Unique geological values of Mt. Teide as the basis of its inclusion on the World Heritage List

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Abstract

UNESCO created in 1972 the World Heritage List to "preserve the world's superb natural and scenic areas and historic sites for the present and future generations of citizens of the entire world". Nominated sites must be of 'outstanding universal value' and meet stringent selection criteria. Teide National Park (TNP) and the already nominated (1987) Hawaiian Volcanoes National Park (HVNP) correspond to the Ocean Island Basalts (OIB). The main geological elements of TNP include Las Cañadas Caldera, one of the most spectacular, best exposed and accessible volcanic calderas on Earth, two active rifts, and two large felsic stratovolcanoes, Teide and Pico Viejo, rising 3718 m above sea level and around 7500 m above the ocean floor, together forming the third highest volcanic structure in the world after the Mauna Loa and Mauna Kea volcanoes on the island of Hawaii. A different geodynamic setting, causing lower fusion and subsidence rates in Tenerife, lead to longer island life and favoured evolution of magmas and the production of large volumes of differentiated volcanics in Tenerife, scant or absent in Hawaii. This fundamental difference provided a main argument for the inscription of TNP in the World Heritage List because both National Parks complement each other to represent the entire range of products, features and landscapes of oceanic islands. Teide National Park was inscribed in the World Heritage List in 2007 for its natural beauty and its "global importance in providing diverse evidence of the geological processes that underpin the evolution of oceanic islands, these values complementing those of existing volcanic properties on the World Heritage List, such as the Hawaii Volcanoes National Park".

Resumen

La UNESCO aprobó en 1972 la Convención sobre la Protección del Patrimonio Mundial Cultural y Natural con objeto de catalogar, preservar y dar a conocer sitios de importancia cultural o natural excepcional para la herencia común de la humanidad, evitando las duplicidades. Volcanes espectaculares con importantes asociaciones de flora y fauna con abundantes endemismos ya habían sido inscritos con profusión, por lo que la nominación del Parque Nacional del Teide debería fundamentarse por ser uno de los más importantes y característicos conjuntos volcánicos de una isla oceánica. Sin embargo, en este aspecto contaba con el obstáculo inicial de la presencia en la Lista del Patrimonio Mundial (PM) del Parque Nacional de los Volcanes de Hawaii (PNVH), inscrito en 1987 por incluir los volcanes Mauna Loa y Kilauea, los dos volcanes oceánicos más activos y masivos del planeta. Tanto el PNT como el PNVH pertenecen al volcanismo de los Basaltos de Islas Oceánicas (OIB). Notables diferencias en el marco geodinámico de Tenerife y Hawaii en las tasas de fusión parcial y de hundimiento por subsidencia han dado lugar a significativas diferencias en la duración de su desarrollo geológico y en la evolución y diversidad de los correspondientes magmas. En el caso de Hawaii, los magmas apenas han evolucionado, constituyendo un volcanismo espectacular y muy activo, pero monótono por su total predominio de los términos basálticos. En Tenerife, en cambio, un orden de magnitud más antigua, los magmas han contado con suficiente tiempo de residencia, a veces en condiciones mucho más someras, para diferenciarse y abarcar todos los términos de la Serie OIB, incluyendo los más evolucionados (fonolitas), que han generado un complejo volcánico de una extraordinaria diversidad donde predominan las rocas, formas y

estructuras volcánicas de magmas diferenciados sin parecida representación en el PNVH. No se trata pues de dos Parques Nacionales similares y por lo tanto una reiteración a evitar, sino de una evidente complementariedad, de tal modo que la inscripción del PNT aseguraba una completa representación del volcanismo de las islas oceánicas.

Key-words: *Ocean islands, Central felsic volcanoes, OIB series, World Heritage sites.*

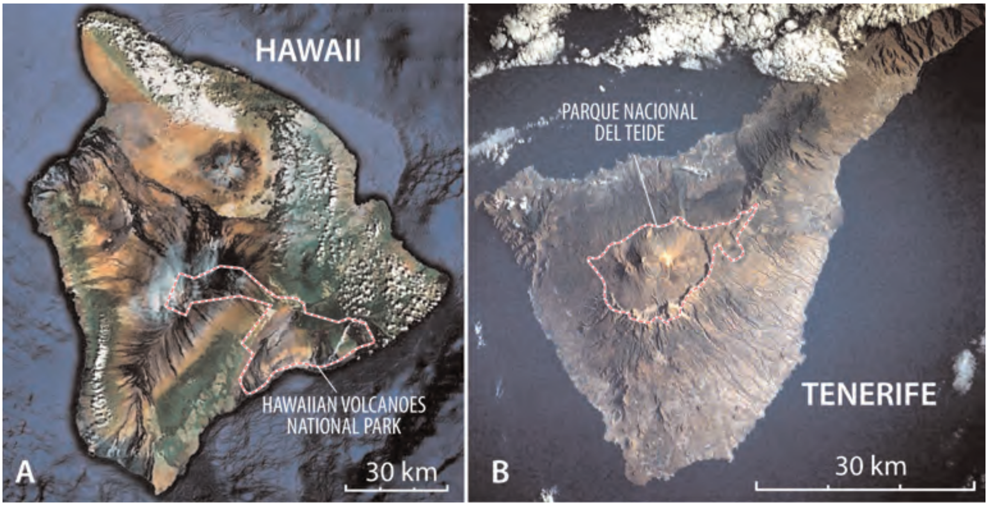

Fig. 1. Satellite images of Hawaii with the limits of the Hawaii Volcanoes National Park, and Tenerife, with Teide National Park in the highest part of the island (images NASA).

