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NOTE ON THE ZONATION OF THE UPPER CENOZOIC VULCANISM OF THE ANDEAN AREA OF CENTRAL-SOUTH CHILE AND ARGENTINA

by

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ABSTRACT

Based on the summaries of published vulcanological papers, as well as new chemical and petrographical analyses of different volcanic centers and areas of this region, it is deduced that there is a change in the nature of the Upper Cenozoic vulcanism, from the Pacific to the Atlantic continental border.

Two petrological series are distinguished: 1) the Circumpacific series, and 2) the extra Andean series. The Circumpacific series is in general calc-alkalic, in contrast with the extra Andean series, which is alkaline.

Within the Circumpacific series two rock groups have been differentiated, which are distributed as parallel chains and are from west to east: the Neogenic volcanic rocks formed mainly by hypersthene andesites with an alkali-lime index of 58.7, and the Pleistocenic-Recent volcanic rocks, formed chiefly by olivine basaltic-andesites, with an alkali-lime index of 56. The first group of rocks, by its petrographical and chemical characteristics, is similar to the major part of the Circucpacific volcanic chains; instead, the second group has some analogies with the "high alumina basalt" series of Japan, except a major content of Na_2O.

The extra Andean series represents the volcanic series farthest away from the Pacific margin. The petrographic sequence is represented by olivine basalts to alkaline trachytic. The alkali-lime index is 51, which indicates an alkaline character in Peacock's sense.

The parallelism of the alkaline increase of the volcanic rocks towards the Atlantic, specially the K_2O content, with the depth of the seismic foci is stated. The origin of the calc-alkaline volcanic chain and the growth of the continent in relation with the sea-floor spreading hypothesis is discussed.

RESUMEN

Sobre la base de la síntesis de los antecedentes vulcanológicos publicados, más nuevos análisis químicos y petrográficos de diferentes centros y áreas volcánicas de esta región, se concluye que existe un cambio en la naturaleza del vulcanismo cenozoico superior, desde el borde continental Pacífico al Atlántico.

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Se distinguen dos series petrológicas: 1) la serie circumpacífica y 2) la serie extra-andina oriental. La serie circumpacífica es en general calcoalcalina, a diferencia de la serie extra andina-oriental, que es alcalina.

Dentro de la serie circumpacífica se han diferenciado dos grupos de rocas que se distribuyen como cordones paralelos y que de Oeste a Este son: las rocas volcánicas neógenas, constituidas principalmente por andesitas de hipersteno con índice álcali-cálcico de 58.7, y las rocas volcánicas pleistocenas recientes, constituidas sobre todo por andesitas basálticas de olivina, con un índice álcali-cálcico de 56. La primera, por sus características petrográficas y químicas, es similar a la mayor parte de los cordones volcánicos circumpacíficos, en cambio la segunda tiene algunas analogías con la serie "high alumina basalt" de Japón, excepto un mayor contenido de Na_2O.

La serie extra-andina oriental representa la serie volcánica más alejada del borde Pacífico; la secuencia petrográfica está representada por basaltos de olivina a traquitas alcalinas. El índice álcali-cálcico es de 51,0, lo que señala un carácter alcalino en el sentido de Peacock.

Se plantea el paralelismo del aumento de la alcalinidad de las rocas volcánicas hacia el Atlántico, especialmente K_2O con el aumento de la profundidad de los focos sísmicos. Se discute el origen del cordón volcánico calcoalcalino y el crecimiento del continente en relación con la hipótesis del desplazamiento del fondo oceánico.

Introduction

This is a synthesis of the chemical and mineralogical features of the Upper Cenozoic volcanic rocks of the Andean area located between parallels 31° and 42° South latitude, and also of rock samples belonging to some extra-Andean volcanoes; both series have been herewith checked and duly discussed in relation to their petrological characteristics (Fig. 1).

The Circumpacific region has been and is being intensely studied by geologists and geophysicists, whose object is to correlate its history with the nature of the upper mantle.

The area covered in this study corresponds to a section of the Andean orogenic belt, which consists of young volcanic chains, seismic zones, an oceanic trench, geosynclinals folded sediments, granitic batholiths, coupled metamorphic belts and peridotitic massifs, all probably delineated by a plate contact zone. Our endeavour is then to give a synthesis of the young volcanic belts with a special reference to the zonality of the Cenozoic volcanic characteristics taken from the continental margin to the interior of the continent.

