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# OPHIOLITE COMPLEX FROM LA TETILLA, SOUTHWESTERN COLOMBIA, SOUTH AMERICA<sup>1</sup>

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## ABSTRACT

A disrupted ophiolitic complex of Cretaceous age from the Romeral fault zone in the southwestern Colombian Andes occurs in the La Tetilla area near Popayan. It represents a peculiar association of low-Ti and high-Ti tholeiitic basalts among the ophiolitic complexes from the Romeral Zone. It includes: (1) A main sequence (with incipient metamorphism under prehnite-pumpellyite to greenschist facies conditions) consisting in ascending order of cumulus wehrlite and gabbro, massive gabbro, and basaltic and doleritic lavas and breccias. The basalts are characterized by the crystallization of clinopyroxene prior to plagioclase (cpx-phyric basalt group) and have a primitive low-Ti tholeiite composition (Mg numbers between 70.6 and 65.4). The clinopyroxene chemistry is consistent with this magmatic affinity. The plutonic rocks can be related to a similar low-Ti tholeiitic magma. (2) A sequence of pervasively metamorphosed basalts (with greenschist facies metamorphism of oceanic type) structurally underlies the main sequence. Basalts are characterized by the order of crystallization: ol-plag-cpx (plag-phyric basalt group) and high-Ti tholeiitic chemistry. (3) A sequence of foliated metabasalts (with greenschist to amphibolite transition metamorphism) including low-Ti picritic and high-Ti tholeiitic basalts. Different tectonic settings can be inferred from the petrological features of the recognized magmatic sequences, but constraints by the regional setting are still insufficient to permit a unique interpretation. The one proposed tentatively is that the low-Ti basalts and the plutonics, which are probably cogenetic, formed in an intraoceanic arc at an early stage of development, similar to many supra-subduction zone ophiolites. The high-Ti basalts could have been associated with the former sequence prior to the tectonic emplacement, and could represent remnants of an ocean island volcanism.

## INTRODUCTION

The Colombian Andes are divided into two distinct domains, an eastern continental area including the Eastern and Central Cordillera and a western oceanic area formed by the Western Cordillera (Aubouin et al. 1977). The predominant rocks of the Eastern Cordillera are Mesozoic folded sediments deposited on a Precambrian-Cambrian crystalline basement, while the Central Cordillera is made of Paleozoic metamorphic rocks of continental origin. The Western Cordillera is formed mainly of basaltic oceanic rocks and associated sediments of Late Mesozoic age. Tertiary sediments fill up the inter-Andean Magdalena and Cauca-Patia valleys, and an important, mainly Mesozoic, magmatic sequence occurs in the Central and Western Cordillera. An important megasuture zone,

known as the Romeral Zone, runs along the contact between the eastern and western domains.

In the southwestern Colombian Andes, dismembered ophiolitic sequences occur along the Romeral Zone (fig. 1). They consist of mafic and ultramafic plutonics, and basaltic rocks associated with cherts and detrital deposits of Mesozoic, mostly Cretaceous, age. They belong to the belt of dislocated oceanic rocks of Mesozoic to Tertiary age which extends from Costa Rica (Nicoya Complex, Kuijpers 1980; Azema and Tournon 1984) and Panama to northern Ecuador (Basic Igneous Complex, Goossens and Rose 1973) and runs through western Colombia, including the Serranía del Baudo along the Pacific coast and Gorgona island offshore (Gansser et al. 1979; Echeverría 1980).

The segment occurring in the southwestern Colombian Andes has been considered to represent oceanic terrains of crustal origin (incomplete ophiolitic complexes) formed during the Cretaceous and obducted onto the South American continental edge at the end of this period (Bourgeois et al. 1982; De Souza

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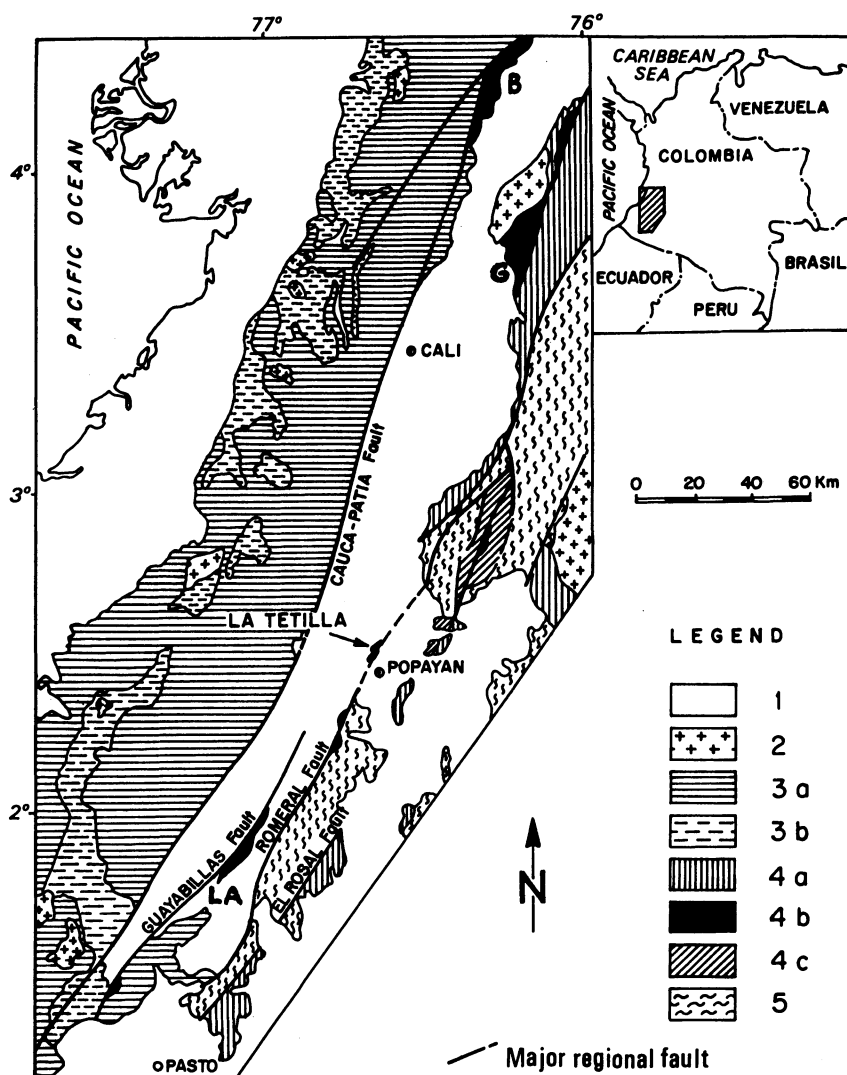


FIG. 1.—Simplified geologic map of Southwestern Colombia. 1 = Quaternary-Neogene continental (volcanogenic p.p.) and marine deposits. 2 = Mesozoic intrusives. 3 = Volcanic-sedimentary complexes from Western Cordillera (Mesozoic): 3a. Basalt, chert, and terrigenous sedimentary rocks; 3b. Metasedimentary rocks. 4 = volcanic and plutonic complexes from Romeral Zone (Mesozoic): 4a. Mafic volcanics; 4b. Mafic-ultramafic plutonics; (B = Bolivar Complex; G = Ginebra Complex; LA = Los Azules Complex); 4c. High-pressure metabasites. 5 = Metamorphic and plutonic rocks from Central Cordillera (Paleozoic).

et al. 1984). In more recent studies (McCourt et al. 1984; Bourgois et al. 1985; Aspden and McCourt 1986) the sequences from the Western Cordillera and those occurring along the western flank of the Central Cordillera are referred to two distinct volcano-tectonic cycles: a younger cycle that ended in Late Cretaceous (Western Cordillera) and an older cycle that ended in earliest Cretaceous (western edge of Central Cordillera).

The original tectonic environment in which the igneous rocks formed is debated. Particularly for the volcanic rocks, ocean ridge (Pichler et al. 1974; Goossens et al. 1977; Millward et al. 1984; McCourt et al. 1984; Aspden and McCourt 1986), or alternatively island arc settings (Barrero 1979), have been inferred from the rock chemistry.

In this paper an ophiolitic (*sensu lato*) complex occurring in the western part of the

Romeral Zone is described. It is located 10 km to the NW of Popayan and crops out over an area of about 50 km<sup>2</sup> dominated by the La Tetilla Mt. This complex, which has not been described in the literature, includes variably metamorphosed basalts and associated sediments, gabbros, and cumulus ultramafics. The petrologic features and detailed petrographic and chemical data on rocks and minerals that are presented here suffice to characterize the tectonic setting of the magmatic lithotypes and the environment of the metamorphism.

#### GEOLOGICAL SETTING

In the southwestern Colombian Andes the ophiolitic fragments occurring along the Romeral Zone are generally fault-bounded bodies elongated approximatively N-S. The La Tetilla complex is one of the small fragments showing mafic-ultramafic plutonic sequences. Similar complexes characterized by the presence of plutonic sequences of much larger extent (up to 100 km in length) include, from N to S, the Bolivar complex (Barrero 1979; Bourgois et al. 1982), the Ginebra complex (Espinosa in press), and the Los Azules complex (Espinosa 1980; De Souza et al. 1984).

The Bolivar complex occurs in the eastern edge of the Western Cordillera and consists, in the lower part, of ultramafic-mafic cumulates (dunite, wehrlite, websterite, gabbro-norite, hornblende, gabbro-norite) grading upward to metabasites derived from gabbros intruded by basaltic dikes (Barrero 1979; Bourgois et al. 1982; Spadea, Delaloye and Espinosa, unpub. data). The metabasites are in faulted contact with a sequence of basaltic lavas with interlayered chert and graywacke. According to Bourgois et al. (1982) this complex represents an ophiolite of Aptian-Albian to early Senonian age, as inferred by paleontological and radiometric dates, but it could also include an extrusive sequence of older, i.e. Barremian, age.

