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Reconstructing eroded paleovolcanoes on Gran Canaria, Canary Islands, using advanced geomorphometry

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ABSTRACT

Original volcanic edifices of two successive stages of Gran Canaria are reconstructed using a geomorphometric analysis of existent or restored paleosurfaces. In the reconstruction, surface fitting was applied preferably to planèzes (i.e. triangular facets of original volcano flanks) and quasi-planar surfaces, QPS (those occurring on planèzes, or scattered, slightly eroded portions derived from original cone surfaces) with the help of red relief image map (RRIM) analysis. Out of the long-lasting, Mid-Miocene to Holocene subaerial evolution of the island, the Late Miocene Fataga volcano and the subsequent, Pliocene Roque Nublo volcanoes were the largest and highest. The eruptive center of Fataga, a composite edifice (12.2–8.8 Ma) that may have grown up excentrically with respect to the previous Tejeda caldera, is well-defined by both two planèzes (named Veneguera–Mogán and Fataga–Tirajana) and QPS remnants. Its calculated original volume, ≤1000 km^3, is close to the largest stratovolcanoes on Earth. However, its ≥3300 m elevation, obtained by exponential fit, may have been significantly lower due to the complex architecture of the summit region, e.g. a caldera responsible for ignimbrite eruptions. Roque Nublo, a 3.7–2.9 Ma stratovolcanic cone, which was superimposed upon the Fataga rocks ≥3 km west of the Fataga center, has left no considerable paleosurfaces behind due to heavy postvolcanic erosion. Yet, its remnant formations preserved in a radial pattern unambiguously define its center. Moreover, surface fitting of the outcropping rocks can be corrected taking the erosion rate for the past 3 Ma into account. Such a corrected surface fit points to a regular-shaped, ≥3000 m-high cone with a 25 km radius and ca. 940 km^3 original volume, also comparable with the dimensions of the largest terrestrial stratovolcanoes.

1. Introduction

The complex evolution of superimposed volcanic edifices at the Canary Islands is probably best exemplified on Gran Canaria, the second largest island (Fig. 1). Its eruptive activity consisted of two volcanic stages typical of the Canaries: a complex shield-building and a rejuvenated stage, respectively (Schmincke, 1976; Carracedo, 1999; Carracedo et al., 2002). These stages were separated by a long erosional gap, and due to a balance between intense volcanism and erosion, all stages are represented in the present-day topography to smaller or greater extent unlike at other Canary Islands. The complex distribution of rocks enhanced by long-term erosion has resulted in a "pancake" structure, of which the higher levels are intensely eroded but often form remnants or outliers (Carracedo and Day, 2002) which is useful for a geomorphological reconstruction.

Although the volcanic stratigraphy and chronology of Gran Canaria is well-known (Fig. 2; Schmincke, 1976; McDougall and Schmincke, 1977; Balcells et al., 1992; van den Bogaard and Schmincke, 1998; Schmincke and Sumita, 1998; Guillou et al., 2004; Menéndez et al., 2008; Rodriguez-Gonzalez et al., 2012), the original morphologies of the island are poorly constrained. Volcanism on Gran Canaria was related mostly to a set of overlapping volcanic edifices that represent four subsequent eruptive activities: (1) the oldest, 14.6–14.0 Ma shield volcano (Güigüí and Horgazales basalts) was followed by the outpouring of the 14.0–13.3 Ma trachitic–rhyolitic Mogán ignimbrites including a caldera stage (Tejeda caldera); (2) emplacement of the trachyphonolitic Montaña Horno rocks (13.3–13.0 Ma) was followed by the trachyphonolitic pyroclastic rocks and lava flows of the Fataga Group (12.4–8.8 Ma) that, at least partly, can be connected to a central (strato)volcano; (3) a rejuvenated activity produced the Roque Nublo Group (4.9–2.6 Ma), connected mostly to the Roque Nublo stratovolcano (3.7–2.9 Ma) that issued out basanitic, trachitic to phonolitic lavas and pyroclastic rocks and was affected by major sector collapses; and (4) the post-Roque Nublo activity (3.0 Ma–3 ka) that was related to

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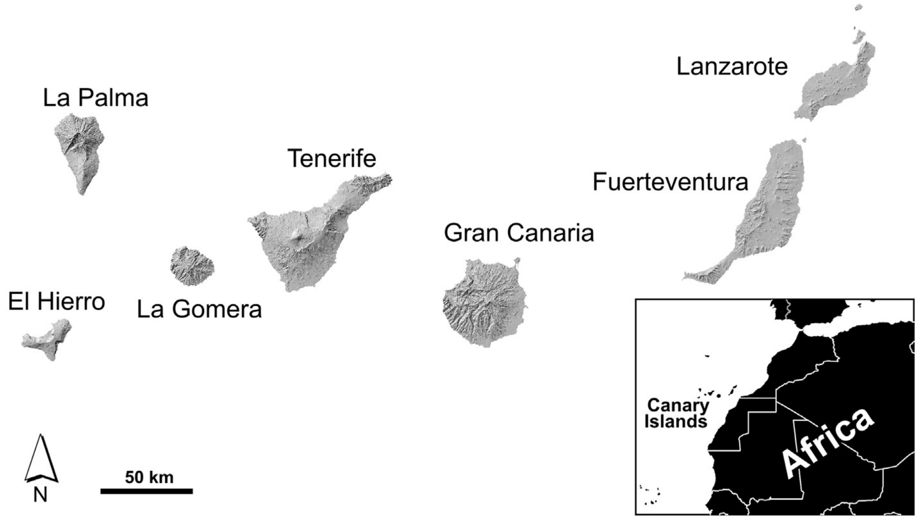

Fig. 1. Geographic setting of the Canary Islands (inset) and DEM representation of their subaerial parts (source of the 10 m DEM: GRAFCAN, 2009).

fissures and small-size monogenetic centers confined mostly to the northeastern part of Gran Canaria. One of the most recent eruptions was radiocarbon dated at 3075 ± 50 years (Nogales and Schmincke, 1969). With regard to the above-mentioned shield-building and rejuvenated stage, the 1st and 2nd eruptive activities are traditionally included in the former and the 3rd and 4th in the latter.

The volume of the submarine portion of Gran Canaria, representing the shield-building stage (1), and consisting of a central shield and its apron, was estimated >24,000 km^3, whereas that of the recent subaerial island 850 km^3 by Schmincke and Sumita (1998). The latter, still considerable volume implies that, despite deep erosion, significant portions of subaerial paleovolcanoes that grew upon the shield have been preserved. However, little has been published on the original geometries and dimensions of individual volcanic edifices. In particular, no GIS-based approach to volcanic geomorphology has been applied so far, although a 10-m resolution digital elevation model (DEM) has been available in the past years (last release: GRAFCAN, 2009), and supported, for instance, drainage basin analysis and erosion rate calculations (Menéndez et al., 2008; Rodriguez-Gonzalez et al., 2012).

This paper focuses on the reconstruction of the two main volcanic edifices of the subaerial island: a late Miocene central volcano related to the Fataga rocks, and the Pliocene Roque Nublo stratovolcano. The reconstruction is based on the topographic manifestation of mappable geological units and, where possible, preserved paleosurfaces.

Our main concept is that the distribution of volcanic rocks belonging to a given volcanic edifice, if not covered by subsequent volcanism, still

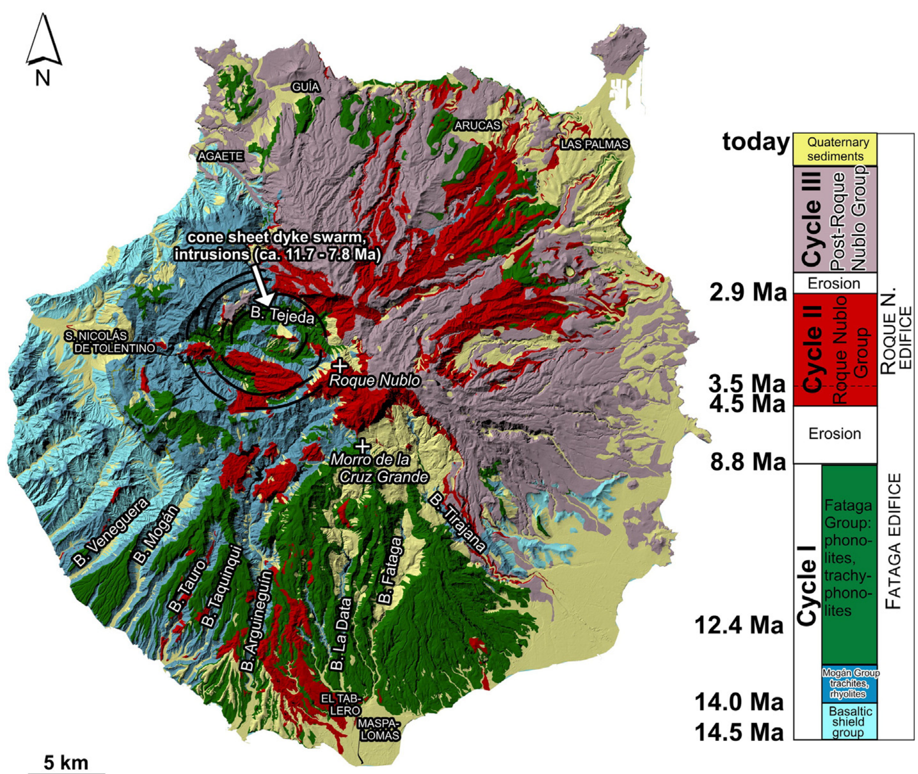

Fig. 2. Simplified geology of Gran Canaria draped on 10 m-resolution DEM image. Stratigraphic column is based on Balcells et al. (1992).