Closely related to the chemical zonality of the Circumpacific vulcanism, an idea has arisen about a possible relationship of this problem with the geophysical and structural features that are mainly connected with the Benioff seismic plane.

Early in the century, Harke and Becke divided the igneous rocks on the basis of their mineralogical, chemical and structural characteristics into two

large groups: The Pacific and the Atlantic series. The Pacific series rocks are calcic and are associated with the orogenic belts. The Atlantic series rocks are alkaline and are associated with non orogenic areas. Further research determined the existence of various types of intermediate rocks, which makes the above mentioned division unreasonable. Recently, according to combined geochemical and geophysical studies, some gradual variations have been established within the restricted petrographical provinces. This stresses the difficulty of applying fixed petrogenetic models.

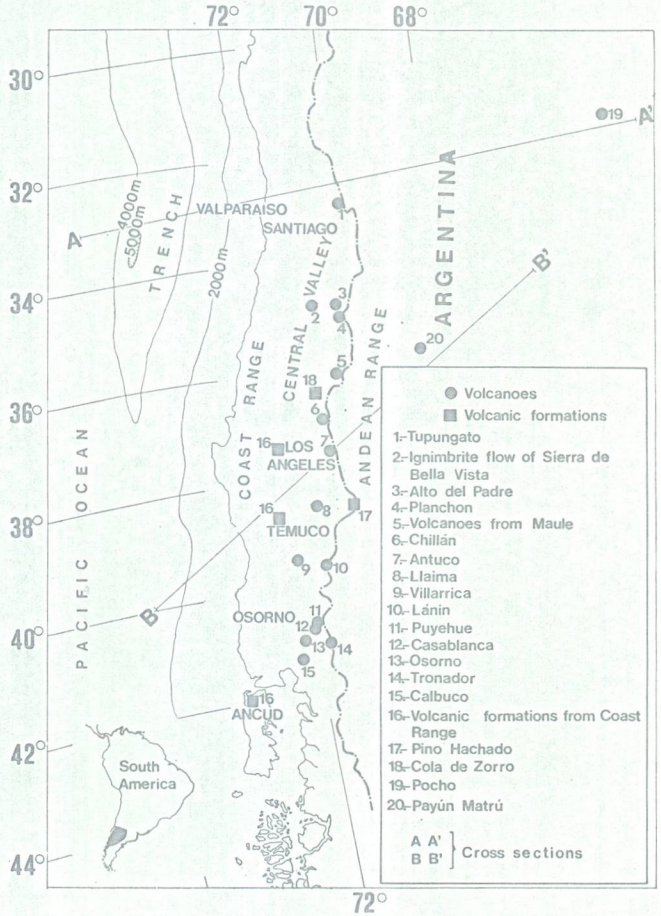

Fig. 1: Index map showing location of the volcanoes and volcanic formation, profils and the trench referred to in the text.

Several researchers have devoted their attention to the problem of volcanic zonality in relation to tectonic and geophysical features in several sections of the Circumpacific area, for example: KUNO (1966 and 1968); RITTMANN (1963); SUGIMURA (1968); GORSHKOV (1962); COATS (1962); KATSUI (1968); DICKINSON and HATHERTON (1967 and 1969).

At present, our knowledge of the Upper Cenozoic vulcanism in the Chilean Andean area and in the Argentine territory is rather incomplete, and most of the works have a preliminary character. However, in the course of recent years a full study of vulcanism in the Chilean area has been launched and this has enabled us to gather numerous isolated data which synthesis we are presenting herewith. We take advantage in incorporating numerous previous projects that are still under preparation.

We shall present in sequential order the previous works related to volcanic areas of different geographic and geologic nature: the Andean volcanic area and the east extra-Andean volcanic area.

Andean volcanic area

This area covers the coastal range, the central valley and most of the Andean watershed in Chile, where volcanoes and volcanic formations of the Upper Cenozoic crop out.

Within this region, two large groups are to be distinguished: 1) volcanic rocks associated with preserved volcanic centers, that are considered Recent-Pleistocene, and 2) older volcanic rocks, that crop out like plateaus without structural data as to places of emission and that we have considered as volcanic formations of Neogenic age.

The latter constitute volcanic plateaus of continental origin in the Andean Range. They contain pyroclastics and lava flows interstratified with marine sediments of the Miocene, particularly in the Coastal Range and the Central Valley of Chile (VERGARA, in preparation). The figure 1 shows the locations where chemical analyses are available.