The Ginebra complex, located in the western flank of the Eastern Cordillera, includes a total of about 400 m of ultramafic-mafic cumulates (dunite, lherzolite, wehrlite, websterite, gabbro-norite) grading upward to metagabbros and metabasalts overlain by metabasites, mostly of volcanoclastic origin, in faulted contact with a suite of basalts (Es-

pinosa in press; Aspden and McCourt 1986). According to Aspden and McCourt (1986) the basaltic sequence (Amaime Formation) and the plutonic one constitute an ophiolite of Late Jurassic-Early Cretaceous age which accreted before about 125–130 Ma. This age is mostly inferred by regional correlations and relationships with calco-alkaline plutonics.

The Los Azules complex shows a sequence of mostly ultramafic cumulates (dunite, wehrlite, lherzolite) overlain by cumulus gabbros in faulted contact with a suite of basaltic lavas (Espinosa 1980). A Mid-Cretaceous age, inferred by radiometric dates, is reported by De Souza et al. (1984).

In small ophiolitic fragments, including plutonic ultramafics from the Romeral Zone, high-pressure rocks are described for which radiometric dates of about 120–125 Ma are reported (Paris and Marin 1978; Orrego et al. 1980; Feininger 1982; Aspden and McCourt 1986).

From the literature data, the picture of the ophiolite occurrences from southwestern Colombian Andes appears to be complex, and the interpretation of the available data is still controversial, particularly as regards the possible existence of groups of different age among the basaltic sequences and in the identification of their structural elements. The La Tetilla ophiolitic rocks have not provided age data because identifiable fossils were not found, and suitable lithotypes for radiometric dating are missing. For these reasons the complex under study is linked to the abovementioned major fragments, including plutonic sequences from the Romeral Zone, based on similarities in structural relations and, partly, in lithology, with the assumption, which requires further investigation, that these complexes belong to a belt of probable Late Cretaceous age.

#### OCCURRENCE AND PETROGRAPHY

The general geology of the area surrounding La Tetilla is described by Orrego (1976). The area is extensively underlain by a Late Tertiary to Quaternary volcanogenic sequence, the Popayan Formation. The ophiolitic rocks are exposed discontinuously and are also dissected by small shallow intrusions of acid rocks (mostly dacites) of probable Late Tertiary age. Most outcrops are bounded by distinct fault-systems. The faults

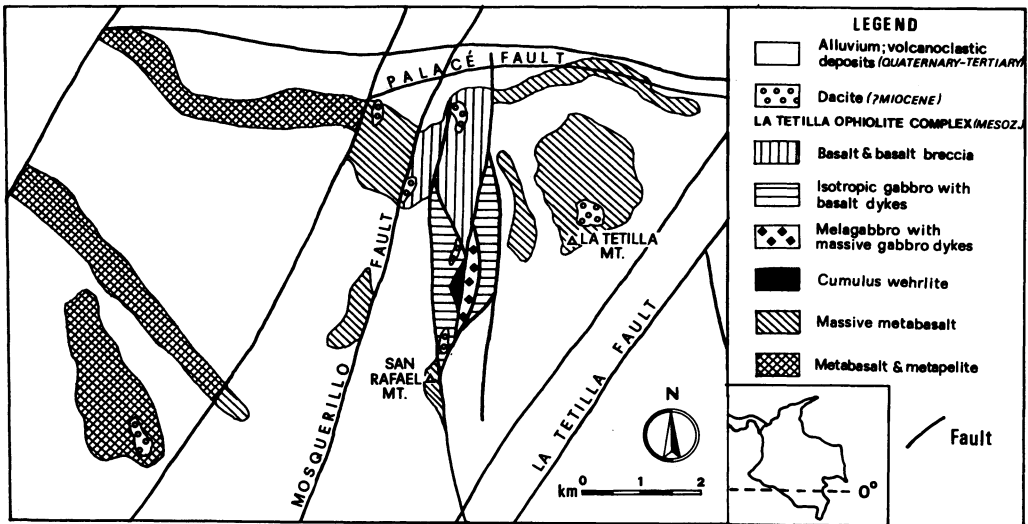


FIG. 2.—Geologic map of La Tetilla area.

show N-S, NE-SW, and E-W strikes (fig. 2) and are known to have been active since the beginning of the Tertiary, or even before (e.g., the Mosquerillo fault). The stratigraphic relations among the ophiolitic lithologies are therefore difficult to reconstruct.

Six lithologic units have been distinguished: they are mapped in fig. 2 and listed in a tectonic-stratigraphic sequence from the top downward in table 1. For each unit, field occurrence and essential petrographical data referring to both the magmatic features and the metamorphic evolution are reported.

**Weakly Metamorphosed Basalt and Basalt Breccia.**—This unit consists of basalt and dolerite which occur as massive lavas and breccias to the west and southwest of La Tetilla as far as San Rafael. The basalts often show sparse dark phenocrysts and amygdulæ of millimetric size. There are associated layers of basaltic arenite consisting of fine-grained heterogeneous basalt detritus. The rocks are weakly metamorphosed, and the following primary lithotypes are recognized (table 2): (a) Aphyric basalt containing magnetite  $\pm$  augite micro-phenocrysts with intergranular groundmass. (b) Oligophyric basalt with augite and plagioclase phenocrysts (often as glomerophyric aggregates) and micro-phenocrysts, with magnetite in addition as micro-phenocrysts. The groundmass has an intergranular texture similar to the type (a)

basalt. (c) Dolerite, with sub-ophitic texture, consisting of fresh augite to pigeonitic augite and saussuritized plagioclase. Relics of the primary plagioclase are in the range An 70–32 by zoning. Magnetite occurs in euhedral grains, and there is a mesostasis derived from glass consisting of chlorite, smectite, and epidote.

The metamorphism shown in this unit is non-pervasive and of very low-grade: the primary minerals are in fact unaltered or poorly altered with the exception of the plagioclase, which is extensively saussuritized. Spinel (after Ti-magnetite) and chlorite (after glass, plagioclase, and augite) are ubiquitous; furthermore some calcite, quartz (often derived from chalcidony), epidote, albite, prehnite and pumpellyite may occur, in most cases filling veins and amygdulæ. No deformation is evident. The metamorphic mineral assemblages are of the prehnite-pumpellyite facies.

**Massive Gabbro Cut by Diabase Dikes.**—Almost massive and completely weathered gabbros occur in different localities between San Rafael and Las Mercedes. Because of weathering, the gabbro can be recognized only by relict texture, and no sample suitable for petrographic study could be collected. It can be identified as a pyroxene gabbro that is rather uniform in composition and affected by a diffuse and weak shearing. Dikes of black aphyric basalt ranging in size from 20 cm to 100 cm intrude the gabbro. The basalt

TABLE 1  
OPHOLITE COMPLEX OF LA TETILLA, SOUTHWESTERN COLOMBIA: STRATIGRAPHIC SUBDIVISIONS

| Unit                        | Occurrence and Lithology                                                   | Petrologic Group (basaltic rocks)                    | Type of Metamorphism                                      | Metamorphic Facies <sup>a</sup> |
|-----------------------------|----------------------------------------------------------------------------|------------------------------------------------------|-----------------------------------------------------------|---------------------------------|
| Basalt and basalt breccia   | massive lavas and breccias, basaltic arenites                              |                                                      |                                                           |                                 |
| Isotropic gabbro and basalt | massive cpx-gabbro, basalt dikes                                           | cpx-phyr basalt                                      | (hydrothermal, static) <sup>b</sup>                       | p-p to gr-sch                   |
| Melagabbro and gabbro       | layered melagabbro (?cumulate), cpx-gabbro dikes                           | cpx-phyr basalt                                      | (hydrothermal, static) (weak shearing)                    | gr-sch                          |
| Cumulus wehrlite            | layered plagioclase ( $\pm$ kaersutite and biotite) wehrlites              |                                                      | (hydrothermal, static)                                    | gr-sch to ?gr-sch/amph          |
| Massive metabasalt          | massive and pillowed lavas, breccias, hyaloclastite, (siltstone and chert) | plag-phyr basalt                                     | hydrothermal, static, locally shearing and mylonitization | gr-sch                          |
| Metabasalt and metapelite   | metabasalts and metadolomite, (qz $\pm$ cc phyllites)                      | plag-phyr basalt<br>cpx-phyr basalt ( $\pm$ Mg-rich) | hydrothermal, dynamic                                     | gr-sch/amph                     |

<sup>a</sup> Abbreviations for facies names: p-p = prehnite-pumpellyite; gr-sch = greenschist; gr-sch/amph = greenschist-amphibolite transition.  
<sup>b</sup> ( ) indicates non-pervasive, mostly selective and poorly developed, recrystallization.

