Volcanism of the Canary Islands: An overview with petrologic characteristics

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Abstract

The study of the volcanic activity that surrounds and builds ocean islands may yield evidence of thermal and chemical anomalies within Earth's mantle. Although not the most typical or famous of ocean islands, the Canaries archipelago is of importance in the understanding of ocean island volcanism and mantle dynamics. The Canary Islands lie in the Atlantic Ocean off the Northwest coast of Africa. The geologic setting is that of an archipelago within a slow-moving tectonic plate close to a passive continental margin. It has been suggested that the islands are the products of "hot spot" volcanism, i.e. the result of a mantle plume. However, more recently it was proposed that the origin of the Canary Islands is likely the result of a sheet-like mantle thermal anomaly aided by regional tectonics and structural geology. Existing geochemical data were analyzed for differences in major oxides among the seven islands and numerous volcanoes of the Canaries. Interpretation of the data yields conclusions about the composition of the mantle source region and the processes of magma evolution. Comparisons are drawn to existing intra-plate oceanic volcanism such as the Hawaiian Islands. This project aims to achieve a better understanding of the dynamics of the Canary Islands and their origin.

Acknowledgements

I would like to express my gratitude toward my thesis advisor and professor, Dr. Michael Barton. His hunger for knowledge is never satisfied, and he has been a source of inspiration throughout my time as a student in the School of Earth Sciences. I am thankful to Dr. Anne Carey for consistently going out of her way to provide guidance in the Geological Sciences program, and for being a resource for my academic and career aspirations in the earth sciences. I am particularly grateful to Shell Oil Company for funding my participation and research in the Shell Undergraduate Research Experience (SURE) program. Last, but not least, I would like to thank my family and friends for helping me to realize my goals in academics and in life.

List of Figures and Tables

Introduction

The Canary Islands are an oceanic island chain that is surrounded by Jurassic age oceanic lithosphere. They lie within the slow-moving African tectonic plate, and are commonly thought to be the result of hotspot volcanism. They have been the subject of numerous scientific studies, but this paper focuses on the geologic history and models for the origin of the islands, including an overview of hypotheses proposed over several decades and a brief review of the petrology of the islands.

The Canaries share similarities with another, more famous archipelago, the Hawaiian Islands. Both of these island chains show evidence for the track of an intra-plate hotspot, but while the Hawaiian Islands define a neatly drawn course of volcanic activity with relatively short periods between volcanic eruptions, the Canaries have more complicated space-time relationships. There are longer gaps between active periods of volcanism, and there is little evidence for the expected subsidence of islands that were supposedly built by an upwelling mantle plume. In addition, volcanic activity has occurred in recent times on nearly every island in the Canaries. In contrast, volcanism on the Hawaiian Islands is constrained to its easternmost areas.

The geological and geophysical data that have been gathered on the Canary Islands presents many questions, and there remains opportunity for interesting research related to the islands' origin. Among the questions to be answered: Why is the rock composition of the Canaries different from that on other oceanic islands? Can a model of the magma chambers below the Canary Islands be constructed? How are the magmas differentiated, and what is their origin? Ultimately, this paper does not intend to answer these questions, but is intended as an overview and introduction into geological research on the Canary Islands.

Geologic Setting and Background

The archipelago of the Canaries consists of seven major islands and several islets. The island chain stretches for approximately 500 km, with the easternmost island 100 km from the coast of NW Africa (Figure 1). Volcanic activity has been occurring at the Canary archipelago for a considerable amount of time, as evidenced by outcrops in the eastern islands with formations over 20 million years old. Because of this long volcanic history, all stages of development of oceanic islands may be observed in this setting. The preservation of rock outcrop as well as ease of geologic observation on the islands is made possible by relatively sparse vegetation and low rainfall, but the island of La Palma is an exception. There is a lack of surface water on the islands, and this has led to extensive groundwater mining. Consequently, there are around 3000 km of tunnels that provide access to the subsurface structure of the volcanoes within the islands. This makes sampling and direct observation a reasonable option for geologists, rather than having to rely on costly geophysical data alone (Carracedo et al., 2002).

It is suggested from magnetic anomalies and seismic refraction data that the Canaries lie over oceanic crust. Bounding the islands are the M25 magnetic anomaly and the S1 "slope" anomaly. The M25 is located near El Hierro and La Palma on the oceanic crust, and it is approximately 56 million years old. The S1 is located between the easternmost part of the Canaries and the coast of Africa, and it is approximately 175 million years old (Roest et al., 1992).

Traditionally, the Canary Islands have been viewed as a special oceanic island group, and the origin of the archipelago has been linked closely with tectonics of the African continent. Now, the Canaries are thought to share more similarities with other hotspot areas like the Hawaiian Islands than previously thought. Among the similarities are the structural (gravitational collapses and rift zones) and constructional features (Figure 2). It is also evident that the Canary Islands experienced both shield building volcanic phases followed by post-erosional stage volcanism as in the Hawaiian Islands (Figure 3). The differences between the island chains include the reduced amount of subsidence of the Canaries, and the geochemical evolution of its magmas (Carracedo et al., 2002). The Canaries are on a very slow moving plate as compared to the Hawaiian Islands. The track of the Canaries volcanism has only been 1.9 meters per year, as opposed to the 10 meters per year average of the Hawaiian archipelago (Figure 4). In addition, the distance vs. time relationship among the Canary Islands is linear like the Hawaiian Islands, with the exception of Lanzarote and La Gomera. Along with the possibility of a mantle plume causing the intra-plate volcanism seen at the Canaries, there have been several other hypotheses proposed over the years, including a propagating fracture, a local extensional ridge, uplifted tectonic blocks, a hot spot, and more recently a unifying model.

The propagating fracture model is based on a proposed geological connection between the Atlas Mountains and the Canary Islands (Anguita & Hernán, 1975). It proposed that a mega-shear fracture connected both regions, and held that when the fracture was in a tensional phase, volcanism at the Canaries would occur by decompression melting. Alternately, when subjected to compressive stresses, periods of volcanic inactivity as well as compressive structures would occur. This explained periods of cyclic volcanism experienced by the Canary archipelago that concurred with compressive phases of the Atlas Mountains. However, the uplift of tectonic blocks, the lack of submarine Cenozoic era faults, and an early terminating South Atlas fault were ultimately obstacles that were not overcome in this hypothesis. In addition, the volume of the Canary Islands was found to be approximately 1.5×10^5 km^2 (Schminke, 1982), and this amount is far greater than could possibly be formed by magma generation in response to lithospheric stretching in the absence of an underlying heat source (McKenzie and Bickle, 1988). Tectonic uplift was also thought to have been responsible for the creation of the Canaries (Anguita & Hernán, 2000).

