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Silvio G Rotolo, Stéphane Scaillet, Fabio Speranza, John C White, Rebecca Williams, et al.. Volcanological evolution of Pantelleria Island (Strait of Sicily) peralkaline volcano: a review. *Comptes Rendus. Géoscience*, 2021, 353 (S2), pp.1-22. 10.5802/crgeos.51 . insu-03429308

**HAL Id: insu-03429308**

**<https://insu.hal.science/insu-03429308v1>**

Submitted on 15 Nov 2021

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INSTITUT DE FRANCE  
Académie des sciences

# *Comptes Rendus*

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## *Géoscience*

### *Sciences de la Planète*

Silvio G. Rotolo, Stéphane Scaillet, Fabio Speranza, John C. White,  
Rebecca Williams and Nina J. Jordan

**Volcanological evolution of Pantelleria Island (Strait of Sicily)  
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Online first

<<https://doi.org/10.5802/crgeos.51>>

**Part of the Special Issue:** Perspectives on alkaline magmas

**Guest editor:** Bruno Scaillet (Institut des Sciences de la Terre d'Orléans, CNRS,  
France)

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Perspectives on alkaline magmas / *Perspectives sur les magmas alcalins*

# Volcanological evolution of Pantelleria Island (Strait of Sicily) peralkaline volcano: a review

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**Abstract.** Pantelleria volcano has a particularly intriguing evolutionary history intimately related to the peralkaline composition of its explosively erupted magmas. Due to the stratigraphic complexity, studies over the last two decades have explored either only the pre-Green Tuff ignimbrite volcanism or the post-Green Tuff activity. We here focus on the whole evolutionary history, detailing the achievements since the first pioneering studies, in order to illustrate how the adoption and integration of progressively more accurate methods (<sup>40</sup>Ar/<sup>39</sup>Ar, paleomagnetism, petrography, and detailed field study) have provided many important independent answers to unresolved questions. We also discuss rheomorphism, a distinct feature at Pantelleria, at various scales and possible evidence for multiple, now hidden, caldera collapses. Although the evolutionary history of Pantelleria has shown that each ignimbrite event was followed by a period of less intense explosivity (as could be the present-day case), new geochronological and geochemical data may indicate a long-term waning of volcanic activity.

**Keywords.** Peralkaline volcanism, Ignimbrites, Paleomagnetism, <sup>40</sup>Ar/<sup>39</sup>Ar, Rheomorphism.

## 1. Introduction

Throughout its geologic history, the island of Pantelleria (Figure 1), the type locality of peralkaline rhy-

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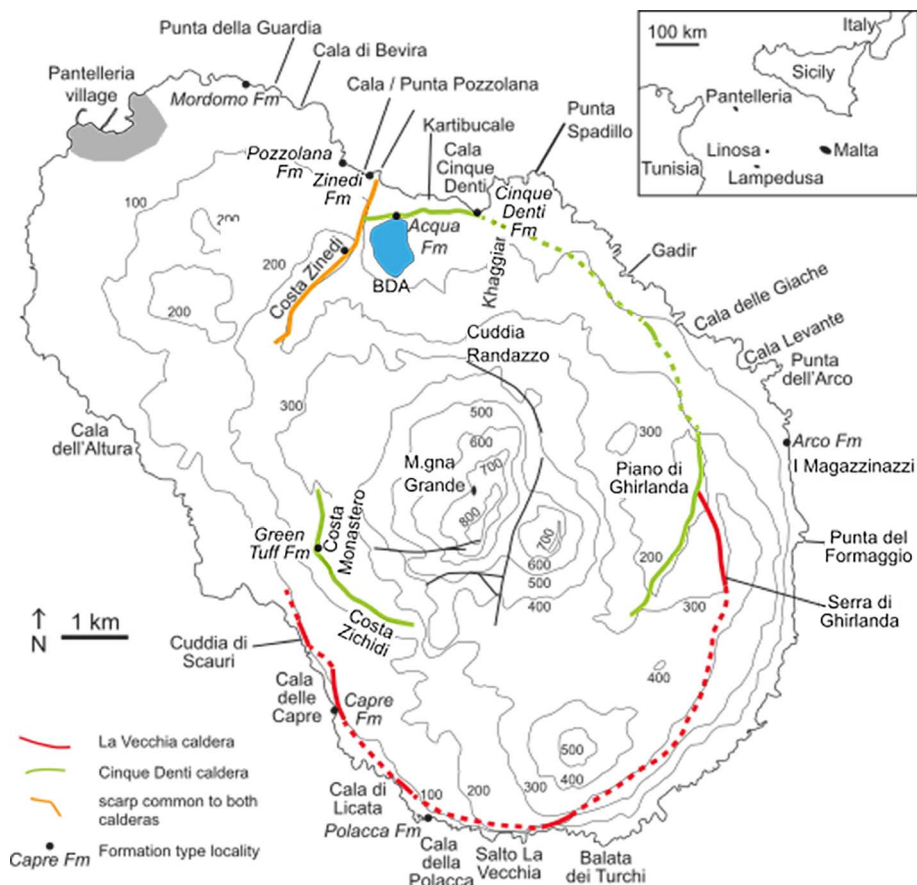
olitic (pantelleritic) magmatism, has been the setting for dominantly explosive volcanism. The relatively low viscosity of these magmas make the pyroclastic deposits particularly prone to rheomorphism and welding, which obscures primary textural and architectural features. This peculiarity, coupled with discontinuous field exposures and a remarkably complex evolutionary history (*viz.*, overlapping explosive events), has contributed to the difficulty in the advancement of our volcano-stratigraphic knowledge of the island. For these reasons, Pantelleria has been paradigmatic in the establishment of integrated field and geochemical techniques in unraveling the volcanic evolution of such active centers.

In order to appreciate fully the evolution of the volcanic stratigraphy at Pantelleria, we briefly review the history of geologic studies on this island that began with Gemmellaro [1829], who reported the results from his field surveys that he integrated with reports from contemporary naturalists. More than fifty years elapsed before Förstner [1881] published the next study of the island, which included a generalized geologic map (1:100.000) and, most significantly, a few chemical analyses of minerals and of a very peculiar and previously undescribed alkali- and silica-rich effusive rock, for which he proposed the name *pantellerite*. In October 1891, a submarine basaltic eruption 5 km west-northwest offshore of Pantelleria town attracted the attention of naturalist and astronomer Riccò [1892], who precisely described the evolution of the eruption, including exploding scoria at sea now known as *lava balloons*. Significantly, he paid great attention to pre- and syn-eruptive phenomena, such as earthquake swarms, bradyseisms, and other macroseismic effects. These early studies [including Bergeat, 1907] sparked the interest of the American petrographer H. S. Washington, who conducted a field campaign in 1905 and subsequently published three papers [Washington, 1913a,b, 1914] that are now considered the foundation for all later studies, not only for the detailed geological descriptions, but especially for the in-depth discussion of the petrography of pantellerite rocks that much improved the early analytical efforts of Förstner.

There was renewed interest in the geology of Pantelleria during the 1960s, with most studies focused on the volcanology of the island. Borsi *et al.* [1963] published a general overview, and Rittmann

[1967] provided the first detailed study of the volcanic stratigraphy in which he distinguished several ignimbrite and pumice fallout deposits, recognized the central caldera structure, and produced a detailed geological map (1:25.000) of the island. His conclusions were confirmed and further developed in several publications by his collaborator Villari [1969, 1970, 1974], who proposed a basic stratigraphy that recognized several ignimbrite units. In particular, Villari focused on the “*Green ignimbrite*”, the youngest and most widespread pyroclastic unit on the island, whose ignimbritic nature was confirmed by Schmincke [1974]. Wright [1980] was the first to attempt to unravel the complex stratigraphy and lateral correlations of the older pyroclastic units, some of which he interpreted as welded air fall deposits instead of ignimbrites. Geochronological (K–Ar) data were first presented by Barberi *et al.* [1969] and Bigazzi *et al.* [1971] and these were later followed by Cornette *et al.* [1983] and Civetta *et al.* [1984, 1988]. Cornette *et al.* [1983] recognized two partially overlapping caldera structures that they termed the *Lago Caldera* and *Monastero Caldera* (50 ka), the latter of which they associated with the eruption of the Green Tuff (GT). Contemporaneously, Mahood and Hildreth [1983] also described two “nested” calderas on the island, which they termed the *La Vecchia Caldera* (93 ka) and *Cinque Denti Caldera* (55 ka), which differed from those proposed by Cornette *et al.* [1983] in terms of location, size, and significance. The remarkably thorough and insightful paper of Mahood and Hildreth [1986] was ahead of its time and provided the first (and, until now, only) comprehensive and integrated description of the structure and volcanological history of the island. Mahood and Hildreth also put a major focus on the stratigraphy of the pre-GT welded and rheomorphic ignimbrites, supported by a large number of K–Ar ages.

