RESEARCH ARTICLE

Effects in North Africa of the 934–940 CE Eldgjá and 1783–1784 CE Laki eruptions (Iceland) revealed by previously unrecognized written sources

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Abstract

In historic times, two catastrophic fissure eruptions originated in the Eastern Volcanic Zone of Iceland, known as Eldgjá eruption (934–940 CE) and Laki eruption (1783–1784 CE). Eldgjá produced 19.7 km^3 of lava flows and 1.3 km^3 of tephra; Laki emitted 14.7 km^3 of lavas and 0.4 km^3 of tephra. They released 232 and 122 megatons of SO_2 into the atmosphere, respectively. Abundant historic descriptions of the effects of the Laki eruption indicate that the SO_2 release produced a sulphuric aerosol that spread across the northern hemisphere with devastating impacts on the population and the environment, especially in Europe. In this study, we present two new written sources that enable the effects of the Eldgjá and Laki eruptions to be fixed to an exact date and place of occurrence in North Africa. These are a medieval North African chronicle known as *Rawḍ al-Qirṭās*, written in 1326 CE and describing events in Morocco, and a chronicle of events in the island of Djerba (southern Tunisia), written by Muhammad b. Yusef al-Musabi in 1792–1793 CE. These previously unrecognized sources describe in detail the fading of sunlight coupled with the persistent presence of a thick fog made up of fine particles carried over from long distances. The chronicles report events in Morocco in the time period October 938–October 939 CE, and in Tunisia in the year 1783 CE. These data can be interpreted as the first detailed evidence of the consequences of the Eldgjá and Laki eruptions in North Africa. They also can be helpful in dating and determining the area of influence of the eruptions; this may be useful for several applications, such as the numerical simulation of these events, or hazard planning in case of possible future similar eruptions from the same Icelandic area.

Keywords Eldgjá eruption · Laki eruption · Historic chronicles · Dry fog · North Africa

Introduction

Very large volcanic eruptions can have important effects on human society and the natural environment. This influence can occur at a scale that potentially ranges from the global (Rampino and Self 1993) to the very local (Baxter et al. 1999), and through different mechanisms that include climate modification, acid rain/aerosol impact, proximal and distal production of pyroclastic deposits, gas emission and tsunami

(Grattan 2006). Catastrophic eruptions, such as the late Pleistocene Toba event, were suggested to coincide with a human genetic bottleneck, possibly pushing the human race to the brink of extinction (Rampino and Ambrose 2000). As an alternative example, Fedele et al. (2002) suggested that the environmental stresses induced in Europe by the ~ 40 ka BP Campanian ignimbrite eruption (Giaccio et al. 2017), originated from southern Italy, fostered the expansion of *Homo sapiens* at the expense of the less adaptable *Homo neanderthalensis*.

More frequently, volcanic eruptions may modify the climate conditions by introducing sulphur gases into the stratosphere, which then oxidize into an aerosol layer. The aerosol reduces non-uniformly the quantity of solar radiation that reaches the Earth's surface, producing a series of anomalous temperature and pressure gradients between low and high latitudes and between continental and oceanic air masses (Robock 2000). Volcanic gases have also direct effects on the environment and the human society, as the gases lead also

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to the formation of acid aerosols and acid rain in the atmosphere. The Icelandic Laki fissure eruption of 1783–1784 CE emitted a huge volume of gases (Thordarson et al. 1996) that formed an acid aerosol (Dry Fog) in the lower atmosphere, which damaged crops and vegetation (Steingrimssom 1998; Thordarson 1990, 1991, 2003) and brought about the death of 24% of the population of Iceland and three-quarters of its livestock (Halfdanarson 1984). The Laki-triggered adverse climate conditions and crop damaging acid rain and fog involved also Europe (Thoroddsen 1879; Thorarinsson 1979; Wood 1984, Wood 1992; Rabartin and Rocher 1993; Thordarson and Self 1993, Thordarson and Self 2003; Highwood and Stevenson 2003; Chenet et al. 2005; Grattan et al. 2005; Oman et al. 2006b; Schmidt et al. 2010, Schmidt et al. 2011; Zambri et al. 2019a, b).

Establishing a link between environmental changes and climate forcing by volcanic aerosols requires a detailed knowledge of the date of the climate event and its characteristics. This allows us to link the effect to the volcanic source. The lack of reliable sources of information on older events may lead to questioning whether the established relationships are fortuitous rather than dependant (Sadler and Grattan 1999). The establishment of a cause-effect relationship can be particularly problematic in case of a poor quality of the chronicles that describe volcanic events and climatically notable phenomena. A reliable and detailed database of volcanic ash dispersal witnesses is of paramount importance for the numerical modelling of the distribution of the volcanic aerosol clouds (Oman et al. 2006a). Accurate modelling is key to better understanding the climate response, as well as the environmental and health effects. Similarly, spatial detailed real data on the past distribution of ashes and aerosols is relevant for building models aimed at assessing possible threats to flights and other means of transportation.

In the present paper, we describe the data uncovered from two forgotten written sources in chronicles from Morocco and Tunisia, dating back to 1326 CE and 1792–1793 CE, respectively. Such chronicles report eye witnesses of phenomena that can be explained solely in terms of the consequences of the 934–940 CE Eldgjá and 1783–1784 CE Laki eruptive events, both of which took place in Iceland. These data represent the first evidence of the effects of the Eldgjá event in North Africa, whereas for the Laki eruption, this is the first detailed report for North Africa. As this can help to date and determine the area of influence of the eruptions, it can be useful for reconstruction of past events as well as for evaluating possible effects of future eruptions from the same volcanic source area.

Geological framework

Iceland results from dynamic uplift and the formation of a kilometres-thick succession of volcanic deposits produced by millions of eruptions, mostly of basaltic lava flows. The average eruption frequency has been in the order of 20–25 events per century since 870 CE (Thordarson and Larsen 2007; Thordarson and Höskuldsson 2008). This major volcanic activity is due to the interaction between the Mid-Atlantic ridge and the Icelandic mantle plume (Vink 1984; Wolfe et al. 1997). Volcanic activity is characterized by basaltic magmas mainly emplaced through dykes, whereas felsic magmas are less significant and limited to central volcanoes. Present-day volcanism in Iceland is confined to five volcano-tectonic zones, namely the Northern, Western, Snæfellsnes and Eastern volcanic zones (Einarsson 2008) (Fig. 1a), plus the Öræfajökull Volcanic Belt located nearby and parallel to the Eastern Volcanic Zone. These zones are marked by normal faults, central volcanoes and eruptive fissures, whose activity is accompanied by plate spreading at about 2 cm/year (DeMets et al. 2010). In historic times, both the catastrophic Eldgjá and Laki fissure eruptions originated in the Eastern Volcanic Zone. Presently, the source zones of these eruptions are expressed by alignments of fractures, normal faults, pyroclastic cones and spatter ramparts. These alignments strike NE-SW, parallel to the local orientation of the Eastern Volcanic Zone (Fig. 1b). This orientation reflects the regional tectonic stress field, since the volcanotectonic rift zones are sub-perpendicular to the least principal stress (σ_3) that trends WNW-ESE (Sigmundsson 2006; Pasquarè Mariotto et al. 2015; Tibaldi et al. 2016; Ziegler et al. 2016). Based on seismic investigations, the Icelandic hotspot is located below the area of the Eldgjá and Laki eruptive fissures (Wolfe et al. 1997). In the following sections, details on the two eruptions will be provided.

