From "Vent" to "Volcanic Field" and "Volcanic Province": Pivotal terms in volcanology that require formal definitions

De "fuente eruptiva" a "campo volcánico" y "provincia volcánica": Términos fundamentales en volcanología que requieren definiciones formales

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ABSTRACT

Precise definitions of concepts facilitate systematization of knowledge, its logical analysis and favor understanding of complex processes. Several pivotal terms in volcanology, such as "vent", "volcano", "volcano field" and "volcanic province", among others, however, remain ill-defined. This work addresses various ambiguities associated with these and other related terms. Although evidently those terms are geologic in nature, it may be convenient to take into consideration some non-geologic criteria to reach less ambiguous, and quantifiable definitions. The evidence presented in this work shows that there is a continuum of structures at various spatial scales and that ambiguities between terms can be removed for the most part, by adopting a set of operational definitions that incorporate non-strictly geological, yet quantifiable criteria. Thus, "Vents" and "Volcanoes" can be distinguished from each other using as a reference three quantifiable measurements (the diameters of two objects and a distance between their centers). Also, they can be distinguished by their belonging to either a "vent field" or a "volcano field", which can be distinguished by reference to a threshold density of ~ 2.5 x10^{-7} structures / m^2, with vent fields having the largest density values. Other terms discussed in the text are "Region", "Province", "Group", "Cluster" and "Complex". Suggested definitions are "Region": a group of nearby provinces, arcs or groups of volcanoes; "Province" denotes a magmatic affinity observed over a large territorial extension (yet smaller than a region). "Group" and "Cluster" denote spatial proximity and their definition depends on a distance used as reference. If the group or cluster also displays magmatic or genetic affinity, then it can be addressed as a volcano complex.

Keywords: volcanology, definitions in science, volcanic field, volcanic province.

RESUMEN

Las definiciones precisas en el ámbito científico facilitan la sistematización del conocimiento, el análisis lógico y favorecen la comprensión de procesos complejos. A pesar de esto, términos fundamentales como "fuente eruptiva", "volcán", "campo volcánico" y "provincia volcánica" no se han definido de manera rigurosa. Este trabajo hace patente varias de las ambigüedades asociadas con esos y otros términos igualmente fundamentales. También se revisan diferentes tipos de evidencia que sugieren que hay un continuo de estructuras volcánicas a través de diferentes escalas espaciales, así como que muchas de las ambigüedades en las definiciones se pueden evitar si se adoptan algunas definiciones operacionales. "Fuente eruptiva" y "Volcán" se pueden distinguir entre sí usando como referencia una medida de distancia y algunas reglas que cuantifican relaciones entre tres cantidades (los diámetros de dos objetos y una distancia entre sus centros). También pueden distinguirse por su pertenencia a un "campo de centros eruptivos" o a un "campo de volcanes", estos últimos siendo distinguibles en base a un umbral de densidad dado por 2.5 x 10-7 estructuras /m2, siendo los campos de centros eruptivos los que tiene mayor densidad. Una "región" puede definirse como un grupo de provincias, arcos o "grupos de volcanes"; "provincia" denota afinidad magmática en una extensión territorial grande (pero de menor tamaño que una "región". "Grupo" y "Cúmulo" denotan proximidad espacial, y su definición depende de la distancia usada como referencia en cada caso. Si el grupo o cúmulo de volcanes presenta afinidad magmática se debe referir como un complejo volcánico.

Palabras clave: volcanología, definiciones en ciencia, campo volcánico, provincia volcánica.

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1. Introduction

This is a perspective/forum article. As such, it presents the personal opinion of the author more evidently than a traditional research paper. Motivation for this paper are comments received over the years, most in anonymous form (more than a few in a rather unfriendly tone), as well as by discussions held over several scientific meetings, all of which show that the lack of precise definitions of pivotal terms in volcanology somehow hampers our understanding of the possible relations that might exist between volcanic constructs and the rest of the physical world that surrounds them. Having explained the motivation, I now explain the purpose of this paper: stimulate broader discussions that could be used to guide a future official definition of a few terms.

Adopting a proactive attitude, I present tentative definitions that are based on quantifiable criteria for the most part. Whether those definitions are later included in an official definition, if the latter is ever issued, is something that the community will decide. Meanwhile, it is worth noting that the definitions proposed in this work are based on my personal experiences as a researcher, and therefore are biased towards those specific examples. Nevertheless, the general definitions presented here are mostly based on quantifiable criteria that are relevant for the intended purposes.

The work is organized as follows. Section 2 presents some thoughts concerning the importance of precise definitions in science, and illustrates that importance with the case of the definition of a planet. Section 2 ends by providing some examples of ill-defined terms in a volcanological context. Sections 3 to 7 present tentative definitions of various terms, each accompanied by the rationale leading to the proposed definition, some examples of applicability, and perceived caveats. Section 8 presents a summary and conclusions.

2. The role of definitions in science

2.1. WHAT IS A GOOD DEFINITION?

Precise definitions of concepts is necessary in all scientific disciplines, as they facilitate the achievement of systematic knowledge that can be analyzed in logical terms (Cohen and Nagel, 1955). Nevertheless, formulating a precise, quantitative definition is not always a simple task. Difficulties arise, among other things, because there are different kinds of definitions, each type having different functions within the structure of science (Caws, 1959). Furthermore, even if attention is focused only on the classic, Aristotelian mode of definition, where things are separated according to their genus and differentia (similarities and differences), it might be challenging to obtain entirely satisfactory definitions of a few terms within specific branches of science due to ambiguities embedded in the everyday language.

Regardless of the function played within the scientific structure, a satisfactory definition must isolate the essence of the thing being defined, separating it from everything else in the observable universe. In so doing, the definition must not be circular and must avoid obscure and figurative language (Cohen and Nagel, 1955). If those characteristics are not fulfilled, then the term can be said to be ill-defined.

Another aspect to consider is that definitions of pivotal terms ideally should be accepted by all practitioners of a given scientific discipline. This is probably the most difficult characteristic to achieve. As pointed out by Davies (2022), the evolution of ideas is analogous to the colonizer effect in island ecosystems in which the first organisms to reach a new island establish themselves and develop without interference, whereas later organisms have more difficulties developing because they have to compete with the organisms already present on that island. The definition of the concept of a "planet" described next is illustrative in this respect.

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2.2. A RECENT EXAMPLE: THE DEFINITION OF A "PLANET"

Unanimous acceptance of a scientific definition may be difficult to be achieved, as illustrated by the current official definition of a "planet". That definition was adopted through a voting process during the closing ceremony of the 2006 general assembly of the International Astronomical Union. A good summary of the entire process can be found on the Wikipedia article (https://en.wikipedia.org/wiki/IAU_definition_of_planet, retrieved on 06/15/25), where links to archived reports and press releases are available. The following short account draws freely from those documents.

Deliberations on an official definition of a "planet" had started two years earlier within a committee of seven individuals who examined the issue from different perspectives (astronomical, geophysical, historical, social). The definition prepared by that committee was modified during the week of the general assembly, where it is reported that several informal meetings took place. During those informal meetings many more individuals than the seven members of the committee appointed for the elaboration of an official definition were involved. As a result, the definition of a planet that was submitted to vote during the closing ceremony of the general assembly was not that of the original committee, but one produced during the informal meetings. That revised definition was approved with a great majority of votes. Nevertheless, and despite the participation of many members of the scientific community, the definition approved on that assembly was not accepted by many scientists. Some presented arguments asking modifications of the official definition, to no avail; others even expressed their determination of not adopting it in their future publications.

