Earth and Planetary Science Letters 432 (2015) 381–390

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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Magnetic properties of tektites and other related impact glasses

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ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form 8 October 2015
Accepted 19 October 2015
Available online xxxx
Editor: B. Marty

Keywords:
magnetic properties
tektite
impact glass
crater

ABSTRACT

We present a comprehensive overview of the magnetic properties of the four known tektite fields and related fully melted impact glasses (Aouelloul, Belize, Darwin, Libyan desert and Wabar glasses, irghizites, and atacamaites), namely magnetic susceptibility and hysteresis properties as well as properties dependent on magnetic grain-size. Tektites appear to be characterized by pure Fe^{2+} paramagnetism, with ferromagnetic traces below 1 ppm. The different tektite fields yield mostly non-overlapping narrow susceptibility ranges. Belize and Darwin glasses share similar characteristics. On the other hand the other studied glasses have wider susceptibility ranges, with median close to paramagnetism (Fe^{2+} and Fe^{3+}) but with a high-susceptibility population bearing variable amounts of magnetite. This signs a fundamental difference between tektites (plus Belize and Darwin glasses) and other studied glasses in terms of oxygen fugacity and heterogeneity during formation, thus bringing new light to the formation processes of these materials. It also appears that selecting the most magnetic glass samples allows to find impactor-rich material, opening new perspectives to identify the type of impactor responsible for the glass generation.

1. Introduction

Magnetic properties provide a rapid and versatile technique to characterize non-destructively the composition of rare materials in terms of content of magnetic elements (mostly Fe, but also Mn, Cr, Ni, and other trace magnetic elements), as well as oxidation state and distribution of these elements among various phases. Such an approach has been exemplified in meteorites (e.g., Rochette et al., 2008, 2012) where magnetic properties, mostly susceptibility, have been used for classification purposes. Magnetic measurements allow to screen large collections, in museums in particular, and to single out anomalous samples worth of further investigations.

High velocity impacts on Earth are able to generate high temperature melted material that can be subsequently ejected away from the crater and quenched as natural glasses (Dressler and Reimold, 2001). These impact glasses have specific composition and properties with respect to volcanic glasses, due to the nature of their source materials and high temperature and pressure formation conditions. Tektites have been identified as a specific type of natural glass, obsidian-like but unrelated to volcanism (Suess, 1900; Koeberl, 1986; Glass, 1990; McCall, 2001). Tektites are homogeneous materials made only of glass, not or poorly vesiculated, that can be found geographically spread over a large strewnfield (500–5000 km size range). The natural shape of tektites usually demonstrates flight in liquid state in the atmosphere (splash-forms). Initial examples were the central European moldavites and the Australasian tektites (Suess, 1900), but soon two other strewnfields were identified, in Ivory Coast and North America (Glass, 1990; Koeberl et al., 1997). An impact origin has been established based on various arguments, including connection with large (>10 km diameter, see Table 1) impact craters (except in the Australasian case). Besides these four canonical examples, a fifth central American strewnfield has been proposed (e.g., Povenmire and Cornec, 2015), originally named Tikal glass (Sentfle et al., 2000), although its characteristics are not as well defined as for the other four cases. Here is it will be named Belize glass as hundreds of specimens have been found in soils from this country. No consensus has been reached yet to rank the Belize glass among tektites. However, it yields redox state and water content typical

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http://dx.doi.org/10.1016/j.epsl.2015.10.030
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Table 1
Magnetic susceptibility (χ) measurements on various tektites and related impact glasses, ordered by average FeO wt%. Corresponding crater diameter (in km), when known, is indicated within brackets. Average χ value in 10^{-9} m^3/kg with s.d. normalized to the mean in %, range, N number of samples measured; poorly defined s.d. within bracket ($N < 8$).

	FeO (wt%)	Average χ (10^{-9} m^3/kg)	s.d. (%)	χ range	N
Tektites					
Moldavite[a] (24)	1.8	35	34	23 to 78	15
Moldavite (24)	1.8	31	19	25 to 60	39
Georgiaite (40)	2.6	49	(8)	44 to 52	3
Bediasite (40)	4	65	24	43 to 129	62
Australasite[a]	4.9	82	10	57 to 103	152
Ivoirite (10)	6.2	103	12	62 to 138	109
Other glasses					
Libyan desert normal	0.1	−2.3	39	−3.3 to −0.6	10
Libyan desert dark	0.1	4.4	71	−0.1 to 10.8	8
Darwin (1.2)	2.6	53	23	34 to 79	45
Aouelloul (0.4)	2.9	82	89	38 to 463	65
Irghizite (6–14)	5.6	164	59	103 to 791	91
Wabar (0.1)	6.1	468	58	125 to 1025	14
Belize glass	7.0	127	5	115 to 137	11
Atacamaite	8.5	302	286	84 to 20 500	3291
Atacamaite >0.5 g	8.5	191	71	84 to 1270	1401
Safford	*0.6*	*380*	*181*	*5 to 2382*	*12*

[a] Indicates measurements from the literature while the other lines correspond to this work, with one literature data for Belize glass. Note that Safford is a site of obsidian like glass presented in the discussion. FeO data is derived from the following references: Koeberl (1986); Koeberl et al. (1997, 1998), Giuli et al. (2002), Howard (2008), Hamman et al. (2013), Senftle et al. (2000). Note that total iron is reported as FeO.

of tektites (Giuli et al., 2014). Other "tektite-related" impact glasses (i.e. with fully melted splash-forms) have been described and will be discussed here.