The figure 1 also shows Recent-Pleistocenic volcanic areas, discussed in this paper, which seems to center principally around the higher Andean Range. The mineralogical and chemical characteristics of these rocks are described in the following papers: LARSSON (1940); GONZALEZ y VERGARA (1962); KLERK (1965); KATSUI and KATZ (1967); VERGARA y KATSUI (1969); THIELE y KATSUI (1969), VERGARA (in preparation).

Neogenic vulcanism

The rocks of this unit are distributed in two elongated zones (B 1), one of which is constituted by a volcanic range which is quite eroded and located along the Coastal Range, as far as Los Angeles in the North and down to Ancud in the South; the second one (B 2) runs along the higher section of the

Andean Range (Fig. 1). Chemical analyses have been taken of the existing rocks in Ancud, Temuco (Pilmahue Formation, GARCIA, 1968) and Los Angeles, in relation to the first one. As regards the second unit, chemical analyses of its existing rocks have been taken in Paso Pino Hachado and in the Cola de Zorro quebrada.

In the Ancud and Temuco region, the rocks of the first unit are interstratified with Miocene fossiliferous marine sediments (GARCIA, 1968, p. 45), an age which was corroborated by potassium-argon determinations, following a similar procedure as with Los Angeles rocks (VERGARA y MUNIZAGA, 1970). There are no radiometric previous data as regards the rocks that crop out in the Cola de Zorro quebrada, although it seems very much like the Ancud-Temuco-Los Angeles Formations, as seen mainly from its lithologic correlation. Rocks belonging to these formations have a tectonic style which is characterized by mild and local folds aside from several gravitational faults.

The rocks belonging to these two elongated zones are quite homogeneous from a petrographical point of view, with the exception of the Pino Hachado Formation. They are mainly formed by andesites with andesine phenocrysts, and labradorite, hyperstene, augite and, in a minor proportion, amphibole. Olivine is very scant. The ground mass is constituted by glass, oligoclasa microlites, orthopyroxene, amphibole, biotite, clorite, iron oxide and tridymite.

These rocks have similar mineralogical features to the Japan calc-alkaline rocks (Hyperstenic Series, KUNO, 1950) and they are also similar, from the chemical point of view, to the Cascade Range (CARMICHAEL, 1964), as shown in the AFM diagram (Fig. 2) where the calc-alkaline trend of the latter region is to be observed. The alkali-lime index of these rocks amounts to 58.7 (calc-alkaline according to Peacock) and it is very similar to the value of the Western Cascade volcanic rocks (alkali-lime index of 60), Central Oregon, and the Neovolcanic zones in Mexico (PECK *et al.*, 1964, p. 48). In the diagram Na_2O K_2O - CaO (NKC) it is shown that these rocks are relatively poor in alkaline.

The Neogenic volcanic Formation that crops out in the pass of Pino Hachado, which links the towns of Temuco (Chile) and Zapala (Argentina), shows a chemical and petrographical nature which differs from the previous one. In this area there crop out an extensive volcanic plain which is almost horizontal, formed by riolitic pyroclastic flows and lava flows of a trachyandesitic composition mainly which contain phenocrystals of intermediate plagioclase, anorthoclase and amphibole rich in titanium. The age of this formation is being checked at present by means of radiometric methods (VERGARA y MUNIZAGA, 1970), although its structural style is similar to that of the Cola de Zorro Formation, which fact suggests that it could be of the same age. For its mineralogical and chemical character, this series is the most alkaline known until now within the Andean range. The figure 3 shows its rich alkaline character in AFM projection and also its tendency to a marked increase in potassium as far as the NKC projection is concerned.

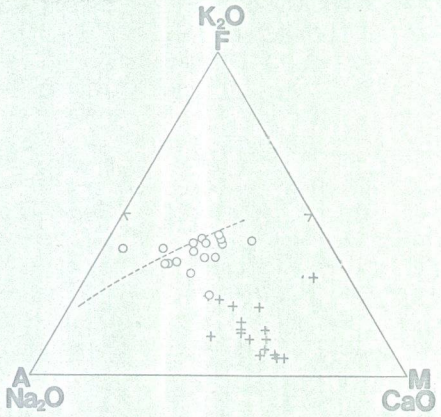

Fig. 2: AFM/NKC diagrams for Neogenic coast range volcanic formations

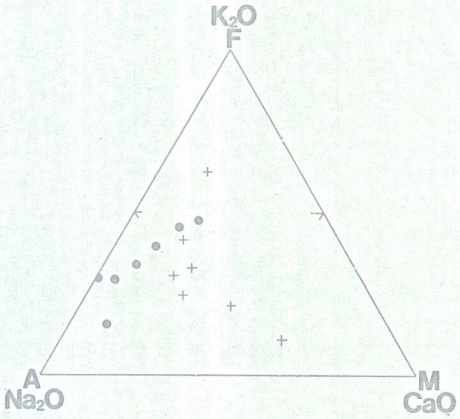

Fig. 3: AFM/NKC diagrams for Pino Hachado volcanic formation.

