Characterization of the Monte Arci (Sardinia) Obsidian Sources

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In the western Mediterranean, obsidian from four volcanic island sources was used beginning in the Neolithic period. The geological sources on Lipari, Palmarola, and Pantelleria have been located and chemically characterized; until now, however, the Monte Arci source in Sardinia was better known from the analysis of archaeological rather than geological specimens. The results of a comprehensive field survey and characterization study of the obsidian sources in Sardinia are presented here, and finally allow all obsidian artefacts of western Mediterranean origin to be attributed to specific sources using minimally destructive and relatively inexpensive methods of analysis. Five chemically distinct sources in the Monte Arci region were exploited, with their location and the physical properties of the obsidian itself contributing to chronologically and spatially diverse frequency-of-use patterns.   © 1997 Academic Press Limited

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Introduction

Provenance studies (see reviews by Dixon, 1976; Tykot, 1995; Williams-Thorpe, 1995) have indicated that obsidian sources on the Italian islands of Lipari, Palmarola, Pantelleria and Sardinia were exploited beginning in the Neolithic period, and obsidian distributed to sites in southern France, peninsular Italy, Corsica, Sardinia, Sicily, Malta and North Africa (Figure 1). Experimental research demonstrated that all four sources could be differentiated based on their trace element composition (Cann & Renfrew, 1964; Belluomini & Taddeucci, 1971; Hallam, Warren & Renfrew, 1976) and neutron activation analysis (NAA) or X-ray fluorescence (XRF) has been used since in many western Mediterranean obsidian provenance studies (Williams-Thorpe, Warren & Barfield, 1979; Williams-Thorpe, Warren & Courtin, 1984; Crummett & Warren, 1985; Bigazzi *et al.*, 1986, 1992; Francaviglia & Piperno, 1987; Ammerman *et al.*, 1990; Ammerman & Polglase, 1993, 1997; Randle, Barfield & Bagolini, 1993; Crisci *et al.*, 1994).

The four island sources can also be differentiated by the date of their geological formation, using potassium–argon (Belluomini *et al.*, 1970; di Paola *et al.*, 1975) or fission-track dating (Bigazzi *et al.*, 1970). Density and refractive index, Mössbauer (Longworth & Warren, 1979; Aramu *et al.*, 1983) and electronic paramagnetic resonance (Mello, 1983) spectra, and magnetic parameters (McDougall, Tarling & Warren, 1983), however, are insufficient discriminators. Isotopic analysis (Gale, 1981) is promising, but

is far too expensive to be applied to large numbers of artefacts.

Furthermore, while the obsidian sources on Lipari (Li) and Palmarola (Pl) were found to be chemically homogeneous (see also Mosheim, 1979; Francaviglia, 1986; Herold, 1986), analyses of artefacts made of obsidian from Pantelleria (Pa) (Francaviglia & Piperno, 1987) and from Sardinia (Cann & Renfrew, 1964; Hallam, Warren & Renfrew, 1976) indicated that multiple, differentiable sources or flows exist on those islands. The location of the Pantellerian sources has been largely resolved (Francaviglia, 1988), while the subject of the Sardinian sources has a very long history. De la Marmora (1839–1840) mentioned several places on Monte Arci where obsidian could be found *in situ*, and Puxeddu (1958) identified four sources, 11 collection centres, and 74 workshops in his survey of the Monte Arci region. Chemical analyses of artefacts suggested the existence of at least three chemically distinct sources—labelled SA, SB, SC (Hallam, Warren & Renfrew, 1976)—but only one (SA) was geologically identified. There is also no discernable difference in the fission-track ages of Sardinian artefacts (Bigazzi *et al.*, 1976; Bigazzi & Radi, 1981; Arias *et al.*, 1984). Four independent studies have been done since to locate fully and characterize chemically the Sardinian sources.

Mackey apparently did a detailed survey and characterization study for her doctoral dissertation in geology at the University of Nottingham, but her thesis was not completed and the only available data come from a brief conference paper (Mackey & Warren,
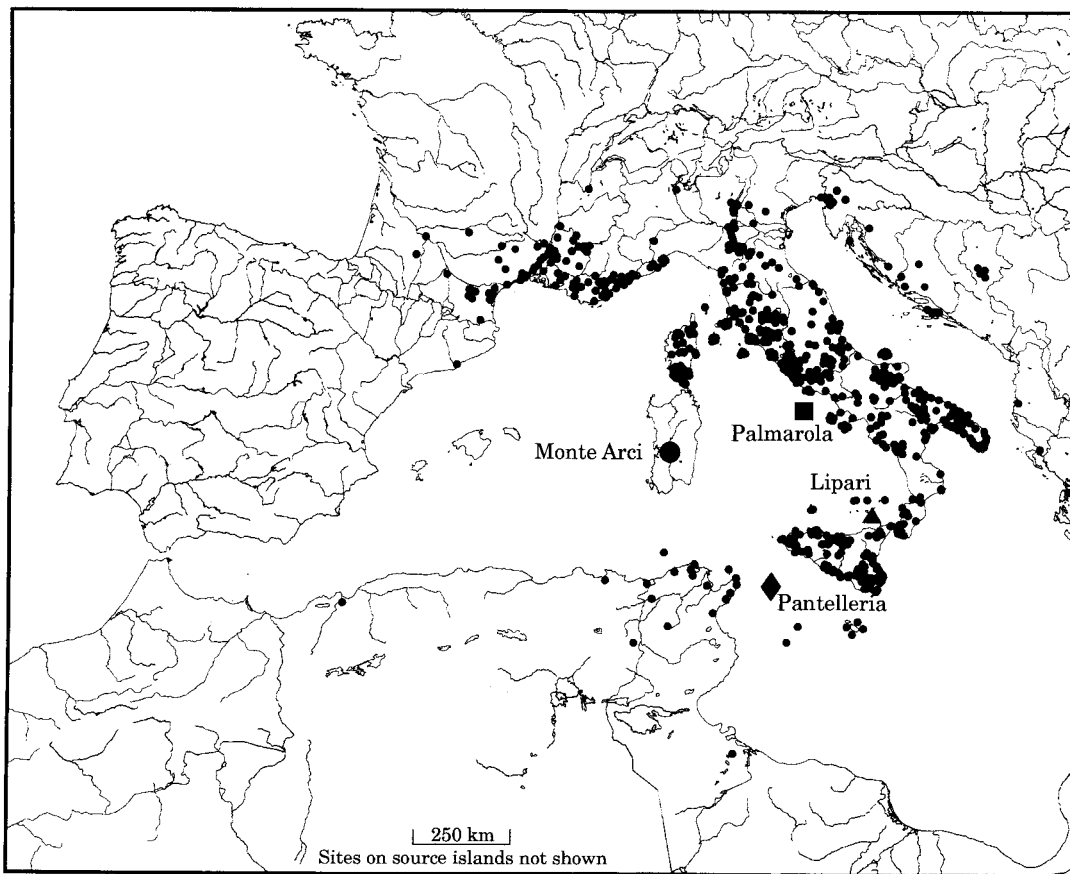
Figure 1. Obsidian sources and archaeological sites with obsidian in the western Mediterranean. The compilation of sites is largely based on Pollmann (1993) and other references listed in Tykot (1995).

1983). In addition to the SA source, two *in situ* sources were located and found to be related to the archaeologically-determined SB group, while the source area for SC group obsidian was established even though *in situ* material was not identified. The number of geological samples tested and the individual data for the analyses remain unknown.