1. Introduction

The UNESCO signatory countries created a legal framework within which to register worldwide cultural and natural diversity, and where possible provide funding for protection, restoration and research (1972 Convention on the Protection of Cultural and Natural World Heritage). The objective was not to compile a list of all sites of value but rather to identify what each country selects for protection on the basis of established objective criteria and to ensure also that the country in question would maintain a suitable level of protection in the future.

In summary, with the list of World Heritage Natural Sites, UNESCO aims to catalogue, preserve and disseminate places of exceptional cultural or natural significance for the common benefit of mankind. One of the rules governing this overall objective states that in order to be included on the World Heritage List the site proposed must comply with at least one of the 10 selection criteria (6 of a cultural nature and the 4 remaining relating to natural issues). Moreover, the chosen site must be considered to be exceptional on a worldwide scale in order to avoid duplications since many such places are undoubtedly of interest but are frequently to be found in other countries also, in which case those previously chosen will have preference (e.g. high-mountain endemisms).

A priori, it could be said that TNP presents more than sufficient values to satisfy all four nature-related criteria (scenic, ecological, biological and geological). However, it was soon understood that only the geological values of this unique volcanic formation could compete successfully, since other sites exhibiting similarly spectacular scenery and valuable endemisms in both flora and fauna were already widely represented on the World Heritage List *(Socorro and Pérez-Torrado, 2008).*

Although focused therefore on the geological values, there was yet another significant obstacle to overcome: the inclusion since 1987 of a spectacular volcanic complex, the Hawaii Volcanoes

National Park (HVNP), which includes Mauna Loa and Kilauea, the highest, largest and most active volcanoes on planet Earth *(Fig. 1)*. Both HVNP and TNP are located on oceanic islands and present apparently similar characteristics. Therefore, justification of the unique values of TNP had to be based on the scientifically complex fact of the magmatic diversity existing between both volcanic settings due to their different evolution in distinct geodynamic environments.

Intense research into the geology of the Canary Islands over the past decades and, specifically, the detailed geochronological and petrological study of Teide volcanic complex carried out between 2001-2006, *(Carracedo et al., 2007)* provided the necessary supporting arguments , as discussed below.

2. Teide Volcanic Complex

Teide is a stratovolcano crowning the island of Tenerife, the largest of the Canaries. At 3718 m above sea-level it is the highest point in Spain *(Fig. 2)*. If the height of this volcanic edifice is measured from its base on the ocean floor, at a depth of some 4000 m, Teide is the third highest volcano on Earth, precisely behind only Mauna Loa and Mauna Kea, in the Hawaiian Islands.

Fig. 2. View from the NE of the Teide volcano topping the island of Tenerife.

From a wider viewpoint, Teide is not only the present culmination of the island of Tenerife but of a much longer process involving the formation of the island chain that makes up the Canary Volcanic Province.

2.1. Teide in the evolution of the Canary Volcanic Province

Although the origin of the Canaries has been associated with diverse processes (e.g. African tectonics, block dynamics), the near-general consensus associates the islands with a mantle anomaly, similar to that of Madeira and Cape Verde.