Eldgjá eruption

The Eldgjá eruption, also known as Eldgjá Fires, occurred in the form of a large-scale fissure eruption within the Katla volcanic system (Larsen et al. 2001) (Fig. 1b). This volcanic system is located in the southern part of the Eastern Volcanic Zone, and is 80 km long from SW to NE. The Katla volcanic system is composed of a central volcano, partly covered by the Mýrdalsjökull ice-cap, and an associated fissure swarm (Fig. 2a). The Eldgjá eruption activated a 75-km stretch of the volcanic system, both within the volcano's caldera and along the fissure swarm to the northeast. This is the largest Holocene volcanic event that occurred at the Katla system. The Eldgjá eruption produced 19.7 km^3 of lava flows (Moreland et al. 2019), 1.3 km^3 of basaltic tephra with a minor component of silicic tephra (Einarsson et al. 1980; Zielinski et al. 1995; Moreland et al. 2019), and 232 megatons of SO_2

Fig. 1 **a** Iceland, with its main volcano-tectonic rift zones (in red), known as Northern (NVZ), Western (WVZ), Snæfellsnes (SVZ) and Eastern (EVZ) volcanic zones. Box shows location of **b**. **b** Location of the Eldgjá and Laki eruptive fissures and related lava flows between the Katla and Grímsvötn volcanoes (modified after Thordarson and Self 1993, and Óladóttir et al. 2008) and of other main historic eruptive fissures
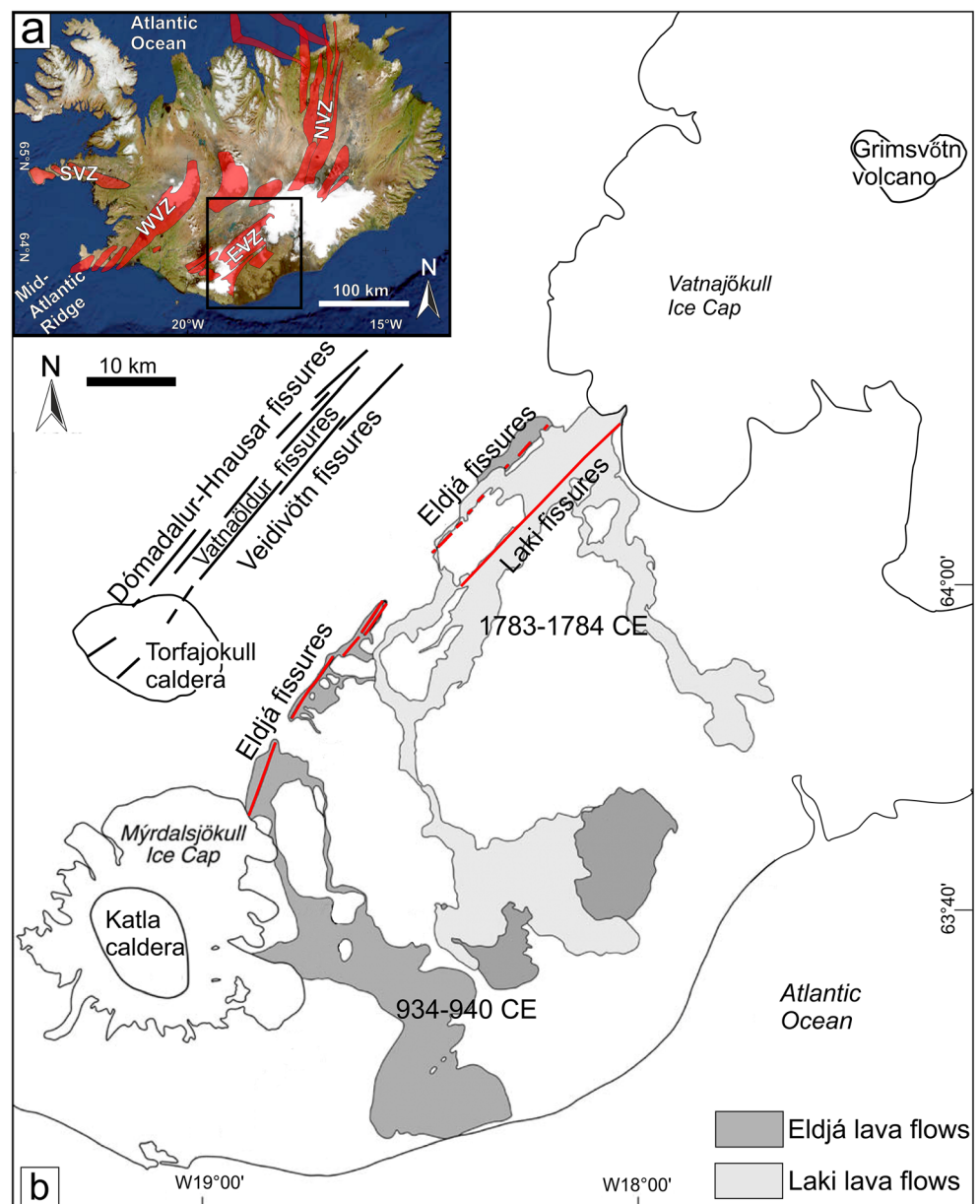
(Thordarson et al. 2001). The presence of the silicic tephra in the eruptive products indicates that the basaltic and felsic magmas were erupted contemporaneously, at least for some time (Larsen et al. 2001). This suggests that the Katla magma chamber was affected by fissuring during the Eldgja eruption, and this enabled the contamination of the more evolved magmas with new basaltic melts. The fissuring may have been originated by regional extension of this rift segment of the Eastern Volcanic Zone, or by upward/lateral propagation of the main dyke that produced the Eldgja fissure. The propagation of rifting in the 930s, along the Eastern Volcanic Zone, was suggested by Óladóttir et al. (2008), who hypothesized that this process resulted in an increase in mantle melting and the ascent of large volumes of basic magmas. More in detail,

Moreland et al. (2019) described the progress of the Eldgjá eruption, which featured 16 explosive phases of sub-Plinian to Plinian intensities, accompanied by eruption plumes rising above 15 km. It lasted longer than Laki and was a more intense event.

