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Obsidian sources and distribution systems in Island Southeast Asia: new results and implications from geochemical research using LA-ICPMS

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ABSTRACT

This paper discusses new evidence of long-distance interaction networks in Island Southeast Asia obtained from geochemical analyses using SEM-EDXA and LA-ICPMS of 101 obsidian samples from 25 locations including seven obsidian sources and 19 archaeological sites. Given that there are obsidian sources distributed throughout much of Island Southeast Asia, the potential for obsidian studies to provide greater understanding of patterns of mobility and exchange in the Pre-Neolithic and Neolithic periods would seem to be considerable. This potential, however, remains largely unrealised as obsidian sourcing has hitherto only been carried out intermittently in Island Southeast Asia using PIXE-PIGME, XRF and other methods.

1. Introduction

Geochemical research on the distribution of obsidian sources and artefacts has produced remarkable insight into prehistoric social interaction in Island Southeast Asia (ISEA) and the Pacific (Spriggs et al., this volume, Summerhayes, 2009; Torrence et al., 2009). Most recently, the identification in East Timor of the long-term exploitation of one single high-silicate obsidian source for more than 40,000 years (Ambrose et al., 2009, Reepmeyer et al., 2011) might, given the local geological context, indicate one of the earliest maritime movements in the world of a prehistoric raw material. Although long-distance transportation of obsidian has been documented in ISEA for the Neolithic period,[1] it has been assumed that this interaction was most likely a singular event (Tykot and Chia, 1997:175) and not incorporated into a widespread exchange system as has been evidenced by the long-distance exchange of Taiwanese jade described by Hung et al. (2007).

The review of previous geological and archaeological research (Spriggs et al., this volume) has shown that this region contains a variety of potential obsidian source locations and a multitude of archaeological sites containing obsidian artefacts. It is therefore somewhat surprising that a raw material which has the proven potential to identify detailed exchange and/or migration routes has been relatively neglected (Pollard et al., 2007, Speakman and Neff, 2005). With this study we attempt to identify obsidian outcrops and raw material transportation in Island Southeast Asia, crucial missing data for understanding social interaction across this complex island network. The new data challenge the hypothesis of only rare

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[1] In the locations covered by this study the ISEA Neolithic begins around 4000/3800 cal BP and ends with the beginning of the Metal Age c.2100 cal BP.

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Fig. 1. Location of archaeological sites and obsidian sources mentioned in the text.

transportation of obsidian in the study area. The study suggests that limited evidence of inter-island obsidian exchange derives from an incomplete dataset rather than typifying prehistoric social patterns.

2. Locations

In this paper we present data of a geochemical study of 101 obsidian samples from eight islands and 25 different locations in Island Southeast Asia (Fig. 1) using scanning electron microscopy energy dispersive x-ray analysis (SEM-EDXA) and laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). The study is a collaboration between Australian, Indonesian and Filipino researchers, as well as other overseas researchers working in Indonesia and East Timor. Through this collaboration it was possible to obtain samples from five obsidian sources in Indonesia (Nagrek A and B [formerly Leles, west Java], Paso outcrop [Lake Tondano area, northern Sulawesi], Tapus [Lake Kerintji area, South Sumatra] and Bandaneira [Banda Islands]) and two from the Philippines (Nagcarlan [central Luzon] and Pagupod [northern Luzon]),[2] as well as from 19 archaeological sites (Table 1).

The source sample from Sumatra derives from a possible secondary deposit of obsidian found by Simanjuntak in 2003 on the surface at Tapus, Rejang Lebong in the Bengkulu area. Source samples from Bandaneira originate from investigations in 2007 by Lape who found several obsidian samples on the surface 500 m ESE of the BN1 site (Lape, 2000a:140, Fig. 1) in the north of the volcanic island of Bandaneira. There are no associated dates available and no obsidian was found in the BN1 site itself, which was dated to the last 1500 years.

[2] For a description of the Nagrek/Leles, Tondano, Nagcarlan and Pagupod sources see Spriggs et al. (this volume).

The study included 56 artefacts originating from well-researched sites such as Ulilang Bundoc on Luzon (eight artefacts of which four came from burial jars; de la Torre, 1997, 2002); Ille cave on the island of Palawan from a layer dating to 11000-9400 cal

Table 1
Location of archaeological sites and obsidian sources discussed in the text.

Region	Island	Site	Reference
		Sources	
Philippines	Luzon	Pagudpod	Neri, 2007
		Nagcarlan	Neri, 2007
Indonesia	Sumatra	Tapus/Kerintji	Simanjuntak, pers. comm. 2003
	Java	Nagrek/Leles	Chia et al., 2008
	Sulawesi	Tondano/ Minahasa	Tanudirjo, 2001
	Banda Islands	Bandaneira	Lape, 2000b
		Sites	
Philippines	Luzon	Ulilang Bundoc	de la Torre, 2002
	Palawan	Ille cave	Paz and Ronquillo, 2004
	Cebu	Lastimoso site	Tiauzon, pers. comm. 2006
		Letigio site	Tiauzon, pers. comm. 2006
	Mindanao	Huluga site	Neri et al., 2005
		Echems Prop.	Neri et al., 2005
		Gales Prop.	Neri et al., 2005
		Dahinos Prop.	Neri et al., 2005
		Daayata Hill Site	Neri et al., 2005
		Ilihan Dako Site	Neri et al., 2005
Indonesia	Sulawesi	Minanga Sipakko	Simanjuntak et al., 2008
		Kamassi	Simanjuntak et al., 2008
	Java	Tugu	Chia et al., 2008
		Pakar Dago	Chia et al., 2008
		Panyanwangan	Chia et al., 2008
	Sumatra	Tapak Harimau	Forestier et al., 2006
		Silabe cave	Forestier et al., 2006
	Banda Islands	Palau Ay, PA1 site	Lape, 2000b

BP (one artefact; Lewis et al., 2008); north Mindanao sites (32 artefacts; Neri, 2007; Neri et al., 2005); Minanga Sipakko in central-west Sulawesi (six artefacts; Simanjuntak, 1994–1995:21, Simanjuntak et al., 2008), the Neolithic site of Kamassi in central-west Sulawesi associated with 68 obsidian flakes which were excavated by Simanjuntak and his team in 2008 (four artefacts found by Anggraeni in 2009 in the back-dirt of the 2008 excavations); the Neolithic open site of Tapak Harimau (near Gunung Kahuripan; four artefacts) and the nearby Pondok Silabe cave in southern Sumatra (one artefact; Forestier et al., 2006, Simanjuntak and Forestier, 2004). These sites are further described in Spriggs et al. (this volume).

Table 2
Summary statistics and weight percent of major element oxides analysed with SEM-EDXA.

