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DETERMINING THE PROVENANCE OF OBSIDIAN IN SOUTHERN PATAGONIA USING OPTICAL PROPERTIES*

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This paper aims to evaluate the optical properties of natural rhyolite obsidians that might be useful in the identification of different sources of archaeological samples. Even though colour, degree of alteration, crystaloclast composition and texture are important properties by which sources can be identified, all of these features do not always lead to an unambiguous distinction. In this regard, the refractive index (N_D) becomes a helpful tool because it is not only sensitive to the chemical composition of natural glasses but also to their different thermal histories. Obsidians from six localities of Patagonia were analysed. Their refractive index measurements (N_D) only range between 1.47 and 1.49, but the N_D values of some of these sources are sufficiently constrained to allow discrimination between them.

KEYWORDS: OBSIDIAN, REFRACTIVE INDICES, OPTICAL PROPERTIES, PATAGONIA

INTRODUCTION

Determination of obsidian provenance has been a widely discussed topic in the worldwide archaeological literature (e.g., Ammerman 1979; Espinosa and Goñi 1999; Escola 2004; Negash and Shackley 2006; Izuho and Sato 2007; Stern *et al*. 2007; Eerkens *et al*. 2008). Different analytical methods have been successfully used to characterize the chemical composition of obsidian (see Ambroz *et al*. 2001). Several sources in Patagonia associated with archaeological materials have previously been geochemically analysed (Stern 2004). It has been recognized that some obsidian specimens have been transported 1000 km away from their geological source (e.g., Volcán Chaitén obsidian on the Santa Cruz coast: Cruz *et al*. 2011; Stern *et al*. 2012), demonstrating the great value of these natural glasses as raw materials for the populations that have inhabited Patagonia since at least the 10th millennium before the present.

Nevertheless, similar chemical compositions of natural glasses does not necessarily imply that they come from the same source. Volcanic activity of different ages could present similar chemical signatures if they were produced under the same tectonic environment. In contrast, refractive indices (N_D) and other optical properties not only vary due to the chemical composition of glasses, but also by their cooling rates. Several researchers, such as Mathews (1951), Kittleman (1963), Latorre (1972) and Church and Johnson (1980), have demonstrated that the N_D values of

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natural glasses decrease with an increasing amount of SiO_2. However, Wondraczek *et al.* (2003) measured the refractive indices of different synthetic glasses before and after heat treatment and concluded that their N_D values depend on the water content in the glasses as well as the presence of nanoscale magnetite particles. According to them, the decrease in the index of refraction could indicate glasses that were cooled more slowly and therefore also provides hints on their thermal history (Wondraczek *et al.* 2003). Thus, refractive indices could be a useful method for discriminating between the sources according to the geological evolution of the obsidian. Also, a detailed description of other optical properties observable in each sample allows one to establish the obsidian features that can easily be compared with other samples, and in this context the N_D value could be a potential tool for source discrimination.

Even though Boyer and Robinson (1956) made the first attempt to characterize archaeological obsidian from North America by refractive index determination, there are few works on this topic and none done in Patagonia. Thus, the main purpose of this paper is to explore the use of some optical features of obsidian, including refractive indices, as complementary techniques to determine their provenance. We analysed obsidians from six different sources of south-central Patagonia using instruments that can be operated with few hours of training and with very little loss of sample. With this contribution, we assess the scope and limitations of such properties as an alternative to chemical composition to determine the provenance of these six different types of obsidian. This alternative could be quicker and cheaper than others, and could be applied by archaeologists with little training.

MATERIALS AND METHODS

Materials

While numerous obsidian studies have been carried out in Patagonia, there are few that characterize the geological sources where the rocks originated. Current knowledge indicates that 12 obsidian sources have been recognized south of parallel 41°S (Fig. 1). The analysis that we propose to carry out requires that the samples to be analysed should come from a known source or have geochemical analyses to confirm their provenience. Of the 12 geological sources, there are six from which it was not possible to obtain samples that met either of these criteria. These comprise Ancud/Chiloé, Sierra Pailemán, Río Villegas, Piedra Parada/Angostura Blanca, Sacanana/Cerro Guacho and Laguna La Larga (Fig. 1). However, thanks to the collaboration of colleagues, we were successful in obtaining a sample from each of the remaining localities: Pire Mahuida ($n = 1$), Sierra Negra/Arroyo Telsen (hereinafter, Arroyo Telsen; $n = 3$), Volcán Chaitén ($n = 1$), Pampa del Asador ($n = 9$), Cordillera Baguales/Calafate (hereinafter, Baguales; $n = 1$) and Seno de Otway/Magallanes (hereinafter, Seno de Otway; $n = 2$) (Fig. 1).

Methods

Standard polarized light microscope techniques were used for qualitative analyses and recognition of obsidian textures, crystaloclast composition and alteration degree. The refractive indices were measured by the immersion method, using white light and mixtures of two miscible liquids: one with a refractive index higher than the most common volcanic glasses and other with a refractive index below them (bromonaphthalene and Vaseline®, respectively: Bonorino 1976; Freund *et al.* 1982). The refractive indices of those mixtures were measured by transmitted light using an Abbe refractometer. Special care was taken in temperature variations of the refractive