Recent-Pleistocenic vulcanism

It is the volcanic belt located in the higher section of the Andean range, whose flows are directly related to central volcanic conducts or to well preserved local fissures, which are distributed following continuous structural lines in the Andean area. From the point of view of their lithology they consti-

tute a petrographical series formed mainly by basaltic andesites and andesites. The most basic rocks contain olivine phenocrysts with a reaction rim, clinopyroxenes (subcalcic augites and augites) and bytownite-labradorite. In the ground mass of these rocks there are clinopyroxenes. In the most acid rocks that constitute from the point of view of their volume a less significant fraction, there appear orthopyroxenes phenocrysts and in the ground mass there are also amphibole and biotite associated with microphenocrysts of iron oxides. In the ground mass of almost all of the series there appear tridymite and interstitial anorthoclase.

According to VERGARA and KATSUI (1969, p. 45) this series of volcanic rocks has many chemical and mineralogical analogies with the Japan "high alumina basalt series". According to the AFM diagram (Fig. 4) a trend of fractionation by crystalization is observed, indicating a mild increase of iron in the intermediate stage and also a residual fraction which is rich in alkalis, particularly with a higher sodium than potassium, which is deduced in the NKC projection where a general tendency towards Na_2O is observed.

Altogether, the Neogenic and Recent-Pleistocenic volcanic formations of the Andean area (Chile), with the exception of Pino Hachado Formation of rocks, have an alkali-lime index of 56.2, which corresponds to the calc-alkaline series according to Peacock, corroborated by the already described mineralogy of each of these units.

Extra-Andean volcanic area

It covers the volcanic regions located east of the oriental versant of the Andean range, which is an area that coincides with the "Andean foreland" of AUBOUIN and BORRELLO (1966, p. 1050).

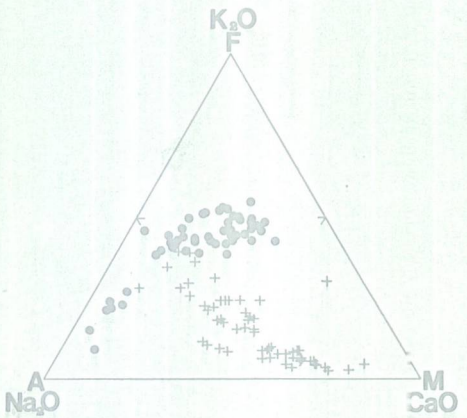

Fig. 4: AFM/NKC diagrams for Pleistocenic-Recent Andean vulcanism.

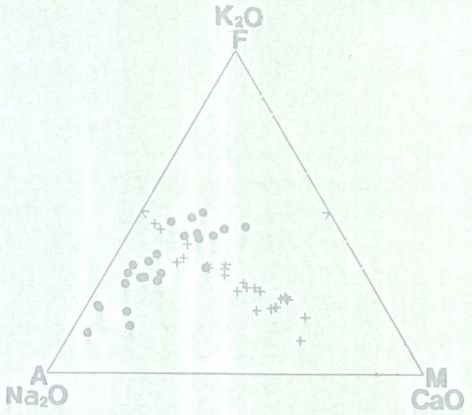

Fig. 5: AFM/NKC diagram for Pocho and Payún-Matrú volcanoes.

The previous data that we were able to gather from this area are scarse. In this respect we have considered the studies of HIECKE-MERLIN and PICCOLI (1961) on the volcanic group of Pocho, located in the Cordoba Sierras, which ranges from Miocene to Quaternary and of the study of LLAMBIAS (1966) on the Payún Matrú volcano, Recent-Pleistocenic, located south of Malargüe, Mendoza.

