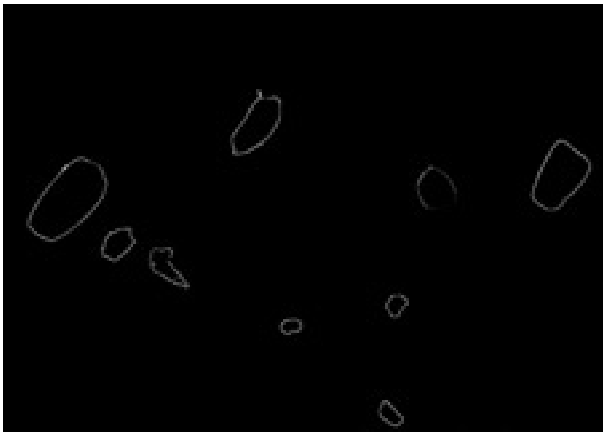

Figure 3 Extracted image of ASTER/VNIR

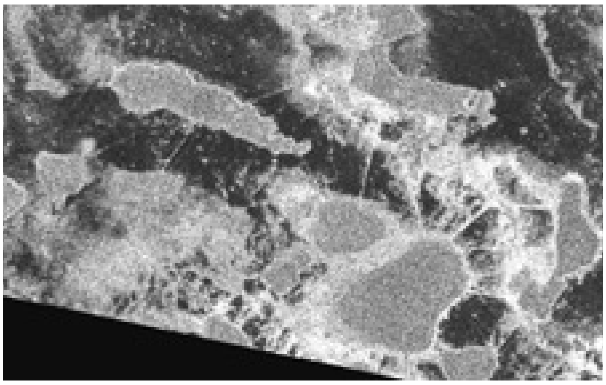

Figure 4 Original image of JERS-1/SAR

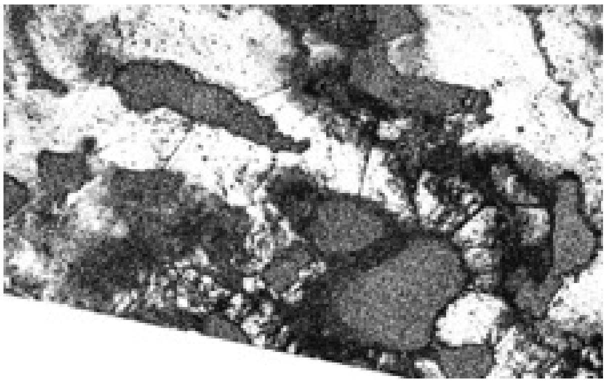

Figure 5 Reversal image of JERS-1/SAR

map for the artificial reservoir was made as the water's edge from Landsat/ETM+.

2-6. Hydraulic Calculation

Hydraulic characteristics were obtained for the water courses surrounding the *loma*. The average velocity was estimated by the Manning's formula.

$$v = \frac{1}{n} h^{2/3} i^{1/2}$$

where v : the average velocity in m/s, n : roughness, h : the water depth in m, and i : the slope. The roughness n was 0.02.

2-7. Soil Tests

The grain size distributions were examined by sampling soils from each site in the *loma*. The minimum grain size was 0.075 mm, while the maximum grain size was 2 mm. At the site 1 soil samples were taken from the surface, 0.5 m, and 0.83 m in depth. At the site 2 soil samples were taken from the surface, 0.66 m, and 1.25 m in depth. At the site 3 soil samples were taken from the surface, 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m in depth. At the site 4 soil samples were taken from the surface, 0.5 m, 1.0 m, 1.5 m, and 2.0 m in depth. The soil textures were categorized by the international method. Over 2 mm grain sized particle is a gravel, over 0.02 mm is sand, over 0.002 mm is silt, and under 0.002 mm is clay. These particle distributions in weight determine soil textures.

2-8. X-ray Diffraction

X-ray diffraction was carried out for iron pieces, beads, and colored pottery. From peak positions each diffraction pattern, elements and molecular structures were identified. An Fe-C system was applied for iron pieces, a $CaCO_3$ system for the beads, and metal elements and clay minerals for the colored pottery.