Spectrum Label		Na_2O %	MgO %	Al_2O_3 %	SiO_2 %	K_2O %	CaO %	TiO_2 %	MnO %	FeO %	totals
Sources											
Philippines											
Luzon											
Pagupod	*n*=2	3.6	5.9	15.3	53.7	0.4	7.8	1.6	0.1	9.7	98.3
	SD	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.2	0.1
Nagcarlan	*n*=1	4.4	0.2	13.8	73.7	4.7	0.8	0.1	0.2	1.2	99.2
Indonesia											
Banda Islands											
Bandaneira	*n*=7	4.9	1.0	14.0	67.8	1.0	3.8	0.9	0.2	5.9	99.5
	SD	0.1	0.3	0.6	1.7	0.1	0.6	0.1	0.0	0.5	1.1
Sulawesi											
Paso	*n*=1	4.5	0.2	12.6	76.1	3.1	1.1	0.3	0.0	1.7	99.5
Java											
Nagrek (A)	*n*=6	3.4	0.1	12.2	76.7	4.9	0.7	0.2	0.0	1.1	99.1
	SD	0.1	0.1	0.1	0.3	0.2	0.1	0.0	0.0	0.1	0.5
Nagrek (B)	*n*=1	3.4	0.3	12.7	76.3	4.9	1.1	0.2	0.1	1.0	99.8
Sumatra											
Tapus	*n*=1	3.9	0.1	12.3	77.4	3.8	0.9	0.3	0.1	0.7	99.4
Artefacts											
Philippines											
Luzon											
Ulilang Bundoc	*n*=8	4.2	0.3	13.5	73.8	4.5	1.0	0.2	0.1	1.6	99.3
	SD	0.5	0.3	0.2	0.3	0.4	0.3	0.1	0.1	0.6	0.2
Cebu											
Calixto Lastimoso site	*n*=1	2.6	1.3	12.4	74.5	3.2	1.8	0.7	0.0	3.0	99.5
Jesus Letigio site	*n*=1	2.6	1.1	12.6	74.9	3.1	1.8	0.6	0.2	2.9	99.7
Jesus Letigio site	*n*=1	1.6	2.1	12.6	73.1	2.5	2.5	0.8	0.2	4.8	100.2
Palawan											
Ille cave	*n*=1	1.3	2.3	12.3	73.3	2.4	2.4	0.9	0.2	4.7	100.0
Mindanao											
North Mindanao sites	*n*=32	4.9	0.1	14.7	70.8	5.6	0.8	0.2	0.1	1.6	99.0
	SD	0.1	0.0	0.1	0.4	0.1	0.1	0.1	0.1	0.1	0.3
Indonesia											
Sulawesi											
Minanga Sipakko	*n*=6	3.9	0.0	12.4	76.1	4.8	0.6	0.1	0.0	1.2	99.1
	SD	0.0	0.0	0.0	0.2	0.0	0.0	0.1	0.0	0.1	0.2
Kamassi	*n*=4	4.0	0.0	12.3	75.9	4.7	0.6	0.1	0.0	1.3	99.0
	SD	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.1	0.1	0.4
Java											
Bandung plateau A	*n*=6	3.3	0.1	12.2	76.6	4.8	0.7	0.2	0.0	1.1	98.8
	SD	0.1	0.1	0.1	0.5	0.2	0.0	0.1	0.0	0.1	0.8
Bandung plateau B	*n*=1	3.4	0.1	12.3	75.2	4.5	0.9	0.3	0.0	1.2	97.8
Sumatra											
Tapak Harimau	*n*=4	4.0	0.1	12.7	76.9	4.3	0.6	0.2	0.1	0.6	99.2
	SD	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.3
Silabe cave	*n*=1	3.9	0.1	12.7	76.9	4.3	0.6	0.2	0.1	0.7	99.5
Banda Islands											
Site PA1	*n*=15	3.8	0.0	12.4	75.7	4.4	0.6	0.1	0.1	0.9	98.1
	SD	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.1	0.1	0.3
Site PA1 outlier	*n*=1	4.6	0.0	12.6	75.5	2.6	1.1	0.0	0.0	0.3	96.8
Standards											
ANU2000 actual	*n*=16	4.87	0.25	13.50	73.26	4.00	1.09	0.33	0.04	1.98	99.41
	SD	0.07	0.03	0.12	0.26	0.10	0.04	0.06	0.05	0.10	0.34
ANU2000 preferred[a]		4.61	0.27	13.91	73.70	3.93	1.41	0.28	0.04	1.43	
	SD	0.29	0.07	0.27	0.28	0.12	0.48	0.03		0.43	
ANU9000 actual	*n*=18	3.94	0.23	12.58	76.31	3.81	1.14	0.24	0.04	1.19	99.58
	SD	0.06	0.03	0.11	0.31	0.06	0.03	0.05	0.04	0.10	0.37
ANU9000 preferred[a]		3.78	0.22	12.68	76.82	3.57	1.43	0.22	0.06	0.93	
	SD	0.17	0.07	0.17	0.93	0.34	0.36	0.02	0.01	0.28	
NIST612 actual	*n*=19	13.84	0.00	1.95	72.15	−0.01	11.64	0.04	0.02	0.00	99.81
	SD	0.18	0.03	0.05	0.31	0.02	0.23	0.03	0.04	0.05	0.09
NIST612 preferred[b]		13.98	0.00	2.11	71.90	0.01	11.93	0.01	0.01	0.02	
	SD	0.56		0.16	0.96	0.00	0.22	0.00	0.00	0.00	

[a] Values taken from Ambrose et al., 2009, Golitko et al., 2010, Glascock unplub. Data.
[b] Values taken from Pearce et al. 1997.

Table 3
Summary statistics and absolute counts in ppm of trace elements analysed by ICPMS.