There is evidence of different uplift for different islands of the Canaries, and this led to the hypothesis of uplifted tectonic blocks (Araña & Ortiz, 1986). In this explanation, compressive tectonic stresses led to crustal thickening and shortening of the ocean floor. This was thought to be the main cause of magmatism and uplift that formed the Canaries. When compressive stresses periodically relaxed, magmas could escape and thus create the islands. This hypothesis accounted for the dynamics of existing active faults among islands, and explained the heights of submarine formations, but could not provide a good reason for the magma being created and for the distribution of Canary Islands volcanism temporally and spatially. (Anguita & Hernán, 2000)

A locally extensional ridge has also been suggested as the origin of the islands. That a rift during the Cenozoic era was responsible for the Canary Islands' origin was suggested due to evidence of a large amount of extension found in basal complexes (Fúster, 1975). The idea was proposed again as part of an enormous rift zone spanning Central Europe to Cape Verde (Oyarzun et al., 1997). The major problem with this hypothesis, however, is that there has been much evidence indicating the oceanic crust surrounding the Canary Islands is Jurassic in age. Additionally, while there are three major dike outcrops, the azimuth of each is different. The model of the rifting event is thus difficult to explain. A further impediment to this hypothesis is the lack of Cenozoic crustal material added onto the sea floor that separates the islands. (Anguita & Hernán, 2000)

A more likely explanation is that a hot spot or mantle plume is responsible for Canaries volcanism, but according to Anguita & Hernán (2000), there are problems with the various forms of this hypothesis. The Canary Islands were first compared to a classic mantle hot spot like the Hawaiian Islands by Morgan (1971). The plume was modeled as a "blob", and also as an upwelling sheet. Long time gaps (up to 7 million years) between interruptions are in contrast to the steadily erupting Hawaiian Islands, with only a gap of 1 million years. The progression of the African tectonic plate as seen in the volcanic activity of the Canary Islands is very irregular. Further complicating the hot spot model is the fact that nearly all of the islands on the Canary archipelago have erupted in relatively recent times. Additionally, the Canary Islands' volcanic activity has been occurring for 30-80 million years and has been separated into different cycles of magmatism. (Anguita & Hernán, 2000) Building on the classic plume and hot spot ideas, the most recent proposed solution for the origin of the Canaries is a unifying model.

Anguita and Hernán (2000) put forth their unifying model to put together past ideas about the Canary Islands. Given the complexity of the space-time relationships involved in volcanism in this region, a more thorough model serves to tie up some loose ends from previous hypotheses. Seismic tomography allowed a mantle thermal anomaly to be imaged under the Canary Islands, North Africa, and central and western Europe (Hoernle et al., 1995). The anomaly exists only in the upper mantle, and is in the shape of a sheet rather than a plume. Therefore, the anomaly is not a plume that originates from the core-mantle boundary. Anguita and Hernán propose that this anomaly is the remnant of a "fossil" plume that entered the upper mantle toward the end of the Triassic (around 200 million years ago). That plume has outcrops of lava flows, tholeiitic dikes, and sills that cover approximately 7 million km^2 of area from SW Europe to NW Africa to North and South America. The actual model proposed (Figure 5) integrates volcanoes of the Atlas Mountains with the magmatic body previously described, and seeks to explain the uplift and time-space relationships associated with volcanism of the Canaries. Magma traveled by fractures created from a failed rift arm in the Mesozoic from the thermal anomaly. The connection is supported by the fact that the Atlas Mountains and the Canary Islands share the same type of structures in faults, and the alternating magmatism at the Canaries coincides with compressive phases of the Atlas Mountains and of the Atlantic. Supported and "unified" in this hypothesis are three main ideas that were proposed previously. The hotspot exists, and has its origin as the thermal anomaly. Next, the propagating fracture allowed the magma from that body to be transported to the surface. Last, tectonic uplift is supported. (Anguita & Hernán, 2000)

Methods

Volcanic samples from the Canary Islands were compiled using the GEOROC database, an online resource maintained by The Max Planck Institute for Chemistry in Mainz. The database is a collection of published chemical analyses of volcanic rocks and mantle xenoliths from studies that have taken place around the world. Included in the data provided by GEOROC are concentrations of major and trace elements, ratios for radiogenic and non-radiogenic isotopes, and analytical ages for samples of whole rock, glasses, minerals, and inclusions.

I focused on volcanic, whole rock analyses from the Canary Islands, and the data were filtered to remove samples that contain evidence for alteration or metamorphism, high water contents, incomplete chemical analyses, and extreme outlying data points. Iron content in the data is reported as either FeO (ferrous oxide), Fe_2O_3 (ferric oxide), or FeOT (total iron). I normalized the iron values so that each sample reported FeOT. This was done by multiplying Fe_2O_3 by the conversion factor 0.8998, and adding this value to any remaining FeO reported in the sample. The samples were separated by each major island of the Canaries, and major oxides were graphed against MgO. These graphs were compared with ones that contain samples from the entire Canaries archipelago (Carracedo et al., 2002).

The practice of using magnesium oxide (MgO) graphed against various major oxides (Mg variation diagrams) allows the composition of volcanic rocks to be easily classified on the basis of having a mafic (magnesium-rich), felsic (silica rich), or an intermediate composition. The extrusive igneous rocks that erupt in the building of ocean islands such as the Canaries can give important information about magma origin, composition, evolutionary processes, and mantle dynamics.

Results and Discussion

The island with the most geochemical analyses is Tenerife (Table 1), and data from this island were plotted against data from each of the other major islands. Each of the islands was similar to Tenerife when viewed as an Mg variation diagram, except for Lanzarote. I have included in this paper plots for Tenerife and Lanzarote (Figure 6) and Tenerife and Gran Canaria (Figure 7). The Tenerife/Lanzarote plots highlight the differences in composition that exist between these islands, and the Tenerife/Gran Canaria comparison is used to show the similarities in composition between islands that are closer to each other temporally and spatially.

The majority of volcanic rocks from the Canary Islands are alkaline and not saturated in silica. This is shown on the total alkaline versus silica (TAS) chart (Figure 8). A mostly bimodal distribution consisting of primarily trachyte-phonolites and basalt-basanites is found on the whole (See Appendix A for naming classification scheme of volcanic rocks). There also exist carbonatites, and with the exception of the Cape Verde islands, the island of Fuerteventura is the only oceanic island that contains carbonatites exposed at the surface (Carracedo et al., 2002).