3. Results

3-1. Analysis Results for the Satellite Data

3-1-1. Extraction of Artificial Reservoirs

Figures 2 and 3 show ASTER images before and after image processing. The extracted reservoirs turn

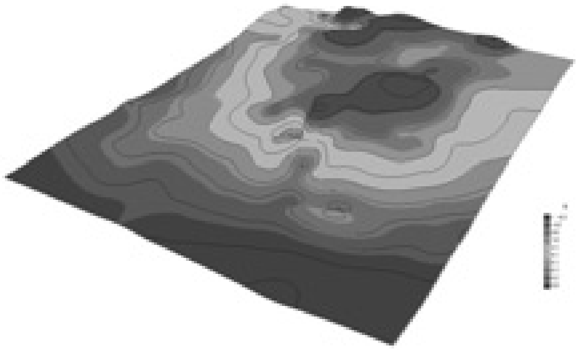

Figure 6 Loma Pancho Román

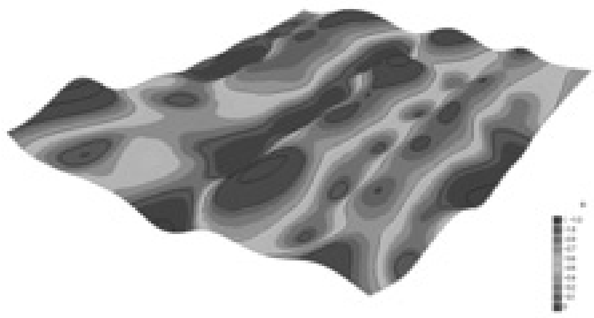

Figure 8 Agricultural field

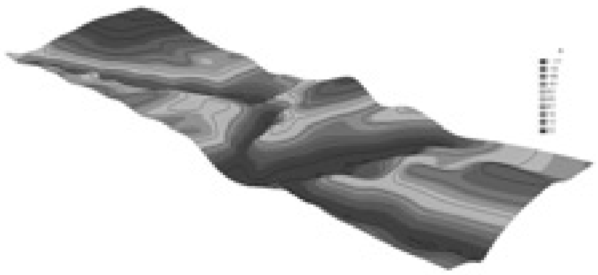

Figure 7 *Terraplénes* and canals

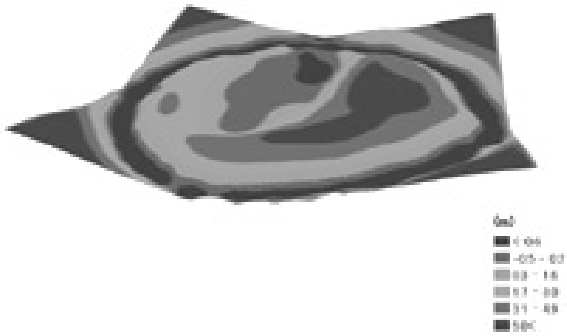

Figure 9 Circle

to the same direction. Their forms were also confirmed as a rectangle or a duck foot. The major axes coincide with the direction of the north east to south west. The areas also coincide each other.

3-1-2. Extraction of the Terraplén (causeway)

Figure 4 shows the original image of JERS-1/SAR before image processing, while Figure 5 shows the reversal image of JERS-1/SAR after image processing. These lineaments are *terraplénes* at Baures in Eastern Beni State. If the *terraplénes* have wider width than the resolution, they can be extracted easily from JERS-1/SAR images. *Terraplénes* were confirmed to extend from one loma to another *loma* radially. Unfortunately the *terraplénes* surrounding *Loma Pancho Román* were not detected from the satellite data.

3-2. Reconstruction of Remains in 3D

The remains were reconstructed in 3D from the field survey. Figures 6, 7, 8, and 9 show *Loma Pancho Román*, *terraplénes* with canals, agricultural fields, and made a circle from the field survey data in three dimension. A view of *Loma Pancho Román* is observed from Figure 6. *Terraplénes* with canals extend and surround *Loma Pancho Román* on the south as shown in Figure 7. In Figure 8, the agricultural field constitutes three ridges with 1.5-m height free from inundation in the wet season and ditches between the ridges as a watercourse in the dry season. The Mojos Plain has clay soils on the surface with poor drainage; therefore these ridges were mounded with nutritive soils in the ditches to improve the drainage and crop productivity. In Figure 9, the circle is surrounded by the watercourse.