TABLE 2  
STUDIED SAMPLES FROM THE LA TETILLA OPHIOLITE COMPLEX

| Sample   | Lithotype;<br>Locality                | Unit                      | Mineral Assemblage<br>(° = magnatic relics)             | Texture<br>(° = relict magma)  | Petrologic Group<br>(basalts) | Chemical<br>Data <sup>a</sup> | Analyzed<br>Minerals <sup>b</sup> |
|----------|---------------------------------------|---------------------------|---------------------------------------------------------|--------------------------------|-------------------------------|-------------------------------|-----------------------------------|
| IGM25770 | Aphyric basalt;<br>NW San Rafael      | Basalt and basalt breccia | °cpx <sup>a</sup> , °pl, °mt, °ap, ab, ep, prh, cc, chl | °aphyric, micro-lithic         | cpx-phyr                      | maj, tr                       | cpx                               |
| IGM25771 | Aphyric basalt;<br>NW San Rafael      | Basalt and basalt breccia | °cpx, °pl, °mt, °ap, ab, phr, cc                        | °aphyric, micro-lithic         | cpx-phyr                      | maj, tr                       | cpx                               |
| IGM25744 | Dolerite;<br>S Cerro San Rafael       | Basalt and basalt breccia | °cpx, °pl, °mt, chl, ss, ppl                            | °sub-ophitic                   | cpx-phyr                      | maj, tr                       | cpx                               |
| CL161    | Aphyric metabasalt;<br>El Cerrito     | Isotropic gabbro & basalt | °cpx, °mt, ab, amph, chl                                | massive, °micro-lithic         | cpx-phyr                      | maj, tr                       |                                   |
| COL67    | Aphyric metabasalt;<br>El Cerrito     | Isotropic gabbro & basalt | °cpx, °mt, ab, amph, chl, phr (veins)                   | massive, °micro-lithic         | cpx-phyr                      | maj, tr                       |                                   |
| COL58    | Oligophyr metabasalt;<br>La Tetilla   | Massive metabasalt        | ab, ss, act-hbl, act, chl, sph, hm                      | massive, °ol-pl ph/inters gdm  | pl-phyr                       | maj, tr                       | amph                              |
| COL56    | Oligophyr metabasalt;<br>La Tetilla   | Massive metabasalt        | ab, ss, act-hbl, act, chl, sph, pyr                     | massive, °pl ph/inters-div gdm | pl-phyr                       | maj, tr                       |                                   |
| CL155    | Oligophyr metabasalt;<br>La Tetilla   | Massive metabasalt        | ab, ss, amph, act, chl, sph                             | massive, °pl ph/inters-div gdm | pl-phyr                       | maj, tr                       |                                   |
| CL156    | Oligophyr metabasalt;<br>La Tetilla   | Massive metabasalt        | ab, ss, amph, act, chl, sph                             | massive, °pl ph/inters-div gdm | pl-phyr                       | maj, tr                       |                                   |
| IGM26713 | Mylonitic metabasalt;<br>W La Tetilla | Massive metabasalt        | ab, chl, ep, amph, sph, pyr                             | mylonitic, foliated & veined   | pl-phyr                       | maj, tr                       | amph                              |
| COL57    | Mylonitic metabasalt;<br>W La Tetilla | Massive metabasalt        | ab, chl, ep, amph, sph, pyr                             | mylonitic, foliated & veined   | pl-phyr                       | maj, tr                       | amph                              |
| IGM26610 | Oligophyr metabasalt;<br>Rio Palacé   | Metabasalt & metapelite   | hbl, act, ep, sph, ab, mt                               | massive, °cpx ph/?microcl gdm  | cpx-phyr (Mg-rich)            | maj, tr                       | amph                              |
| COL55    | Metadolerite;<br>Rio Palacé           | Metabasalt & metapelite   | amph, pl, ab, ss, ep, sph                               | blasto-ophitic, weak foliation | cpx-phyr                      | maj, tr                       | amph, feld                        |

|       |                                  |                        |                                                            |                              |         |                            |
|-------|----------------------------------|------------------------|------------------------------------------------------------|------------------------------|---------|----------------------------|
| COL62 | Gabbro;<br>SSW Cerro La Peña     | Melagabbro &<br>gabbro | °cpx, °pl, °mt, ss,<br>amph, chl, sph                      | °sub-ophitic                 | maj, tr | amph                       |
| COL63 | Melagabbro;<br>SSW Cerro La Peña | Melagabbro &<br>gabbro | °cpx, °pl, °mt, °amph,<br>act, chl, mtm, chd, cc           | °hypidiomorphic,<br>°layered | maj, tr |                            |
| COL59 | Wehrlite;<br>Cerro La Peña       | Cumulus wehr-<br>lite  | °ol, °cpx, °opx, °pl, °sp,<br>°kaer, °bio, hbl, ser,<br>ss | °adcumultitic                | maj, tr | cpx, opx, sp,<br>kaer, hbl |
| COL61 | Wehrlite;<br>Cerro La Peña       | Cumulus wehr-<br>lite  | °ol, °cpx, °opx, °pl, °sp,<br>°kaer, °bio, hbl, ser,<br>ss | °adcumultitic                | maj, tr | ol, cpx, opx, pl,<br>kaer  |
| COL60 | Wehrlite;<br>Cerro La Peña       | Cumulus wehr-<br>lite  | °ol, °cpx, °sp, °bio, ser,<br>act, ss                      | °adcumultitic                | maj, tr | ol, bio                    |

NOTE.—Abbreviations for mineral names: cpx = clinopyroxene; opx = orthopyroxene; pl = plagioclase; mt = magnetite; ap = apatite; ab = albite; ep = epidote; prh = prehnite; cc = calcite; chl = chlorite; ss = saussurite; ppl = pumpellyite; amphib = amphibole; act = actinolite; hbl = hornblende; sph = sphene; hm = haematite; pyr = pyrite; mtm = montmorillonoids; chc = chalcidony; kaer = kaersutite and Ti-hastingsite; bio = biotite; ser = serpentine; ph = phenocrysts within intersertal, intersertal-divergent, microclitic groundmass.  
 a Whole-rock chemistry determined by X-ray fluorescence analysis using fused discs for major elements and pressed powder discs for trace elements: calibrations used USGS, NIM, CRPG rock standards, with corrections for absorption and interelement interference.

<sup>b</sup> Determined by electron microprobe analyses at 15–17 Kev on the ARL-SEMQ microprobe using minerals as standards.

is mostly fresh with virtually no deformation. It is similar in relict magmatic features to the type (a) basalt from the previously described unit. Metamorphic recrystallization of the basalt is more diffuse and pervasive than for type (a) basalt, but also of a static character. Mineral assemblages consisting mostly of albite, actinolite-hornblende, sphene, and epidote are developed, which indicate the greenschist facies.

**Melagabbro Intruded by Massive Gabbro.**—Only one occurrence of these lithotypes has been found, located at the foot of Cerro La Peña on the SSW slope. The melagabbro probably belongs to the cumulus sequence, of which the wehrlites described below are representative. The massive gabbro occurs as a vertical dike of unknown thickness.

The melagabbro shows advance weathering, but low-grade metamorphism is discerned. It is identified as an olivine pyroxene-rich gabbro of cumulus origin, as suggested by the occurrence of relict euhedral olivine included in the clinopyroxene, and by the uneven distribution in parallel bands of the latter mineral. The pyroxene is largely preserved and shows amphibole (now replaced by actinolite and chlorite) overgrown at the border of isolated individuals. The olivine is replaced by montmorillonoids, calcite, and in places by chalcidony. Plagioclase occurs in subhedral crystals and is replaced by chlorite, chalcidony, and calcite. Magnetite and apatite are the accessories.

The massive gabbro occurring as dikes is a clinopyroxene gabbro with sub-ophitic texture consisting of augite, saussuritized and partly chloritized plagioclase, magnetite, and apatite. There are small amounts of secondary amphibole (hornblende-actinolite) and of chlorite which indicate an incipient greenschist metamorphism.

**Cumulus Wehrlite.**—The Cerro La Peña is underlain by fresh wehrlites showing a distinct weakly inclined magmatic foliation. The rocks are dark gray, medium-grained, with poikilitic pyroxene and some accessory minerals (plagioclase and biotite) recognizable in hand specimens. The wehrlites show moderate modal variations, and consist mainly of olivine (77–80% by volume), clinopyroxene (9–15%), and plagioclase (about 7–8%) An

82–83. Minor components are black spinel, orthopyroxene, reddish brown amphibole, and red biotite. Brownish green grading to green hornblende is overgrown on the reddish brown amphibole by sub-solidus recrystallization. Actinolite and serpentine (after olivine), saussurite (after plagioclase), chlorite (after bronzite), and magnetite (exsolved from olivine, primary amphibole, and biotite) are the main secondary minerals. There is textural evidence of a cumulus origin of olivine and spinel. Bronzite and endiopside are partly cumulus phases, while plagioclase as well as amphibole and biotite are clearly post-cumulus. The following order of crystallization is suggested by the textural relations of cumulus- and post-cumulus phases:  $sp - ol - opx + cpx - pl - kaer - bio$ . It is consistent with the occurrence, within the wehrlite, of pockets of dolerite consisting of clinopyroxene, plagioclase, and magnetite and showing a sub-ophitic texture.

**Massive Metabasalt.**—This unit crops out at La Tetilla Mt. where it is exposed continuously over an area of about  $400 \times 250$  m and also at San Rafael Mt. and along the bed of Guadabara river. It consists of metabasalts occurring both as pillow-lavas and massive bodies (lava flows or sills). The pillows are about  $0.5 \times 1.5$  m in size and moderately deformed. The metabasalts are uniformly fine-grained blackish rocks containing a few plagioclase phenocrysts. There are associated hyaloclastite and basalt breccia layers. Locally (western slope of La Tetilla) there are basalt layers less than 1 m thick which show evidence of shearing and mylonitization and of intense recrystallization with the development of a network of quartz and actinolite veins. Rarely, sedimentary rocks (graywacke and siltstone) are interposed among the pillow-lavas (SW slope of La Tetilla).

The basaltic protoliths are easily recognizable in spite of the complete metamorphic recrystallization. They are aphyric and oligophyric basalts with minor plagioclase, and rarely olivine phenocrysts, plagioclase microphenocrysts, and intersertal or divergent groundmass.

The pervasive metamorphic recrystallization is characterized by assemblages of albite after plagioclase, amphibole (actinolite and actinolitic hornblende) after pyroxene, chlorite after pyroxene and olivine with small

amounts of sphene, epidote, and quartz. They indicate greenschist conditions.

Some actinolite, quartz, albite and calcite appear related to a late retrograde metamorphism under lower-grade conditions.