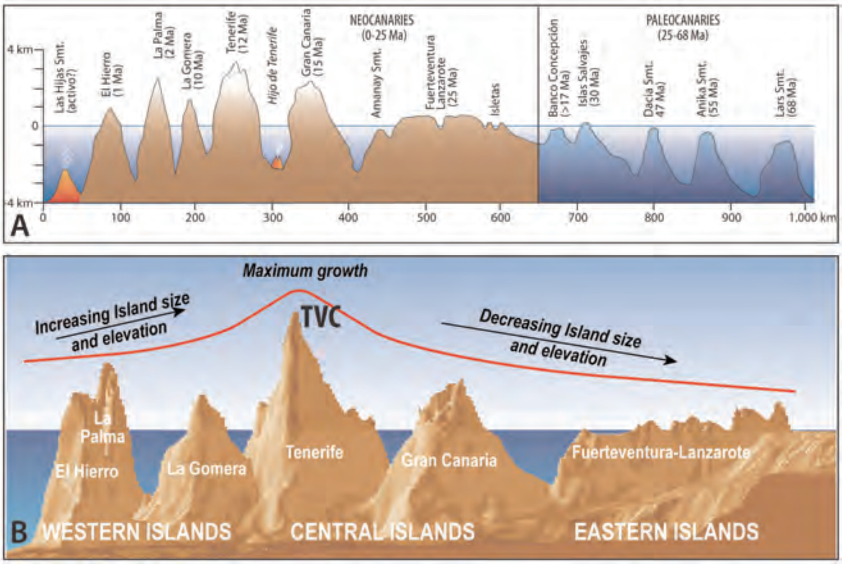

Fig. 3.- A. Schematic diagram showing the age progressive chain of islands and seamounts that forms the Canary Volcanic Province (ages from Geldmacher et al. 2001; Guillou et al. 2004a, b). B. Computer-generated cross section of the Canary Islands, showing age versus height. At present, Tenerife represents the peak of evolutionary development in the Canarian archipelago (Carracedo et al. 1998)

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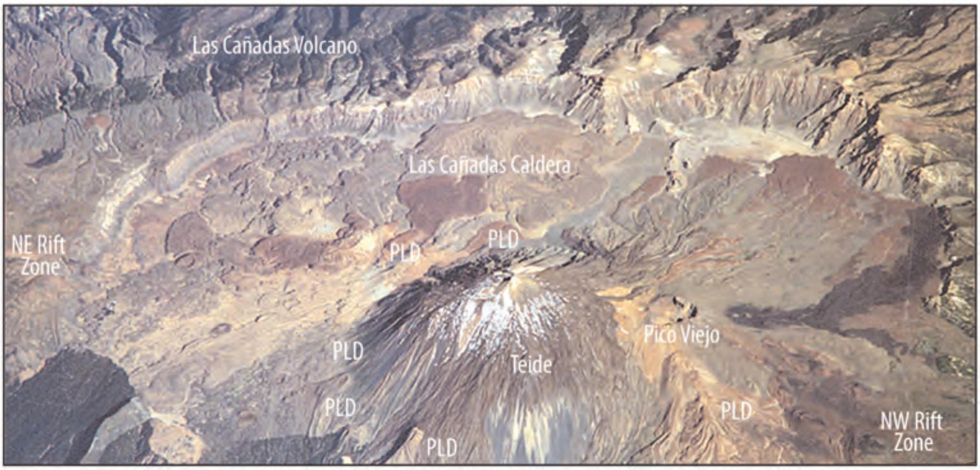

Fig. 4. NASA International Space Station photo from 339 km altitude showing the main components of the Teide Volcanic Complex. PLD: Peripheral Lava Dome.

This very long-lasting anomaly has been considered to be the cause of the alignment of oceanic volcanoes that begins with the Lars seamount, dated at 68 Ma *(Geldmacher et al., 2005)* and reaches the most recently formed island of El Hierro. This alignment forms the Canary Volcanic Province (CVP), a good part of which is now submerged *(Fig. 3A)*.

In the emerged part of the CVP it is evident– and in agreement with the radiometric ages obtained– that Tenerife, which occupies a central position, is also the most developed island, currently among those that have not yet attained their maximum development and those that, having passed this stage, are now in the dismantling stage due to erosion *(Carracedo et al., 1999; Schmincke, 1982)*.

Finally, the TVC is, within the island of Tenerife, the culmination of its development until present *(Fig. 3B)*. UNESCO criterion viii for the inscription of a site confers extraordinary relevance to "the representative examples of processes underway that involve important stages in the history of the Earth", in this case the development and culmination of one of the main volcanic provinces of oceanic islands of the planet, where the TVC undoubtedly offers a unique consideration.

2.2. Elements of Teide Volcanic Complex

From the geological point of view, Teide stratovolcano is only a part of a much wider system: the Teide Volcanic Complex (TVC), which includes moreover another central overlapping edifice (Pico Viejo) and a group of peripheral domes *(Fig. 4)*. It would not be feasible to separate this group of eruptions resulting from the oldest central volcanism of Tenerife (Las Cañadas Volcano), were the entire TVC not defined by an isochron: the lateral landslide that gave place

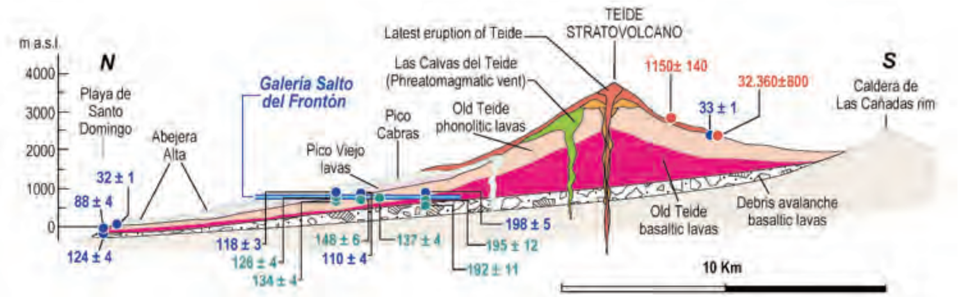

Fig. 5. North-South cross section of the Caldera de Las Cañadas and the nested Teide Volcanic Complex. The galería Salto del Frontón is shown penetrating the entire postcollapse sequence, showing the composition and age of the volcanic formations filling the collapse embayment. The deepest part of the section, from ~3400 m, was not suitable for dating because of the high degree of alteration.