Spectrum Label		P	Sc	Ti	V	Cr	Mn	Co	Cu	As	Rb	Sr	Y	Zr	Nb	Mo	Sn	Cs	Ba
Philippines																			
Luzon																			
Pagupod	*n*=2	1056.1	20.7	10092.5	145.5	194.5	1035.4	36.8	95.7	0.2	8.2	195.8	15.9	80.7	9.3	0.69	1.0	0.1	82.1
	SD	0.4	0.1	35.4	0.3	12.7	5.3	0.1	0.2	0.0	0.0	1.2	0.1	0.6	0.0	0.00	0.0	0.0	0.3
Nagcarlan	*n*=1	96.9	6.1	1061.1	0.7	1.4	525.3	0.4	4.8	12.7	144.5	68.3	30.8	161.1	11.0	3.61	2.3	7.3	571.1
Indonesia																			
Banda Islands																			
Bandaneira	*n*=7	1179.9	23.5	6095.3	28.6	0.7	1439.7	5.2	7.5	3.6	28.5	146.4	51.0	144.3	3.4	1.21	1.6	1.9	279.5
	SD	166.2	1.7	626.0	11.5	0.1	59.4	0.9	0.6	0.3	2.2	7.9	2.2	9.9	0.2	0.08	0.1	0.1	18.2
Sulawesi																			
Paso	*n*=1	126.9	11.0	1494.2	1.4	1.2	519.0	0.8	10.2	6.9	81.3	71.4	39.3	203.7	5.8	2.75	2.0	4.4	373.5
Java																			
Nagrek (A)	*n*=6	46.0	4.9	765.4	2.0	1.0	234.1	0.6	5.6	13.2	187.2	29.6	37.6	96.4	7.5	3.58	3.6	11.7	316.0
	SD	0.8	0.1	9.7	0.1	0.1	5.6	0.1	0.4	0.3	5.4	0.6	0.4	1.1	0.1	0.10	0.1	0.4	5.4
Nagrek (B)	*n*=1	86.2	5.3	1206.3	3.2	1.0	233.9	0.8	8.1	11.4	170.6	46.9	31.9	141.7	7.1	3.65	3.3	10.2	397.2
Sumatra																			
Tapus	*n*=1	70.5	4.5	660.4	0.4	1.3	306.7	0.4	1.9	14.6	136.7	67.1	20.2	71.4	5.6	2.15	2.1	8.0	520.3
Philippines																			
Luzon																			
Ulilang Bundoc	*n*=8	102.7	6.9	1072.9	0.8	1.3	533.5	0.5	7.7	12.7	151.3	68.1	32.4	168.0	11.2	3.85	2.5	8.2	601.5
	SD	3.3	0.1	14.5	0.0	0.2	10.8	0.0	0.9	0.2	1.7	1.8	0.3	2.3	0.1	0.09	0.1	0.1	7.1
Cebu																			
Calixto Lastimoso	*n*=1	141.7	6.4	1578.4	5.5	1.3	440.9	0.6	2.4	6.6	52.2	166.1	17.3	115.0	2.2	3.01	0.7	1.5	456.6
Jesus Letigio site	*n*=1	276.1	13.5	5510.7	80.2	82.0	737.7	12.6	3.1	0.5	122.0	136.4	26.9	262.8	17.6	0.19	0.7	7.0	382.6
Jesus Letigio site	*n*=1	375.8	13.2	5388.8	82.9	85.4	712.3	13.0	4.3	0.7	126.5	138.1	26.6	260.2	17.3	0.23	0.9	7.3	375.5
Palawan																			
Ille cave	*n*=1	488.3	13.1	5249.7	78.6	115.8	751.1	15.1	2.8	1.0	119.4	134.4	25.6	248.8	17.0	0.20	1.0	7.1	372.8
Mindanao																			
North Mindanao	*n*=32	84.6	4.9	1440.8	1.2	1.2	718.2	0.5	13.3	14.1	276.6	2.5	28.6	292.8	22.2	13.74	3.8	11.6	1.9
	SD	6.2	0.3	85.1	0.4	0.3	19.6	0.0	1.1	0.5	5.4	0.2	0.6	12.8	0.4	0.36	0.1	0.4	0.2
Indonesia																			
Sulawesi																			
Minanga Sipakko	*n*=6	20.8	3.1	555.8	0.0	1.2	200.8	0.0	3.6	9.3	277.6	11.7	76.6	148.7	22.0	3.00	10.9	21.8	234.2
	SD	0.4	0.0	5.1	0.0	0.1	4.1	0.0	0.3	0.1	1.6	0.5	0.5	0.7	0.2	0.03	0.1	0.1	9.1
Kamassi	*n*=4	37.8	3.9	571.7	0.0	bdl	206.2	0.0	4.3	6.9	301.0	13.2	86.2	163.2	21.7	3.10	12.4	24.1	265.2
	SD	0.6	0.1	11.4	0.0	0.0	2.9	0.0	0.2	0.2	1.3	0.4	0.5	2.2	0.1	0.09	0.1	0.2	13.2
Java																			
Bandung plateau A	*n*=6	46.4	5.0	767.5	2.0	1.0	232.2	0.6	5.4	13.0	183.7	29.5	37.7	97.0	7.5	3.51	3.6	11.4	314.6
	SD	0.6	0.1	12.1	0.1	0.1	6.5	0.1	0.5	0.0	2.6	0.5	0.5	1.1	0.1	0.03	0.1	0.1	4.4
Bandung plateau B	*n*=1	82.4	5.3	1178.2	3.1	0.9	230.4	0.8	8.7	11.5	167.2	45.3	31.3	137.9	7.1	3.61	3.3	10.0	390.4
Sumatra																			
Tapak Harimau	*n*=4	69.0	4.0	693.4	0.8	1.2	833.6	0.2	0.5	2.0	130.0	66.7	14.9	50.6	11.8	2.80	1.1	5.4	492.1
	SD	1.3	0.3	171.4	0.4	0.0	61.8	0.2	0.1	0.1	2.9	1.2	0.0	0.2	0.7	0.03	0.1	0.0	16.3
Silabe cave	*n*=1	69.2	3.7	602.5	0.7	1.4	808.8	0.1	0.4	1.9	127.0	66.7	14.8	50.5	11.4	2.73	1.0	5.3	480.5
Banda Islands																			
Site PA1	*n*=15	52.0	5.3	251.0	0.2	1.0	478.7	0.1	0.5	13.7	222.3	23.7	19.3	48.7	8.6	1.04	3.2	13.7	397.7
	SD	0.7	0.2	3.5	0.0	0.2	12.7	0.0	0.0	0.3	2.8	0.9	0.4	0.9	0.1	0.03	0.1	0.1	14.9
Site PA1 outlier	*n*=1	78.7	5.6	303.6	0.1	1.0	298.5	4.9	1.8	16.2	239.3	20.2	25.3	65.8	12.1	2.50	5.2	17.2	411.7
ANU2000	*n*=16	185.7	6.6	2014.2	5.6	1.3	452.4	1.4	3.4	2.1	147.8	58.7	32.1	284.1	42.5	3.52	3.2	2.0	642.4
	SD	9.7	0.7	58.9	0.1	0.5	11.9	0.0	0.2	0.1	5.5	2.7	1.4	12.2	0.9	0.06	0.2	0.1	39.4
ANU2000 preferred[a]		185.8	4.6	2022.0	5.6	1.4	469.8	1.5	5.5		149.2	63.4	36.2	303.9	44.0	3.60	3.70	2.0	649.8
		5.7	1.0	24.0	0.2	0.1	26.6	0.1	2.7		10.3	11.8	4.8	11.4	2.3		0.99	0.0	40.1
ANU9000	*n*=18	139.9	6.5	1626.3	5.7	1.1	454.1	0.6	3.1	6.8	51.5	169.8	17.8	119.1	2.2	3.06	0.9	1.5	465.0
	SD	5.7	0.7	45.7	0.1	0.5	13.7	0.0	0.2	0.7	1.8	7.5	0.7	4.6	0.0	0.06	0.1	0.1	25.0
ANU9000 preferred[a]		138.5	4.4	1406.5	5.8	1.0	448.3	0.7	4.6		51.9	205.9	19.1	126.7	2.6	3.23	1.3	1.5	458.3
		10.1	1.3	246.8	0.4	0.0	25.7	0.1	1.4		1.2	46.6	2.3	10.1	0.5	0.12	0.8	0.0	24.8
NIST612 preferred[b]		55.2	41.0	48.5	38.2	42.5	38.5	35.1	36.8	37.3	31.6	76.4	37.8	36.0	38.1	38.3	37.7	41.6	38.5

[a] Values taken from Ambrose et al. 2009, Golitko et al. 2010, Glascock unplub. Data.
[b] Values taken from Pearce et al. 1997.

In addition, 26 artefacts from newly discovered sites on Cebu, the Banda Islands and west Java were included in the analysis. Recently, two obsidian artefacts were found by Tiauzon at the Lastimoso site on the surface of an uplifted limestone hilltop located in Sitio Opaw, Baragay Sta. Filomena some 2.2 km from the southwest coast of Cebu (referred to briefly in Neri, 2007:156). These surface finds were associated with a mixed-aged midden of marine shells and decorated earthenware pottery, as well as Asiatic tradeware porcelain of the last few hundred years. No radiocarbon dates are available for the site, although some of the pottery shows a similar decorative technique to the Lubong site in Carcar dated to 1980–1565 cal BP (Peterson, 2005, data recalibrated).[3] One artefact was found on a second site, Letigio, which is located on a hilltop

[3] Radiocarbon dates available in the literature have been recalculated for this study from the original data using CALIB 6.01 (Stuiver et al., 2011), calibration using IntCal09 and Marine09 (Reimer et al., 2009).