Most of what was published over the next two decades focused on specific petrological and volcanological aspects of the geology of Pantelleria [Avanzinelli *et al.*, 2004, Behncke *et al.*, 2006, Bonaccorso and Mattia, 2000, Civetta *et al.*, 1998, De Guidi and Monaco, 2009, Esperança and Crisci, 1995, Ferla and Meli, 2006, Fulignati *et al.*, 1997, Kovalenko *et al.*, 1994, Lowenstern, 1994, Lowenstern and Mahood, 1991, Mattia *et al.*, 2007, Perugini *et al.*, 2002, Prosperini *et al.*, 2000, Stevenson and Wilson, 1997, Wall-



**Figure 1.** Map of Pantelleria with principal location names and type localities for ignimbrite formations. BDA = Bagno dell' Acqua lake.

mann *et al.*, 1988, White *et al.*, 2005, 2009], with a sharp increase in studies produced over the past ten years [Arzilli *et al.*, 2020, Avanzinelli *et al.*, 2014, Baginski *et al.*, 2018, Campagnola *et al.*, 2016, Conte *et al.*, 2014, Di Carlo *et al.*, 2010, Di Genova *et al.*, 2013, Fouré *et al.*, 2012, Gioncada and Landi, 2010, Giuffrida *et al.*, 2020, Jordan *et al.*, 2021, Hughes *et al.*, 2017, Kelly *et al.*, 2014, Lanzo *et al.*, 2013, Liszewska *et al.*, 2018, Neave, 2020, Neave *et al.*, 2012, Richard, 2015, Romano *et al.*, 2018, 2019, 2020, Romengo *et al.*, 2012, Rotolo *et al.*, 2013, 2017, Scaillet *et al.*, 2011, 2013, Speranza *et al.*, 2010, 2012, White *et al.*, 2020]. Notably missing until 2007 were stratigraphic and geochronological studies, implicitly suggesting to some extent that the great effort made during the 1980s was still considered valid and that methodological improvements in geochronological methods

had yet to come. The first  $^{40}\text{Ar}/^{39}\text{Ar}$  study of a pantelleritic enclave in an ignimbrite produced the oldest age reported on Pantelleria [ $517 \pm 19$  ka, Rotolo and Villa, 2001], which defined a lower limit for the onset of pantellerite magma production and sparked new interest in the geochronology and volcanic stratigraphy of the island [Jordan *et al.*, 2018, Rotolo *et al.*, 2007, 2013, Scaillet *et al.*, 2011, 2013, Speranza *et al.*, 2010, 2012].

The principal aim of this paper is to review and summarize the existing volcano-stratigraphic knowledge of Pantelleria, which is otherwise scattered between pre- and post-GT papers. In doing so, we try to highlight how methodological improvements have had a decisive impact on developing a fully integrated stratigraphy and time-integrated evolutionary history of the system, portraying a vol-

**Table 1.** Comparative nomenclature of Pantelleria ignimbrites and their ages

Jordan et al. [2018]	$^{40}\text{Ar}/^{39}\text{Ar}$ age	Rotolo et al. [2013]	$^{40}\text{Ar}/^{39}\text{Ar}$ age (ka)	Speranza et al. [2012]	Mahood and Hildreth [1986]	K/Ar age (ka)	Wright [1980]
Formations		Units		Units (correlations)	Units		Units
Green Tuff	46 <sup>(*)</sup>				Green Tuff	45–50 47–51 <sup>(**)</sup>	B
Mordomo		D = Z	85	D = Z	Z	78–84	C, D, E
Acqua		F = Q	107	F	F	88–97	F, G
Cinque Denti	128	P	123	P	P	104–110 104–116	G, g, U
Capre	138	Welded breccia (Br 1)	140–146	Welded breccia	Breccia	124–133	
Arco	179	S	171	S	S	104–127	
Polacca	187	M	181	M	M	162–209	G
Pozzolana	/				H	169–178	H
Zinedi	/				I	/	I
				(locally = Q)		189	

(\*) Age from Scaillet et al. [2013]; (\*\*) age from Civetta et al. [1988].

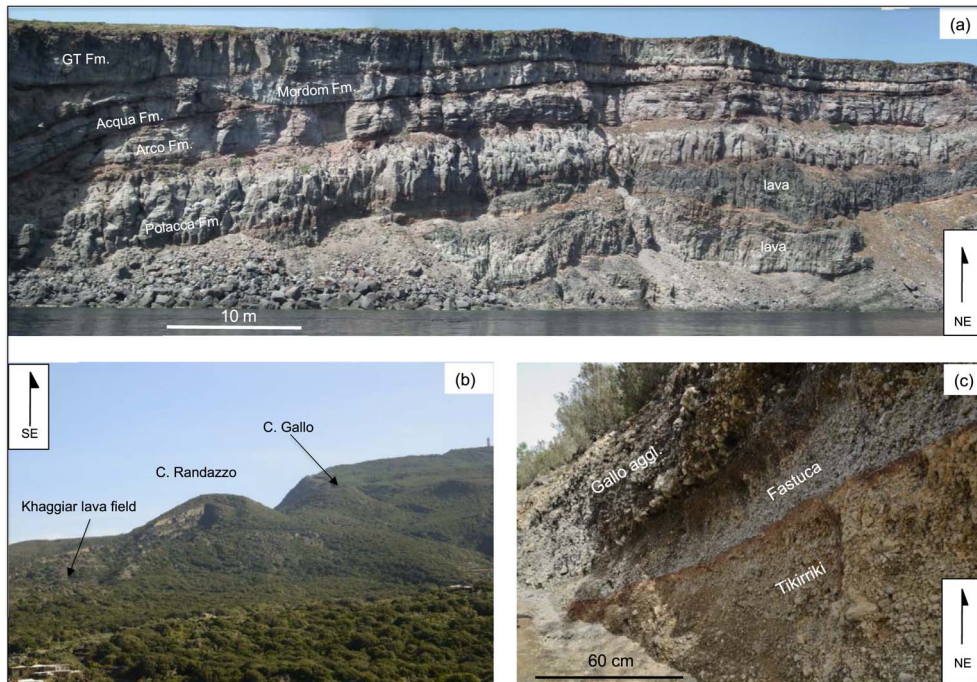
canological scenario that has far-reaching implications for, but not strictly limited to, other peralkaline volcanoes.

## 2. The pre-GT volcanological evolution

Rittmann [1967] published the first pre-GT stratigraphy based on eight measured sections and distinguished several ignimbrite and fall units, which he labeled A (younger) to G (older). Villari [1974], on the basis of field evidence and petrographic analyses, recognized several ignimbrite sheets (uncorrelated between different sections), identified a single caldera and distinguished the units as either pre- or post-caldera ignimbrites. The field-based stratigraphic study of Wright [1980], correlated seven welded tuffs across the island (without defining their type localities), plus eight other uncorrelated (minor) members. These were named using non-sequential capital letters, a rather confusing and non-intuitive nomenclature that would continue to be used until 2018. From older to younger these were: I, H, G, F, E, D, C, and B, with the youngest one corresponding to

the GT. On the basis of 37 K/Ar ages coupled with extensive field work, Mahood and Hildreth [1986] described the first detailed stratigraphy of the pre-GT eruptive cycles and units, and recognized nine informal units of welded tuffs/ignimbrites, most of which blanket the entire island. Although their stratigraphy was substantially different in many critical ways from Wright's [1980] (Table 1), they maintained and adapted his convention for naming the units (from older to younger: I, H, M, S, P, Q, F, D, Z and GT), but also did not define any type sections. They did, however, attribute a lithic-rich welded pyroclastic unit visible in the vertical scarp at Cala delle Capre as the caldera-forming unit of the La Vecchia caldera (Figure 1).

Many years later, Speranza et al. [2012] applied paleomagnetic methods to the pre-GT ignimbrites and simplified Mahood and Hildreth's [1986] stratigraphy by merging some ignimbrite units (D and Z) previously considered distinct. They also correlated two pyroclastic breccia units on the opposite sides of the island (NE: Cala Cinque Denti, SW: Cala delle Capre, Figure 1) to the La Vecchia caldera collapse



**Figure 2.** Pre-GT volcanism: field section at Cala della Polacca (SW). (b) Post-GT volcanism: Cuddia Randazzo pumice cone encircling a pantellerite lava dome whose break-up originated in the 2.5 km long Khaggiar lava field. (c) Post-GT volcanism: pumice deposits belonging to young eruptions (Table 2) in the road cut just south of C. Gallo.

and constrained it to 160–130 ka. These new interpretations were integrated with a new geochronological ( $^{40}\text{Ar}/^{39}\text{Ar}$  laser-ablation) study of these units [Rotolo *et al.*, 2013] with the following results: (i) the age of the La Vecchia caldera collapse was more tightly constrained to 146–140 ka by dating the juvenile material in the same pyroclastic breccias studied by Speranza *et al.* [2012]; (ii) the age of eruption of other five ignimbrites was substantially refined as follows [following Mahood and Hildreth, 1986]: M =  $181 \pm 1.2$  ka, S =  $171 \pm 1.7$  ka, P =  $123 \pm 1.6$  ka, F =  $107 \pm 1.4$  ka, Z =  $85 \pm 1.5$  ka; and (iii) the conclusion by Speranza *et al.* [2012] on the correlation of the D and Z units was confirmed and dated at 85 ka and units P and Q were also found to be correlative.