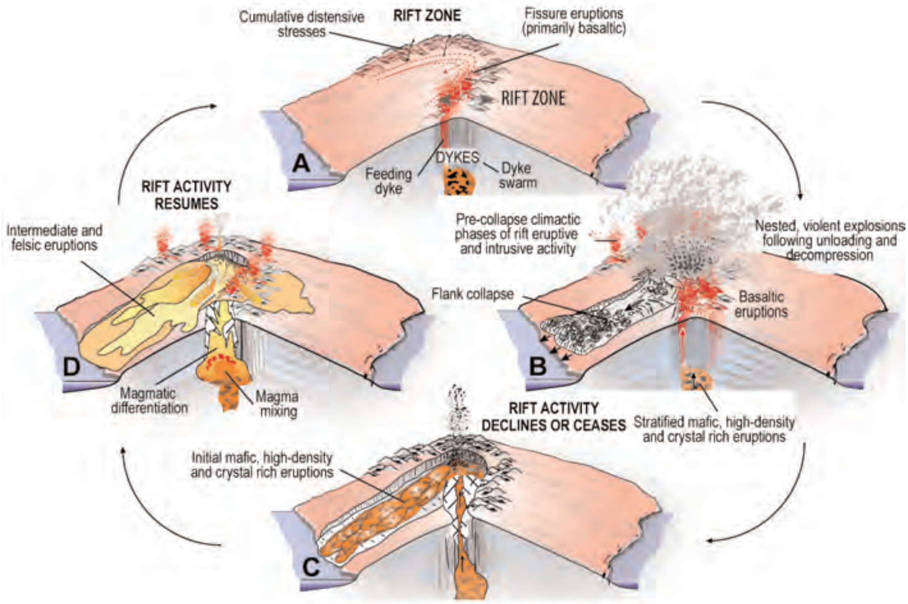

Fig. 6. Schematic model of Canary Island rift evolution. Note that the rift evolution proceeds until high intrusive activity causes flank collapses to occur. Following such a catastrophic collapse, the plumbing system needs to readjust, leading to structural and petrologic modifications. The behaviour of similar rifts on different islands of the Canarian Archipelago, some of which have completed their cycle of activity, suggests that the TVC may have reached a terminal stage in the Holocene epoch, reaching the final stages of one of these cycles (after Carracedo et al. 2011).

200-180 ka ago to the Caldera de Las Cañadas *(Ancochea et al., 1999; Martí et al., 1994)*, within which the Teide volcanic complex grew nested *(Carracedo et al., 2013)*. On the other hand, it is likewise impossible to dissociate clearly this central felsic complex from the basic fissural eruptions of the NW and NE Rift Zones, with which it establishes a bimodal series where a gradual compositional variation exists rather than a clear separation.

The central stratovolcanoes

Teide stratovolcano may be a unique example of the formation of an central oceanic volcano as the result of a giant landslide. The obtained radiometric ages *(Fig. 5)*, both at outcrops and in the interior of underground water tunnels excavated to exploit the central aquifer, and by using diverse methods (^{14}C, $^{40}Ar/^{39}Ar$, $^{40}Ar/^{39}Ar$), have led to the reconstruction of the filling-in stages of the landslide basin to the building of present-day Teide *(Carracedo et al., 2007, 2013)*.

Felsic stratovolcanoes associated with hotspots abound in areas of continental crust where the ascending magma melts a part of that crust, giving place to felsic magmas. However, this circumstance is not fulfilled at hotspots, acting on oceanic crust, and therefore felsic magmas are scarce and derive from differentiation processes. However, stratovolcanoes such as Teide do not exist in Hawaii *(Carracedo, 1999)*, but why does one occur in Tenerife, likewise located on oceanic crust? Several factors may determine these differences. The Hawaiian hotspot is much more fertile than the Canarian *(Walker, 1990)*, quickly building large insular edifices that, because of their weight upon a thin flexible oceanic crust, sink in a few million years due to subsidence. This is the reason why the oldest of the emerged Hawaiian Islands (Kauai) is only about 6 Ma old *(Clague and Dalrymple, 1987)*, contrasting with more than 20 Ma for Fuerteventura.

In reality the island of Hawaii grows so fast because its eruptions are practically continuous, although subsidence compensates and surpasses this growth, the emerged stage of these islands thus being comparatively much shorter. The Canaries, on the contrary, situated over older and thicker crust and in close proximity to the African continent, scarcely undergo subsi-

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dence, remaining emerged for much longer periods (Tenerife is at least 12 Ma old). This longer volcanic history, with longer periods between eruptions (greater residence time of the magmas), favour magmatic differentiation processes, such as those that have given place to the formation of Teide *(Ablay and Martí, 2000; Carracedo et al., 2013; Wiesmaier et al., 2013)*.