3-3. Contour Map of Artificial Reservoir

Figure 10 shows a satellite image for the artificial reservoir, and Figure 11 shows a contour map in depth produced from this image and the survey data. The major axis is over 3 km. But the most depth ranges between 1.2 and 1.3 m, and indicates almost a constant value: a uniform distribution, which is different from natural lakes. In general, the natural lakes show an exponential distribution. Therefore, these disperse lakes might be artificial.

Flow rates for five canals of the *loma* were

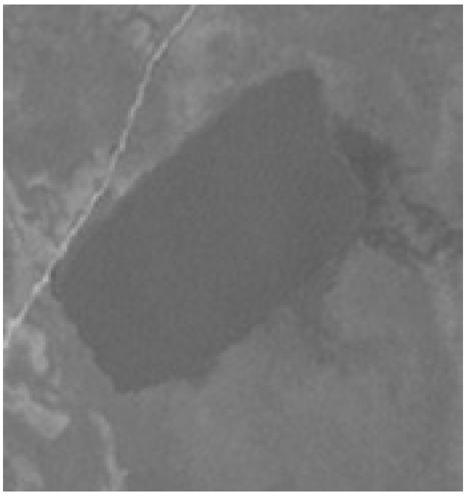

Figure 10 Landsat/ETM+ image for the artificial reservoir

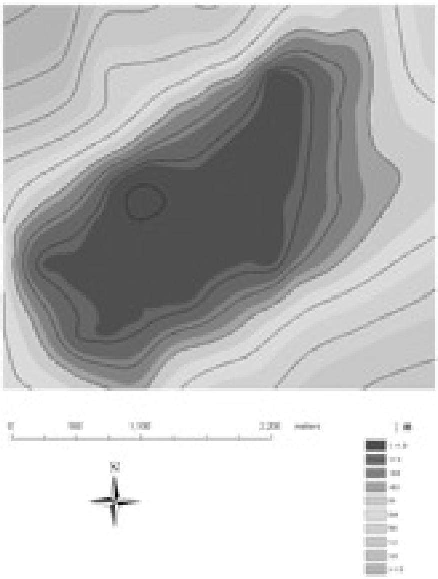

Figure 11 Contour map of the reservoir

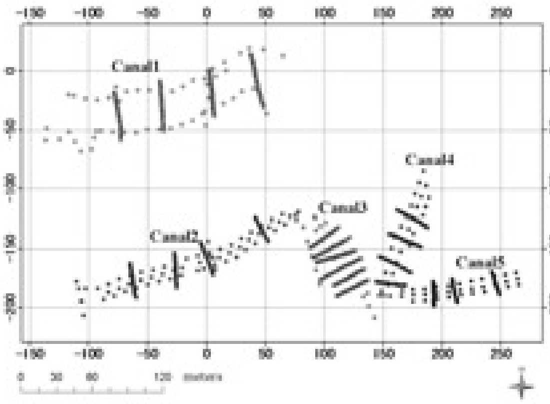

Figure 12 Survey plots for canals

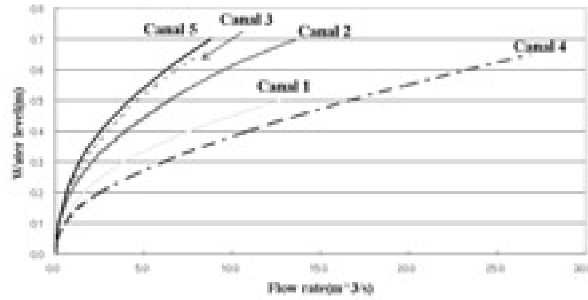

Figure 13 H-Q curves each canal

estimated. In Figure 12, each canal is shown as survey plots. Based on the survey plot data, height-flow rate curves were estimated as shown in Figure 13. The slopes of the canals were 0.0037 for Canal 1, 0.0069 for Canal 2, 0.0040 for Canal 3, 0.0112 for Canal 4, and 0.0040 for Canal 5. Estimated flow rates were 12.7 m^3/s for Canal 1, 13.6 m^3/s for Canal 2, 8.3 m^3/s for Canal 3, 26.9 m^3/s for Canal 4, and 17.9 m^3/s for Canal 5. The average estimated flow velocity and rate of the canals were 2.8 m/s and 14.1 m^3/s, and the range of the estimated flow velocity and rates were between 1.9 and 4.0 m/s, and 8.3 and 26.9 m^3/s. These values mean that the canals had the same capacity as the medium rivers, which would allow small balsa boats run in the canals and prepared for agricultural water.