In regard to the age of this eruption, Oppenheimer et al. (2018) used high-temporal resolution glaciochemical records from Greenland to bracket the beginning of the event at the spring of 939 CE, although other previous authors proposed 934 to 938 as the inception age (Zielinski et al. 1995), as will be detailed in another section. The eruption continued, at least episodically, until the fall of 940 CE. This is corroborated also by (i) contemporary observation of a blood-red Sun in 939 CE as recorded in an Irish chronicle, indicative of volcanic haze

Fig. 2 a View of NE termination of the approximately 75-km-long Eldgjá eruptive fissure, as seen from Ofaerufoss. Here, termination of eruptive fissure is characterized by the presence of a graben, which was formed during at least one previous rifting episode, and was then reactivated during 939–940 CE. b View of SE portion of 27-km-long Laki eruptive fissure, as seen from Mt. Laki. Eruptive fissure is characterized by alignment of fractured monogenic cones within graben-like structure induced by feeder dyke. Photo courtesy of Valerio Acocella
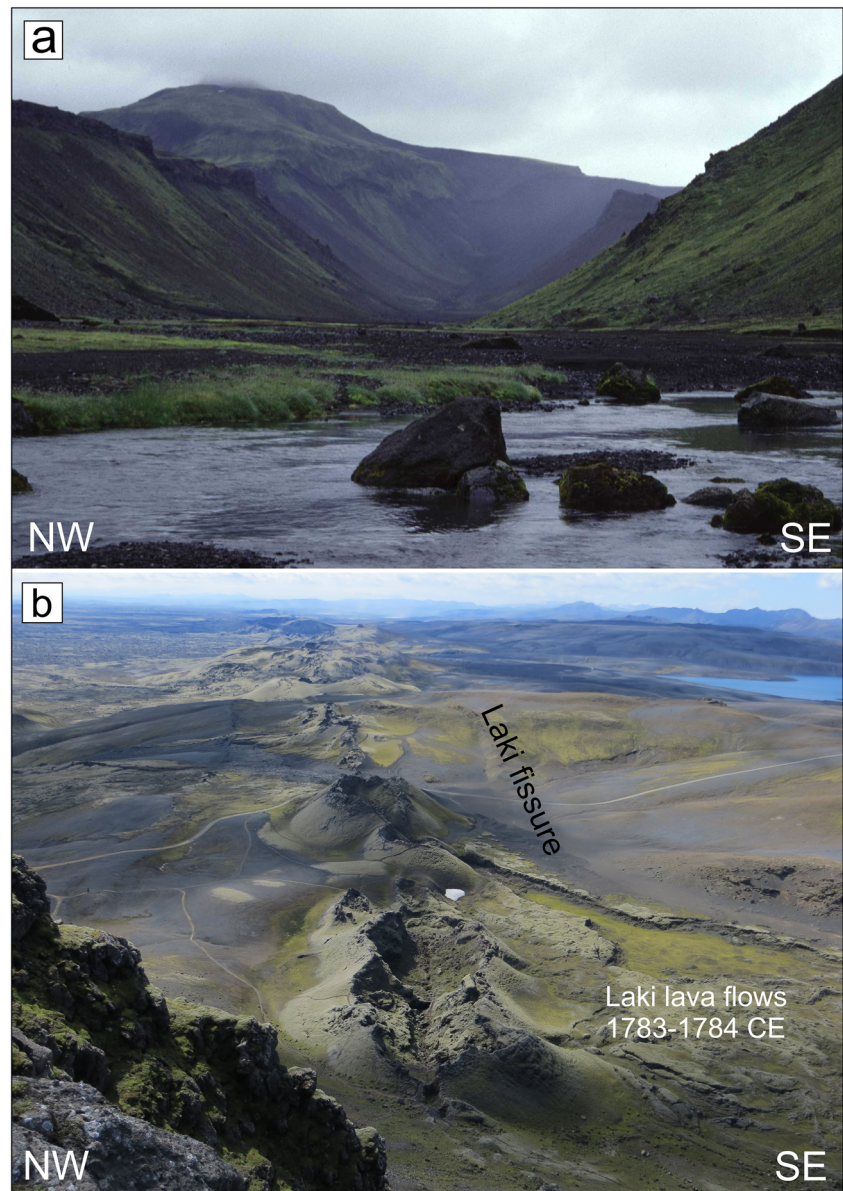
(McCarthy and Breen 1997), and (ii) tree ring analyses that indicate a pronounced northern hemisphere summer cooling in 940 CE (Stoffel et al. 2015), which is consistent with the large volumes of sulphur injected into the atmosphere. The date of 939 CE is also consistent with Greenland ice core records (Sigl et al. 2015), further historical accounts of meteorological and astronomical phenomena (Stothers 1998; Fei and Zhou 2006), and environmental records (Oman et al. 2006b; Baillie and McAneney 2015).

Laki eruption

The Laki (Lakagígar) eruption, also known in Iceland as Skaftáreldar (Skaftá Fires), occurred in the form of a fissure eruption southwest of Grímsvötn volcano (Fig. 1b), the latter

being covered by the Vatnajökull glacier (Björnsson and Einarsson 1990). Even if the Laki event produced less volcanic material than the Eldgjá eruption, it had the most devastating impact on the population and the environment, although this may be derived also from larger population and more abundant and better reports. The eruption began on 8 June 1783 and ended on 7 February 1784 CE (Thordarson and Self 1993). Eyewitnesses, reported in Thordarson et al. (2003a), describe that during the first days of the Laki eruption, the fires were seen in the southwestern part of the fissure system, suggesting that magma reached the surface, at first, midway between the Katla and the Grímsvötn central volcanoes. Thereafter, magma reached the surface further northeast, leading to the gradual propagation of the fissure system in the same direction, and triggering ten major eruptive episodes

during the first 5 months of activity. Each episode was characterized first by an explosive phase that persisted for 0.5–4 days, followed by a long-lasting phase of lava emission and fountaining (Thordarson and Self 2003). The explosive activity ranged from the Strombolian to the sub-Plinian type. The eruptive activity was most intense during the first 1.5 months, followed by a decline marked, in the last 3 months, solely by lava and gas emission (Thordarson and Self 2003). Finally, the activity occurred also at Grímsvötn volcano. Nowadays, the Laki fissure is expressed by a 27-km-long row of 140 pyroclastic cones and spatter ramparts, locally interleaved by fissures and normal faults (Fig. 2b). These volcanic edifices are elliptical in plan view, and most have a longer axis coincident with the NE-SW alignment of the whole structure. All these data suggest that a dyke rose from a large deep-seated reservoir and intercepted the surface firstly in the southwestern sector of the fissure system, and then propagated towards the NE. Finally, the eruption involved also the shallower crustal magma chamber of Grímsvötn volcano (Gudmundsson 1987; Sigmarsson et al. 1991; Thordarson and Self 1993).

In total, the Laki fissure system emitted 14.7 km³ (Dense Rock Equivalent—DRE) of lava flows, 0.4 km³ of tephra (Thordarson and Self 2003) and 122 megatons of SO_2 into the atmosphere, which resulted in a sulphuric aerosol hanging over the northern hemisphere for more than 5 months (Thordarson et al. 1996). In particular, the average discharge from the eruption column was about $1–2.5 \times 10^3$ m³ s⁻¹, giving calculated mean eruption column height of 7–9 km asl (Woods 1993). Lamb (1970) and Jonsson (1990) suggested that, during the most vigorous parts of the eruptive period (i.e. the first 3 to 5 months), the eruptive column transported volatiles and fine ashes up to altitudes of 7–13 km, whereas for Thordarson and Self (1993) the column was up to 13–15 km high. This implies that the eruptive column was capable of injecting huge amounts of material into the westerly jet stream that dominates at the northern latitudes in the upper troposphere and lower stratosphere. The jet stream was responsible for the spread of the finest ashes and aerosol in Europe (Fiacco et al. 1994; Thordarson and Self 2003).

