RODINGITES OF THE LOS AZULES OPHIOLITIC SEQUENCE IN THE WESTERN CORDILLERA OF THE COLOMBIAN ANDES

BY

Armando ESPINOSA [1]

INTRODUCTION

The Los Azules massif is situated in the south-west Colombian Andes at 2° N 77° W. It is an elongated body, 25 by 9 km, orientated approximately NNE. It consists of a partly eroded ophiolitic sequence which is thought to have been formed at a Pacific mid-ocean ridge and which has been incorporated into the South American continental margin probably during the Lower Cretaceous. The sequence, from bottom to top consists of ultrabasic cumulates (clinopyroxene bearing dunite, wehrlites, and plagioclase peridotites), basic cumulates, and pillow lavas with associated rocks.

The tectonic history of the massif has been described by Espinosa (1978). Two phases of movement, post-dating the emplacement of the ophiolitic sequence on the western flank of the central Cordillera, have been recognised (see Fig. 1): the first termed the Mosquerillo, is of Pre-tertiary age, and was followed by a period of intense erosion and deposition of Tertiary sediments; the second mainly affected the Tertiary sediments.

A serpentinized band, about 100 m wide, is found within the dunites, parallel to and in contact with the Mosquerillo fault. The degree of serpentinization in this band decreases towards the east and also downwards, passing into increasingly fresh dunites (see Fig. 2).

In the serpentinized zone, small greyish-white lenticular masses are observed, deformed and sometimes boudinaged. These are old gabbro dykes which have been typically rodingitized. Transitions between fresh and completely rodingitized dykes are sometimes seen. In some strongly rodingitized and boudinaged dykes, rounded forms similar to ophispherites (Vuagnat 1953) can be observed.

A number of rare rodingite blocks of another type, which appear to be tectonic inclusions are found next to some of the rodingitized gabbro dykes. These, however,

[1] Department of Mineralogy, University of Geneva, Rue des Maraîchers 13, CH-1211 Geneva 4, Switzerland.

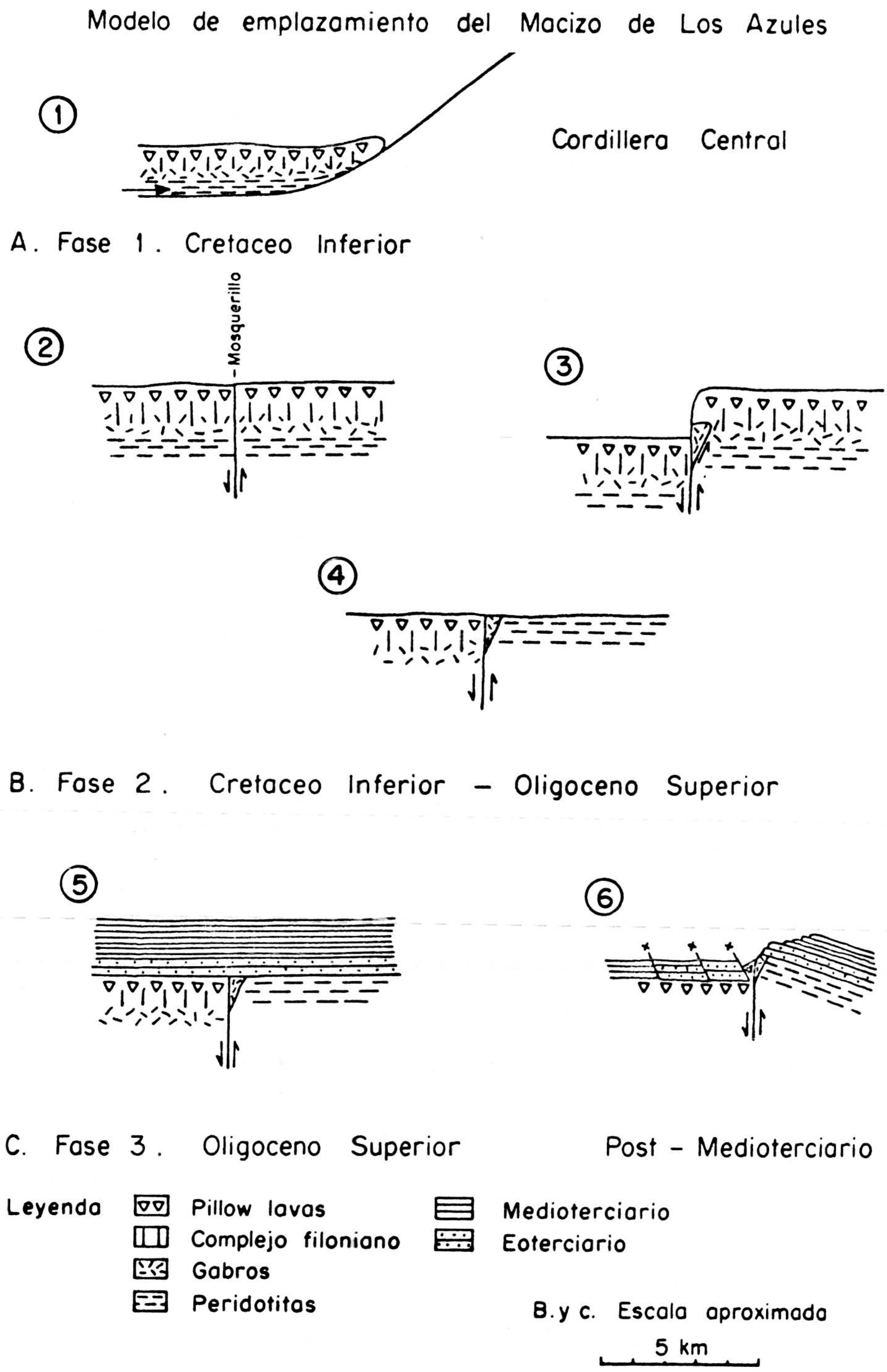

FIG. 1.

Tectonic evolution of Los Azules massif (from Espinosa, 1978). The gabbros illustrated here are non-rodingitized cumulates. The serpentinized band is not visible on this scale.

are not described in this study. A similar rock has been observed elsewhere in southwest Colombia in the serpentinite of El Tambo (Dept. of Nariño) near the Quebrada Arrayan.