**Metabasalt and Metapelite.**—This unit is exposed discontinuously along the bed of Rio Palacé at the height of Las Mercedes and for about 5 km to the east. It is composed of metabasites showing mostly foliated structures and different relict magmatic textures which range from doleritic to microlithic, sometimes micro-porphyrific. The metapelites, which probably represent the sedimentary cover of the original basalts, are distinctly foliated phyllites containing variable amounts of quartz and calcite.

The metadolerites consist of green hornblende and actinolitic hornblende, oligoclase, epidote, and sphene. Calcite and quartz occur in small amounts. Some actinolite occurs in veins and bordering the hornblende. The mineral assemblages indicate a main metamorphic event of greenschist-amphibolite transition facies and a late greenschist facies overprinting.

#### MINERAL CHEMISTRY

Electron microprobe analyses of magmatic pyroxenes from the basalt and basalt breccia unit have been made on a dolerite and two aphyric basalt samples. For the wehrlites, all identified magmatic phases and the sub-solidus amphibole have been analyzed. Finally, the chemistry of amphiboles occurring in metabasites from different stratigraphic units has been investigated to provide useful data for an evaluation of the metamorphic conditions, particularly for the extrusive sequence. For each group of rocks, representative analyses of minerals are reported in tables 3, 4, and 5.

**Pyroxenes from the Basalt and Basalt Breccia Unit.**—The analytical data reported in table 3 and plotted in a classificative diagram in figure 3 show similar chemistries and fractionation trends for the pyroxenes from the dolerite and the two aphyric basalt samples. The pyroxenes range from augite to subcalcic augite with high  $Mg/(Mg + Fe)$  ratios and low  $AlVI/AlIV$  ratios. The Ti and Na contents are relatively low. Cr shows dispersed and mostly high values. The chemical data clearly show that these pyroxenes crys-

TABLE 3

REPRESENTATIVE ANALYSES AND STRUCTURAL FORMULAE OF CLINOPYROXENES FROM THE LA TETILLA OPHIOLITE BASALTS (CPX-PHYR BASALT GROUP)

| Sample<br>Rock type                          | IGM25744<br>Dolerite |        |        |        | IGM25770<br>Aphyric basalt |        |       |        | IGM25771<br>Aphyric basalt |        |        |
|----------------------------------------------|----------------------|--------|--------|--------|----------------------------|--------|-------|--------|----------------------------|--------|--------|
| Occurrence                                   | c                    | c      | c      | r      | mcl                        | mph    | mcl   | mcl    | mcl                        | mcl    | mcl    |
| SiO <sub>2</sub>                             | 52.83                | 53.01  | 54.11  | 52.11  | 52.87                      | 52.93  | 50.86 | 50.83  | 52.24                      | 53.33  | 53.42  |
| TiO <sub>2</sub>                             | .34                  | .34    | .29    | .45    | .31                        | .30    | .53   | .35    | .24                        | .29    | .20    |
| Al <sub>2</sub> O <sub>3</sub>               | 2.61                 | 2.46   | 1.46   | 1.80   | 2.11                       | 2.55   | 3.18  | 2.99   | 3.17                       | 2.19   | 2.21   |
| FeO                                          | 6.46                 | 6.10   | 6.62   | 11.90  | 10.28                      | 6.18   | 8.35  | 11.34  | 6.62                       | 6.48   | 6.81   |
| MnO                                          | .13                  | .16    | .18    | .30    | .24                        | .17    | .22   | .23    | .21                        | .20    | .21    |
| MgO                                          | 17.85                | 18.45  | 19.75  | 17.66  | 18.04                      | 19.16  | 17.30 | 16.05  | 17.51                      | 17.76  | 18.04  |
| CaO                                          | 19.74                | 19.57  | 17.78  | 16.20  | 16.74                      | 18.50  | 18.71 | 17.22  | 19.66                      | 19.86  | 18.89  |
| Na <sub>2</sub> O                            | .16                  | .12    | .14    | .09    | .13                        | .17    | .18   | .23    | .21                        | .11    | .20    |
| Cr <sub>2</sub> O <sub>3</sub>               | .34                  | .63    | .06    | .00    | .08                        | .53    | .35   | .77    | .33                        | .24    | .30    |
| Total                                        | 100.46               | 100.84 | 100.39 | 100.52 | 100.80                     | 100.50 | 99.70 | 100.12 | 100.19                     | 100.46 | 100.28 |
| Structural formulae on the base of 6 oxygens |                      |        |        |        |                            |        |       |        |                            |        |        |
| Si                                           | 1.926                | 1.922  | 1.960  | 1.929  | 1.937                      | 1.921  | 1.887 | 1.898  | 1.912                      | 1.943  | 1.947  |
| Al <sup>IV</sup>                             | .074                 | .078   | .040   | .071   | .063                       | .079   | .113  | .102   | .088                       | .057   | .053   |
| Al <sup>VI</sup>                             | .038                 | .028   | .023   | .008   | .028                       | .030   | .026  | .030   | .049                       | .037   | .042   |
| Ti                                           | .009                 | .007   | .008   | .013   | .009                       | .008   | .015  | .010   | .007                       | .008   | .005   |
| Fe                                           | .197                 | .185   | .201   | .368   | .315                       | .188   | .259  | .354   | .203                       | .197   | .208   |
| Mn                                           | .004                 | .005   | .006   | .009   | .007                       | .005   | .007  | .007   | .007                       | .006   | .006   |
| Mg                                           | .970                 | .997   | 1.066  | .974   | .985                       | 1.036  | .957  | .893   | .955                       | .964   | .980   |
| Ca                                           | .771                 | .760   | .690   | .643   | .657                       | .720   | .744  | .689   | .771                       | .775   | .738   |
| Na                                           | .011                 | .008   | .010   | .006   | .009                       | .012   | .013  | .017   | .015                       | .008   | .014   |
| Cr                                           | .010                 | .018   | .002   | .000   | .002                       | .015   | .010  | .023   | .010                       | .007   | .009   |
| Total                                        | 4.010                | 4.008  | 4.005  | 4.022  | 4.013                      | 4.014  | 4.030 | 4.023  | 4.017                      | 4.003  | 4.002  |
| Atomic proportion (%)                        |                      |        |        |        |                            |        |       |        |                            |        |        |
| Ca                                           | 39.8                 | 39.1   | 35.2   | 32.4   | 33.6                       | 37.0   | 38.0  | 35.6   | 40.0                       | 40.0   | 38.3   |
| Mg                                           | 50.0                 | 51.4   | 54.5   | 49.1   | 50.3                       | 53.3   | 48.8  | 46.1   | 49.5                       | 49.8   | 50.9   |
| Fe                                           | 10.2                 | 9.5    | 10.3   | 18.5   | 16.1                       | 9.7    | 13.2  | 18.3   | 10.5                       | 10.2   | 10.8   |
| Mg                                           | 83.1                 | 84.4   | 84.1   | 72.6   | 75.8                       | 84.6   | 78.7  | 71.6   | 82.5                       | 83.0   | 82.5   |
| Mg + Fe                                      |                      |        |        |        |                            |        |       |        |                            |        |        |

NOTE.—c = core of coarse crystal; r = rim; mcl = microlith; mph = micro-phenocryst.

tallized from similar and poorly fractionated magmas of tholeiitic type. Compared with clinopyroxenes from tholeiites of different magmatic affinities, they resemble those of low-K tholeiitic, i.e. island arc, basalts (Leterrier et al. 1982; Beccaluva, oral communication). This indication is in agreement with the total rock chemistry that is discussed in a later section.

**Primary and Subsidiary Minerals from the Wehrlites.—Olivine.** Two representative analyses of olivines are reported in table 4. They show Mg numbers between 83.8 and 86.3, significant contents of Al, Ca, and Ti, and high NiO. The abundances of NiO and the iron enrichment are in the range of olivine from layered intrusions (Simkin and Smith 1970).

**Pyroxenes.** In table 4 two average analyses

of poikilitic clinopyroxenes, and representative analyses of a fine-grained (intercumulus?) crystal and a grain from a dolerite pocket are reported. All these pyroxenes plot in the endiopside field (fig. 3), and no significant fractionation is shown. As for minor elements, a high Cr content and low contents of Ti and Na are shown. In these features they are similar to the clinopyroxenes from the cpx-phyric basalt group. This is consistent with other petrological and geochemical features suggesting comagmatic relationships among these lithotypes. Two representative analyses of orthopyroxene are reported in table 4; plotted in the pyroxene quadrilateral (fig. 3) they show a Ca-rich bronzite composition.