3-4. Soil Tests

The soil at the *loma* was *Ferralsol*, ferro-alumina or ferrous soils, with yellow and red colors. Particles were sands and silts, and soil textures were loam, sandy loam and silty loam with over 50 % of sand as shown in Figures 14 to 17. All the sites have the similar soil size distributions and independence of depth. That means all sites were covered with almost uniform soils from the surface to 2-m depth.

3-5. X-ray Diffraction

Element and structure analysis with X-ray diffraction was applied for iron pieces, beads, and pottery dug at Site 2. Each sample was radiated on the surface and matrix. The iron pieces were almost alpha-iron with smooth surface, which suggests modern processing for commercial products as shown in Figures 18 and 19. Dating technique showed the bones were buried about 1000 years ago. Therefore, iron pieces might be mixed in modern times. Beads constitute $CaCO_3$, which especially indicated one of fresh water shells as shown in Figures 20 and 21. Pottery constitutes clay

Table 2 Flow velocity and rate each canal

Canal 1											
Water depth(m)	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Flow veloeity(m/s)	0.0	0.4	0.7	0.9	1.0	1.2	1.4	1.5	1.6	1.8	1.9
Flow rate(m^3/s)	0.0	0.1	0.3	0.8	1.6	2.6	3.9	5.6	7.6	9.9	12.7

Canal 2															
Water depth(m)	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70
Flow veloeity(m/s)	0.0	0.6	0.9	1.2	1.4	1.6	1.9	2.1	2.3	2.4	2.6	2.8	3.0	3.1	3.3
Flow rate(m^3/s)	0.0	0.1	0.2	0.5	0.9	1.4	2.1	3.0	4.0	5.2	6.5	7.9	9.5	11.5	13.6

Canal 3														
Water depth(m)	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
Flow veloeity(m/s)	0.0	0.4	0.7	0.9	1.1	1.2	1.4	1.6	1.7	1.9	2.0	2.1	2.2	2.4
Flow rate(m^3/s)	0.0	0.0	0.2	0.4	0.7	1.1	1.6	2.2	2.9	3.7	4.6	5.7	6.8	8.3

Canal 4														
Water depth(m)	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
Flow veloeity(m/s)	0.0	0.7	1.1	1.5	1.8	2.1	2.4	2.6	2.9	3.1	3.3	3.5	3.8	4.0
Flow rate(m^3/s)	0.0	0.1	0.5	1.3	2.5	4.2	6.1	8.4	10.9	13.6	16.6	19.8	23.3	26.9

Canal 5															
Water depth(m)	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70
Flow veloeity(m/s)	0.0	0.4	0.7	0.9	1.1	1.2	1.4	1.6	1.7	1.8	2.0	2.1	2.2	2.4	2.5
Flow rate(m^3/s)	0.0	0.1	0.2	0.4	0.6	1.0	1.4	1.9	2.6	3.3	4.2	5.2	6.3	7.5	8.8

minerals as shown in Figures 22 and 23. Colored surface also indicated clay minerals. As die any metal elements were not detected. Colored elements should be different from clay elements.

4. Discussion

4-1. Satellite Data Analysis for Archaeology

Preliminary investigation was successful for the remains excavation by using satellite data, ASTER and Landsat images. Thereby, before the remains excavation the preliminary research could start with the satellite data. Next, 3D images estimated the flow rate of canals from field survey data. Moreover, these results might estimate the agricultural products and the population archaeologically.

4-2. Surface State from Soil Size Distribution

From soil size distributions, the soil texture was uniform from the surface to 2 m depth, which means the remains might be on almost the same date in the soil. Soil textures were silty loam, loam, and sandy loam with 50-90% sand, the elements of which were *Ferralsol,* ferro-alumina or ferrous soils, with yellow and red colors. These soils cover the loma thick. The remains dug this time were in these soils.

5. Conclusions

This study follows the remains excavation for the Mojos culture and a series of analysis for the satellite data and field survey were carried out to obtain 3D maps and hydraulic characteristic for the canals. The next conclusions were drawn.