The Los Azules rodingites are particularly abundant in a zone several hundred meters wide in the serpentinite band, to the north of the El Bordo-Bolivar road, about 3 km east of Guayabillas. They can be observed in the Quebrada Seca stream, a feeder of the Colerin.

The gabbro dykes were emplaced in the dunite at a time when the latter was probably still hot, as indicated by the absence of chilled margins.

Their original mineralogical composition is similar to those of the gabbroic cumulates in the ophiolitic sequence with plagioclase, clinopyroxene and brown hornblende as essential minerals. They have a coarse-grained intergranular texture.

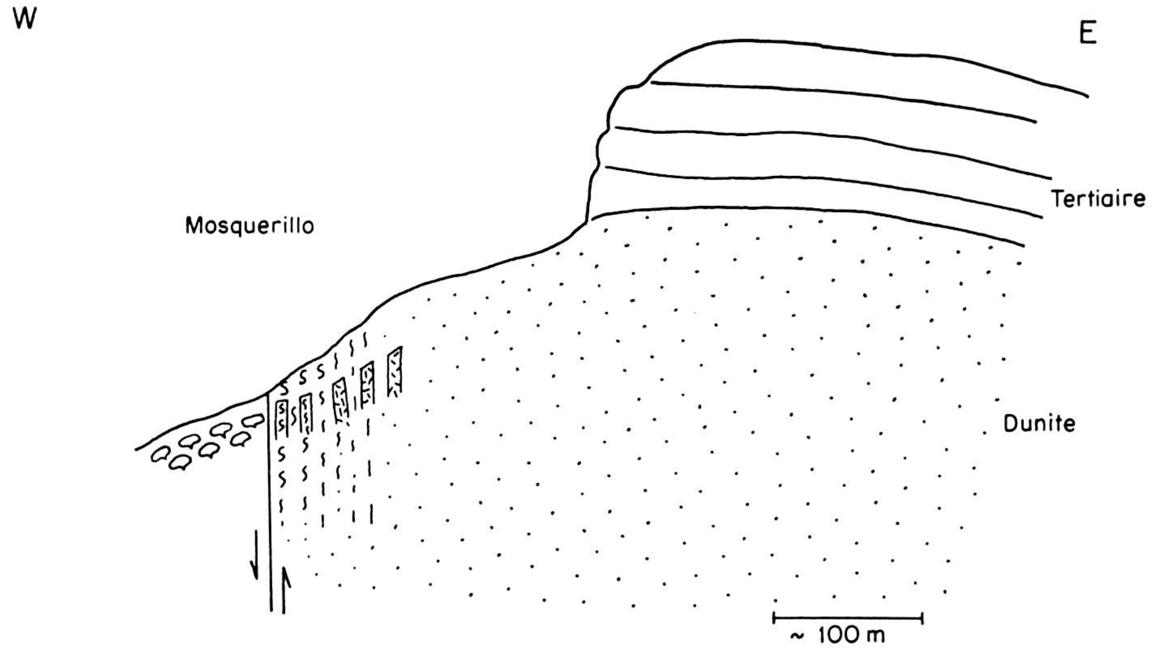

FIG. 2.

Schematic diagram illustrating the serpentinized band, between phases 5 and 6 (see Fig. 1). The degree of serpentinization and rodingitization diminishes downwards and towards the east

DESCRIPTIONS OF SAMPLES

Several rodingites are described in this section in order of increasing rodingitization and starting with a fresh gabbro dyke.

Sample No. 217: Fresh Gabbro

This is a weakly-altered, fine to medium grained, dark rock. Plagioclases can be easily distinguished by eye from the ferromagnesian minerals because of their white colour and their powdery aspect caused by alteration. The rock shows no trace of deformation.

Under the microscope it has a coarse-grained intersertal texture. Clinopyroxene and brown-green hornblende are developed within a mesh of plagioclase laths which are often altered. The hornblende, a result of the reaction of pyroxene with the residual magma, is poikilitic in places, enclosing crystals of plagioclase and relics of pyroxene. The plagioclase sections are only rarely well preserved. Generally, the interior of a section may be fresh in some places and altered elsewhere. When fresh it has a relatively high relief, the composition being An_{60}. The pyroxenes often occur as idiomorphic short prismatic crystals of medium size. Their composition is that of a diopside-augite with $n_Y = 1.686 \pm 0.001$ and $2V = 51°$.

The replacement of pyroxene by hornblende occurs preferentially along cleavages (110). This mineral, almost as abundant as pyroxene, never occurs in idiomorphic crystals, its edges often being irregular. Other minerals noted in small quantities are magnesian chlorite, actinolite, epidote, sphene, apatite and ilmenite.

Sample No 606 : Gabbro weakly rodingitized

This sample comes from the centre of a dyke about 40 cm thick. It is a medium-grained greyish-white rock in which the grey pyroxenes, surrounded by a light-coloured groundmass, can be easily recognised. There are several veinlets present but no trace of deformation.

Microscopically, clinopyroxene, more or less fresh, constitutes about 50% of the rock. Between these crystals are dark brown pseudomorphs of a rodingitized mineral which appears to have been poikilitic and which was probably originally a brown hornblende.

The edges of the clinopyroxenes are ragged and irregular as a result of the rodingitization. The numerous clots of hydrogarnet must correspond to clots of amphibole inside the pyroxenes in fresh gabbros. Alteration is so advanced in some pyroxenes that only a few relics remain.

The material surrounding the pyroxene is a product of the alteration of plagioclase, brown hornblende and some pyroxene and consists of hibschite, vesuvianite and chlorite. It often occurs as a fine groundmass, blackish-brown in colour, containing some chlorite and frequent aggregates of hibschite and vesuvianite.

Hibschite, isotropic and with high relief, occurs as square or hexagonal sections, surrounded by chlorite; and when broken in several sections is weakly birefringent. Vesuvianite appears as small prisms with a high relief, low birefringence, anomalous purplish or brown polarisation colours and straight extinction. It is found either surrounding hibschite or in monomineralic veinlets. The chlorite is of a magnesian variety, colourless with grey polarisation colours, straight extinction, and is length fast. Some second generation diopside is seen in veinlets, sometimes accompanying primary clinopyroxene. Small amounts of actinolite are developed between crystals of the latter.