**Plagioclase.** Some relict plagioclase may be found in cores of altered crystals: one rep-

TABLE 4  
SELECTED ANALYSES OF MAGMATIC AND SUBSOLIDUS MINERALS OF WEHLITES FROM THE LA TETILLA OPHIOLITE COMPLEX

| Mineral                        | Olivine |       |       | Clinopyroxene |       |       | Orthopyroxene |       |       | Amphibole |       |       | Spinel |       |       | Plagioclase |       | Biotite |
|--------------------------------|---------|-------|-------|---------------|-------|-------|---------------|-------|-------|-----------|-------|-------|--------|-------|-------|-------------|-------|---------|
|                                | COL61   | COL60 | COL60 | COL61         | COL59 | COL59 | COL61         | COL59 | COL59 | COL61     | COL59 | COL59 | COL59  | COL59 | COL59 | COL61       | COL61 |         |
| Sample Occurrence              | euh     | euh   | euh   | poikb         | dol   | ahg   | anh           | anh   | anh   | cen       | cen   | bor   | ol     | ol    | dol   |             |       | COL60   |
| SiO <sub>2</sub>               | 40.34   | 41.41 | 42.07 | 51.91         | 52.43 | 52.45 | 55.86         | 55.63 | 55.63 | 44.81     | 44.33 | 49.46 | 52.06  | 35    | 3.43  | 47.17       |       | 40.87   |
| TiO <sub>2</sub>               | .02     | .00   | .05   | .24           | .18   | .20   | .28           | .45   | .45   | 3.73      | 4.05  | 3.48  | .32    | 16.16 | 0.61  | .00         |       | 5.76    |
| Al <sub>2</sub> O <sub>3</sub> | .03     | .02   | .02   | 2.79          | 2.86  | 2.74  | 1.27          | 1.52  | 1.52  | 9.52      | 9.97  | 9.50  | 4.75   | 22.40 | 14.48 | 32.81       |       | 12.98   |
| FeO <sub>tot</sub>             | 14.81   | 14.80 | 12.36 | 4.54          | 5.20  | 5.03  | 9.07          | 11.99 | 11.99 | 6.70      | 6.89  | 7.93  | 7.92   | 7.79  | 25.79 | .22         |       | 6.62    |
| MnO                            | .25     | .25   | .29   | .16           | .14   | .18   | .28           | .32   | .32   | .10       | .11   | .15   | .20    | .24   | .12   | .00         |       | .05     |
| MgO                            | 43.54   | 42.58 | 43.84 | 17.64         | 16.76 | 16.33 | 29.39         | 27.31 | 27.31 | 18.33     | 17.78 | 20.19 | 21.43  | 11.79 | 10.16 | .05         |       | 20.46   |
| CaO                            | .21     | .00   | .31   | 21.30         | 20.95 | 21.76 | 2.35          | 1.73  | 1.73  | 12.30     | 11.78 | 11.01 | 11.28  |       |       | 17.45       |       | .05     |
| Na <sub>2</sub> O              |         |       |       | .24           | .16   | .14   | .09           | .01   | .01   | .48       | .60   | .56   | .12    |       |       | 2.05        |       | .84     |
| K <sub>2</sub> O               |         |       |       |               |       |       |               |       |       | .19       | .77   | .03   | .04    |       |       | .06         |       | .25     |
| Cr <sub>2</sub> O <sub>3</sub> | .04     | .08   | .07   | 1.06          | 1.14  | 1.02  | .44           | .29   | .29   |           |       |       | .02    | 48.48 | 48.59 |             |       |         |
| NiO                            | .35     | .30   | .37   | .00           | .00   | .00   | .17           |       |       |           |       |       |        |       |       |             |       |         |
| Total                          | 99.59   | 99.44 | 99.38 | 99.88         | 99.53 | 99.05 | 99.20         | 99.25 | 99.25 | 99.77     | 98.90 | 99.56 | 99.87  | 99.42 | 99.75 | 99.81       |       | 96.54   |
| Atomic proportions %           |         |       |       |               |       |       |               |       |       |           |       |       |        |       |       |             |       |         |
| Ca                             | .3      | .0    | .4    | 43.1          | 43.5  | 45.3  | 4.6           | 3.5   |       |           |       |       |        |       |       |             |       |         |
| Mg                             | 83.7    | 83.7  | 86.0  | 49.7          | 48.4  | 47.3  | 81.3          | 77.4  |       |           |       |       |        | 56.2  | 48.4  |             |       | 35.6    |
| Fe                             | 16.0    | 16.3  | 13.6  | 7.2           | 8.3   | 7.3   | 14.1          | 19.1  |       |           |       |       |        |       |       |             |       |         |
| Mg                             | 84.0    | 83.7  | 86.3  | 87.4          | 85.6  | 86.5  | 85.2          | 80.3  |       |           |       |       |        | 68.8  | 69.2  |             |       | 72.3    |
| Mg + Fe                        |         |       |       |               |       |       |               |       |       |           |       |       |        |       |       |             |       |         |

Note: —euh = euhedral grain; poik = poikilitic grain; poikb = border of poikilitic grain; dol = within dolerite pocket; anh = anhedral grain; ol = enclosed within olivine; cen = center of crystal; bor = border of crystal.

\* Included 0.22% NiO = 0.26 atoms.



TABLE 5

REPRESENTATIVE ANALYSES OF AMPHIBOLES FROM METABASALTS AND A METAGABBRO FROM THE LA TETILLA OPHIOLITE COMPLEX

| Sample Occurrence              | COL58 px-mcl | COL58 px-mcl | IGM 26713 px-mcl | IGM 26713 px-mcl | COL57 myl | COL57 vein | IGM 26610 gdm | IGM 26610 gdm | IGM 26610 gdm | IGM 26610 px-ph |
|--------------------------------|--------------|--------------|------------------|------------------|-----------|------------|---------------|---------------|---------------|-----------------|
| SiO <sub>2</sub>               | 49.17        | 48.79        | 49.99            | 49.26            | 51.64     | 51.39      | 46.77         | 46.46         | 46.35         | 46.17           |
| TiO <sub>2</sub>               | .27          | .59          | .18              | .29              | .18       | .16        | .11           | .22           | .33           | .18             |
| Al <sub>2</sub> O <sub>3</sub> | 6.26         | 5.17         | 3.88             | 5.16             | 3.14      | 3.09       | 9.20          | 9.11          | 8.61          | 9.10            |
| FeO <sub>tot</sub>             | 17.86        | 16.29        | 20.38            | 17.74            | 17.67     | 18.95      | 12.27         | 12.25         | 12.47         | 12.82           |
| MnO                            | .29          | .26          | .59              | .27              | .17       | .32        | .16           | .13           | .17           | .17             |
| MgO                            | 10.58        | 13.67        | 11.51            | 12.97            | 13.62     | 12.55      | 14.46         | 14.68         | 14.58         | 14.69           |
| CaO                            | 12.81        | 13.04        | 10.92            | 12.05            | 12.04     | 11.62      | 12.24         | 12.27         | 11.88         | 12.00           |
| Na <sub>2</sub> O              | .46          | .33          | .43              | .51              | .30       | .25        | 1.63          | 1.69          | 1.67          | 1.66            |
| K <sub>2</sub> O               | .25          | .23          | .10              | .24              | .11       | .10        | .28           | .26           | .31           | .06             |
| Cr <sub>2</sub> O <sub>3</sub> | .14          | .13          | .00              | .08              | .00       | .00        | 1.12          | 1.21          | 1.11          | .89             |
| Total                          | 98.09        | 98.50        | 97.98            | 98.57            | 98.87     | 98.43      | 98.24         | 98.28         | 97.48         | 97.74           |

| Sample Occurrence              | IGM 26610 px-ph | IGM 26610 px-ph | IGM 26610 amg | IGM 26610 px-ph | COL55 sh-px | COL55 sh-px | COL55 sh-px | COL62 px-bd | COL62 px-bd | COL62 px-bd |
|--------------------------------|-----------------|-----------------|---------------|-----------------|-------------|-------------|-------------|-------------|-------------|-------------|
| SiO <sub>2</sub>               | 45.47           | 46.38           | 52.92         | 53.42           | 45.04       | 49.99       | 49.42       | 49.97       | 50.63       | 48.39       |
| TiO <sub>2</sub>               | .15             | .13             | .07           | .00             | .22         | .19         | .16         | 1.22        | .83         | .90         |
| Al <sub>2</sub> O <sub>3</sub> | 8.81            | 8.74            | 2.14          | 2.23            | 9.50        | 6.10        | 7.03        | 6.08        | 5.37        | 6.29        |
| FeO <sub>tot</sub>             | 15.08           | 15.54           | 11.28         | 10.20           | 16.09       | 13.33       | 12.16       | 15.13       | 14.66       | 15.24       |
| MnO                            | .27             | .23             | .29           | .22             | .24         | .23         | .16         | .18         | .13         | .12         |
| MgO                            | 13.61           | 12.95           | 17.35         | 18.20           | 12.70       | 15.36       | 15.81       | 12.77       | 13.24       | 13.73       |
| CaO                            | 11.81           | 11.96           | 12.58         | 12.50           | 12.02       | 12.21       | 12.43       | 11.68       | 11.74       | 12.39       |
| Na <sub>2</sub> O              | 1.77            | 1.73            | .61           | .54             | 2.15        | 1.46        | 1.31        | .97         | .70         | .95         |
| K <sub>2</sub> O               | .06             | .19             | .32           | .36             | .19         | .09         | .21         | .11         | .09         | .11         |
| Cr <sub>2</sub> O <sub>3</sub> | .04             | .04             | .00           | .10             | .52         | .05         | .11         | .01         | .01         | .04         |
| Total                          | 97.07           | 97.89           | 97.56         | 97.77           | 98.67       | 99.01       | 98.80       | 98.12       | 97.40       | 98.16       |

NOTE.—px-mcl = after pyroxene microlith; myl = within mylonite band; gdm = from pervasively recrystallized groundmass; px-ph = after pyroxene phenocryst; amg = within amygdale; sh-px = after subhedral pyroxene; px-bd = replacing fresh pyroxene at border.

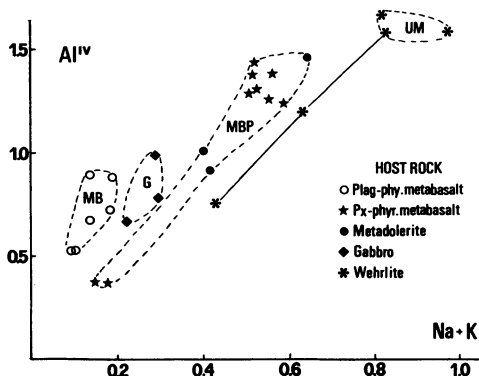


FIG. 4.—AlIV and alkali contents of amphiboles from mafic and ultramafic rocks. Magmatic (UM) and metamorphic amphiboles from wehrlites are shown: the solid line connects compositions of a zoned crystal. Metamorphic amphiboles from the melagabbro and gabbro unit (G), from the metabasalt and metapelite (MBP), and from the massive metabasalt (MB) units are specified.