It was only after a combined field,  $^{40}\text{Ar}/^{39}\text{Ar}$ , and petrographic study [Jordan, 2014], later integrated later with paleomagnetic and additional  $^{40}\text{Ar}/^{39}\text{Ar}$  data [Jordan *et al.*, 2018], that each of these ignimbrite units (and related pumice fallout, when present) were finally tied to a clearly defined type

locality and renamed accordingly (Table 1). This was a major step forward over the poorly defined and counter-intuitive letter-based scheme. The resulting stratigraphic reconstruction clarified the structural and volcanic dynamics of the Pantelleria edifice by better delineating paroxysmal events and their recurrence through time; they also emphasized the occurrence of an indefinite number of active local centers producing lower explosivity eruptions between each ignimbrite [inter-ignimbrite activity, Jordan, 2014, Jordan *et al.*, 2018]. The erupted (onshore) volumes of these ignimbrites, although limited by the impossibility of knowing the amount of tephra deposited at sea, varied between 0.15 to  $0.64 \text{ km}^3$  (D.R.E.), the largest of these belonging to the Polacca Fm. ( $187 \pm 2$  ka, Figure 2a) [Jordan *et al.*, 2018]. An important observation of Jordan [2014] and Jordan *et al.* [2018] is the occurrence of lithic breccias in five different ignimbrites, strongly suggesting that at least five caldera collapses occurred, although their morpho-structural

**Table 2.** Comparison of ages determined with different methods for four key post-GT eruptions

	$^{40}\text{Ar}/^{39}\text{Ar}^{(1)}$	P-mag <sup>(2)</sup>	K/Ar <sup>(3)</sup>	$^{14}\text{C}^{(1)}$	$^{14}\text{C}^{(4)}$	$^{14}\text{C}^{(5)}$
Gallo	$7.09 \pm 0.8$	5.9–6.2			$3.03 \pm 0.3$	$5.7 \pm 0.1$
Randazzo fall			$8.2 \pm 1.7$		$5.42 \pm 0.22$	
					$5.75 \pm 0.08$	
Khaggiar lava flow	$8.0 \pm 0.8$	5.9–6.2	$5.5 \pm 5.0$			
			$8.5 \pm 4.5$			
			$11.0 \pm 3.0$			
Fastuca	$9.70 \pm 0.6$	6.2–6.8		$6.0\text{--}5.8 \pm 0.03$		$6.1 \pm 0.1$

<sup>(1)</sup>Scaillet *et al.* [2011]; <sup>(2)</sup>Speranza *et al.* [2010]; <sup>(3)</sup>Civetta *et al.* [1988]; <sup>(4)</sup>Mahood and Hildreth [1986]; <sup>(5)</sup>Civetta *et al.* [1998]. Error in ages is reported as 2-sigma values.

remnants are now totally buried with the exception of the two clearly visible, though discontinuous, La Vecchia and Cinque Denti caldera scarps.

### 3. The Green Tuff

The GT, the ninth and the youngest of the known and exposed Pantelleria ignimbrites, is undoubtedly the most studied eruptive unit at Pantelleria. Although the age of the GT has long been correlated with the peralkaline distal ash Y-6 [Keller *et al.*, 1978, Anastasakis and Pe-Piper, 2006, Margari *et al.*, 2007], its age was only loosely constrained by a few low-resolution K/Ar dates varying between  $46.9 \pm 2.0$  ka and  $50.8 \pm 3.6$  ka [Cornette *et al.*, 1983, Civetta *et al.*, 1988] and  $45 \pm 4$  ka to  $50 \pm 4$  ka [Mahood and Hildreth, 1986]. It was only recently that this age was refined to a higher resolution estimate at  $45.7 \pm 1.0$  ka by  $^{40}\text{Ar}/^{39}\text{Ar}$  laser-ablation dating [Scaillet *et al.*, 2013].

The emplacement dynamics of the GT have been variably interpreted through time. Once viewed as (i) a lava flow [Washington, 1914] or (ii) a welded fall [Mahood, 1984, Wolff and Wright, 1981a,b, Wright, 1980], it later became clear that it involved more high-energy dynamics, consisting of either (iii) a compound ignimbrite [Mahood and Hildreth, 1983, 1986, Orsi and Sheridan, 1984, Villari, 1970], (iv) a diluted ash-flow [Schmincke, 1974], and/or (v) a welded low aspect-ratio ignimbrite [Williams, 2010, Williams *et al.*, 2014]. The frequent and variable-scale rheomorphic folding was interpreted either as post-depositional [Mahood and Hildreth, 1986, Villari, 1970, Wolff and Wright, 1981a,b] or syn-depositional

(with a diachronous emplacement of the pyroclastic currents during essentially three eruptive phases, Catalano *et al.*, 2007, 2014). The GT was correlated to the younger caldera collapse, whose remnants are recognized in the Monastero scarp [*“Monastero caldera”* of Cornette *et al.*, 1983] and the scarp at Cala Cinque Denti [*“Cinque Denti caldera”*, of Mahood and Hildreth, 1986].

The innovative study by Williams [2010] focused on high-resolution chemostratigraphy of multiple sections of the GT. The whole ignimbrite deposit, preceded by a basal unwelded pumice fallout member that crops out in only a few places, was divided into eight time slices [*“entrachrons”* of Branney and Kokeelaar, 2002], each representative of an eruptive timing of a few minutes. Time slices were chemically correlated across the island, providing diachronous snapshots of the areas progressively inundated by the pyroclastic density current (PDC), each with different runout distances influenced by the pre-existing topography: some pulses by-passed topographic barriers whereas others were instead partially or totally halted by the terrain, during the brief time interval ( $\leq 1.5$  h) during which the current was emplaced [Williams *et al.*, 2014]. Williams [2010] questioned whether the GT was the actual eruption that created the Cinque Denti caldera, citing a lack of clear evidence for large-scale caldera collapse during the GT eruption and suggesting that the Cinque Denti scarp could, in many places, be older. The only evidence found for syn-eruptive collapse is a small-volume pyroclastic breccia within the GT section at Monastero, which is proposed as the type locality for the GT ignimbrite (except for its basal fall-



out member, which was defined at the Khattibucale scarp; Williams, 2010).

The (onland) volume of the GT has been recently re-evaluated at  $0.28 \text{ km}^3$  (D.R.E.) [Jordan *et al.*, 2018], much lower than previous estimates of  $0.49 \text{ km}^3$  and  $0.60 \text{ km}^3$  D.R.E. [Mahood and Hildreth, 1986, Wolff and Wright, 1981b, respectively].

#### 4. The post-Green Tuff volcanological evolution

Volcanism following the GT was distributed throughout a large number (>40) of different centers closely spaced in time and space and characterized by mildly explosive and/or effusive activity. Mafic local centers are largely confined to the northwest of the island and are not found within the caldera, felsic centers are commonly found on or near caldera faults [Jordan, 2014].

The first post-caldera event was the eruption of Monte Gibeles–Montagna Grande trachyte lava (ca.  $3 \text{ km}^3$  according to Mahood and Hildreth, 1986) in the center of the young caldera. Cornette *et al.* [1983] and Mahood and Hildreth [1983] both supported Washington's view regarding the uplift of the M.gna Grande trachyte lava block [first proposed by Förstner, 1881], with these latter authors providing detailed descriptions of the bordering faults, the hinge, and the offset (“trapdoor uplift”) that caused the displacement of the M. Gibeles source vent. Cornette *et al.* [1983] and Civetta *et al.* [1984], provided the first K/Ar ages (nine in total) for the reconstruction of the recent eruptive history. These were followed by twelve more K/Ar and six  $^{14}\text{C}$  ages by Mahood and Hildreth [1986], who proposed a general stratigraphic scheme framed as a “morpho-structural” subdivision of eruptive centers based on their position between or along the caldera rim and radial intra-/extra-caldera faults. Civetta *et al.* [1988] added 39 new K/Ar ages on lavas and tephra, and based on field evidence (e.g., paleosols) proposed a more precise interpretation involving six eruptive cycles, the first being the eruption of the GT and the second the eruption of trachyte from the M. Gibeles vent. Several vents were active during the most recent (sixth) cycle, such as the composite Cuddia Randazzo center (K/Ar age,  $8.2 \pm 1.7 \text{ ka}$ ), which consists of a pumice ring surrounding a coeval pantellerite lava dome (Figure 2b), whose rupture

produced the Khaggiar lava field, which reaches the sea at Punta Spadillo, 2.5 km away from the source vent. The most energetic (strombolian/sub-Plinian) event was the Fastuca eruption, whose source vent is located on the northern slope of M. Grande [Orsi *et al.*, 1991, Rotolo *et al.*, 2007].