La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Er	Tm	Yb	Lu	Ta	W	^{206}Pb	^{207}Pb	^{208}Pb	Th	U
6.1	12.7	1.68	7.7	2.6	1.05	3.2	0.50	3.2	1.66	0.23	1.50	0.21	0.50	0.19	0.7	0.7	0.7	0.9	0.2
0.0	0.0	0.01	0.0	0.0	0.01	0.0	0.01	0.0	0.03	0.00	0.00	0.00	0.01	0.00	0.0	0.0	0.0	0.0	0.0
23.7	49.4	5.53	19.9	4.7	0.63	4.6	0.74	5.1	3.41	0.51	3.74	0.57	0.75	2.04	23.1	21.5	22.3	13.4	4.3
11.3	28.7	4.11	18.8	6.1	1.74	7.5	1.26	8.9	5.80	0.87	6.05	0.91	0.22	0.94	12.6	11.5	12.1	2.9	0.9
0.6	1.5	0.17	0.7	0.2	0.05	0.2	0.04	0.3	0.24	0.05	0.30	0.04	0.02	0.08	0.7	0.7	0.7	0.2	0.1
14.9	37.7	4.70	19.0	5.2	0.84	5.6	0.94	6.7	4.32	0.69	4.75	0.72	0.43	0.96	16.6	15.7	15.9	5.8	1.6
26.1	57.9	6.38	22.5	5.5	0.37	5.6	0.91	6.2	4.00	0.61	4.13	0.61	0.75	2.77	19.3	17.8	18.6	21.6	5.1
0.3	0.8	0.12	0.3	0.1	0.01	0.1	0.02	0.1	0.07	0.01	0.07	0.01	0.01	0.06	0.8	0.7	0.9	0.3	0.1
23.8	51.5	5.62	19.5	4.6	0.46	4.7	0.75	5.2	3.39	0.52	3.61	0.55	0.71	2.61	18.1	16.8	17.5	19.3	4.7
24.7	49.6	5.06	16.7	3.7	0.45	3.2	0.48	3.3	2.14	0.34	2.48	0.38	0.59	2.66	22.6	20.8	21.9	15.1	3.3
25.4	53.9	6.07	21.6	5.0	0.68	4.9	0.79	5.4	3.53	0.55	3.92	0.61	0.77	2.20	25.2	23.1	24.0	14.4	4.7
0.2	0.5	0.07	0.3	0.1	0.03	0.1	0.02	0.1	0.09	0.02	0.07	0.02	0.01	0.05	0.4	0.4	0.5	0.3	0.1
11.0	23.8	2.95	10.9	2.7	0.58	2.5	0.39	3.0	1.82	0.29	2.14	0.35	0.14	0.35	9.9	9.1	9.3	2.5	1.6
38.4	80.2	8.74	29.8	6.2	1.20	5.5	0.83	5.0	2.83	0.42	2.86	0.44	1.33	0.91	4.5	3.8	4.1	14.9	2.6
38.0	78.6	8.54	29.4	6.1	1.17	5.6	0.79	5.1	2.75	0.42	2.97	0.40	1.33	1.05	5.9	5.4	5.6	14.6	2.8
36.9	76.8	8.39	28.7	6.0	1.15	5.5	0.77	4.9	2.68	0.42	2.90	0.40	1.27	1.39	6.1	5.8	5.8	15.3	2.6
26.3	57.2	6.34	21.2	4.7	0.18	4.3	0.68	4.6	3.25	0.54	4.07	0.62	1.60	3.33	24.7	23.3	24.1	17.2	7.4
0.6	1.4	0.16	0.5	0.2	0.02	0.1	0.02	0.1	0.10	0.02	0.09	0.02	0.06	0.13	0.5	0.6	0.5	0.8	0.3
26.3	63.8	8.26	39.8	16.1	0.87	15.9	2.41	14.7	7.52	1.05	6.69	0.92	2.05	8.86	49.9	45.4	47.5	35.7	11.0
0.4	0.7	0.07	0.3	0.2	0.01	0.1	0.02	0.1	0.07	0.02	0.07	0.02	0.02	0.08	0.4	0.2	0.3	0.2	0.1
30.1	72.6	9.67	46.6	18.6	1.00	18.4	2.80	16.7	8.49	1.20	7.66	1.04	2.19	9.33	55.1	50.5	51.9	41.1	11.6
0.8	1.8	0.22	1.0	0.2	0.02	0.3	0.02	0.1	0.04	0.02	0.09	0.02	0.01	0.11	0.8	0.5	0.5	0.5	0.1
26.1	57.7	6.34	22.4	5.5	0.37	5.6	0.91	6.2	4.02	0.61	4.10	0.61	0.76	2.74	18.8	17.3	18.1	21.5	5.0
0.3	0.6	0.08	0.3	0.1	0.01	0.2	0.03	0.1	0.09	0.01	0.08	0.01	0.01	0.05	0.3	0.2	0.3	0.3	0.1
23.7	51.5	5.56	19.2	4.5	0.44	4.7	0.74	5.0	3.30	0.50	3.49	0.53	0.70	2.59	17.8	16.5	17.2	19.1	4.6
21.7	42.0	4.12	12.7	2.6	0.41	2.3	0.35	2.4	1.56	0.26	1.90	0.31	0.98	1.79	14.5	13.4	14.1	16.9	4.3
0.1	0.1	0.01	0.0	0.0	0.01	0.0	0.00	0.0	0.02	0.01	0.02	0.01	0.02	0.02	0.3	0.3	0.3	0.1	0.0
21.4	41.7	4.10	12.7	2.5	0.41	2.2	0.35	2.3	1.57	0.25	1.88	0.31	0.95	1.79	14.7	13.4	13.9	16.8	4.3
19.2	36.9	3.57	11.5	2.8	0.23	2.9	0.47	3.2	2.05	0.31	2.23	0.34	1.09	2.09	40.1	36.5	38.2	16.9	5.4
0.4	0.9	0.08	0.2	0.1	0.02	0.1	0.01	0.1	0.07	0.01	0.05	0.01	0.03	0.05	1.2	1.0	1.1	0.6	0.1
18.7	42.2	4.50	15.8	4.0	0.27	4.0	0.67	4.3	2.56	0.42	2.81	0.42	1.20	3.00	45.0	41.2	43.3	16.6	5.4
36.0	72.0	7.42	24.3	5.1	0.87	5.2	0.81	5.4	3.52	0.54	3.82	0.58	3.08	1.29	6.8	6.2	6.4	10.6	3.0
1.8	3.5	0.40	1.3	0.2	0.05	0.2	0.04	0.3	0.16	0.02	0.18	0.03	0.13	0.04	0.3	0.3	0.3	0.9	0.2
39.1	77.2	8.90	26.7	5.41	0.96	5.6	0.95	5.9	3.86	0.62	4.24	0.63	2.99	1.33	10.0	6.4	6.7	12.4	3.2
1.8	3.8		3.7	0.54	0.06	0.6	0.06	0.4	0.34		0.41	0.08	0.13		4.3			2.5	0.5
11.3	24.3	3.00	11.4	2.7	0.60	2.7	0.42	2.8	1.97	0.31	2.26	0.36	0.14	0.37	10.1	9.2	9.5	2.5	1.6
0.5	1.0	0.15	0.6	0.1	0.03	0.1	0.02	0.1	0.09	0.01	0.10	0.02	0.01	0.02	0.4	0.4	0.4	0.2	0.1
12.1	25.4	3.6	13.2	2.8	0.62	2.7	0.48	3.0	2.02	0.35	2.34	0.37	0.14	0.38	10.4	9.6	9.9	2.7	1.7
0.8	1.3	0.6	1.8	0.2	0.0524	0.1	0.01	0.3	0.1131	0.08	0.1411	0.0263	0.00	0.03	0.1	0.3	0.2	0.3	0.2
35.5	38.2	37.1	35.0	36.4	34.6	37.1	36.3	35.7	38.0	37.7	39.5	37.6	39.8	39.6			38.7	37.3	36.9

approximately 1 km to the north of the Lastimoso site and 2.4 km from the coast. The site context is similar to the Lastimoso site, although tradeware porcelain is absent.

Artefacts from the Banda Islands derive from archaeological excavations of the Neolithic site on Pulau Ay (16 artefacts: site PA1) (Lape, 2000a, also Spriggs et al., this volume).

Simanjuntak collected obsidian from the surface of three sites on the Bandung plateau of west Java (seven artefacts; Chia et al., 2008), including two flakes each from Tugu (Cimenyan) and Pakar Dago, and three from Panyawangan.

3. Method

For sample preparation each piece of obsidian was washed in an ultra-sonic bath for 10 min and then cut with a 200 μm diamond wire saw to minimise material loss. The fluid which moisturises the wire while sectioning the sample was a mixture of tap water and detergent. An approximately 1 mm^3 piece was sectioned from each sample and embedded in an epoxy resin. The constructed mount, 50 × 25 × 4 mm in size, can carry up to 40 samples, set in a 10 × 4 array. Excess resin was removed from the sample mount using sandpaper and the surface was flat mirror polished. For the EDX analysis the samples were coated with a 30 nm thick carbon film.