(1) The extraction of artificial reservoirs and production of maps were completed with the satellite data and the field survey. Especially the satellite data were available widely and timely for the objective area and the preliminary research of the remains excavation.

(2) 3D maps were obtained for the remains and their surroundings with the field survey data. 3D images are available for some estimates and restoration of the remains.

(3) Flow rates for the ancient canals were estimated from the field survey. The average estimated flow rate was 14.1 m^3/s and the same as the urban medium rivers. Next, these results might estimate the agricultural products and the population archaeologically.

(4) From soil size distributions, the soil texture was uniform from the surface to 2 m depth, which means the remains might be on almost the same

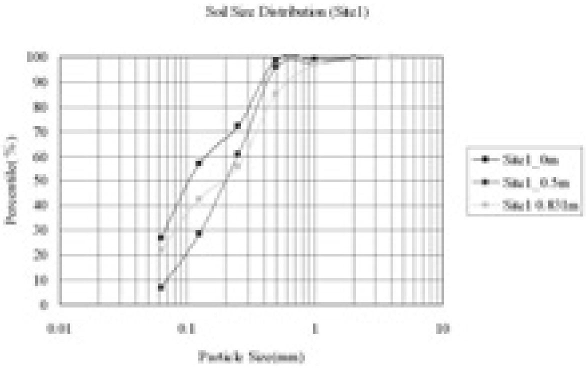

Figure 14 Soil size distribution (Site 1)

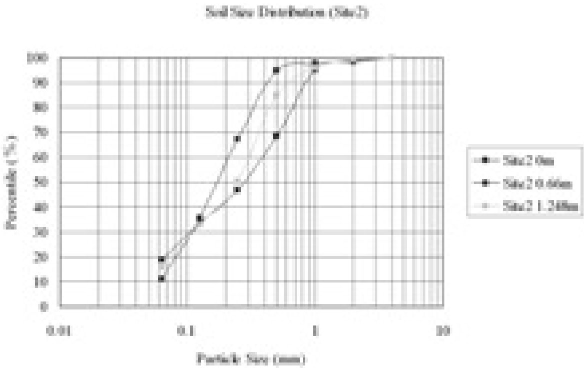

Figure 15 Soil size distribution (Site 2)

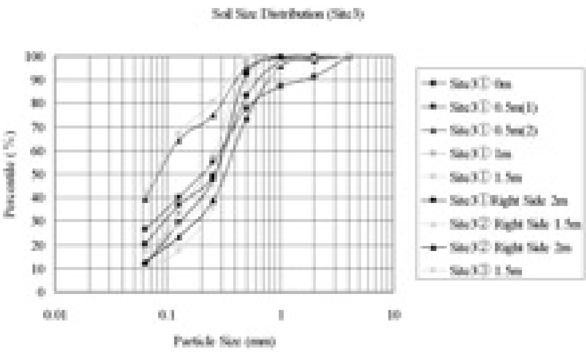

Figure 16 Soil size distribution (Site 3)

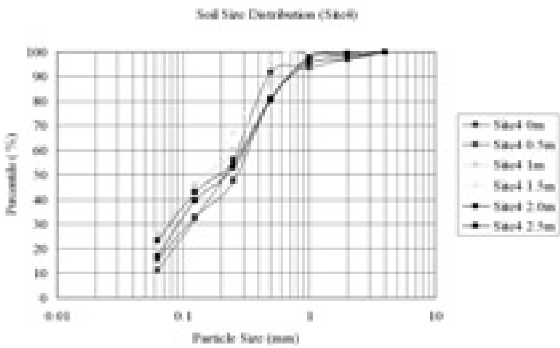

Figure 17 Soil size distribution (Site 4)