The poor age resolution of the K/Ar method (with  $\pm 2\text{--}6 \text{ ka}$   $2\sigma$  errors) was not precise enough to allow discrimination between young eruptive units in order to place tighter constraints on the youngest eruptions. To distinguish these, Speranza *et al.* [2010] performed the first application of paleomagnetic methods to three key eruptions. Their youngest documented deposit is the Cuddia Gallo agglutinate (Figure 2c), which they bracketed between 5.9 and 6.2 ka, contemporaneous with the Khaggiar lava flow. For comparison, previous K/Ar ages yielded  $8.2 \pm 1.7 \text{ ka}$  (Civetta *et al.* [1988], Cuddia Randazzo pumice, co-genetic with Khaggiar lava), whereas  $^{14}\text{C}$  gave  $5.4 \pm 0.2 \text{ ka}$ , on an early Khaggiar lava flow [Mahood and Hildreth, 1986] (Figure 2b, Table 2).

Scaillet *et al.* [2011] conducted the first  $^{40}\text{Ar}/^{39}\text{Ar}$  high-resolution laser-ablation dating on anorthoclase phenocrysts from lavas and pumices erupted during the last 20 ka. Due to the very young ages (7–15 ka) and rather K-poor feldspar composition resulting in low  $^{40}\text{Ar}^*$  yield, this proved a more efficient approach at resolving the occurrence of  $^{40}\text{Ar}_{\text{xs}}$  and/or contamination with feldspar xenocrysts that plagued earlier K/Ar attempts (conducted on large-size aliquots). Scaillet *et al.* [2011] were successful in obtaining new and more precise ages for the recent intra-caldera activity. In particular, the Fastuca eruption was dated at  $9.7 \pm 0.6 \text{ ka}$ . Scaillet *et al.* [2011] concluded that the eruptive pace is on a long-term wane and coupled this to an overall (though minor) tendency in decreasing differentiation of pantellerite magmas. Further, these new and better-resolved  $^{40}\text{Ar}/^{39}\text{Ar}$  data and field observations [see discussion in Scaillet *et al.*, 2011] do not support the five cycles subdivision of post-GT activity proposed by Civetta *et al.* [1988].

Table 2 summarizes the ages of the three youngest eruptions at Pantelleria obtained by different methods: the  $^{40}\text{Ar}/^{39}\text{Ar}$  ages are seen to be systematically older than paleomagnetically derived paleosecular variation-tied estimates, which are in turn comparable or slightly older than  $^{14}\text{C}$  ages. K/Ar ages appear rather dispersed with relatively high uncertain-

ties. The bias between  $^{40}\text{Ar}/^{39}\text{Ar}$  and  $^{14}\text{C}$  estimates is well known [Civetta *et al.*, 1998, Mahood and Hildreth, 1986] and was interpreted by Scaillet *et al.* [2011] as intrinsic to the  $^{14}\text{C}$  method, possibly due to inefficient insulation of the tephra/soil horizon hosting the charcoal and consequent contamination with modern carbon.

## 5. Discussion

### 5.1. *Methodological improvements: application of paleomagnetism to assess correlation of rheomorphic ignimbrite scattered outcrops*

Paleomagnetism addresses the direction and intensity of magnetization measured in volcanic rocks that in turn may reflect the local characteristics of the geomagnetic field (direction and intensity) at the time of eruption and cooling [e.g., Butler, 1992]. A volcanic rock acquires its magnetization when it cools below the Curie temperature ( $T_c$ ) of its dominant ferromagnetic mineral (typically magnetite, with a  $T_c$  of 575 °C) to the ambient temperature. After the volcanic rock has cooled, its magnetization is “frozen” and does not change even when the characteristics of the geomagnetic field change. Direct observations during the last five centuries have shown that both direction and intensity of the geomagnetic field change quite rapidly (up to 6° direction change per century in Europe, e.g., Lanza *et al.*, 2005), a phenomenon known as secular variation (SV) of the geomagnetic field.

The fast temporal change of paleosecular variation (PSV) of the geomagnetic field along with routinely achieved accuracy of paleomagnetic direction determination in volcanics (directions defined with confidence cones of 2°–4° of radius) imply that two volcanics emplaced only 100–200 years apart can be paleomagnetically discriminated. Such high resolution of paleomagnetic age correlation can fully complement radiometric dating: the latter yields absolute ages, while the former—with a dating resolution of about a century—may definitely establish whether two scattered volcanic outcrops belong to the same eruption or not. The best resolution of K/Ar dating is on the order of few millennia, while for laser-based  $^{40}\text{Ar}/^{39}\text{Ar}$  techniques can resolve down to 1 ka or better (up to a century for sanidine, Renne *et al.*, 1997). For lower-K anorthoclase crystals it is close

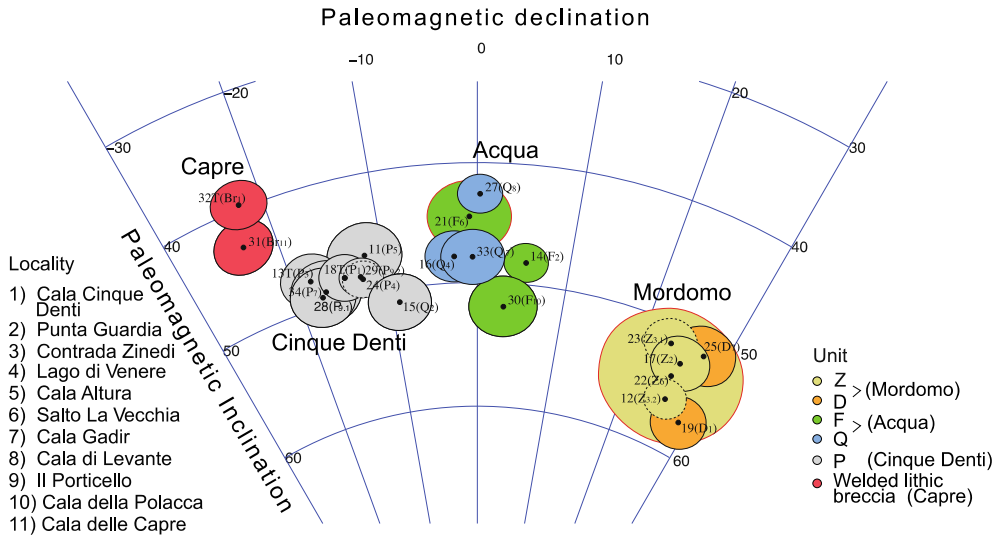
to 0.5 ka [Scaillet *et al.*, 2011] and PSV-based paleomagnetic dating can provide valuable temporal and cross-correlative constraints to complement existing  $^{40}\text{Ar}/^{39}\text{Ar}$  ages.

Paleomagnetism had been previously used to assess whether individual lava flows belonged to the same lava field [Bogue and Coe, 1981, Coe *et al.*, 2005, Hagstrum and Champion, 1994, Speranza *et al.*, 2008], whether different welded scoriae were produced by the same eruption [Zanella *et al.*, 2001], and—concerning ignimbrite correlation only in the pioneer works by Grommé *et al.* [1972] and Ort *et al.* [1999] on the mid-Tertiary ignimbrites from the western US and the Campanian ignimbrite from the Phlegraean Fields, respectively. Pantelleria seemed to be an ideal target to use the paleomagnetic correlation method, as the pre-GT ignimbrites were exposed only at isolated sea coves, with many difficulties in their correlation, given also the rheomorphism and the frequent in-depth lateral lithofacies variations. K/Ar dating by Mahood and Hildreth [1986] had not solved the question, as age error bars of ignimbrite units Z, D, F, and Q overlapped. Speranza *et al.* [2012] collected 23 paleomagnetic sites from the aforementioned ignimbrites plus ignimbrite P and the so-called “welded lithic breccia” considered by Mahood and Hildreth [1986] to relate to the La Vecchia caldera collapse.