Written sources

Eldgjá event

Previously known data

The recent study by Oppenheimer et al. (2018) summarizes the existing data, both from physical evidence and written sources, and puts forward 939 CE as the most likely date of the event inception. Previous different estimations of an approximate date were proposed by Hammer et al. (1980): 934 ±

2 CE; by Zielinski et al. (1995): 938 ± 4 CE; and by Vinther et al. (2006): 933 ± 1 CE. These studies have taken into consideration above all acidity, conductivity and basaltic glass shards found in the GISP2 Greenland ice core, combined with tree-ring records from northern Europe. Oman et al. (2006b), working with climate change models and the water level of the Nile compared with the Laki explosion of 1783, also inferred the year 939 CE.

Up to the present day, the only written source reporting phenomena connected with this eruption is an Irish chronicle, *Chronicum Scotorum* (in McCarthy and Breen 1997). The record for the year 939 CE says: *Dath fola forsan ngréin o tosach laoí go medhón laoí arnamarach*, which is, literally, "Colour of blood was on the sun from the beginning of one day to the middle of the following day". The short duration of the phenomenon (one day and half) "strongly suggests that it is an observation of the initial plume emerging from Eldgjá" (McCarthy and Breen 1997). A shortcoming of this testimony is the uncertainty regarding the date. Unlike many other Medieval chronicles from elsewhere, here each entry is not preceded by a number but by the word *Kalendae*, marking the beginning of a new year. In this way, assessing the year numbering requires a thorough philological work aimed at inferring it from the sequence of Kalendae, starting from well-known events and taking into account the possible mistakes and omission of lines by the copyists (McCarthy 1998). Suffice it to say that the *Annals of Clonmacnoise*, quoted by Stothers (1998), describe the same phenomenon in almost the same words and the whole entry of that year is clearly taken from the *Chronicon Scotorum*, but it is assigned to 933 CE.

Most probably, the Irish chronicle was not the only written testimony of this phenomenon and a thorough research in the multitude of existing Medieval chronicles might reveal similar observations. However, it is not easy to pick out information actually related to the eruption, because in the very same year, 939 CE, a total solar eclipse took place on 19 July, at 09:27:56 Dynamical Time, according to *NASA Five Millennium Canon of Solar Eclipses* (NASA n.d.): the path of totality ran across the Balkans, northern Italy, most of Spain and Portugal, while the rest of Europe was affected by a partial eclipse (Fig. 3). As a consequence, generic records of anomalous darkening of the sun could easily refer to this phenomenon rather than to the consequences of the volcanic eruption. Only detailed descriptions of phenomena lasting longer than a few hours seem reliable sources of information about the spread of volcanic material in the atmosphere. The further written sources quoted by Oppenheimer et al. (2018) are either too vague and inconclusive or clearly pointing to the eclipse. As a matter of fact, the *Res Gestae Saxonicae* (The Deeds of the Saxons) written by Widukind of Corvey (died after 973 CE) describe an event that happened on an undetermined date (anyway, before 936 CE) and for an unknown duration: *ante regis Heinrici excessum multa prodigia monstrata sunt, ita ut solis splendor forinsecus*
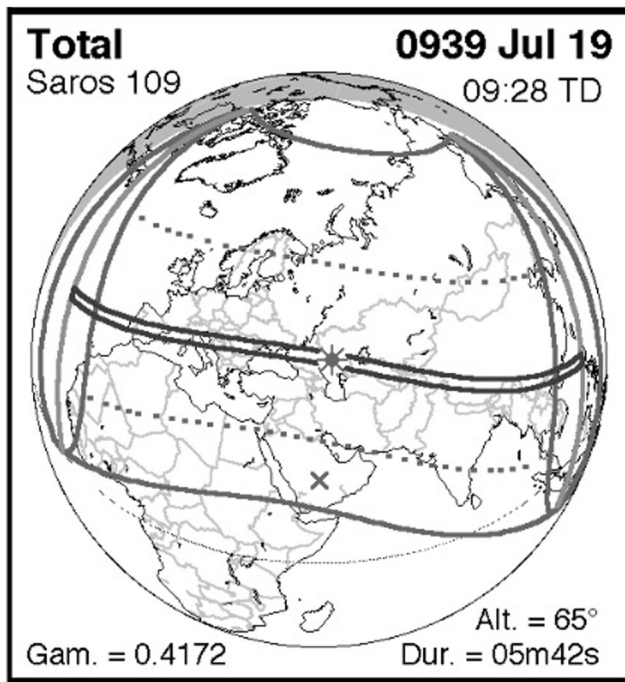
Total   **0939 Jul 19**
Saros 109   09:28 TD

Alt. = 65°
Gam. = 0.4172   Dur. = 05m42s

Fig. 3 In the very same year 939 CE, a total solar eclipse took place on 19 July, according to NASA Five Millennium Canon of Solar Eclipses. The path of totality ran across the Balkans, northern Italy, most of Spain and Portugal, while the rest of Europe was affected by a partial eclipse.

aere absque nubilo pene nullus appareret, intrinsecus autem per fenestras domorum rubeus tamquam sanguis infunderetur "before the death of king Henry (the Fowler, dated 936 CE) many wonders appeared, so that the brightness of the sun outdoors in an unclouded sky appeared almost nil, while it penetrated indoors through the windows of the houses reddish like blood". Moreover, the author explicitly remarks on the lack of clouds in the sky, which seems more indicative of an eclipse than a phenomenon caused by volcanic material dispersed in the air. As to the anonymous chronicle from Monte Cassino, it clearly refers to the eclipse: *DCCCCXXXIX. Indictione 12. 13. die stante mense Julio fer. 6. Luna 29. Obscuratus est Sol ab hora tertia usque pene horam quintam. Aspiciebamus nos Solem, et non habebat ullam fortitudinem, nec ad splendorem, nec ad colorem. Videbamus vero Coelum, et mutatus erat color illius tamquam lividus, et alii dixerunt ut viderent solem tamquam dimidium*, that is: "(year) 939, 12th indiction, on the 13th day of July, 6th *feria* (i.e. Friday), Moon 29th: the Sun was veiled from the 3rd to the 5th hours of the day (i.e. about 9 to 11 AM). We could look at the Sun, and it had no strength either for brightness or for colour. Indeed, we saw the Sky, but its colour was altered, somehow livid, and some people said that they saw the Sun almost halved" (Muratori 1725: col. 961, this text is slightly different from the edition quoted by Oppenheimer et al. 2018). The date should be amended to 19 July, because this day corresponds to Friday and the new moon. The coincidence in date with the astronomical event, the short duration of the phenomenon (2 h) and the fact that people observed a reduced

portion of the solar disc, unanimously point to the observation of the partial eclipse that took place in central and southern Italy.

New written sources

A new testimony worth taking into consideration is the *Supplementum chronicarum*, written by the Augustinian monk Jacobus Philippus Foresti and first published in Venice in 1483. After the election of the 20th Doge of Venice Pietro Badoer Participazio (which took place in 939), this chronicle records: "In quest'anno medesimo per alcun giorno el sole apparve come sangue", i.e. "in this same year, for some days, the sun appeared like blood" (Foresti 1535). This seems to be a genuine allusion to a phenomenon similar to the one described in the Irish chronicle, lasting "some days" and consisting in a reddish coloration of the sun, probably observed in northern Italy.