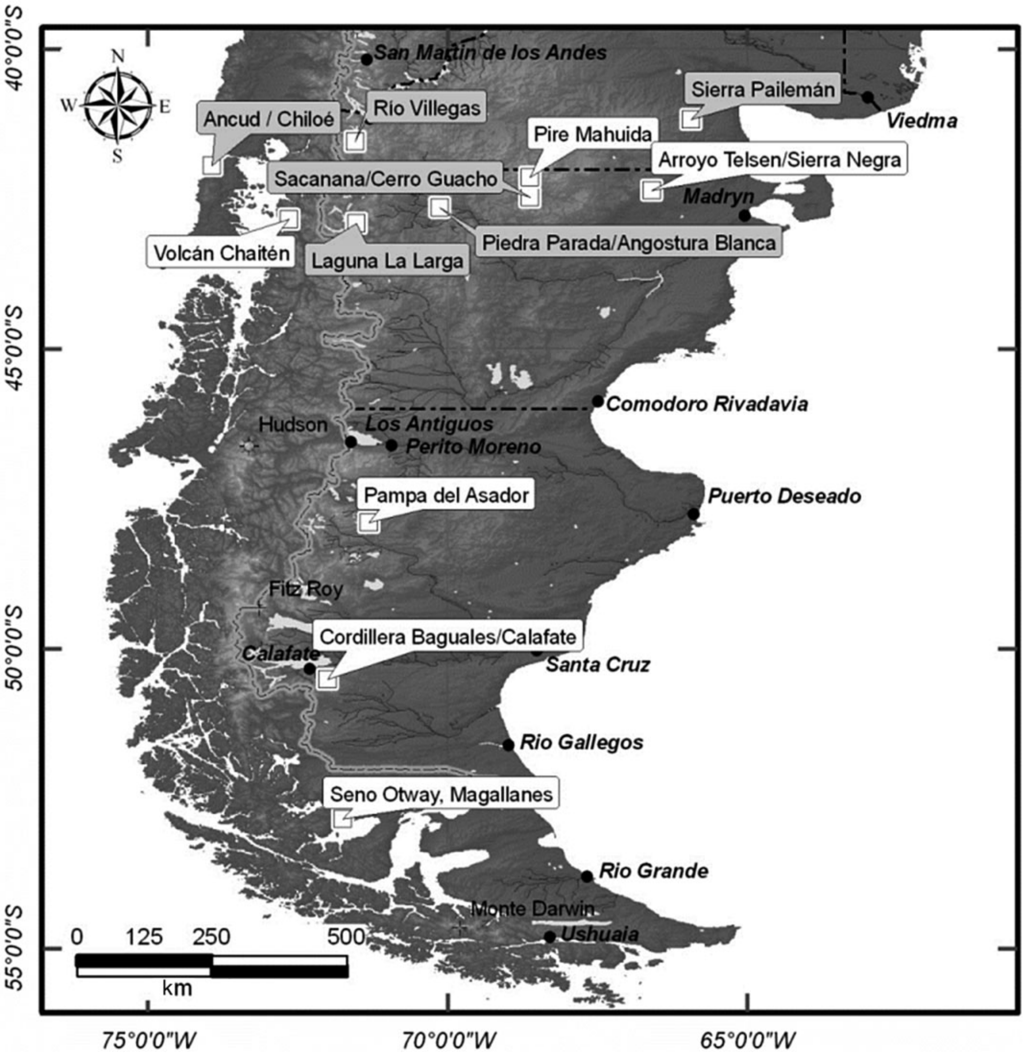


Figure 1 *A simplified location map of Patagonia, indicating all of the regions mentioned in the text. The localities studied in this contribution are indicated with a white text background.*

indices. We controlled the laboratory temperature to be close to 25°C. Values of N_D obtained at different temperatures had to be corrected. The correction factor was determined by measuring 11 refractive indices at different temperatures to obtain the variation of N_D per degree (dN_D/dT) and calculating the average of those values (see Table 2 below, fourth and fifth columns). Thus, refractive indices measured above or below 25°C were corrected by adding or subtracting 0.00036 for each Celsius degree. The accuracy of the measurement was controlled by the refractive index of the Abbe standard glass before each measurement operation. To obtain a reliable value of N_D, the refractive index measurements were performed a minimum of four times on each sample (Table 3 below).

RESULTS

Natural deposits and optical properties of Patagonian obsidians

The following summarizes the location (Fig. 1), the most relevant geological features, the history, the archaeological distribution (using the bibliography already available) and the optical properties of the six sources discussed in this paper, from north to south. The main optical properties are summarized in Table 1 and published chemical analyses (Stern 2004; Bellelli *et al.* 2006) are presented in Table 2.

Pire Mahuida (68°37′33″W/42°07′50″S) This deposit is located in the north-central Chubut province (Fig. 1) in a possible Oligocene volcanic field (Page *et al.* 1987; Salani and Page 1989; Salani 1990). In some sectors of this volcanism, there are small pyroclastic deposits surrounding the emission centre (Salani 1990). These flow-banded rhyolites represent an acid magmatism. Obsidian is available in layers characterized by botryoidal surfaces, where they reach a size of 5 cm on average (Salani 1990). It is important to highlight that Pire Mahuida obsidian has not been mentioned in the archaeological literature before and no chemical composition has been published.

This obsidian occurs as black pebbles with light and dark bands (Fig. 2 (a)). This banding is observed microscopically and is generated by textural variations (fractures and crystaloclasts) that alternate in more or less dense aggregates of about 0.05 mm in width. Crystaloclasts of these glasses are only composed of opaque minerals, smaller than 0.01 mm, which represent less than 1% of the total volume. This obsidian also shows an incipient degree of devitrification.

Arroyo Telsen (66°36′00″W/42°21′10″S) This deposit is located in the central plateau of Chubut, in the Sierra Negra area (Fig. 1). Telsen peralkaline obsidians are associated with an acid volcanism environment, restricted to large effusive centres located in the southern Somuncurá massif. In particular, Sierra Negra corresponds to a weathered basalt outcrop presenting obsidian pebbles at its bottom levels (Stern *et al.* 2000). Volcanism in this area started in the Eocene but the pyroclastic events generally occurred during the Miocene. These are included in the Quiñelaf eruptive complex and probably in the Somuncurá formation. According to Ardolino and Franchi (1993) and Ramos and Kay (1992), this magmatism is associated with a hotspot intruded in an inter-plate environment through extensional structures. One sample presents an age of 14.6 Ma (Stern *et al.* 2000; Stern 2004), which is consistent with the late stage of formation of the Somuncurá plateau.