The paleomagnetic analysis of Pantelleria ignimbrites was successful due to their highly welded character allowing easy coring of compact yet relatively soft ignimbrite matrix. Also, scatter in paleomagnetic direction (Figure 3) proved to be smaller than in lavas, probably due to: (1) the lack of post-emplacment tilt in ignimbrites, compared to lava field sectors with continuous lava supply over weeks or months that can push and tilt already solidified lava blocks; (2) much smaller magnetization intensity of ignimbrites with respect to lavas, implying much smaller magnetic anomalies generated by buried deposits or the volcanic unit itself; local magnetic anomalies in fact represent one of the most significant scatter source of paleomagnetic directions from volcanics [Baag *et al.*, 1995, Speranza *et al.*, 2006].

The main results reached by the paleomagnetic study of the pre-GT ignimbrites by Speranza *et al.* [2012] are as follows:

- Ignimbrites D and Z (now called “Mordomo”



**Figure 3.** Equal-area projection (lower hemisphere) of mean paleomagnetic directions from ignimbrites of Pantelleria (the “COS” suffix of each site is omitted) by Speranza *et al.* [2012]. Ellipses about the paleomagnetic directions are the projections of alfa-95 confidence cones. Sampling localities initials (detailed in the left) are within each ellipsis in subscript in brackets, at the right of old unit denomination after Mahood and Hildreth [1986]. Updated formational names are after Jordan *et al.* [2018]. The scattered paleomagnetic direction from site Cos20 (Lago di Venere) is omitted. Clustered paleomagnetic directions demonstrate that ignimbrites D/Z (updated name: Mordomo Fm.) and F/Q (Acqua Fm.) coincide, and that the two sites from welded lithic breccia belong to the same ignimbrite (Capre). See Speranza *et al.* [2012] for details.

after Jordan *et al.*, 2018) are both characterized by high 20°–30° declination and 50°–60° inclination values suggesting a common emplacement. This result turned out to be fully consistent with the new <sup>40</sup>Ar/<sup>39</sup>Ar determinations by Rotolo *et al.* [2013]. Considered together these data indicate a pooled age of 84.7 ± 0.5 ka (2σ, MSWD = 1.15) for this depositional unit.

- A lithic-rich ignimbrite exposed below ignimbrite P (now called “Cinque Denti”) at Cala Cinque Denti (NE Pantelleria coast) paleomagnetically correlates with the “welded lithic breccia” of Cala delle Capre [SW Pantelleria, Mahood and Hildreth, 1986], demonstrating that the La Vecchia caldera-forming eruption occurred at 130–160 ka, based on available K/Ar ages by Mahood and Hildreth [1986]. Such age window was later fully confirmed, and substantially refined at

140.0 ± 1.5 ka by <sup>40</sup>Ar/<sup>39</sup>Ar dating in Rotolo *et al.* [2013] for the now called “Capre” ignimbrite, later <sup>40</sup>Ar/<sup>39</sup>Ar dated at a similar age of 137.9 ± 0.8 ka by Jordan *et al.* [2018].

- The paleomagnetic directions of F and Q ignimbrites share similar directional data (within <10°), but Speranza *et al.* [2012] did not realize that they could represent the same event. Relying on <sup>40</sup>Ar/<sup>39</sup>Ar dating, the F/Q ignimbrite correspondence was first proposed by Rotolo *et al.* [2013] and integrated as such in the latest volcanic stratigraphy by Jordan *et al.* [2018], who called it “Acqua” ignimbrite.

To sum up, the integration of paleomagnetism, <sup>40</sup>Ar/<sup>39</sup>Ar radiometric dating and stratigraphic analysis allowed solving the timing of pre-GT ignimbrite emplacement with a resolution that would have never been attainable using only one or two of those methods. Paleomagnetism of welded ign-

imbrites proved to yield very reliable results, more accurate than those obtained by lavas.

The work by Speranza *et al.* [2012], along with pioneer papers by Grommé *et al.* [1972] and Ort *et al.* [1999], and more recent contributions by Ort *et al.* [2013], Finn *et al.* [2016] and Kirscher *et al.* [2020] on the Bolivia, Idaho, and Armenia ignimbrites, respectively, prove that paleomagnetism represents probably the best tool to assess the correlation of ignimbrite outcrops and proximal versus distal volcanic deposits. We expect that in future, paleomagnetism will be highly used on worldwide welded ignimbrites to solve similar volcanological problems, in combination with high-resolution  $^{40}\text{Ar}/^{39}\text{Ar}$ .

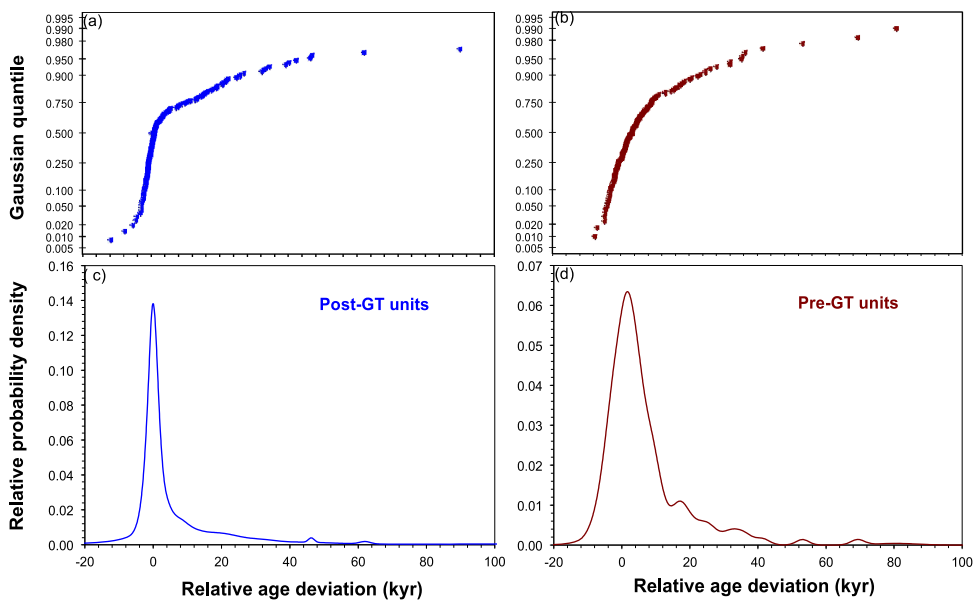
## 5.2. Methodological improvements: $^{39}\text{Ar}/^{40}\text{Ar}$ dating of young and K-poor feldspar

Although PSV-tied directional data can provide an efficient high-resolution correlation tool in a tightly Earth-referenced coordinate frame,  $^{40}\text{Ar}/^{39}\text{Ar}$  remains essential in terms of absolute temporal control. This is especially so for progressively older units both because a master PSV curve has not been established worldwide, and none locally extends very far back in time.  $^{40}\text{Ar}/^{39}\text{Ar}$  ages are also insensitive to tectonic unrest and post-cooling tilting characterizing explosive volcanoes (sector collapse, caldera resurgence/foundering, bradyseism, etc.). Methodological progress in the past two decades has considerably improved the resolution of the  $^{40}\text{Ar}/^{39}\text{Ar}$  technique in terms of either target (lava flows, fall units, ignimbrite flows) and material processing (single vs. bulk crystal dating, single vs. multiple ion collection). As stated earlier, laser-based  $^{40}\text{Ar}/^{39}\text{Ar}$  techniques have reached a resolution narrowing to a century for sanidine [Renne *et al.*, 1997]. Such a performance came about as the result of greatly improved blank levels permitted by laser-based extraction systems compared to older furnace setups. In such systems, the effective  $^{40}\text{Ar}/^{39}\text{Ar}$  resolution scales linearly with the K content of the sample such that a fivefold reduction in K results in a fivefold reduction in absolute precision [Scaillet, 2000], practically affording a limiting precision five times bigger ( $\pm 0.5$  ka,  $2\sigma$ ) for lower-K anorthoclase crystals typical of peralkaline rhyolites [Scaillet *et al.*, 2011].

Detailed  $^{40}\text{Ar}/^{39}\text{Ar}$  work at Pantelleria have shown that, beyond precision the major obstacle to building a tightly resolved chronostratigraphy is the occurrence of mixed  $^{40}\text{Ar}/^{39}\text{Ar}$  systematics characterized by internally discordant ages scattering beyond individual analytical errors. Except for the GT [Scaillet *et al.*, 2013] and several lava flows and small-sized Strombolian eruptions [Scaillet *et al.*, 2011, 2013, Rotolo *et al.*, 2013], about a half of all units dated so far have proved to be affected by such systematics. Scaillet *et al.* [2011] devised a dedicated two-step protocol combining multi-grain fusion (about 10–15 crystal at a time) with pre-degassing in vacuo to improve both the radiogenic yield and the removal of surface-bound volatiles potentially carrying excess  $^{40}\text{Ar}$ . By screening out low-T steps featuring anomalously old ages, this proved essential in producing the first high-resolution  $^{40}\text{Ar}/^{39}\text{Ar}$  ages ever produced on such youthful mildly K-enriched material. Systematic application of this approach to selected post-GT units showed this excess component to be dominantly derived from late-stage interaction with atmospheric or hydrothermal agent (i.e., secondary, non-magmatic, component).

