

# ULTRABASIC-BASIC INTRUSIVE VIZCAINO LAYERED COMPLEX AND VIZCAINO OPHIOLITE (SOUTHERN BAJA CALIFORNIA, MEXICO)

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## ABSTRACT

Two ultrabasic-basic rocks-bearing units occur in the Vizcaino Peninsula of Southern Baja California (Mexico) : the Vizcaino Layered Complex (VLC) and the San Hipolito Zone (SHZ). The VLC consists of two sequences : the lower Puerto Nuevo Sequence (serpentinite breccia, harzburgite, dunite, cyclic units), and the upper La Pintada Sequence (cyclic units, gabbros, diorites). The SHZ consists of serpentinite, actinote schists, microgabbros, spilitic pillow lavas, ophicalcites, radiolarites, tuffs, greywackes, interbedded limestone and dolomite, siliceous sandstones, and volcanosedimentary strata. The VLC is an autochthonous complex generated by a magma underplating, which is intrusive into the San Pablo Metamorphic Complex (SPMC) (amphibole-biotite gneiss with lenses of granite, migmatitic amphibolitic gneiss, orthoamphibolites). Originally, together with its metamorphic roof, the SPMC, it constituted a continental magmatic arc. The SHZ, a former Late Triassic marginal sea, is an allochthonous Carnian (?) -Norian ophiolitic unit, emplaced as a nappe upon the VLC during the Liassic. During the Late Triassic (starting at  $\pm 220$  Ma) this zone underwent a long lived extensional event, during which plagiogranite dykes and dolerite/albitite dykes were emplaced into it, whereas the San Hipolito Basin opened behind it. Then, different units of the VLC were exhumed and exposed by low angle normal listric faults. It seems that the upper part of the VLC, La Pintada Sequence and the SPMC were then displaced to their present position of San Pablo-La Pintada. During the Liassic compressional phase the plagiogranite dykes were boudinaged, and slices of the SHZ Nappe came to rest upon every one of the units of the Puerto Nuevo Sequence, including the serpentinite breccia (which gave way to the erroneous notion of the so-called Puerto Nuevo Mélange of previous literature).

**Keywords:** arc, marginal sea, magma underplating, ophiolite, Vizcaino, Baja California, tectonics

## LAS ROCAS INTRUSIVAS BASICAS-ULTRABASICAS DEL COMPLEJO ESTRATIFICADO DEL VIZCAINO Y LA OFIOLITA DEL VIZCAINO (BAJA CALIFORNIA SUR, MÉXICO)

### RESUMEN

En la Península del Vizcaino, Baja California Sur (México), se encuentran dos unidades de rocas básicas-ultrabásicas: el Complejo Estratificado del Vizcaino (CEV) y la Zona San Hipólito (ZSH). El CEV consiste de dos secuencias actualmente separadas, de arriba hacia abajo: la Secuencia de Puerto Nuevo (brecha de serpentinita, harzburgita, dunita, unidades cíclicas), y la Secuencia de La Pintada (unidades cíclicas, gabros, dioritas). La ZSH consiste de serpentinitas, esquistos actinolíticos, microgabros, pillow lavas espiliticas, oficalcitas, radiolaritas, tobas, grauvacas, intercalaciones de calizas y dolomías, areniscas silíceas, y depósitos volcánosedimentarios). El CEV, producto de una acreción magmática sub-cortical, es intrusivo en el Complejo Metamórfico San Pablo (CMSP) (gneises anfibolíticos y biotíticos con lentes de granito, gneises migmatítico-anfibolíticos, orto-anfibolitas). El CEV y su techo metamórfico, el CMSP, constituyen un arco magmático continental. La ZSH, depósitos de un mar marginal del Triásico Superior (Cárnico?-Nórico), es una unidad ofiolítica alóctona, una cobijadura emplazada durante el Liásico arriba del CEV. Durante el Triásico Superior el CEV fue sometido a un largo evento distensivo durante el cual se emplazaron diques de plagiogranito y de dolerita/albitita, mientras que atrás de él se abrió la cuenca San Hipólito. Las diferentes unidades del VLC fueron entonces exhumadas y expuestas por fallas normales listricas, por las cuales la Secuencia de La Pintada y el SPMC fueron desplazados y llevados a su posición actual de San Pablo-La Pintada. Durante la fase compresiva del Liasico los diques de plagiogranito sufrieron budinaje, y la Cobijadura de la SHZ, frecuentemente desmembrada, llegó a descansar sobre las diferentes unidades de la Secuencia de Puerto Nuevo, incluyendo la brecha de serpentinita - lo que dió lugar a la noción errónea del Mélange de Puerto Nuevo de la literatura.

**Palabras clave:** arco, mar marginal, acreción magmática subcortical, ofiolitas, Vizcaino, Baja California, tectónica

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## INTRODUCTION

### Foreword

This paper has had a sad pre-natal history that ought to be told.

(a) In 1999 it has been submitted to a European magazine specializing in ophiolites. It has been rejected mainly because of the advice of T. E. Moore, acting as a reviewer.

In his comment T. E. Moore wrote: *“The primary objective of this paper, stated on p. 3-4, is to show that the mafic-ultramafic complex in the Vizcaino Peninsula is (1) the result of magma underplating of continental crust rather than construction of an ophiolite in an oceanic setting and (2) that the overlying sedimentary section is allochthonous with respect to the mafic and ultramafic rocks. [...] I believe that this model can be rejected on the basis of field relations such as those described in Kimbrough (1985) and Moore (1983, 1985).”*

It is very much worth noting, however, that in a subsequent article published in 2003 in the Special Paper 734 of the GSA, D.L. Kimbrough and T. E. Moore wrote: *“Mesozoic ophiolites in the Vizcaino Peninsula and Cedros Island region of Baja California Sur are suprasubduction zone Cordilleran-type ophiolites structurally juxtaposed with underlying high pressure-temperature subduction complex assemblage”*

It would seem that between 1999 and 2003 a geological revolution has taken place in the Vizcaino ! But indeed their new assumption derives from the fact that - at long last ! - they seem to accept that the San Hipolito unit (Radelli's San Hipolito Zone) presents the assemblage of a marginal sea (with a floor only in part “oceanic”, variable volcanogenic detritus, and sedimentary strata). This is something I have put in evidence not only in my manuscript of 1999, but already in a note of 1994. Furthermore, in a note of 1993 Radelli and Castro had clearly divided the San Hipolito unit (Zone) from the main basic-ultrabasic body of Vizcaino. This is something that Kimbrough and Moore (2003) were not able to do. They still suppose that, contrary to geometric and petrographic evidences, the main basic-ultrabasic body of the Vizcaino and the San Hipolito Zone belong in the same structural unit, for which they continue to speak of *“Late Triassic ocean crust”*. [And it is worth notice that Sedlock begins an article of that same GSA Special Paper 734 stating that *“Ophiolites are remnants of oceanic lithosphere that are exposed at Earth's surface”*].

Now they should explain how an ocean could be found in a supra-subduction zone ...

In his comment to my manuscript of 1999 Moore denies the reality of the old crustal structural zone of the San Pablo Metamorphic Complex. It would be too long and tedious to discuss point by point the biased Moore's assertions on this

respect. Let me cite but one of Moore's conclusions: *“... these units do not display penetrative fabric or mylonitic textures common in migmatites (which is not true). Instead, they are spectacular zone of xenoliths of hornfelsed mafic rocks country rocks (sic!) that have been magmatically stopped into a large Jurassic or Early Cretaceous pluton of tonalite or granodiorite composition that adjoins the amphibolite unit”*. Let alone the petrographic difficulties of such a malevolent interpretation, such interpretation is easily disproven by the following observation: the Upper Triassic albitites (Barnes and Mattison, 1981 in Kimbrough and Moore, 2003) of San Pablo were not affected by those intrusion and consequent metamorphism. Thus, unless the Jurassic or early Cretaceous intrusions are assigned teleonomic qualities, the structures that can be observed, not from the San Pablo road but either on foot or by boat, and described by Radelli, are obviously and necessarily pre-Upper Triassic in geological age.

The only supra-subduction zone at least in part “oceanic” is of course a marginal sea. And a marginal sea implies an arc dividing it from the real ocean (think for instance of Japan). In spite of all Moore's fuss, the San Pablo Metamorphic Complex, with its granites and its biotitic gneisses, simply corresponds to such an arc.

A last note. In his comment to my manuscript Moore, willing to deny the existence of my San Hipolito nappe, wrote also: *“[...] there is absolutely no evidence of repeated section, older on younger, or deeper level on higher rocks anywhere in the Vizcaino Peninsula that would provide direct evidence for contraction deformation in main basement rock units on the Peninsula”*. What is now evident is that Moore has no notion of the different behaviour of the outer and inner zones of an orogen. Almost a century after Argand this is very sad, to say the less. Possibly, in the Alps he would conclude that the Flysch à Helmintoïdes Nappe is simply a transgressive sequence ...

It is not my intention to enter a polemics with the authors above. Indeed, no discussion is possible with people who think that only what is published in the USA deserves a recognition. All I wish is to establish the order of certain facts.