reflects the original morphology of a volcano. Preferably, remnant surfaces of volcano flanks (planèzes) are to be used, or those close to the original surface. Planèzes are polygonal, generally triangular facets, dipping outward from a volcanic edifice and separated by pathways of fluvial or glacial erosion (Cotton, 1952; Ollier, 1988) which incise the flanks of the volcano. Finding such geomorphic elements makes it possible to fit ideal original surfaces. In the following, after summarizing the background and the state of the art of the two addressed volcanoes, the applied methodology is presented. Finally, we discuss the reliability and the paleo-geomorphological implications of the morphometric results.

2. Geological-volcanological background

Gran Canaria, together with Tenerife, La Gomera, La Palma, El Hierro, Lanzarote and Fuerteventura, are located on Jurassic oceanic crust at water depths of 3000 to 4000 m (Uchupi et al., 1976; Acosta et al., 2003). The volcanism of the archipelago, along with the surrounding seamount province, has developed due to a shallow-source hotspot since early Cretaceous times (Morgan, 1983; Geldmacher et al., 2005; van den Bogaard, 2013). The origin of the hot spot (e.g. fixed, or attached to some extent to the African continent) is still debated (Duggen et al., 2009; van den Bogaard, 2013; Zaczek et al., 2015). Gran Canaria, being one of the central islands some 200 km offshore Africa, started its subaerial activity 15 Ma ago. At present, due to the intense erosion, the remnant of this subaerial volcanism, that is, the volume of the island, is 818 km^3 based on the 10-m DEM (Table 1).

Of the eruptive activities summarized above, the relatively short-living subaerial shield formations are not represented enough in the topography to infer respective paleovolcanic edifices, although Schmincke (1976) and Schmincke and Sumita (1998) proposed a number of amalgamated shields on the basis of gravimetry, and Carracedo et al. (2002), using dyke distribution data, suggested one main shield in the north. Subsequently, the outpouring of the Mogán ignimbrites (300–500 km^3 in volume: Carracedo et al., 2002) was associated with the formation of the Tejeda collapse caldera (Schmincke and Swanson, 1966), truncating the shield volcano. The caldera that hosts thick intracaldera ignimbrites and intrusive rocks (including subsequent cone sheet dykes: e.g. Schirnick et al., 1999) was later deeply dissected and eroded, partly uplifted, but is still seen in present-day topography. However, its rim and outer slopes are covered by post-Mogán rocks (Fig. 2), i.e. the Fataga Group (Section 2.1), and the subsequent, scattered Roque Nublo and post-Roque Nublo Groups (2.2), and this coverage prevents to model an associated (pre-caldera) edifice, even if the extracaldera Mogán ignimbrites show periclinal dips (relative to caldera rim) which may be used in further work.

Table 1
Volume estimates of the reconstructed Fataga and Roque Nublo paleovolcanoes.

Present day total Gran Canaria (subaerial)	818 km^3
Fataga volcano	
Below exponential surface fit, based on planèzes	1369 km^3
Below linear surface fit, based on planèzes	1344 km^3
Below lower (pre-Fataga) exponential surface fit	390 km^3
Original edifice volume of Fataga volcano	979 km^3 (exponential fit)
	954 km^3 (linear fit)
Volume loss truncating a cone with a 5 km-large caldera	−25 km^3
Roque Nublo volcano	
Below exponential surface fit to existant Roque Nublo rocks	1199 km^3
Below exponential surface fit to erosionally corrected RN rocks	1388 km^3
Below lower (pre-Roque Nublo) exponential surface fit	445 km^3
Original edifice volume of Roque Nublo Volcano	754 km^3 (exponential fit)
	943 km^3 (erosion added)
Volume addition by a Teide- or Fuji-like summit	+31 km^3

2.1. Fataga edifice

The first edifice that seems to be reconstructable from present topography is represented stratigraphically by the Fataga Group (Fig. 3). Even more voluminous than Mogán ignimbrites, the Fataga pyroclastic rocks and lavas of trachyphonolitic–phonolitic composition (>500 km^3: van den Bogaard and Schmincke, 1998; Carracedo et al., 2002) may have been connected partly to central vents and ring fractures of Tejeda caldera (Schmincke, 1976; Schmincke and Sumita, 1998; Jutzeler et al., 2010). However, at least a part of them may have also been issued out from a newly built shield- or, rather, stratovolcano, particularly in the late stage (Schmincke, 1976, 1993; Carracedo et al., 2002; Schmincke and Sumita, 2010). In map representation, Carracedo and Day (2002) termed it a “late resurgent dome”. Recently, Donoghue et al. (2010) argued for a “large volcanic edifice”, since, as they propose, there should be high altitude that produced enhanced infiltration of rainfall, effective in the alteration of intrusive/subvolcanic rocks. The existence of such a volcano seems to be also supported by the fact that the middle and especially the upper part of the Fataga Group contains debris avalanche deposits (i.e. vertical drop required). These deposits are little exposed on land, but well recognizable from offshore drilling (cf. Schmincke and Sumita, 2010). Hereafter, for simplicity, the long-lived post-Mogán (late Miocene) edifice is called the Fataga volcano.

Since the pure existence of such a volcano is poorly constrained, not surprisingly its dimensions are not clarified either: Schmincke (1993) proposed a 2500 m edifice height during the peak of volcanic activity, whereas Acosta et al. (2003) mentioned 2000 m elevation of the island after the first-stage volcanism. Certainly, any elevation estimate for a paleovolcano depends on the type of volcano and the complexity of the summit (e.g. a simple cone vs multiple/compound edifice; with or without a caldera). Carracedo et al. (2002) and Schmincke and Sumita (2010), without further constraints, located the center of the volcano around Morro de la Cruz Grande (1539 m), the highest elevation of the Fataga rocks at present (Fig. 2).

Composing mostly the southern flanks of Gran Canaria, the Fataga Group is divided into Lower, Middle and Upper Fataga formations erupted in different times 12.4 to 8.8 Ma ago. Within this interval, Lower Fataga formation (12.4–12.3 Ma) with little volumetric contribution to the volcano is an up to 200 m-thick succession of lavas and ignimbrites cropping out in stratigraphically low position of valleys.

The Middle Fataga Formation (12.1–11.4 Ma), in contrast, comprises widespread ignimbrite consisting of at least five ignimbrite cooling units tens of meters thick each, and minor lava successions. The uppermost ignimbrite, the 11.8 Ma Ayagaures Ignimbrite (Jutzeler et al., 2010), represents a 20–25 m-thick cooling unit consisting of as many as <20 individual flow units spread over a large area. Middle Fataga Formation can be found dominantly in the S–SW sector of Gran Canaria, covering long, outward-dipping ridges and surfaces dissected by ravines (e.g. Veneguera, Tauro, Taquinqui, Arguineguín, La Data and Fataga “barranco”: Fig. 2). Certainly, such a situation is the result of geomorphic inversion, since the ignimbrites were valley-filling deposits during the growth of the Fataga edifice. As resistant rocks, they have been later exhumed and enhanced, while other, less resistant rocks, even original ridges, have been eroded. Especially well-preserved is a triangular surface of a ridge located between Veneguera and Mogán ravines (Yepes and Rodríguez-Peces, 2012), interpreted as a planèze. Hereafter, this topographic feature is called the Veneguera-Mogán Planèze (Fig. 3). We mention that the narrow northern tip of this planèze consists of Upper Fataga lava rocks.