A different picture emerged for the older, more explosive, ignimbrite deposits constituting the bulk of the volcano infrastructure prior to the deposition of the GT. Unlike the GT, which displayed well-behaved  $^{40}\text{Ar}/^{39}\text{Ar}$  data permitting an age of  $45.7 \pm 1.0$  ka to be confidently resolved [Scaillet *et al.*, 2013], 7 out of 13 pre-GT ignimbrite samples showed discordant  $^{40}\text{Ar}/^{39}\text{Ar}$  patterns with internal age variations as great as 400 ka (but more commonly  $<40$  ka). Notably, such internal variations arise despite the application of the two-step protocol, pointing to the primary (syn-magmatic or syn-depositional) origin of the anomalous ages [Rotolo *et al.*, 2013]. An age in excess of the depositional time may arise due to excess  $^{40}\text{Ar}$  contamination in the magma reservoir proper (i.e., via Ar dissolved in the melt, cf. Esser *et al.* [1997]), or as a result of syn-eruptive incorporation of xenocrysts from older deposits, or entrained by the magma en route to the surface.

A characteristic feature of within-unit  $^{40}\text{Ar}/^{39}\text{Ar}$  variations is that they cover a relatively reproducible time span, from about zero to  $\sim 50$  kyr. When plotted as a probability density of the age in excess of the depositional age (Figure 4), such systematics reveal striking differences between pre-GT and post-

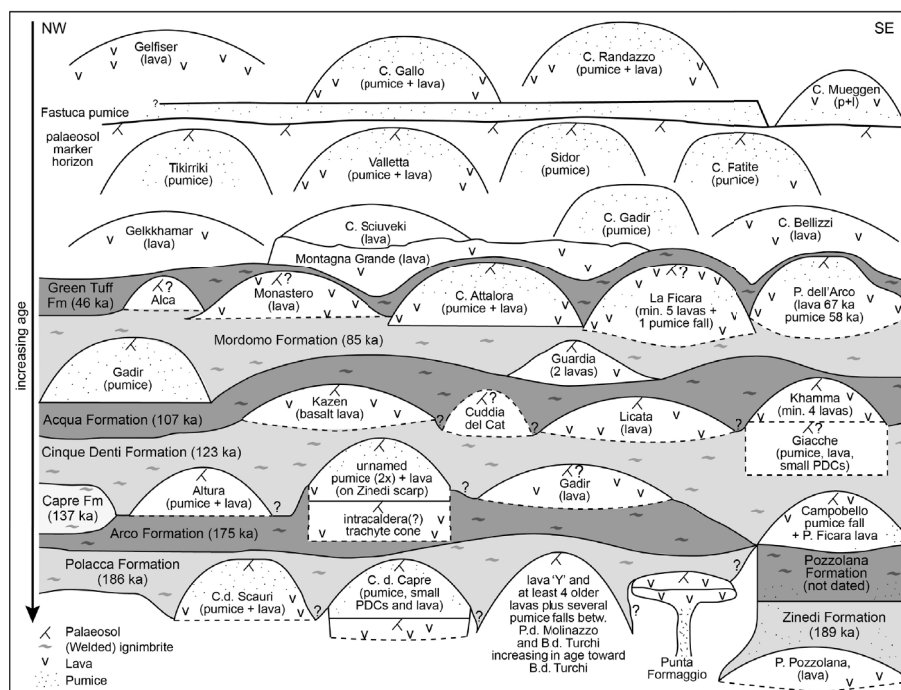


**Figure 4.** Age deviation probability distribution of anorthoclase  $^{40}\text{Ar}/^{39}\text{Ar}$  data from Pantelleria eruptive units predating or post-dating the GT eruption. (a, b) age deviation calculated relative to the depositional age of the parent unit [data from Scaillet *et al.*, 2011, and Rotolo *et al.*, 2013]. (c, d) relative probability density distributions showing the presence of pre-eruptive xenocrysts with a tail extending beyond the dominant near-zero peak. Upper plots: quantile plots scaled assuming a Gaussian distribution. A linear array indicates a Gaussian distribution, which occurs only for the data populating the peak of the post-GT data.

GT units. While both distributions peak near the origin (i.e., no excess  $^{40}\text{Ar}$ ), post-GT  $^{40}\text{Ar}/^{39}\text{Ar}$  ages are more sharply peaked and quite rapidly fade away past 5 kyr of the depositional age (Figure 4c). In contrast, Pre-GT units display a broader distribution with a tail extending well beyond the depositional age, up to 50 kyr and older (Figure 4d). A characteristic break in slope also occurs in the quantile distribution of the sorted post-GT data (Figure 4a) that is not apparent in the pre-GT data distribution which is more rounded and never achieves a linear trend across the data populating the peak (Figure 4b). This statistical difference hints at an intrinsically different mechanism of xenocrystic incorporation. While incorporation of reworked epiclastic/subvolcanic products is clearly accidental in both cases, it is more extensive in the pre-GT ignimbrites units than in the lower-energy post-GT fall deposits. In the latter case, syn-eruptive re-incorporation of older material can be understood to occur at shallower levels than in the higher-energy, highly disruptive, caldera-forming

eruptions.

In this connection, it is remarkable that half of the pre-GT ignimbrites affected by xenocrysts locally display homogeneous (xenocryst-free) systematics [Rotolo *et al.*, 2013, Jordan *et al.*, 2018]. The coexistence in a single depositional unit of lateral variations in xenocryst contamination, with the local absence thereof, indicates that epiclastic mixing dynamics or within-reservoir melt/rock interactions were locally controlled. Should the latter apply, the local control on xenocrystic incorporation would imply sector zoning in the reservoir and, possibly, piecemeal caldera collapse to preserve such a zoning during deposition. With continuous progress in single-grain  $^{40}\text{Ar}/^{39}\text{Ar}$  resolution [Jordan *et al.*, 2018] and data productivity, Pantelleria clearly will provide excellent opportunities to refine such time-spatial eruptive dynamics based on systematic  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of anorthoclase.



**Figure 5.** Schematic chronological representation of Pantelleria volcanological evolution based on most recent geochronological ( $^{40}\text{Ar}/^{39}\text{Ar}$ ), paleomagnetic and field data [Jordan *et al.*, 2018, Rotolo *et al.*, 2007, 2013, Scaillet *et al.*, 2011, 2013, Speranza *et al.*, 2010, 2012]. Dashed lines (pre-GT section) or open bases (post-GT section) indicate that the basal contact is not seen in the field. Post-GT basaltic centers have been omitted for clarity.

## 6. Physical volcanology of a peralkaline volcano

### 6.1. Local eruption centers versus ignimbrite-forming eruptions

As a defining locality for peralkaline volcanism, it is worth considering the general eruptive styles of Pantelleria eruptions. Broadly, there are ignimbrite eruptions and local (monogenetic) centers, as portrayed in Figure 5 in a scheme that integrates the most recent geochronological, paleomagnetic, and field data for pre- and post-GT eruptive units [Jordan *et al.*, 2018, Rotolo *et al.*, 2007, 2013, Scaillet *et al.*, 2011, 2013, Speranza *et al.*, 2010, 2012]. Ignimbrite eruptions are large eruptions from the caldera. Local centers can be effusive or explosive and have occurred throughout the entire  $\geq 324$  ka subaerial volcanic history [Jordan *et al.*, 2018, Scaillet *et al.*, 2011

and references therein]. They can produce small ignimbrites, pumice falls and lavas (sometimes spatter fed) and typically show transitions between explosive and effusive activity [Stevenson and Wilson, 1997]. They may be cone- or shield-shaped with a limited dispersal, which in most cases does not exceed several hundred meters ( $\geq 3$  km for the Fastuca eruption, Rotolo *et al.*, 2007) so they are best termed strombolian. Eruption style, magnitude, and periodicity are similar whether pre-GT or post-GT [Jordan *et al.*, 2018].

Whilst the GT is an important marker horizon in that it is widespread and easily recognizable, it should not be used to mark any particular change in eruptive style in Pantelleria's eruptive history. Pumice falls associated with the ignimbrite-forming eruptions are rare; only the GT, Cinque Denti, and Arco Formations have associated pumice falls and these are relatively thin and not widespread. Eruption

columns were sub-Plinian at most [Williams, 2010, Jordan, 2014]. Other peralkaline volcanoes do not produce widespread Plinian precursor pumice falls either [e.g., Terceira: Self, 1976; Kenya: Leat, 1991; Gran Canaria: Schmincke and Sumita, 1998]. This may be because of low magma viscosity and the fact that peralkaline eruptions do not form tall stable eruption columns [Mahood, 1984]. This is a key difference between peralkaline and metaluminous eruptions.