However, no written sources from lower latitudes are known to date. Yet, another source, still unnoticed by volcanologists, allows us to confirm 939 CE as the date of the Eldgjá eruption, and provides some more details as to the consequences it had in North Africa. It is a chronicle from Morocco, which does not report vague and inconclusive events, but points overtly to the typical consequence of an eruption, namely the fading of sunlight over a long period, associated with the presence of a thick fog made up of fine particles carried over a long distance. The phenomenon is recorded in a medieval North African chronicle known as *Rawḍ al-Qirṭās* ("The Gardens of Paper"), which was written in 1326 CE (and from here onward we refer to the critical edition of 1843) and is one of the most important sources on the history of Morocco in the first centuries of the Islamic conquest. Concerning the Islamic year 327, that began on 28 October 938 and ended on 16 October 939 CE, the chronicle reports (Fig. 4a):

وفي سنة سبع وعشرين وثلاث مائة كانت سنة الغمام اقام الغمام بالمغرب خمسة ايام لا يرى الناس فيها الشمس ولا يرى أحد من الارض الا موضع وقوفه فخاف الناس لذلك واخرجوا الصدقات وتابوا فكشف عنهم ذلك الغمام

(Rawḍ al-qirṭās 1843, p. 61 Ar.), that is: "and in the year three hundred twenty seven, there was the "year of the clouds": the (veil of) clouds dwelled five days in Morocco. Through it, people could not see the Sun, and nobody could see the ground beyond the place where he stayed. People were afraid for this reason, offered alms and repented, and these clouds were removed from over them".

Another chronicle, written much later, records the same phenomenon in a similar way. The *Kitāb al-Istiqṣā li-akhbār duwal al-Maghrib al-Aqṣā* ("Book of Inquiry into the affairs
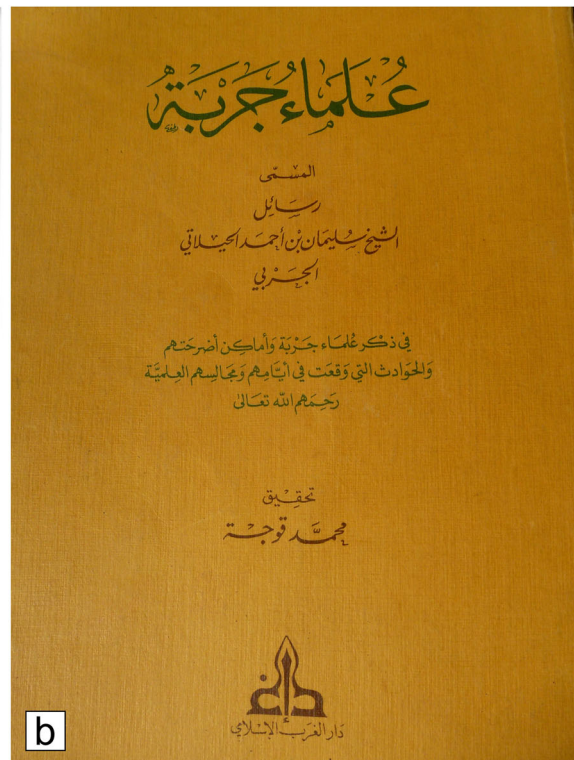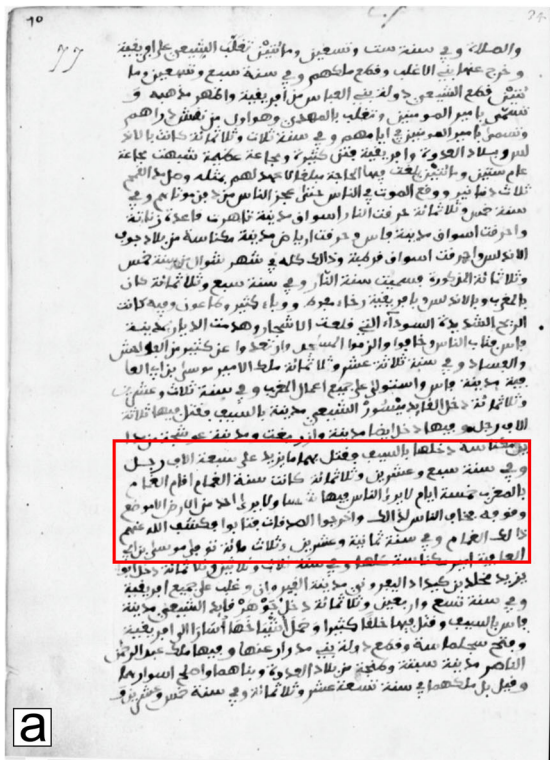
Fig. 4 **a** Photo of the page containing the above described facts on Morocco (the relevant phrase is highlighted by a red rectangle) in a chronicle of the year 327 Islamic Era (938/939 CE), contained in a manuscript of *Rawḍ al-qirṭās* copied in 1689. Bibliothèque nationale de France, Département des manuscrits, Arabe 1869. **b** Front cover of Rasâ'il al-Ḥîlâtî (1998), where a chronicle by Muḥammad b. Yūsuf al-Muṣʿabī on atmospheric phenomena in the 18th Century at Djerba (Tunisia) was published

of the Lands of the Farthest West") is a long and detailed chronicle of events concerning Morocco, in ten volumes, written by Aḥmad ibn Khālid al-Naṣīrī (1835–1897). It was first published in 1894. Hereunder is the description of the phenomenon provided in this work:

وفي سنة سبع وعشرين وثلاثمائة ظهر ببلاد المغرب غمام كثيف دام خمسة أيام، لم ير الناس فيها شمسا، وكان الشخص لا يرى من الأرض فيه إلا موضع قدميه فتاب الناس وأخرجوا الصدقات فكشف الله عنهم وما بهم وسميت سنة الغمام

(Istiqṣā 1997: I, 249) that is: "and in the year three hundred twenty seven, there appeared in the country of Morocco thick clouds, which lasted five days, during which people could not see any sun. A person could not see the land [around him], save the spot where he was standing. The people repented, offered alms, and God removed (these clouds) from over them. And it was called "the year of the clouds"". Despite some slight differences in wording, the core information is almost identical to the passage in the *Rawḍ al-Qirṭās*, which might be the ultimate source. As a matter of fact, the author relied on a number of previous sources, and *Rawḍ al-Qirṭās* was surely one of them. Nevertheless, an independent source that handed down an almost identical content cannot be ruled

out, given the difference in wording and in the passages that precede and follow the chronicle of this year.

In order to describe the meteorological phenomenon, both chronicles use the word *ghamām* "clouds", accompanied, in *Kitāb al-Istiqṣā*, by the epithet *kathīf* "thick". The word *ghamām* is a collective, from which the nomen unitatis *ghamāma*, "one cloud" is derived. The most common and neutral word for "clouds" in Arabic is *saḥāb*, while the use of *ghamām* insists on a special quality of the clouds. It comes from a root meaning "cover, veil, conceal", and the huge vocabulary by Lane (1863–1893) reports the explanation given by the Arab lexicographers themselves: "they are so called because they veil the sky, or because they veil the light of the sun".