The Upper Fataga Formation (11.0–8.8 Ma) includes mostly thick lavas (≥800 m in total), interbedded with minor fallout tephra and ignimbrites (e.g. Arguineguín ignimbrites; van den Bogaard and

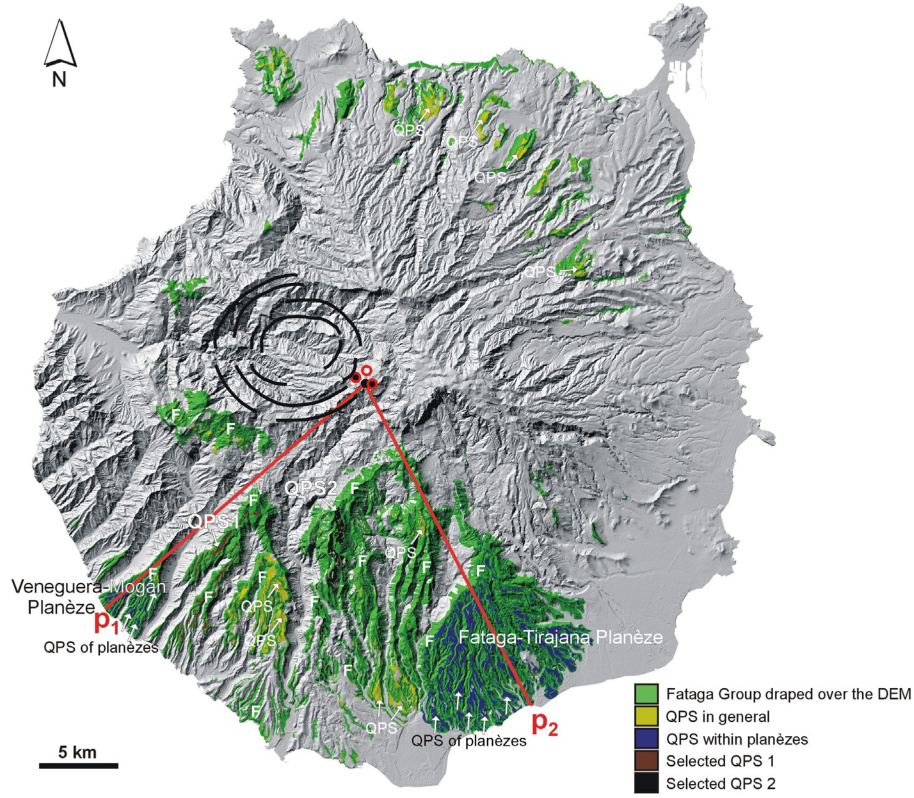

Fig. 3. Representation of the Fataga Group and its differently defined paleosurfaces draped on the 10 m-resolution hillshaded relief image. Quasi-planar surfaces in general (QPS) and within the Veneguera–Mogán and Fataga–Tirajana planèzes (QPS of planèzes) are indicated (for QPS definition, see Methodology and Fig. 5), as well as two selected examples of QPS (1 and 2) that are located along linear, radial ridges. (These QPS examples also appear in Fig. 6.) Section lines p1 and p2 show the position of topographic profiles in Fig. 6a, c. Filled dots in the middle of the island show the location of the projected center for three exponential fits (fit of all surfaces belonging to the Fataga Group, fit of QPS within the Fataga Group and fit of QPS of the planèzes), whereas empty dots show the centers for the three linear fits. Cone sheet dykes as in Fig. 2 are also indicated.

Schmincke, 1998). The largest occurrence of the lavas can be found between the Fataga and Tirajana ravines, the upper catchment of the latter being a huge erosional depression of Late Miocene or Pleistocene age (Lomoschitz et al., 2002; Schmincke and Sumita, 2010). The large, triangular flank between these two ravines, slightly dissected by minor drainage but preserving a uniform outward dip, is interpreted again as a planèze (called Fataga-Tirajana Planèze: Fig. 3). Other minor occurrences of Upper Fataga lavas crop out between Guía and Arucas towns in the north, forming small buttes divided, and in some places overflown, by the youngest Pleistocene lavas of Gran Canaria. The Middle and Upper Fataga volcanism was associated with the latest-stage intrusion of the above mentioned cone sheet dyke swarm, confined areally mostly to Tejeda caldera; more precisely, to the erosionally enlarged upper catchment area of the ravine of B. Tejeda (Fig. 2). The ages of some of the dykes (<8 Ma) post-date the Upper Fataga rocks.

2.2. Roque Nublo edifice

After the formation of the Fataga edifice, Gran Canaria was characterized by long-term (~4 Ma) dormancy with intense erosion (Schmincke, 1968; van den Bogaard and Schmincke, 1998; Schneider et al., 2004). Most radial valleys, cut into the flanks of the Fataga edifice, were formed during that time. Due to trade winds that hit the N parts as well as the prevailing humid climates since mid-Miocene times, erosion carved the steepest canyons into the N flanks of the island (Schmincke, 1968). After millions of years, such a paleotopography controlled the evolution of the new Roque Nublo stratovolcano (Schmincke, 1976; Carracedo et al., 2002) that grew upon the eroded Fataga cone and, at the same time, filled the existing radial ravines. The Roque Nublo rocks comprise up to 700 m-thick valley-filling lava flows and breccias on the N and E parts of Gran Canaria (van den Bogaard and Schmincke, 1998). Eruptive activity of the growing stratovolcano, in addition, may have re-incised previous valleys (Pérez-Torrado et al., 1997).

Stratigraphically, the Roque Nublo Group (Fig. 4) is divided into six formations, the first of which, El Tablero, consists of monogenetic centers and lava flows mostly in the south emplaced prior to the growth of the stratovolcano (Pérez-Torrado et al., 1997). The subsequent formations (Riscos de Chapin, Rincon de Tejeda, Tirajana, Tenteniguada and Ayacata) that make up the Roque Nublo stratovolcano (3.7–2.9 Ma) include lava flows at the base, pyroclastic rocks and breccias interbedded with lava flows in the lower part, massive breccias in the middle part, and intrusives and lava flows in the upper central part (van den Bogaard and Schmincke, 1998). The volcanic succession has a composition from tholeiitic and alkali basalts to trachytes and from basanites to phonolites and nephelinites.

Within the evolution of the stratovolcano, gravitational sector collapses producing huge debris avalanches (up to 14 km^3 on land: Mehl and Schmincke, 1999) were of particular importance toward the latest stage of the stratovolcano (Garcia-Cacho et al., 1994; Pérez-Torrado et al., 1995; Mehl and Schmincke, 1999). They mostly affected the S flanks (Ayacata Formation), filling, for instance, the steep paleocanyon of Arguineguín (see Fig. 2), but were also spread to other directions. The debris avalanches run as far as 25 km from source, and can be pointed out in submarine setting as well (Funck and Schmincke, 1998), representing additional volumes of up to 70 km^3 (Carracedo and Day, 2002).

After the sector collapse events at the stratovolcano (ca. 3 Ma), intense erosion has continued, removing a great part of the debris-avalanche deposits and incising again the infilled valleys (e.g. Menéndez

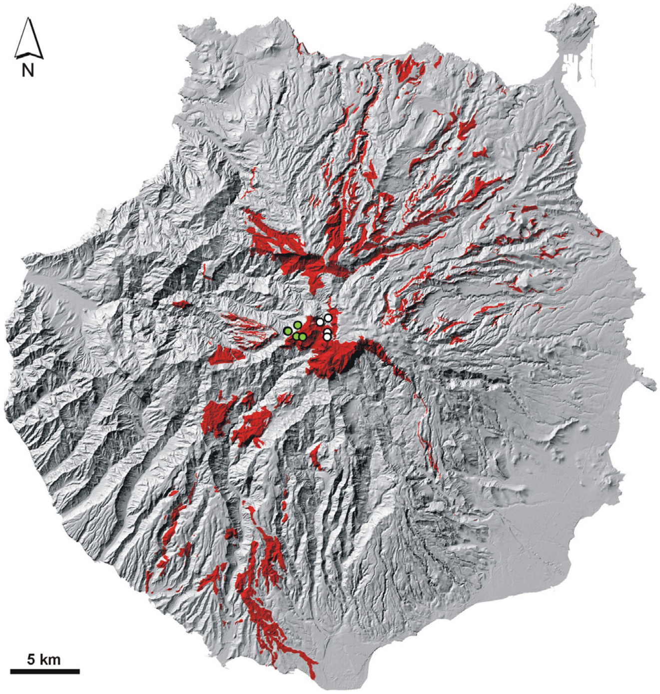

Fig. 4. Geological representation of rocks of the Roque Nublo Group (Balcells et al., 1992) draped on the 10 m-resolution DEM image. White dots show the location of the centers of surface fit for the Roque Nublo edifice (see Fig. 7). For comparison, the centers of Fataga fits (Fig. 3) are also shown.

et al., 2008). Like the case of Fataga, the valley-filling debris-avalanche deposits as resistant rocks have become exhumed, now forming ridges or valley sides at most places. For instance, after new incision, a further 100 m vertical erosion relative to the original Miocene canyon floor has occurred in the renewed ravine of Arguineguín (Mehl and Schmincke, 1999). Such an intense surface denudation means that only fragments of the radially arranged original Roque Nublo volcanic rocks have been preserved (Figs. 2 and 4), without planèzes, which makes paleovolcanic reconstruction difficult.