The obsidian samples in this study were examined with a JEOL JSM6400 SEM equipped with an Oxford ISIS EDXA (Oxford instruments Link ISIS 3.3 software) for eight major elements (Na, Mg, Al, Si, Ca, K, Ti, Mn and Fe) at the Research School of Biological Sciences at the ANU (Table 2). The SEM–EDXA was calibrated with eleven mineral standards (Albite 15 kV, MgO 15 kV, Sanidine [$KAlSi_3O_8$], CeP_5O_{14}, FeS_2, NaCl, Diopside, TiO_2 15 kV, Cr_2O_3 15 kV, pure Mn 15 kV, Fe_2O_3), against the NIST612 Standard Reference Material. The calculated SiO_2 content was employed to calibrate ICPMS analysis (Ambrose et al., 2009).

LA-ICPMS (Table 3) analysis was conducted in the Research School of Earth Sciences at the ANU (Falkner et al., 1995, Longerich et al., 1996, for detailed experimental set-up and methods used see Reepmeyer, 2008). Samples were analysed in an AGILENT 7500S ICPMS combined with a Lambda Physik 193 nm wavelength ArF laser ablation system, with the laser diameter set at 86 μm. The sample was ablated in a He atmosphere with power delivered to the sample surface of about 20 mJ. The ablated aerosol was carried to the ICP by a 30:70 mix of He and Ar. Internal calibration was against the NIST612 Standard Reference Material, measured in a round-robin fashion with a maximum of 10 analysis brackets. Counts for 31 isotopes (^{31}P, ^{45}Sc, ^{49}Ti, ^{51}V, ^{55}Mn, ^{63}Cu, ^{85}Rb, ^{88}Sr, ^{89}Y, ^{90}Zr, ^{93}Nb, ^{95}Mo, ^{118}Sn, ^{133}Cs, ^{138}Ba, ^{139}La, ^{140}Ce, ^{144}Nd, ^{147}Sm, ^{153}Eu, ^{158}Gd, ^{162}Dy, ^{166}Er, ^{174}Yb, ^{175}Lu, ^{181}Ta, ^{186}W, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th and ^{238}U) were determined by calculating the mean counts for each isotope from three analysis runs per sample. For multivariate statistical analysis, the C2 package was employed (Juggins, 2005). Absolute parts per million (ppm) counts of 31 elements were log ($\log_{10}$) transformed and examined with Principal Components Analysis (PCA, Baxter, 2006).

Overall precision and accuracy of both methods was assessed by two high-silicate obsidian standards from Wekwok, Admiralty Islands (ANU2000) and Kutau/Bao, West New Britain (ANU9000) (Reepmeyer, 2008; Summerhayes, 2009). Preferred values of the standards derive from exemplary determination of inter-laboratory and inter-method comparability including LA-ICPMS analyses from the Field Museum of Natural History Elemental Analysis Facility (Golitko et al., 2010) based on a slightly different internal calibration protocol than used in this study as outlined in Gratuze et al. (2001); NAA data from Missouri University Research Reactor (Bird et al., 1997, Torrence, pers. comm.) and previous runs of LA-ICPMS at the ANU (Ambrose et al., 2009). High precision of $<2-3\%$ at 1σ standard deviation is achieved by SEM-EDXA in analysing major elements with high concentrations in the matrix, such as SiO_2, Na_2O, K_2O, Al_2O_3 and FeO. Analysing major elements with low counts, such as TiO_2 and MnO decreases the precision to 5–10%. LA-ICPMS in general shows good precision of 1σ standard deviation at $<5\%$. Calibrating LA-ICPMS with an external method has proven to be an efficient way to acquire high-resolution data and long-term stability in results. Accuracy of the combined analysis shows high correlation in all measured elemental concentrations between preferred values and actual measurements at around 1σ standard deviation overlap.

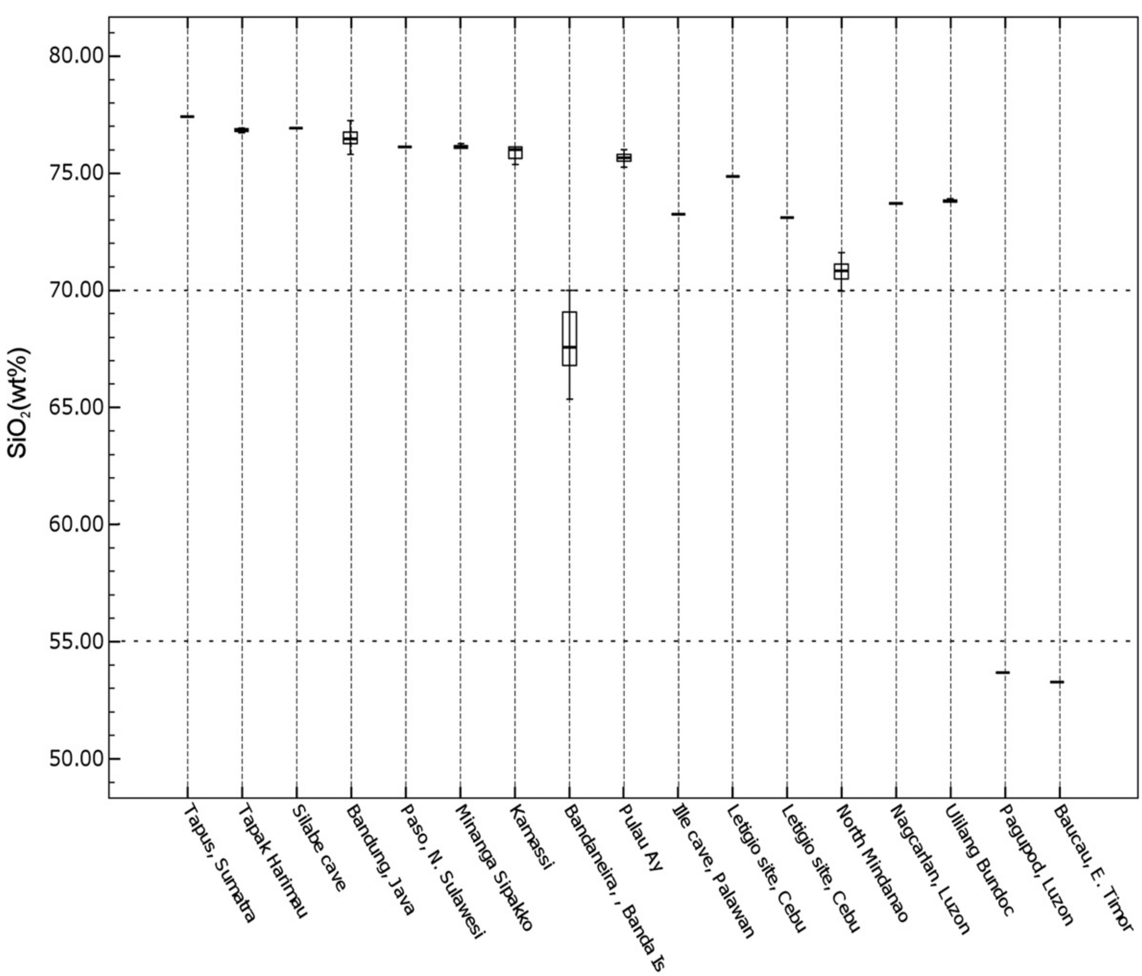

Fig. 2. A comparison of SiO_2 (wt%) abundances of obsidian sources and sites in Indonesia and the Philippines.