The sources do not specify which part of Morocco was attained by this phenomenon, but exactly the lack of specification seems to point to the whole country (stretching southward well beyond 30° N), or most of it. The chronicle of *Rawḍ al-Qirṭās* around this year reports, above all, facts referring to its capital city, Fez (34° 59′ 27″ N), but this is not the case of Kitāb al-Istiqṣā, which, in these years, records only the most important facts regarding the whole of Morocco. Another clue pointing to a general observation of the phenomenon is the fact that the year was "named" after it. The custom of "naming" the years after a remarkable event or a person (eponym), rather than "counting"

them starting from a conventional date, was widespread in North Africa in ancient times, and lasted until recently among the Tuaregs. Of course, the event chosen must be well known by most of the population.

These Arabic sources provide precious information, as (i) they confirm the date of the effects of the Eldgjá eruption with some precision, (ii) they testify that the area affected by the consequences of the eruption encompassed North Africa, and (iii) they describe sunlight being veiled for 5 days, i.e. three times longer than the duration of the phenomenon observed in Ireland.

Laki event

Previously known data for North Africa

Unlike the ancient Eldgjá eruption, dating back to an epoch when the spreading of information was very slow and scarce, the Laki eruption took place in a period when a large network of journals, gazettes and scientific reviews already existed, so that reports of the event, descriptions more or less accurate and tentative explanations are numerous. This is true, above all, for Europe and North America; we will not provide details of these records here, as they are very well summarized in works by Thordarson and Self (1993, 2003).

Instead, in the Islamic world, where printing had not been introduced yet, the situation was much different, and we know very little of the consequences of this eruption in that area. What we know, until now, comes from the letters written by European correspondents settled in the Ottoman Empire, for instance those that record the presence of the "dry fog" in Istanbul, Smyrna and Tripoli of Levant in the issues of 9 September and 3 October 1783 of the *Gazette de France*. DeMarée and Ogilvie (2017) recapitulate all the places where the phenomenon was recorded and list the sources of the reports. Those who cite North Africa as an area subjected to the phenomenon mostly fail to cite the source of this information, or ultimately rely on second-hand information, usually from Lamanon (1784) or Mourgue de Montredon (1784). But these authors limit themselves to vague statements, as Lamanon (1784), who wrote: *Il est probable, d'après les relations, que ce brouillard a couvert à peu-près toute l'Europe, les Isles de la Méditerranée, une partie de l'Afrique, sans ce que nous ignorons* "it is probable, according to the reports, that this fog covered almost all Europe, the Mediterranean Islands, a part of Africa, besides what we are ignorant of", while Mourgue de Montredon (1784) wrote: *Ces vapeurs (...) étoient fort répandues, puisque nous avons appris que ce phénomène a été aperçu non seulement dans toute l'Europe, mais même en Asie, en Afrique et au loin dans les pleines mers du Nord et de l'Ouest* "these vapours ... were very widespread, given that we got news that this phenomenon has been observed not only in all Europe, but even in Asia, Africa and as far as the Northern and Western seas".

The most detailed information comes from the Neapolitan scientist Michele Torcia, who shared it with many contemporary scientists across Europe. In a letter dated 9 September 1783, he wrote (Torcia 1784): *Die Finsternis war noch stärker auf der Südlichen Küste des mittelländischen Meeres. Unsere Korallenfischer haben dieses Jahr bey der Insel Galeata, und bey Tabarca an der Küste von Tunis nichts ausrichten können. Eine ihrer Barken gieng durch den Stoß einer andern zu Grunde. Briefe aus allen Provinzen des Königreichs bezeugten, daß das Wachstum dieses Nebels, überall stufenweis, und gleich war, nur mit dem Unterschied, daß es in den südlichen Gegenden früher, und mit mehrer Kraft geschah. Kurz, er war in der Mitte des Sommers, wo man sonsten von keinem Nebel weiß, am stärksten* "The darkness was even stronger on the southern coast of the Mediterranean Sea. Our coral fishermen [from Torre del Greco] could arrange nothing this year by the island of Galite and by Tabarka on the coast of Tunis. One of their barks perished after the crash with another. Letters from all provinces of the kingdom testified that the growth of this mist was gradual and the same everywhere, with the only difference that it occurred earlier and with more force in the southern regions. In short, it was strongest in the middle of summer, when no fog is otherwise known of" (see also Torcia 1783).

New written sources

We discovered an indigenous report from North Africa that comes from a short chronicle of events on the island of Djerba (southern Tunisia), written by Muḥammad b. Yūsuf al-Muṣʿabī (d. 1207 h = 1792–1793 CE) and inserted by M. Gouja as an appendix to an older chronicle by Sulaymān al-Ḫīlātī. Al-Muṣʿabī reports the following events (Hîlâtî 1998: 100–102) (Fig. 4b):

وقع الطّاعون بإفريقيّة عام ثمانية وتسعين ومائة وألف، وصار يتنقّل من بلاد إلى بلاد، وأخلى كثيرا من البيوت. إلى أن وصل إلى جربة في فرار العجمي عام تسعة وتسعين ومائة وألف

هذا، وقبل ظهور الطّاعون في عام ثمانية وتسعين ومائة وألف، ظهر غيم عظيم كالدّخان، ومكث نحو نصف شهر، والشمس تطلع لا شُعاع لها وهي حمراء كأنّها مخسوفة وتغرب كذلك. وإذا كان وقت العصر أيضا ذهب شعاعها إلى أن تغيب كذلك. وتغيّر الهواء واحمرّ كثيرا.

"In the year one thousand one hundred ninety-eight, the plague fell upon Ifriqiya (= Tunisia) and began to spread from a region to another, ravaging many households, until it arrived in Djerba during the month of February of the *ajami* calendar, the year one thousand one hundred ninety-nine. (...)

So, and before the plague made its appearance in the year one thousand one hundred ninety-eight, a huge mist similar to smoke made its appearance and lingered approximately half a month. The sun rose without its beams and red as if an eclipse

was taking place, and it set in the same conditions. Also, even at the moment of *asr* (afternoon prayer) its beams went on being absent in the same way. And the air changed and became quite reddish."

The time references of this chronicle belong to two different systems of time computing: the Islamic year, consisting of twelve lunar months, i.e. 354 or 355 days, and the so-called *ajami* calendar, that is the Julian calendar still in use today in North Africa for the sake of husbandry. The Islamic year 1198 began on 26 November 1783 and ended on 14 November 1784. The plague alluded to in the report, started spreading in Tunisia during that year and reached the island some months later, after the beginning of the following year 1199, that is during the month of *furar*, i.e. February/March 1785. According to the detailed description by Valensi (1969): 1543–1548), the epidemic disease, al-*ṭāʿūn* in Arabic, was bubonic plague ("une maladie violente avec bubons, charbons et tous les autres caractères de la peste": p. 1544). It was imported from Alexandria, where it had already appeared since 1783, and first manifested itself in Tunis in April 1784. Subsequently, it spread at increasing speed, slowly at the beginning, faster from October onwards. In December, some regions were still unaffected: the West between Béja and Tabarka, and the South with Djerba. The first cases in Djerba were recorded in January 1785, and the pestilence in Tunisia ended in August of the same year. This chronology is fully in accordance with the description by al-Musʿabī and confirms that the spread of plague occupied a great part of the Islamic year 1198 (chronology of the contagion in Valensi 1969; for the phenomenon of plague in the wider framework of the Ottoman Empire, see Panzac 1985 and Speziale 1997). The fading of the sun took place some time before the beginning of that year (November 1783): a period fully consistent with what was observed in Europe, namely June/July 1783.