### The terms of the problem

The huge bodies of ultrabasic and basic rocks of the Vizcaino Peninsula - peridotite (partly serpentized) to gabbro of the Puerto Nuevo Sequence, overlain in places by the pillow basalts and associated facies of the Upper Triassic San Hipolito Formation - were first described by Mina (1956).

They have already been discussed, in terms of Plate Tectonics, by Rangin (1982), Moore (1984a, 1984b), Kimbrough (1985), Moore (1986) and Sedlock (1988,

1993), among others. Basically, all of these authors have interpreted these rocks as a Triassic ophiolite, considered as an obducted slab of oceanic lithosphere, resting on a supposedly subduction-related and metamorphic blocks-bearing unit interpreted as a *mélange*, the so-called Puerto Nuevo *mélange*.

Also, they seemed to agree that the above units, together with the younger and overlying San Andres volcanic unit, extend onto Cedros Island, farther to the northwest (see also Kienast and Rangin, 1982). It is beyond the scope of this paper to discuss this hypothesis. But a note on this topic is nonetheless in order. None of their assumed pre-Tithonian formations is known to be fossiliferous in both areas (e.g., the deposits considered as Upper Triassic are fossiliferous in the Vizcaino Peninsula, but they are not in Cedros; and, conversely, the deposits considered as belonging to the San Andres volcanic arc in both areas are fossiliferous only in Cedros). This may be fortuitous. But as things stand, it casts some doubt on the correlations suggested between the units of the two areas. And in any case, a correlation between the so-called Puerto Nuevo *mélange* (cf *supra*) and the *mélange* of Cedros should be considered out of question, as will be shown later on.

Besides, Kimbrough (1985) and Sedlock (1988, 1993) have proposed that in the area of Vizcaino-Cedros several "terranes" occur, the lowermost of which being the so-called Puerto Nuevo *mélange* (FIGURE. 1). More recently, on the other hand, these "terranes" have been reassembled into a unique, ophiolitic, Cochimi Terrane (Sedlock et al., 1993; Ortega-Gutierrez et al., 1994).

What follows is based on the results of field work carried out by the author with the assistance of several of his students between 1990 and 1997, particularly on a 1: 50 000 scale geological mapping of the area, of which the FIGURES 2, 3, 4, 5, 6 and 9 are simplified versions.

A comparison of the results of this geological mapping (FIGURES 2, 3, and 4) with the map of fig. 1 suffices to disprove the reality of the *terranes* postulated by Kimbrough (1985) and Sedlock (1988). This point will not be directly addressed henceforth in this paper.

*It is the aim of this paper to show the following, naturally inter-related points:*

*(I) the main ultrabasic-basic sequence, the Puerto Nuevo Sequence (harzburgite, dunite, cyclic units of dunite, pyroxenite and gabbro) of the Vizcaino Peninsula, is not an obducted slab of oceanic lithosphere; it is instead a part of a layered complex, the Vizcaino Layered Complex, which also includes, upwards, isotropic gabbros, diorites (La Pintada Sequence);*

*(II) the Vizcaino Layered Complex is related to a magma underplating of continental crust, sensu Fyfe (1992);*

*(III) the San Hipolito Formation (Zone) belongs in a different, allochthonous, tectonic unit, the San Hipolito Nappe, emplaced upon the Vizcaino Layered Complex during the Liassic (Radelli, 1994, 1995),*

## GEOLOGICAL OVERVIEW

In the Vizcaino Peninsula the following units are cropping out :

(14) Miocene-Quaternary cover: sedimentary and volcanic (not to be discussed in this paper);

(13) Valle Formation: sedimentary, fossiliferous, *Albian to Cenomania*..

(12) Eugenia Formation: volcanic and sedimentary, partly fossiliferous, *Tithonian to Neocomian*.

*Hand 10 - San Andres Volcanic Arc:*

(11) Tonalites and gabbros that during the *Malm* intruded the

(10) San Andres Volcanics: un-fossiliferous, propilitic lavas (*probably Dogger*).

----- upper limit of penetrative deformation -----

(9) San Hipolito Formation : chlorite schists, marbles, hornblende-actinolite schists, sedimentary and volcanic, fossiliferous, *Late Triassic* (Late Carnian ?- Norian), that during the *Liassic* was emplaced as an allochthon (*nappe*) upon the Vizcaino Layered Complex.

(8) *Upper Triassic* ( $\pm 220$  Ma), dolerite/albitite dykes, and plagiogranite dykes (boudinaged later on), crossing the peridotites (3) of the Puerto Nuevo Sequence

*7 to 2 - Vizcaino Layered Complex*

7 to 4 - La Pintada Sequence

(7) Micro-gabbro.

(6) Diorites and tonalites

(5) Isotropic gabbros and hornblendites

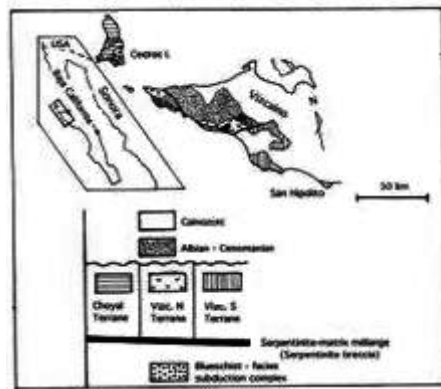
4 to 2 - Puerto Nuevo Sequence

(4) Cyclic Units: alternating peridotites, pyroxenites and gabbros.

(3) Peridotites: serpentinized harzburgites, dunites, and minor wehrlites

(2) Serpentinite breccia.

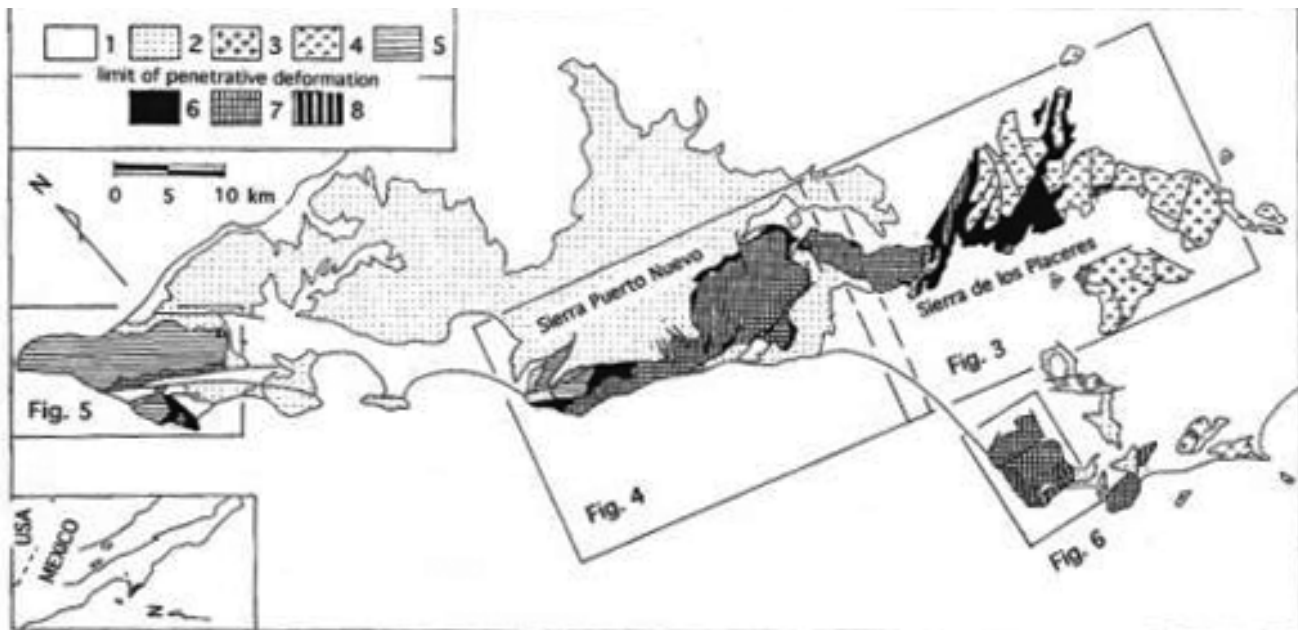
(1) *San Pablo Metamorphic Complex*: hornblende amphibolites, hornblende-biotite and biotite gneiss, meta-granite, and migmatites.



**FIGURE 1.** Terrane Map of Vizcaino-Cedros, after Sedlock (1988).

The Albian-Cenomanian of the map corresponds to the Valle Formation of the present paper. The terranes are defined as follows (Sedlock, 1988, 1993). Choyal Terrane of Cedros: Middle Jurassic oceanic arc/ophiolite complex, and overlying Jurassic strata. Vizcaino Norte Terrane: Upper Triassic ophiolite, conformably overlying tuffaceous sedimentary rocks, and Upper Jurassic-Lower Cretaceous volcanoclastic rocks. Vizcaino Sur Terrane: Upper Triassic ophiolite, Upper Triassic-Lower Jurassic chert, limestone, breccia, and sandstone; and Middle Jurassic to Lower Cretaceous tonalite.