Fresh volcanic rock analyses indicate that a majority of samples are either moderately alkaline or highly alkaline in composition (Figure 8). Tholeiitic rocks are found only in two places: a recent eruption on Lanzarote, and in the oldest units of Gran Canaria. Olivine nephelinites and olivine melilitites, which are ultra-alkaline rocks, are found primarily in the most recent phases of volcanic activity at Fuerteventura and Gran Canaria. (Carracedo et al., 2002) The basalts of the Canary Islands are alkaline where shield-building is represented (Figure 2). In the declining stages of volcanism, phonolites and trachytes are predominant. Nephelinites and basanites comprise the rocks found in rejuvenation stages (Viñuela, 2007).

Hierro and Lanzarote have the least felsic rocks, and this is seen in the case of Lanzarote in Figure 6. In contrast, Tenerife and Gran Canaria have the highest percentages of felsic rocks (Figures 6 and 7). (Carracedo et al., 2002) The Mg variation diagrams show trends that are similar amongst the islands (Figure 9). MgO decreases in basalts, basanites, and nephelinites, while FeO and CaO decrease somewhat. Al_2O_3 increases rapidly, and TiO_2 rises slightly (Figure 9). According to Carracedo et al., these variations represent the primary role that olivine and clinopyroxene play in magma differentiation (2002). These variations and the history of magma differentiation will be compared with other oceanic islands in the future.

Conclusions and Recommendations for Future Work

The Canary Islands are an oceanic island archipelago that lie on old oceanic crust (Jurassic) and are complex with respect to the geochemical composition of its magmas, its volcanic history, and relations to regional tectonics. Many hypotheses have been put forth for their origin, including a propagating fracture, a local extensional ridge, uplifted tectonic blocks, classic and modified hotspot models, and a unifying model based on a mantle thermal anomaly. The composition of the volcanic rocks found on the islands is mainly alkaline, but shows a bimodal distribution. The similarities to the Hawaiian Islands support the conjecture of an active hotspot, but the differences in magma composition and space-time relationships beg further explanation and study.

The Canary Islands have been the subject of much scientific research in the geosciences. However, there is certainly more that could be done. The overall composition of the lithologies that make up the Canaries is known, but a more complex modeling of the magma chambers could be developed. This includes study of the pressures and temperatures of crystallization, which could lead to a more precise location of active magmatism under the archipelago. One could break down the analyses from island to island and within individual volcanoes to help constrain the model.

The complex geologic and tectonic setting of the Canary archipelago, the Atlas Mountains, and the individual islands themselves allows many avenues of research from petrologic studies to geophysical surveys and structural interpretations. There remains more to be known in the understanding of mantle plumes and how ocean island chains form. Studies related to the evolution and mixing of magmas may prove useful to understanding the compositional differences in the Canaries between certain islands and volcanoes, and how they compare to other oceanic islands.

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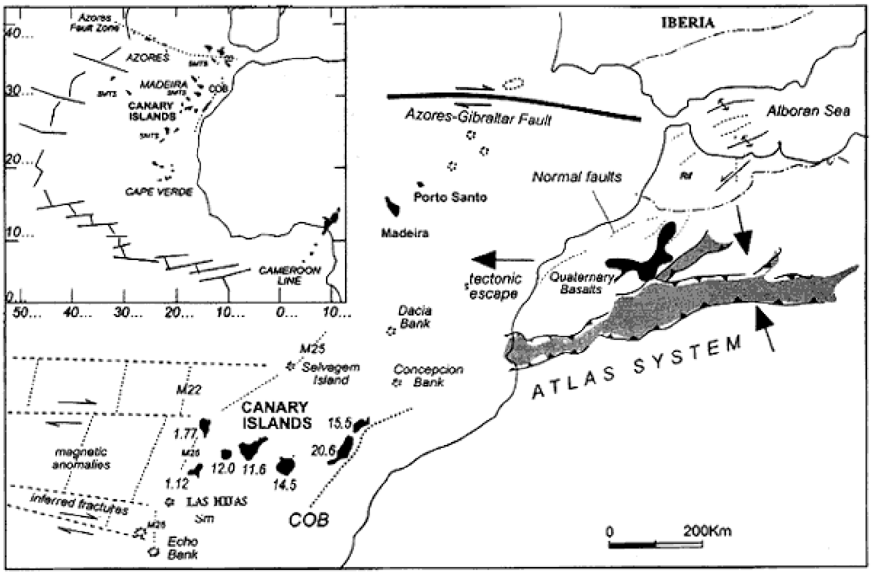


Figure 1. Geographic and geodynamic setting of the Northwest African continental margin showing the Canary Islands and other island groups. (Carracedo et al., 2002)