The poor preservation of rocks led to contrasting estimates about the dimensions of the original volcanic edifice by the researchers. First, Anguita et al. (1991) assumed a 3000 m-high edifice with only a (surprisingly small) 20 km^3 volume. Garcia-Cacho et al. (1994) suggested a 2500 m-high edifice with 100 km^3 volume and covering 250 km^2 area. The same height was proposed by Pérez-Torrado et al. (1995) and Carracedo et al. (2002), but assuming 540 km^2 area for the volcano, and 200 km^3 volume, respectively. Mehl and Schmincke (1999) and Acosta et al. (2003), by analog of Teide, imagined a 3500 m-high volcano, and according to the former authors a 36 km^3 collapsed volume is one third or quarter of the original cone. Schmincke and Sumita (2010) further reduced the assumed cone height to 2000 m (above the 1200 m-elevated basement). These discrepancies obviously call for better constraining the original volcano dimensions.

3. Methodology

Surface reconstruction of paleovolcanoes has been recently addressed by two slightly different geomorphometric methods (e.g. Lahitte et al., 2012; Favalli et al., 2014; Ricci et al., 2015). The first one considers selected ridges on the volcano flanks as being the least eroded parts of the original surfaces, whereas Favalli et al. (2014) focusses on the most likely shape of the paleovolcano by surface fitting using a minimization procedure. Although both methods can yield similar results, we used the more robust second approach. In the following, we present the procedure we applied.

Fitting a surface means that parametric surfaces described by

$$z = f(x, y, \alpha) \tag{1}$$

where x, y and z are the three space coordinates and α is the parameter vector. The input values of the parameters are chosen in order to fit the parametric surface to the given dataset, so the set of points x, y and z that satisfy the above equation defines a surface as close as possible to the real data. In our case the dataset is composed of a set of points of the 10-m resolution DEM selected by geological unit (e.g. those of the geological map in Fig. 2) and/or if they fulfill some morphological criteria. In this paper, for simplicity, the fitted geometric surfaces are generic cones with linear or exponential profiles, which have been proven adequate when trying to fit/reconstruct simple volcanic edifices (Karátson et al., 2010; Favalli et al., 2014).

Optimally, the surface fitting method benefits from the presence of remnant surfaces of original volcano flanks, especially the above-mentioned planèzes, which can be used for inferring the shape of the volcanic edifice starting from some basic assumptions such as an original circular symmetry. In order to consider only the least eroded remnants, in this work we make use of a “trick” for fitting surfaces to ridges or, more precisely, local heights with peculiar geometry. For this purpose, the red relief image map (RRIM, Chiba et al., 2008) of the study area is produced that can clearly visualize topographic slope, concavity and convexity at the same time, and this way effectively represents fine geomorphic features even of a largely flat surface. By using the RRIM, not only planèzes as a whole, but also local planar surfaces can be successfully extracted (see Section 3.2).

3.1. Surface fit

For fitting geometric surfaces to DEM portions and calculating the related error, we use the minimization library MINUIT which is made freely available at the European Organization for Nuclear Research (downloadable at www.cern.ch/minuit;CN/ASD Group MINUIT, 1993). Given a parametric surface of Eq. (1), we determine the parameters values by minimizing the root mean square error (*RMSE*) between the parametric surface and the DEM:

$$RMSE = \sqrt{\frac{\sum_{i,j}\left[H_{i,j} - f\left(x_i, y_j, \alpha\right)\right]^2}{n}} \tag{2}$$

where the integers i and j span the row and column positions of the DEM grid; x_i, y_j and $H_{i,j}$ are the x, y and z coordinate positions, respectively, of the DEM point identified by i and j; and n is the total number of DEM points.

We will use here only two simple parametric functions representing conical surfaces (hence with an assumed central symmetry) with linear and exponential profiles (e.g. Favalli et al., 2014). Taking the center of symmetry as the reference origin, we can express a conical surface with linear profile (i.e. a simple cone) as the set of points satisfying the linear relationship:

$$z = m\,R + q \tag{3}$$

where R is the planar distance from the origin, z is the elevation and m and q are constants representing the elevation of the apex and the tangent of the slope, respectively. Therefore, in this case, the parameter vector α is given by the two quantities m and q. Similarly, a conical surface defined by an exponential profile can be parameterized as:

$$z = a\;\exp(b\,R) + c \tag{4}$$

where, again, R and z are the planar distance from the center of origin and the elevation of a generic point describing the surface, respectively, and a, b and c are the three components of parameter vector α. In this case the height of the cone apex is $a + c$.

In many cases, especially in order to reconstruct dissected edifices, a better approximation of original surface is given by the envelope of the highest elevated points, i.e. ridges. There are various ways to give the due emphasis to locally elevated points. One way to do this is to define an 'ad hoc' weighting in Eq. (1) (Favalli et al., 2014). An alternative way is to minimize the following expression (which is no longer a true *RMSE* value, as indicated by the asterisk):

$$RMSE^* = \sqrt{\frac{\sum_{i,j}\left[H_{i,j} - f\left(x_i, y_j, \alpha\right)\right]^{\kappa_{i,j}}}{n}} \tag{5}$$

where $\kappa_{i,j}$ is no longer a constant equal to 2 but may be dependent of the data point. For example, if $\kappa_{i,j}$ is equal to 2 when $H_{i,j} - f(x_i,y_j,\alpha)$ is positive, and equal to 0.5 when $H_{i,j} - f(x_i,y_j,\alpha)$ is negative, then the contribution to *RMSE* by the points under the fitting surface is highly suppressed. Fitting by minimizing Eq. (5) yields a surface that covers most of the points and allows only a small number of points to remain above the surface itself.

3.2. Red relief image map

The red relief image technique (RRIM: Chiba et al., 2008) produces a "red image" by adjusting the chrome value of red to the topographic slope and its brightness to the openness value (Yokoyama et al., 2002), which in turn is the mean value between the positive and negative opennesses. Negative and positive opennesses are local indicators of the concavity and convexity of a surface, respectively. RRIM is then a multi-layered image which is able to give information about slope, concavity and convexity of the surface and to represent topographic details (Fig. 5b).

The slope is the first derivative of the DEM (e.g. Zevenbergen and Thorne, 1987) calculated by applying the Sobel filter as:

$$S = \arctan\left[\sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2}\right] \tag{6}$$

The openness parameters were introduced by Yokoyama et al. (2002) who defined the positive (ϕ_L) and negative (ψ_L) openness respectively as:

$$\Phi_L = \frac{1}{n}\sum_{i=1}^{n}\phi_i \tag{7}$$

$$\Psi_L = \frac{1}{n}\sum_{i=1}^{n}\psi_i \tag{8}$$

where ϕ_i and ψ_i are respectively the zenith angle and the nadir angle along the i-th direction (Fig. 5a), the subscript L refers to the maximum horizontal search radius considered (Fig. 5a). Both positive and negative opennesses are always mathematically positive quantities. Positive openness measures the "openness of the terrain to the sky" while negative openness is the "below-ground" openness (Yokoyama et al., 2002). Negative openness takes high values inside valleys, gullies and craters, while positive openness takes high values on crests and ridges (Fig. 5b).

Finally, openness parameter, *op*, was defined and calculated also by Chiba et al. (2008) as:

$$op = \frac{1}{2}(\Phi_L - \Psi_L). \tag{9}$$

The *op* value is dependent on the chosen search radius L and is positive when the surface is locally, at the scale L, convex upward (i.e. crests and ridges), and negative when the surface is concave upward (i.e. in valleys, gullies and craters; Fig. 5a, b).

Fig. 5c is the color diagram of the RRIM shown in Fig. 5b. Topographic slope is shown as the chroma value of red and openness is shown as brightness. As a result, the top of the ridges appears in white, the bottom of valleys in black, steep slopes in bright red, and flat surfaces in gray. It is worth noting that Fig. 5c is a subset of the whole possible values of openness/slopes that are shown in Fig. 5d. Indeed, the parameter space of Fig. 5c was clipped with the aim of producing nicely contrasting image by removing outliers with extreme values of either openness or slope. Since the preserved (almost flat) areas of the planèzes have neither high slope nor very high or very low openness values, the clipping performed to produce the RRIM does not introduce any error in the successive classifications based on this map.