Sample No. 608 : Partly rodingitized gabbro

This sample is from a boudinaged dyke about 20 cm thick and the two contacts with the serpentinized dunite can be seen. Two whitish bands, 1-2 cm thick are developed parallel to and about 4 cm from each edge. They are composed mainly of pyroxene and hornblende. On either side of these bands the granular texture of an original medium-grained gabbro can be recognised.

In thin section, the relics of clinopyroxene are surrounded by a brownish, isotropic groundmass. The advanced state of rodingitization in comparison with the previous sample means that there are few individual crystals which are rather widely serparated and of small size.

The pyroxenes are generally surrounded by hibschite and a magnesian chlorite. Often, all that is left is an elongated form filled with chlorite and with a few pyroxene relics. The rodingitized mass surrounding the pyroxene consists of hibschite, vesuvianite and chlorite. It frequently occurs as a fine groundmass where hibschite and vesuvianite are intimately mixed together with small masses of chlorite flakes. However, hibschite and vesuvianite do occur locally in small aggregates of idiomorphic crystals with a little chlorite. Vesuvianite also occurs in little veins on its own or with a small amount of chlorite. In the parallel bands near the edges, noted above, primary structures can sometimes be distinguished. These are large crystals of pyroxene or hornblende surrounded by a fine-grained rodingitized groundmass. These two bands must be pegmatitic in origin. Finally, calcite which occurs in small grains in the rodingitized groundmass is relatively abundant.

The contact of the rodingite with the surrounding rocks consists of a very thin chloritic border which is practically non-existant in places.

Sample No. 865 : Strongly rodingitized gabbro

This sample, 20 cm in diameter, was collected from a strongly boudinaged dyke, and has a rounded form, similar to the rodingites described by Vuagnat (1953) as ophispherites. The dark exterior skin is formed by serpentinized dunite while inside, the rodingite is fine-grained and whitish. There is no chloritic border.

Under the microscope, the rock is heavily rodingitized, all the primary minerals and structures having been altered. Only a brownish groundmass of high relief and composed of hibschite and vesuvianite, remains. This contains abundant chlorite and is cut by chlorite veins containing idiomorphic hibschite and vesuvianite crystals. The chlorite within the rodingitized mass is a length-slow Fe-chlorite with anomalous blue polarisation colours, whereas that in the veinlets is a greyish-brown Mg-Fe chlorite which is length fast. The vesuvianite in the veinlets occurs as small length fast prisms with high relief, anomalous brown or grey polarisation colours and straight extinction. Hibschite occurs as small grains with square or hexagonal sections, isotropic and with high relief. Calcite is quite abundant as medium sized crystals or as small scattered grains.

CHEMICAL COMPOSITION

Eight samples were analysed by XRF and for three of these, both the margin and the centre of the dyke were analyzed (see Table 1).

In general, these rocks are high in CaO (17-27%) and H_2O (3-6%) and low in SiO_2 (37-42%), Na_2O (<0.25%) and K_2O (<0.1%).

TABLE 1.

Chemical composition of rodingites and associated rocks.
606, 865, 608B = rodingitized dykes (centre) ; 608A = rodingitized dyke (edge) ;
217, 604, 226 = fresh gabbros ; 45 = serpentinized dunite ; 559 = fresh dunite.

	606	865B	608A	608B	217	604	226	45	559
SiO_2	42.80	33.30	40.55	4.91	50.35	47.93	46.34	39.69	36.90
Al_2O_3	14.57	10.06	9.61	9.93	13.77	8.26	9.73	0.98	2.11
TiO_2	0.57	1.89	0.51	0.80	1.34	1.01	0.84	0.06	0.11
FeO	1.56	2.89	1.05	1.33	4.60	6.57	5.85	2.16	2.91
Fe_2O_3	4.86	12.30	4.82	3.63	2.56	2.52	2.77	5.72	10.93
CaO	20.72	20.41	23.99	27.65	13.21	15.54	15.47	0.24	2.61
MgO	11.50	11.69	13.38	10.31	7.30	13.06	12.57	38.77	33.95
Na_2O	0.01	0.21	0.38	0.01	2.72	1.57	1.79	0.01	0.09
K_2O	0.01	0.01	0.01	0.01	0.84	0.44	0.89	0.02	0.03
MnO	0.11	0.21	0.20	0.17	0.12	0.16	0.16	0.10	0.19
P_2O_5	0.12	0.25	0.04	0.16	0.11	0.13	0.06	0.03	0.03
H_2O	2.95	6.51	5.34	2.87	1.67	0.80	0.63	12.50	10.27
CO_2	0.70	0.01	0.59	1.83	1.07	2.20	2.31	0.01	0.01
Total	100.46	99.94	100.46	99.59	99.67	100.19	99.41	100.27	100.13

In order to compare the chemistry of the rodingites with that of the original gabbros, five fresh gabbros were analyzed. A plot of SiO_2 v. H_2O (Fig. 3) shows a strong enrichment in H_2O and loss of SiO_2 by comparison with fresh gabbros containing less than 3% H_2O and 43-52% SiO_2. The plots of CaO v. Na_2O and CaO v. K_2O (Fig. 4) show the increase of CaO and loss of alkalis in the rodingites: CaO rises from around 15% in gabbros to more than 20% in the rodingites whereas the alkalis decrease from 1.5% to less than 0.1%.

From this it may be concluded that rodingitization causes a strong enrichment in CaO and H_2O together with a loss of SiO_2 and alkalis. MgO and Al_2O_3 show a small increase and small decrease respectively.