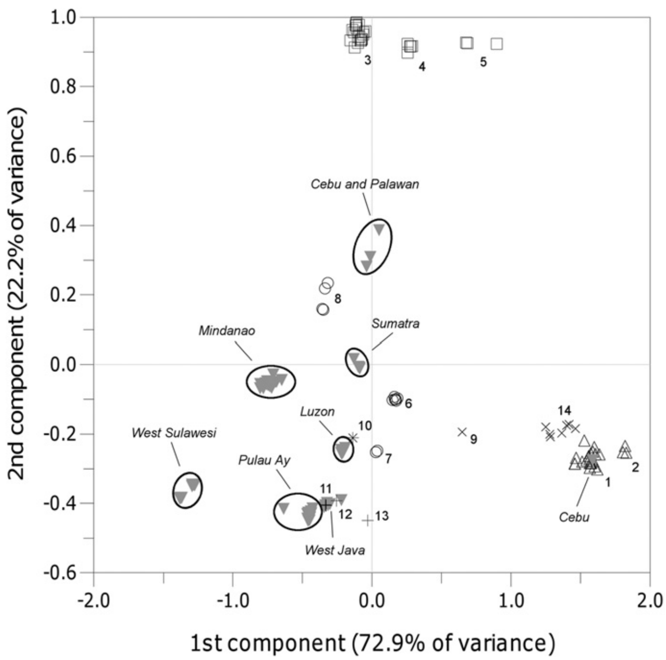

Fig. 3. Principal Component Analysis of major obsidian sources in PNG and Island SE Asia using Rb, Nb, Cs, Ta, W, ^{208}Pb, Th and U comparing with obsidian artefacts found in Island SE Asia. **Obsidian sources**: 1 Kutau/Bao, WNB; 2 Mopir, WNB; 3 Lou, AD; 4 Manus, Southwest; 5 Manus, Lepong; 6 Igaweta, West Fergusson; 7 Fagalulu, West Fergusson; 8 East Fergusson; 9 Paso, North Sulawesi; 10 Nagcarlan, Luzon; 11 Leles/Nagrek A, Bandung; 12 Nagrek B, Bandung; 13 Tapus, Sumatra; 14 Bandaneira, Banda Islands.

Inter-method accuracy has been discussed as showing discrepancies of measured elemental concentrations of up to 20% (Bellot-Gurlet et al., 2005, Bugoi et al., 2004, Glascock, 1999; Hancock and Carter, 2010; James et al., 2005). As discussed above our results show better inter-method accuracy in general at around 5%. Therefore, we assume that calculated discrepancies of selected elements such as MnO and Mn, measured in both analyses, might derive from impurities in the matrix of sample.

SEM-EDXA as well as LA-ICPMS employed in this study can both be described as micro-analytical techniques. A major advantage of micro-analytical techniques, the analysis of small areas in contrast to bulk analyses like NAA, XRF, PIXE-PIGME or solution ICPMS, brings with it new challenges to inter-method comparability. One important observation analysing relative low-silicate obsidian sources is the occurrence of phenocrysts in the matrix of the raw material. Some of these phenocrysts are macroscopically visible (mainly plagioclase, Ca–Na alumino-silicates), but micro-phenocrysts might also occur, for example titano-magnite concretions (Deer et al., 1992). Variable results of major element concentrations such as Na, K, Ca, Ti, Mn and Fe ensue if differing volumes of glass, plagioclase and microphenocrysts are encountered in an ablation pit, especially if focussed on large micro-phenocrysts ~100 μm. This indicates a problem of micro-analytical techniques in comparing data from true bulk analysis of rock specimens containing microphenocrysts where a detailed choice of the excited area is limited and therefore the average of a much larger sample volume is analysed (Reepmeyer, 2008; Reepmeyer et al., in press).

4. Results

The 101 samples used in this study consist of 19 samples from seven obsidian sources and 82 obsidian artefacts from 19 archaeological sites which are included in a multi-element analysis (Table 1). The geochemical compositions of the artefacts are compared with the source samples and an additional dataset of eight obsidian sources from Island Melanesia. The Melanesian source samples derive from the obsidian collection of Archaeology and Natural History in the School of Culture, History and Language of the ANU and have been previously analysed using SEM-EDXA and LA-ICPMS (Ambrose et al., 2009, Reepmeyer, 2009). Table 2 presents summary statistics of major elements analysed with EDXA and Table 3 presents data of the LA-ICPMS analysis.

Examining the distribution of SiO_2 wt% (Fig. 2) content from sources of ISEA there is a noticeable decrease of SiO_2 between sources originating from the Sunda Arc to the west and sources in the Philippines arc systems to the north. Sources from the Celebes seem to have a similar SiO_2 content as seen on the Western Sunda

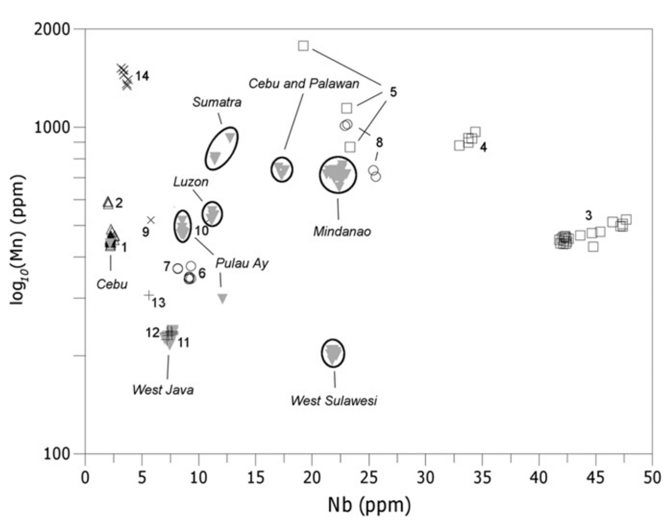

Fig. 4. A comparison of absolute counts of Nb (ppm) and Mn (ppm). Obsidian sources: 1 Kutau/Bao, WNB; 2 Mopir, WNB; 3 Lou, AD; 4 Manus, Southwest; 5 Manus, Lepong; 6 Igaweta, West Fergusson; 7 Fagalulu, West Fergusson; 8 East Fergusson; 9 Paso, North Sulawesi; 10 Nagcarlan, Luzon; 11 Leles/Nagrek A, Bandung; 12 Nagrek B, Bandung; 13 Tapus, Sumatra; 14 Bandaneira, Banda Islands.

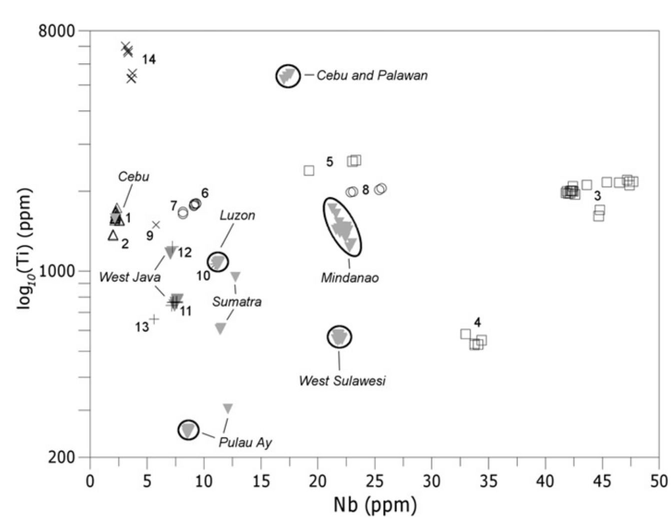

Fig. 5. A comparison of absolute counts of Nb (ppm) and Ti (ppm). Obsidian sources: 1 Kutau/Bao, WNB; 2 Mopir, WNB; 3 Lou, AD; 4 Manus, Southwest; 5 Manus, Lepong; 6 Igaweta, West Fergusson; 7 Fagalulu, West Fergusson; 8 East Fergusson; 9 Paso, North Sulawesi; 10 Nagcarlan, Luzon; 11 Leles/Nagrek A, Bandung; 12 Nagrek B, Bandung; 13 Tapus, Sumatra; 14 Bandaneira, Banda Islands.