Even when there are numerous opposing opinions, the official definition of a planet adopted by the IAU at its 2006 general assembly still prevails. That definition is routinely used without paying much attention to the few formal issues that sometimes may require a slight departure in specific contexts. In any case, the official definition is accepted by a large proportion of practitioners in that branch of science, and serves as a common point of reference upon which specific issues can be assessed. Such definition is also referred to in texts of a less technical nature that are read by the population at large.

2.3. WHAT TERMS NEED MORE PRECISE DEFINITIONS IN VOLCANOLOGY?

Turning attention to the context of the study of volcanoes and their activity, terms such as "volcano", "vent", "volcanic field" and "volcanic province" do not satisfy the desirable characteristics of a good definition, and therefore are ill-defined. For example, both "volcanoes" and "vents" tend to be defined as the places on Earth where magma, lava flows, and other products erupted. Those two words are also often defined in terms of each other. As an example, take the definition from the USGS web-page about the nature of volcanoes: "The term volcano also refers to the opening or vent through which the molten rock and associated gases are expelled" (https://pubs.usgs.gov/gip/volc/nature.html, retrieved on 12/5/23). Similarly, the Google AI definition of a vent begins by stating "A volcanic vent is an opening in the earth's crust", and that of a volcano states "A volcano is an opening in a planet's or moon crust". Thus, if both a vent and a volcano are openings on the Earth's crust, it can be concluded that a vent is a volcano, and also that a volcano is a vent. Thus, such definition is ambiguous (circular definition is a more descriptive term, but ambiguous serves the purpose).

Other examples of the ambiguity existing between volcano and vent can be found in the several definitions of the pivotal term "volcano" documented in various papers included in the book edited by Cañón-Tapia and Szakács (2010). For example, in Table 1 of Borgia et al. (2010), there are 21 definitions of "volcano" taken from publications written by volcanologists that range from 1911 to 2008. Four of those definitions

Table 1. Sample of definitions of a 'Volcanic Field' published in specialized publications.

	Definition of volcanic field	Reference
1	An area of low-eruptive flux comprised of small, generally well-dispersed basaltic volcanoes that often form during a single eruption period (monogenetic) with large periods of quiescence between each eruption.	van den Hove et al. (2017)
2	One or more volcanoes within an area defined by elevated spatial vent density, and typically comprising a single structural/tectonic setting.	Valentine and Connor (2015)
3	Especially large clusters of volcanoes, with or without a central volcano.	Lockwood and Hazlett (2010)
4	Areas enclosing small, probably monogenetic, dominantly basaltic volcanic edifices.	Connor and Conway (2000)
5	A group of at least five independent volcanoes, showing evidence of not being the result of a single eruption.	Cañón-Tapia (2016)
6	A region of distributed volcanism.	Runge et al. (2015)

literally indicate that "a volcano is a vent" and other 6 indicate that a volcano is a place or opening where magma is coming out from below the surface, which essentially is the definition of a vent. Other definitions on the same table refer to a volcano as a hill, a mountain or an edifice. A different definition is suggested by Szakács (2010), who envisages a volcano as a geologic system (see also Cañón-Tapia and Walker, 2004), and yet another definition provided by K. Nemeth is that a volcano is the accumulated sum of products erupted through a vent, whereas the vent is a 2D entity that cuts a volcanic conduit at the surface. Thus, even when most volcanologists know very clearly what is a volcano, especially when they have been studying them for many, many years, the evidence summarized in the previous lines make clear several points. 1) there are too many alternative definitions of a "volcano", 2) most definitions tend to be circular superposing the terms "volcano" and "vent", and 3) taken the two previous items, there is a real problem concerning the definition of those two terms.

Similarly, there are several alternative definitions of "volcanic field" (Table 1). In addition to the various definitions of a volcanic field, this term has been used interchangeably in some occasions with "volcanic province" (Cvetković et al., 2010; Elshaafi and Gudmundsson, 2016; Lindsay and Feeley, 2003). These few examples illustrate the underlying ambiguity in the definitions of those terms. Furthermore, although sometimes an unofficial hierarchy between field and province is apparent, in which "province" is considered as of a larger area than a "field", such hierarchical relationship sometimes is reversed. For example, in the following quote from Elshaafi and Gudmundsson (2017): "together the provinces form one of the largest volcanic fields in North Africa" the provinces are considered to be smaller than the field.

Other related, and ill-defined terms are "volcanic group" and "volcanic cluster" that sometimes are used with rather specific and distinctive meanings. Closely related is the half-forgotten term "volcanic -complex". It should be noted that "volcanic-complex" is a term that undoubtedly continues to be used in many situations, especially within the geothermal community, and often in reference to a volcano-plutonic combination. It also may be used abundantly in a volcanic context in specific countries. Nevertheless, those uses do not alter the fact that this term has not been used as commonly as it should be expected in the context of spatial distribution of volcanic edifices, being often replaced indistinctly by volcanic-group or volcanic cluster. Hence the reason why I refer to "volcanic complex" as "half-forgotten" and not as an "entirely forgotten" term.

Other terms as "crater", "eruptive center", "belt", "chain", "single eruption", etc. are also ill-defined. Undoubtedly, it will be convenient to revise their definitions. However, many of those terms are left out of this work due to limitations of space.

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2.4 CONCEPTUAL VS. OPERATIONAL DEFINITIONS

Among the different types of definitions (Caws, 1959), it may be important to explicitly mention two in the present context. A conceptual definition aims to describe the abstract nature of a concept whereas an operational definition specifies how a concept can be measured, observed or applied in a given study. The relation between these types of definitions is not always simple, as measurement may occasionally reveal aspects of a term that were unsuspected in its original conceptual formulation. In those cases, a process of conceptual re-definition may be necessary. Most definitions in volcanology are more akin to the conceptual type than to the operational type. While there is of course nothing wrong with that approach, it has proved to be insufficient to provide unambiguous definitions of many terms, as mentioned in the previous section. As shown in the remainder of this paper, an operational approach seems promising for reaching a more satisfactory definition of various pivotal terms in volcanology.

3. An operational distinction between vent and volcano

As briefly explained in the previous section, a conceptual/geologic distinction between a vent and a volcano is not straightforward. Somewhat intuitively, and despite the many instances in which both terms are used as synonyms, it can be considered that a vent is part of a volcano and not the other way around. Thus, it can be considered that a vent denotes an object that is smaller than a volcano, which gives us a clue as to what type of metric can be used to move towards an operational definition. Nevertheless, using the size of an object as the only quantifiable criteria to distinguish between vents and volcanoes may not be appropriate because there are vents of one volcano that are larger than some volcanoes located in a different setting. For example, Diamond Head is a pyroclastic vent formed on top of Ko'olau volcano on the island of O'ahu, Hawai'i. The basal diameter of Diamond Head is larger than the basal diameter of Riverol volcano at the San Quintín volcanic field (1.8 vs. 1.3 km of diameter, respectively). Thus, it is not possible to state that all vents are smaller than all volcanoes, and therefore, it is not possible to unambiguously define both terms on the basis of a size threshold that separates vents from volcanoes. Clearly, a different approach is required.