These transformations have occured in all rodingites observed so far. The processes responsible for this transformation were first explained by Hess and

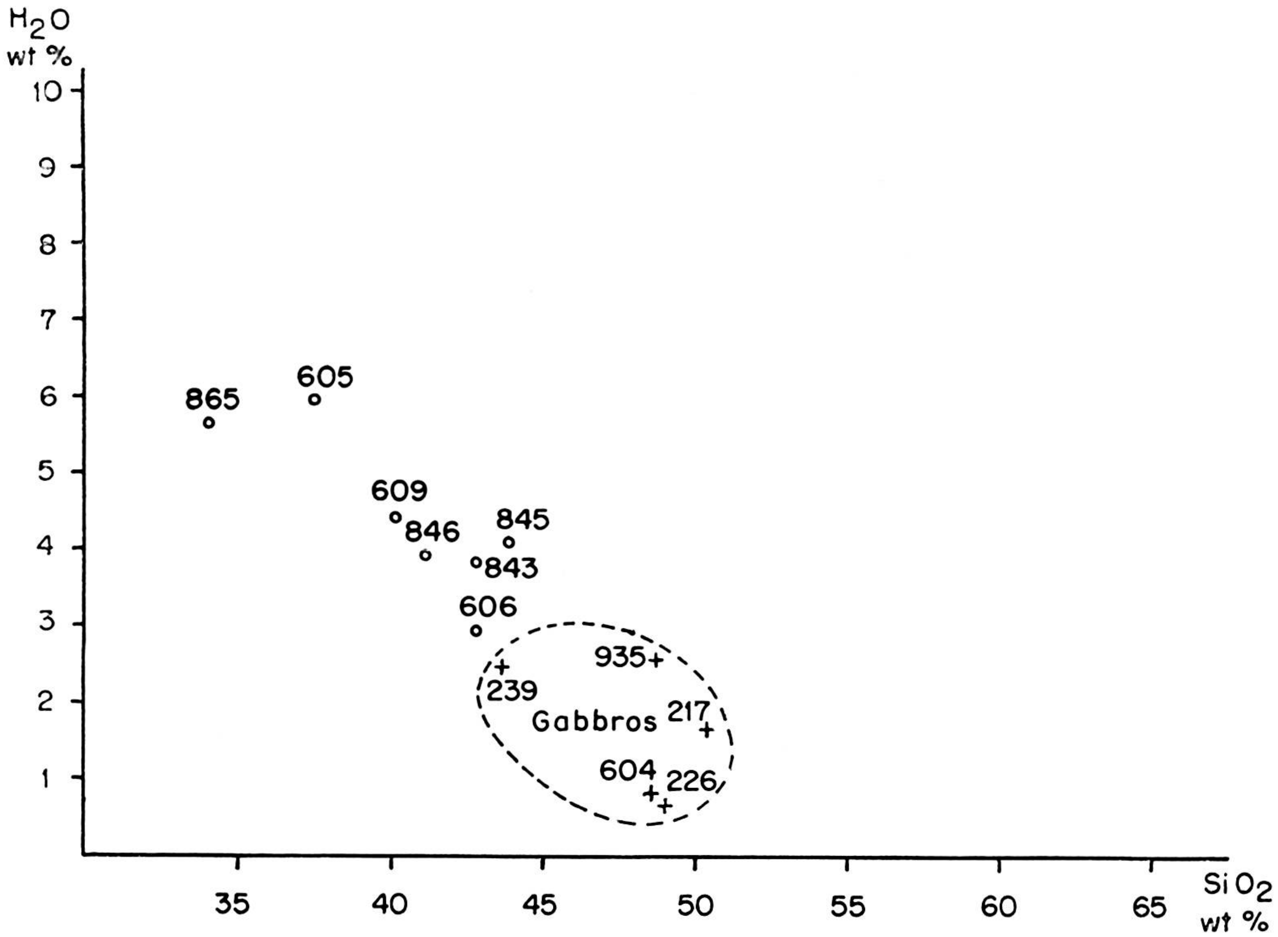

FIG. 3.

Plot of SiO_2 vs H_2O for rodingites and fresh gabbros from the Los Azules massif.
o = Rodingites; + = Gabbros

Otalora (1964). Noting that all rodingites are found in strongly serpentinized zones, they proposed that metasomatism took place between the rodingite and the surrounding rocks during serpentinization. In particular, calcium enrichment could be explained by its mobility after serpentinization of pyroxenes in the surrounding rocks. This hypothesis seems to be accepted by most authors.

In the light of such an hypothesis, it seems pertinent to compare the chemical composition of the centre and borders of rodingitized dykes with that of fresh gabbros and of the surrounding ultramafic rocks. This is shown in Fig. 5 and 6, and the behaviour of calcium is particularly interesting. It can be seen that the Ca-enrichment in rodingite compared to gabbro corresponds to a Ca-loss from the peridotite during serpentinization. It seems that calcium has migrated from the ultramafics into the gabbro.

There is also an increase of MgO and H_2O in the rodingites. This is, no doubt, also linked with serpentinization; the serpentinite is definitely richer in these two components than the original dunite. Some MgO and H_2O must also have penetrated into the gabbro during rodingitization.

Al_2O_3 decreases in the rodingite whereas it increases in the serpentinite compared to dunite, indicating that the serpentinite may be enriched in this element at the expense of the gabbro.

The alkalis show a net loss in the rodingite but stay constant in the ultramafic rock. A small increase in Na_2O at the edge of the dykes remains unexplained at the moment.