Archaeological materials made with this obsidian have been identified at the foot of the Sierra Negra and on the bed of a nearby stream. Also, this obsidian is the most frequently selected in the Valdés Peninsula sites (Chubut province), ~100 km to the east. It has also been identified between archaeological materials ~100 km south of its outcrop (Stern *et al.* 2000; Gómez Otero and Stern 2005).

Arroyo Telsen obsidian is presented as black to translucent grey angular pebbles (Fig. 2 (b)). In this obsidian, we have also observed fine bands (1 mm thick) of colourless and light brown glass (Fig. 2 (c)). These latter bands present a higher degree of devitrification. The crystaloclasts represent close to 5% of the total volume and most of them reach 0.2 mm in length. They mainly correspond to alkali feldspar (Fig. 2 (d)) and scarce opaque minerals with very tiny size. This kind of peralkaline obsidian contains little water (Table 2) and does not present signs of devitrification, except in the case mentioned above.

Table 1 *Petrographic characteristics of obsidians from each source: in each case, the grey shading shows the distinguishing features*

	Pire Mahuida	*Arroyo Telsen*	*Volcán Chaiten*	*Pampa del Asador*	*Baguales*	*Seno de Otway*
Colour	Black	Black to translucent grey	Translucent grey	Mainly black; often black and red	Light grey–greenish	Dark green to grey
Textures	Microscopically banding	Macroscopically banding	Macroscopically banding	Macroscopically massive or banding with microscopic radial, parallel, subparallel or random fractures	Microscopically banding	Macroscopically banding Radial fractures
Crystaloclasts	<1% opaque minerals	5% potassium feldspar/plagioclase <1% opaque minerals	<1% potassium feldspar <1% quartz 1% opaque minerals	<1% plagioclase <1% zircon <1% opaque minerals	<20% potassium feldspar	–
Alteration degree	Incipient	–	Incipient	–	Advanced	Advanced

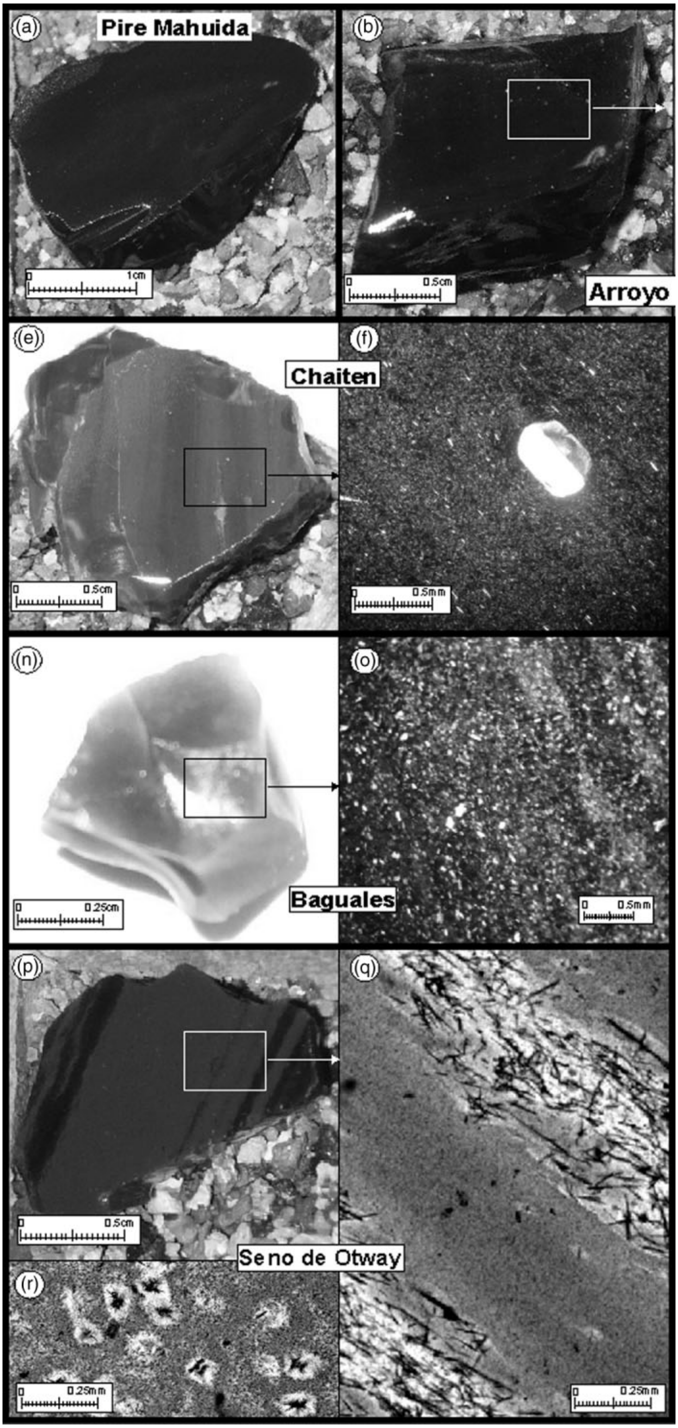
Table 2 *Published chemical analyses of the obsidian sources studied in this contribution (from Stern 2004; Bellelli* et al. *2006)*