Other factors that may contribute to the formation of these oceanic stratovolcanoes are massive landslides in response to the progressive instability due to increase in height of the volcanoes. On an island, the sudden collapse of a flank *(A and B in Fig. 6)* implies arresting the feeding system *(C in Fig. 6)*, which favours the ascent and shallow emplacement of the magma and concentration of eruptions within the collapse basin. The emplacement of magma at shallower levels and long residence periods favour magmatic differentiation *(D in Fig. 6)*, and thus the volcano that develops nested within the collapse basin evolves from initial basaltic emissions towards intermediate and differentiated terms *(see Fig. 5)*. The "density filter" originated as the height of the nested stratovolcano increases reinforces this trend *(Davidson and De Silva, 2000)*. Taking into account that basaltic magmas are much heavier than the differentiated equivalents, the excess pressure (Pex) required for the magma to ascend to the emission centre compensating the lithostatic pressure of the magma (P) increases with the altitude of the latter *(Fig. 7-1)*, while the lateral pressure of the magma increases at the base of the volcano. On reaching a critical altitude, estimated empirically at about 3000 m *(Fig. 7-2)*, the lateral pressure forces the formation of radial fractures and, eventually, the intrusion of cryptodomes *(Fig. 7-3)* and the eruption of lava domes *(Fig. 7-2)*.

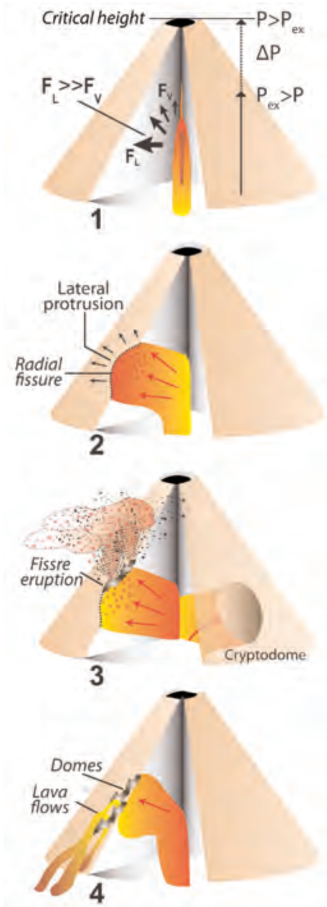
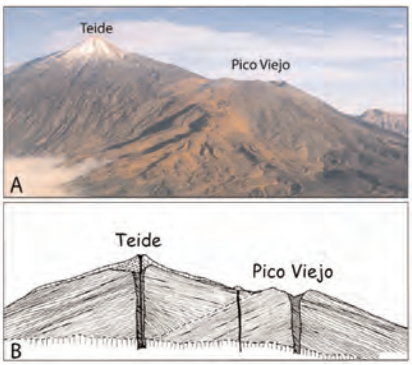


Fig. 7. Schematic diagram showing the relationship between the increasing lithostatic pressure of a growing stratocone (e.g. Teide Volcano) and the magmatic overpressure required for the magma to ascend to the summit of the volcano. 1 When the critical height is reached, the vertical push of magma is changed to lateral. 2 Bulging may result in radial dykes and related radial fissures. 3 Eventually, evolved fissure eruptions from radial fractures begin, with initial explosive phases. 4 Finally, effusive phases produce thick evolved (phonolitic) lava flows and coulées.



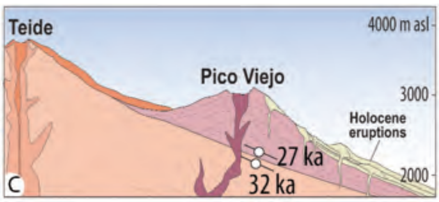


Fig. 8. A. Teide and Pico Viejo (PV) composite volcanoes topping the island of Tenerife with heights of 3718 m and 3100 m asl. In the foreground the Roques Blancos parasitic lava dome and thick phonolitic coulées. B. These central stratocones have been considered to be twin volcanoes, with the Teide edifice overlapping Pico Viejo (figure from Fúster et al., 1968). C. Volcanic stratigraphy based on new 14C and K/Ar ages dating the T-PV volcano shows Pico Viejo to be a parasitic stratocone, apparently developed after the Teide stratocone was already at its terminal phase (Carracedo et al., 2007).

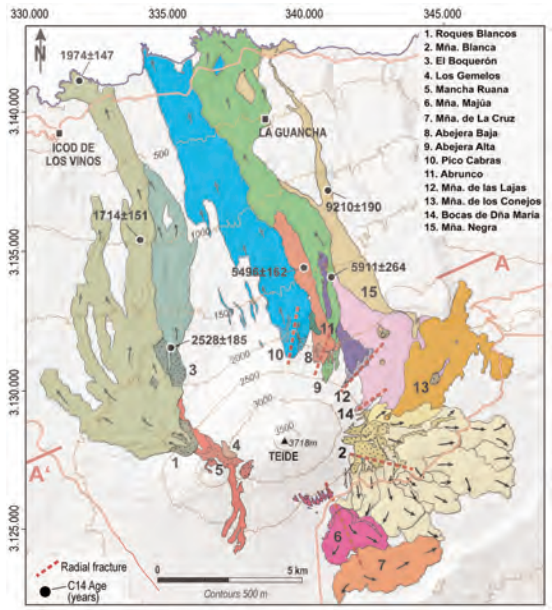


Fig. 9. Phonolitic lava domes of the T-PV volcanic complex. Ages (14C) in years B.P. (Carracedo et al., 2007).