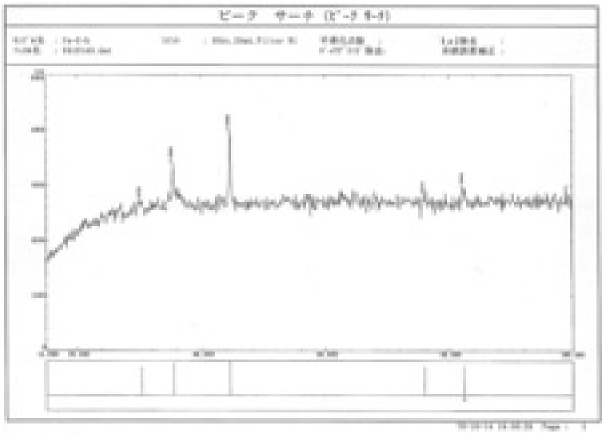

Figure 18 X-ray diffraction for the iron surface

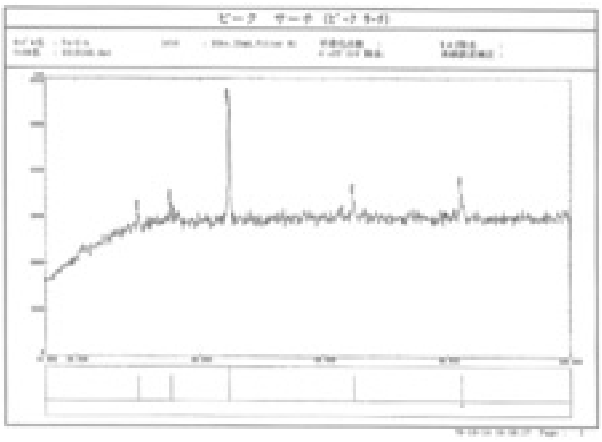

Figure 19 X-ray diffraction for the iron matrix

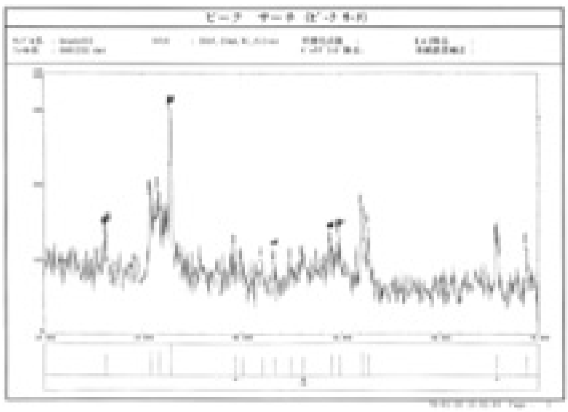

Figure 20 X-ray diffraction for the bead surface

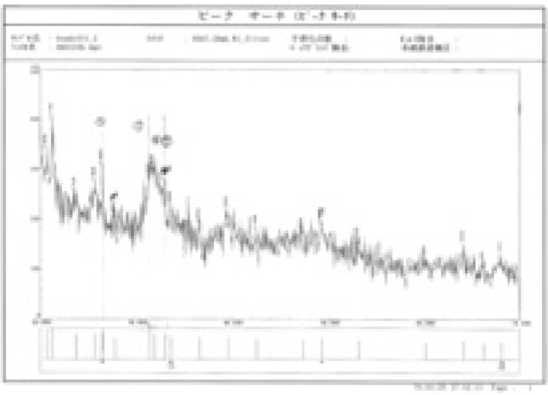

Figure 21 X－ray diffraction for the bead matrix

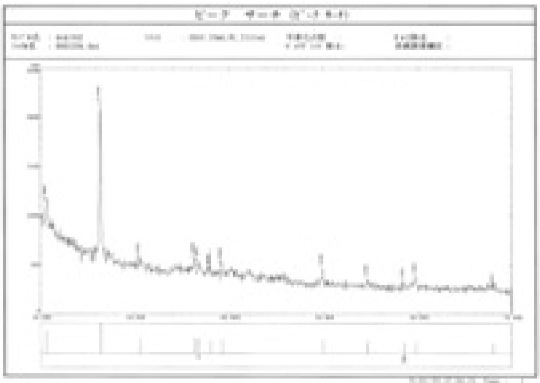

Figure 22 X-ray diffraction for the pottery surface

date in the soil. Soil textures were silty loam, loam, and sandy loam with 50-90% sand, the elements of which were *Ferralsol*, ferro-alumina or ferrous soils, with yellow and red colors.