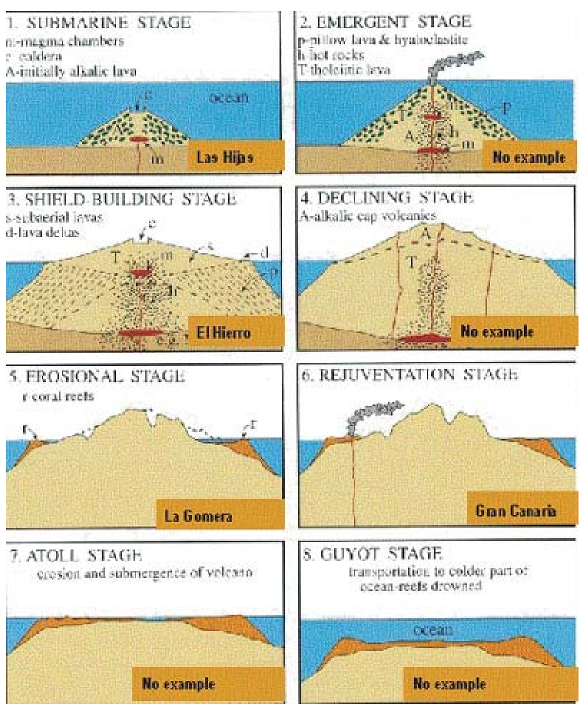
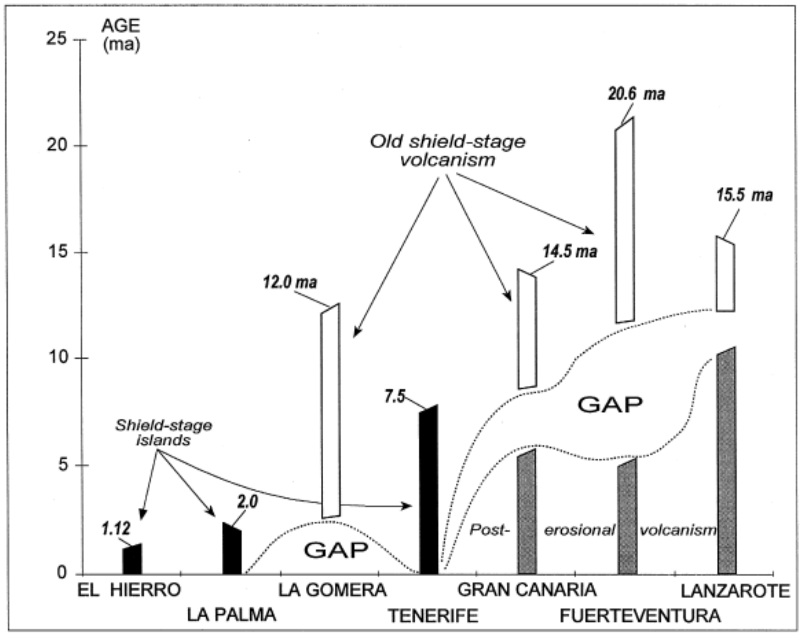
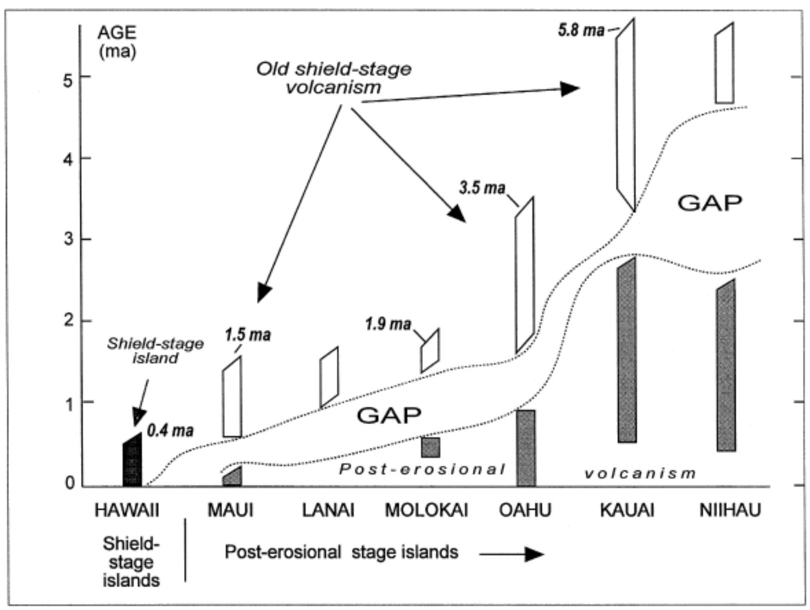


Figure 2. The stages of construction of oceanic islands with examples from the Canaries. (Viñuela, 2007)



A)



B)

Figure 3. Published K/Ar ages from lavas of the Canary Islands (A) and the Hawaiian Islands. The gaps in eruptive activity give rise to two main stratigraphic units within the archipelagos: Shield stage, and post-erosional stage volcanic activity. (Carracedo, 1999)

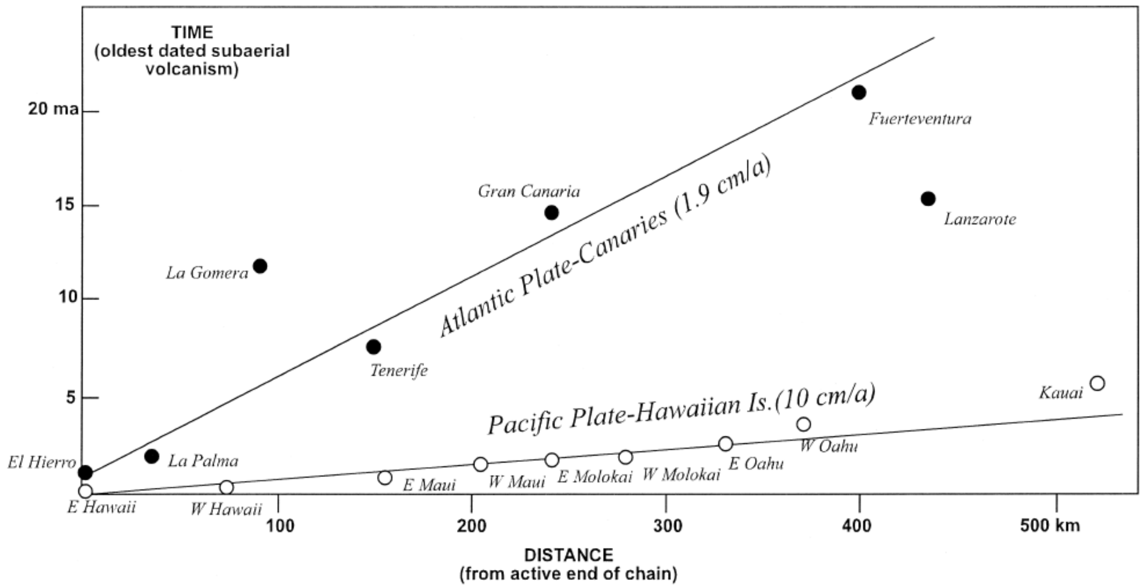


Figure 4. The space-time relationships of eruptive activity of the Hawaiian Islands and the Canary Islands. (Carracedo et al., 1998)

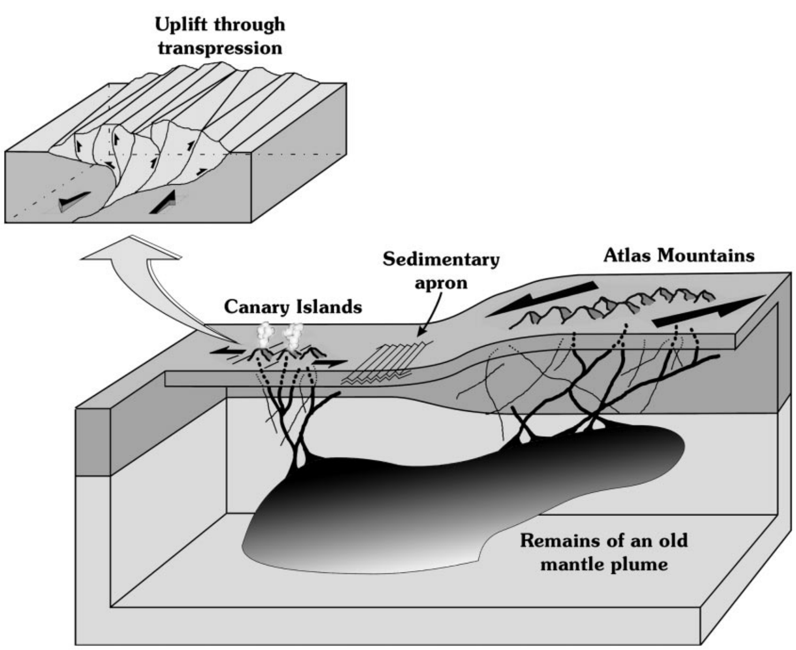


Figure 5. The unifying model of the origin of the Canary Islands. (Anguita & Hernán, 2000)