Arc. In general, sources in Java, Sumatra and Sulawesi display very high counts of SiO_2 of >76.5 wt% in contrast to the Nagcarlan source in central Luzon with ~73 wt% SiO_2 and the Pagupod pitchstone source with only ~53 wt% SiO_2. Sources found on the Banda Arc are in general of lower silicate composition than Sunda Arc sources. Ambrose et al. (2009) reported one pitchstone source in Baucau, East Timor, with only ~53 wt% SiO_2, Jezek and Hutchinson's (1978) Ambon source in the Moluccas had only 71 wt% SiO_2 and the source from Bandaneira contained only ~67 wt% SiO_2. It is unlikely that the reported high-silicate source obsidian artefacts on Timor (Ambrose et al., 2009, Reepmeyer et al., 2011) come from Timor itself. They were most probably imported from a non-Timor source.

To assess the complex dataset of this study, 31 element concentrations measured with SEM-EDXA and LA-ICPMS were tested for their quality to separate sources from each other. Principle Component Regression on the first and second score ranked the measurements of Rb, Nb, Cs, Ta, W, ^{208}Pb, Th and U highest. These elements were explored with the unsupervised discrimination method of Principal Components Analysis (PCA). PCA is particularly useful in reducing the complexity of a multi-variable dataset as it orders cases in relation to their similarity and dissimilarity along eigenvectors. The PCA on the material (the first eigenvector representing 72.9% of the variance and the second 22.2%) showed a clear separation of all obsidian sources from each other (Fig. 3). Higher standard deviations within several sources, for example in the Lou and Manus sources in the Admiralty Islands or the Kutau/Bao sources in West New Britain are well presented in the PCA plot.

Correlating sources and 82 obsidian artefacts, a clear pattern for the discrimination of different regions emerges. Only 16 obsidian artefacts of the assemblage can be unambiguously geochemically fingerprinted to source locations. All artefacts found in the site of Ulilang Bundoc on Luzon were previously sourced to the Nagcarlan source in central Luzon (Neri and de la Torre, 2007). This provenance is confirmed. Artefacts found on the Bandung plateau of west Java are fingerprinted locally to both the Nagrek (formerly Leles) A and B outcrops. Although the majority of the artefacts originate from Nagrek A, one artefact was sourced to the Nagrek B outcrop suggesting that both deposits were utilised in the past. Finally, one artefact found in the Lastimoso site on Cebu is sourced to the Kutau/Bao source in West New Britain. This is currently the northernmost distribution of this material. Unfortunately, the artefact was found on the surface and is undated.

The remaining 66 artefacts cannot be sourced to a specific location although several matches between sites are found. Two artefacts, one found in Ille cave on Palawan and one at the Letigio site on Cebu originate from the same unknown source. Quaternary volcanism and associated high-silicate facies do not occur on Palawan Island (Suzuki et al., 2000; Yumul Jr. et al., 2009), therefore it is clear that any obsidians transported to Ille cave must originate from a non-Palawan source. The third artefact from Cebu is currently unsourced, but shows similarities with the obsidians from Letigio and Ille Cave, indicating that there might be some variation within this specific source. However, until further research is done this interpretation remains speculative (cf. Reepmeyer and Clark, 2010). All artefacts found in the northern Mindanao sites originate from a single source, the low standard deviation implying a single outcrop.

The ten artefacts found in two sites in central-west Sulawesi (Kamassi and Minanga Sipakko) show comparable variance in their composition suggesting intra-source variation of a single obsidian source (Figs. 4 and 5), but do not match the composition of the two analysed source samples from the Tondano area in northern Sulawesi (cf. Ambrose et al., 2009 for geochemical results from one Tondano source sample). The enriched K_2O and highly depleted Ti content of the artefacts are similar to leucocratic rocks found in the Dondo Super Suite in central Sulawesi (Elburg et al., 2003:254, Table 2). The extremely high ^{208}Pb values (>45ppm) which are rare in all known obsidian sources in ISEA and the Pacific, can also be found in this formation in central Sulawesi. The only comparably high amounts of ^{208}Pb (>40ppm) occur in obsidian artefacts from Pulau Ay in the Banda Islands. The artefacts from Pulau Ay could be sourced to a single high-silicate obsidian source but do not match the dacitic glass source known on Bandaneira. The high-silicate content of the artefacts suggests a non-Banda Island and most likely a non-Moluccan source. One outlier showed significant lower Mn and K_2O, but slightly enriched values in almost all remaining major and trace elements (Tables 1 and 2). Finally, the five artefacts analysed from the Silabe cave and Tapak Harimau in south Sumatra show a high correlation (independent t-test: df 3, t 0.320, σ 0.629) and might derive from the same source, but do not match the analysed Tapus source in the Bengkulu area. The elemental composition suggests an additional local source in south Sumatra.

Some further evidence of inter-island transportation of obsidian provides a comparison of the presented dataset with previous analysed sources in ISEA using PIXE-PIGME (Table 4, Bird, 1996; Bird et al., 1981, Smith et al., 1977). The four sources reported in previous publications were found on Sumatra (Kerintji), Java (Leles and Mt Kiamis) and Sulawesi (Minahasa). Additionally, artefacts were analysed from the island of Talaud and a compositional match with a group of artefacts from the Bukit Tengkorak site in Sabah was found (Bellwood and Koon, 1989; Tykot and Chia, 1997).

Although different methods of chemical analysis usually detect elements with slightly different precision, as discussed above, there is a reasonable correlation between the EDXA and LA-ICPMS data and previous PIXE-PIGME results of source samples from the Kerintji and Tapus sources, the Leles and Nagrek A and the Minahasa and Tondano sources (Figs. 6 and 7), which are assumed to represent the same outcrops. The presented data supports the recent study by Poupeau et al. (2010) comparing SEM-EDS, PIXE-PIGME and EDXRF datasets, which identified a good correlation in accuracy between these methods.

Table 4
Summary statistics of PIXE-PIGME data (taken from Bird, 1996).

		Na_2O %	Al_2O_3 %	SiO_2 %	K_2O %	CaO %	FeO %	F	Ti	Mn	Zn	Rb	Sr	Y	Zr	Nb
Kerintji	$n=3$	3.50	11.50	73.45	3.62	1.10	1.14	261	715	381	29	133	104	5	72	1
	SD	0.37	0.75	5.38	0.21	0.08	0.22	14		18	2	11	11	5	2	2
Leles	$n=7$	3.22	11.79	71.67	4.49	0.91	1.29	678	760	267	33	163	47	35	108	3
	SD	0.38	0.40	7.49	0.70	0.22	0.10	85	142	44	5	20	20	5	22	3
Kiamis	$n=3$	3.55	12.11	80.22	4.42	1.30	1.54	619	724	378	62	213	84	15	141	5
	SD															
Minahasa	$n=11$	3.95	12.04	72.52	3.37	1.23	1.99	663	1509	537	88	76	77	37	226	5
	SD	0.30	0.32	7.49	0.34	0.18	0.13	24	111	48	51	10	8	5	33	4
Talaud	$n=4$	4.52	13.77	59.26	5.81	0.98	1.94	1270	1289	778	91	274	8	23	344	25
	SD	0.09	0.47	3.42	0.54	0.08	0.08	17	72	61	13	12	3	11	25	4

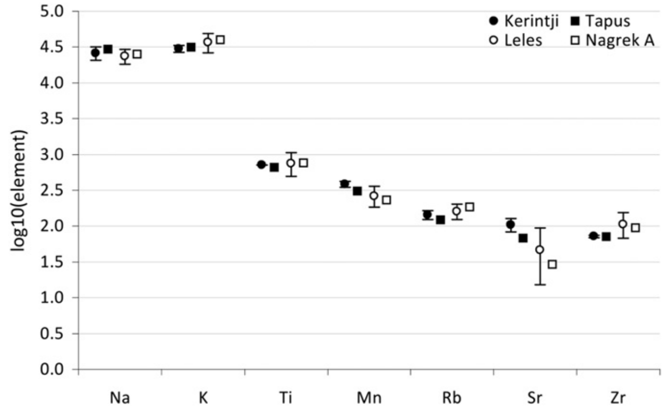

Fig. 6. A comparison of summary statistics (mean, error bars representing 2σ, log_{10} transformed) of absolute counts of Na, K, Ti, Mn, Rb, Sr and Zr for Leles, Nagrek A, Kerintji and Tapus.