Source	*Arroyo Telsen*			*Volcán Chaitén*	*Pampa del Asador*		*Baguales*	*Seno de Otway*
Number of samples	*1*	*1 (type T/SCII)*	*1 (type T/SCI)*	*1*	*16 (major elements); 132 (trace elements) (type PDAI)*	*5 (major elements); 20 (trace elements) (type PDAIIa)*	*6 (major elements); 37 (trace elements)*	*4 (major elements); 10 (trace elements)*
Reference	*Bellelli* et al. *(2006)*	*Stern (2004)*	*Stern (2004)*	*Stern (2004)*	*Stern (2004)*	*Stern (2004)*	*Stern (2004)*	*Stern (2004)*
SiO_2	73.49	74.86	72.4	75.58	75.56	76.6	74.96	72.22
TiO_2	0.12	0.14	0.14	0.11	0.08	0.06	0.08	0.09
Al_2O_3	11.03	10.68	11.41	13.78	13.22	12.53	11.74	11.74
Fe_2O_3	3.57	3.77	2.39	1.58	0.44	0.48	1.24	1.2
FeO	*	*	1.00	*	0.92	0.69	0.95	0.88
MnO	0.13	0.12	0.14	0.07	0.04	0.03	0.03	0.04
MgO	–0.01	0.02	0.01	0.22	0.05	0.01	0.01	0.08
CaO	0.09	0.16	0.07	1.33	0.72	0.65	0.16	0.5
Na_2O	6.48	5.86	7.35	4.16	4.08	3.92	5.4	4
K_2O	3.92	4	4.44	3.07	4.82	4.7	4.11	4.5
P_2O_5	0.03	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	0.36	0.39	0.5	0.16	0.27	0.25	1.35	5.7
Total	**99.23**	**100**	**99.85**	**100.03**	**100.2**	**99.92**	**100.03**	**100.95**

Cs	9.1	6.3	8.6	8.6	10.2	12.7	11.6	6.9
Rb	585	502	640	127	195	237	321	181
Sr	bdl	3	0.6	148	34	1.9	2.3	24
Ba	7	7	bdl	650	242	7.8	8.5	126
Th	80	57.8	66.6	15.8	19.1	19.5	45.1	23.1
U	18	14.1	21	4.3	5.4	6.1	12.7	5.3
Sc	n.a.	0.98	0.25	2	7.4	9.6	1.7	2.8
Nb	471	332	616	9	25	28	153	39
Ta	41	14.7	31.6	n.a.	2.1	2.6	14.6	2.7
Zr	752	2240	3156	88	137	132	724	130
Hf	78	57	76.2	2.9	5.6	6.3	27.2	6.2
Y	232	170	322	13	35	50	146	42
La	208	151	181	28.3	38.6	23.2	41.8	31.2
Ce	334	326	404	49.5	69.2	55.1	98	70.4
Nd	176	141	170	18	31.9	27.1	50.6	34.7
Sm	42	31.8	42.8	2.96	6.79	7.94	17.9	7.58
Eu	3.85	2.24	2.84	0.53	0.29	0.1	0.58	0.17
Tb	7	5.3	6.51	0.38	1.1	1.39	3.85	1.21
Yb	19	14.8	17.8	1.49	3.66	4.88	9.98	4.01
Lu	2.69	1.88	2.71	0.22	0.49	0.72	1.32	0.58

*, Total Fe as Fe_2O_3.

Abbreviations: n.a., not analysed; bdl, below detection limit.


(a)
Pire Mahuida
1cm
(b)
0.5cm
Arroyo
(e)
Chaiten
0.5cm
(f)
0.5mm
(n)
0.25cm
Baguales
(o)
0.5mm
(p)
0.5cm
Seno de Otway
(q)
0.25mm
(r)
0.25mm