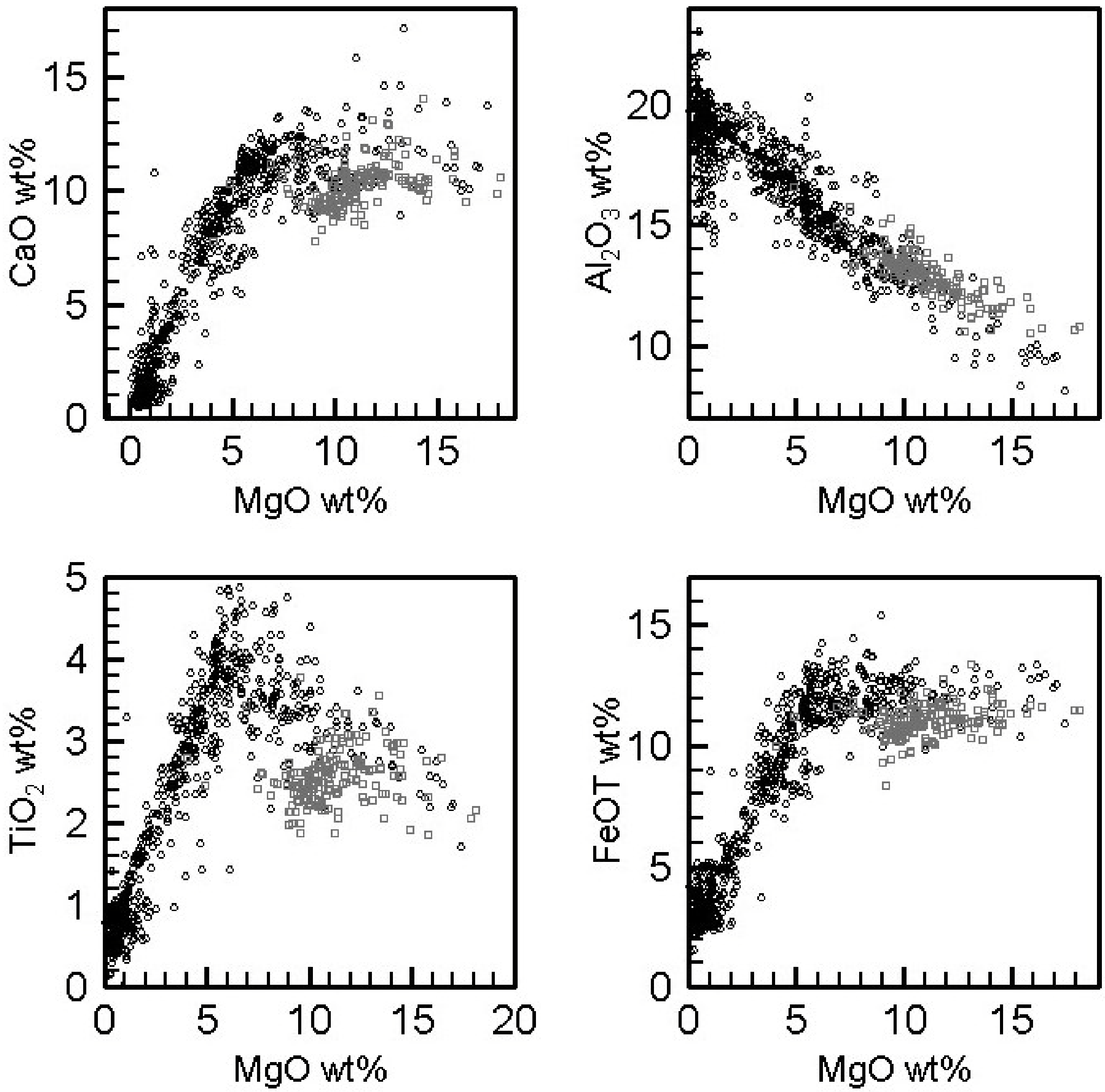


Figure 6. Mg variation diagrams for Tenerife (black) and Lanzarote (gray).