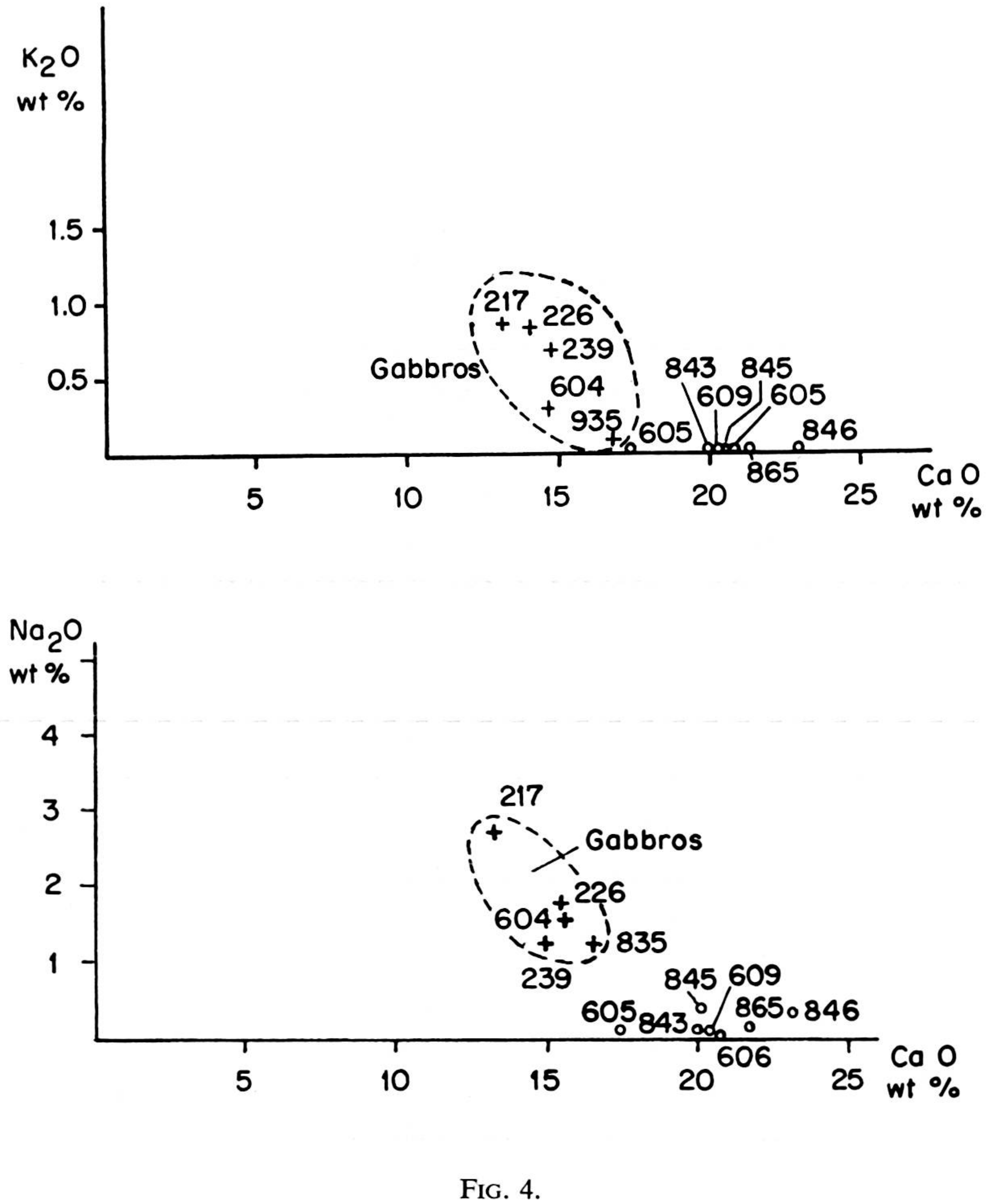

FIG. 4.

CaO vs K_2O and CaO vs Na_2O for rodingites and fresh gabbros from the Los Azules massif. o = Rodingites; + = Gabbros

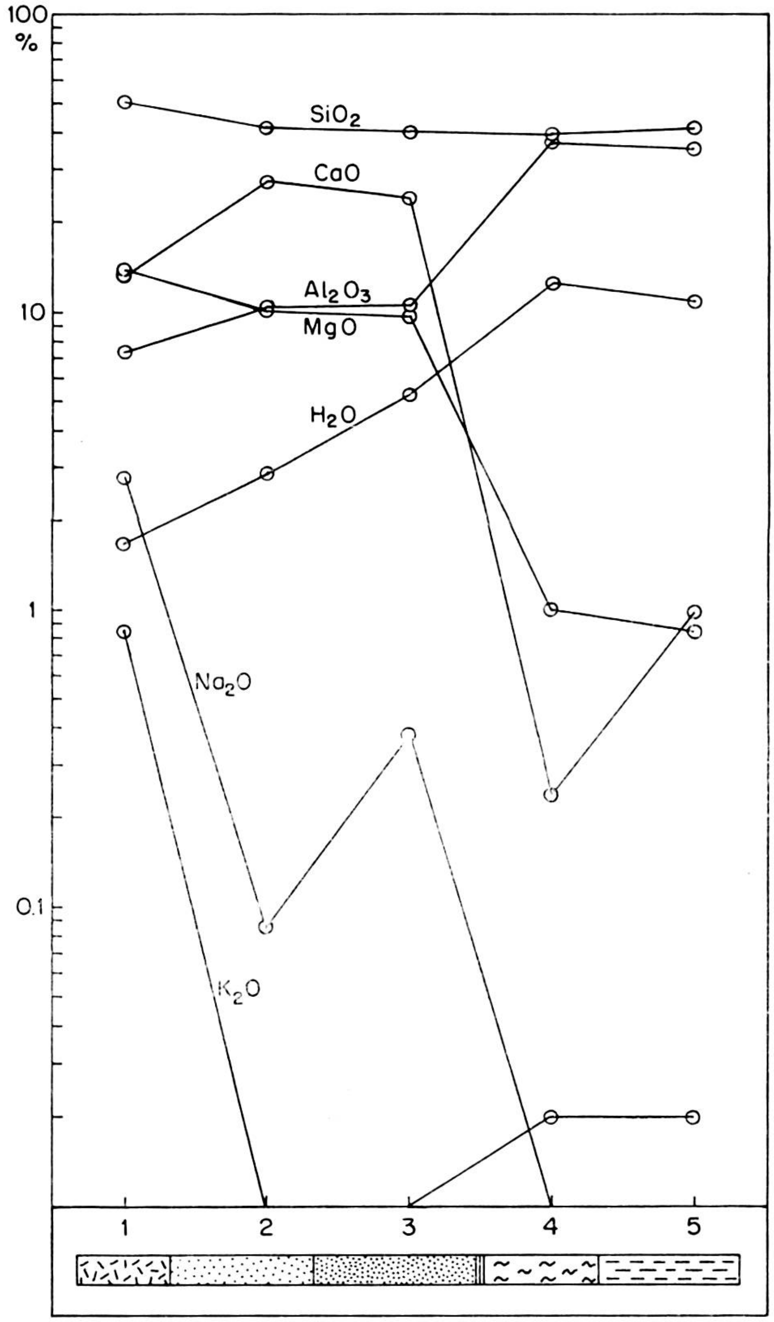

FIG. 5.

Chemical variations within the serpentinite-rodingite association in Los Azules.
1. Fresh gabbro; 2. Center of rodingitized dyke (Sample 608); 3. Edge of rodingitized dyke (Sample 608); 4. Serpentinite; 5. Dunite. Semilogarithmic scale, in weight %.