3.3. Quasi-planar surface (QPS) classification

The reconstruction of a paleovolcano shape, as introduced above, can be based on the identification of planèzes first of all. Out of the two studied volcanic edifices of Gran Canaria, the Fataga volcano shows outer flanks identical with, or close to, the original surfaces. Fig. 5b shows one of the two examples, the Veneguera-Mogán planèze.

However, since planèzes might be dissected by small-scale erosional gullies (see Figs. 2 and 3), not all topographic points belonging to the two above-defined planèze areas can be useful. In addition, there might be other, more scattered paleosurfaces that also represent original cone remnants. Therefore, with the help of a supervised classification of the RRIM of Gran Canaria topography, we identified all those points of planèzes and other surface points of the Fataga rocks that belong to locally planar surfaces, hereafter called QPS (quasi-planar surfaces). This approach does not apply to Roque Nublo which shows no planèzes or QPS at all.

The QPS areas of Fataga have been determined by supervised classification involving: i) identification of the training areas; ii) extraction of appropriate geomorphic parameters (openness and slope values) from RRIM and its scatter plot (Fig. 5d); and iii) classification and visual validation of the classification process (Fig. 5e, f). Fig. 5d presents the scatter plot of openness vs slope for all the surface (discretized in DEM cells) belonging to the Fataga Group. The QPS areas that are to be extracted have, as they are quasi-planar, low positive values of openness from 0 to ~5°, and low values of slope from 0 to ~20° (yellow dots in Fig. 5d).

The openness parameter is very useful for classifying the flat areas on planèzes because, in contrast to the curvature parameter, it is calculated not locally, but for a certain (as large as possible) horizontal scale L. As a consequence, openness takes into account the surrounding morphology within a given L and is able to detect if a flat surface is a local high bounded by the incisions and valleys (positive values of openness) or is a local low bounded by walls and ridges (negative values of openness). Positive and low values of openness correspond to a morphology similar to a plateau surrounded by incisions, while ridges or planar walls of ridges can be easily identified (and excluded) because they have high values of openness. In addition, the QPS have relatively low slope values. Examination of the scatter plot (Fig. 5d) and visual inspection of the classified images (Fig. 5e, f) reveal that QPS, in particular those belonging to the planèze areas, are correctly classified.

4. Results and discussion: implications to paleovolcano dimensions

The geometry of preserved paleosurfaces belonging to overlapping but different edifices makes it possible to infer the original morphologies of Gran Canaria and calculate both original and eroded volcano volumes. However, before discussing the two selected paleovolcanoes in our study, we emphasize that the reliability of the reconstruction

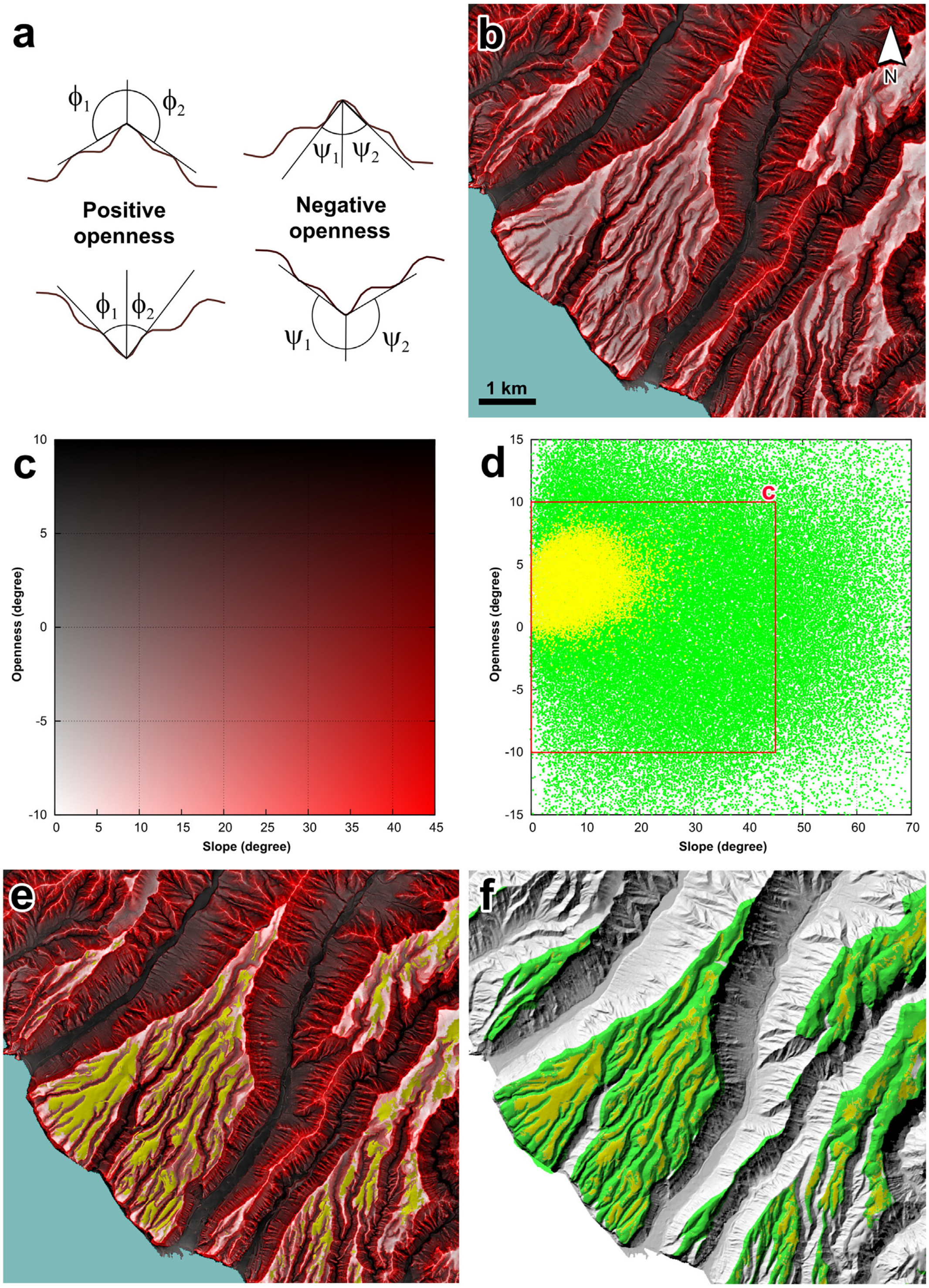

Fig. 5. Example of extraction of quasi-planar surfaces (QPS) using the example of Veneguera–Mogán planèze. a) Conceptual diagram illustrating the angles used in the definition of positive and negative openness (Eqs. (7) and (8), after Yokoyama et al., 2002) used for the Red Relief Image Maps (RRIM; Chiba et al. (2008). b) RIMM for a portion of Gran Canaria including the Veneguera–Mogán visually determined planèze belonging to the Fataga edifice. c) Color diagram showing the correspondence between slope and openness and the RRIM hues: topographic slope is shown as chroma value of red (y axis) and slope as brightness (x axis). d) Scatter plot of openness vs slope at DEM points belonging to superficial remnants of the Fataga edifice; yellow points are the ones classified as QPS (openness from 0 to ~5°, slope from 0 to ~20°). e) Visual verification of the classification results shown in (d). QPS points indeed constitute quasi-planar surfaces within the planèze. f) Hillshaded relief map showing the surface outcrops of the Fataga edifice (green areas) and the QPS points (in yellow).

largely depends on how much the surfaces taken into account are uneroded or even intact. The more likely that a certain elevation data set represents a paleosurface, i.e. the surface really existed at a time, the more reliable is our morphometric reconstruction. In this respect, whereas planèzes might be more or less uneroded (i.e. Fataga volcano), taking all points of a geologic unit (even cropping out at the present surface) may be misleading (i.e. Roque Nublo volcano), since they represent not typically paleosurfaces but any eroded rock deep in the paleovolcano stratigraphy. For this reason, the rate of erosion should also be taken into account (see Section 4.2).