Some aspects concerning the differences between vents and volcanoes were indirectly addressed by Cañón-Tapia (2016) when examining the conditions associated with the spatial independence of volcanic edifices. As remarked by Cañón-Tapia (2016), the independence of volcanic edifices may be defined at various time- and spatial scales when the influence of the magma reservoirs and plumbing components of a volcano are taken into consideration. A volcanic edifice is not necessarily a synonym of volcano, and for the time being can be defined as the object that is created upon one or several eruptions. Such object will be referred in the following as a construct. The construct may have positive or negative relief relative to the level of the surface before the eruption. Positive reliefs are commonly cones or shields, and negative constructs are often referred to as craters, but it also includes maars and tuff rings (sensu strictu the walls of a maar or a tuff ring will be a small positive relief, but the most visually important structure in this case is the hole in the ground enclosed by those walls). In any case, it is possible in most cases to associate two geometric entities to a given volcanic edifice. One of those entities is the geometric center of such a construct, the other is a line defining its perimeter (which will be called basal diameter in the following). Commonly those two entities can be placed in a map and be described in terms of coordinates and distances using topographic contours as a guide. Leaving aside concerns about the precision with which those quantities can be determined, it is possible to focus attention in the form in which those entities can be used to arrive at an operational definition of vent and volcano. The operational definition is provided in this case by resorting to the rules of separation of independent volcanic edifices as indicated by Cañón-Tapia (2016).

In that work, it was suggested that two volcanic edifices can be considered independent if their geometric centers are separated by a horizontal distance larger than the sum of their basal radii. If the geometric centers are closer than the shortest of the basal radius, the edifices are not-independent (Figure 1 of Cañon-Tapia, 2016). Other criteria of independence based on plumbing systems and/or eruptive events are possible, but for the present purposed the definition based on distances seems to be the more useful.

Although the above definition applies to the independence of volcanic edifices, it can be adopted to distinguish a volcano from a vent as follows. If the two volcanic constructs are independent, then they can be referred to as volcanoes. If the edifices (or structures) are not independent, it may be adequate to speak of vents. Thus, using as a reference a quantifiable measurement (distance), and a few specific rules quantifying the relation between three measurables (the diameters of two objects and a distance between their centers) it is possible to identify a qualitatively measurable difference between "vents" and "volcanoes" that does not rely only on the sizes of each of those concepts.

3.1. "VENTS" AND "PARASITIC VOLCANOES"

Yokoyama (2015) defined "Parasitic volcanoes" as "volcanic features …. of varying diameter and height situated either beside the main cones or at the flanks and bases of volcanoes". In some cases, the particular feature may be a cone (volcanic edifice) large enough to be called a "volcano" if it was considered in isolation of its surroundings. In other cases, a parasitic volcano is regarded as a "vent". Although the term "parasitic volcano" may be useful on some occasions, as it conveys the idea of a geologic, genetic connection with the larger structure, it is confusing when trying to separate the definitions of vents and volcanoes. If the operational definition of the previous section is applied, however, it is clear that all the parasitic volcanoes that are located at the flanks of a main (larger) edifice should be considered vents, therefore eliminating the confusion between terms.

3.2. CAVEATS

The operational definition stated above tells us the quantities that need to be compared with each other, and establishes a general, qualitative rule that may be used to separate volcano from vent. Although this rule may be easy to apply when dealing with volcanism at a specific location, it does not provide a more precise definition of both terms. In order to achieve that objective, it is necessary to stipulate a numeric reference that can be used to distinguish between both concepts. The following section provides information that contributes to such an end.

4. From single structures to "fields"

Settle (1979) distinguished "volcano cone fields" from "platform cone fields" based on the general slope of the base upon which a group of cinder cones were emplaced. The slightly more pronounced slope typical of volcano cone fields was always related with the presence of a larger volcanic edifice over which many small edifices were constructed. Adopting the operational distinction between vents and volcanoes of the previous section, it turns out that volcano cone fields are formed by vents rather than by independent volcanoes, whereas platform cone fields are formed mostly by volcanoes. Consequently "volcano cone fields" should be more properly called "vent fields". Likewise, platform cone fields can be called volcano fields.

The distinction between both the proposed vent fields and volcano fields is clearly related with the spatial scale at which the independence of structures is being analyzed. This spatial implication may be advantageous when attempting to describe the interconnectivity below the surface that may exist between structures observed at that surface. The proposed operational distinction between vent-fields and volcano-fields also may be benefic when attempting to make analyses of volcanic activity at a regional-tectonic scale, because it will allow for the comparison of akin features with relative ease, without mixing up fields that may be entirely different in their underlying architecture.

4.1. THE RELEVANCE OF SPATIAL DENSITY

To further formalize the distinction between vent-fields and volcano-fields it is convenient to consider the relevance of a different measurable: the spatial density provided by the number of structures (vents or volcanoes)/km^2. Several issues concerning this quantity need to be noted. On their analysis of "volcanic fields", Le Corvec et al. (2013) included two volcano cone fields (Etna and Pinacate) among the 34 "fields" that they included in their report. Notably, those two locations display the highest density (number of eruptive points/area) of their 34 fields. If the density of structures is determined on Mauna Kea and Kilimanjaro (two other volcano cone fields studied by Settle in 1979, but not included on the study of Le Corvec et al. 2013), the same trend of high density is obtained.

Based on the information provided by Cañón-Tapia (2016), a high density of eruptive points is also consistent with observations made on places like the Cu-Lao Re group (aka. Ly Son volcanic field, Vietnam) and Babuyan Claro Island, Philippines, both of which seem to be the subaerial expression of much larger submarine structures. This situation also applies to all the volcanic edifices located on the island of Rapa Nui, Chile, which is the emerged part of a much larger structure that defines a giant shield volcano.

All the above observations suggest a density trend that might be useful to establish a quantitative distinction between vent fields and volcano fields. Available information (Table 2) indicates that distinction between vent fields and volcano fields is not possible if reference is made only to the area occupied by the centers of eruption. Nevertheless, the division between vent fields and volcano fields seems to be more natural if attention is focused on the density of structures (number of eruptive centers divided by occupied area). The threshold allowing distinction between the two types of fields is around 2 x 10^{-7} and 2.5 x 10^{-7} structures /m^2, with vent fields having the largest density values.

4.2. EXAMPLE OF APPLICATION

Kirishima volcano provides an interesting example that illustrates the utility of adopting a quantitative measure to distinguish vent fields from volcano fields. Kirishima is listed as a shield volcano on the Smithsonian Institution catalogue, whereas the general information provided on the same catalogue describes it as a "large group of more than 20 Quaternary volcanoes …[that] consists of stratovolcanoes, pyroclastic cones, maars and underlying shield volcanoes located over an area of 20 x 30 km". Comparison between the classification and the description provided by the Smithsonian catalogue raises two questions: Is this one volcano, or a group of volcanoes? How can one volcano be at the same time a group of 20 volcanoes? The ambiguities in the information provided by the Smithsonian Institution catalogue is clearly a consequence of the ill-defined definition of the terms vent and volcano. If a distinction between volcano and vent is introduced based on spatial density, as suggested above, such ambiguity can be easily avoided.