Francaviglia (1986) analysed some 172 geological samples from five source locations in Sardinia, but gave little information about the deposits themselves, and did not publish individual sample data either. Two of these sources contain obsidian nodules too small to have been utilized for artefacts, and one of the outcrops identified by Mackey was not tested. Francaviglia's main contribution was the identification of two subgroups of the SC source, neither found *in situ*, and the demonstration that all of the main Mediterranean obsidian sources (SA, SB, SC, Li, Pa, PI, Melos, Giali) could be distinguished on the basis of their major element composition alone.

Herold (1986) also did a survey and analysis of the Sardinian sources for his Ph.D. Thesis in geological science at the University of Karlsruhe, but these data too have not been formally published. He characterized four chemical subgroups among numerous

localities with small unworkable nodules, in addition to the same four workable sources identified by Mackey; his data also revealed significant differences in the major and trace element composition of Mackey's two SB source groups.

Finally, Tykot (1991, 1992, 1995) completed an extensive programme of survey and analysis of the obsidian sources, finally locating the SC source *in situ*, while confirming that five distinct chemical sources are represented among archaeological artefacts. This research was also designed to demonstrate the utility of low-cost, major-element analysis for determining the provenance of hundreds of artefacts and making significant interpretations about geographic and chronological variations in obsidian source exploitation.

Monte Arci Field Survey

Unaware at the time of either Herold's or Francaviglia's efforts, my own fieldwork at Monte Arci began in 1987 with a survey of the zones previously identified as containing acidic lavas (Beccaluva *et al.*, 1974*a*, *b*; Assorgia *et al.*, 1976), and hence possibly
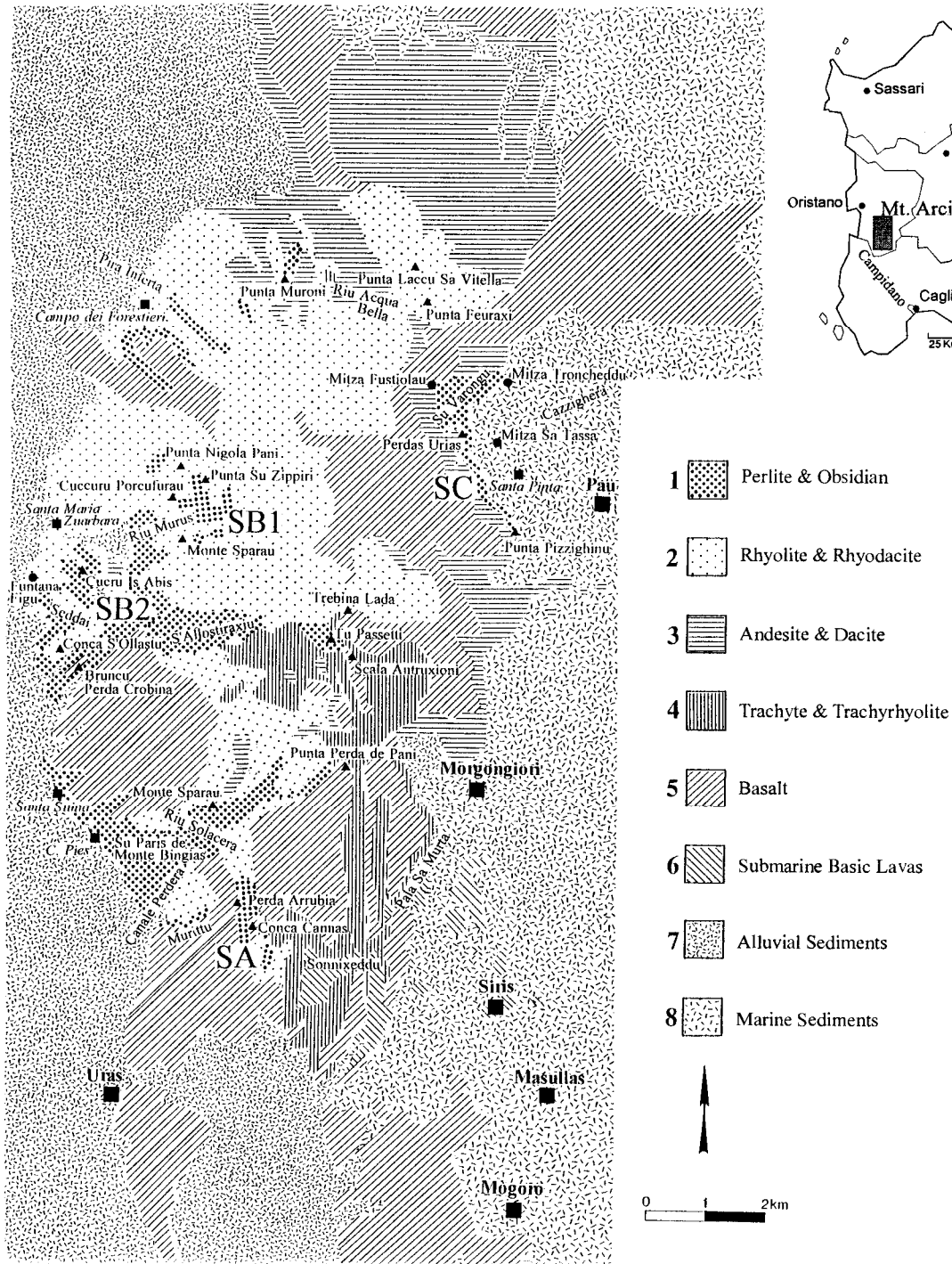
Figure 2. Geological map of Monte Arci, Sardinia showing sites where obsidian was collected.

obsidian (Figure 2). Some unworked obsidian was in fact found in many of these areas, although often as float nodules or as millimetre-sized specks in a rock matrix. The results of the survey are presented here.

The best-known source is located below the peak of Conca Cannas, north-east of Uras, where obsidian occurs in an abandoned perlite quarry along with rhyolite and trachyte. Obsidian is frequently found as small specks within a perlitic matrix along the Riu Cannas, and rising up to Conca Cannas itself (elevation 382 m a.s.l.). No trace of obsidian was found near Perda Arrubia, nor near Sonnixeddu. One can find rather small, unworkable nodules of obsidian in a broad area to the south and east of the quarry, while
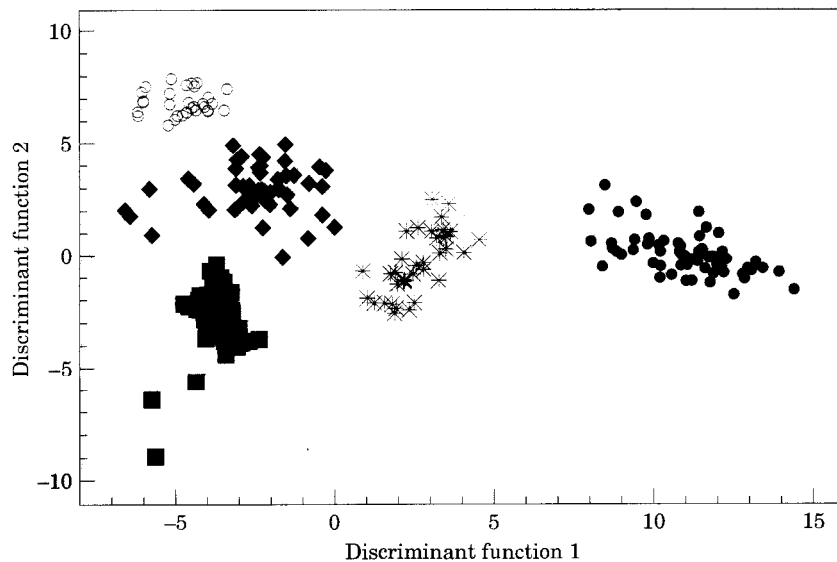
Figure 3. Discriminant analysis of ICP-MS data for the Monte Arci obsidian sources. The discriminant functions are derived from the elemental concentrations of Ba, Mn, Sc, Rb, Sr, Y, La and Ce. ■: SA; *: SB1; ◆: SB2; ●: SC1; ○: SC2.