At the same time, using either planèzes (and QPS points in general) or just outcropping points, an indirect argument for the reliability of both paleoedifice reconstruction of Fataga and Roque Nublo is the position of the calculated centers. Namely, the best fitting centers are clustered in agreement with the respective edifices: the centers of the reconstructed Fataga volcano are all located within a circle with a radius of only 600 m (Fig. 3) and, similarly, all centers of the reconstructed Roque Nublo volcano can be found within a circle with a radius of only 700 m (Fig. 4). The Fataga and Roque Nublo clusters of centers are ~2.4 km apart (Fig. 4).

4.1. Fataga volcano

The Middle and Upper Fataga formations occur widespread in the southern flanks of Gran Canaria sometimes in great thickness (Fig. 3). In the central part of the island, the Fataga rocks have been almost completely removed, much has been preserved on the marginal flanks (not to mention some probably buried rocks under Pliocene/Quaternary formations in the north). As shown earlier, there are a number of arguments that the Fataga rocks were related to a central (strato)volcano: the presence of widespread lava flows and debris-avalanche deposits, and the alteration of intrusive rocks possibly related to the infiltration of rainfall from high altitudes (i.e. a large volcano: Donoghue et al., 2010).

However, considering the 3 Ma-long eruptive period of the Fataga Group and, in particular, the ≥2 Ma difference between the age of the rocks that make up the two studied planèzes, there is no question that the Fataga volcano should have consisted of overlapping edifices or volcano clusters. Yet, remarkably, all types of surface fits locate the center of the Fataga rocks at almost a single point, which is 6–7 km northward from the previously suggested Morro de la Cruz Grande, somewhere around Roque Nublo within the present-day Tejeda Caldera (Fig. 2). Notably, the center is offside with respect to the center of the cone sheet dyke swarm (Fig. 3), which may imply a structural/ geomorphological excentricity of the Fataga volcano relative to the feeding system. Alternatively, or in addition, the upper catchment of B. Tejeda, an erosionally enlarged depression that hosts the Fataga cone sheet dykes, may be related to (even inherited from) a late-stage (excentric?) caldera of the Fataga edifice.

We should also consider that the elevation points on which the projected centers are based have different meanings relative to paleosurfaces. Fig. 3 shows the points taken for the geomorphological reconstruction, that is the Fataga Group irrespective of their location relative to original morphology, which certainly results in a poorly defined point cloud (overlying the even older Mogán rocks with lower elevation, cf. Fig. 6). In other words, these regions contain many points inside the original Fataga volcano. On the contrary, when taking into account the QPS points, the elevation range is more confined, proving that they are closer to an original surface. Even better are the QPS points of the planèzes, since, obviously, they display a narrow distribution.

On this basis, we propose that the Fataga planèzes in fact represent the original surfaces of the lower flanks of the paleovolcano, therefore their topographic profiles can be taken reliably for reconstructing its shape. Such an expectation is matched by subjectively selecting two real profiles (see Figs. 3 and 6), starting from the projected center and going across the planèzes. These profiles, despite they show how deep canyons have been incised in the Fataga Group, yet testify that the intense erosion has not or just slightly affected the surface of the planèzes.

We should explain the discrepancy between QPS points and planèzes with respect to their different slope. Even if the QPS selection resulted in a relatively narrow elevation range (see Figs. 3 and 6), the dip of the point cloud defines a gentler slope than that of the planèzes. Such a smaller slope value might reflect that even if these points are arranged now as planar segments, these are not planèzes. The original planèzes have been somewhat eroded, and in this way the present planar fragments are just inherited surfaces from previous planèzes not preserving paleoaltitudes anymore. As a consequence, though these points are close to the original surface, they have undergone significant erosion, and therefore occur at lower (and within this, more diverse) elevations. As the effect of erosion increases with altitude, it is obvious that the QPS areas are converging to planèzes downslope. To summarize, the QPS points scattered within the Fataga Group, even if inherited from planèzes, cannot be used to reconstruct the original volcano shape.

In contrast, as mentioned above, the Veneguera–Mogán and Fataga–Tirajana planèzes represent reliable clue to the paleovolcano, but they correspond to two different stratigraphic units marked by an elevation difference. The Upper Fataga rocks, covering all the area of Fataga-Tirajana as well as the margins of Veneguera-Mogán planèze, show extra thickness of up to 100–200 m relative to Lower Fataga. However, their well-fitted shared center and paleocone surface implies that despite these formations represent two different growth stages, the two resultant geomorphic "envelopes" define one original cone surface.

To determine the paleovolcano shape, the two planèzes have been fitted by regression lines. Assuming a stratovolcano rather than a shield (following Carracedo et al., 2002 and Schmincke and Sumita, 2010), an exponential fit is preferred against a linear fit (Fig. 6), even if the *RMSE* of the two regression is actually the same, 55 m for the linear and 59 m for the exponential fit. However, when constraining the original elevation, the two fitted surfaces do make differences, since the exponential fit points to a 3300 m-high summit, compared to the 2500 m-high summit obtained from the linear fit (Fig. 6).

Such an elevation exceeds any previous estimates. However, one should be cautious, since a regular-shaped stratovolcano with a single summit of high elevation might not have existed (or only for a short time). Rather, as mentioned before, the Fataga volcano could have been a multiple, clustered, or even collapsed, edifice, with a number of successive eruption centers (perhaps small calderas) during its growth. A hypothetical 5 km-large caldera truncating the summit is depicted in Figs. 6 and 8. Nevertheless, the huge dimensions of any 'Fataga Volcano', supporting the expectation of Donoghue et al. (2010), are obvious (Table 1). If we consider only the present-day volume of the Fataga Group (based on the geological map), its upper and lower envelopes – i.e. the maximum volume contained within the point cloud of its dots in Fig. 6c – represent ca. 600 km^3. In order to calculate the original volume, that is, the existing plus eroded rocks of the Fataga volcano, we took the surface of the overlying Mogán rocks, and the reconstructed exponential profile fitted to the planèzes. A volume defined by these two profiles is ≤1000 km^3 (constrained by either exponential or linear fit, Table 1), comparable to the largest stratovolcanic edifices on Earth (e.g. Shiveluch and Etna: cf. Wadge, 1982). However, for the aforementioned reasons, such a volume might have been somewhat less due to the more likely complex morphology of the summit. For example. a hypothetical 5 km-large caldera, shown in Fig. 6, reduces the volume with 25 km^3 (Table 1). In any case, Fig. 8 depicts the ideal conical summit showing the island-wide dimensions of the Fataga volcano.

4.2. Roque Nublo

Compared to Fataga, much more rocks of Roque Nublo have been eroded since the late Pliocene (in the past 3 Ma). However, the high stratigraphic position and, at the same time, the possibly high (2500–3500 m) elevation of the Roque Nublo volcano that has been coupled with the past and recent humid climate on Gran Canaria (cf. Meco et al., 2003) gives explanation for the intense erosion, in addition to significant collapsed volumes missing from the edifice. Compared to Fataga, it should be noted that the preservation of Fataga planèzes is not due to a lower erosion rate, but to the differential erosion affecting the lower volcano flanks.

On Roque Nublo, as mentioned above, only insignificant paleosurfaces have been preserved without planèzes. Therefore, any geomorphological reconstruction can only rely on the outcropping, mosaic-like occurrences of Roque Nublo rocks. At the same time, even