The heavier basaltic lava is the first to fail to reach the volcano summit, favouring the emission of the lighter, more differentiated lava. An efficient density filter is thus established, explaining Teide's evolution *(see Fig. 5)*.

Pico Viejo volcano formed attached to Teide's west flank, possibly when the latter had surpassed the critical height *(Fig. 8A)*. Pico Viejo initially repeats the pattern of emission of basaltic lava, and subsequently intermediate and differentiated lavas (phonolites). Although it had been assumed that Pico Viejo was earlier than Teide *(Fúster et al., 1968, Fig. 8B)*, field observations and radiometric ages indicate the contrary *(Fig. 8 C)*.

Peripheral domes

The group of phonolitic domes surrounding the base of Teide are highly spectacular and unique volcanic structures. The greater part of those that outcrop have been dated in the Holocene *(Fig. 9)*.

A noteworthy characteristic of these features is their extraordinary length of the lava flows despite their phonolitic composition *(Balcells y Hernández Pacheco, 1989)*. The lava flow domes emplaced in subhorizontal areas (e.g., in the interior of the Caldera de Las Cañadas, *Figs. 9 and 10A)* form thick, short, typically flat-topped and roughly circular lava flows, accumulated around the emission centre (tortas in volcanological terminology). Domes located on a slope give rise to lava flows that run over very long distances (coulées), generally reaching the coast some >15 km distant *(Fig. 10B)*. A solidified outer lava crust appears to be a mechanism contributing to keep the lava thermally isolated and may explain the fact that TVC phonolitic lavas can travel over the same long distances as the much more fluid basaltic lavas.

Rift zones

Although the TVC is situated at the junction of a triple rift system (NW, NE and S), the greater part of eruptive activity that occurred after the collapse of the Caldera de Las Cañadas took place in the first two, particularly in the NW rift *(Fig. 11)*. The

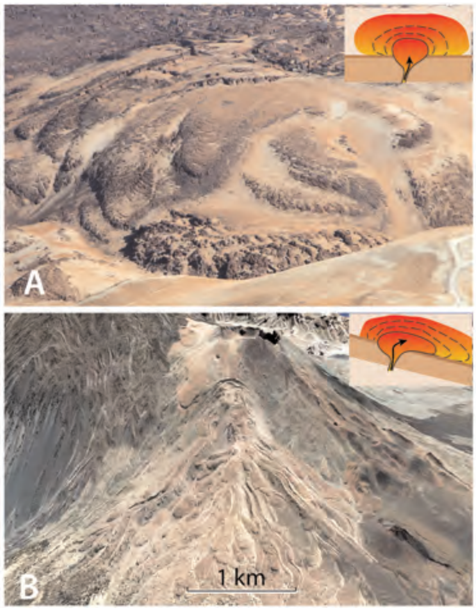


Fig. 10. A. Montaña Rajada, phonolitic lava dome (torta) formed on a flat ground (the floor of Las Cañadas Caldera), with the characteristic external structure "in rosette". B. The Roques Blancos lava dome, built on the steep flank of Pico Viejo, emitted phonolitic coulées that reached the northern coast, about 15 km distant. Notice the pressure ridges, perpendicular to the direction of flow, and the convex ogives.

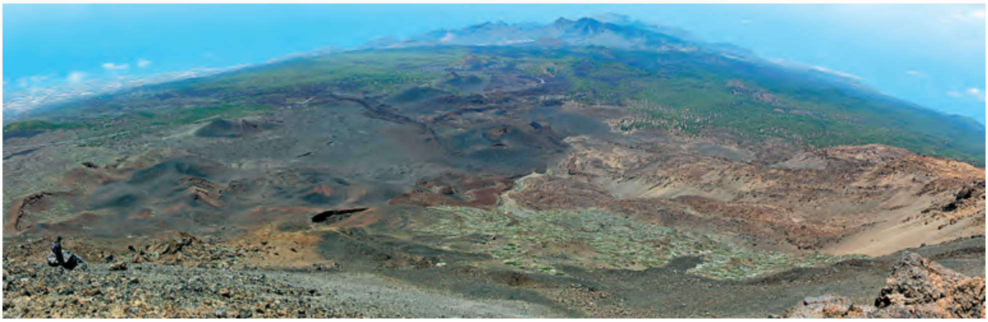


Fig. 11. View of the NW rift zone from PV summit, with the Teno Miocene shield in the background.