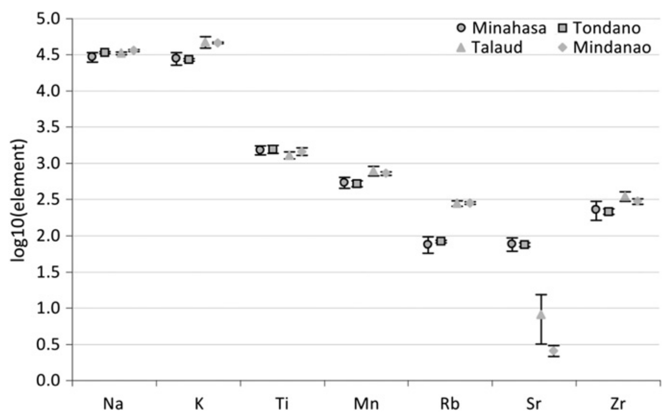

Fig. 7. A comparison of summary statistics (mean, error bars representing 2σ, log_{10} transformed) of absolute counts of Na, K, Ti, Mn, Rb, Sr and Zr for Minahasa, Tondano, Talaud and North Mindanao sites.

Fig. 7 presents additional comparison between artefacts from northern Mindanao and the Talaud piece. The correlations between these artefacts are comparable to variations within source locations. In particular, the depleted Sr values show a striking similarity (Tables 3 and 4) suggesting that these artefacts originate from the same obsidian source, as therefore must some of the artefacts from Bukit Tengkorak.

5. Discussion and conclusion

The study shows that the current dataset of seven utilised obsidian sources in ISEA is far from complete. Evidence has been presented that a minimum of six additional obsidian sources, possibly more, were utilised in the past. The lower SiO_2 content of the artefacts found in Cebu, Palawan and Mindanao suggests two additional sources in the Philippines region. Artefacts found in central-west Sulawesi, the Banda Islands and Sumatra imply at least three additional sources on the Sunda-Banda Arc. Adding the single high-silicate source of unknown location somewhere in the Timor region (Ambrose et al., 2009, Reepmeyer et al., 2011), indicates that at least six sources of obsidian in ISEA are currently unlocated.

In this study, local (here defined as non-sea transported obsidian, cf. Ambrose et al., 2009, Reepmeyer et al., 2011) use of obsidian has been shown for Ulilang Bundoc, central Luzon, and on the Bandung plateau, west Java. Additionally, it has been suggested that local sources of obsidian have been utilised in Tapak Harimau and the Silabe cave in South Sumatra. In central-west Sulawesi, obsidian artefacts from Minanga Sipakko and Kamassi might share variations of a single local source, although these data are not decisive and need further research.

Evidence for inter-island transportation of obsidian raw material has been found in several instances. A match between obsidian artefacts from Ille cave on Palawan and an artefact from the Letigio site on Cebu indicates sea-transport of obsidian. If the artefacts dated to the terminal Pleistocene (Lewis et al., 2008) at Ille cave are located in primary deposition, the comparison to the probable mid-Neolithic site context of the Letigio artefact would suggest a significant time-depth for the exploitation of this obsidian outcrop. Inter-island connections have also been suggested for the artefacts from the PA1, Pulau Ay site in the Banda Islands as no obsidian outcrop has been found on Pulau Ay so far. The 32 samples from the northern Mindanao sites suggest a more intensive utilisation of obsidian on this island, which might derive from a local source. The present data from geological research indicate that several locations of Quaternary dacitic volcanism can be found on Mindanao. Comparison with PIXE-PIGME data matched the single artefact from Talaud with the Mindanao artefacts, indicating that there was contact between these islands during Neolithic times. Previous analyses had already demonstrated that some obsidians from Bukit Tengkorak in Sabah on Borneo were from the same source as the Talaud piece (Bellwood and Koon, 1989), thus extending the distribution of obsidians from this putative Mindanao source. Additional evidence for long-distance obsidian transportation has been presented with the single obsidian artefact from the Lastimoso site on Cebu which has been provenanced to West New Britain, some 3500 km away to the east.

The notion of a Pre-Neolithic time-depth of inter-island interaction networks as suggested by possible Pleistocene-aged artefacts from Ille cave and a probable off-island source for obsidian artefacts from East Timor is supported by suggestions of Pre-Neolithic contact between Bukit Tengkorak and Talaud. Further evidence may confirm a pattern of terminal Pleistocene to mid-Holocene, Pre-Neolithic inter-island obsidian transportation similar to that attested in New Guinea and adjacent islands involving West New Britain sources (Torrence et al., 2004, 2009).

The review of previous research on archaeological sites and the general geology/geochemistry of ISEA (Spriggs et al., this volume) has shown that there are several major gaps in our knowledge of past interaction between distant communities in the region. The new program of geochemical research has made a contribution in closing several of these gaps, but many issues remain unresolved.

The general lack of identified and systematically sampled obsidian sources is a major obstacle in understanding obsidian distribution systems in ISEA. It is proposed that future projects and surveys include geological investigation of possible undetected obsidian outcrops in Borneo, Sulawesi, Mindanao, and particularly the Moluccas and the Lesser Sunda chain. These aims get easier to achieve as new geochemical analytical techniques, for example non-destructive portable XRF machines (Sheppard et al., 2010), become more widely available. The techniques allow for in situ analysis of outcrops and larger ensembles of obsidian artefacts, avoiding the danger of biased selection of artefacts. The limited range of elements and limited precision and accuracy of these techniques can be managed by developing analytical protocols in which selected sub-sets of artefacts are analysed with more precise and accurate techniques, such as ICPMS and Neutron Activation Analysis.

The identification of Kutau/Bao obsidian on Cebu, although currently undated, indicates potential new directions for migration/communication routes in relation to the dispersal of the Austronesian language family. Neolithic interaction networks and even possible back-migration from the Bismarck Archipelago have been suggested by the identification of Kutau/Bao obsidian in Bukit Tengkorak (Bellwood and Dizon, 2008; Bellwood and Koon, 1989). The detection of Kutau/Bao obsidian in ISEA in a second site as far north as Cebu provides further support. In relation to understanding processes involved in the Austronesian expansion, a significant new discovery concerns a possible mid-Holocene interaction networks connecting the well-researched site of Bukit Tengkorak with the area to the east of Borneo. The Sabah – Talaud – Mindanao artefact source similarities could suggest that the spread of Neolithic innovations occurred along communication routes that were established in the Pre-Neolithic, mid-Holocene period. It should be noted, however, that the only Pre-Neolithic context found so far in this regard is at Bukit Tengkorak; the Talaud and Mindanao finds are all from Neolithic sites. The newly identified Cebu – Palawan connection, possibly already established in the terminal Pleistocene, adds further evidence of inter-island interaction networks possibly active during Pre-Neolithic times.

Unfortunately, many of these connections are currently based only on limited evidence from single samples, and additional research is needed to verify these connections. This new program of detailed geochemical analysis of obsidian exploitation and distribution, however, has shown the high potential of these kind of studies for understanding complex prehistoric interactions in ISEA.

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