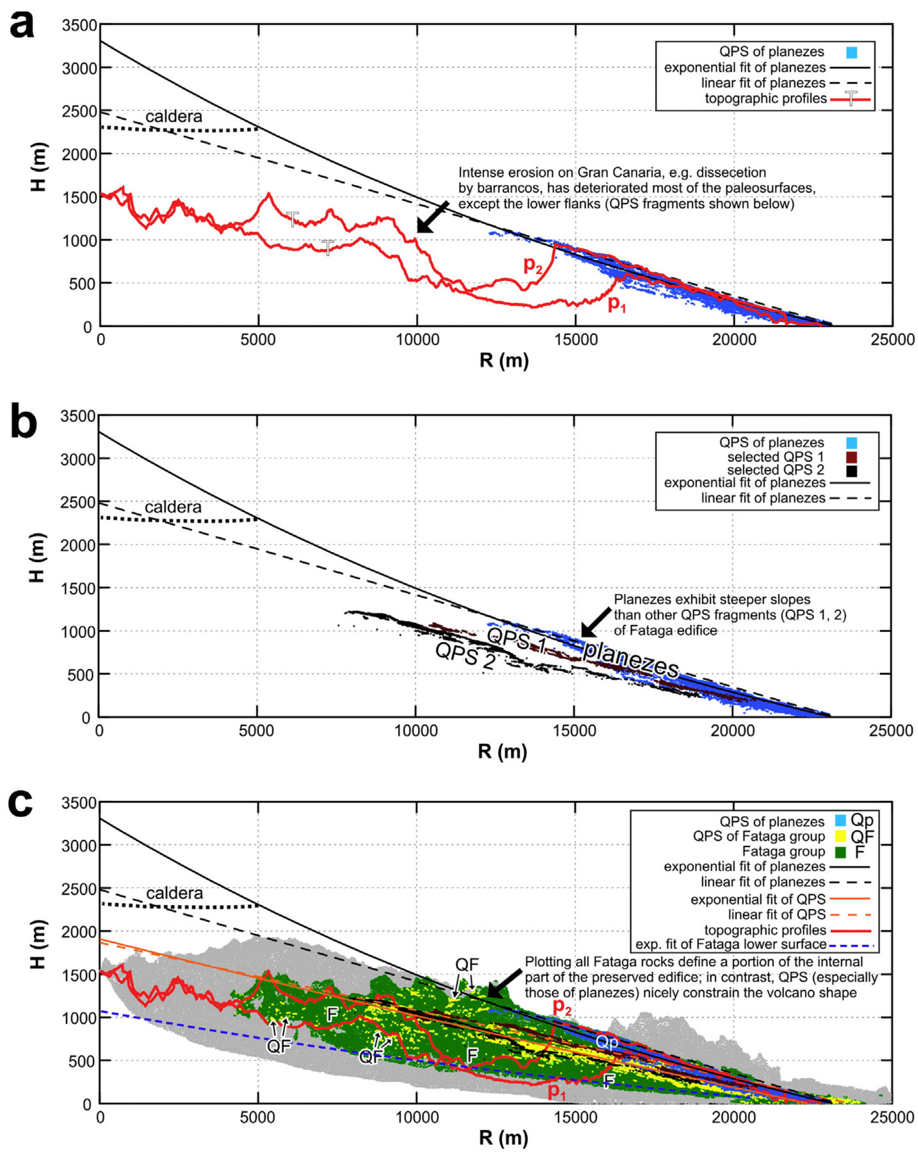

Fig. 6. Reconstruction of the Fataga volcano using surface fitting. a) Best fits of the QPS of the Fataga planèzes; for comparison, topographic profiles in Fig. 3 are shown. b) The same best fits of the QPS of the Fataga planèzes also representing selected QPS areas shown in Fig. 3. c) The same best fits of QPS of the Fataga planèzes and that of the whole Fataga Group. In addition to QPS dots, all surface outrcop points of Fataga Group are indicated, and gray dots mark the surface of the whole Gran Canaria. Topographic profiles as well as selected QPS areas in Fig. 3 are also shown.

if these fragments are eroded, their radial arrangement (Fig. 4) gives an impression at first sight about the center of the volcano, which is verified by using the minimization of surface fit. We note again that the reconstructed center is close to, but not identical with, that of the Fataga volcano (the summit projections are ca. 3 km apart); the new, superimposed Roque Nublo volcano grew up excentrically.

Because the Roque Nublo rocks have been eroded to a smaller or greater extent, fitting the outcropping points – and this way obtaining "paleosurfaces" – does not give the original shape. Therefore, fitting of the present rocks (to a regular shape) can only be considered a minimum estimate; as seen in Fig. 7, the best-fitting surface of Roque Nublo outcrop points gives a shape with a summit altitude of ca. 2900 m. To add a general erosion rate that has affected Roque Nublo since its extinction (ca. 3 Ma), we can benefit from incision rates obtained by Menéndez et al. (2008) via drainage basin analysis using a 1:5000 scale digital map of Gran Canaria. For the past 3.5 Ma, these authors calculated the mean incision amounts of 141 to 211 m, corresponding to erosion rates of an order of ca. 0.1 mm yr^{-1}. Although incision rates cannot be directly converted to erosion rates (the latter could have been smaller), we can consider them as maximum values, their mean being 176 m. We applied this mean value to Roque Nublo in the following way: the elevation of the outcropping points closest to the calculated center were increased with this value, whereas the periphery with half the value, and all area in between proportionally, in order to reflect higher erosion rates at higher elevations. The new "erosionally corrected" exponential curve is shown in Fig. 7. Such an ideal-shaped volcano, ≥3000 m high, may have or may not have existed, and could have been truncated – possibly several times during its growth – by the aforementioned sector collapses, reducing its summit elevation.

On the other hand, when assessing the original altitude, in addition to the applied erosion rates, we cannot rule out that the uppermost cone was even steeper. If the profile of present-day Teide (3718 m) and a highly symmetrical, similar-elevation stratovolcano of Fuji (3776 m), is compared using the SRTM DEM data, the resultant points can also be fitted by an exponential curve. This fit implies an even higher

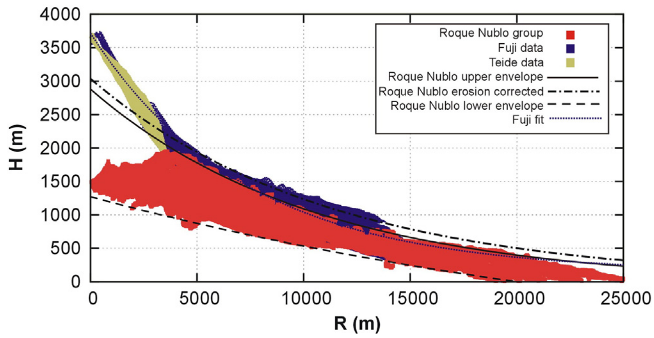

Fig. 7. Height vs radius plot of points of the Roque Nublo Group (with no apparent preserved paleosurfaces) showing the possible reconstruction of the Roque Nublo volcano. The "capping" technique surface fitting is used to find both upper and lower envelopes. Taking erosion into account (termed as "erosionally corrected curve") using data from Menéndez et al. (2008) (see text), increases elevation by ca. 100 m on average. In addition, for evaluating the upper flanks' slopes, profiles of active, similar-sized volcanoes (Teide, Tenerife and Fuji, Honshu) are also shown using SRTM data. For Fuji, surface points were fitted with an exponential profile defined in Eq. (1). *RMSE* for the Fuji fit is 60 m. The apparent similarity of the profile to the "erosionally corrected" Roque Nublo curve makes it likely that the uppermost flanks of Roque Nublo were steeper, reaching elevations as high as 3500 m.

(≥3500 m) summit (Fig. 7). However, we emphasize that this speculation is beyond the "ground truth" of Roque Nublo points. Nevertheless, Fig. 9 depicts a superimposed "Teide-like" cap in addition to the erosionally corrected Roque Nublo paleovolcano as a simple, regular-shaped stratovolcano.

When calculating the paleovolcano volume of the Roque Nublo cone, the volume of the ≥3000 m erosionally corrected cone (Table 1) is constrained by the lower envelope of the underlying Fataga (and other older) rocks (Fig. 7). Surprisingly, the result (943 km^3) far exceeds previous estimates ≤200 km^3. Out of the high value, erosionally removed volume since 3 Ma is 189 km^3. The uncertainty of elevation variations in the 100-m order have little effect: the mentioned upper-cone addition by a Teide- or Fuji-like profile (i.e. 600–700 m elevation increase) yields only ~30 km^3 additional volume (Table 1).

As discussed by many authors, and testified by our reconstruction, the distal products of the Roque Nublo volcano partly filled the lower reaches of paleocanyons existant during its birth, i.e. at the beginning of the Pliocene epoch. After the intense erosion of the Roque Nublo rocks (Fig. 4), the vast majority of the distal volumes have been removed and the remnants of the group occur mostly on ridges, presenting examples of geomorphic inversion.