Holocene eruptions and all historic (<500 years) events were concentrated in this rift with the exception of the 1705 Arafo-Fasnia-Siete Fuentes eruption.

If the distribution and composition of the eruptions that took place in this NW rift during the Holocene are observed it can be seen that at the distal end with respect to the central volcanoes the eruptions are basaltic, intermediate in composition in the central section of the rift, and phonolitic close to and within the central complex *(Fig. 12)*. This indicates a bimodal distribution that functions due to interaction of a surficial chamber in which the magma have differentiate and give way to the central phonolitic stratovolcanoes, with basaltic magma feeding simultaneous eruptions in the NW rift. This bimodal distribution has characterised volcanism in Tenerife over the past several thousands of years and will very probably continue to do so in the future *(Ablay and Martí, 2000; Wiesmaier et al., 2012, 2013)*.

Recent research shows that the area of distribution of the phonolitic eruptions in this Teide volcanic system has been decreasing in extent over the last few thousand years *(Fig.12)*, which appears to be in concordance with a terminal cycle in which the differentiated magma chamber contracts and cools *(Carracedo et al., 2004)*, although it could be reactivated by an injection of magma from depth.

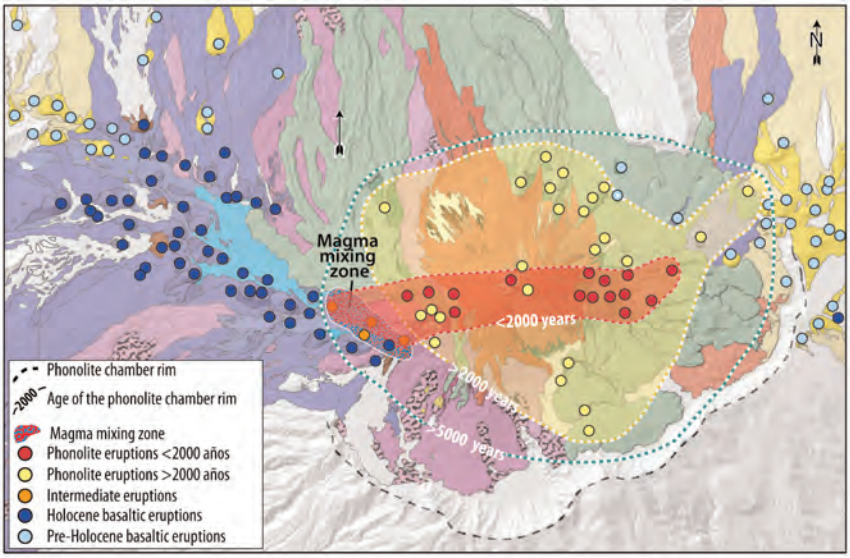


Fig. 12. Bimodal distribution of the composition of lavas in eruptions produced along the active NW and NE rifts. The greatest concentration of highly evolved eruptions (phonolites) occurs in the area where the rifts converge, where the Teide–Pico Viejo stratovolcanoes and their peripheral domes formed. In contrast, less evolved magmas (basaltic, basanitic) erupted at the distal ends of the rifts. Intermediate composition lavas and magma mixing (basaltic–phonolitic) occur at the centre of the rifts. Note the reduction in size of the phonolitic chamber in the last 5000 years (from Carracedo et al., 2004).

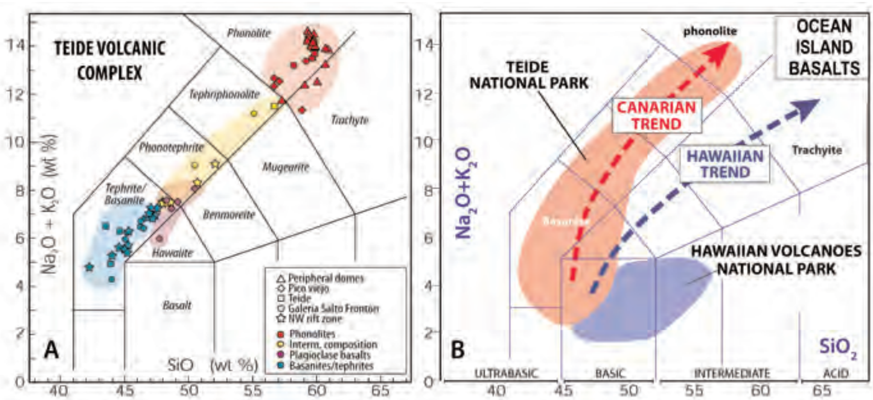


Fig. 13. Basic argument demonstrating that Mt Teide is an exceptional volcano, and how the Teide National Park could complement the Hawaiian Volcanoes National Park in representing ocean volcanoes on the World Heritage List. As shown in the TAS diagram, because of geodynamic differences in the development of both islands, the HVNP comprises only mafic lavas, while the TNP includes all terms in the magmatic variation trend, from mafic to very evolved phonolites. These differences are reflected in the types of volcanism in both archipelagos, and thus in the variety of their respective volcanic forms, structures and landscapes.