(5) In the analysis of X-ray diffraction, iron pieces might be mixed in modern times. Beads constitute

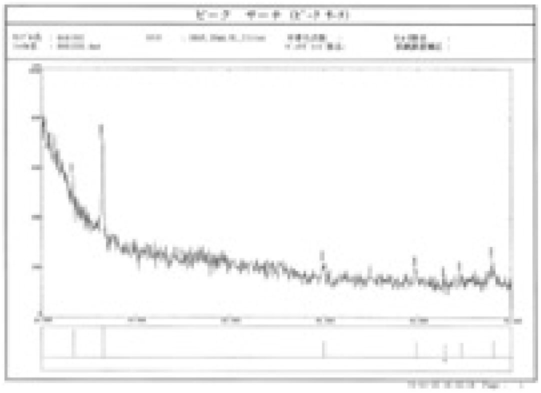

Figure 23 X-ray diffraction for the pottery matrix

$CaCO_3$, which especially indicated one of fresh water shells. Pottery constitutes clay minerals. Colored surface also indicated clay minerals.

Acknowledgement: The authors greatly appreciate for Professor Fumie Seki's analysis of X-ray diffraction for iron pieces, beads, and pottery.

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(Abstract)

Analysis for the Mojos Project in August, 2005, was reported using satellite data, the field survey, soil tests and X-ray diffraction. The satellite data were Landsat ETM, ASTER, and JERS1/SAR for land cover classification and identification for the objects. The objective remains were ***Loma*** (hill), artificial reservoirs, agricultural fields, and circles. The field surveys were carried out by the total station. The results were plotted on the GIS software to make contour maps and bird's-eye views. Soil tests were soil size analysis for samples at digging areas. X-ray diffractions were carried out for iron pieces, beads, and earthenware dug. The extraction of artificial reservoirs and production of maps were completed with the satellite data and the field survey. Especially the satellite data were available widely and timely for the objective area and the preliminary research of the remains excavation. 3D maps were obtained for the remains and their surroundings with the field survey data. 3D images are available for some estimates and restoration of the remains. Flow rates for the ancient canals were estimated from the field survey. The average estimated flow rate was 14.1 m^3/s and the same as the urban medium rivers. Next, these results might estimate the agricultural products and the population archaeologically. From soil size distributions, the soil texture was uniform from the surface to 2 m depth, which means the remains might be on almost the same date in the soil. Soil textures were silty loam, loam, and sandy loam with 50-90% sand, the elements of which were ***Ferralsol***, ferro-alumina or ferrous soils, with yellow and red colors. In the analysis of X-ray diffraction, iron pieces might be mixed in modern times. Beads constitute $CaCO_3$, which especially indicated one of fresh water shells. Pottery constitutes clay minerals. Colored surface also indicated clay minerals. The research will discover the total Mojos civilization in the next investigation.

モホス遺跡発掘調査のためのリモートセンシングと測量

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2005年８月に実施したモホス遺跡発掘予備調査において、衛星データおよび測量の解析、土質試験、X 線回折結果について報告する。衛星データは、Landsat ETM, ASTER, JERS1/SAR を使用し、土地被覆分類を中心に対象の同定に使用した。対象遺跡としては、ロマ、テラプレン、人造湖、農耕地、サークルである。測量はトータルステーションで行われた。測量結果は GIS 上に入力され、等高線図と鳥瞰図を作成した。土質試験は、発掘場所より採取し粒度試験を行った。X 線回折は、採掘した鉄試料、ビーズ、土器顔料に対して行った。衛星画像を使用して人造湖の抽出と現地図が作成できた。衛星画像は広範囲にリアルタイムで現地情報を得ることができ、遺跡発掘の事前調査に利用することができる。現地測量結果を使用して、遺跡とその周辺地を３次元化することができた。作成した立体画像は様々な角度から遺跡を見ることができ、復元も可能である。測量結果から古代水路の流量を推定した。推定平均流量は14.1m^3/s となり、ほぼ都市の中小河川程度の流量があった。今後、この結果をもとに当時の人々の農業生産量や人口推定が可能であると考える。土壌の粒度は、表層から２m まではほぼ相似であり、砂分が50－90%含むシルト・ローム、ローム、砂質ロームであり、黄色ないし一部赤色であった。この範囲で発掘された遺物はほぼ同一年代と推定される。遺物の X 線回折では、ごく表層の鉄試料は近代のものが混在したが、ビーズは淡水性貝類、土器の彩色は、粘土鉱物であると判断された。今後の継続調査により、3000年前と同定された年代におけるアマゾン古代文明の全体像が明らかになることが期待される。