Using as a base the geological map prepared by Imura (1992) and Google Earth images, I obtained the coordinates of the most prominent eruptive centers on the Kirishima region, and calculated a density using the convex hull command and appropriate ellipsoid of reference in MatLab. The resulting density is 2.3977 x 10^{-7} eruptive centers/m^2.

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Table 2. List of zones of distributed volcanism arranged in increasing order of density (number of eruptive centers /m²)

Name	# of eruptive centers	Area (m²)	Density
Sikhote-Alin	6	3.00E+10	2.00E-10
Tunkin Depression	11	6.75E+09	1.63E-09
Kunlun	13	4.82E+09	2.70E-09
Vitim Plateau	15	4.90E+09	3.06E-09
Zamboanga	151	4.89E+10	3.09E-09
West Luzon	6	1.89E+09	3.17E-09
Azas Plateau	12	3.00E+09	4.01E-09
Jom-Bolok	16	3.00E+09	5.33E-09
Taupo Volcanic Zone	54	7.14E+09	7.56E-09
Khanuy Gol	8	9.53E+08	8.39E-09
Yucca Mountain	39	4.64E+09	8.41E-09
Leizhou Bandao	5	4.47E+08	1.12E-08
Todra	142	1.14E+10	1.25E-08
Al-Haruj	435	2.70E+10	1.61E-08
Dariganga	226	1.16E+10	1.95E-08
Snake River	507	2.58E+10	1.97E-08
Armenia	152	7.27E+09	2.09E-08
San Ignacio	144	6.54E+09	2.20E-08
Dar-Alages	22	9.67E+08	2.27E-08
Lipari	25	8.47E+08	2.95E-08
Xalapa	59	1.71E+09	3.45E-08
Karapinar Field	368	9.89E+09	3.72E-08
Arshan	32	8.01E+08	3.99E-08
San Borja	280	6.84E+09	4.09E-08
Basilan	41	9.87E+08	4.15E-08
Boring	88	1.95E+09	4.51E-08
San Pablo	52	1.07E+09	4.86E-08
Wudalianchi	18	3.66E+08	4.91E-08
Hauraki Rift	14	2.84E+08	4.92E-08
Chichinautzin	181	3.48E+09	5.20E-08
Keluo Group	10	1.84E+08	5.43E-08
St Michael	84	1.53E+09	5.49E-08
Ghegam Ridge	74	1.32E+09	5.62E-08
Lower Chindwin	26	4.61E+08	5.63E-08

Such result provides quantitative support to refer to this group as a vent field rather than a volcano field. More importantly, it helps to remove the ambiguity conveyed by the comparison of the current classification and description of this place. The classification of the Smithsonian remains valid (one shield volcano), but the description provided in that catalogue should be changed to read "a group of more than 20 large Quaternary vents some of which might have erupted more than once". In other words, Kirishima is one volcano that includes a group of 20 or more vents.

4.3. CAVEATS

Available evidence suggests that a spatial density of 2.5 x 10^{-7} eruptive centers/m^2 can be adopted as a tentative reference to quantitatively discriminate between volcano fields and vent fields. This metric also can provide a quantitative basis to distinguish between volcano and vent in some cases: if a volcanic edifice is in the neighborhood of other volcanic structures, it may be possible to calculate the density of all the neighboring structures. Depending of the results, it should be easy to call individual structures as a vent or as a volcano depending on whether it is located within a vent-field or a volcano-field.

It should be noted here, however, that the numerical reference might require fine-tuning as more quantitative evidence from many more locations on Earth and in other planets is gathered. It also should be noted that there are other aspects related to "volcano fields" that might influence its definition. Several of the most relevant parameters that need to be taken in consideration are discussed in the following sections.

5. How many volcanoes define a volcano-field?

Leaving aside the distinction between vent fields and volcano fields, by examining the definitions collected in Table 1 it becomes evident that there is no agreement concerning the minimum number of volcanoes required to form a field. Actually, only one definition among those included in Table 1, makes an explicit statement on this regard, mentioning a minimum of five independent volcanoes that are not the product of a single eruption. In the following lines, the evidence supporting five as an adequate lower bound to define a group of volcanoes as a field is examined.

Pragmatically, there is no point in establishing a minimum number of objects needed to form a field if there are no candidate areas that have such a low number of structures. Consequently, a first step consists in examining the number of volcanoes in as many volcano fields as possible. Somewhat surprisingly, it is difficult to find the precise number of structures that form a given field in many cases either because the published literature on that particular field does not provide a numeric estimate of the structures that form that field, or because different works offer different numbers for the same field. For that reason, the following approach was adopted here. A list of fields for which a precise number of structures is reported was extracted from the catalogue of volcanism of the Smithsonian Institution. That list was complemented through a literature search of specialized reports of most fields for which there was not a specific number mentioned in the catalogue. If two different sources quoted different numbers, the smallest number was systematically selected. The final list contains 84 volcanic fields, representing 25% of the reported volcanic fields on the original catalogue.

In addition to Earth, volcanic fields are present in other planets. For this reason, it was considered convenient to examine available information about those locations as well. Addington (2001) reported the number of structures and areas covered by 179 fields on Venus, representing 28% of the total number of volcanic fields identified up to 2001 on that planet. This proportion of volcanic fields is similar to the cutoff described above for Earth. In consequence, it is considered that equivalent amounts of information are available from those two planets, and therefore, both sources of

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Table 2. List of zones of distributed volcanism arranged in increasing order of density (number of eruptive centers /m²)[continuation]

Name	# of eruptive centers	Area (m²)	Density
Jolo	63	1.04E+09	6.05E-08
Santa Clara	81	1.32E+09	6.14E-08
Honggeertu	12	1.66E+08	7.21E-08
Jaraguay	216	2.94E+09	7.35E-08
San Francisco	360	4.65E+09	7.74E-08
Tengchong	39	4.43E+08	8.79E-08
Campi Flegrei	19	2.06E+08	9.20E-08
Auckland Sur	62	6.69E+08	9.26E-08
Es Safa	185	1.98E+09	9.34E-08
Longgang Group	116	1.23E+09	9.40E-08
Abu	56	5.87E+08	9.53E-08
Taryatu-Chulutu	19	1.75E+08	1.08E-07
Eifel	224	2.03E+09	1.10E-07
Pali Aike	467	4.08E+09	1.14E-07
Camargo	340	2.82E+09	1.21E-07
Pre-Chaine Des Puys	28	2.27E+08	1.23E-07
Springerville	359	2.82E+09	1.27E-07
Auckland	36	2.81E+08	1.32E-07
Potrillo	158	1.20E+09	1.32E-07
South Auckland	92	6.54E+08	1.41E-07
Jeju	304	1.88E+09	1.53E-07
Kula	55	3.23E+08	1.70E-07
Chaine Des Puys	107	5.47E+08	1.96E-07
Samsari Volcanic Center	47	2.33E+08	2.02E-07
Camiguin	11	5.40E+07	2.02E-07
Tskhouk-Karckar	118	5.33E+08	2.19E-07
Middle Gobi	88	4.00E+08	2.20E-07
Pinacate	453	1.78E+09	2.54E-07
Haut Dong Nai	14	5.20E+07	2.64E-07
Qal´Eh Hasan Ali	12	2.20E+07	5.36E-07
Etna	189	3.26E+08	5.79E-07
Babuyan Claro	7	1.10E+07	6.34E-07
Dacht-I-Navar Group	20	2.45E+08	8.14E-07
Cu-Lao Re Group	5	2.04E+06	2.44E-06

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information can contribute equally to establish a useful minimum number of structures that need to be considered to define a volcano field.