### 6.2. *Caldera-forming eruptions*

Of eight ignimbrites pre-GT, five comprise of variably widespread significant lithic breccias (GT, Mordomo, Acqua, Arco, and Polacca Formations). Of these, the Acqua breccia is the thickest at ~5 m. Lithic breccias are interpreted to represent an energetic phase of the eruption coupled with vent erosion or widening and are therefore commonly thought to indicate caldera collapse phases of an ignimbrite eruption [Walker, 1985, Druitt and Bacon, 1986]. Only the lithic breccias in the Mordomo Formation and in the Acqua Formation contain plutonic clasts, evidencing excavation from the vent or magma reservoir wall rocks and therefore are the two most likely candidates for caldera-forming eruptions.

There is no compelling evidence for single climactic collapse phases during the GT, Arco or Polacca eruptions. However, as they contain at least local breccias, it is likely that progressive and incremental collapse occurred along reactivated scarps [Walker, 1984].

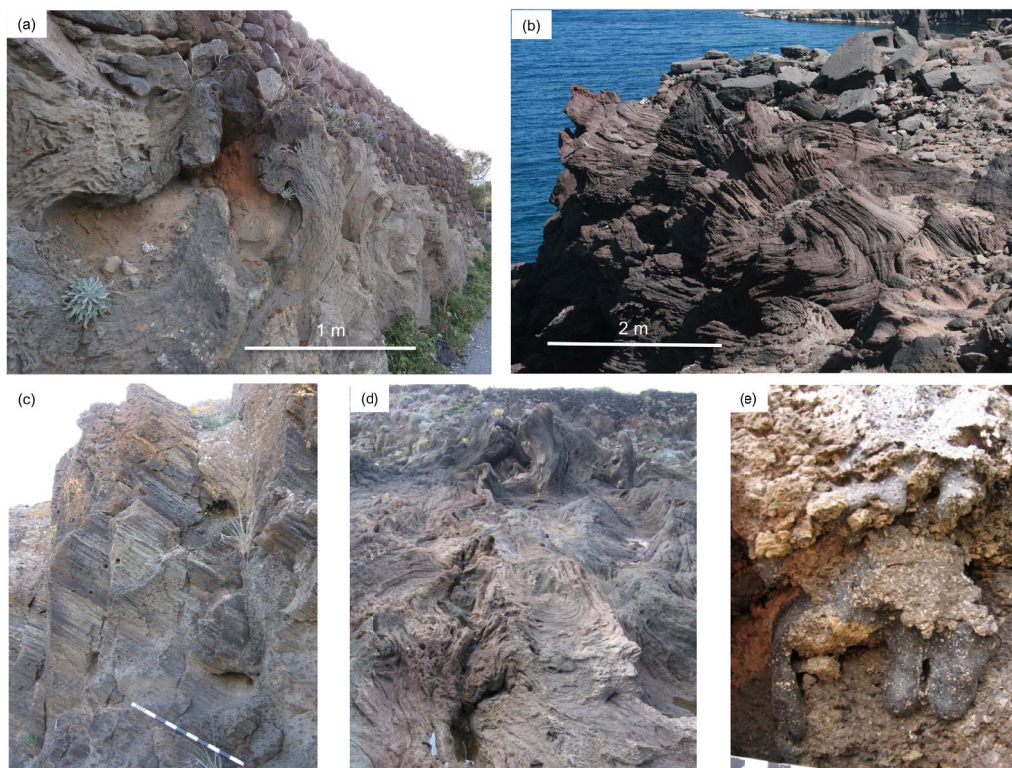
### 6.3. *Welding and rheomorphism*

Pantelleria is famed for its welded and rheomorphic pumice falls [e.g., Cala di Tramontana center, Stevenson and Wilson, 1997] and ignimbrites [e.g., The Green Tuff, Orsi and Sheridan, 1984]. The styles and features of Pantelleria rheomorphic ignimbrites are similar to those of other high-grade to extremely high-grade ignimbrites [e.g., the Greys Landing ignimbrite, Idaho, Andrews *et al.*, 2008] including stretching of pumice blocks and lapilli, lineations and foliations, folds on the micro- to meter scale), ramp structures, pull apart structures and tension gashes, gas blisters, upper and basal autobreccias, and rotated clasts (Figure 6a–e). Features more particular to peralkaline rheomorphism

include welding throughout the deposit despite thin deposit thicknesses (even <0.5 m) and on steep slopes, large gas cavities, small glass shards or “globules” showing spherical shapes, and round bubbles in previously deformed pumice particles [Schmincke and Swanson, 1967, Gibson, 1970, Korrington, 1971, Schmincke, 1974, Williams, 2010, Jordan *et al.*, 2018].

Rheomorphism in the ignimbrites is predominantly syn-depositional [Branney *et al.*, 2004, Williams, 2010, Jordan *et al.*, 2018]; hot, sticky particles agglutinated as an aggrading deposit from a PDC. The low viscosities meant that the overriding current was able to cause shearing in the underlying deposit where analysis of kinematic indicators show a change of shear direction with height through the deposit, from which it is possible to infer flow direction of the overriding PDC [Williams, 2010, following Andrews and Branney, 2005, Sumner and Branney, 2002]. In places, there is evidence for post-depositional flow, dominantly down slope [Wolff and Wright, 1981b, Williams, 2010]. The presence of spherical vesicles in strongly flattened fiamme records late-stage exsolution of a gas phase and revesiculation.

Low viscosities [Baker and Vaillancourt, 1994, Di Genova *et al.*, 2013, Mahood, 1984] due to elevated water [Barclay *et al.*, 1996, Lanzo *et al.*, 2013, Lowenstern and Mahood, 1991] and halogen contents [Aines *et al.*, 1990, Carroll, 2005, Gioncada and Landi, 2010, Lanzo *et al.*, 2013, Lowenstern, 1994], despite the rather low pre-eruptive temperatures [Di Carlo *et al.*, 2010, Romano *et al.*, 2018, 2020] and low glass transition temperatures [418–552 °C, Di Genova *et al.*, 2013] of peralkaline melts, are all thought to favor the welding of peralkaline eruptive materials [Dingwell *et al.*, 1998, Quane and Russell, 2005]. Eruption columns are inferred to be low, which minimizes cooling of pyroclastic particles during fountaining [Mahood and Hildreth, 1986]. Early pre-eruptive temperature estimates for the GT assumed high temperatures (~950 °C) based on low viscosities [Mahood, 1984] and the scant data available from Fe–Ti oxide geothermometry, 933–960 °C [Carmichael, 1967, Wolff and Wright, 1981a,b]. But more recent work with silicate mineral equilibrium [White *et al.*, 2005] and experimental petrology [Di Carlo *et al.*, 2010, Romano *et al.*, 2020] have shown these earlier values to be overestimated by >200 °C. The GT, the most rheomorphic of all the ignimbrites, is strongly



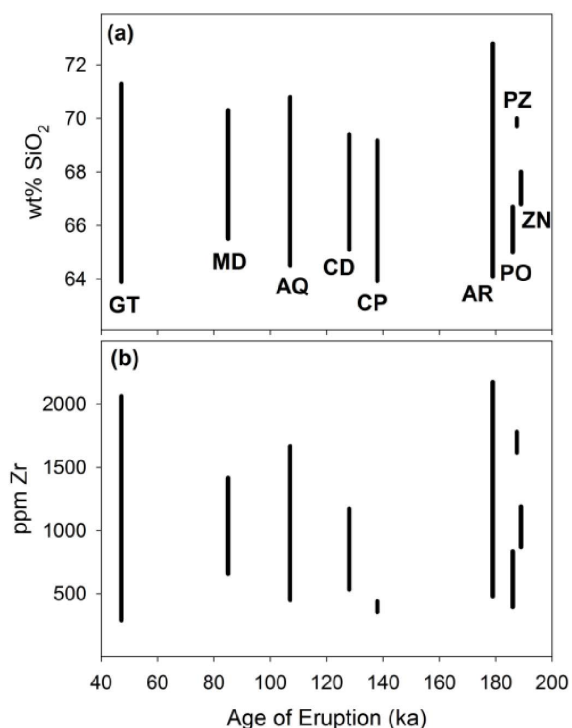
**Figure 6.** Rheomorphism at various scales. (a) Rheomorphic folding in the GT ignimbrite and (b) in Cinque Denti ignimbrite. (c) Rodded lineations observed in the GT ignimbrite (current direction is from right to left). (d) Rare, localized example of extreme rheomorphism of the GT ignimbrite: large U-shape fold in upper surface, folding foliation. (e) Vitrophyric droplets in the upper trachytic autobreccia of the GT ignimbrite (small scale divisions in 1 cm). This ooze-out feature indicates there were lenses of very low viscosity melt (such as fiamme) compared to the surrounding matrix during cooling.

peralkaline with very high chlorine concentrations (up to 1.1 wt%, Williams, 2010, Lanzo *et al.*, 2013; up to 0.7 wt% for groundmass glass of Mordomo Fm., Jordan, 2014). It should be noted that pre-eruptive  $H_2O_{\text{melt}}$  contents from melt inclusions in the GT [ $H_2O \leq 4.2$  wt%, Lanzo *et al.*, 2013] are comparable with contents from much lower explosivity pantellerite eruptions ( $H_2O_{\text{max}} = 4.4$  wt%, Gioncada and Landi [2010]) and with  $H_2O_{\text{melt}}$  inferred from phase equilibria experiments [Di Carlo *et al.*, 2010, Romano *et al.*, 2020]. This evidence may suggest that other than the pre-eruptive  $H_2O_{\text{melt}}$  eruptive triggers must be considered; one might be related to an abrupt syn-eruptive viscosity increase due to nanolites growth [Càceres *et al.*, 2020, Di Genova *et al.*, 2020].