4.3. Effects of uplift and tilting on volumetry

Several Canarian islands have experienced shorter to longer lived uplift and/or tilt (Acosta et al., 2003; Menéndez et al., 2008). Differential uplift may be due to the combination of isostatic rebound, magmatic underplating and erosional unloading (Menéndez et al., 2008), the latter including repeated sector collapses (e.g. Garcia-Cacho et al.,

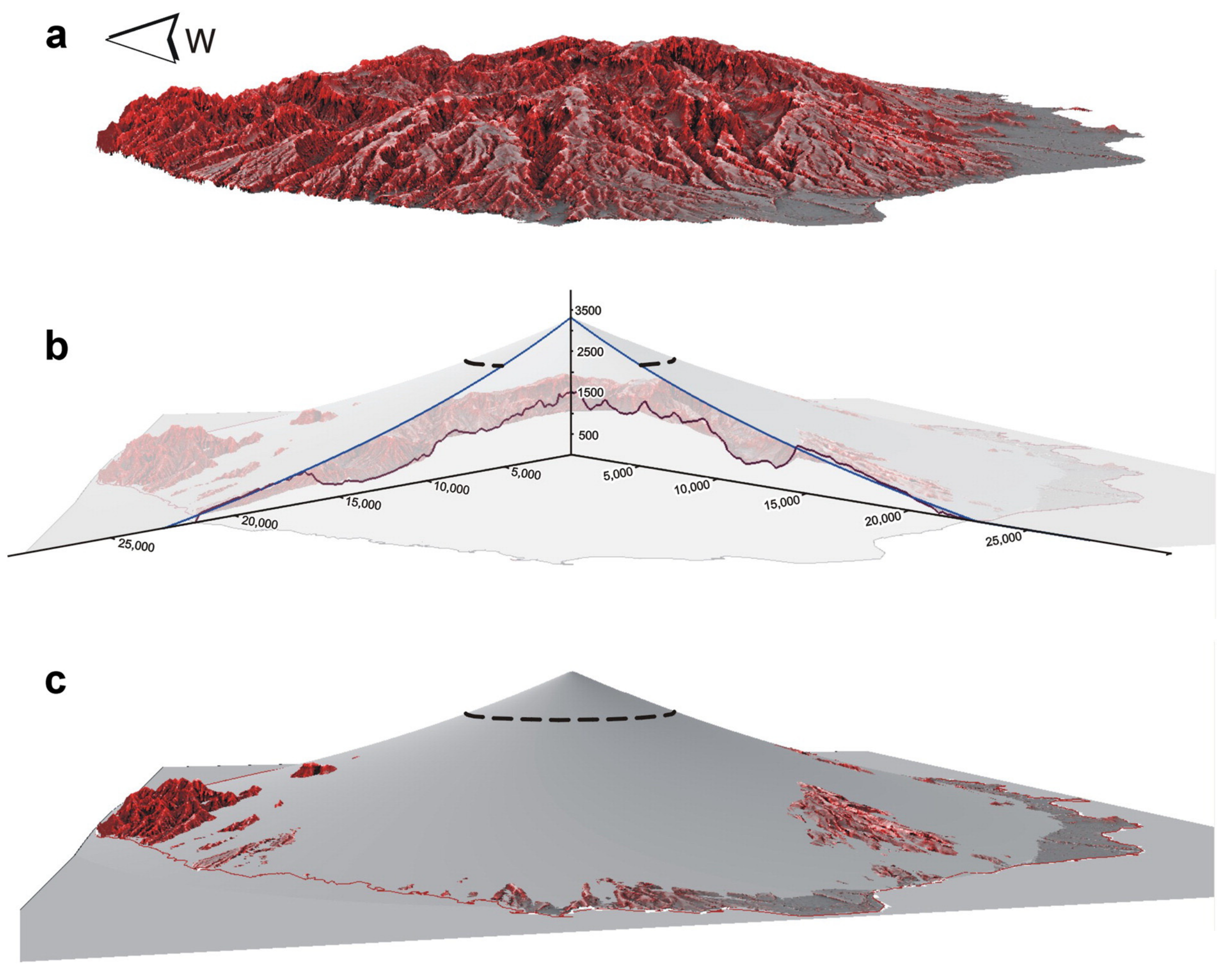

Fig. 8. 3D view of the reconstruction of the Fataga edifice. View is from the S. a) 3D view of the red relief image map (RRIM) of Gran Canaria. b) Section of the best fitting conical surface with an exponential profile overlain on the RRIM. Zigzagging lines inside the island are the two topographic profiles shown in Figs. 3 and 6. c) Hillshaded representation of the best fitting conical surface with an exponential profile. Coast line of present day Gran Canaria is marked; dashed line is the hypothetical 5 km-wide caldera. In the western side, the preserved Horgazales-Güigüí massif of the shield stage forms an outlier.

1994; Funck and Schmincke, 1998; Mehl and Schmincke, 1999; Krastel et al., 2001; Yepes et al., 2013). In particular, at Gran Canaria, lithospheric flexure due to the adjacent Tenerife has resulted in a westward tilt of the island since 4 Ma (Pérez-Torrado et al., 2002).

Obviously, tilting affects paleovolume calculations. However, quantification of tilting is difficult, especially on an island scale; for example, the available data show ca. 50–100 m maximum vertical difference between unevenly uplifted pillow lavas in the W (ca. 40 m a.s.l.) and NE parts (ca. 140 m a.s.l.: Guillou et al., 2004), which is reflected in contrasting uplift rates (between 0.021 to 0.024 mm yr^{-1}, respectively; Menéndez et al., 2008).

Even if these data do not confirm an overall tilting of Gran Canaria, we can calculate how much tilt can be deduced based on the differential uplift and what is its consequence on paleovolume calculations. Assuming an island radius of 22 km, a tilt by 1°, fixing one end of the island, is 768 m. This means that tilting by 100 m adds a very little geometric distortion to the reconstructed cone shape. In numerical details, if one island side is fixed and the opposite side uplifted by 100 m, the extra volume added is 76 km^3, that is, 7.6% of a total island volume of 1000 km^3, roughly corresponding to the Fataga volcano. Nevertheless, such a possible error can be added to the figures given in Table 1.

5. Conclusions

In Gran Canaria, the geometry of presently outcropping geological formations of two successive paleovolcanoes: the Fataga and Roque Nublo edifices has been used for reconstructing the original volcano morphology. Despite deep erosion throughout the island, significant remnants of both volcanoes can be found either as paleosurfaces (planèze remnants and QPS for Fataga) or eroded rocks possibly close to the original surface (for Roque Nublo). The main results of the reconstruction are as follows.

1) The Fataga volcano, which was a composite edifice active between 12.2–8.8 Ma, shows two well-preserved planèze remnants. When restoring the original volcano shape, the QPS of the planèzes define an edifice with 950–980 km^3 volume, which matches that of the largest stratovolcanic complexes on Earth. This figure contains erosion because on what it is based, i.e. planèzes, have only been slightly affected by erosion. If fitted by an exponential profile, the volcano shows an original height of ca. 3300 m; however, in reality the edifice could have been lower (i.e. truncated by a smaller or larger caldera: Fig. 8). Considering that the two planèzes correspond to different eruptive units emplaced with a 1–2 Ma difference, we suggest a complex and less regular summit morphology towering above the lower flanks. Notably, the growth of the Fataga volcano seems to be excentric with respect to the mostly coeval cone sheet dykes, that are exposed in the B. Tejeda erosional depression to the west of the reconstructed center.
2) After a significant erosional gap, Roque Nublo, a shorter-lived volcano (3.7–2.9 Ma), was superimposed somewhat offside with respect to the Fataga rocks. In part, deeply eroded canyons carved in the Fataga rocks served as base level for the volcano. Due to its high elevation, the steep, conical shape, and the prevailing climate, much of the Roque Nublo volcano has been eroded, including the overwhelming majority of paleosurfaces. However, the distribution of its rocks unambiguously points to a simple, conical edifice with a well-defined center. Adding erosion rates effective since 3 Ma (i.e. its extinction), dimensions of an erosionally corrected, reconstructed cone imply a ≥ 3000 m-high volcano (Fig. 9) with up to 50 km diameter and ca. 940 km^3 volume, exceeding previous estimates. Moreover, its summit could have been even higher (cf. present-day Teide), but volumetrically increased with only ~30 km^3.
3) The good fit of regular surfaces to scattered remnants of eroded rocks in Gran Canaria, following the methodology of Favalli et al. (2014), is suggested as a reliable approach to reconstruct original volcanoes worldwide. The precision of the presented, GIS-based procedure, combined with chronostratigraphy and accurate interpretation of paleosurfaces, makes the method a useful tool to resolve uncertainties given by other, qualitative estimations.

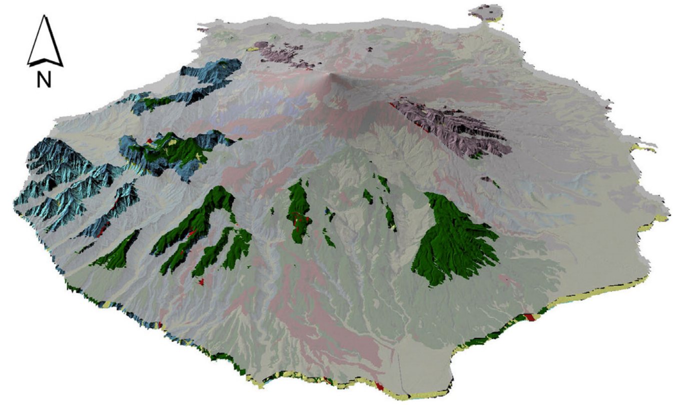

Fig. 9. Reconstruction of Roque Nublo depicted as a 3D oblique view fit.

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