Compare with the maps of FIGURES 2, 3, 4, 5, and 6. Note that the terranes here above do not correspond to the objective geologic units of the area, as discussed in the text.



**FIGURE 2.** Simplified geological map and index map of Vizcaino Peninsula.

- 1 – Undifferentiated, sedimentary and volcanic Cainozoic;
- 2 – Valle Formation (Albian – Cenomanian);
- 3 – Tonalite (Malm);
- 4 – San Andres Volcanics/San Andres Volcanic arc (probably Dogger);
- 5 – Eugenia Formation (Tithonian – Neocomian);
- 6 – San Hipolito Zone: Allochthonous, ophiolitic Upper Triassic, emplaced as a nappe during the Liassic;
- 7 and 8 – Puerto Nuevo - La Pintada Zone (magmatic arc):
- 7 – Ultrabasic – basic rocks of the Vizcaino layered Complex (Puerto Nuevo and La Pintada Sequences) intrusive into
- 8 – San Pablo Metamorphic Complex.

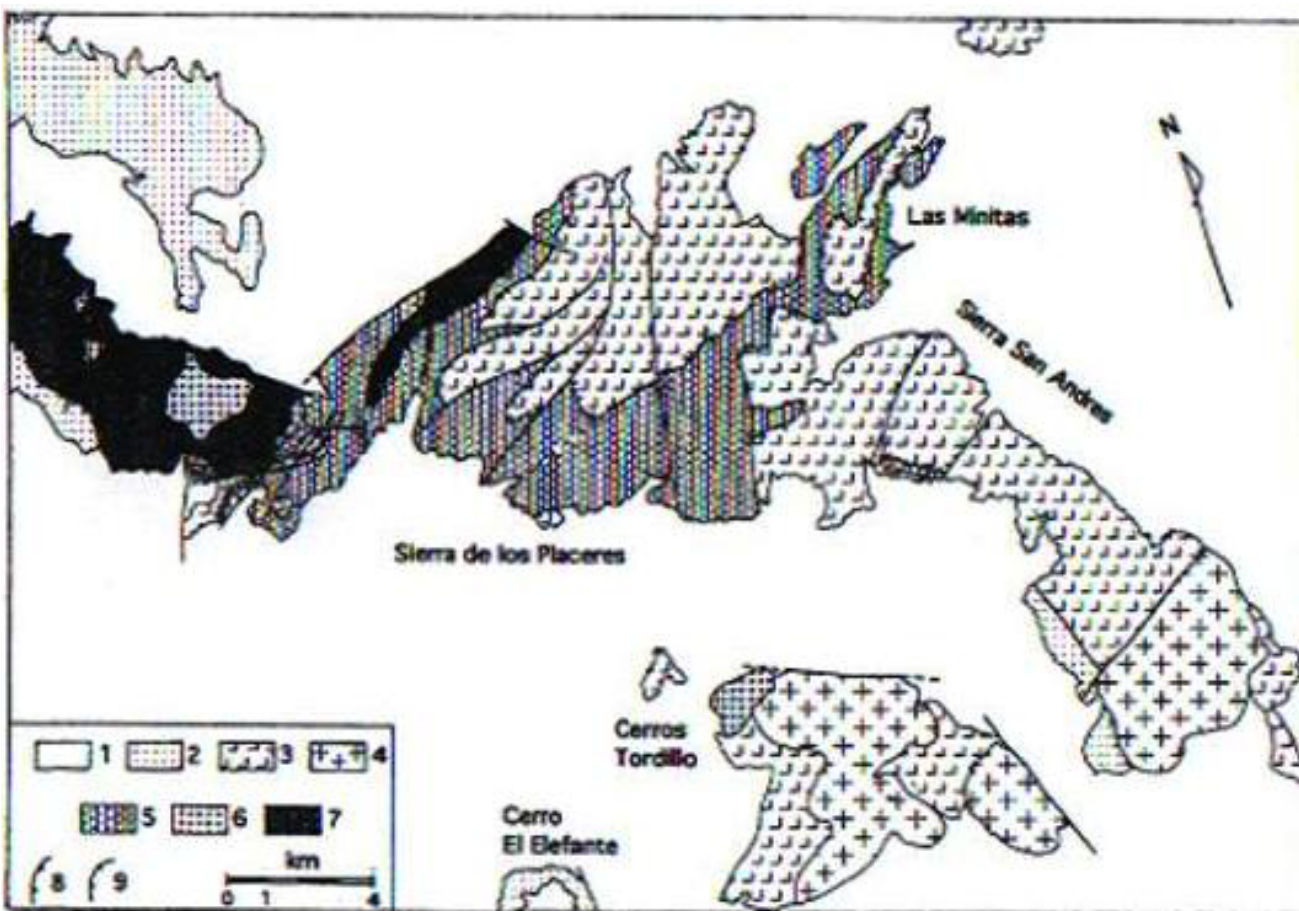


FIGURE 3. Geologic map of Sierra de los Placeres and Sierra San Andres.

1 – Undifferentiated, sedimentary and volcanic Cainozoic; 2 – Valle Formation (Albian – Cenomanian); 3 – San Andres Volcanics/San Andres Volcanic arc (probably Dogger); 4 – Tonalite (Malm); 5 – San Hipolito Zone: Allochthonous, ophiolitic Upper Triassic, emplaced as a nappe during the Liassic; 6 and 7 – Vizcaino Layered Complex, Puerto Nuevo Sequence: 6 – Cyclic Units (here mainly gabbro); 7 – Peridotites, 8 – Nappe, 9 – Detachment.

### Summarized post-Liassic stratigraphy

This paper deals with units 1 to 9. However, to give a reason for certain structural complexities that appear on the geological map of the area, a few words on its post-Liassic formations are in order.

Upon the San Hipolito allochthon (nappe) emplaced during the Liassic (cf. infra) the *San Andres Volcanic Arc* occurs in the southern part of the Peninsula (Sierra de los Placeres and Sierra de Campo Nuevo, coast and islands of Bahia Asuncion) (Troughton, 1974; Rangin, 1982). The history of this arc began during the *Dogger* (Radelli, 1994) with the emplacement of the *San Andres Volcanics*, followed, during the *Malm*, by that of *tonalitic bodies* radiometrically dated 154 to 142 Ma (Rangin, 1982), which intrude both said San Andres Volcanics and the gabbro of El Tordillo (cf. infra). The *San Andres Volcanics* (FIGURES 2, 3) consist of a 1000 m thick pile of often agglomeratic andesite and subordinate

basalt, both showing a propylitic alteration but no penetrative deformation. Based on their geochemical character, Rangin (1982) postulated that these rocks belong in a volcanic arc, the San Andres-Cedros Volcanic Arc, paleontologically dated as Jurassic on Cedros Island.

The *Eugenia Formation*, which crops out in the northern part of the Peninsula (FIGURES 2, 4, and 5), consists, from its base upwards, of: (i) 300 to 400 m of pillow basalts [Morro Hermoso Formation s. str. of Rangin (1982), or Morro Hermoso Member] crossed by diabase dykes, with an interbedded sedimentary unit containing a *Tithonian* fauna in their upper part (Rangin, 1982); (ii) a 2500 m thick sequence of graywacke, claystone and conglomerate with poorly rounded volcanic pebbles, interbedded calcareous strata and pyroclastic deposits and, in its lower part, some interbedded basalt flows establishing its continuity with the underlying Morro Hermoso Member. From its paleontological content and position underneath the Albian-

Cenomanian Valle Formation, the Eugenia Formation has been assigned a *Tithonian-Neocomian* geological age (Rangin, 1982; Radelli, 1994).

The *Valle Formation* (FIGURES 2, 3, 4, 5, and 6), paleontologically dated as *Albian to Cenomanian* (Rangin, 1982), consists of a thick package of conglomerate and flysch-like strata. The conglomerates contain clasts of diorite, gabbro, and of volcanic rocks.

## STRATIGRAPHY AND PETROGRAPHY OF THE PRE-LIASSIC UNITS

After this preamble, the pre-Liassic units, which constitute the topic of this paper, will be described in their chronological order, from older to younger.