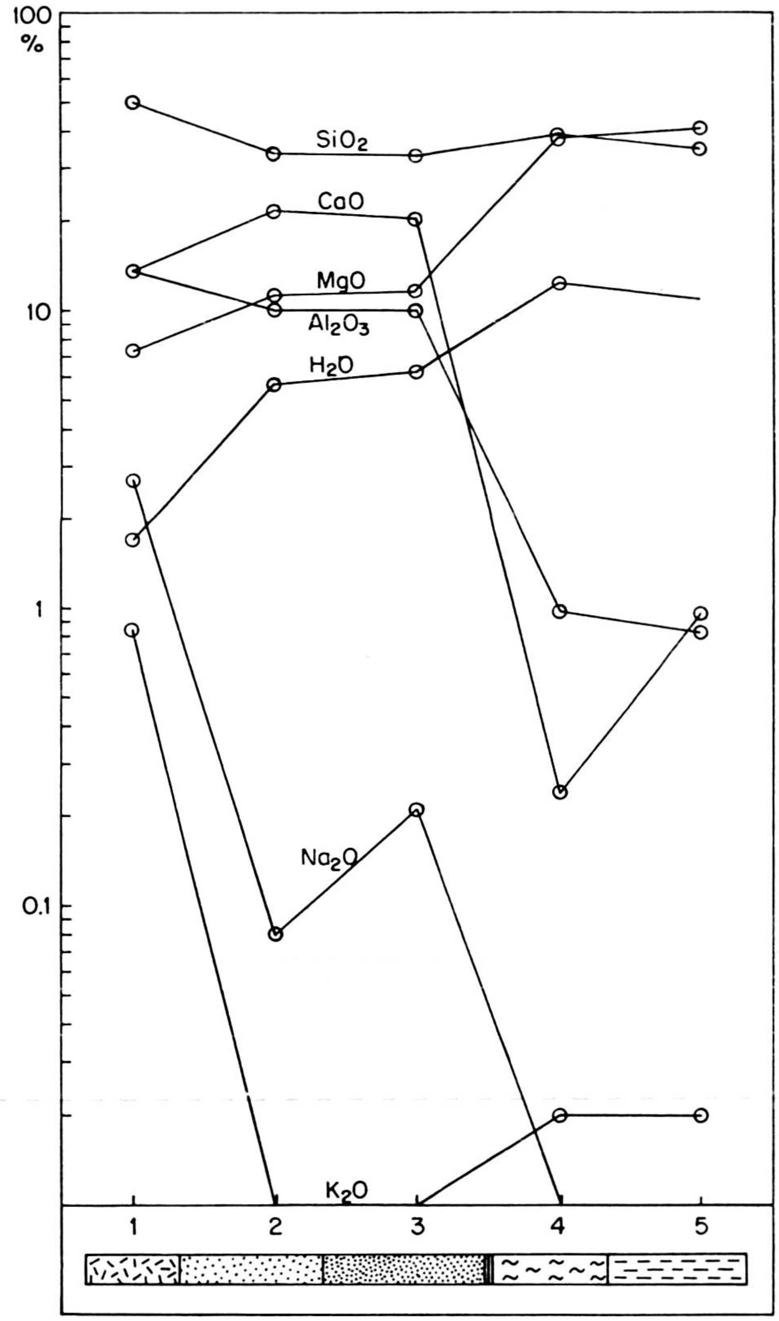

FIG. 6.

Chemical variations within the serpentinite-rodingite association in Los Azules.
1. Fresh gabbro; 2. Center of rodingitized dyke (Sample 865); 3. Edge of rodingitized dyke (Sample 865); 4. Serpentinite; 5. Dunite. Semilogarithmic scale, in weight %.

CONDITIONS OF FORMATION

The constant association of rodingites with strongly serpentinized zones indicates that rodingitization is a by-product of serpentinization and therefore the two phenomena must have taken place under the same physical and chemical conditions. There seems to be no doubt about the relationship between rodingitization and serpentinization in the Los Azules massif, the weakly rodingitized dykes being associated with weakly serpentinized zones and dykes with high Ca-enrichment being formed in zones where the ultramafics have been almost completely serpentinized.

Several authors believe that chrysotile and lizardite are not stable above 350° C while antigorite may have a larger stability field up to 550° C (Barnes and O'Neil, 1969; Faust and Fahey, 1961; Iishi and Saito, 1973; Yoder, 1967). In the Los Azules massif serpentinites in contact with the rodingite are mostly composed of chrysotile and lizardite, with a few flakes of antigorite. Thus the temperature of rodingitization must have been near the limit between the two fields, e.g. 300-400° C.

It is possible in certain cases to estimate the conditions of rodingitization, particularly the temperature, by other methods. The work of Flint *et al.* (1941) has shown that Ca_3Al_2 (SiO_4) (grossular) and Ca_3Al_2 $(OH)_{12}$ are the end members of a series of solid solutions known as hydrogrossular. The relation between degree of hydration and temperature of formation for this series was established by Yoder (1950) and Carlson (1956). Pistorius and Kennedy (1960) established the same kind of relationship for temperatures above 500° C.

The method of Carlson was used for seven rodingite samples. Hydrogrossular unit cell constants were obtained by X-ray diffraction using the Gandolfi and Hägg cameras, and verified on an X-ray diffractometer. Several hydrogrossulars of different

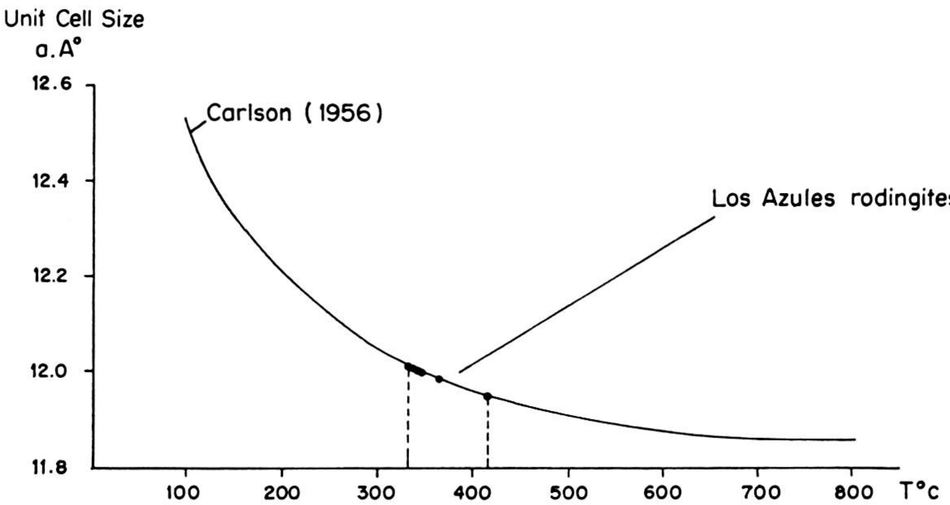

FIG. 7.