The available evidence indicates that although in both planets there are a few fields with a large number of volcanoes, the vast majority tend to have a relatively small number. Focusing on the lower range of the distribution, it turns out that only 5 fields on Earth have less than five volcanoes whereas there is no field on Venus that has less than seven volcanoes.

In conclusion, it seems that a minimum of five independent volcanoes is a suitable number to be used in the definition of a volcano field. Groups of 4 or less volcanoes, if they exist, may have a different genetic connotation than the groups properly called fields in this section.

6. Volcano clusters, groups and complexes

Although the terms "group" and "cluster" are generally synonymous, both terms have evolved to have somewhat distinctive characteristics in volcanic contexts. Somewhat intuitively a "volcano-group" can be used to loosely denote a set of volcanoes that are spatially related, regardless of their number, or of their genetic or magmatic associations. In contrast, "volcano cluster" has been increasingly used to denote a group of volcanoes that are spatially, temporally and genetically related (Aguilar et al., 2022).

Although the just stated difference between a volcano group and a volcano cluster seems reasonable and sufficiently precise to satisfy the conditions of a good definition, it turns out that "volcano cluster" is an ill-defined term because it has been used with different connotations in the literature. Among the various uses of volcano cluster it is possible to mention the following: 1) a specific group of volcanoes within a volcano field (Avellán et al., 2024), 2) a group of stratovolcanoes along a sector of a volcanic arc (Lally et al., 2023), 3) a group of two or more distinct polygenetic edifices (Davidson and de Silva, 2000), 4) an entire volcano field (Tang et al., 2023) and, 5) groups of volcanoes that are defined based on a clustering algorithm that uses as information only the coordinates of the volcanoes in a region. It must be noted that the groups that are defined according to the latter five criteria do not necessarily imply a shared geochemical or petrological composition, or actually any temporal association. Consequently, the interpretation of such spatially-defined groups (or clusters) has a different connotation than when the term is interpreted in relation with a petrological or temporal association.

As it can be observed from the preceding lines, the term "volcano-cluster" has too many connotations that might lead to unnecessary confusions. Nevertheless, given the increasing frequency at which "cluster" is being used with temporal and genetic connotations, it is necessary to be aware that there might be a semantic difference when two groups of workers describe one region as a volcano cluster. In order to avoid confusion when using the term "volcano cluster", it is noted here that a definition in terms of the spatial, temporal and genetic relation of volcanoes was already provided by the definition of a "volcano complex" issued by Francis (1995).

Francis defined a volcano complex as "extensive assemblages of spatially, temporally,, and genetically related major and minor centers with their associated lava flows and pyroclastic rocks". In other words, this is the exact same definition of a "volcano cluster" as used by Aguilar et al. (2022).

The reasons why the transposition of terms in which "complex" was substituted by "cluster" are unknown. In any case, because there is a term that already implies similarities in variables other than spatial location, it seems reasonable to retain "volcano complex" when such associations are implied, leaving the terms "volcano cluster" and "volcano group" to loosely describe groups of volcanoes that are in close spatial proximity with each other, without implying any other type of genetic, temporal or compositional relationship.

6.1. OPERATIVE DEFINITION OF A GROUP

Defining a group of volcanoes is not a simple task even if we focus attention only on spatial distance. Complications arise because many different clustering algorithms can be used for that purpose, and all of those algorithms lead to different results. Those algorithms can be separated in five broad classes: partitioning, model-based, hierarchical, grid-based and density-based (Fahad et al., 2014). Partitioning and model-based algorithms are relatively simple to use, but require a priori specification of the number of expected groups, which is not always available, or otherwise justifiable. Hierarchical and grid-based algorithms are also relatively simple to use, but favor identification of groups that have common attributes (similar density or similar area covered, for example) and therefore are not easy to implement in cases in which groups may have very different characteristics. Finally, density-based algorithms are capable to discover groups of arbitrary shapes and contrasting characteristics with relative efficiency, but might be slightly more complex to implement than the other algorithm categories. As pointed out by Fahad et al. (2014), no algorithm performs well for all evaluations of performance and all suffer some degree of stability problems. Consequently, selection of a specific algorithm remains an essentially subjective task in which personal preferences of the researcher completing the analysis cannot be eliminated. In the context of volcanic fields several approaches of group identification have been proposed (e.g., Cañón-Tapia, 2013; Cañón-Tapia, 2016; Connor and Hill, 1995; Connor, 1987; Mazzarini, 2007; Mazzarini et al., 2010). The various results reported in those works indicate that the definition of a group of volcanoes depends on the algorithm used during the analysis. This situation is clearly unsatisfactory.

Regardless of the algorithm selected to complete the formal identification of different groups of objects given the decided metric of reference, all groups will tend to be formed by satisfying a principle of maximum similarity. When the metric to be used is limited to the physical, horizontal distance between the objects to be separated into groups, the maximization of similarity becomes equal to a criterion of spatial proximity. Note that even in this case there is no unambiguous and universal definition of the boundaries between groups, because such definition depends on other criteria used to draw such a boundary. For example, one person may consider that an area of larger density of structures needs to be distinguished from an area where the density diminishes, but another person may note that both areas under comparison are contrastingly different, and that therefore the direct comparison with each other does not represent a significant difference. Both perspectives may have a valid point in their favor, so at the end it is not possible to decide which criteria is more effective without knowing more details of the situation under consideration.

A solution to this dilemma can be found if an operative definition of a group of objects is achieved simultaneously with a definition of what objects need to be excluded from the group being defined. In terms of a metric exclusively denoting spatial distance between objects, such definitions can be expressed as follows:

A group is defined when the maximum nearest neighbor distance of any object belonging to the group (hereafter called Within Group Distance, or WGD) is smaller than the minimum nearest neighbor distance between an object that does not belong to the group and any object of the group (hereafter called the Between Group Distance, or BGD). Parting from such definition, a self-contained metric can be obtained for any population of structures by making reference to the distribution of nearest neighbor distances (NND) of the whole population. Using those NND as reference, it is possible to identify which objects belong to one group, and which do not belong to that group simultaneously when a specific value for the WGD is chosen. Thus, even when two persons may disagree on what should be the value of the WGD, their disagreement will be expressed in relation to a quantitative measure.

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6.2. EXAMPLES OF APPLICATION

To illustrate the form in which the above operative definition of group can be applied in volcanic contexts, different regions that had been previously studied in the search of groups were revisited. Unlike previous works in which different clustering algorithms were used simultaneously, however, the following procedure was adopted here. First, the nearest neighbor distance NND was calculated for each structure in the database. Second, the maximum NND of the region was determined. This distance is the default regional WGD. Third, using the Two Point Azimuth algorithm with a restricted distance (Cebriá et al., 2011), all the linear segments having two structures separated by the regional WGD were plotted in a map. Fourth, the resulting map was examined to identify independent groups of structures, and those groups were compared with the groups identified in previous works. It should be noted that in the current procedure all the structures that are interconnected with a line comply with the operative definition issued above, and therefore are a single group, whereas volcanoes that are part of a different group will be separated by spaces devoid of straight lines. The distance between those groups (if any), is clearly larger than the prescribed regional WGD. Because interest resides here in the possibility of using the location of vents as a guide to define boundaries of fields, the figures presented in this section omitted a background image of the topography, although all locations have been georeferenced. Use of a uniform grey background and red line segments serves to highlight the spatial relations between objects, facilitating the description of findings.