fist-sized obsidian nodules are abundant in a more restricted area. These nodules average 10–15 cm in diameter, but can reach nearly 40 cm in length and 7 kg in mass. Conca Cannas obsidian is generally quite glassy, black but often so translucent that microlite crystals can be seen with the unaided eye. The micro-lites are often directionally oriented, representing the original flow structure, but are never large enough to be classified as phenocrysts. Francaviglia (1986: 314) reported obsidian blocks up to several tens of cm not only at Conca Cannas, but also along the Canale Perdera and Riu Solacera surrounding Su Paris de Monte Bingias; the obsidian I found in these localities was not this massive, and was neither plentiful nor in situ. Only loose material of workable size was found at Su Paris, and some of unworkable size at Monte Sparau (south), despite the considerable exposures resulting from current gravel and perlite quarrying activity. Herold (1986), however, reported some blocks 10–20 cm in size from Monte Sparau. I found no obsidian near the ruins of C. Pies and S. Suina.

Obsidian-bearing deposits continue to the north, along the western flanks of Monte Arci. I found in situ obsidian 15–17 cm in length on the slope of Bruncu Perda Crobina, beginning at an elevation under 100 m in the west, and up to an elevation of perhaps 400 m to the northeast. Scatters of unworked obsidian are com-mon in the low plain to the west of Conca s'Ollastu, while a source at Cucru Is Abis appears to begin at an elevation of 230 m and flows down to the west near Funtana Figu. Obsidian may be found in a modern gravel quarry there, below the Seddai cliff-face, along with the rare minerals tridimite and osumilite (de Michele, 1975: 172–173; Exel, 1986: 78). The quarry is primarily basalt, but also includes trachyte and rhyolite, and I observed obsidian blocks up to 1 m

in length. Hardly any obsidian occurs, though, in another quarry (mostly quartz) less than 1 km to the north.

Obsidian also occurs in the area east of Santa Maria Zuarbara, usually at much higher elevations. A few km north-east of the church, obsidian may be found in situ on the slope of Cuccuru Porcufurau, in blocks up to 30 cm in length at elevations 250–300 m a.s.l.; 3–5 cm nodules of obsidian occur abundantly at Punta Su Zippiri at an elevation of 500 m, and less frequently at Punta Nigola Pani at an elevation of 350 m. Workable blocks of obsidian also occur along the Riu Murus near Monte Sparau (north). Obsidian from these localities on the western flanks of Monte Arci is frequently as glassy as the Conca Cannas material, but may be less translucent and more grey in colour. This obsidian also can feature white phenocrysts 1–3 mm in diameter, which may make the fracture subconchoidal if frequent enough. Many pieces do not have any phenocrysts, however, and some are virtually trans-parent. Only the most meagre surface scatter was found further north by the Campo dei Forestieri, near where Bigazzi et al. (1976) took a sample for fission-track dating, and no obsidian was observed near Punta Muroni.

On the north-eastern side of Monte Arci lies the Perdas Urias source zone, which is actually a large ridge running north-north-west from Punta Pizzighinu to the plateau of Su Varongu. I located in situ obsidian there, for the first time, in a perlitic matrix at about 600 m altitude near Punta Pizzighinu. The primary material includes specimens up to 17 cm in length, while secondary deposits are abundant at lower ele-vations. Natural blocks up to 30 cm were observed redeposited near Santa Pinta, just below the actual peak of Perdas Urias, near Mitza Troncheddu to the

Table 1. Analyses of standard reference material USNM 143965 (Kakanui, New Zealand hornblende)

		SiO$_2$	Al$_2$O$_3$	TiO$_2$	FeO	Fe$_2$O$_3$	MgO	CaO	Na$_2$O	K$_2$O	P$_2$O$_5$	MnO	Total
Probe	Ave	40·08	14·34	4·73		11·38	13·00	9·99	2·73	2·08	0·16	0·09	98·53
	S.D.	0·24	0·10	0·05		0·14	0·09	0·07	0·04	0·03	0·02	0·02	0·38
	N	43	43	43		43	43	43	43	42	24	24	43
CA		40·37	14·90	4·72	7·95	3·30	12·80	10·30	2·60	2·05	0·00	0·09	99·08

Electron microprobe analyses by this author; chemical analysis (CA) by Jarosewich (1972) and Jarosewich *et al.* (1979).
All figures in percent.

Table 2. Electron microprobe data for type SA obsidian

Cat.	SiO$_2$	Al$_2$O$_3$	TiO$_2$	Fe$_2$O$_3$	MgO	CaO	Na$_2$O	K$_2$O	MnO	P$_2$O$_5$	BaO	Total
187	74·66	13·46	0·10	1·24	0·09	0·59	3·49	5·24	0·08	0·05	0·01	99·00
188	74·75	13·47	0·10	1·12	0·07	0·58	3·45	5·31	0·08	0·05	0·02	99·00
189	74·65	13·46	0·10	1·23	0·08	0·59	3·43	5·30	0·08	0·04	0·03	99·00
190	74·53	13·56	0·10	1·27	0·09	0·60	3·43	5·28	0·08	0·05	0·01	99·00
191	74·55	13·53	0·09	1·27	0·06	0·62	3·49	5·21	0·09	0·06	0·02	99·00
192	74·78	13·39	0·09	1·23	0·07	0·59	3·36	5·32	0·09	0·06	0·03	99·00
193	74·69	13·42	0·09	1·24	0·08	0·59	3·40	5·32	0·07	0·06	0·04	99·00
194	74·69	13·42	0·09	1·29	0·08	0·59	3·44	5·26	0·08	0·05	0·02	99·00
544	74·87	13·46	0·10	1·14	0·06	0·57	3·39	5·27	0·09	0·06	0·01	99·00
545	75·16	13·27	0·09	1·16	0·06	0·55	3·36	5·21	0·08	0·05	0·00	99·00
546	74·68	13·46	0·09	1·24	0·08	0·60	3·44	5·25	0·09	0·05	0·03	99·00
547	74·91	13·44	0·08	1·12	0·05	0·57	3·49	5·16	0·09	0·05	0·04	99·00
548	75·18	13·38	0·09	1·05	0·05	0·55	3·39	5·13	0·09	0·05	0·02	99·00
624	75·04	13·43	0·08	1·13	0·07	0·53	3·40	5·13	0·09	0·06	0·04	99·00
625	74·62	13·55	0·10	1·25	0·08	0·57	3·41	5·27	0·08	0·05	0·02	99·00
626	74·81	13·52	0·09	1·18	0·09	0·57	3·43	5·18	0·09	0·04	0·00	99·00
628	74·65	13·72	0·08	1·13	0·08	0·61	3·58	5·01	0·08	0·04	0·01	99·00
629	74·73	13·49	0·10	1·27	0·09	0·58	3·39	5·21	0·08	0·05	0·01	99·00
668	74·48	13·58	0·09	1·25	0·09	0·56	3·46	5·34	0·09	0·06	0·00	99·00
669	74·88	13·26	0·09	1·27	0·05	0·59	3·38	5·34	0·07	0·06	0·01	99·00
654	74·68	13·46	0·09	1·23	0·05	0·60	3·49	5·26	0·07	0·06	0·01	99·00
655	74·60	13·49	0·09	1·19	0·06	0·59	3·49	5·32	0·08	0·06	0·02	99·00
656	74·85	13·35	0·09	1·23	0·07	0·59	3·38	5·28	0·07	0·05	0·03	99·00
185	74·85	13·53	0·07	1·19	0·11	0·59	3·40	5·07	na	na	0·03	98·85
186	75·12	13·36	0·06	1·25	0·08	0·56	3·30	5·11	na	na	0·02	98·85
217	74·77	13·60	0·07	1·27	0·11	0·60	3·37	5·04	na	na	0·02	98·85
279	74·73	13·47	0·11	1·20	0·06	0·58	3·32	5·39	na	na	na	98·85
280	74·71	13·48	0·10	1·21	0·08	0·57	3·30	5·41	na	na	na	98·85
281	74·72	13·39	0·10	1·29	0·08	0·58	3·35	5·33	na	na	na	98·85
282	74·63	13·43	0·09	1·28	0·07	0·59	3·30	5·45	na	na	na	98·85
315	74·59	13·49	0·09	1·30	0·09	0·59	3·35	5·35	na	na	na	98·85
Ave	74·76	13·46	0·09	1·22	0·08	0·58	3·41	5·25	0·08	0·05	0·02	99·00
S.D.	0·17	0·09	0·01	0·06	0·02	0·02	0·06	0·10	0·01	0·01	0·01	