Indeed, observing *Fig. 12* it can be seen that the phonolitic eruptions of the last 2000 years appear to occur only at the proximal parts of the NW and NE rifts, closer to the central system.

3. Magmatic diversity at the Teide Volcanic Complex

The dual magma feeding systems, one deep and primitive that feeds the rifts, and the other surficial and differentiated associated with the central system, explain the fact that the entire series of alkaline basalts is represented in the TVC *(Fig. 13)*.

In turn, this wide range of magmas has its correlation in an extraordinary diversity of eruptive products, structures and mechanisms,

Representation of the volcanic products and features of the Oceanic Island Basalts (OIB) magmatic series in Teide and Hawaii National Parks

Type of magma (OIB magmatic series)	Volcanics rocks	Volcanics features		Parque Nacional del Teide	Hawaii Volcanoes National Park
INITIAL TERMS	Tholeiites BasanieEs Basalts	Lava flows and related features	*aa*	YES (abundant)	YES (abundant)
			pahoehoe	YES	YES (abundant)
			lava tubes and channels	YES	YES (abundant)
			lava lakes	YES	YES (abundant)
		Pyroclasts	*lapilli and scoria beds*	YES (abundant)	YES (abundant)
		Volcanic cones	*lapilli and scoria (Strombolian) cones*	YES (abundant)	YES (abundant)
			phreatomagmatic tuff- rings and maars	YES	Present
INTERMEDIATE AND MAGMA MIXING	Trachybasalts Tephrites Hawaiites, etc.	Lava flows and related features	*lava flows, lava tubes, lava lakes, etc.*	YES	NO
		Pyroclasts	*lapilli and scoria beds*	YES	NO
		Volcanic cones	*lapilli and scoria (Strombolian) cones*	YES	NO
		Magma mixing	*intermediate and evolved lavas in a single eruption*	YES	NO
FELSIC TERMS	Phonolites Benmoreites Trachytes	Lava flows and related features	*lava flows, lava tubes, lava lakes, etc.*	YES	NO
		Pyroclasts	*phonolitic pumice and scoria beds*	YES	NO
			alternating layers of basaltic lapilli and phonolitic pumice	YES	NO
		Volcanic cones	*phonolitic pumice and scoria cones*	YES	NO
			phonolitic domes and lava domes	YES	NO
			phonolitic stratocones	YES	NO

Fig. 14. A simple example to illustrate the complementariness of TNP and the Hawaiian Volcanoes National Park is the comparison with two unique picture galleries, one devoted to the Old Masters and the other to Modern Art. Both would be equally necessary to represent universal art, which could not be achieved independently.

giving place to a true natural laboratory of this type of oceanic volcanism *(Rodríguez-Badiola et al., 2006; Pérez-Torrado et al., 2013)*.

A great difference can be observed between the volcanic diversity at Teide and that existing in the Hawaii Volcanoes National Park since only basaltic magmas exist in the latter, differentiated terms being absent *(Fig. 14)*.

4. TNP as a complement of HVNP

The ideas expressed lead to the clear conclusion that there exists a significant number of volcanic features and products, those that are related to intermediate and differentiated magmas, that are not present in the HVNP but are to be found in TNP *(Table 1)*. Thus, only the joint presence of both National Parks achieves a complete and unsurpassable representation of oceanic islands volcanism, readily justifying the inclusion of TNP on the World Heritage List of Natural Sites.

A comparison that proved to be useful in explaining these fundamentally petrological and volcanological arguments to the general public was that both National Parks are like two museums, one of which displays only the works of Old Masters and Modern Art, while the other contains Contemporary Art *(Fig. 14)*. It is obvious that Universal Art would only be adequately represented by the sum of the collections of both museums.

5. Conclusions

Both oceanic archipelagos of reference, the Hawaiian Islands and the Canary Islands, have played a transcendental role in the development of Volcanology and knowledge of oceanic volcano evolution. In the former field of study the island of Hawaii is the more noteworthy, having practically permanent eruptive activity for the last 400 ka, and the Hawaii Volcanoes National Park, with its extraordinary representation of the basaltic volcanism of shield development stages, inscribed in 1987 as a UNESCO World Heritage asset.

Teide National Park covers a volcanic complex formed in the last 200 ka and comprised of basaltic rifts and a central system of differentiated stratovolcanoes.

The UNESCO policy of not repeating properties of similar characteristics (in this case, oceanic volcanoes) implied a serious obstacle to achieving the inscription of TNP, despite its spectacular geological values, especially the forms and structures characteristic of the volcanism of differentiated magmas of the Teide Volcanic Complex.

However, the apparent difficulty turn out to be a crucial opportunity because the absence of differentiated volcanism in the HVNP, contrarily to what occurs in the Teide National Park, strengthened the inscription application of the TNP based on its complementariness, since only with both National Parks the World Heritage achieved a complete representation of oceanic island volcanism.

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