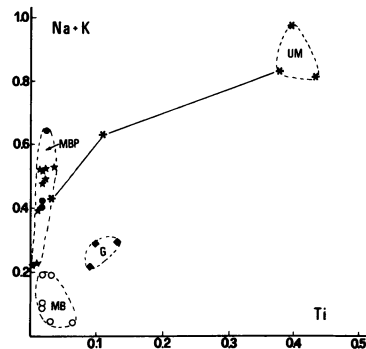


FIG. 5.—Na + K vs. Ti contents of amphiboles from mafic and ultramafic rocks from the La Tetilla complex. Symbols as in figure 4.

units are reported in table 6. The different basaltic lithotypes distinguished by relict magmatic features can be discriminated chemically on the basis of major or trace elements.

**Basalt and basalt breccia unit.** The analyzed samples include two aphyric basalts and a dolerite. They are weakly fractionated rocks (Mg numbers between 65.4 and 70.6) characterized by low  $\text{TiO}_2$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ , and  $\text{P}_2\text{O}_5$  contents. In terms of major element concentrations, they are classified as low-Ti sub-alkaline basalts with tholeiitic affinity. The trace elements suggest a similarity with magmas of primitive island-arcs (Pearce et al. 1984). Sr and Ba which, given the low degree of alteration of the analyzed samples, can be used as petrogenetic indicators, are close to average island-arc tholeiite values, as are Zr and Nb, while the Y contents are in the low range of this magma type. The Zr/Y ratios are therefore mostly higher than those of arc tholeiites (Pearce and Norry 1982). The relatively low Ti/V ratios of around 20 also suggest island-arc magmas (Shervais, 1982). However, indications contrasting with this predicted affinity are given by Cr which is a few times more abundant than in typical arc tholeiites, and by Ni, which is several times higher than in typical arc tholeiites. The high contents of these compatible elements give consequently rather ambiguous results if certain discriminant diagrams for magma types are used, like the Cr-Y (Pearce 1980) and Ti/Cr-Ni (Beccaluva et al. 1979).

**Massive gabbro cut by basalt dikes.** Two analyses of dike basalts from this unit (actually greenschist facies metabasalts) are reported. They are almost identical in major elements chemistry to the basalts from the basalt and basalt breccia unit, as expected by the similarities of relict mineralogical and textural features. The reported data on some incompatible elements are also consistent with an affinity with island-arc tholeiites, like the previous group of rocks.

**Massive metabasalt unit.** Four analyzed rocks are oligophyric basalts with plagioclase phenocrysts showing a complete metamorphic recrystallization (greenschist facies) of static type. One sample (IGM26713) derives from a basalt showing similar metamorphic recrystallization under greenschist facies conditions which followed an intense

shearing to produce mylonite bands. The chemical data show that the analyzed rocks are homogeneous tholeiitic basalts relatively rich in Ti (fig. 6). For a characterization of the parent magma type, mostly high field-strength elements (Zr, Y, Nb, V, Cr) are considered. Their low mobilities during metamorphism is suggested by the small differences of their levels between the massive metabasalts and the mylonitic metabasalt (sample 26713). The abundances and ratios of Zr, Y, and Cr are close to the characteristic values of within-plate tholeiitic magmas (Pearce 1980; Pearce and Norry 1979; Shervais 1982). Plots of Ti, Zr, and V are shown in figures 7 and 8. The differences, with respect to the low-Ti tholeiitic basalt group described above, are evident from these diagrams.

**Metabasalt and metapelite unit.** A metadolerite and a metabasalt with relict pyphyric texture have been analyzed. The two samples are significantly different. The first one (COL55) has a tholeiitic composition relatively high in Ti. Major and trace element contents are in the range of the high-Ti tholeiites from the massive metabasalt unit. The second sample (IGM26610) shows a primitive basalt composition (Mg number 69.8). The high MgO (12.96%) is distinct, as are Cr (951 ppm) and Ni (288 ppm). Ti and the other analyzed incompatible elements are low and close to the values of the low-Ti tholeiites from the basalt and basalt breccia unit (figs. 6, 7, and 8). The high contents of the ferromagnesian elements suggests similarity with high-Mg and low-Ti basalts of picritic type.

**Mafic and Ultramafic Plutonics.**—Five analyses of plutonic rocks from the melagabbro and massive gabbro unit and from the cumulus wehrlite unit are presented in table 6. The analyzed samples include a massive gabbro, a melagabbro, and three wehrlites. All these samples show a relatively high degree of alteration, particularly the melagabbro (water content higher than 5%). An evaluation of their magmatic features may nevertheless be made, considering the immobile and less mobile elements, like Mg, Fe, Ti, P, Zr, Y, Cr, and Ni.

The massive gabbro (sample COL62) is chemically similar to the less fractionated basalt from the low-Ti tholeiitic type. The three analyzed wehrlites exhibit small but