All figures in percent.
na: not analysed.

north, and in the low hills of Cazzighera to the east. Mitza Sa Tassa appears to be a large lithic reduction centre, and should be investigated further. Given the presence of secondary obsidian deposits, it would not have been necessary for prehistoric people to collect raw material directly from its source. Perdas Urias obsidian exhibits a great range in physical appearance, although it is almost always black and opaque. Many nodules have distinct alternating black and grey bands, some material is devitrified and weathered on its surface, a few pieces have red streaks, and rare examples are beer-bottle brown with high translucency.

Lastly, some obsidian was found in the Ceca quarry near Pala Sa Murta, which Francaviglia (1986) had reported as being of two chemical types. The only *in situ* obsidian I found was never greater than 1 cm in diameter, and there were no surface scatters of natural or flaked obsidian to suggest human activity there. I did not visit the area of Trebina Lada and Tu Passetti.

This field research demonstrated that: (1) large quantities of type SA obsidian occur near Conca Cannas in accessible, primary geological deposits; (2) equally large quantities of workable-size material occur in diffuse localities (both primary and secondary) along the western flanks of Monte Arci, and that at least one is probably the source of the archaeologically-determined SB group; (3) large quantities of type SC obsidian are available in the Perdas Urias zone, mainly

Table 3. Electron microprobe data for type SB1 obsidian

Cat.	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	BaO	Total
683	73·26	13·84	0·20	1·68	0·21	0·98	3·50	5·12	0·13	0·04	0·05	99·00
684	73·86	13·72	0·16	1·30	0·13	0·79	3·50	5·34	0·10	0·05	0·05	99·00
685	73·55	13·64	0·17	1·62	0·17	0·78	3·47	5·40	0·11	0·05	0·04	99·00
688	74·34	13·53	0·14	1·17	0·08	0·72	3·35	5·47	0·09	0·05	0·06	99·00
689	73·85	13·54	0·16	1·53	0·14	0·76	3·47	5·33	0·10	0·05	0·07	99·00
708	73·49	13·65	0·19	1·57	0·16	0·72	3·31	5·68	0·12	0·03	0·08	99·00
710	73·60	13·75	0·18	1·35	0·13	0·74	3·33	5·70	0·12	0·04	0·07	99·00
711	73·67	13·69	0·18	1·39	0·15	0·74	3·27	5·74	0·11	0·04	0·02	99·00
713	73·98	13·62	0·15	1·32	0·13	0·77	3·47	5·40	0·07	0·06	0·03	99·00
714	73·55	13·69	0·19	1·48	0·16	0·76	3·30	5·63	0·12	0·04	0·08	99·00
722	73·88	13·68	0·15	1·29	0·12	0·70	3·43	5·60	0·09	0·03	0·03	99·00
723	74·08	13·64	0·14	1·27	0·13	0·75	3·42	5·43	0·09	0·04	0·01	99·00
724	73·95	13·54	0·14	1·53	0·10	0·73	3·36	5·47	0·10	0·05	0·02	99·00
725	74·11	13·56	0·15	1·27	0·10	0·75	3·37	5·48	0·10	0·06	0·05	99·00
726	74·05	13·64	0·15	1·28	0·10	0·76	3·37	5·46	0·09	0·06	0·04	99·00
729	73·22	13·80	0·25	1·31	0·16	0·83	3·58	5·62	0·11	0·03	0·08	99·00
734	74·40	13·49	0·13	1·18	0·08	0·70	3·28	5·57	0·09	0·05	0·03	99·00
735	74·13	13·54	0·14	1·30	0·13	0·74	3·30	5·54	0·09	0·05	0·02	99·00
736	74·59	13·46	0·14	1·05	0·06	0·69	3·50	5·33	0·09	0·03	0·06	99·00
737	74·38	13·52	0·14	1·21	0·07	0·72	3·48	5·33	0·07	0·04	0·04	99·00
Ave	73·90	13·63	0·16	1·36	0·13	0·76	3·40	5·48	0·10	0·04	0·05	99·00
S.D.	0·37	0·10	0·03	0·16	0·04	0·06	0·09	0·15	0·02	0·01	0·02	

All figures in percent.

Table 4. Electron microprobe data for type SB2 obsidian

Cat.	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	BaO	Total
310	75·48	12·94	0·11	1·12	0·10	0·54	3·28	5·23	0·11	0·07	0·03	99·00
311	75·34	13·06	0·11	1·10	0·10	0·54	3·33	5·27	0·10	0·04	0·02	99·00
312	75·47	12·99	0·12	1·06	0·10	0·56	3·22	5·29	0·12	0·06	0·02	99·00
313	75·47	12·99	0·12	1·06	0·10	0·56	3·22	5·29	0·12	0·06	0·02	99·00
314	75·19	13·07	0·12	1·09	0·14	0·59	3·37	5·25	na	na	0·03	98·85
742	74·99	13·02	0·13	1·25	0·10	0·56	3·39	5·42	0·08	0·04	0·02	99·00
743	75·08	12·98	0·11	1·29	0·09	0·57	3·34	5·41	0·08	0·04	0·01	99·00
745	74·71	13·16	0·15	1·21	0·13	0·60	3·40	5·49	0·08	0·04	0·03	99·00
747	74·08	13·56	0·13	1·32	0·13	0·67	3·37	5·54	0·09	0·06	0·05	99·00
756	75·12	13·05	0·14	1·06	0·12	0·59	3·33	5·47	0·07	0·03	0·02	99·00
757	74·44	13·22	0·16	1·25	0·14	0·65	3·27	5·73	0·08	0·03	0·03	99·00
759	74·66	13·23	0·15	1·02	0·10	0·60	3·39	5·68	0·09	0·04	0·04	99·00
760	74·63	13·24	0·15	1·14	0·13	0·62	3·30	5·63	0·08	0·04	0·04	99·00
761	74·45	13·22	0·15	1·24	0·14	0·60	3·19	5·86	0·07	0·05	0·03	99·00
821	75·01	13·00	0·13	1·17	0·12	0·59	3·32	5·52	0·08	0·03	0·03	99·00
822	74·84	13·06	0·14	1·35	0·11	0·60	3·30	5·46	0·07	0·03	0·04	99·00
823	74·73	13·09	0·14	1·24	0·12	0·60	3·41	5·51	0·08	0·04	0·04	99·00
824	74·94	13·08	0·13	1·23	0·11	0·59	3·30	5·51	0·07	0·03	0·01	99·00
825	74·96	13·03	0·13	1·23	0·11	0·60	3·31	5·49	0·08	0·05	0·01	99·00
Ave	74·93	13·10	0·13	1·18	0·12	0·59	3·32	5·48	0·09	0·04	0·03	99·00
S.D.	0·37	0·14	0·01	0·10	0·01	0·03	0·06	0·17	0·02	0·01	0·01	