### SAN PABLO METAMORPHIC COMPLEX

The San Pablo Metamorphic Complex crops out in the vicinities of the fisherman camp of San Pablo, in the southwestern part of Sierra La Pintada (FIGURES 2 and 3). *From the bottom upwards, this Complex consists of a continuum of amphibole-biotite and biotite gneiss with irregular bodies and lenses of granite, migmatitic amphibolitic gneiss (lit-par-lit and agmatite) often showing pygmatic folds, and ortho-amphibolites.*

The first notice of this complex as a whole has been given, together with a short description, by Radelli and Castro Leyva (1993), who interpreted it as an autochthon. Later on it has

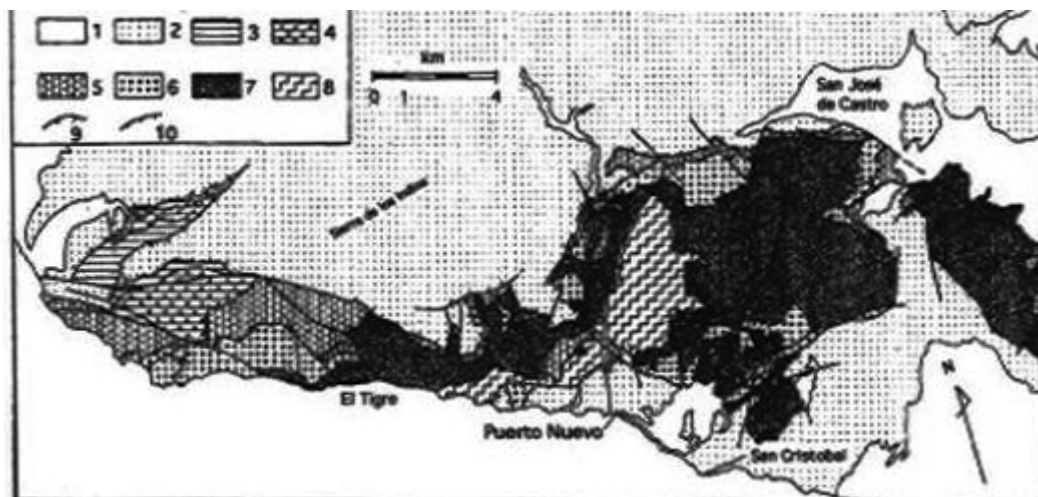
been discussed by Radelli (1994, 1995). Of all of its rocks, only the orthoamphibolites had been previously noticed and discussed (Rangin, 1982). However, Rangin (1982) did not take into account their relationships with the other country rocks mentioned here-above, and thus he interpreted them, erroneously, as a part of his oceanic slab.

For sake of clarity, it is better to describe the *San Pablo Metamorphic Complex* starting from its higher term, the ortho-amphibolites and going down-section.

The *orthoamphibolites* - which are dark, dense, tightly folded - make up the bulk of the coastal mountains around San Pablo. They consist of idioblastic hornblende and subordinate plagioclase (labradorite) with, as accessory minerals, orthopyroxene, magnetite, and ilmenite which can be locally abundant.

In the southern part of their exposures (roughly from the vicinities of the road to San Pablo southwards), these amphibolites are crossed by a number of partly shredded *pink aplitic-pegmatitic dykes*, from one to a few metres thick and up to a few hundreds of metres long. Their mineralogical composition consists of alkali feldspar, muscovite, and very subordinate quartz. It is a field evidence - and this point is important for what follows - that these dykes do not penetrate into the surrounding bodies of gabbro and diorite.

North and east from San Pablo (FIGURES 3 and 9) a different situation occurs. At first, light-coloured to whitish *bodies of fine to medium grained feldspathic rock, occur there within the amphibolites*. They are made up of oligoclase-andesine, K-feldspar and quartz, and vary in thickness from a few millimetres to approximately 50 m. Spectacular outcrops



**FIGURE 4.** Geologic map of Sierra El Tigre – Sierra Puerto Nuevo.

1 – Undifferentiated, sedimentary and volcanic Cainozoic; 2 – Valle Formation (Albian – Cenomanian); 3 and 4 - Eugenia Formation (Tithonian – Valanginian): 3 – Sedimentary Member (conglomerate, greywacke and claystone); 4 – Volcanic member (pillow lavas); 5 - San Hipolito Zone: Allochthonous, ophiolitic Upper Triassic, emplaced as a nappe during the Liassic; 6, 7 and 8 - Vizcaino Layered Complex, Puerto Nuevo Sequence: 6 – Cyclic Units (and gabbros); 7 – Peridotites; 8 – Serpentinite Breccia. 9 – Nappe, 10 – Detachment.

of such bodies can be seen from the sea on the coastal cliffs of the mountains north of San Pablo, where the leucocratic material, chiefly in thick tabular bodies, accounts for about 20 to 30% of the outcrops. The bodies of this feldspathic material are planar to lenticular, and are developed both parallel and across the schistosity of the amphibolites. At their contact, the feldspathic material appears lobate, the amphibolite in cusps. Millimetre to metre sized septa of amphibolite are very common within the feldspathic material.

Farther away, and downwards, from the main amphibolite (FIGURES 10 to 13) the amount of feldspathic material increases, and the mountains begin to acquire a light-coloured, greyish aspect. The most common facies is one of *lit-par-lit amphibolitic gneiss*, hosting well developed *pygmatic folds*, accompanied by *amphibolitic agmatite*. These facies are followed, downwards, by *amphibolitic-biotitic gneiss* that contains irregular bodies of *foliated hololeucocratic granite*.

*Pygmatic folds* are widespread, whereas only small septa of the amphibolite remain. Still downwards, the rock consist of a *feldspathic groundmass with a texture close to nebulitic* in which only very thin amphibolitic films occur, corresponding to (or transposed into) schistosity planes, and of *foliated hololeucocratic granite*.

Whether that continuum of facies is the result of a “granitic”

injection into the amphibolites or of metamorphism of a bi-modal volcanic sequence, as suggested by the lobate relationship between the feldspathic material and the amphibolite, is still an open question. But what is beyond question is that the structures that can be observed within this complex, and have been described above, are not found in the sequence of La Pintada, which is intrusive into it (cf. infra). This establishes the San Pablo Metamorphic Complex as a unit older than La Pintada, and a fortiori than Puerto Nuevo, into which La Pintada grades downwards (cf. infra).

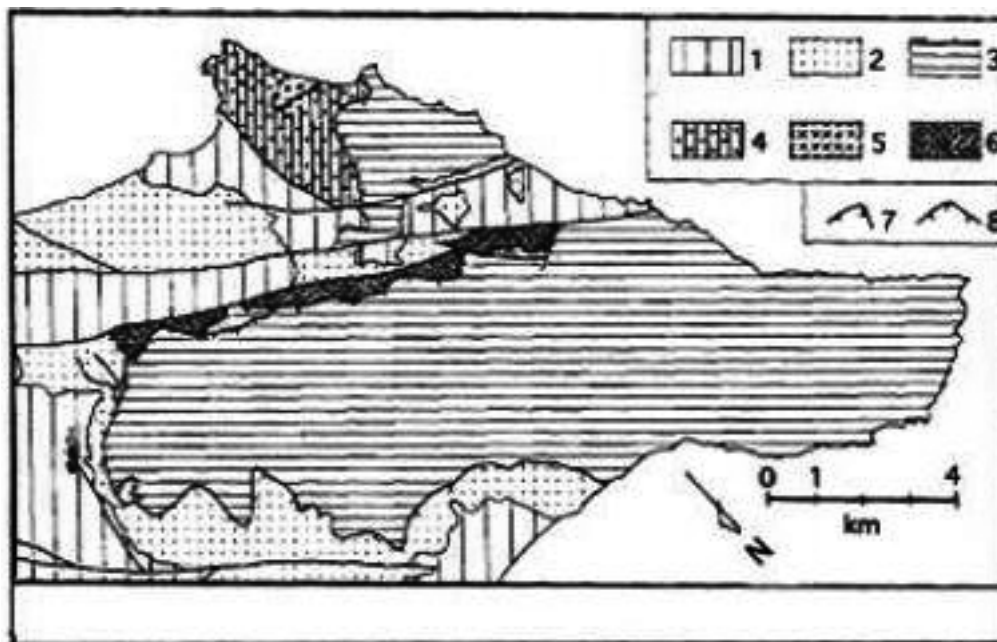
### VIZCAINO LAYERED COMPLEX

### PUERTO NUEVO SEQUENCE

#### Serpentinite Breccia

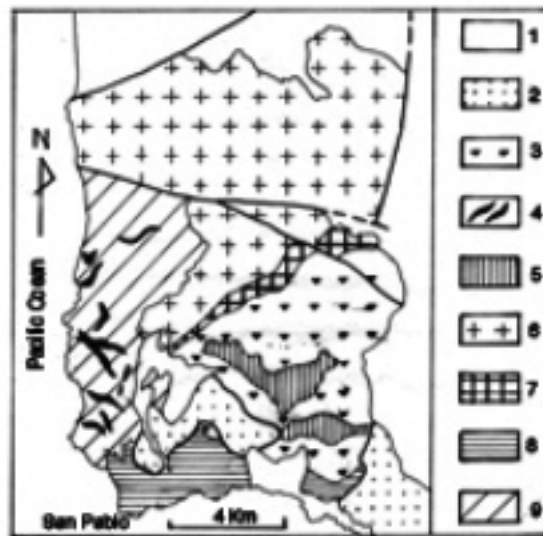
The lowermost known term of the Puerto Nuevo Sequence is a large serpentinite breccia, exposed in the Puerto Nuevo (or Sal-si-puedes) Canyon (FIGURE 4).

In previous literature, this unit has been considered a *mélange* (Rangin, 1982; Kienast and Rangin, 1982; Moore, 1986); as a *mélange* and at the same time as a *terrane* (Sedlock, 1988); and as the tectonic sole of the Puerto Nuevo Sequence by Radelli and Castro-Leyva (1993), when, unfortunately, they still accepted the erroneous concept that the Puerto Nuevo Sequence was a slab of oceanic lithosphere.