6.2.1. BAJA CALIFORNIA

A general description of Baja California volcanic fields was provided by Germa et al. (2013); alternative results of clustering were presented by (Cañón-Tapia, 2020). The database used here includes seven volcano-fields located on the Baja California Peninsula. The regional WGD is 15 km. Figure 1 shows the line segments joining any two volcanoes separated by a maximal distance equal to the WGD (red lines) and the vents using a different symbol for each field. As it can be seen in the figure, there is a one-to-one correspondence between the areas defined by red lines and the groups previously defined. This reflects the fact that the regional WGD characterizes all fields well, and that the BGD in all cases is larger than the regional WGD in all cases.

6.2.2. WASHINGTON CASCADES

A summary of the geological work made on the area of the Washington Cascades was provided by (Hildreth, 2007). This area is characterized by including 13 different groups of volcanoes, although the boundaries between those groups have not been unambiguously defined. A total of 528 volcanoes were identified and separated on those 13 groups using an interactive algorithm by Cañón-Tapia (2024).

As shown in Figure 2a, when the regional WGD is equal to the maximal NND, the entire region becomes an interconnected network of volcanoes. The network includes sections with a high density of red lines, which broadly coincide with the geologically significant groups (distinguished by symbol and color on the figure). If a smaller regional WGD is applied (Figure 2b), the network of volcanoes splits on separate nodes, but also leaves some isolated volcanoes, or groups of less than five volcanoes that are disconnected from the main sections of interconnected volcanoes. Although the geologically significant groups agree much better with the groups defined by interconnected red lines, it is seen that not all the volcanoes of one geological group are interconnected among themselves, nor every geological group defines an interconnected group that is separated (*i.e.*, not joined by any red line) from an adjacent group. In some cases the union between adjacent groups takes place along many red lines, but in most cases that connection is established only through a limited number of red lines. To some extent,

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this indicates the overlapping of volcanic systems, as well as the presence of a limited number of volcanoes that are located at the zone where two systems overlap with each other. In order to have the 13 geologically significant groups completely independent from each other (*i.e.*, not joined by red lines), it is necessary to generate the diagram with a regional WGD of 5 km. In this case, however, many of the geologically significant groups are not identified by a single plexus of red lines, but also split in more than one section. This observation reflects that each group has its own characteristic WGD, and that a single regional value does not capture the regional variability.

6.2.3. PINACATE

A description of the Pinacate area with emphasis on the identification of groups of eruptive centers was given by Cañón-Tapia and Jacobo-Bojorquez (2023). In their study they identified eight main groups of vents, with several vents that were

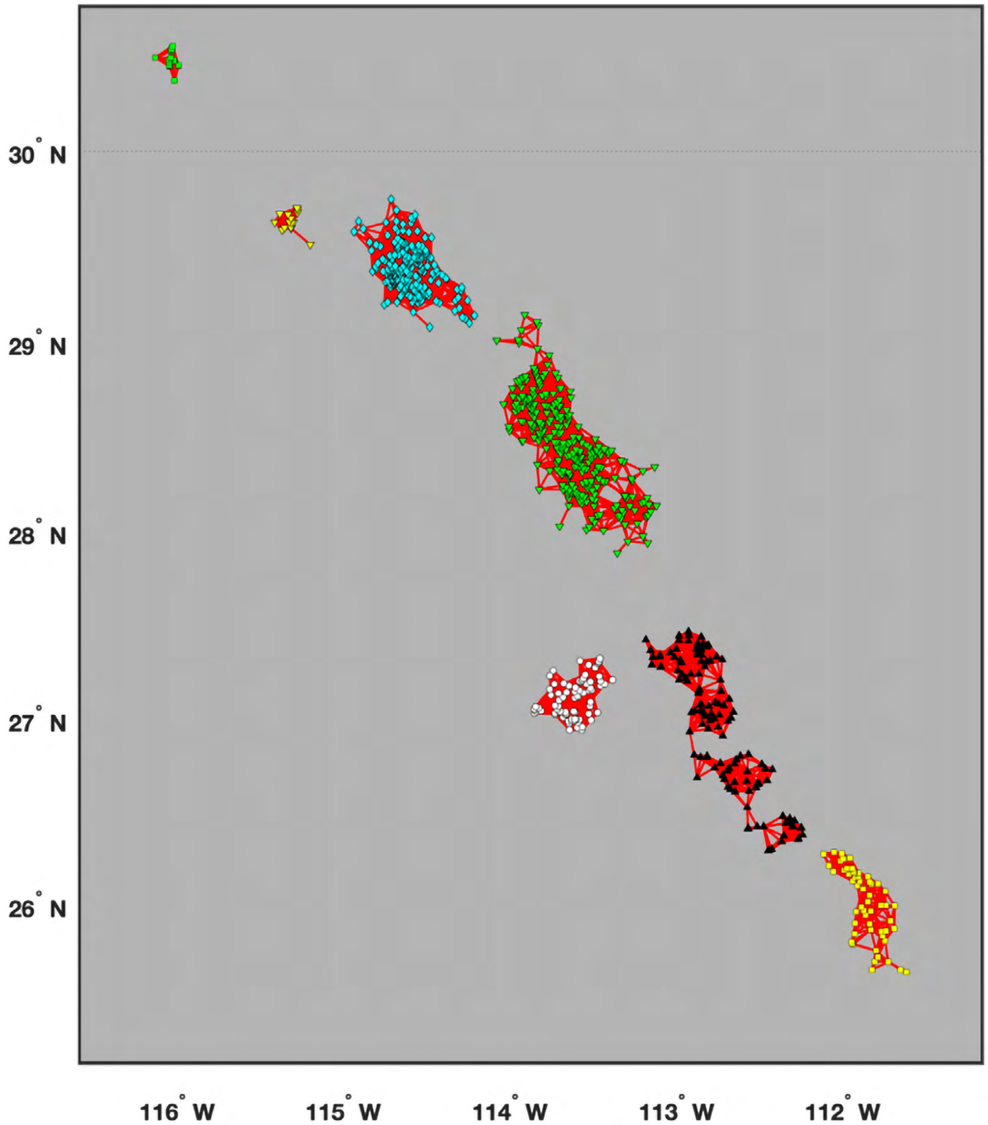

Figure 1 Eruptive centers on the Peninsula of Baja California. Volcanoes associated with each of the seven fields identified on that Peninsula are shown with different symbols. Red lines were drawn between any two eruptive centers that were separated by a maximum distance equal to 15 km. Background geology and topography removed intentionally. See text for discussion.