The word used here to describe the phenomenon is *ghaym*, another collective (nomen unitatis: *ghayma*) meaning "clouds", "when one sees not a sun by reason of much covering of the sky", but also "mist" and "thirst" (Lane 1863-1893), a lexical choice that fits well the definition "brouillard sec" or "dry fog" usually employed by the contemporary scientists in Europe. The special quality of the mist is further specified by the expression *ka al-dukhān* "similar to smoke". The comparison made with a solar eclipse (*ka annahā makhsūfa*) confirms that the author was aware that the phenomenon was not an eclipse. The chronological data, the duration and the description of the atmospheric phenomena confirm that this report is to be connected to the Laki fissure eruption. The new source, coming from Djerba, at 33° 17′ N, attests that this is the southernmost site in the Mediterranean basin where the phenomenon was observed; this confirms the report of Torcia (1784) "that it occurred earlier and with more force in the southern regions" of Tunisia.

Discussion

Diffusion of Eldgjá and Laki aerosols in North Africa

The use of written sources describing phenomena that can be attributed to the consequences of eruptions, as in the cases described here, allows us to precisely date and reconstruct the effects of a historic volcanic event. The chronicles reporting specific events that occurred in Tunisia and Morocco indicate that a dense dry fog did take place on 939 CE and some time before November 1783 CE. The haze observed in the cited localities in North Africa was almost certainly caused by volcanic aerosol, as no major volcanic gases absorb or scatter visible light significantly (Ammann and Burtscher 1993). Our data have two possible consequences: (i) they might confirm the recent reassessment of the 939 CE dating of the Eldgjá eruption put forward by Oppenheimer et al. (2018), based on high-temporal resolution glaciochemical records from Greenland ice cores, or (ii) considering the other authors that suggest an older age of the eruption inception, our data confirm that the Eldgjá eruption was still going in 939 CE but at that time it had become purely magmatic in terms of its activity, allowing for massive SO_2 loading of the atmosphere. Our data also document a wider diffusion of the products related to the two eruptions, if compared with what was previously known: the Laki products reached definitively the Latitude of at least 33° N, and probably further south since the fog was still extremely dense. Moreover, the chronicles referring to Morocco (Eldgjá eruption) described a phenomenon that should have affected most of the country (stretching southward well beyond 30° N). This conclusion also highlights the need for a deeper awareness of the related hazards to which circum-Mediterranean areas may be subjected, including North Africa. Such hazards are linked to the possibility of similar eruptions taking place in the future, and are represented by the threats posed to flights and other means of transportation, and also by economic-social issues, as detailed further below.

Our results can also be compared with some previous numerical modelling of aerosol diffusion consequent to the Laki eruption. Chenet et al. (2005) reconstructed the Laki-induced aerosol circulation using an Atmospheric General Circulation Model; they found that after the six major explosive volcanic phases, at the end of July 1783, significant concentrations of aerosols at the Earth's surface extended also over the Northern Africa, decreasing but still present up to October 1783 and then vanishing. Our results confirm this modelling. Oman et al. (2006a) used the NASA Goddard Institute for Space Studies modelE climate model, coupled to a sulphur cycle chemistry model, to show that the aerosols emitted by the Northern Hemisphere high-latitude volcanic eruptions remain mostly confined north of 30° N Latitude, although our data suggest the diffuse presence of aerosols also at this latitude

and possibly further south. Schmidt et al. (2010) analysed the impact on aerosol microphysical processes, such as the nucleation of new particles and their growth to cloud condensation nuclei, using a comprehensive Global Model of Aerosol Processes. Although their study focuses on the altitudes of clouds formation, it shows an increase of factor 2 in the number of particles linked to cloud condensation nuclei in Northern Africa.

Possible reoccurrence of events

The area where the Eldgjá and Laki eruptions originated belongs to the most active portion of the volcanotectonic zones of Iceland. The Eastern Volcanic Zone, in fact, hosts several of the most active central volcanoes of the country, namely Bardarbunga, Eyjafjallajökull, Torfajökull, Hekla, Katlaand Grímsvötn, and the nearby Öræfajökull belonging to the intraplate Öræfajökull Volcanic Belt (Thordarson and Höskuldsson 2008). In fact, the Eastern Volcanic Zone was the site of the most powerful historic and prehistoric fissure eruptions. Apart from Eldgjá and Laki, other similar eruptions occurred nearby: in the so-called Veidivotn area (Thordarson et al. 2003b), huge volumes of lavas and ashes were outpoured from three fissure systems striking NE-SW, parallel to Eldgjá and Laki (Fig. 1b). The development of these fissures is consistent with the regional tectonic extension direction, which in turns favours magma uprising along this trend. The recentmost eruption, known as Veidivotn, took place in 1480 ± 11 CE on the easternmost fissure in the Veidivotn area (Larsen 1984). Lava flows and ashes were emitted by a 40-km-long system of segmented fissures. The bulk of the material produced by this eruption is basaltic tephra, corresponding to a volume of 3.5 km^3 (Larsen 1984). The Vatnaoldur eruption took place in about 900 CE, possibly supported by Greenland ice core chronology that suggests a date of 897–898 CE (Hammer et al. 1980) and finally precisely dated by Grönvold et al. (1995) to 871 CE. The eruption occurred along a 42-km-long discontinuous fissure system, which reappears 12–13 km to the SW within Torfajökull volcano (Fig. 1b). Both basaltic and silicic tephra were erupted, corresponding to a volume of 3.3 km^3 (Larsen 1984). The Domadalshraun-Tjorvahraun eruption occurred in about 150 CE along an at least 8-km-long fissure, which probably extends further to the NE underneath the pyroclastic deposits of the other two younger eruptions. The southwestern termination of the fissure system extends into Torfajökull volcano, and the eruption was manly of the effusive type. Although we are aware that these three fissure eruptions are smaller in magnitude than Eldgjá and Laki, if we consider all their ages we obtain a recurrence period of about 374 years in the last 1870 years. Considering the continuous extensional strain that affects this area as a consequence of plate spreading, in the order of 12 mm/year (Jónsson et al. 1997), which favours magma

uprising, and the presence of the mantle plume below the Eastern Volcanic Zone (Vink 1984; Wolfe et al. 1997), the occurrence of another main fissure eruption in the same source area within the next 150 years is extremely likely. Another eight to nine similar fissure eruptions occurred in prehistoric times (Johannesson et al. 1990; Thordarson et al. 2003b; Thordarson and Höskuldsson 2008), comprising the dated Hólmsá Fires (ca. 6800 a BP) and the NAAZO/Vedde eruption (ca. 12000 a BP, Birks et al. 1996). If we consider the whole Iceland, and we refer only to the most powerful fissure eruptions, four main events occurred during the last 1130 years: (1) Eldgjá 934–940 CE, (2) Hallmundarhraun ~ 950 CE (Western Volcanic Zone), (3) Frambrunipre thirteenth century (Northern Volcanic Zone), and (4) Laki 1783–1784 CE (Thordarson and Larsen 2007). This suggests, for the whole Iceland, an average recurrence rate of 270 years for large-volume fissure eruptions in historic times.