All figures in percent.
na: not analysed.

in secondary deposits; and (4) small pieces of unworkable-sized obsidian may be found *in situ* at several additional Monte Arci localities, in perlitic or pyroclastic matrices.

Chemical Characterization

Resolution is clearly the most important consideration in the characterization of western Mediterranean obsidian sources. In the case of Sardinia at least, a large island with its own indigenous population and culture, the differential exploitation of three source groups has already been noted, while obsidian outcrops have been found in multiple, discontinuous localities, especially along the western flanks of Monte Arci. Geological specimens collected during my survey of these source areas were chemically analysed, to investigate whether additional geological subgroups could be defined, and subsequently to serve as references for the provenance attribution of archaeological

Table 5. Electron microprobe data for type SC obsidian

Cat.	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	BaO	Total
195	72·65	13·89	0·28	nd	nd	0·81	3·19	6·07	0·11	0·07	na	98·90
205	72·73	13·90	0·25	nd	nd	0·79	3·35	5·90	0·11	0·03	na	98·90
206	72·41	14·06	0·29	1·81	0·30	0·87	3·21	5·76	0·12	0·06	0·11	99·00
212	nd	14·10	0·28	nd	nd	0·80	3·34	5·82	0·11	0·05	0·12	99·00
901	72·57	13·84	0·29	1·71	0·26	0·85	3·24	5·93	na	na	0·14	98·85
902	72·97	13·78	0·26	1·39	0·16	0·85	3·24	6·12	na	na	0·09	98·85
936	72·65	13·91	0·29	1·52	0·21	0·84	3·31	5·95	0·14	0·03	0·12	99·00
946	72·44	14·09	0·28	1·50	0·25	0·93	3·34	5·92	0·14	0·03	0·10	99·00
947	72·27	14·08	0·29	1·67	0·29	0·89	3·28	5·96	0·13	0·02	0·11	99·00
948	72·32	14·02	0·29	1·64	0·29	0·86	3·28	6·03	0·13	0·03	0·10	99·00
949	72·36	14·06	0·28	1·57	0·24	0·95	3·29	5·96	0·15	0·03	0·11	99·00
950	72·80	13·95	0·24	1·50	0·21	0·81	3·24	6·01	0·13	0·03	0·08	99·00
967	72·58	14·03	0·29	1·39	0·22	0·87	3·23	6·09	0·15	0·02	0·14	99·00
968	72·54	14·00	0·29	1·52	0·22	0·87	3·36	5·95	0·14	0·03	0·08	99·00
969	72·40	14·08	0·29	1·72	0·27	0·89	3·32	5·79	0·13	0·03	0·09	99·00
970	72·45	13·97	0·28	1·78	0·26	0·86	3·24	5·89	0·14	0·04	0·09	99·00
971	72·04	14·21	0·31	1·80	0·27	0·94	3·26	5·91	0·13	0·03	0·09	99·00
974	72·82	14·11	0·20	1·33	0·13	0·90	3·38	5·87	0·11	0·04	0·09	99·00
976	72·30	14·14	0·29	1·49	0·23	0·94	3·25	6·02	0·17	0·05	0·11	99·00
977	73·34	13·89	0·23	1·11	0·08	0·82	3·27	6·00	0·13	0·03	0·09	99·00
978	72·69	13·99	0·25	1·31	0·21	0·88	3·37	6·06	0·14	0·01	0·09	99·00
979	72·95	13·92	0·24	1·35	0·17	0·87	3·26	5·96	0·14	0·04	0·10	99·00
986	72·71	13·86	0·28	1·51	0·23	0·89	3·32	5·93	0·13	0·03	0·10	99·00
991	72·57	13·92	0·28	1·55	0·24	0·89	3·21	6·05	0·14	0·02	0·12	99·00
992	72·33	14·20	0·30	1·46	0·23	0·88	3·26	6·07	0·15	0·04	0·09	99·00
993	72·30	14·20	0·29	1·42	0·28	0·98	3·31	5·90	0·15	0·02	0·16	99·00
994	72·29	14·14	0·29	1·54	0·25	0·98	3·33	5·89	0·14	0·03	0·13	99·00
995	72·24	14·14	0·28	1·43	0·20	1·19	3·68	5·59	na	na	0·10	98·85
996	72·69	13·74	0·29	1·66	0·21	0·87	3·29	6·03	na	na	0·08	98·85
997	72·17	14·13	0·26	1·59	0·28	1·12	nd	nd	na	na	0·11	98·85
1001	72·22	14·05	0·30	1·70	0·26	0·98	3·37	5·91	na	na	0·06	98·85
1002	72·63	13·87	0·29	1·49	0·20	0·90	3·38	5·96	na	na	0·14	98·85
1003	72·35	14·00	0·28	1·61	0·17	0·98	3·35	6·03	na	na	0·08	98·85
1004	72·48	14·01	0·28	1·40	0·29	0·98	3·30	6·04	na	na	0·08	98·85
1005	72·80	13·88	0·29	1·42	0·13	0·88	3·33	6·02	na	na	0·10	98·85
1006	72·54	13·75	0·29	1·73	0·24	0·86	3·28	6·04	na	na	0·12	98·85
1026	72·83	13·97	0·19	1·31	0·11	0·74	3·49	6·09	na	na	0·11	98·85
1027	72·58	13·80	0·28	1·69	0·26	0·89	3·33	5·90	na	na	0·12	98·85
1728	72·70	13·97	0·28	1·49	0·21	0·87	3·25	6·00	0·09	0·05	na	99·00
Ave	72·55	13·99	0·27	1·53	0·22	0·90	3·31	5·96	0·13	0·03	0·10	99·00
S.D.	0·26	0·12	0·03	0·16	0·05	0·08	0·08	0·10	0·02	0·01	0·03	

All figures in percent.
nd: no data; na: not analysed.

samples. My intention of analysing many hundreds of artefacts constrained the choice of analytical methods for reasons of time, expense, and the need to be minimally destructive to ancient materials.

One hundred and eighty-six geological specimens from more than 20 Monte Arci source localities were analysed for 38 major and trace elements by ICP mass spectrometry (ICP-MS) using a Fisons PQ 2 Plus located in the Department of Earth and Planetary Sciences at Harvard University (for a review of the archaeological applications of this technique, see Tykot & Young, 1996). Since the purpose of these initial analyses was to explore whether additional sub-groups could be chemically distinguished, rather than to characterize them quantitatively, calibration curves were generated for only some elements, and the data produced should not be considered indicative of the actual composition of the samples although in most cases they are reasonably close (Tykot, 1995).