The petrographic sequence of both volcanoes is represented by olivine basalt, trachyandesite, andesites and trachytes. They are characterized by modal anorthoclase, alkaline amphibole asd oxihornblende, diopsidic augite and titanoaugite. Chemically, they contain a high percentage of alkali, potassium in particular, which is represented by feldspatoides in the norm. However, modal feldspatoides have not been described. The alkaline character of this series is corroborated by its alkali-lime index of 51 which, according to Peacock's classification, is of alkaline character.

In the combined AFM/NKC diagram (Fig. 5) for the samples of the Pocho and Payún Matrú volcanoes, the projection AFM shows the marked alkaline character of this series, and the NKL projection shows a tendency towards balanced increase of potassium and sodium.

General conclusions

From the chemical and mineralogical data already described we can deduce that there are two significant petrologic series of volcanic rocks: 1) the calc-alkaline series of the Circumpacific margin, and 2) the alkaline series of the extra-Andean volcanic area. In order to make these petrologic differences salient, we shall analyse two transverse profiles of the Andes (A-A' and B-B',

figure 1), by establishing a contrast between the chemical features of the volcanic rocks that crop out in these areas. The figure 6 stands for the A-A' profile of figure 1, which establishes a relationship between the Tupungato and Pocho volcanoes with the distribution in depth of the seismic centers. The oceanic trench has also been drawn to show the topographic unevenness.

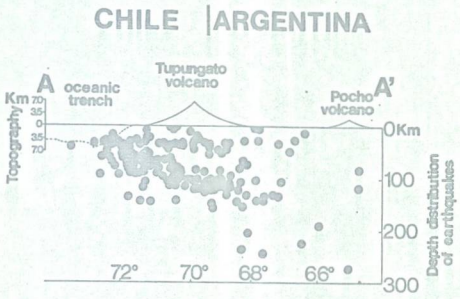

Fig. 6: A-A' profil showing the depth distribution of earthquakes between 30° S and 35° S and its relation with Tupungato and Pocho volcanoes.

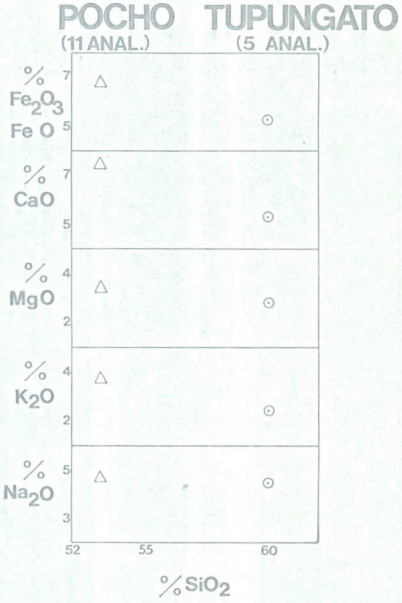

Fig. 7: Variation diagram for Tupungato and Pocho Volcanoes.

Figure 7 stands for a diagram of simple variation as regards averages of chemical analyses of these volcanoes. In both of them, it is observed that the average corresponds to rocks of intermediate composition an that the Pocho rocks are relatively richer in potassium. There is in this profile a concordance between the increase of the depth of the seismic centers and the increase of alkalinity of the volcanic rocks.

It has also been observed in several regions of the Circumpacific margin that the Quaternary volcanoes appear restricted to regions which are located about the site of seismic epicenters of intermediate depth within the Benioff zone. BENIOFF (1954) suggested that this seismic zone could be an adequate spot for the production of volcanic magma in low pressure zones resulting from extension. If we accept the hypothesis that the magma which gives origin to these volcanic rocks is produced alongside this seismic region, the depth in which these rocks are generated would range between 80 and 290 km, corresponding approximately to the "low velocity layer" of the upper mantle, similar to the pattern proposed by DICKINSON and HATHERTON (1967 and 1969) for the areas of Circumpacific continental islands and margins.

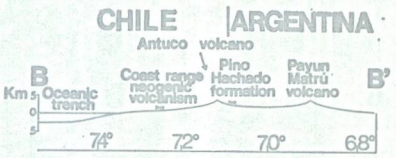

Fig. 8: B-B' profil showing the relation between different volcanoes and volcanics formation referred to in the text.

Figure 8 stands for a profile (B-B', figure 1) of the southern section of the area studied presently. According to KAUSEL and LOMNITZ (1968), this region would not have a Benioff zone and most of the seismic centers would have an insignificant depth and would be located in the coastal zone. This profile cuts different stripes of volcanic rocks which indicate a gradual change from calc-alkaline rocks in the Neogenic range of the Cordillera de la Costa to alkaline rocks of the Payún Matrú volcano.