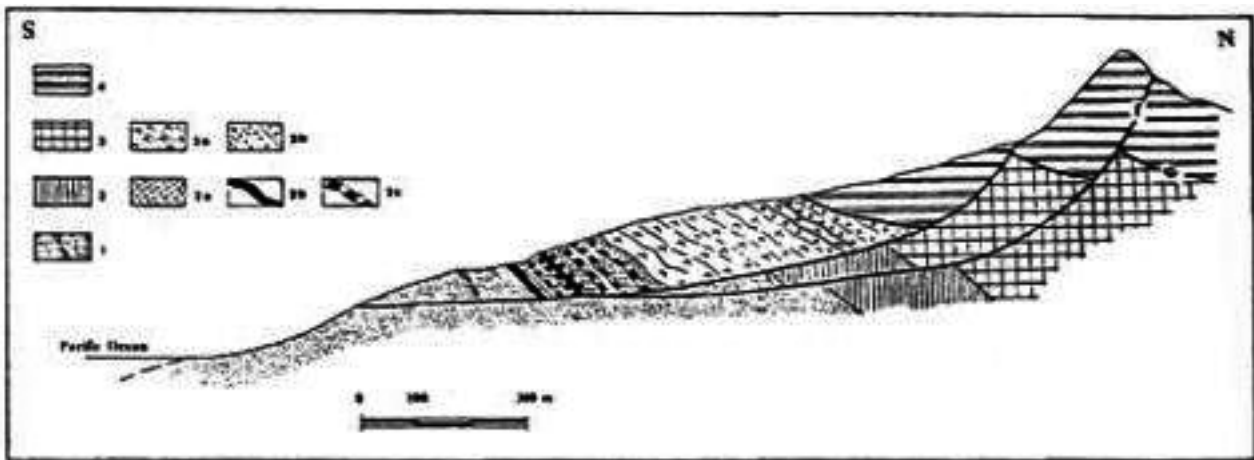


**FIGURE 5.** Geologic map of Punta Eugenia.

1 – Undifferentiated, sedimentary and volcanic Cainozoic; 2 – Valle Formation (Albian – Cenomanian); 3 – Eugenia Formation (Tithonian – Valanginian); 4 – San Hipolito Zone: Allochthonous, ophiolitic Upper Triassic, emplaced as a nappe during the Liassic; 5 and 6 – Vizcaino Layered Complex, Puerto Nuevo Sequence: 5 – Gabbro; 6 – Peridotites. 7 – Nappe; 8 – Detachment.



**FIGURE 6.** Geologic map of San Pablo – La Pintada area.  
 1 – Undifferentiated, sedimentary and volcanic Cainozoic; 2 – Valle Formation (Albian – Cenomanian); 3 - Upper Jurassic (Malm) Gabbro and tonalite; 4 – Doleritic/albititic dykes (Upper Triassic); 5 - San Hipolito Zone - Allochthonous, ophiolitic Upper Triassic, emplaced as a nappe during the Liassic; ornblende-actinote schists; 6 and 7 - Vizcaino Layered Complex, La Pintada Sequence: 6 – Gabbros and diorite; 7 – Cyclic Units.  
 8 and 9 – San Pablo Metamorphic Complex: 8 – Amphibolites; 9 – Gneiss and migmatites.



**FIGURE 7.** El Tigre Section.  
 1 to 3 - Vizcaino Layered Complex, Puerto Nuevo Sequence;  
 2 and 3 Cyclic Units:  
 1 – Peridotites (mostly dunites with chromitites);  
 2 – Undifferentiated Cyclic Units; 2a – dunite; 2b – pyroxene gabbro;  
 2c – pyroxenite.  
 3 – Undifferentiated gabbros; 3a – norite and gabbronorite; 3b – ferrogabbro;  
 4 – Upper Triassic San Hipolito Formation (San Hipolito Nappe, emplaced during the Liassic).  
 The starting point of the section is at the old mining works of El Tigre nearest to the now abandoned mining road.



This breccia consists of a groundmass of chrysotile  $\pm$  antigorite  $\pm$  chlorite within which irregular millimetric- to decametric-sized bodies of serpentinized harzburgite appear here and there. The groundmass of the breccia is fine to very fine grained (it appears often as a flour), schistose, and friable. It is, thus, an easy prey for the erosion, so that the arroyos cut into it show almost vertical, greyish to whitish walls. Petrographically, the serpentinized harzburgitic blocks of the breccia do not differ from the serpentinized harzburgites that overly the breccia itself. The boundary between the breccia as a whole and the overlying serpentinized harzburgites, as well as that between its groundmass and its blocks of serpentinized harzburgite, is by no means a well defined one. In fact, they differ from each other only in their different strength of schistosity and serpentinization, which vary whimsically. This is so much so that Moore (1986), for whom this breccia is a *mélange*, was forced to write: “The *mélange* is *structurally, but gradationally* (my italics), overlain by serpentinized harzburgite” - hardly the description of a tectonic contact between two different structural units.

Blocks of pyroxenite and exotic blocks of metamorphic rocks are associated with this breccia - hence the *mélange* concept of Rangin (1982), Kienast and Rangin (1982) and Moore (1986). However, such facies do not belong to the breccia, as it will be shown later on.

### Peridotites

The peridotites are by far the most abundant facies of the Puerto Nuevo Sequence. They include, upwards, harzburgites, dunites with layers of cumulate chromite, and subordinate wehrlites. Most of the time, all of them are strongly serpentinized, so that, macroscopically, they appear as a mass of fractured soapstone; only in one occasion, on a boulder of Puerto Nuevo beach, which appears at low tide, their real structure of a strongly folded tectonite could have been appreciated.

Often they contain magnesite, which in places constitutes economic or sub-economic deposits. The *harzburgites* consist of a groundmass of chrysotile, antigorite, chlorite and Fe-oxides, in which, under the microscope, are still recognizable: olivine (chiefly by its habit outlined by Fe-oxides); some crystals, but generally only relicts, of enstatite; rare grains of plagioclase; and in places grains of chromite. Generally, the *dunites* consist, essentially, of a groundmass of chrysotile, antigorite, chlorite and Fe-oxides. But in places they show a banded, near-mylonitic structure, with finely granulated olivine alternating with, or enveloping lenses of, less granulated olivine, where relicts of diopside are still preserved. The *wehrlites* occur as irregular, less than 10 m thick, layers in the upper part of the dunites. Their mineralogical composition is olivine (partly serpentinized), diopside, subordinate enstatite, and Fe-oxides.

### Chromitites

Layered, from a few cm to several (< 10) m thick, bodies of *cumulate chromite* occur at several localities within the Puerto Nuevo Sequence, always in the uppermost part of the dunites, near the base of the Cyclic Units. The most important of these occurrences are those of El Tigre Mine (El Tigre section, FIGURES 4 and 7) and those that, for wanting of a better name, I called “Minas de Juan” (midway from El Tigre to Puerto Nuevo). The continuity of the primitive layered bodies has been disrupted by younger tectonic movements, and in particular by the extensional tectonics that affected the whole sequence. As a consequence, at present, the individual chromite bodies are from about 1 m to some 10 m long and, as far as it is known, up to about 15 m wide. However, the fact that the deposit of these bodies has been stratigraphically controlled is confirmed by what follows. At “Minas de Juan” the bodies of chromite, although disrupted, clearly occur at different levels. ICP-AES analyses carried out at the Institut Dolomieu, University Joseph Fourier of Grenoble (Castro-Leyva, 1992) show the

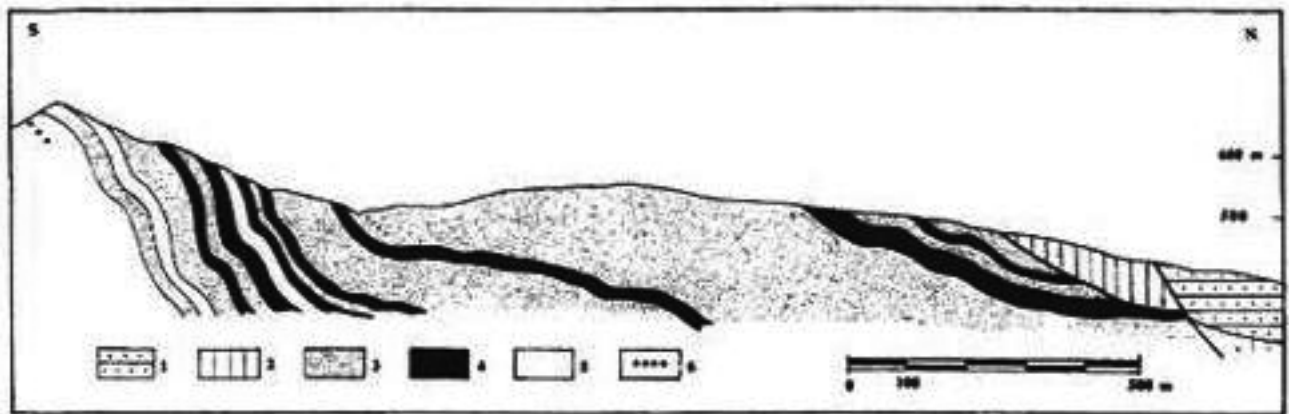


FIGURE 8. San Miguel Section.