Exploratory graphical and statistical analysis of the data, including cluster, principal components and discriminant analysis revealed no more than five meaningful source groups of workable obsidian. Thirty-six source specimens were then quantitatively analysed by XRF spectroscopy and the results were found to compare favourably with published XRF data for the Monte Arci sources, confirming that the source groups determined by ICP-MS are identical to those established by Mackey & Warren (1983: SA, SC and two SB groups) and Francaviglia (1986: SA, SB and two SC groups).

A bivariate plot of the first two discriminant functions based on the ICP-MS data for eight selected trace elements shows these groups to be quite distinct (Figure 3). The source localities of the geological samples are as follows: SA (Conca Cannas quarries plus surface finds from Su Paris de Monte Bingias and near Monte Sparau south); SB1 (Cuccuru Porcufurau,

Table 6. Summary of electron microprobe data for western Mediterranean obsidian sources

Source		SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	BaO	Total
SA	Ave	74·72	13·40	0·09	1·25	0·08	0·59	3·45	5·25	0·08	0·06	0·02	99·00
	S.D.	0·25	0·15	0·01	0·09	0·01	0·03	0·11	0·13	0·01	0·01	0·02	
	N	204	205	206	206	206	205	204	204	60	60	201	
SB1	Ave	73·84	13·62	0·17	1·35	0·13	0·75	3·38	5·56	0·10	0·04	0·05	99·00
	S.D.	0·35	0·10	0·03	0·17	0·04	0·06	0·10	0·20	0·02	0·01	0·02	
	N	28	28	28	28	28	28	28	28	21	21	28	
SB2	Ave	75·08	12·97	0·13	1·15	0·11	0·57	3·36	5·46	0·08	0·04	0·02	99·00
	S.D.	0·27	0·14	0·02	0·09	0·02	0·02	0·06	0·11	0·01	0·01	0·02	
	N	127	129	130	129	130	130	128	128	81	81	130	
SC	Ave	72·71	13·92	0·27	1·52	0·20	0·87	3·31	5·90	0·14	0·03	0·11	99·00
	S.D.	0·34	0·18	0·03	0·19	0·06	0·08	0·11	0·18	0·01	0·01	0·02	
	N	336	337	338	333	335	337	336	336	120	120	336	
Li	Ave	74·51	12·75	0·08	1·63	0·03	0·72	4·03	5·13	0·05	0·06	0·01	99·00
	S.D.	0·22	0·14	0·01	0·08	0·01	0·04	0·10	0·09	0·05	0·01	0·01	
	N	20	20	20	20 ·	20	20	19	19	9	9	20	
Pa1	Ave	70·78	7·47	0·22	8·50	0·01	0·26	7·16	4·23	0·03	0·30	0·03	99·00
	S.D.	0·10	0·03	0·01	0·05	0·00	0·00	0·11	0·04	0·00	0·01	0·01	
	N	3	3	3	3	3	3	3	3	3	3	3	
Pa2	Ave	66·23	10·17	0·61	8·90	0·15	0·53	7·56	4·56	0·05	0·35	0·02	99·00
	S.D.	0·15	0·70	0·00	0·57	0·02	0·04	0·09	0·16	0·00	0·00	0·01	
	N	2	2	2	2	2	2	2	2	1	1	2	

All figures in percent.

Punta Nigola Pani, Punta Su Zippiri, and Monte Sparau north); SB2 (Cucru Is Abis, Seddai and Bruncu Perda Crobina); SC1 (Punta Pizzighinu, plus secondary deposits near Perdas Urias, Mitza Sa Tassa, and Santa Pinta, and surface finds near Su Varongu and Mitza Troncheddu); and SC2 (secondary deposits near Perdas Urias and Santa Pinta). The discovery that both SC1 and SC2 obsidian, with extremely similar chemical characteristics except for Sr concentration, can be found together in detrital contexts in the Santa Pinta area, suggests that the distinction between the two SC types is unimportant for archaeological purposes, since it would have been impossible to select one type over the other and both occur within the same area. All useful Mediterranean source distinctions can be made, therefore, on the basis of major/minor element concentrations.

Electron microprobe analysis using wavelength dispersive X-ray spectrometers (WDS) was thus selected as the method of choice for characterizing geological specimens and analysing large numbers of archaeological artefacts since only a tiny 1–2 mm sample is needed, sample preparation is minimal, analytical precision is superior to laser ablation ICP-MS, and the per-sample cost is a fraction of the price of XRF or NAA. The microprobe (or scanning electron microscope) with energy dispersive spectrometers (EDS) has been used for obsidian studies in Europe (Biró & Pozsgai, 1984; Biró, Pozsgai & Vlader, 1986), the Near East (Keller & Seifried, 1990), and East Africa (Merrick & Brown, 1984; Merrick, Brown & Nash, 1994), but it must be noted that, for most obsidians, TiO_2, MgO, MnO, P_2O_5, and BaO are usually below the minimum detection limits of SEM or microprobe EDS systems. Since TiO_2, MgO, and BaO are important for discriminating

among the Mediterranean obsidian sources, WDS is necessary for provenance studies in this region (see Verità *et al.*, 1994 for a comparative study of EDS and WDS).

Epoxy disks of 1 in. diameter were prepared, each with 18 holes 2 mm in diameter. Obsidian samples were inserted along with additional epoxy, and allowed to dry. The disks were then polished flat using a series of successively finer grinding wheels, and finally with 10 μ and 1 μ diamond paste. The disks were carbon-coated prior to analysis to minimize local surface charging under the electron beam. Samples were analysed using a Cameca MBX electron microprobe in the Department of Earth & Planetary Sciences at Harvard University. Samples were excited by a relatively wide (40 μ) 15 keV electron beam, and the X-radiation was measured by WDS with counting times of 10–80 s per element. All analyses were internally calibrated against pure mineral standards, and the measured X-ray intensities were corrected for matrix effects, absorption, and secondary fluorescence by the Bence-Albee correction program. A standard reference material was repeatedly measured to ensure consistency between analytical sessions, and to enable comparison with results from other laboratories and by other methods (Table 1).