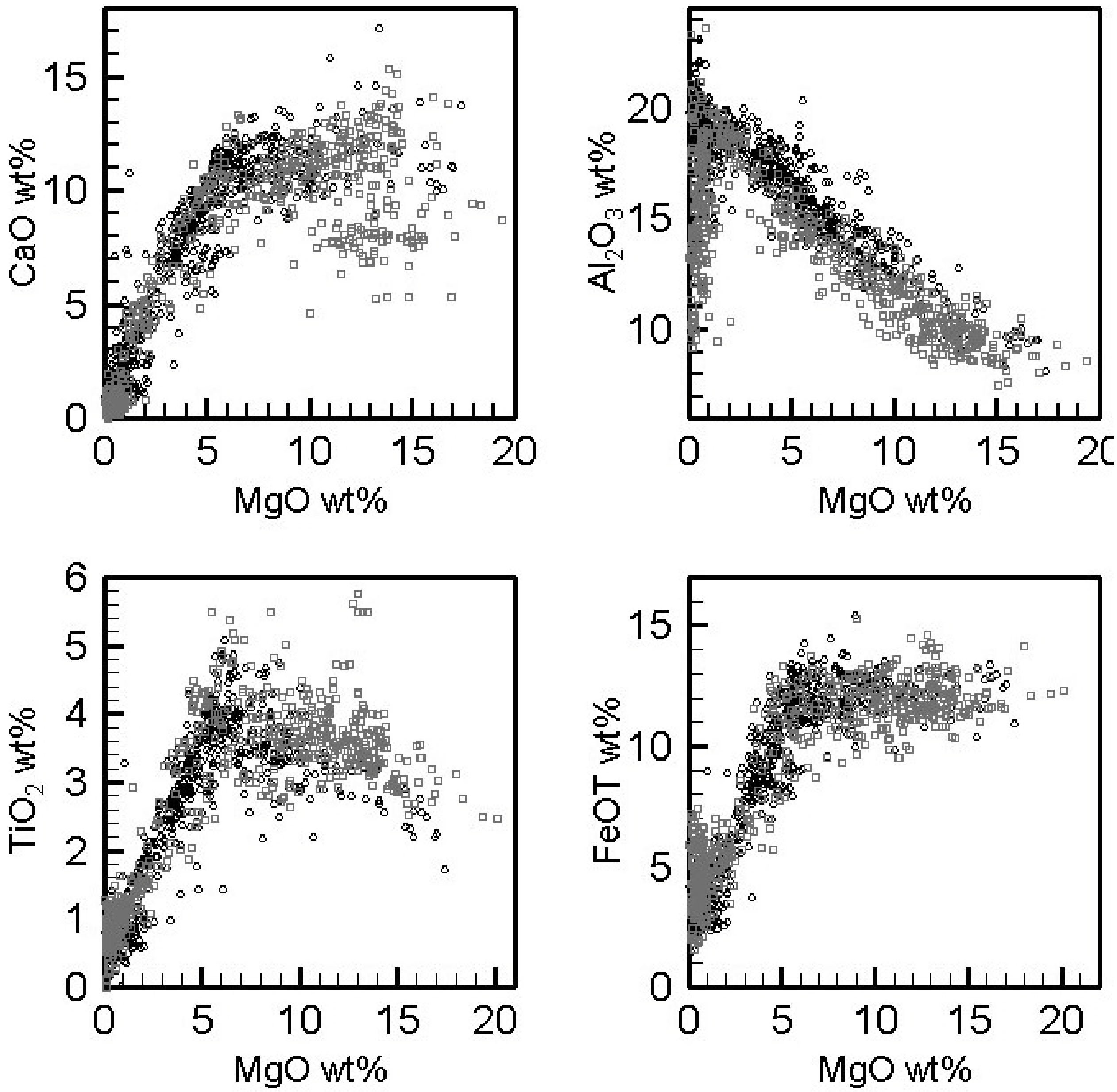


Figure 7. Mg variation diagrams for Tenerife (black) and Gran Canaria (gray).

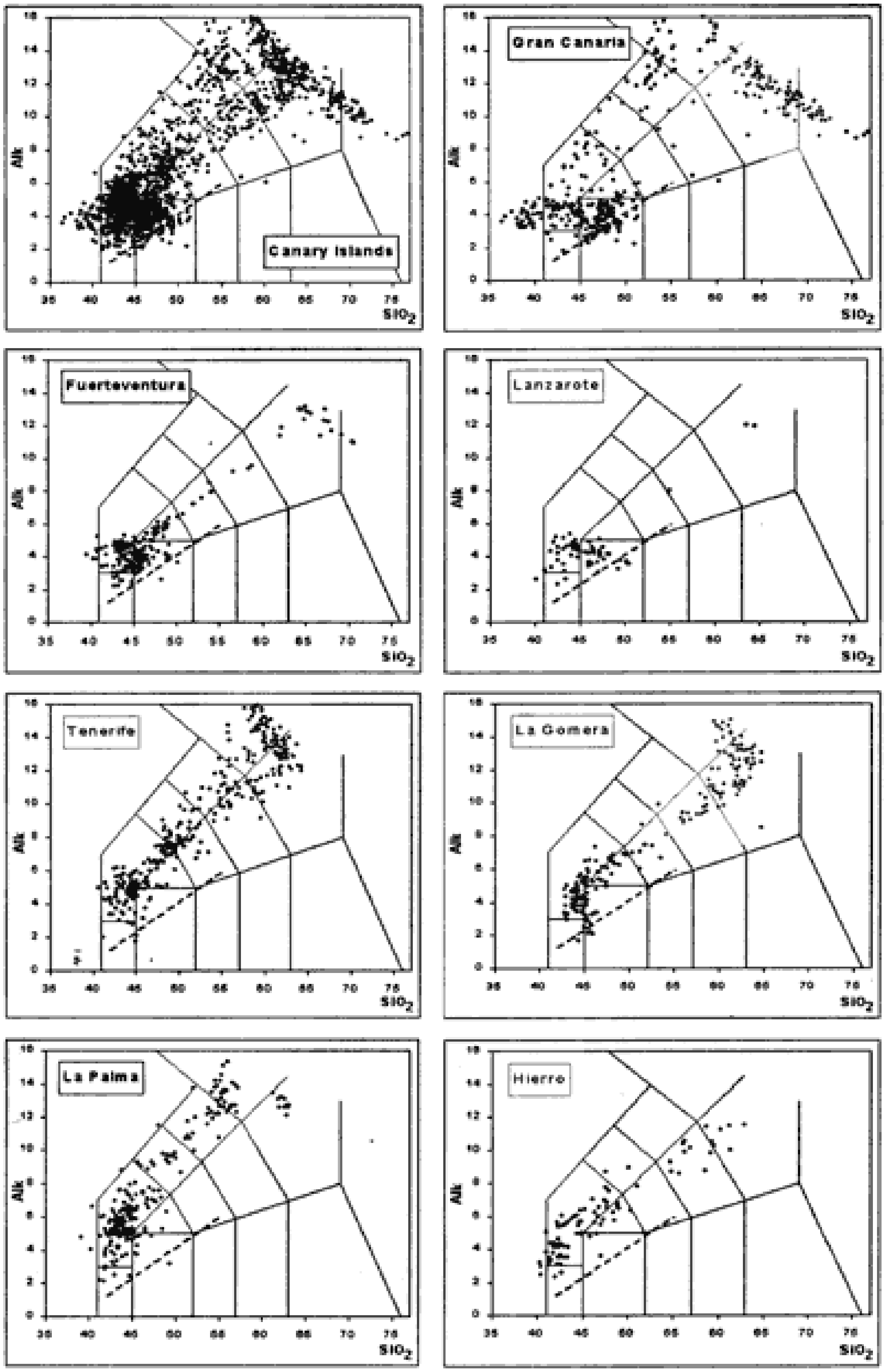


Figure 8. Diagrams of total alkali versus silica (TAS). The dashed line represents the alkali-tholeiite boundary. (Carracedo et al., 2002)