1 – Valle Formation (Albian to Cenomanian); 2 – Upper Triassic San Hipolito Formation (San Hipolito Nappe, emplaced during the Liassic);



FIGURE 9. Migmatites of San Pablo as seen from the sea.

following compositional variations for the chromites of the lower and the upper levels there (samples TC 71, 68; and TC 65, 63, 62, 61, 58, 55, respectively; all data are in %): Cr<sub>2</sub>O<sub>3</sub>: 55 - 47.4; FeO: 13.57 - 12.34; Mn: 0.14 - 0.12; MgO: 14.89 - 14.39; TiO<sub>2</sub> : 0.19 - 0.21; Al<sub>2</sub>O<sub>3</sub> : 15.46 - 18.57. These variations (upwards increase of Al<sub>2</sub>O<sub>3</sub> and decrease of Cr<sub>2</sub>O<sub>3</sub> in particular) correspond to a normal chemical evolution, congruent with the stratigraphic position of the chromite levels there.

### Cyclic Units

The dunites are followed upwards by a zone, up to 700 m thick, of Cyclic Units. There *dunites*, *wehrlites* (same as those described above), *pyroxenites* and *gabbros* (mostly gabbronorites) alternate with each other in tabular bodies, lenses, and dyke-like structures.

The *pyroxenites* essentially consist of hypersthene and olivine (< 10%). Their texture varies from equigranular to pegmatitic, depending on the development of their crystals of hypersthene (from less than 1 mm to several cm).

The *gabbros* of this zone include *pyroxene gabbro*, *olivine gabbronorite*, *gabbronorite* (which is the most common of these facies), and *ferrogabbro*. The *pyroxene gabbros* are equigranular to pegmatitic, depending on the size of their pyroxene crystals. Essentially, they consist of augite and hypersthene (70-80 %, with augite > hypersthene), and bytownite-labradorite (20-30%). They show incipient chloritization. The *olivine gabbronorites* are equigranular and composed of bytownite-labradorite, hypersthene, augite generally replaced by actinolite, serpentinized olivine, and opaque oxides. The *gabbronorites* are equigranular to pegmatitic, depending on the development of their pyroxene crystals. Essentially, they consist of bytownite-labradorite, both intracumulus hypersthene and augite, olivine (<10%), and opaque oxides. Chlorite occurs within their planes of shearing. The *ferrogabbros* are equigranular and essentially

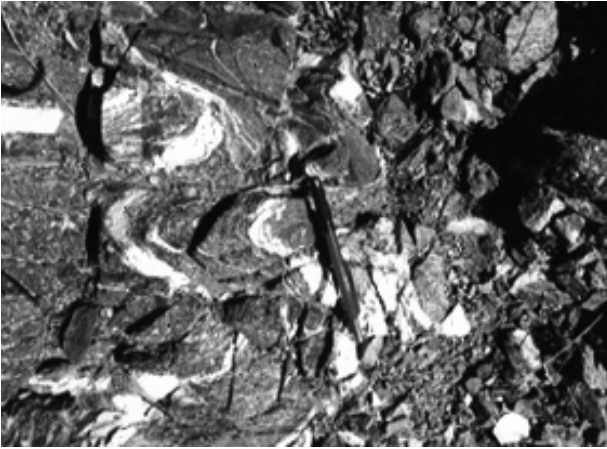
consist, in decreasing order of abundance, of augite, hypersthene, bytownite-labradorite, magnetite, ilmenite, titano-magnetite and Fe-oxides. In places they underwent amphibolitization: a green amphibole replaces the pyroxene, with a concomitant formation of albite and epidote, whereas the ilmenite is replaced by titanite and magnetite. Generally, the gabbros show strong chloritization, varying degree of olivine serpentinization, and in some instances a rodingitization. Often they are saussuritic, cataclastic and sheared. Along their planes of cleavage, and developing itself also into the fractures of the plagioclase eventually, actinolite replaces the original clinopyroxene.

The development of this zone of Cyclic Units is not homogeneous all over the area of the Vizcaino Peninsula. The descriptions above are based on exposures in the area of Mina del Tigre (FIGURE 7), and at "Minas de Juan", where, below the gabbros into which it grades, this zone presents a bacon-like layered structure. But this is not the case, for example, at San Miguel-Santa Monica, at Sierra de los Ajos, or on the northern slope of the valley of Arroyo San Cristobal. At San Miguel-Santa Monica (fig. 8) this zone begins with gabbro, is mostly gabbronorite, with few bodies of peridotite and a number of large interlayered, generally pegmatitic bodies of pyroxenite. At Sierra Los Ajos, about 5 km east of Puerto Nuevo, what appears from afar as a whitish gabbro is in fact constituted by Cyclic Units. It begins with gabbro and is mainly gabbro, but it contains quite a number of interlayered thin bodies of peridotite and pyroxenite which are less thick and less widespread than at San Miguel-Santa Monica. On the northern slope of the valley of Arroyo San Cristobal this zone is mainly gabbro and subordinate pyroxenite with only one interlayered peridotite. It is evident in the field, however, that the thickness of this zone at San Miguel-Santa Monica, Los Ajos, San Cristobal and elsewhere is roughly equivalent to that of the sum of the Cyclic Units with a bacon-like structure plus the gabbros of Mina del Tigre.

The norites and particularly the pyroxenites of these Cyclic Units are frequently, not to say commonly, fairly pegmatitic. Since the Vizcaino Layered Complex is a Supra Subduction Zone unit (cf. infra), this seems to indicate that, during its differentiation, a large amount of water has been released into the lithospheric mantle, probably by serpentinized peridotites of the oceanic plate being consumed at the corresponding subduction zone (Scamberulli et al., 1995).

### LA PINTADA SEQUENCE

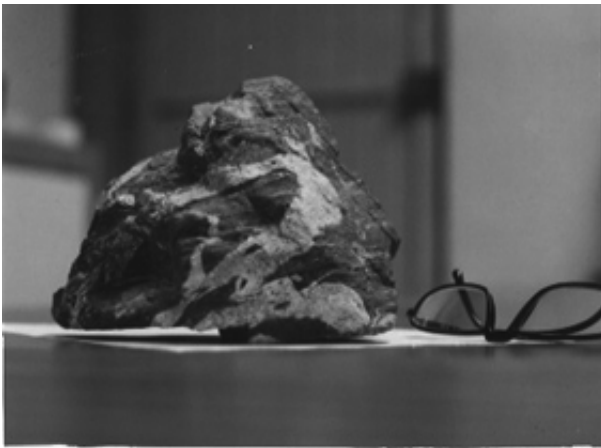
This sequence consists, above the Cyclic Units, of gabbro, diorite, and it is cut by a swarm of dykes and masses of fine-grained dolerites and albitophyres (FIGURE 3).



10



12



11



13

FIGURES 10 to 13. Migmatites of San Pablo: From injected amphibolites to foliated granite

### Cyclic Units

The lowermost outcrop of the area is peridotite. It is followed by a some 100 m thick series of *alternating pyroxenite, gabbro, and peridotite*, which ends with a *layered pyroxene gabbro*. In all ways this association is the same as that of the Cyclic Units of the Puerto Nuevo Sequence discussed here-above.

### Gabbro and diorite

The layered gabbro at the top of the Cyclic Units grades into a large mass of *isotropic gabbro, which, in turn, grades into, and is overlain by, diorite/tonalite*. Together, these rocks constitute the main mountains of Sierra La Pintada and, southeastwards, San Roque. There, the *gabbros, mostly norite, occasionally troctolite* are generally coarse-grained, equigranular to gently pegmatitic, show a texture from cumulate to holocrystalline and are composed by labradorite, augite and subordinate bronzite, with minor amounts of magnetite, ilmenite, and alteration products. *Hornblendites*, with cm-sized perfectly euhedral crystals of hornblende,

are associated with the gabbros. The *diorites* are medium- to fine-grained and equigranular, but for local development of phenocrysts of euhedral hornblende. Generally, they are composed of andesine, hornblende, occasional biotite, with minor amounts of titanomagnetite, chromomagnetite and ilmenite. Quartz-bearing, tonalitic facies have also been observed.