In the figure 9 we have compiled the chemical average of volcanoes and volcanic formations and we have projected it in simple variation diagram in order to find specific chemical differences. The chemical averages show that in general these rocks are of an intermediate composition and that only the contents of Fe_2O_3 plus FeO presents a gradual change which agrees with the silica contents. The rest of the oxides keep an approximate relationship to what is considered normal with the exception of the Payún Matrú rocks which do not coincide with the general trend due to their high alkaline content, spe-

cially potassium, and a deficit of magnesium and calcium. It is also observed in this profile that there is a change to an increase of the alkaline quality of the volcanic rocks towards the east, and that migh not have any relationship with the Benioff seismic zone, just as in the previous case.

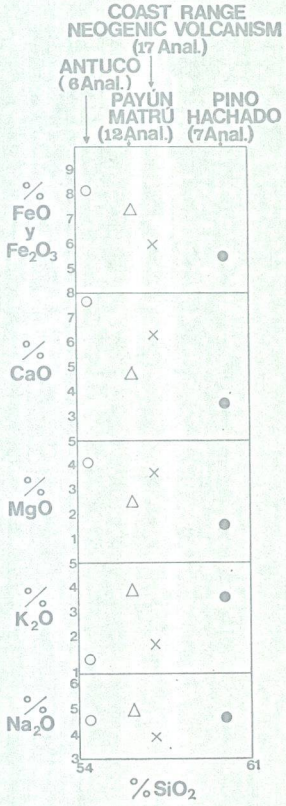

Fig. 9: Variation diagram for Coast Range Neogenic vulcanism Antuco, Pino Hachado Formation and Payún-Matrú volcano.

Figure 10 shows the variation in the content of Na_2O and K_2O regarding the silica of the chemical analyses of the volcanic rocks corresponding to the Andean area and the extra-Andean volcanic zone. In relation to the Na_2O there are no significant differences between the volcanic series studied, but they do exist in relation to the average of orogenic andesites of TAYLOR

and WHITTE (1965), and of basaltic andesites of Izu Kakone, Japan (COATS, 1968) which are notoriously deficient in sodium, all this in relation to the calc-alkaline series of the Andes.

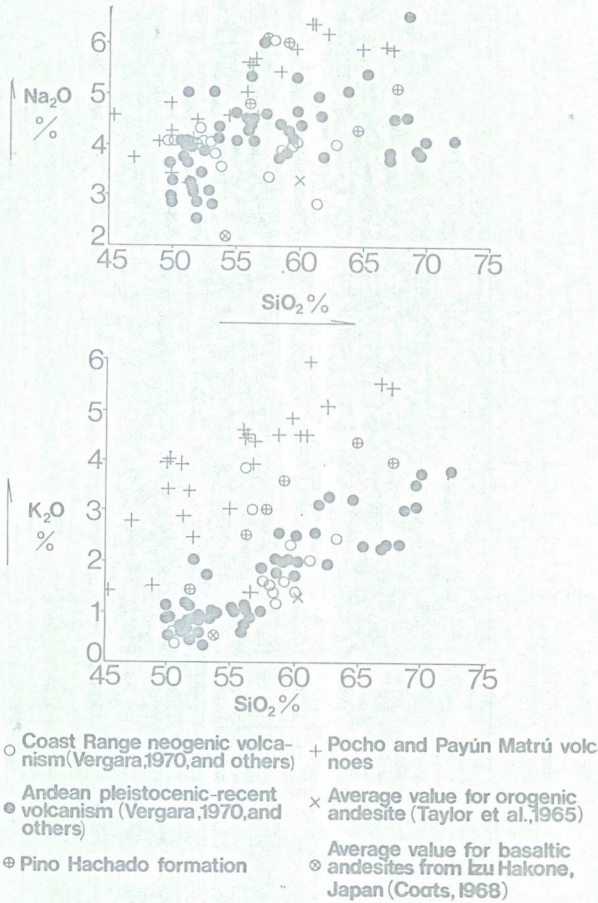

Fig. 10: Partial Harker variation diagram of Na_2O and K_2O vs % SiO_2 for all volcanic rocks referred to in the text.