## 7. Did the eruptive pace and the erupted magma volume condition melt evolution and melt productivity?

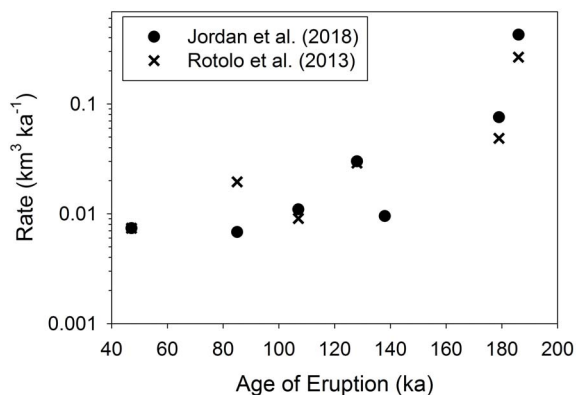
The depth and the pre-eruptive conditions of pantellerite magma have been constrained at  $P = 0.5\text{--}1.2$  kbar,  $T = 730$  °C,  $H_2O_{\text{melt}} = 4\%$  [Di Carlo *et al.*, 2010, Gioncada and Landi, 2010, Lanzo *et al.*, 2013, Romano *et al.*, 2020], and at  $P = 1\text{--}1.5$  kbar,  $T = 925$  °C,  $H_2O_{\text{melt}} = 2\%$  for trachyte magma (top member of the GT sequence; Romano *et al.* [2018, 2019]). The presence of a long-lived magma reservoir at mid-crustal levels ( $\sim 8$  km) that has efficiently homogenized basaltic melts and served as the source of parental magmas to the erupted trachytes and rhyolites was proposed by White *et al.* [2020] and





**Figure 7.** Ages of ignimbrites [Jordan *et al.*, 2018, Rotolo *et al.*, 2013, Scaillet *et al.*, 2013] plotted versus the range of whole rock compositions for SiO<sub>2</sub> (a) and Zr (b) presented in Jordan *et al.* [2021]. Ignimbrite units displayed include: **GT**, GT Fm.; **MD**, Mordomo Fm.; **AQ**, Acqua Fm.; **CD**, Cinque Denti Fm.; **CP**, Capre Fm.; **AR**, Arco Fm.; **PO**, Polacca Fm.; **PZ**, Pozzolana Fm.; **ZN**, Zinedi Fm. Capre Fm. analyses are from Rotolo *et al.* [2013] and Jordan [2014].

is supported by the nearly identical incompatible trace-element ratios and patterns on multi-element diagrams recorded in the ignimbrites [Jordan *et al.*, 2021]. These ignimbrites have several common compositional characteristics in addition to similar trace-element ratios, including range of SiO<sub>2</sub> (~64–71 wt%; Figure 7a) and Zr (~500–2000 ppm; Figure 7b) but differ in terms of peralkalinity, iron enrichment, and degree of silica oversaturation [Jordan *et al.*, 2021]. Most of the felsic eruptive products at Pantelleria have been comenditic trachytes and comendites, with only the earliest (Zinedi Fm.) and latest (GT Fm.) ignimbrites having a pantelleritic affinity. Whether these differences are due to pressure,



**Figure 8.** Ages of ignimbrites plotted versus the calculate rate of magma generation. Estimates for the volume of each eruption from Rotolo *et al.* [2013] and Jordan *et al.* [2018].

water content, oxygen fugacity, or something else is beyond the scope of this paper and will be the focus of future studies. However, similar range in both SiO<sub>2</sub> and Zr strongly suggest similar degrees and rates of differentiation from trachyte to rhyolite. Considering both effusive and explosive products, Mahood and Hildreth [1986] suggested a frequent rate ( $13 \pm 6$  ka) for felsic eruptions on Pantelleria over the past 190 ka. However, when one considers only the seven major ignimbrites to erupt over the past 186 ka, there has been a steady increase in time between eruptions accompanied by a decrease in eruptive volumes which seems to suggest an overall decline in magmatic activity at Pantelleria (Figure 8) with rates declining from 0.076 to 0.007 km<sup>3</sup>·ka<sup>-1</sup>. These calculated rates based on the data of Jordan *et al.* [2021] are consistent with the estimates of 0.008–0.055 km<sup>3</sup>·ka<sup>-1</sup> calculated by Mahood and Hildreth [1986]. Calculated rates using the volume estimates of Rotolo *et al.* [2013] also show a similar, secular decline from 0.049 to 0.007 km<sup>3</sup>·ka<sup>-1</sup>. This waning tendency was also observed by Scaillet *et al.* [2011] in post-GT mildly explosive activity.

## 8. Conclusions

The history of the Pantelleria peralkaline volcano is usually divided into an early history dominated by nine ignimbrite eruptions and at least two, but up to five, caldera collapses, followed by a later (post-GT)

history, characterized by numerous (>40) low explosivity to effusive eruptions produced from several closely spaced (spatially and temporally) eruptive vents.

The ignimbrites have a remarkably complex stratigraphy due to discontinuous exposures, rapid lateral facies variations, and ubiquitous but highly variable welding and rheomorphism. Inter-ignimbrite activity was characterized by small to moderate explosive or effusive eruptions from scattered vents, whose remnants are now only in few places poorly visible along some coastal scarps. The periodicity of ignimbrite-forming eruptions alternated with lower magnitude events (in a geological scenario that could be similar to the present day one following the eruption of the GT), which raises many still-unanswered questions about triggering mechanisms.

For the above reasons, Pantelleria represents an emblematic case history about the approaches adopted to untangle the volcanostratigraphy and portray its evolutionary history. Early approaches, based on field studies supported by K/Ar ages, defined a basis for future studies, but suffered heavily from the obfuscation caused by the rheological peculiarities of peralkaline magmas and tephra that added to the intrinsic uncertainty of the K/Ar dating. Only in the past ten years has the pre- and post-GT stratigraphy been investigated with multiple absolute/correlative chronological methods ( $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology, paleomagnetism) coupled to accurate field and petrographic characterization of pyroclastic products. Despite the possible drawbacks about the application of paleomagnetic methods on peralkaline rheomorphic ignimbrites (in principle still plastic below the closure temperature of principal ferromagnetic minerals) and the ability to date K-poor feldspars in young rocks by  $^{40}\text{Ar}/^{39}\text{Ar}$ , the congruence of these two methods, within a well-defined field and petrographic context, provided answers to the majority of the open problems with a resolution otherwise unattainable.

Combining  $^{40}\text{Ar}/^{39}\text{Ar}$  ages with petrochemical data of seven major ignimbrites erupted during the last 186 ka reveal a slight stretching of ignimbrite recurrence time, coupled to a decrease in erupted magma volumes. This tendency apparently holds also for the post-GT eruptive activity (violent strombolian at most).

Recommendations for future research include additional  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of the post-GT trachyte lavas and some still undated minor ignimbrites and local centers, and additional paleomagnetic studies of the emplacement temperatures of some key ignimbrites. Also, the variations in degrees of rheomorphism, and a structural study with detailed analysis of the viscosity, pre- and syn-eruptive halogen content and emplacement temperature, could be a valuable avenue for future study.

## Acknowledgments

We wish to thank two anonymous reviewers for their thorough and helpful comments. The Ar/Ar facility at ISTO is supported by the LABEX project VOLTAIRE (ANR-10-LABX-100-01), the Région Centre project ARGON, and the project EQUIPEX PLANEX (ANR-11-EQPX-0036). RW acknowledges Natural Environment Research Council studentship grant NER/S/A/2006/14156. NJJ gratefully acknowledges funding from the German Academic Exchange Service, Geological Society of London, Mineralogical Society of Great Britain and Ireland, Geologists Association, Quaternary Research Association, Volcanic and Magmatic Studies Group and the Department of Geology at the University of Leicester.

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