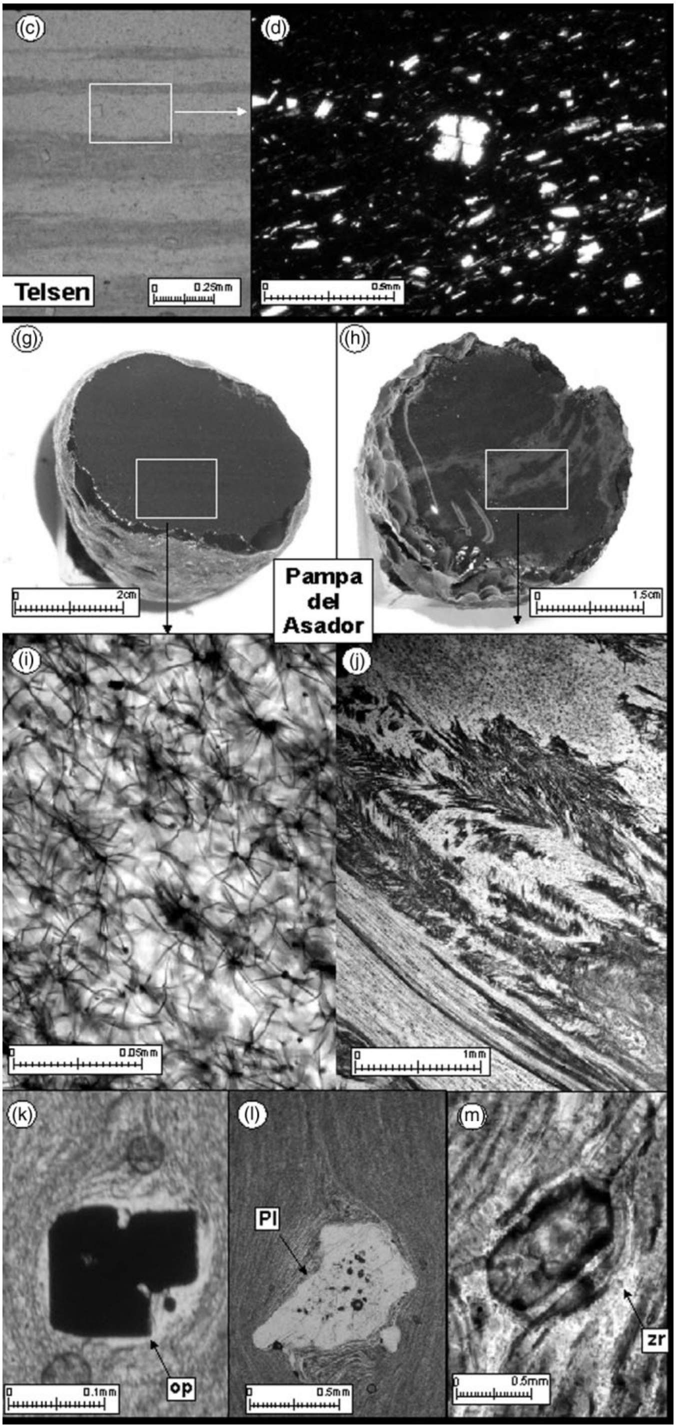

(c)
(d)
Telsen
0 0.25mm
0 0.5mm
(g)
(h)
0 2cm
Pampa del Asador
0 1.5cm
(i)
(j)
0 0.05mm
0 1mm
(k)
(l)
(m)
Pl
op
zr
0 0.1mm
0 0.5mm
0 0.5mm

Figure 2 (previous page) *The studied obsidians: (a) Pire Mahuida obsidian; (b–d) an Arroyo Telsen sample, with their characteristic banding composed of orientated crystaloclasts; (e) a photograph of the studied Volcán Chaitén obsidian; (f) a microscopic view of the same sample, with a feldspar crystaloclast in the middle and the alteration surrounding it; (g, h) Pampa del Asador obsidians with uniform colour and red banding; (i–m) microphotographs of Pampa del Asador samples showing that different composition of glasses produce different colours, and the different mineral species that compose their crystaloclasts; (n, o) macro- and microscopic images of Baguales obsidian and their alteration products; (p,q,r) a Seno de Otway sample that shows the banding textures and its alteration.*

Volcán Chaitén (72°40′W/42°50′S) The Chaitén volcano is located in the western margin of Chile (Fig. 1). This deposit is associated with arc volcanism involving oceanic plate subduction (Bellelli *et al*. 2006). The Chaitén volcano is a rhyolitic dome within a collapse caldera located on the south-west flank of the Michinmahuida volcano, located north-east of the town of Chaitén (López-Escobar *et al*. 1991, 1993; in Stern *et al*. 2002). This calc-alkaline obsidian has been constrained at 0.1 Ma (Stern 2004) and most likely formed during the last large eruption at *c.*10 000 BP (Naranjo and Stern 2004).

Its most dense archaeological distribution is located in coastal sites located as far as 400 km to the north and south of this source (Stern and Curry 1995). Recently, however, archaeological materials made with Chaitén Volcano obsidian have been identified as far away as ~1000 km, in Monte León National Park and Pali Aike volcanic field, Santa Cruz, Argentina (Cruz *et al*. 2011; Stern *et al*. 2012; Charlin pers. comm.).

This obsidian occurs as grey translucent pebbles with banded textures. These bands are of colourless and light brown glass, in some cases discontinuous, of variable thickness (between 0.1 mm and 0.9 mm) (Fig. 2 (e)). Its most conspicuous feature is the presence of alkali feldspar and quartz crystaloclasts that reach 0.6 mm in length and represent less than 1% of the total volume (Fig. 2 (f)). Opaque minerals occur as accessory species (1% of the total volume), with diameters smaller than 0.01 mm. This obsidian shows an incipient degree of devitrification, indicated by the presence of 0.05 mm low-birefringence secondary minerals that are orientated subparallel.

Pampa del Asador (71°19′W/47°53′S) Pampa del Asador is part of the volcanic plateau of Patagonia (Ramos and Kay 1992; Fig. 1), where metaluminous obsidian pebbles occur within fluvioglacial deposits (Espinosa and Goñi 1999). Some samples were also found in the creeks that cut the plateau (Stern 1999). There is also obsidian in lower-elevation sectors, carried by numerous drainage channels and in lower pampas. The general distribution suggests that the primary source is located near Pampa del Asador. Some pebbles have been dated in a range of 4.9–6.4 Ma, which happen to coincide with the formation of some basaltic plateaux from the Meseta del Águila area, west of Pampa del Asador (Ramos and Kay 1992). At least three chemically different types of obsidian have been described from Pampa del Asador (Stern 1999, 2004).

In terms of archaeological representation, samples from the Pampa del Asador source are widely distributed in south-central Patagonia in space and time. In this sense, artefacts of this obsidian have been found as far away as the Valdés Peninsula (Stern *et al*. 2000; Stern 2004), the Strait of Magellan and Tierra del Fuego (Stern *et al*. 1995a; Stern 2004)—roughly 800, 500 and 600 km from the source, respectively. With regard to chronology, this glass has been used in some archaeological sites since at least 9700 years BP (Stern *et al*. 1995b; Stern 1999, 2004).

This obsidian is presented in the form of rounded black pebbles with a brown or grey alteration surface a few millimetres thick. Although some samples can be massive (Fig. 2 (g)), banding textures 1–3 mm wide frequently occur (Fig. 2h). Most importantly, the banded textures are due to different compositional varieties: colourless and reddish glasses a few centimetres wide (Figs 2 (h) and 2 (j)). Other samples are composed of light and dark bands. Plagioclase, zircon and opaque are the most common crystaloclasts. Plagioclase (1%) is present as crystals that reach 2 mm in length (Fig. 2 (l)). The zircons have prismatic shapes from 0.05 mm in length and do not exceed 1% of the volume of samples (Fig. 2 (m)). Opaque minerals (below 1%) show cubic shapes with sizes that vary between 0.01 mm (more frequent) and 0.2 mm (Fig. 2 (k)). Although secondary minerals were not observed in the studied samples, radial (Fig. 2 (i)), parallel, sub-parallel or random fractures could indicate an incipient process of alteration.