One hundred and twenty-five geological obsidian samples were analysed for SiO_2, Al_2O_3, TiO_2, Fe_2O_3, MgO, CaO, Na_2O, K_2O, MnO, P_2O_5, and BaO. Ten replicate analyses each of five samples (279–282, 315) were done to illustrate the chemical homogeneity of the obsidian; three points were analysed on most other samples to ensure that microlites or other heterogeneous inclusions did not contribute to the analysis. It was necessary to purge the results of only a few of the
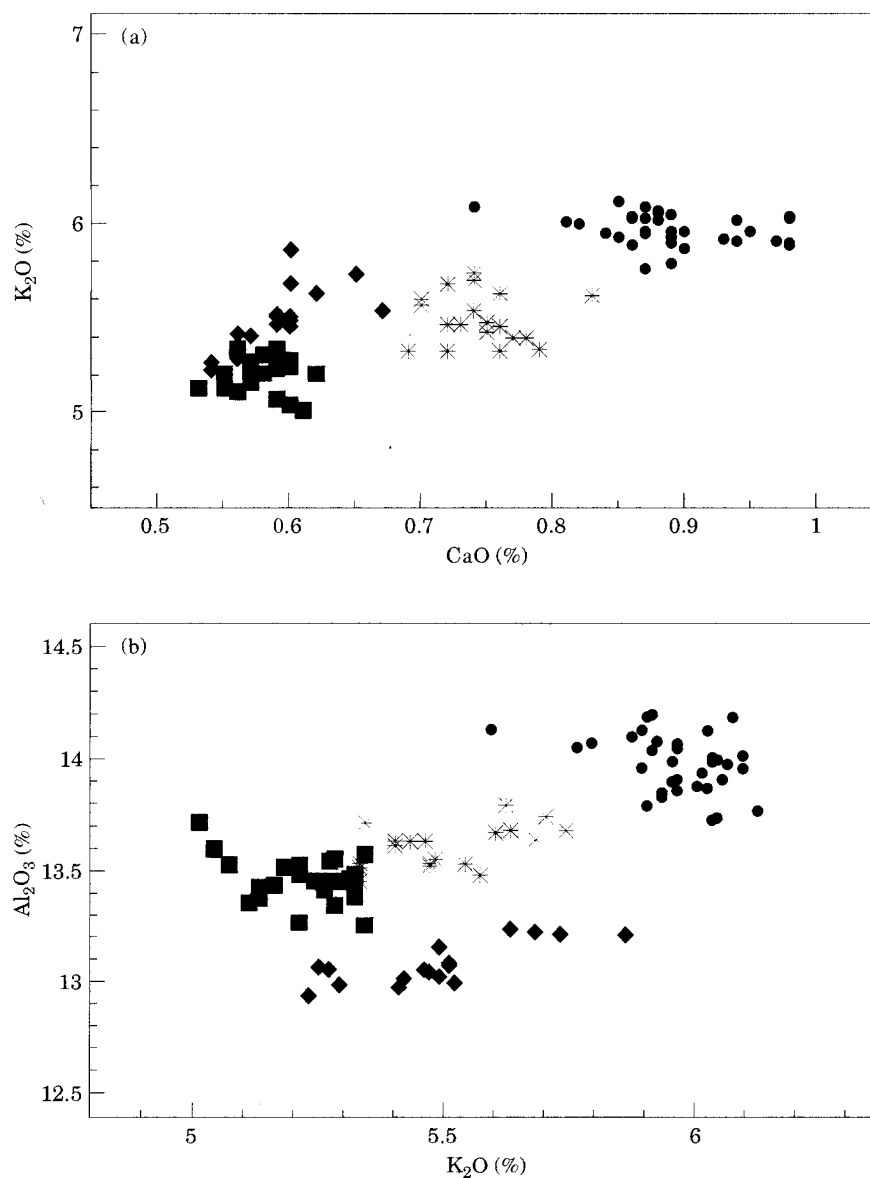
Figure 4. Bivariate plots of major element data for geological samples of Monte Arci obsidian: (a) CaO versus K_2O; (b) K_2O versus Al_2O_3. Two outliers, both surface finds, not shown. ■: SA; *: SB1; ◆: SB2; ●: SC.

433 analyses. Furthermore, the broad beam minimized the influence of tiny microlite inclusions (typically high in iron) on the overall composition of the sample, as well as preventing the heat-induced decomposition of alkali elements during analysis. For each sample, the analyses were normalized to total 99·00% (allowing 1% for water and trace elements) and averaged (Tables 2–5).

Type SA obsidian (Table 2) is characterized by relatively high concentrations of SiO_2, and lower concentrations of TiO_2, MgO, and K_2O than the other Monte Arci sources. Type SB1 obsidian (Table 3) has less SiO_2, and slightly more of the other elements analysed, while type SB2 (Table 4) is similar to type SA

but has less Al_2O_3 and slightly more TiO_2, MgO, and K_2O. Type SC obsidian (Table 5) has very low concentrations of SiO_2 and the highest concentrations of the other elements analysed except Na_2O.

Microprobe data for obsidian samples from the western Mediterranean sources indicate that significant differences exist in their major element composition (Table 6). Monte Arci obsidian is easily distinguished from Lipari and Palmarola obsidian by its Na_2O concentration (<3·5 versus >4·0%), while the peralkaline obsidian from Pantelleria is easily distinguished by its extremely low SiO_2, Al_2O_3, and CaO, and its extremely high Fe_2O_3 and Na_2O concentrations. Two of the Pantellerian sub-groups are distinguishable
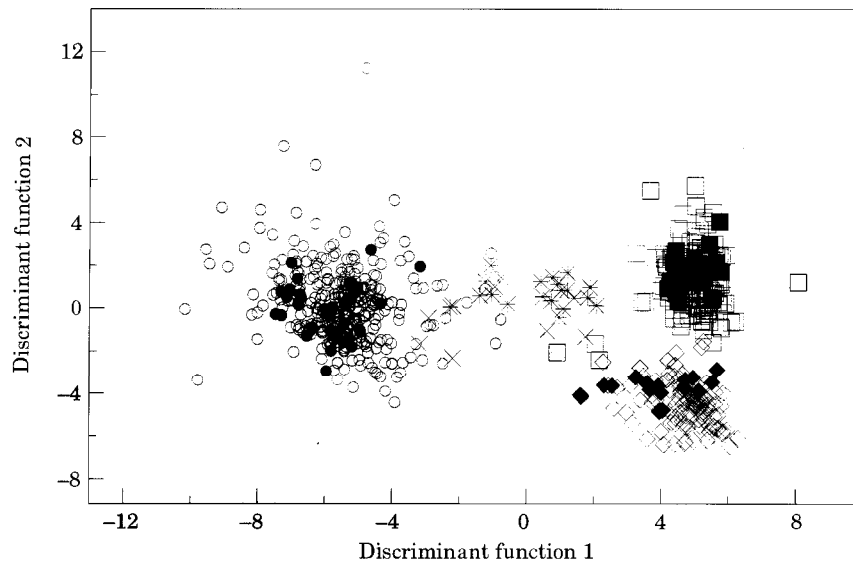
Figure 5. Discriminant analysis of electron microprobe data for the Monte Arci obsidian sources. Both geological and archaeological samples are shown. The discriminant functions are derived from the geological data in Tables 2–5: DF1=0·58072 • SiO_2 − 1·40352 • Al_2O_3 − 20·30589 • TiO_2+11·00677 • MgO − 9·99900 • CaO+4·86276 • Na_2O − 2·24592 • K_2O − 14·49277 • BaO − 17·46740; DF2= − 4·49666 • SiO_2+ 4·56449 • Al_2O_3 − 6·04055 • TiO_2 − 28·20329 • MgO − 10·34828 • CaO − 5·42388 • Na_2O − 8·03540 • K_2O − 5·08363 • BaO+345·99296. Geological samples: ■: SA; *: SB1; ◆: SC2; ●: SC; Artefacts: □: SA; X: SB1; ◇: SB2; ○: SC.

among the small number of samples I tested, with significant differences in SiO_2, Al_2O_3, TiO_2, MgO, and CaO. My Pa1 group corresponds to the Upper Balata dei Turchi flow near the southern coast of Pantelleria, while my Pa2 group corresponds with the less-frequently used pitchy obsidian from Gelkhamar (see Francaviglia, 1988).