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difficult to associate with any one of the main groups. Based on several field relationships, the eight groups were tentatively grouped to form four larger groups that could represent vents associated with larger shield volcanoes. It is noted here that El Pinacate area is very close to the threshold density defined above to separate volcano fields from vent fields. The regional WGD in this case is 9 km. This distance of reference leads to a single group that interconnects all the vents in the area (Figure 3a). If a regional WGD of 2.15 km is used, the organization of the groups in separate systems is more or less evident. The four shields tentatively identified would be defined by groups 1, 2 to 4, the combination of 5 and 6, and 8, respectively. In this figure is also clear that the connection between the north and south parts of the area takes place through two corridors. One is a suite of vents that were difficult to associate with any group previously, and the other connection is a branch of group 4 that extends to the south, connecting group 4 with group 6.

Regardless of the veracity of each of the associations implied by the results, it is clear that the WGD in this case is of little use to identify individual groups, and also that even a regional WGD of less than 2.5 km leads to somewhat uncertain divisions.

6.2.4. *JEJU ISLAND*

Jeju island, South Korea, is one of the regions with higher density of volcanic structures in the world. The distribution of volcanic vents in Jeju island has been made by Cañón-Tapia (2021). The nine groups identified in that work were compared with the distribution of zones of magma at depth known through seismic studies (Song et al., 2018). That comparison revealed that vent distribution patterns can be complicated by the vertical superposition of different levels of magma storage. The regional WGD obtained from the NND is equal to 6 km. This distance of reference yields an entirely interconnected network of vents that form a single group (Figure 4a). If a regional WGD of 2.5 km is adopted, the interconnection of vents starts to resolve some independent groups, but those groups have a different character than the groups of vents probably associated with various magma bodies. As is the case of the Pinacate, a

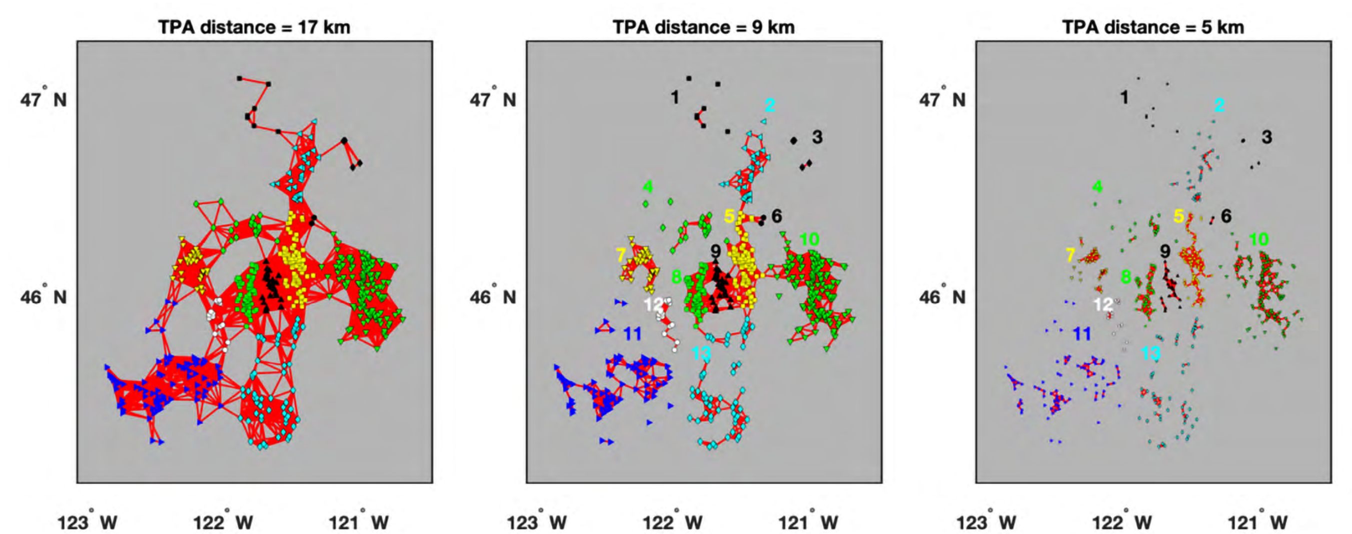

Figure 2 Eruptive centers on the Washington Cascades. Volcanoes associated with each of the 13 fields identified on that area are shown with different symbols, and indicated by the numbers in panels b and c. Red lines were drawn between any two eruptive centers that were separated by a maximum distance equal to a) 17 km, b) 9 km and c) 5 km. The size of the symbols in c) was decreased for the lines to be visible. Background geology and topography removed intentionally. See text for discussion.

reduced regional WGD leads to divisions that do not seem to have a geological significance.

6.2.5. ONE LARGE FIELD OR SEVERAL ADJACENT SMALLER FIELDS?

The examples presented above indicate that a regional WGD may not always capture the complexity of the distribution of volcanic structures at a large scale. Different groups may have contrasting WGD despite being located in close proximity to each other. Nevertheless, for the two volcano fields presented, a regional WGD exceeding 5 km seems to be enough to identify the different geologically significant groups of volcanoes in the region.

In contrast, for the areas characterized by their high spatial density of structures, (vent fields) the regional WGD obtained from a NND produced an entirely interconnected network that continues to be observed unless a regional WGD of less than 2.5 km is used. This observation can be used to add a new constraint to the definition that separates volcano fields from vent fields. The constraint is that volcano fields can be detected as independent groups of interconnected structures when a regional WGD exceeding 5 km is used.

7. Region, Province and Group

The use of the terms "region", "province" and "group" in a volcanic context is somewhat unclear, as it can be seen from the presentation of volcanic regions and region groups of the Smithsonian Institution (https://volcano.si.edu/volcanolistregions.cfm). In that text, it is stated that 140 volcanic regions have been identified, and