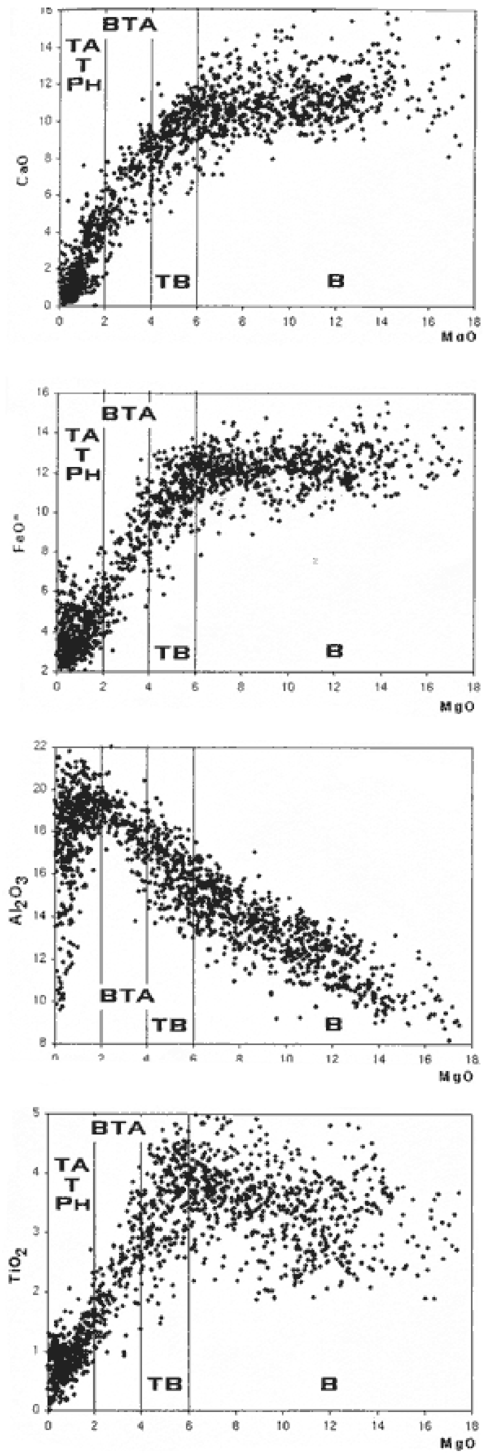


Figure 9. Mg variation diagrams for all islands of the Canaries. Key: B, basaltic rocks; BTA, basaltic trachyandesites and phonotephirites; PH, phonolites; T, trachytes; TA, trachyandesites and tephriphonolites; TB, trachybasalts and tephrites. (Carracedo et al., 2002)

Table 1. Quantity of geochemical analyses by island.

Island	Number of Samples
El Hierro	157
Fuerteventura	138
Gran Canaria	693
La Gomera	186
La Palma	324
Lanzarote	187
Tenerife	753

Appendix A

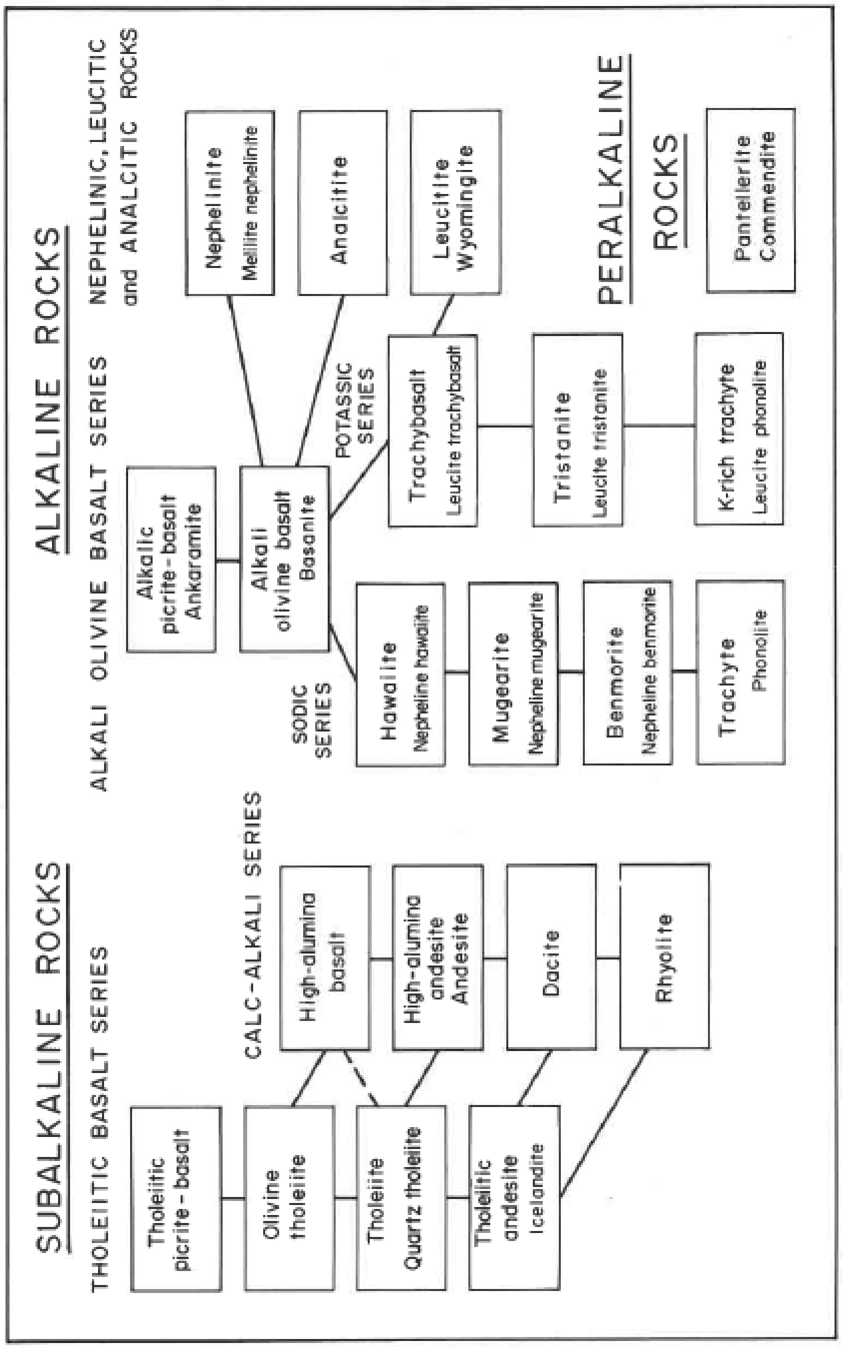


Figure A-1. General classification scheme for common volcanic rocks. Lines join commonly associated rocks. Small print highlights variants of a particular rock. (Irvine and Baragar, 1971)