Baguales (72°15′W/50°40′S) Geological deposits of this variety of obsidian have not yet been found (Franco pers. comm.; Stern pers. comm.). This peralkaline obsidian was identified from geochemical analyses of archaeological artefacts (Stern and Franco 2000). Their fragments have been recovered from archaeological sites along the southern and eastern edges of Argentino lake, in the upper Santa Cruz River and near the Atlantic coast (Stern and Franco 2000; Fig. 1). The age of this obsidian is constrained around 2.3 Ma; hence it is correlated with the basaltic lavas of the Vizcachas plateau and the Baguales range in the upper Santa Cruz River basin, and their proportion in the archaeological assemblages increases towards the Baguales range. In the Pali Aike and Cueva Fell archaeological localities, it is present from 8500 to 6500 years BP (Stern 2004). In particular, in Pali Aike this obsidian is the most abundant and persists until historical times (Charlin 2009).

On the basis of the surface characteristics of the collected samples, the Baguales obsidian probably occurs in veins (Franco pers. comm.). The most remarkable feature is the light grey–greenish colour (Fig. 2 (n)). Thin sections of this glass present dark bands of about 0.1 and 0.9 mm inside the colourless background. This obsidian presents crystaloclasts of alkali feldspar (<20% of the total volume), the size of which does not exceed 0.1 mm (Fig. 2 (o)). This glass shows a high degree of devitrification, demonstrated by the presence of low-birefringence prismatic minerals.

Seno de Otway (71°56′00″W/52°50′40″S) This type of hydrated calc-alkaline obsidian has been identified from the analysis of artefacts found in coastal maritime archaeological sites, around the Otway Sea (Fig. 1), and, in smaller amounts, on terrestrial hunter–gatherer sites in the Magellanic region (Stern and Prieto 1991). Although the geological source is still unknown, its age of about 17.1 Ma (Stern and Prieto 1991; San Román and Prieto 2004) and its Sr composition suggest a relationship between this obsidian and the Miocene volcanic belt of the Strait of Magellan (Stern and Prieto 1991; San Román and Prieto 2004).

The archaeological distribution of this obsidian is more restricted than other sources. Its frequency in archaeological sites increases towards the Otway Sea (Stern and Prieto 1991). Samples from the Cueva Fell site are evidence that Seno de Otway obsidian has been used for at least the past 6500 years (San Román and Prieto 2004; Stern 2004).

This obsidian occurs in individual fragments within breccias (Stern and Prieto 1991; San Román and Prieto 2004). Even though a grey colour is usually present, dark green is the most common one. It also presents banding textures composed of colourless and greenish glasses about 4 mm wide (Fig. 2 (p)). Colourless glass indicates a higher degree of alteration than that produced in radial aggregates of minerals with second-order birefringence (Figs 2 (q) and 2 (r)).

The study of the sources described above allows us to highlight the fact that there are some optical properties of the obsidians that can be helpful in discriminating between them. Even though most of the samples present different colours, the Baguales source can easily be identified by its green to grey tonalities. Macroscopic colour is also useful in identifying the Pampa del Asador obsidian, due to its characteristic red bands, and also that from Pire Mahuida, due to its uniform black colour. On the other hand, using polarized light microscopy, the composition of the crystaloclasts and the degree of alteration seem to be the most helpful optical features for identifying some sources. The Volcán Chaitén and Seno de Otway obsidians, for example, are the most altered ones, while Pampa del Asador has several crystaloclasts composed of alkali feldspar, quartz and zircon. The main optical properties of each source are summarized in Table 1.

Refractive indices

Because of the unequal number of available samples, the number of measurements for each locality is different (Table 3). Thus the average and dispersion measures of the refractive indices for each source were calculated to evaluate the general trend, the variance of the index values and the intrinsic variability of each locality (Table 4). Pampa del Asador is the site that shows the highest standard deviation, followed by Arroyo Telsen. This pattern suggests that these are the sources with the greatest variability and dispersion of refractive indices (Fig. 3).

To evaluate the existence of significant differences in the means of the different sources, we conducted a parametric analysis of variance (one-way ANOVA) of the total number of measurements of each sample (a minimum of four) (Sokal and Rohlf 1979). The results show significant differences (ANOVA; $F = 16.43$, $P < 0.00$ or $P(\text{same}) = 4.803\text{E}{-}11$) between groups at a probability level of 95% ($P = 0.05$): this means that there are differences between two samples at least. We chose to apply an ANOVA because our samples meet the condition or assumption of homogeneity of variances based on means (Levene $P = 0.1546$) calculated using the Levene test. These tests were carried out using the Past program (Hammer *et al.* 2001).

The *post hoc* pairwise comparison Tukey test shows which pairs have significant differences in their refractive indices means (Table 5). The diagonal represents the comparison of each site with itself, and therefore is not a value of interest. More than the value of the test comparison of means, we are interested in the probability that the difference between pairs, which appears in the upper right half of the matrix (in bold), is significant. As can be seen, not all couples are significantly different ($P < 0.05$), but there are pairs that differ significantly (coloured grey). The values of this test show that there are significant differences between the means of the refractive indices of the following sources: Arroyo Telsen – Volcán Chaitén, Arroyo Telsen – Pampa del Asador, Arroyo Telsen – Pire Mahuida, Volcán Chaitén – Baguales, Volcán Chaitén – Seno de Otway, Baguales – Pire Mahuida and Seno de Otway – Pire Mahuida.