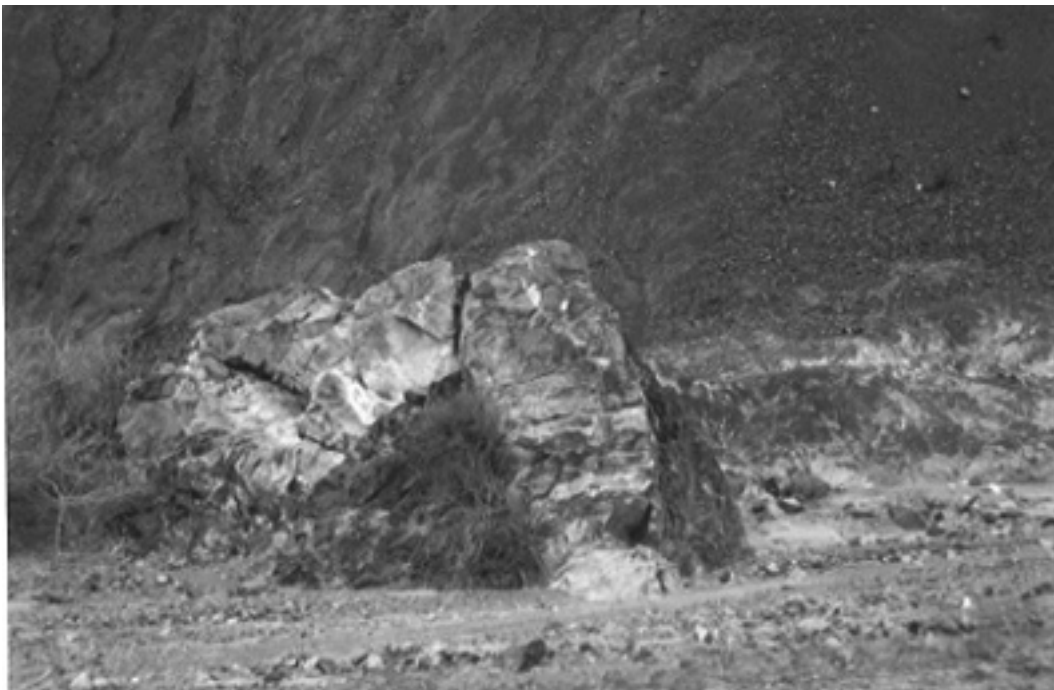
Wherever their contact can be observed, gabbros and diorites appear definitively as intrusive into the San Pablo Complex.

### THE UPPER TRIASSIC UNITS

In the Vizcaino Peninsula, there are three Upper Triassic units: a number of dykes of plagiogranite, and a swarm of albititic-doleritic dykes, both dated radiometrically, and the San Hipolito Formation, dated paleontologically. All of them are related to a phase of strong extensional tectonics that opened the original San Hipolito basin (marginal sea) and, in its foreland, the space into which said dykes were intruded.



**FIGURE 14.** Upper Triassic boudinaged plagiogranite dykes: boudinaged (Arroyo Sal-si-puedes, road to Puerto Nuevo).



**FIGURE 15.** Upper Triassic un-boudinaged plagiogranite dykes. The original structure of the dykes is well preserved (Arroyo San Cristobal)



**FIGURE 16.** Actinolite schist, a slice of the sole of the San Hipolito Nappe (dark) resting with a near-horizontal contact upon the Serpentinite Breccia (whitish) showing a flour structure. The slope on the right is also a part of the San Hipolito Nappe. Arroyo Sal-si-puedes few kilometers from Puerto Nuevo.

### Plagiogranite

On either slope of the northern part of the Puerto Nuevo Canyon, as well as of the valley of Arroyo San Cristobal, metric to decametric sized bodies of *plagiogranite* (mostly *trondhjemite*: oligoclase-andesine, quartz, biotite, amphibole) are found within the peridotites. In a few outcrops it can still be observed how such bodies have been emplaced as 1m to about 10m thick dykes. But most of the time they are boudinaged strongly enough to appear as lenticular blocks within the hosting peridotitic-serpentinitic mass (FIGURES 14 and 15). These rocks have furnished two U/Pb radiometric ages of  $\pm 220$  Ma (Kimbrough, 1985), corresponding to the Carnian-Norian boundary (Odin and Odin, 1990).

### Doleritic and Albititic dykes

In the area of San Pablo (FIGURE 3) a swarm of *doleritic and albititic dykes* cut the San Pablo Complex (Radelli, 1995). The individual dykes are from 5 to about 20 m thick, and from about 100 m to some 2 km long; the outcrops of the cupolas are from 1 to 2 hectares, at the most. The rocks of these bodies are strongly weathered and possibly hydrothermally altered, so that their outcrops are easily recognized for a typical reddish-brown to chocolate color, and a mellow aspect and consistency. In the samples that escaped total alteration, at least relicts of their primary minerals are still recognizable. These are andesine-oligoclase in laths, intersertal grains of augite (diabase texture), minor quartz, small amounts of titanomagnetite, and ilmenite. *Spilitic to albitophytic parageneses* - sericitized plagioclase, chlorite, actinolite (replacing augite), epidote, albite  $\pm$  orthoclase, quartz and carbonates - have also been observed.



**FIGURE 17.** Aspect and structure of the San Hipolito Formation in the vicinities of Puerto Escondido.

Hosted by the San Pablo Metamorphic Complex, these dykes occur from the immediate vicinities of the gabbros and diorite, but they have never been observed cutting either these the gabbros and the diorites or the underlying Cyclic Units. In previous papers (Radelli, 1994, Vatin-Perignon et al., 1998) they have been interpreted as the highest preserved product of the magma that gave way to the Puerto Nuevo and La Pintada Sequences, affecting the San Pablo Metamorphic Complex, the roof of that magmatic intrusion. However, geochemical reasons (Vatin-Perignon et al., 2000) suggested that they must be dissociated from that phenomenon, and in fact they furnished a radiometric age of  $221 \pm 2$  Ma, corresponding to the limit Carnian-Norian (Barnes *in* Kimbrough and Moore, 2003). Thus, same as the plagiogranite dykes, they belong in the San Hipolito cycle (see below).

### San Hipolito Formation. San Hipolito Zone.

This formation has been first recognized at Punta San Hipolito, outside this study area (fig. 1), where it contains a rich Upper Triassic (Carnian?-Norian) fossil fauna, mainly *Halobia* (Rangin, 1982; A. Tollmann, pers. comm.), as well as olistolithes of fusulinid-bearing Permian limestone. Within the study area, Dávila and Pessagno (1986) confirmed its Late Carnian (?)-Norian age, based on radiolarians. In this study (FIGURES. 4 and 5), this formation has been followed cartographically from Sierra de los Placeres in the south to the area of Puerto Escondido-Punta Quebrada in the north, on either side of, and above, the antiformal block of Puerto Nuevo (Radelli, 1994).

\* Near the Road San Pablo – San Roque, and near Puerto Nuevo along the road of Sal-si—puedes Canyon, the San Hipolito consists of *hornblende-actinolite schists with calcareous lenses*. They are porphyroblastic, fine grained,



**FIGURE 18.** San Hipolito Nappe resting upon the peridotites and the boudinaged plagiogranite dykes in Arroyo San Cristobal. In the background appear the UB-B series, upwards: peridotites, cyclic units and gabbros.

and consist of hornblende and actinolite in a quartz-feldspathic matrix, with subordinate chlorite, epidote, calcite, and titanite. At *San Pablo – San Roque* they occur, as huge roughly tabular septa within Jurassic gabbros of the San Andres Arc (FIGURE 3) - a situation interpreted as resulting from the emplacement of the gabbros by cauldron subsidence. At Canyon Sal-si-puedes they clearly occur as a nappe resting upon the Serpentinite Breccia (FIGURE 16).

\* From the western part of Sierra de los Placeres to the northwestern part of Sierra de Campo Nuevo the San Hipolito consists of serpentinites, microgabbros, spilitic pillow lavas, ophicalcites, radiolarites, with minor interbedded tuffs and claystones. Here it corresponds to the shredded ophiolites (*ophiolites dilacerées*) of Rangin (1982), to the so-called *Sierra de Placeres mélange* of Moore (1986), and in part to the *Vizcaino Sur Terrane* of Sedlock (1988).

\* At Cerro La Minita (northeastern end of Sierra de los Placeres) and in the hills immediately south of it and southeast of Sierra de la Banderita it consists of serpentinites, chloritized pillow lavas, alternating beds of light colored to whitish tuffs, fine grained greywacke and sandstone with poorly preserved radiolarian and dark shale.

\* South of the Puerto Nuevo block the San Hipolito Formation is represented in the eastern vicinities of the San José de Castro - Bahía Asunción Road, by serpentinites and spilites; in the Sierras El Chorrillo and Los Ajos (some 5 km east of Puerto Nuevo), and in the valley of Arroyo San Cristobal (FIGURES 16 and 17) by abundant ophicalcites, spilites, volcano-sedimentary strata, thin bedded gray siliceous deposits, radiolarites, with interbedded limestone and pink dolomite; on either side of the Puerto Nuevo Canyon, at about 2 km from Puerto Nuevo, by ophicalcites, light gray limestone, and some sandstone.

\* North of the Puerto Nuevo block the San Hipolito consists, in a hill some 3 km northeast of Puerto San José, of spilites and volcano-sedimentary strata; in a almost continuous strip that from a point about 2 km southwest of San José de Castro extends itself into the Ranchs of Santa Mónica and San Miguel, reaches the Puerto Nuevo Canyon and continues in the Sierra de Puerto Nuevo, of spilites, pillow lavas, red radiolarites, sometimes coarse volcano-sedimentary strata, with both interbedded limestone and minor pink dolomite.