Impact on society

In regard to the impacts on aviation and other means of transport, based on the new data on Tunisia and Morocco, we suggest that a volcanic plume emitted by an eruption similar to Eldgjá or Laki may cover a wide area, extending even as far as North Africa, and may reach the cruising altitude of most planes. For comparison, the Eyjafjallajökull eruption in 2010 produced a total of 0.27 ± 0.07 km^3 tephra (uncompacted volume) (Gudmundsson et al. 2012), a much smaller volume than that produced by the afore-described, older fissure eruptions that ranges from 0.4 to 3.5 km^3 (Larsen 1984). The difference is remarkable even if we consider also the amount of the Eyjafjallajökull tephra transported out of the craters with meltwater and the amount of magma emplaced as lava: the total mass erupted is $4.8 \pm 1.2 \cdot 10^{11}$ kg, or 0.18 ± 0.05 km^3 DRE (using $\rho DRE = 2600$ kg m^{-3}) (Gudmundsson et al. 2012). However, the Eyjafjallajökull eruption caused the temporary interruption of civil and cargo flights throughout most of the world, with severe economic effects. The International Air Transport Association estimated that the airline industry worldwide lost US$ 200 million/day, and the total loss for the airline industry was around US$ 1.7 billion (Mazzocchi et al. 2010). Moreover, it was estimated that airports lost US$ 98 million over the six-day closure, during which over 95,000 flights were cancelled (Mazzocchi et al. 2010). This was the consequence of volcanic particle dispersion, mostly linked to the production of fine ash due to both magmatic and phreatomagmatic fragmentation (Gudmundsson et al. 2012). In fact, it is the tephra's grain size that mostly controls the potential for ashes to be transported over long distances. Although fine ash is not usually the main product of basaltic fissure eruptions, huge quantities can be generated if there is interaction between magma and water, in the form of groundwater or river/lake or a glacier, all characteristic features of the

Eastern Volcanic Zone. Not only ash particles of sub-micrometre size but also SO_2 and sulphuric acid could cause damage to airframes, and their deposits can accumulate in turbines leading to their overheating during flight (Casadevall et al. 1996; Miller and Casadevall 2000). This represents both a hazard for flights, and also an important economic problem stemming from the blockage of air traffic. Moreover, sulphate aerosols accelerate corrosion, leading to the need for increased maintenance and decreasing engine lifetime (Loughlin et al. 2012). Based on our data, we suggest that also maritime transport may be affected in the Mediterranean area, by the possibility of severely reduced visibility, as testified to also by the events reported by Torcia (1784), with the sinking of a boat off Tunisia due to the thick fog produced by volcanic material from the Laki eruption.

Regarding other economic-social effects of the possible southward spread of eruptive products as far as North Africa, they may be brought about by air pollution due to volcanic gases and aerosol, acid rain and deposition of acids and other aerosols. The residents may suffer respiratory difficulty, worsened in North Africa by the poor housing conditions that do not guarantee an adequate insulation from the outdoor environment. At the same time, crops and vegetation may be damaged, in a region where agriculture and sheep-farming are the main source of livelihood. Of course, these effects may be variable both spatially and temporally at the local scale, being controlled by eruption dynamics and the influence of regional-to-local scale meteorological conditions.

Conclusions

We uncovered two ancient written sources that allow us to identify the date and place of occurrence, in North Africa, of phenomena that can be interpreted only in terms of the effects of the dispersal of volcanic material from faraway locations. A medieval North African chronicle known as Rawḍ al-Qirṭās, written in 1326 CE, describes events that occurred in the Islamic year 327, which corresponds to the period 28 October 938–16 October 939 CE. The chronicle reports a dense fog that persisted for five days in Morocco. It was so dense that people could not see the sun or the ground beyond the place where they stood. Another chronicle describes events that occurred in the island of Djerba (southern Tunisia), written by Muhammad b. Yusef al-Musabi in 1792–1793 CE. The event, which occurred sometime before November 1783, was characterized by a huge fog that obscured a red Sun and that persisted for half a month.

The times and phenomena described are perfectly consistent with the effects produced by two catastrophic fissure eruptions that originated in the Eastern Volcanic Zone of Iceland, known as the Eldgjá eruption (934–940 CE) and the Laki eruption (1783–1784 CE). Eldgjá produced 19.7 km³ of lava flows and 1.3 km³ of tephra; Laki 14.7 km³ of lavas and 0.4 km³ of tephra. The Laki eruption also released 122 megatons of SO_2 into the atmosphere, which produced a sulphuric aerosol that spread throughout the northern hemisphere, as indicated by numerous historic chronicles in Europe.

The previously unrecognized sources describe in detail the fading of sunlight coupled with the persistent presence of a thick fog made of fine particles, representing the first clear evidence of the involvement of North Africa in the dispersal of volcanic products from the Eldgjá and Laki eruptions. The arrival of volcanic aerosols at Djerba some time before November 1783 is fully consistent with similar effects observed in Europe during June–July 1783.

These data can help to date and determine the area of influence of the phenomena linked to these two eruptions; this, in turn, is useful for several applications such as the numerical simulation of these events or hazard planning. With respect to volcanic hazards, in the eruption source zone of Iceland, the continuous plate spreading and active rifting, as well as the presence of a hot spot and a mid-oceanic ridge, reinforce the possibility of future, similar fissure eruptions; several of such volcanic events took place, in Iceland, in prehistoric/historic times, indicating a recurrence period of 374 to 270 years. A volcanic plume coupled with the dominant westerly jet stream would once again lead to the dispersal of the finer volcanic products towards Europe and North Africa, representing an important threat to air and maritime transportation, as well as a major source of air and soil pollution.

Besides the results in the Earth Sciences sphere, regarding a better determination of some long-range effects of Icelandic volcanic eruptions, this research also has consequences on an epistemological level, demonstrating the importance of integrating data from the humanities with data from "hard" disciplines. Of particular importance is the fact of carrying out research on indigenous sources from the Islamic world, to overcome a Eurocentric vision, which would be only partial and therefore misleading. Among the few studies that have so far adopted a similar approach, we can mention the work of Alan Mikhail (2017), who, precisely with regard to the consequences of the Laki explosion as far as Egypt, integrates the modern scientific data with the observations recorded in the archives and chronicles of the Ottoman Empire (Chapter 10: Egypt, Iceland, SO_2, p. 184–197). Establishing a dialogue between different disciplines and between distant worlds and cultures is not easy, but it can lead to a beneficial enrichment of knowledge.

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Data availability Not applicable

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Code availability Not applicable.

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