DISCUSSION

Current knowledge indicates that there are 12 obsidian deposits found south of parallel 41°S in South America, but it is worth emphasizing that this most probably does not reflect all of the potential obsidian sources in Patagonia. This could be due to the lack of detailed studies of geological deposits, and might be associated with the scarce exploration of this region and the small size of the obsidian layer outcrops. Therefore, it is highly likely that many undiscovered deposits still exist, but that they could be smaller than the ones studied here and clearly less significant from an archaeological perspective.

The data that we have obtained show that obsidians from the same source vary in optical properties, more frequently than was initially thought. Several differences in the refractive

Table 3 *Refractive indices* (N_D)*. The second and third columns represent the* N_D *value measured at room temperature. In the fourth and fifth columns are the measurements of the* N_D *to ~10°C above room temperature. The correction factor,* $dN_D/dT = 0.00036$*, was calculated on the basis of these latter measures. Thus all the ND were standardized at 20°C, as indicated by the last column.*

Source	T_1 *(degrees)*	N_{D1}	T_2 *(degrees)*	N_{D2}	$N_{D\ (20°)}$
Pire Mahuida	25.0	1.4761	37.0	1.4718	1.4779
	24.5	1.4756	38.0	1.4713	1.4772
	25.0	1.4761	38.0	1.4718	1.4779
	26.0	1.4781	–	–	1.4802
	26.0	1.4829	–	–	1.4848
Arroyo Telsen	26.0	1.4844	–	–	1.4865
	26.0	1.4921	–	–	1.4942
	26.5	1.4931	–	–	1.4953
	26.0	1.4873	–	–	1.4894
	23.0	1.4873	–	–	1.4883
	25.0	1.4887	38.0	1.4844	1.4905
	24.5	1.4882	38.0	1.4834	1.4898
	24.5	1.4907	–	–	1.4922
	26.0	1.4800	–	–	1.4822
	24.0	1.4887	38.5	1.4834	1.4901
	26.0	1.4921	–	–	1.4943
	26.0	1.4834	–	–	1.4855
	25.0	1.4902	–	–	1.4920
	25.5	1.4921	–	–	1.4941
	27.5	1.4931	–	–	1.4957
	26.5	1.4877	–	–	1.4900
Volcán Chaitén	25.0	1.4747	–	–	1.4764
	25.5	1.4800	–	–	1.4820
	25.0	1.4800	–	–	1.4818
	25.0	1.4771	–	–	1.4789
	25.0	1.4795	–	–	1.4813
Baguales	26.0	1.4824	–	–	1.4846
	25.0	1.4863	–	–	1.4881
	24.5	1.4853	–	–	1.4869
	25.5	1.4863	–	–	1.4882
	25.0	1.4868	–	–	1.4883
Seno de Otway	25.0	1.4800	–	–	1.4818
	25.0	1.4848	–	–	1.4866
	24.5	1.4907	–	–	1.4922
	25.0	1.4800	–	–	1.4818
	24.7	1.4800	–	–	1.4817
	25.5	1.4849	–	–	1.4868
	25.0	1.4863	–	–	1.4881
	24.6	1.4863	–	–	1.4880
	24.5	1.4877	–	–	1.4893
	25.0	1.4882	–	–	1.4900
	24.5	1.4882	–	–	1.4898

Table 3 *Continued*

Source	T_1 *(degrees)*	N_{D1}	T_2 *(degrees)*	N_{D2}	$N_{D\ (20°)}$
Pampa del Asador	24.5	1.4751	–	–	1.4767
	26.0	1.4766	–	–	1.4787
	25.5	1.4824	–	–	1.4844
	26.0	1.4824	–	–	1.4845
	26.0	1.4824	–	–	1.4845
	24.0	1.4766	–	–	1.4780
	24.5	1.4795	–	–	1.4787
	25.5	1.4795	–	–	1.4815
	26.0	1.4815	–	–	1.4836
	25.0	1.4742	–	–	1.4759
	25.5	1.4756	–	–	1.4776
	25.5	1.4824	–	–	1.4844
	25.5	1.4868	–	–	1.4887
	26.0	1.4853	–	–	1.4875
	25.0	1.4863	38.5	1.4824	1.4881
	24.5	1.4873	38.0	1.4815	1.4888
	25.0	1.4863	–	–	1.4881
	25.0	1.4863	–	–	1.4881
	26.0	1.4858	38.0	1.4815	1.4880
	25.0	1.4781	–	–	1.4798
	25.5	1.4786	–	–	1.4805
	25.5	1.4810	–	–	1.4829
	26.0	1.4853	–	–	1.4875
	26.5	1.4834	–	–	1.4856
	27.0	1.4863	–	–	1.4887
	24.5	1.4781	–	–	1.4796
	25.0	1.4786	–	–	1.4803
	25.0	1.4800	–	–	1.4818
	25.0	1.4791	–	–	1.4808
	25.0	1.4815	–	–	1.4832
	24.5	1.4786	–	–	1.4801
	25.0	1.4786	–	–	1.4803
	25.0	1.4786	–	–	1.4803
	25.0	1.4737	–	–	1.4755
	25.0	1.4766	33.0	1.4737	1.4784
	24.0	1.4776	38.0	1.4737	1.4790
	25.0	1.4737	–	–	1.4755
	24.5	1.4771	–	–	1.4787
	24.5	1.4824	–	–	1.4840
	24.5	1.4815	–	–	1.4830
	26.0	1.4810	–	–	1.4831
	26.0	1.4810	–	–	1.4831

indices, colours, crystal inclusions and chemistry have been documented in samples from the same deposit. It is noteworthy that to determine the mineralogical and textural properties of the obsidians that characterize each locality, petrological studies of the volcanism that has extruded them must be performed. Because most of the obsidian deposits do not have a suitable geological