The size of tektites is typically in the centimetre range, although much smaller samples have been found in the sedimentary record and called microtektites (Glass, 1990). Microtektites have been described associated to three tektite fields (Australasian, Ivory Coast and North American), and are scattered almost globally as illustrated by the Australasian strewnfield traced from China to Australia, Madagascar and Antarctica (Folco et al., 2008).

Magnetic properties of tektites have been investigated by Werner and Borradaile (1998) concerning the australasite and moldavite strewnfields, while the Belize strewnfield has been investigated by Senftle et al. (2000) and Hoffmann et al. (2013). One purpose of the present contribution is to extend the database to the Ivory Coast (ivoirite) and North American (bediasite and georgiaite) tektites, as well as to impact glasses with characteristics close to tektites, i.e. fully melted material with splash-forms and moderate vesiculation. The glasses studied in this paper are the previously described irghizites, Aouelloul, Darwin, Libyan Desert and Wabar glasses (e.g., Koeberl, 1986; Koeberl et al., 1998; Howard and Haines, 2007; Giuli et al., 2003; Hamman et al., 2013), as well as the newly discovered atacamaites (Devouard et al., 2014). We also report on "tektite-like" volcanic glass found in Safford (Arizona), to evaluate the ability of magnetic properties to discriminate volcanic from impact glasses.

One central question in impact glasses is to trace a possible meteoritic contamination in the overall terrestrial composition (Koeberl, 1998). This quest is not often fruitful as the average contamination may be only at trace level. One potential application of magnetic measurements on a large number of tektites and related glass samples is the detection of samples anomalously rich in magnetic elements (Fe, Ni, ...) pointing toward a larger meteoritic contamination, as done by Tagle et al. (2014) using Ni content screening of australasites.

2. Sample and methods

Glass samples were weighted and their low field magnetic susceptibility (χ) measured either in the laboratory at CEREGE using a high sensitivity MFK1 kappabridge, or directly in the collections using portable instruments (MSB2 and SM30 instruments) and following procedures and calibration described in Sagnotti et al. (2003), Gattacceca et al. (2004), and Rochette et al. (2009). Raw signal after sample holder correction is proportional to sample mass, thus limiting the lower size measurable with sufficient accuracy. MFK1, SM30 and MS2B noise level reaches 10^{-9} m^3/kg for a 0.1, 5 and 10 g sample, respectively. MFK1 and MS2B are restricted to sample masses below about 40 g (depending on sample shape), while SM30 can be used for larger samples. We measured ivoirites, georgiaites and bediasites directly in the London and Paris Natural History museums, as well as in the private collection of A. Carion in Paris. When using SM30 or MS2B, we did not consider samples that yield a precision worse than 10%. In the case of MS2B this represents a lower mass limit of 1 g considering the typical χ of 100×10^{-9} m^3/kg for tektites. Data from australasites, moldavites and Belize glass are derived from the literature (Werner and Borradaile, 1998; Senftle et al., 2000; Hoffmann et al., 2013). We also measured a collection of moldavites and Belize glass using a Kappabridge. Irghizites from D.D. Badyukov collection (Vernadsky Institute, Moscow, Russia) were measured in the Schmidt Institute of Physics of the Earth RAS (Moscow, Russia) using the MFK1, while our own field collection for the newly discovered impact glass strewnfield in Atacama (Devouard et al., 2014) was measured with the MFK1 at CEREGE. For other impact glasses, i.e. Aouelloul, Darwin, Libyan desert, and Wabar we report essentially MFK1 measurements made on samples acquired or loaned from private collectors. The seminal work of Senftle and Thorpe (1959) on moldavites, australasites and a few other glasses will not be directly integrated in the present low field susceptibility database. Indeed their measurements were performed on mg size samples using a high variable field Curie balance (minimum field of 0.39 T), providing by extrapolation the high field susceptibility and saturation magnetization.

The measured low field susceptibility is the sum of the para-, dia- and ferro-magnetic susceptibilities. Paramagnetic susceptibility (χ_p) arising from magnetic elements diluted in glass can be predicted based on chemical composition and oxidation state. While FeO content in tektites is usually above 2 wt%, Mn is around 600 ppm, and Cr, Ni, Co are mostly below 100 ppm (Koeberl, 1986, 1990). Therefore we can obtain good estimates of χ_p using FeO analyses alone. At room temperature and assuming neg-