For Sardinia, bivariate plots of CaO versus K_2O and K_2O versus Al_2O_3 illustrate the substantial compositional differences among the Monte Arci obsidian flows, and the possibility of attributing artefacts to individual sources based on their major element composition (Figure 4). K_2O concentration alone can often distinguish SA from SB from SC (5·24 ± 0·12; 5·48 ± 0·17; and 5·89 ± 0·34%, respectively); SB1 has 1·2% lower SiO_2 and 0·7% higher Al_2O_3 than SB2; and type SC obsidian is distinguished from all other western Mediterranean obsidians by its high Al_2O_3 (13·9%), MnO (0·14%), and BaO (0·11%). A bivariate plot of the first two discriminant functions determined using the program BMDP 7M emphasizes the multivariate compositional differences among the Monte Arci sources (Figure 5), with the posterior probability of each geological sample belonging to its correct source group exceeding 99% in all but three cases. These three have clearly skewed values for only some elements, presumably reflecting the limitations of an analytical method which provides data for only a tiny point on the surface of a potentially heterogeneous and possibly weathered sample.

The "jackknifing" option in BMDP 7M was similarly used to compute Mahalanobis' D^2 and posterior probabilities for unknown (archaeological) samples, which were not included in the calculation of the

discriminant functions. Ninety-five percent of all artefacts were attributed to individual Monte Arci sources with greater than 95% probability, although my own assessment of each sample's compositional data and physical appearance suggests that 1% of these artefacts are actually misclassified for the same reasons described above. The statistical uncertainty over the remaining 5% nearly always questions attributions involving the SB1 source, which is intermediate in composition to the other Monte Arci sources, but which was used for artefacts only rarely. Individual assessment resolved the provenance of all but three of the 600 artefacts analysed to a single Monte Arci source.

Conclusions

Natural blocks of workable obsidian are found abundantly in the Monte Arci area of Sardinia, and analyses of geological specimens from various localities there has demonstrated the existence of nine chemically differentiable source groups, including five (SA, SB1, SB2, SC1, SC2) which were used for making prehistoric stone tools. Trace element characterization is necessary to distinguish among these five source groups, but the minor chemical distinction between the geographically-intermingled SC1 and SC2 types is not of archaeological significance. Major element analyses are therefore sufficient for determining the provenance of artefacts from all Mediterranean obsidian sources. Knowledge of provenance (and hence composition) is critical for obsidian hydration dating (Michels et al., 1984; Stevenson & Ellis, 1997) as well as for reconstructing prehistoric exchange networks.
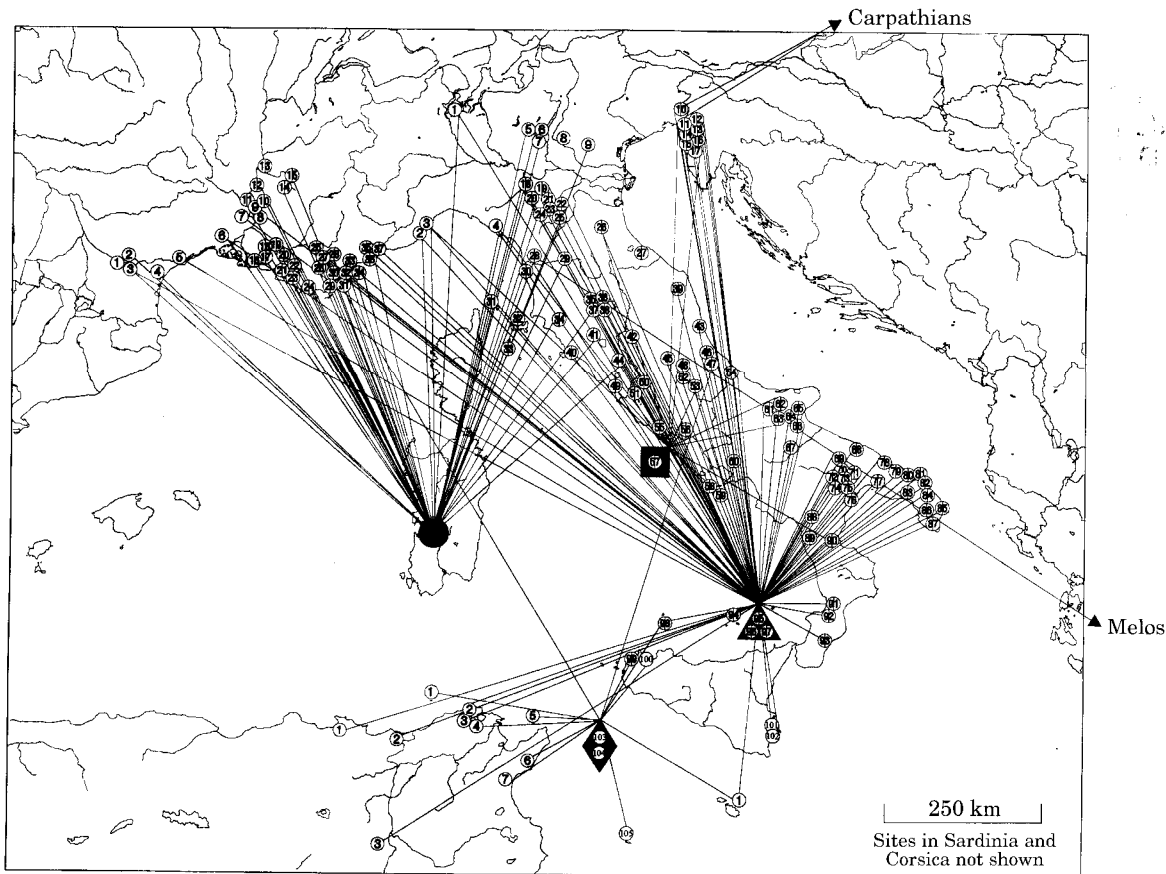
Figure 6. Obsidian distribution in the western Mediterranean. References and analytical data for all analyses are compiled in Tykot (1995).

The exploited Sardinian obsidian sources are located in different areas of the Monte Arci volcanic complex and vary in their accessibility, as well as in the quantity and quality of the obsidian available at each locality. Type SA obsidian is abundantly found in large nodules within a soft perlitic matrix, in a very concentrated location (Conca Cannas) easily accessible at the southwestern foot of Monte Arci. In contrast, large blocks of type SB2 occur in smaller quantities, but at multiple source localities (Bruncu Perda Crobina, Conca s'Ollastu, Seddai, Cucru Is Abis), also easily accessible on the western flanks of Monte Arci. Type SB1, usually found in localized deposits as small nodules within a much harder volcanic matrix, is also less accessible as it occurs at higher elevations towards the interior of Monte Arci. Large nodules of type SC obsidian, also originating from soft perlitic matrices, are quite abundant judging from material found in secondary contexts, although only a single *in situ* exposure has been identified. The SC source zone is located at very high elevations on the eastern side of Monte Arci, with easy access only from the south or further east.

The ability to determine obsidian provenance using inexpensive, minimally destructive analytical techniques permits large numbers of artefacts to be tested, and statistically significant distribution patterns to be

revealed. Electron microprobe analysis of more than 600 obsidian artefacts from about 50 archaeological sites in Sardinia, Corsica, and northern Italy indicates that geographic and chronological variation existed in the frequency-of-use of the Monte Arci sources (Tykot, 1995, 1996, 1997), patterns which were not apparent in earlier studies of limited numbers of artefacts. Provenance studies can and should become a routine part of excavation programmes at sites where the lithic assemblage is likely to contain obsidian from more than one source, a situation which applies to most of the western Mediterranean (Figure 6). When integrated with typological, technological, and use–wear studies, a more complete understanding of human behaviour in the Neolithic western Mediterranean will result.

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