TABLE 6

## CHEMICAL ANALYSES OF VOLCANIC AND PLUTONIC ROCKS FROM THE LA TETILLA OPHIOLITE COMPLEX

| Unit<br>Rock type<br>Sample<br>wt% | Basalt & bas. breccia |       |       |        | Isotr. gab. & bas. |       |       |       | Massive metabasalt |       |       |        | Metabas. & metapel. |        |       |       | Melag. & gab. |       |     |     | Cumulus wehrlite |       |     |     |
|------------------------------------|-----------------------|-------|-------|--------|--------------------|-------|-------|-------|--------------------|-------|-------|--------|---------------------|--------|-------|-------|---------------|-------|-----|-----|------------------|-------|-----|-----|
|                                    | AB                    | AB    | DOL   | IGM    | AB                 | AB    | COL67 | COL58 | COL56              | CL155 | CL156 | IGM    | OB                  | DOL    | GA    | MGA   | COL63         | COL59 | WEH | WEH | COL61            | COL60 | WEH | WEH |
| SiO <sub>2</sub>                   | 51.24                 | 48.46 | 49.67 | 49.80  | 49.94              | 49.94 | 49.78 | 47.63 | 47.81              | 48.88 | 49.80 | 46.58  | 47.73               | 50.22  | 47.94 | 42.12 | 39.96         | 40.57 |     |     |                  |       |     |     |
| TiO <sub>2</sub>                   | .97                   | .92   | .62   | .88    | .88                | .88   | 2.21  | 2.28  | 2.21               | 2.17  | 2.15  | 1.15   | 2.28                | .70    | .67   | .40   | .34           | .35   |     |     |                  |       |     |     |
| Al <sub>2</sub> O <sub>3</sub>     | 13.80                 | 14.05 | 13.84 | 14.66  | 13.72              | 13.35 | 13.99 | 14.08 | 13.86              | 13.79 | 13.79 | 11.36  | 13.44               | 13.70  | 8.81  | 6.26  | 4.73          | 5.59  |     |     |                  |       |     |     |
| Fe <sub>2</sub> O <sub>3</sub>     | 2.19                  | 2.47  | 1.91  | 3.06   | 2.39               | 1.87  | 1.47  | 2.98  | 1.83               | 2.35  | 2.35  | 4.07   | 5.85                | 2.57   | 2.90  | 3.49  | 4.30          | 4.04  |     |     |                  |       |     |     |
| FeO                                | 6.55                  | 6.80  | 6.73  | 6.66   | 7.18               | 8.88  | 9.33  | 7.88  | 8.85               | 7.96  | 7.96  | 7.67   | 5.66                | 4.77   | 6.05  | 6.34  | 6.49          | 6.39  |     |     |                  |       |     |     |
| MnO                                | .16                   | .17   | .17   | .17    | .17                | .18   | .19   | .19   | .17                | .18   | .19   | .19    | .17                 | .14    | .14   | .17   | .17           | .16   |     |     |                  |       |     |     |
| MgO                                | 8.40                  | 9.26  | 10.02 | 8.81   | 8.78               | 7.08  | 7.36  | 7.03  | 7.49               | 6.66  | 6.66  | 12.96  | 7.66                | 9.84   | 17.75 | 27.49 | 30.92         | 29.66 |     |     |                  |       |     |     |
| CaO                                | 11.56                 | 11.54 | 11.60 | 12.29  | 11.84              | 9.43  | 11.79 | 12.47 | 11.10              | 12.27 | 12.27 | 10.63  | 10.47               | 12.80  | 9.76  | 6.10  | 5.50          | 5.47  |     |     |                  |       |     |     |
| Na <sub>2</sub> O                  | 1.96                  | 2.20  | 2.30  | 1.75   | 2.02               | 3.27  | 2.60  | 1.95  | 2.35               | 2.44  | 2.44  | 2.25   | 3.64                | 2.56   | .22   | .43   | .12           | .05   |     |     |                  |       |     |     |
| K <sub>2</sub> O                   | .20                   | .16   | .23   | .23    | .18                | .33   | .41   | .68   | .42                | .25   | .25   | .37    | .10                 | .53    | .01   | .14   | .03           | .05   |     |     |                  |       |     |     |
| P <sub>2</sub> O <sub>5</sub>      | .09                   | .09   | .05   | .10    | .12                | .22   | .21   | .21   | .21                | .22   | .22   | .20    | .19                 | .08    | .06   | .05   | .04           | .03   |     |     |                  |       |     |     |
| H <sub>2</sub> O <sup>a</sup>      | 2.34                  | 3.17  | 2.79  | 1.79   | 2.09               | 2.67  | 2.21  | 1.78  | 1.88               | 1.32  | 1.32  | 3.24   | 1.76                | 2.51   | 5.13  | 6.55  | 7.27          | 7.21  |     |     |                  |       |     |     |
| CO <sub>2</sub>                    | .17                   | .40   | .00   | .00    | .18                | .03   | .39   | .41   | .99                | .64   | .99   | 100.67 | .36                 | .02    | .04   | .00   | .00           | .00   |     |     |                  |       |     |     |
| Total                              | 99.63                 | 99.69 | 99.93 | 100.20 | 99.31              | 99.45 | 99.50 | 99.64 | 99.63              | 99.40 | 99.40 | 100.67 | 99.31               | 100.46 | 99.48 | 99.54 | 99.87         | 99.57 |     |     |                  |       |     |     |
| ppm                                |                       |       |       |        |                    |       |       |       |                    |       |       |        |                     |        |       |       |               |       |     |     |                  |       |     |     |
| Zr                                 | 56                    | 51    | 40    | 34     | 47                 | 130   | 136   | 111   | 106                | 134   | 134   | 59     | 94                  | 42     | 14    | 4     | nd            | nd    |     |     |                  |       |     |     |
| Y                                  | 14                    | 14    | 12    | 13     | 12                 | 23    | 21    | 21    | 19                 | 22    | 22    | 16     | 19                  | 10     | 6     | nd    | nd            | nd    |     |     |                  |       |     |     |
| Nb                                 | 4                     | 3     | 2     | na     | 4                  | 18    | 17    | na    | na                 | 18    | 18    | 5      | 8                   | 5      | na    | na    | na            | na    |     |     |                  |       |     |     |
| Cr                                 | 443                   | 472   | 641   | na     | na                 | 365   | 349   | 387   | 343                | 276   | 276   | 951    | 443                 | 1046   | 1904  | 2831  | 3160          | 3068  |     |     |                  |       |     |     |
| V                                  | 274                   | 275   | 240   | na     | na                 | 380   | 356   | 280   | 382                | 356   | 356   | 326    | 370                 | 254    | 185   | 149   | 102           | 107   |     |     |                  |       |     |     |
| Rb                                 | nd                    | nd    | nd    | na     | na                 | 3     | 5     | 15    | 3                  | 3     | nd    | 3      | 1                   | 8      | nd    | nd    | nd            | nd    |     |     |                  |       |     |     |
| Sr                                 | 118                   | 119   | 209   | 103    | na                 | 268   | 286   | 235   | 271                | 277   | 277   | 145    | 306                 | 153    | 20    | 41    | 23            | 41    |     |     |                  |       |     |     |
| Ba                                 | 57                    | 52    | 49    | na     | na                 | 58    | 87    | 71    | 98                 | 51    | 55    | 55     | na                  | 53     | 25    | 38    | 41            | 18    |     |     |                  |       |     |     |
| Ni                                 | 138                   | 144   | 164   | na     | 134                | 121   | 117   | 114   | 119                | 121   | 121   | 288    | 126                 | 169    | 652   | 1142  | 1335          | 1297  |     |     |                  |       |     |     |
| Cu                                 | 25                    | na    | 78    | na     | na                 | 216   | 260   | 237   | 198                | 182   | 182   | na     | na                  | 35     | 50    | 70    | 32            | 36    |     |     |                  |       |     |     |
| Zn                                 | 55                    | 58    | 56    | na     | na                 | 61    | 62    | 50    | 91                 | 112   | 112   | 69     | 83                  | 33     | 47    | 55    | 49            | 51    |     |     |                  |       |     |     |
| Hf                                 | nd                    | nd    | nd    | na     | na                 | 1     | 2     | 2     | 1                  | 2     | 2     | 1      | 1                   | nd     | nd    | nd    | nd            | nd    |     |     |                  |       |     |     |
| Mg number <sup>a</sup>             | 66.6                  | 67.5  | 70.6  | 65.4   | 65.6               | 57.6  | 58.3  | 57.4  | 59.1               | 57.2  | 57.2  | 69.8   | 58.6                | 73.8   | 80.6  | 85.4  | 85.8          | 85.3  |     |     |                  |       |     |     |
| Ti/Zr                              | 103.8                 | 108.1 | 97.8  | 155.2  | 112.2              | 101.9 | 100.5 | 119.4 | 127.7              | 96.2  | 96.2  | 116.9  | 145.4               | 99.9   | 286.9 |       |               |       |     |     |                  |       |     |     |
| Ti/Cr                              | 13.1                  | 11.7  | 5.8   | ...    | ...                | 36.3  | 39.2  | 34.2  | 37.9               | 46.7  | 46.7  | 23.9   | 30.9                | 4.0    | 2.1   |       |               |       |     |     |                  |       |     |     |
| Zr/Y                               | 4.0                   | 3.6   | 3.2   | 2.6    | 3.9                | 5.7   | 6.5   | 5.3   | 5.6                | 6.1   | 6.1   | 3.7    | 4.9                 | 4.2    | 2.3   |       |               |       |     |     |                  |       |     |     |
| Nb/Y                               | .29                   | .21   | .25   | ...    | .33                | .78   | .81   | ...   | ...                | .82   | .82   | .31    | .42                 | .50    | ...   |       |               |       |     |     |                  |       |     |     |

Note.—(Ab = aphyric basalt; DOL = dolerite; OB = oligophytic basalt; MB = microthitic basalt; GA = gabbro; MGA = melagabbro; WEH = wehrlite). not analyzed. nd = not detectable.  
<sup>a</sup> % molecular Mg/(Mg + Fe<sup>2+</sup>) calculated for a ferric/ferrous iron ratio = 0.15.

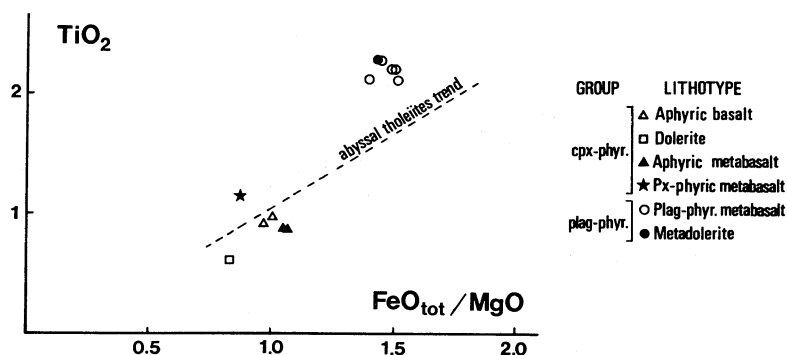
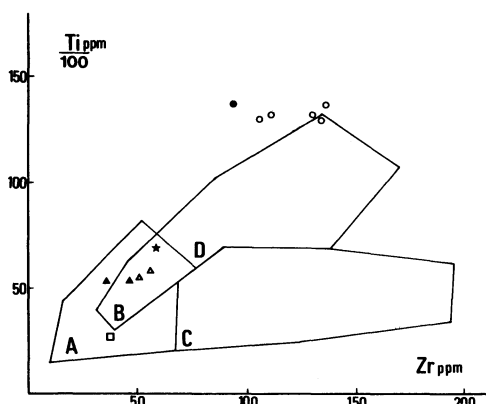
FIG. 6.— $\text{TiO}_2$  vs.  $\text{FeO}_{\text{tot}}/\text{MgO}$  diagram for basaltic rocks.

FIG. 7.—Ti-Zr diagram (Pearce and Cann 1973), of basaltic rocks. Fields A and B are island-arc tholeiites, fields B and D are abyssal basalts, and field C is calc-alkali basalt. Symbols are as in figure 6.

significant differences in chemistry as is shown by the variation diagram of some selected elements against  $\text{MgO}$  (fig. 9). There is evidence of linear relationships and a positive correlation with total  $\text{FeO}$ ,  $\text{Cr}$ , and  $\text{Ni}$ , which clearly reflects dilution effects of the dominant cumulus phases, i.e., olivine and spinel, and a negative correlation with  $\text{TiO}_2$ . In the same diagram the melagabbro plots close to the regression lines of  $\text{Cr}$  and  $\text{Ni}$  displayed by the wehrlites, indicating the effects of the depletion of olivine and spinel in the cumulus phase, while  $\text{TiO}_2$  shows a relative enrichment.

An insight into cumulus processes responsible for these trends is provided by the variations toward a parent magma of which the gabbro (sample COL62) can be considered the most probable representative on the basis

of its magmatic features. Plot of the gabbro in figure 9 shows linear relationships of  $\text{Cr}$  and  $\text{Ni}$  with the cumulus rocks, which are interpreted as mixing lines between the liquid and the early cumulus phases, so providing evidence for a mainly heteradcumulus process. For  $\text{TiO}_2$ , linear relationships are also shown with the wehrlites, but not for the melagabbro, which is relatively enriched in  $\text{TiO}_2$ . This enrichment may be related to the effects of a Ti-rich phase among the cumulus minerals, probably a spinel changing toward a more Ti- and Fe-rich composition.

#### COMPARISON WITH OTHER COLOMBIAN OPHIOLITES

On the basis of the data presented in this study, a comparison between La Tetilla and other ophiolitic complexes from southwest-

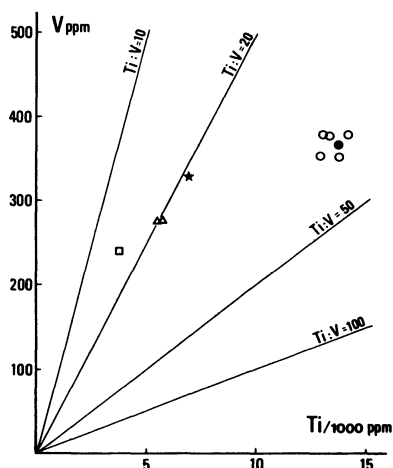


FIG. 8.—V-Ti diagram (Shervais 1982) for basaltic rocks. Symbols as in figure 6.