Relationship between unit cell size and temperature of formation for hydrogrossulars, after Carlson (1956), with the result from the Los Azules rodingites.

aspects were determined from each sample in order to be sure that there were no appreciable variations inside a sample. The results (Fig. 7) indicate a temperature of formation of about 340 to 420° C which is in agreement with the rodingite-serpentinite association at Los Azules. Nevertheless, these temperatures are only an estimate as there are many unknowns concerning the stability field of hydrogrossular. As pointed out by Zabinski (1965), it is necessary to take into account the presence of vesuvianite as well as of hydrogrossular. In addition, the known stability fields of hydrogrossular are valid only for $P_{H_2O} = P_T$ whereas in many geological environments this condition may not have been obtained. Pistorius and Kennedy (1960) have shown that whenever $P_{H_2O} < P_T$ the temperature of formation of hydrogrossular is reduced.

The pressure conditions are difficult to estimate as the formation of hydrogrossular is independent of pressure, although it may be more favourable at higher pressure (Yoder 1950, Carlson 1956, Pistorius and Kennedy 1960). Coleman (1967) has described rodingites associated with high-pressure facies. However, there are no indications that rodingitization occurred under such conditions in the Los Azules massif.

Based on the high density of rodingites and their high content of water, Coleman (1967) believes that P_{H_2O} must have been nearly the same as P_T, e.g. about 4 Kb. Honnorez (1975) comes to the same conclusion with regard to rodingites from the Mid-Atlantic ridge.

TECTONIC SITUATION

It has been noted earlier that the serpentinization of peridotites in the Los Azules massif occurs on the Mosquerillo fault and therefore the degree of serpentinization decreases away from the fault.

The only explanation of the decrease in serpentinization downwards, in agreement with the tectonic evolution of the massif, requires the serpentinization to have taken place during phase 3 (Fig. 1) at which time the sequence must have been on the ocean floor. Thus serpentinization would only have been able to affect a vertical band on the eastern side of the fault.

The age of the Mosquerillo fault, considered up to now as being pre-Tertiary (Espinosa 1978), can now be estimated more precisely. It is known that during the Upper Cretaceous, the Los Azules massif was not submerged as the important sediments and submarine volcanics typical of most of Western Colombia (Grupo Dagua, Hubach and Alvarado 1945; and Grupo Diabasico, Nelson 1962) are not found above it, but several kilometers to the west. Instead, the Los Azules massif is overlain by Tertiary sediments (Mosquera Formation, Grosse, 1935). The age of the Mosquerillo fault must therefore lie between the emplacement of the sequence and the Upper Cretaceous regression. If the emplacement is Lower Cretaceous in age, the fault must be of mid-Cretaceous age.

CONCLUSION

The rodingites of Los Azules have a character common to most other rodingites described up to now, particularly in their association with a strongly serpentinized zone; and a chemical composition showing CaO and H_2O enrichment and loss of SiO_2 and alkalis. The chemical properties are probably a result of metasomatism of gabbro and peridotite during serpentinization.

Important information concerning the history of the Los Azules massif has also been obtained in this study. It has been shown that the serpentinization can be associated with the Mosquerillo fault and that the physico-chemical conditions at the time can be estimated from the rodingites. Finally, it has been possible to propose an age for the serpentinization and therefore for the Mosquerillo fault associated with it.

ACKNOWLEDGMENTS

This work forms part of a Ph.D. thesis in preparation on the ophiolites of South-West Colombia. I would like to thank my supervisor, Prof. M. Vuagnat, for his helpful suggestions and encouragement. I am indebted to Dr. H. Sarp (Musée d'Histoire naturelle, Geneva) for his advice in mineralogy, and to Dr. H. de Souza for advice and suggestions.

REFERENCES

Barnes, I. and J. R. O'Neil (1969). The relationship between fluids in some fresh alpine-type ultramafics and possible modern serpentinization, Western United States. *Geol. Soc. Am. Bull.*, 80, 1947-1960.

Carlson, E. T. (1956). Hydrogarnet formation in the system lime-alumina-silica-water. *U.S. Natl. Bur. Standards Jour. Research*, 56, 327-335.

Coleman, R. G. (1967). Low-temperature reaction zones and alpine ultramafic rocks of California, Oregon and Washington. *U.S. Geol. Surv. Bull.*, 1247, 49 p.

—— (1971). Petrologic and Geophysical nature of serpentinites. *Geol. Soc. Am. Bull.*, 82, 897-918.

Dal Piaz, G. V. (1969). Filoni rodingitici zone di reazione a bassa temperatura al contatto tettonico tra serpentine e rocce incassanti nelle Alpi occidentali italiane. *Rend. Soc. Ital. Mineral. Petrol.*, 25, 263-315.

Espinosa, A. (1978, in press). Sobre una secuencia ofiolitica incompleta, el Macizo de Los Azules, Cordillera Occidental de Colombia. *Seg. Congr. Col. Geol.*, Bogota.

Faust, G. T. and J. J. Fahey (1962). The serpentine-group minerals. *U.S. Geol. Surv. Prof. Paper 384-A*, 1-91.

Flint, E. P., H. P. McMurdie and L. S. Wells (1938). Formation of hydrated calcium silicates at elevated temperatures and pressures. *U.S. Natl. Bur. Standards Journ. Research*, 21, 617-638.

—— (1941). Hydrothermal and X-ray Studies of the Garnet-hydrogarnet Series and the Relationship of the Series to Hydration Products of Portland Cement. *U.S. Natl. Bur. Standards Jour. Research*, 26, 13-33.

GROSSE, E. (1935*b*). Acerca de la Geologia del Sur de Colombia. *Comp. Est. Geol. Ofic. Col., Serv. Geol. Nal.*, 3, 139-231.

HESS, H. and G. OTALORA (1964). Mineralogical Chemical Composition of the Mayagüez Serpentinite Cores, in *A Study of Serpentinite. Natl. Acad. Sci. — Natl. Research Council Publ. 1188*, 152-168.