Table 4 *The average and dispersion measures of the refractive indices of the sources analysed*

	Pire Mahuida	*Arroyo Telsen*	*Volcán Chaitén*	*Pampa del Asasdor*	*Baguales*	*Seno de Otway*
Population size	5	16	5	42	5	11
Mean	1.4796	1.4907	1.4800	1.4824	1.4872	1.4870
Standard error	0.0014	0.0009	0.0011	0.0006	0.0006	0.0011
Variance	1.03×10^{-5}	1.41×10^{-5}	6.5×10^{-6}	1.58×10^{-5}	1.7×10^{-6}	1.24×10^{-5}
Standard deviation	0.0032	0.0038	0.0025	0.0040	0.0013	0.0035
Median	1.4780	1.4905	1.4810	1.4825	1.4880	1.4880

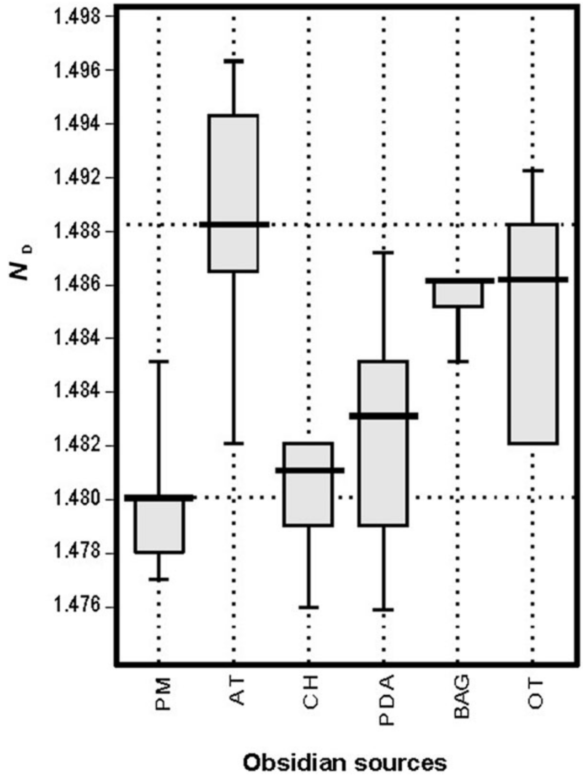


Figure 3 *The graph of the average and central trends of the refractive indices* ($N_{D(20°)}$) *of each source: PM, Pire Mahuida; AT, Arroyo Telsen; CH, Volcán Chaitén; PDA, Pampa del Asador; BAG, Baguales; OT, Seno de Otway.*

characterization, the representativeness of each analysed sample cannot be considered to be totally precise.

As mentioned above, the chemical composition of natural glasses (mainly the amounts of SiO_2, H_2O and Fe_3O_4) is one of the factors that control the refractive index. In order to study any possible correlation, Table 2 shows the chemical composition of each locality according to the published chemical analyses. All the data compiled show that even though the obsidians present

Table 5 *Pairwise comparisons by means of Tukey's test of the sources: the grey shading indicates values that have significant differences at a probability level of 95%* ($P < 0.05$)

	Pire Mahuida	*Arroyo Telsen*	*Volcán Chaitén*	*Pampa del Asador*	*Baguales*	*Seno de Otway*
Pire Mahuida	0	0.0001	0.9999	0.6592	0.0017	0.0024
Arroyo Telsen	8.3470	0	0.0001	0.0006	0.4407	0.3767
Volcán Chaitén	0.3017	8.0460	0	0.7862	0.0034	0.0048
Pampa del Asador	2.1350	6.2130	1.8330	0	0.1245	0.1567
Baguales	5.7320	2.6160	5.4300	3.5970	0	1.0000
Seno de Otway	5.5810	2.7670	5.2790	3.4460	0.1508	0

similar values of their major elements, these localities can be identified by the amounts of some of the minor elements (Stern 2004). The results in our present study suggest that the values of N_D do not vary according to the alkaline signature of the glasses. However, many more chemical analyses would be necessary, together with N_D measures for each deposit, before any potential correlation between these two variables could be established precisely. On the other hand, chemical analyses would have to be carried out on the same glass shards on which the N_D values were measured. However, the sparse amounts of obsidian available from some localities do not yet allow us to perform this study.

CONCLUSIONS

The results of the present study lead to the following suggestions:

- The colour, banding textures, alteration degree and crystaloclast composition are the most important optical properties for identifying the sources described in this study.
- The N_D value obtained from each source enables us to establish that the refractive index of Patagonian obsidian varies between 1.47 and 1.49, which is consistent with natural rhyolitic glasses.
- The N_D measurements from Pire Mahuida, Arroyo Telsen and Volcán Chaitén show that these are the sources that present the greatest differences, whereas Pampa del Asador, Baguales and Seno de Otway localities show smaller differences, and hence this technique should in the future be complemented by other optical properties for greater precision in identifying the source.
- Finally, our analysis suggests that the N_D value could not be correlated with the physical properties observed in hand samples. Volcán Chaitén and Baguales, for example, show similar colours and textures and different refractive indices; while Pampa del Asador and Seno de Otway show the opposite behaviour.

Even given the few observations just mentioned, we have advanced the exploration of the use of refractive indices as a way of determining the identity of obsidian sources. We have demonstrated that the various obsidians have a different pattern in their indices that is the result of their particular history—which, in itself, validates our pursuit of this line of work. The relative simplicity of this technique, together with its strong results and the need for only small samples, makes it a very attractive alternative in view of the large percentage of obsidian-made archaeological materials represented in many of the archaeological sites of Patagonia.

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