With respect to the contents of K_2O a gradual change has been observed for the first time, in which there is an increase from the volcanic series bordering the Pacific to the Atlantic. In addition there is a corroboration of the chemical similarity between the Neogenic volcanic formations of the Coastal

Range and the recent Pleistocenic volcanic rocks of the Andean area. The paso Pino Hachado series also stands in an intermediate position between the richest and the poorest members in relation to potassium contents. They are very similar in relation to the orogenic andesites of TAYLOR and WHITTE (1965) and the basalt andesites of Izu Hakone, Japan (COATS, 1968).

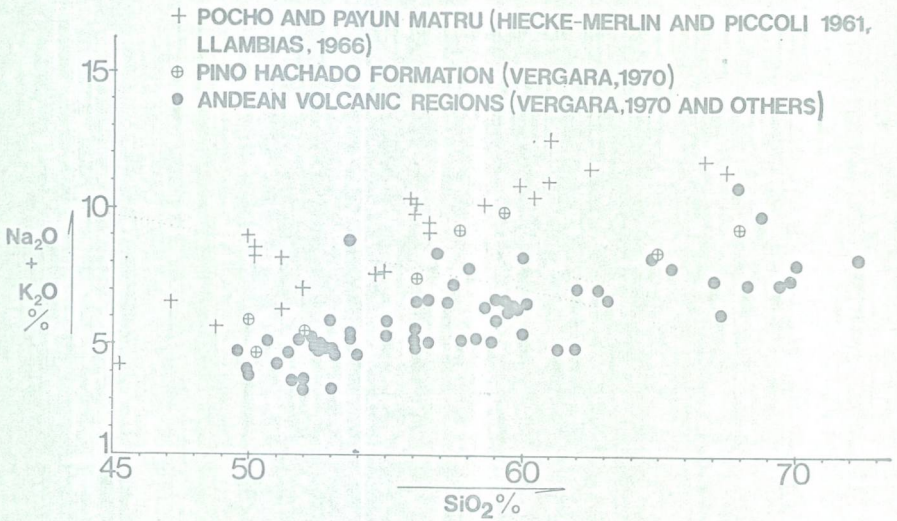

Fig. 11: Partial Harker variation diagram of ($Na_2O + K_2O$) vs % SiO_2 for the volcanic rocks referred to in the text.

Figure 11 shows a diagram of the variation of Na_2O plus K_2O vs silica in the different volcanic rocks considered in this paper. There is a gradual change brought about by an increase of the alkaline contents from the calc-alkaline series of the Circumpacific margin to the east (towards the Atlantic) which resulted in the mineralogical and petrographical changes already pointed out. Figure 12 shows the average lines as regards the contents of Na_2O plus K_2O of the volcanic series in order to compare them with the other volcanic series of the Circumpacific margin. The arrow point out the corresponding alkaline-lime index. The vertical axis to the right shows the "serial index" of RITTMANN (1963) which indicates a "medium Pacific" character for the Andean calc-alkaline series and a "weak Atlantic" character for the extra-Andean area of the alkaline series; the volcanic formation of Pino Hachado shows a transitional stage between them. In the same diagram we have drawn with dotted lines the area corresponding to the "high alumina basalt series" which was defined by KUNO (1960) for the Cenozoic volcanic rocks of Central Japan.

The average of the Andean volcanic series is richer in alkalis than the Japanese series; the content of Na_2O of the Andean calc-alkaline series being more abundant.

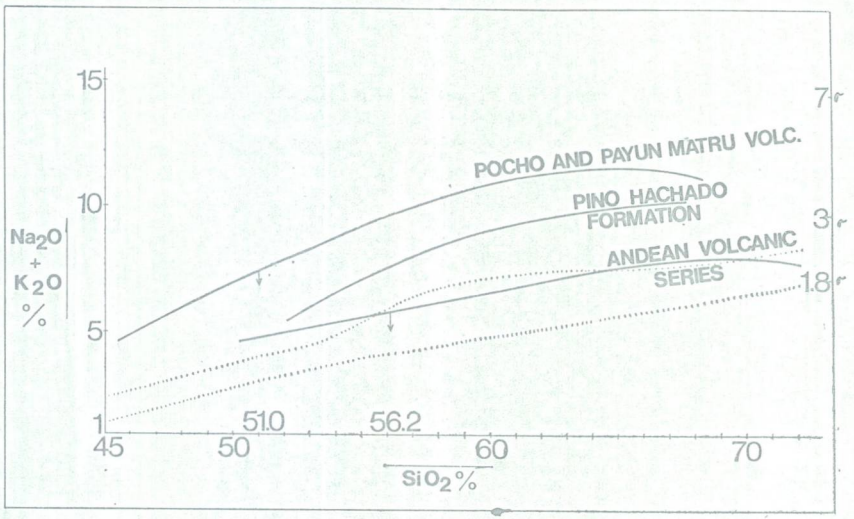

Fig. 12: Relation between (Na_2O + K_2O) vs % SiO_2 from the volcanic rocks referred to in the text. The arrows show the alkali-lime index and in the right vertical axes are shown the "serial values" of Rittmann.