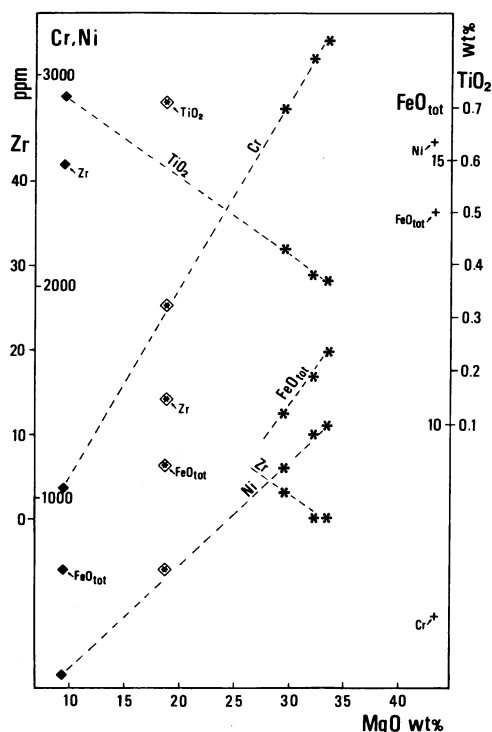


FIG. 9.—Variation diagram of selected major and trace elements vs. MgO for plutonic rocks. Regression lines (dashed, fitted by eye) are drawn for the wehrlites and for elements showing linear variations toward the gabbro. The average olivine from wehrlite is also plotted (cross).

ern Colombia is restricted to petrological features, particularly the magmatic mineralogy and texture, and the rock geochemistry, resulting from either previous studies (Barrero 1979; Espinosa 1980; McCourt et al. 1984; Millward et al. 1984; Aspden and McCourt 1986) or from unpublished data by the authors of this study.

The petrography of the plutonic rocks from the previously mentioned major complexes (Bolívar, Ginebra, and Los Azules) is first considered. Their plutonic sequences, though significantly different, are characterized by wehrlites (and also websterites) among the cumulus ultramafics, and by gabbro-norites among the mafic rocks (except perhaps at Los Azules). The occurrence of magmatic amphiboles in mafic and, in some cases, also in ultramafic plutonics is another distinctive feature. The plutonic rocks from La Tetilla complex show similar characteristics, particularly the crystallization sequence, which

controls assemblages in cumulates and the occurrence of hydrous magmatic phases. An origin from magmas genetically similar can be therefore inferred.

The rocks of extrusive origin primarily associated with these plutonic sequences can be compared in terms of both petrography and chemical composition. There are significant differences within and among the considered complexes. However, their overall petrological features, including the phenocryst mineralogy in porphyritic basalts, characterized by cpx alone or preceding plagioclase in the crystallization sequence, and the major and trace element chemistry, indicate that most derive from low-Ti tholeiitic magmas similar to those inferred for La Tetilla. As an example, V vs. Ti is plotted in figure 10, where it is seen that the high V/Ti ratios indicative of island arc tholeiites are characteristic of most of the complexes, but that a few genetically ambiguous rocks occur also.

#### DISCUSSION AND CONCLUSIONS

*Evidence for Distinct Petrologic Types of Basalts.*—For the mafic extrusives from La Tetilla area (lavas and dike rocks in origin) the mineralogy of the phenocrysts (though occurring sparsely) and the whole-rock chemistry (close to the composition of liquids in lavas which are mostly aphyric and oligophyric) can provide useful indications for their petrogenesis.

On petrographic evidence, two groups are recognized: (a) clinopyroxene-phyric basalts characterized by the crystallization of pyroxene before plagioclase and the early appearance of magnetite; and (b) plagioclase-phyric basalts in which plagioclase crystallized before pyroxene, and eventually olivine occurred as an early magmatic phase. Group (a) is characterized chemically by a low-Ti tholeiitic composition of primitive type (Mg numbers around 65–70). Group (b) shows a high-Ti tholeiitic chemistry with Mg numbers lower than the former group (around 57–59). The two groups thus recognized are unlikely to be strictly cogenetic, as they are quite sufficiently different in crystallization sequence. The two petrologic groups occur in distinct units distinguished by different metamorphic evolutions, but are also associated together, and with high-Mg basalts, pet-

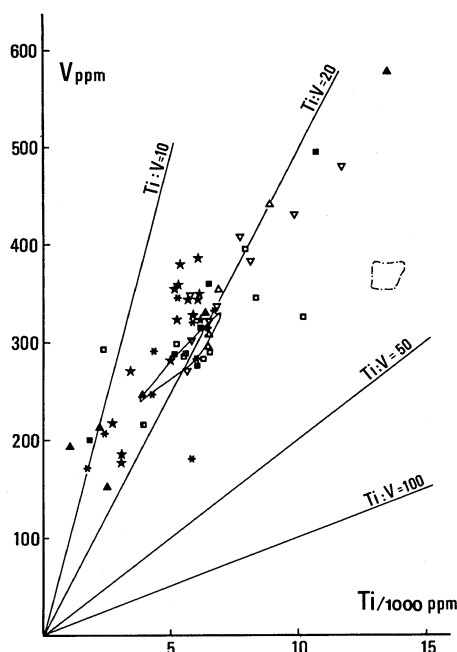


FIG. 10.—Comparison of V and Ti relations between the La Tetilla basaltic rocks and mafic extrusions from southwestern Colombia. Symbols: solid envelope = field of low-Ti tholeiites from La Tetilla complex; dashed envelope = field of high-Ti tholeiites from La Tetilla complex; filled triangle = metabasalts related to the plutonic sequence from the Bolivar complex; filled square = metavolcanics related to the plutonic sequence from the Ginebra complex; inverted triangle = basalts from the Western Cordillera; triangle = basalts from La Primavera-Trujillo section (Bolivar area); square = basalts from western Central Cordillera; diamond = basalts associated with plutonics from the Los Azules complex; asterisk = basalts from the El Bordo-El Penol section (Western Cordillera); filled star = basalts from the Ricaurte-Altaqueres section (Western Cordillera). Sources: this study; present author (unpublished data); Millward et al. (1984); Aspdén and McCourt (1986).

rographically similar to the cpx-phyric type, with a low-Ti picritic chemistry.

It is highly probable that the plutonic sequence is cogenetic with the cpx-phyric basalt type, notwithstanding that very few lithologies are represented. In fact, the crystallization sequence (ol + sp - opx + cpx - pl) and the phase composition (particularly of pyroxenes and spinel) of the wehrlites point to a parent magma similar to the low-Ti tholeiite type.

**Tectonic Setting.**—For the cpx-phyric

basalt group (low-Ti tholeiites), most petrological data (crystallization sequence, pyroxene chemistry, whole rock geochemistry) suggest an affinity with primitive island arc magmas. As the same set of data point to cogenetic relationships with the mafic-ultramafic plutonics, it can be inferred that the low-Ti basalts and the plutonic sequence are remnants of oceanic crust (upper volcanics and underlying magma chamber) generated in an immature arc. These rocks should be regarded, therefore, as parts of ophiolites generated in supra-subduction zones (Pearce et al. 1984), which are proving to be a very common type (Beccaluva et al. 1983). Constraints by a more detailed knowledge of the regional setting are necessary to verify this hypothesis.

For the plag-phyric basalt group (high-Ti tholeiites), suggestions about the eruptive environment are mostly provided by geochemical data. The within-plate character of these basalts, joined with the evidence for a sub-seafloor environment of their metamorphism, suggest an ocean island origin. Identification of their tectonic setting is still hypothetical, being inferred mainly on petrological evidence.

**Metamorphic Evolution.**—In the complex including the low-Ti basalt unit and the plutonic sequence, the recorded metamorphism is static and characterized by poorly developed recrystallization. The grade is low, and increases from the extrusive (prehnite-pumpellyite facies) toward the plutonic sequence (greenschist facies). The degree of recrystallization increases from the basalt to the massive gabbro and decreases toward the cumulus plutonics. The latter, in fact, show a very scanty metamorphic alteration. These features recall the hydrothermal metamorphism of oceanic crust far from a fracture zone, as recognized in actual ocean crust and in ophiolite sequences (Coleman 1984), which is often characterized in the plutonic section by downward decreasing alteration from lower hydration.

In the massive metabasalt and the metabasalt and metapelite unit, the recrystallization is pervasive, and there is evidence of variable stress which produced either penetrative or sparse deformation and acted mostly prior to recrystallization. The textural and mineralogical features, particularly the

chemistry and strong zoning of the amphiboles, indicate a hydrothermal metamorphism which could have developed mostly in an oceanic environment. Based on experimental data (Liou et al. 1974; Moody et al. 1983), the estimated conditions of the metamorphic climax in the massive metabasalt unit are around 450–500°C at low pressure (<5 kb as indicated by the amphibole chemistry) and moderately oxidizing conditions (as indicated by the presence of epidote). The mode of occurrence and environment of the primary sequence suggest an even lower pressure. For the metabasalt and metapelite unit, temperatures above 550°C, less oxidizing conditions or, alternatively, higher pressure at the same  $fO_2$  are deduced.

**Relationships between low-Ti and high-Ti Basalts.**—As the stratigraphic relations between low- and high-Ti basalts are insufficiently known, it is difficult to picture magma evolution in time and space. Indications by: (a) the structural position of the low-Ti sequence above the high-Ti one; (b) the

absence of high-Ti rocks (basalt and gabbro) among the dikes intruding the plutonic sequence; (c) the association of basalts related to the two petrologic types before metamorphism; and (d) the dominant imprint of oceanic metamorphism in all lithotypes, could suggest that the high-Ti basalts are partly older than the low-Ti sequence, and that the two groups were associated prior to their tectonic emplacement. Under this reconstruction, the La Tetilla complex can be considered an ophiolite *sensu lato*, being composed of tectonically associated, partly non-cogenetic rocks.

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