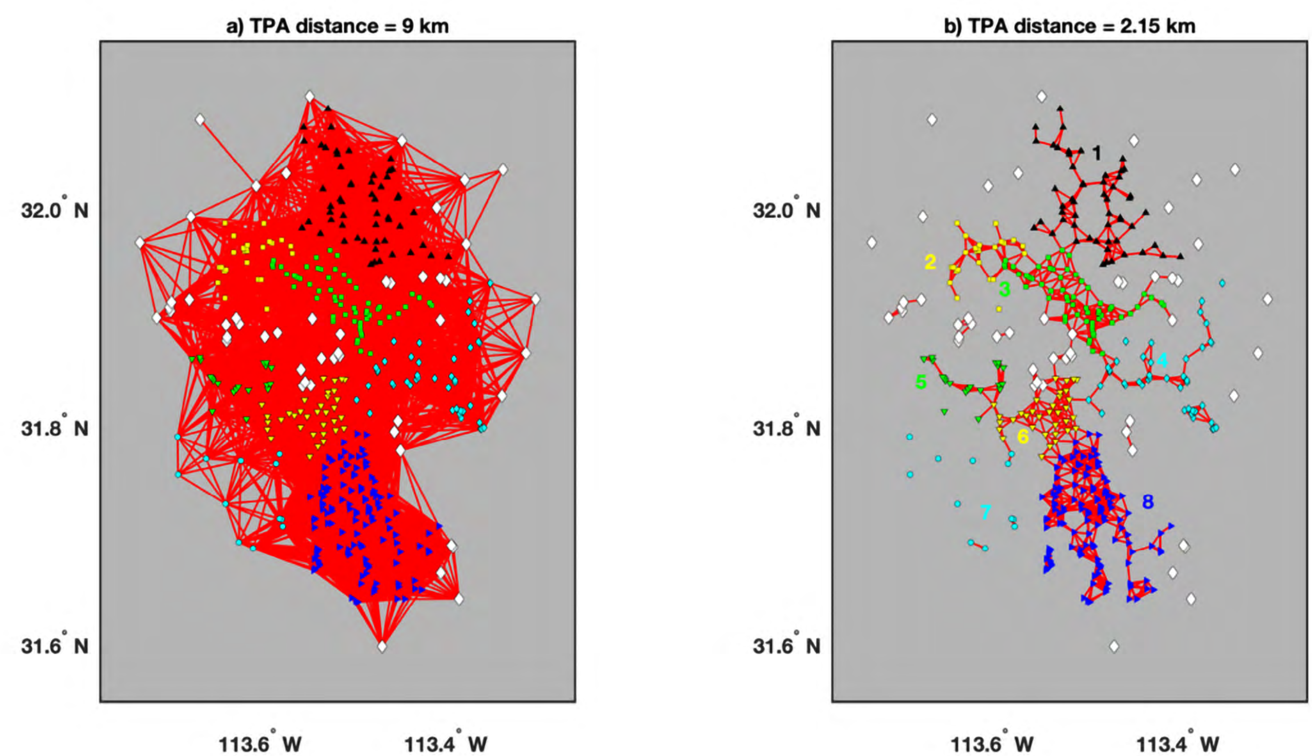

Figure 3 Eruptive centers on the Pinacate area. Volcanoes associated with each of the nine groups identified on that area are shown with different symbols, and indicated by numbers in b). Vents associated with the disperse group (number 9) are only marked by the white diamonds. Red lines were drawn between any two eruptive centers that were separated by a maximum distance equal to a) 9 km and b) 2.5 km. Background geology and topography removed intentionally. See text for discussion.

those regions have been organized in 19 groups. Up to that point, there is nothing strange with the usage of the terms. Upon inspection of the list provided, however, it is seen that each of the 19 groups of regions is formed by Groups, Provinces and Arcs. Most notably, the wording used on that webpage is such that it defines groups of regions that do not contain a single region.

Perhaps it may be argued that from an etymological point of view, both "region" and "province" can be considered to be entirely synonymous with each other, because both terms denote a territorial extension in which some type of administrative rule and government is enforced. Thus, it would be natural for a group of regions to be formed by provinces. This possibility implies, however, that a Group and an Arc are also synonymous of Region, which will tend to complicate things because it establishes affinities that may not be granted in many cases. The confusion is reinforced when in the text of the Smithsonian Institute it is read that a region can be one out of five possible types: 1) an arc, 2) a rift province, 3) an intraplate, back-arc, mixed or uncertain province, 4) a hotspot group, or 5) a fault or fracture group. With that many possibilities it is challenging to appreciate similarities and differences between the various possible combinations of characteristics, or to have an unambiguous definition of a volcanic region.

The solution to this problem is straightforward, and actually is already present in the same page of the Smithsonian Institute (albeit it will require minor modifications to the text). A region can be defined as a group of nearby provinces, arcs or groups of volcanoes (as it is implicit on the 19 tables presented in the Smithsonian Institution web-page). This definition of a region establishes a hierarchy of sizes in the territorial extension that distinguishes "regions" from "provinces". Regions are the largest territorial extensions. Provinces, arcs and groups of volcanoes do not have to be defined in more formal terms because their use does not lead to any specific contradiction or circular definition. If so desired, however, it could be considered thar Arc is related to subduction, Province denotes a magmatic affinity observed over a large territorial extension (yet smaller than a region) and group denotes spatial proximity. If the group also displays some magmatic or genetic affinity then it can be addressed as a volcano-complex.

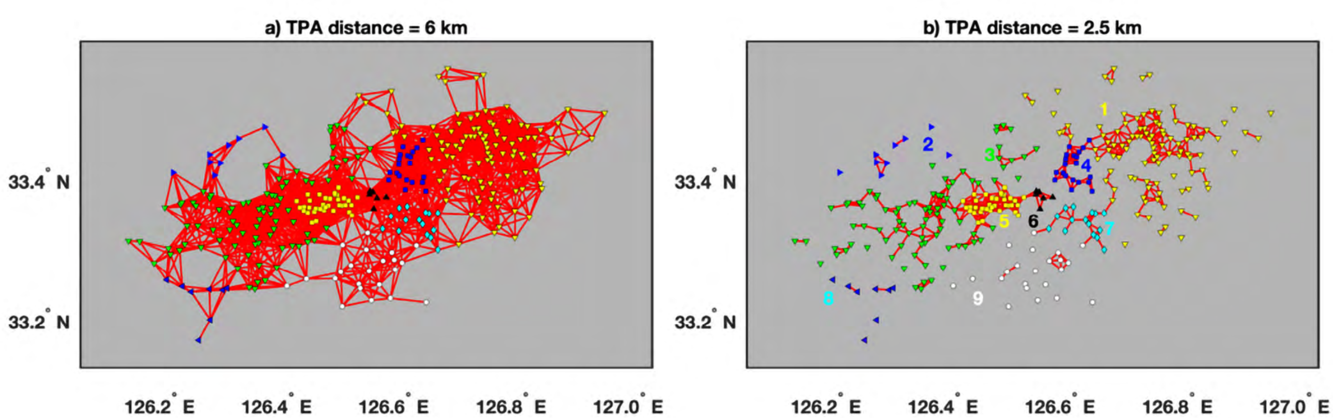

Figure 4 Eruptive centers on the Jeju island area. Volcanoes associated with each of the nine groups identified on that area are shown with different symbols, and indicated by numbers in b). Red lines were drawn between any two eruptive centers that were separated by a maximum distance equal to a) 6 km and b) 2.5 km. Background geology and topography removed intentionally. See text for discussion..

8. Summary and conclusions

Throughout this paper it has been shown that it is possible to unambiguously define pivotal terms in volcanology, such as "vent", "volcano", "volcano complex", "volcano group", "volcano cluster", "vent field", "volcano field", "volcanic province" and "volcanic region". Group and cluster retain a generic meaning denoting spatial proximity without any reference to the scale of such proximity, the rest of the mentioned terms include spatial restrictions in their definition, progressing form the smallest (vent) to the largest (region). Thus, a volcano may contain several vents, a volcano complex may contain several volcanoes and vents, a vent field contains several vents and may be equivalent to a volcano, a volcano field contains several volcanoes and also may include vents, vent fields and volcano complexes, a volcanic province may include several volcano fields and a volcanic region may include several volcanic provinces. Qualitatively, vent fields and volcano fields can be distinguished from each other by measuring the density of eruptive centers per area, with the former presenting a density larger than 2 x $10^{-7}/m^2$ and the latter having a density smaller than that threshold. In addition, individual vent and volcano fields will tend to define a single interconnected group of structures if a reference distance of less than 2.5 km is used, whereas adjacent volcano fields can be distinguished from each other using reference distances larger than 5 km. Provinces can include several fields, and regions can include several provinces or volcano groups.

Contributions of authors

The conceptualization of the topic, the preparation of figures and tables, and the analysis were carried out by the author.

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Conflict of interest

The author has no conflicts of interest to declare.

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