Final comments

The sea floor spreading has apparently been confirmed on the Chilean coast by means of strong magnetic and chronometric evidences and, on the other hand, it has been questioned due to the presence of undisturbed sediments in the trench. PITMAN and HEIRTZLER (1966) suggested that the average speed of the sea floor spreading in the southern section of the east Pacific Rise relative the South American continent has been 4.5 centimeters per year during the last 10 million years. HERRON and HAYES (1969), in their geophysical study of the Chile Ridge, have also reported the magnetic evidences that this mid ocean ridge has been the place of the sea floor spreading towards the South American continent in at least two stages: the oldest at 25-50 million years and the latter which started 10 million years ago. It has been suggested that the penetration of sediments, basalts, metabasalts and serpentinites underneath the continent, takes place alongside the Benioff seismic zone and it has also been suggested that there is a relationship between the seismic frequency and the speed of descent of these materials (RALEIGH and LEE, 1968).

The area studied herewith shows two different gotectonic models which could be interrelated with diferent models of the sea floor spreading (Fig. 1). The northern area presents a trench associated with the Benioff seismic zone which penetrates underneath the continent. In the southern section the trench diminishes its depth down to 2.000 m and the Benioff seismic zone is not found. According to SCHOLL *et al.*, (1968) the basin does not contain sediments to the north of Valparaíso and it is partially or totally full to the south of that city. Besides, the sediments do not appear to show the effects of compression that could be thought of, according to the hypothesis of the sea floor spreading. SEYFERT (1969), LOMNITZ (1969), RALEIGH and LEE (1968) have proposed different tectonic models which would coincide with the hypothesis of the sea floor spreading and that explain the lack of deformation on the sedimentary filling.

Lately, CECIONI (1970) has suggested that the sinking of the oceanic plate would be located in the eastern margin of the Central Valley, where the sedimentary marine Miocene abruptly sinks.

The tectonic analysis about the influence of the Chile Ridge in the section of the oceanic plate facing the area studied herewith has been up to now very complex due to the lack of adequate information. Nevertheless, there seems to be in the southern section a slow-down of the sea floor spreading speed disregarding the existence of the Benioff seismic zone and an increase in the thickness of the sedimentary filling of the basin, which could be directly related to a slow-down of the spreading speed (RALEIGH and LEE, 1968).

Due to the fact that the average of the large lava flows of the Upper Cenozoic vulcanism of the continental margins and arcs of islands located in the Pacific has a calc-alkaline, andesitic nature, of more or less similar features to the value of the average composition of the crust, the problem of the origin of these volcanic rocks seems to be connected with the origin and growth of the continents and also to the sea floor spreading.

One of the most currently accepted hypotheses for the understanding of the calc-alkaline and andesitic rock generation, has been the assimilation or contamination of basaltic magmas with crustal rocks. However, according to TAYLOR and WHITTE (1965, p. 272) the most recent studies of Sr^{87}/Sr^{86} isotopes and of the trace elements of some of the Circumpacific volcanic rocks, do not suggest the addition of quantities of crustal material.

The possibility that basalts or sediments, or hydrated metabasalts be permanently incorporated in the mantle through the plane of continental thrust as a sequence of the sea floor spreading, as it has been postulated by several authors in relation to the area covered in this study, opens up a field for new hypotheses leading to the explanation of the formation of these soda rich rocks, and the growth of the Andes. COATS (1962, p. 102) considered as a hypothesis for the generation of calc-alkaline volcanic rocks of the Aleutian Arc the penetration of humid sediments through the thrust plane that would reach

the mantle and would provide the crustal material necessary for the formation of these rocks.

The possibility of having new data regarding the penetration of this oceanic crustal material in the mantle and the presence of the richly calc-alkaline Neogenic volcanic ridge, would most likely solve many of the fundamental mysteries about the geotectonics of this section of the Andes.

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