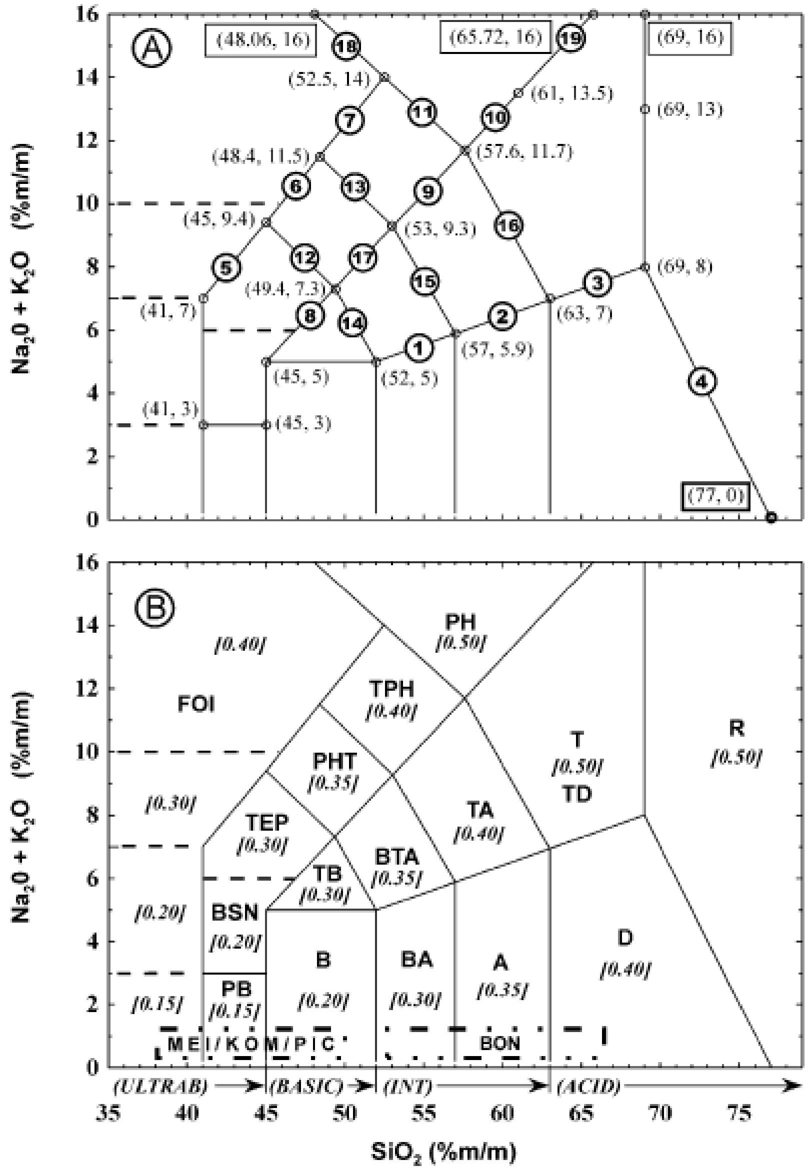


Figure A-2. Total Alkali vs. Silica (TAS) classification scheme for volcanic rocks. (Verma et al., 2002)

Table A-1. Abbreviations of volcanic rock types. (Verma et al., 2002)

Abbreviation	Rock type	Condition
A	Andesite	—
B	Basalt	—
B, alk	Alkali basalt	Nen
B, subal	Subalkali basalt	Hyn
BA	Basaltic andesite	—
BSN, bsn	Basanite, basanite	$Ol_n \geqslant 10$, $Ab_n \geqslant 5$, $Ne_n < 20$
BSN, mnp	Basanite, melanephelinite	$Ol_n \geqslant 10$, $Ab_n < 5$, $Ne_n < 20$
BSN, np	Basanite, nephelinite	$Ol_n \geqslant 10$, $Ne_n \geqslant 20$
BTA, mug	Basaltic trachyandesite, mugearite	$(Na_2O-2) \geqslant K_2O$ (%m/m)
BTA, sho	Basaltic trachyandesite, shoshonite	$(Na_2O-2) < K_2O$ (%m/m)
D	Dacite	—
FOI, bsn	Foidite, basanite	$Ab_n \geqslant 5$, $Ne_n < 20$
FOI, mnp	Foidite, melanephelinite	$Ab_n < 5$, $Ne_n < 20$
FOI, np	Foidite, nephelinite	$Ne_n \geqslant 20$
PB	Picrobasalt	—
PH	Phonolite	—
PHT	Phonotephrite	—
R	Rhyolite	—
R, palk	Peralkaline rhyolite	$PI \geqslant 1$
T	Trachyte	$Q_n < 20$ in QAPF
T, palk	Peralkaline trachyte	$PI \geqslant 1$
TA	Trachyandesite	—
TA, ben	Trachyandesite, benmoreite	$(Na_2O-2) \geqslant K_2O$ (%m/m)
TA, lat	Trachyandesite, latite	$(Na_2O-2) < K_2O$ (%m/m)
TB	Trachybasalt	—
TB, haw	Trachybasalt, hawaiite	$(Na_2O-2) \geqslant K_2O$ (%m/m)
TB, pot	Potassic trachybasalt	$(Na_2O-2) < K_2O$ (%m/m)
TD	Trachydacite	$Q_n \geqslant 20$ in QAPF
TEP, bsn	Tephrite, basanite	$Ol_n < 10$, $Ab_n \geqslant 5$, $Ne_n < 20$
TEP, mnp	Tephrite, melanephelinite	$Ol_n < 10$, $Ab_n < 5$, $Ne_n < 20$
TEP, np	Tephrite, nephelinite	$Ol_n < 10$, $Ne_n \geqslant 20$
TPH	Tephriphonolite	—
MEI	Meimechite	—
KOM	Komaiite	—
PIC	Picrite	—
BON	Boninite	—

[a] Hyn = Hypersthene normative, Nen = Nepheline normative. Ab_n, Ne_n, Ol_n, Q_n represent percentage of normative albite, nepheline, olivine, and quartz, respectively. PI = peralkaline index = $(Na_2O + K_2O)/Al_2O_3$ (molecular ratio). QAPF = Quartz-alkalifeldspar-plagioclase-feldspathoid double-triangle (Le Maitre et al., 1989)