HONNOREZ, J. (1975). Petrology of Rodingites from the Equatorial Mid-Atlantic Fracture Zones and Their Geotectonic Significance. *Contr. Mineral. Petrol.*, 49, 233-257.

HUBACH, E. e B. ALVARADO (1945). La altiplanicie de Paletara (Dpto del Cauca). *Comp. Est. Geol. Ofic. Col., Serv. Geol. Nal.*, 6, 39-59.

IISHI, K. and M. SAITO (1973). Synthesis of antigorite. *Am. Mineralogist*, 58, 915-919.

NELSON, H. W. (1962*b*). Contribución al Conocimiento de la Cordillera Occidental, Sección Carretera Cali-Buenaventura. *Bol. Geol. Nal.*, 10, 81-108.

PISTORIUS, C. W. F. T. and G. C. KENNEDY (1960). Stability relations of grossularite and hydrogrossularite at high temperatures and pressures. *Am. Journ. Sci.*, 258, 247-257.

SARP, H. (1976). Etude géologique et pétrographique du Cortège ophiolitique de la région située au Nord-Ouest de Yesilova (Burdur-Turquie): *Thèse 1731, Univ. de Genève.*

VUAGNAT, M. (1953). Sur un phénomène de métasomatisme dans les roches vertes du Montgenèvre (Hautes-Alpes). *Bull. Soc. Franç. Miner. Crist.*, 76, 438-450.

—— (1967). Quelques réflexions sur les ophisphérites et les rodingites. *Rend. Soc. Mineral. Ital.*, 23, 471-482.

YODER, H. S. (1950). Stability relations of grossularite. *J. Geol.*, 58, 221-253.

YODER, H. S., Jr. (1967). Spilites and Serpentinites. *Carnegie Inst. Washington Year Book*, 65, 269-279.

ZABINSKI, W. (1965). Studium mineralow grupy hydrogranatu. *Rozp. Ak. Gorniczo — Hutnicza w Krakowie*, 102, 1-91.

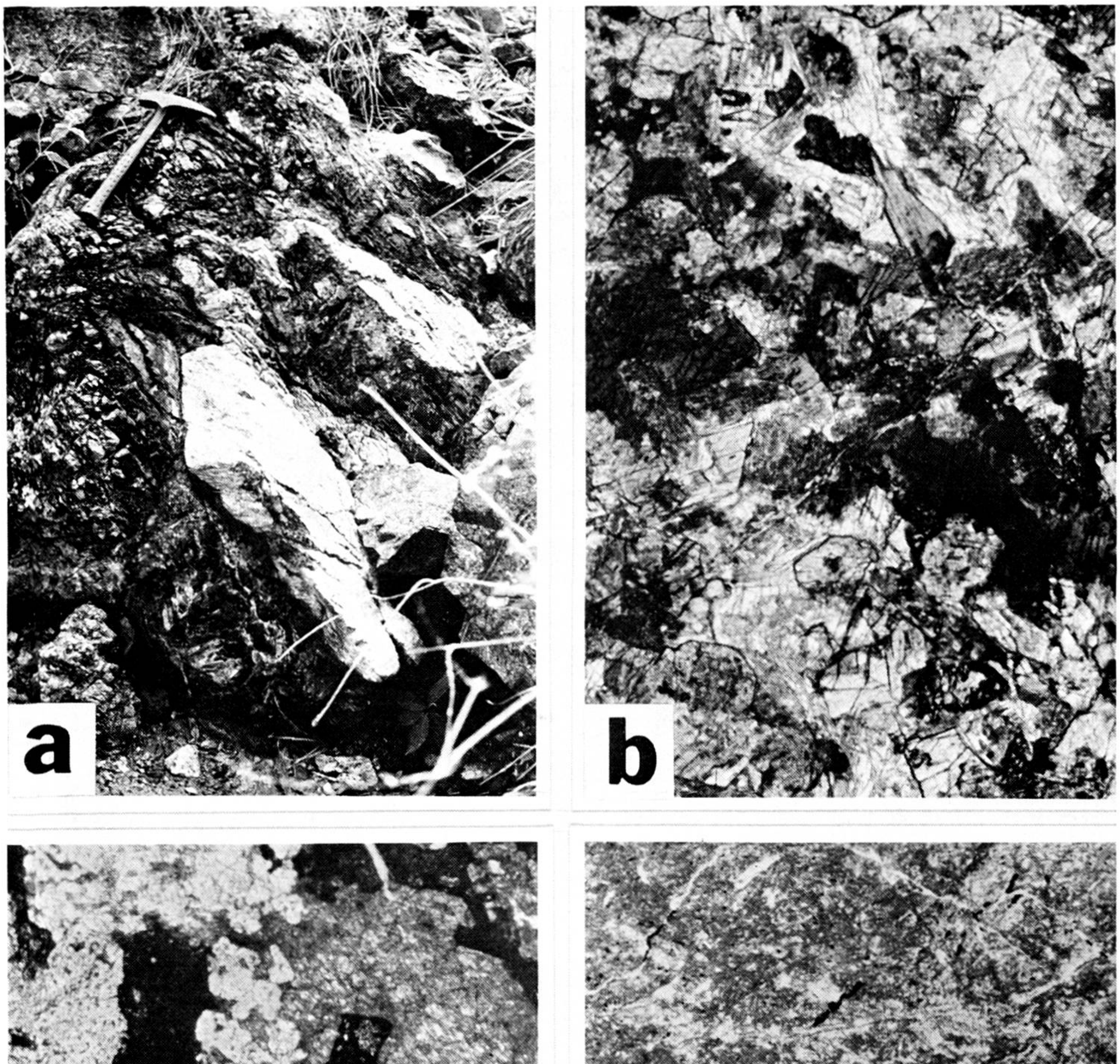
a
b
c
d

PLATE I*a*

a) Dyke of rodingitized gabbro. Quebrada Seca, Guayabilias.

PLATE I*b*

b) Fresh gabbro (Sample 217), with plagioclase, clinopyroxene and poikilitic hornblende. × 12, in plane polarized light.

PLATE I*c*

c) Weakly rodingitized gabbro (Sample 606) showing rodingitized poikilitic hornblende and plagioclase, and fresh clinopyroxenes. × 8, in plane polarized light.

PLATE I*d*

d) Strongly rodingitized gabbro (Sample 865). All primary structures have been destroyed. × 8, in plane polarized light.