\* At San Miguel Ranch it corresponds to the Morro Hermoso Formation of Rangin (1982), which this author considered as Jurassic, but which subsequently has been proven to be Upper

Triassic by Dávila and Pessagno (1986).] It corresponds as well, at least in part, to the “Upper Triassic volcanics” of Sierra de Puerto Nuevo of Moore (1986).

\* From the last outcrop above westwards, the San Hipolito disappears tectonically for about 6 km. It appears again, however, along the same trend, to be largely exposed in the Sierra del Tigre and in the area of Puerto Escondido (Rangin, 1982). Here it consists of chloritized basaltic pillow lavas with interbedded basaltic breccia and small lenses of radiolaria-bearing limestone (Barnes and Mattinson, 1981), reddish siliceous sandstones, a bed of pink dolomite, and, at Puerto Escondido, of thin bedded green, white, and reddish sandy tuffs (FIGURE 17).

\* At Punta Quebrada (FIGURE. 6), the area of its westernmost outcrops, the San Hipolito includes serpentinites (Rangin, 1982), basaltic pillow lavas with interbedded limestones and volcanic breccias, a bed of pink dolomite, silicified vitreous tuff, green, brown, red, and whitish calcareous tuff, sandstone, and calcareous siliceous shale (Dávila and Pessagno, 1986).

Thus, although all of its facies are not found at all of its outcrops, the continuity, the oneness, of the San Hipolito from Punta Quebrada to Sierra de los Placeres is established upon the fact that at least one, and generally more, of its lithologic units can be recognized from one of its outcrops to the next, its bed of pink dolomite constituting a particularly good marker.

## TECTONICS

### Summarized Tectonics Of The Post-Liassic Units

The *San Andres Arc* is one of the structures of the continuum of the Nevadian orogenic belts of North-West America (Roure, 1984; Radelli and Calmus, 1988; Radelli et al., 1993). The basal contact of the San Andres volcanics is tectonic. According to Rangin (1982) it corresponds to an overthrust (nappe emplaced upon the Upper Triassic San Hipolito Formation); but, according to Sedlock (1988), Radelli and Castro (1993), and Radelli (1994) this contact is a low angle normal fault, which is in agreement with the fact that said volcanics are not penetratively deformed, as one would expect in a formation having traveled from afar. However, the Rangin's (1982) hypothesis cannot be altogether excluded for, as pointed out by Rangin (written comm., 1993), if these volcanics had been displaced along normal faults, one should find across their previous substratum their feeder dykes, of which none has been observed so far. Thus, this matter cannot be put to rest yet.

The *Eugenia Formation* (Tithonian to Neocomian) has been accumulated near the source of its clastic materials and it is interpreted as a *marine molasse* (Rangin, 1982; Radelli, 1994), the *marine molasse of the San Andres orogen*, that it post-dates. The Eugenia Formation is gently folded, and always divided by generally listric normal faults from its substratum.

The Albian-Cenomanian *Valle Formation* is a *marine molasse*, which bears witness of the Mid-Cretaceous (Oregonian) Orogeny well documented elsewhere in Baja California (Rangin, 1982; Radelli, 1988a, 1988b). The Valle Formation is gently folded - as, for instance, in the huge antiform (*plis de fond*) of the Puerto Nuevo section. This phase of folding, that postdates the Oregonian one and predates the opening of the Miocene basins (cf. infra), corresponds by definition to the *Laramide Orogeny*. On the other hand, the Valle Formation is always detached from the underlying units along normal, and seemingly listric, faults. Most probably, these faults correspond to the *Miocene extensional phase* which opened the *Upper Cainozoic basins* of the Peninsula, and caused its pre-Liassic rocks to crop out in the three separate blocks of Tortuga-Eugenia, Sierra El Tigre-Sierra Placeres-Sierra Campo Nuevo, and Sierra La Pintada (FIGURE 2).

## TECTONICS OF THE PRE-LIASSIC UNITS

### San Hipolito Zone San Hipolito Nappe

The Upper Triassic sequence of the San Hipolito was accumulated within a marginal sea, with a partly “oceanic” floor, from which derived its ophiolitic facies. Therefore, in sound tectonic terms, the San Hipolito ought to be considered, and dealt with, rather than as a formation, as a zone - the *San Hipolito Zone*.

The San Hipolito is always strongly, and often isoclinally, folded, cleavaged, and sheared. It rests (FIGURES 2, 3, 4, 14, 15, 16), always with a well defined tectonic contact, upon everyone of the units (peridotites, cyclic units with gabbros) of the Puerto Nuevo Sequence, including the Serpentinite Breccia, as well as upon the boudinaged dykes of Upper Triassic Plagiogranite as in Arroyo San Cristobal (FIGURES 18 and 19). On the other hand - and this is important - a San Hipolito dyke complex occurs only locally, showing always a tectonic relationship with the underlain Puerto Nuevo sequence.

Based on these field relationships the San Hipolito Zone is established as an allochthon, the *San Hipolito Nappe* lying upon the Upper Triassic dykes of plagiogranite, and covered as it is by the Dogger Volcanics of the San Andres Arc, the San Hipolito



**FIGURE 19.** Structure of the San Hipolito Nappe at the outcrop shown on FIGURE 18. Note the penetrative deformation.

Nappe was obviously emplaced during the Liassic (Nevadian Orogeny).

For clarity, a last note is in order, which concerns the geology of Vizcaino Peninsula and of Baja California as a whole. As it has been shown, during the Late Triassic the San Hipolito marginal sea was opened behind the Puerto Nuevo-La Pintada Zone.

A marginal sea is bounded on the one hand by an arc, and on the other hand by a continental block. In the case in point the arc obviously corresponds to the Puerto Nuevo-La Pintada Zone. Had Baja California always had its present setting facing the Pacific Ocean the problem of the necessary continental block could be resolved only by unrestrained imagination, introducing some elusive and since-gone-away micro-continent. Fortunately, this is not necessary. As indicated by its fusulinids (Perez Ramos, 2001), the Paleozoic platform of central and southern Sonora is a large tethysian (gondwanian) unit. In Sonora, it occurs as an allochthon emplaced upon Lower Cretaceous sedimentary formations (Radelli et al., 1993). In Baja California parts of the same unit occur as olistolithes (Permian limestone) in the Upper Triassic San Hipolito Formation at San Hipolito (Rangin, 1984), and as olistostromes (Permian limestone) in the Upper Triassic of the area of El Volcan (Radelli, 1993 and references there). Thus, although its precise original location and the causes and the mode of its displacement are a matter of discussion, it seems that the San Hipolito marginal sea, bounded on one side by the Arc of Vizcaino, was bounded on the other side by this platform.

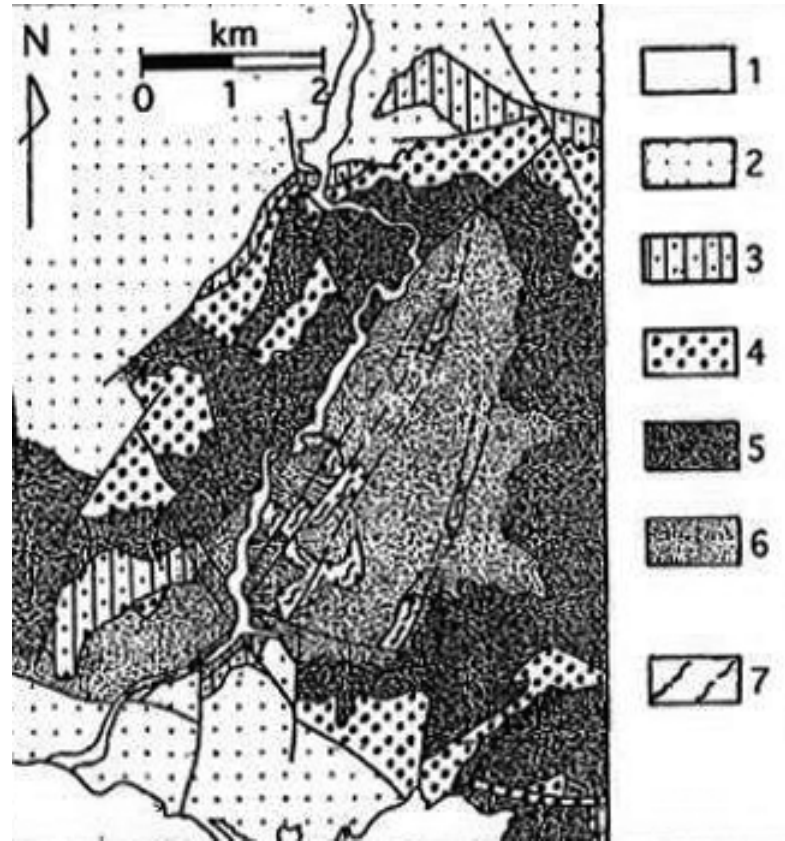
*The metamorphic blocks of the sole of the San Hipolito Nappe (the so-called exotic blocks of the so-called Puerto Nuevo. Mélange of previous authors).*

Folded and sheared blocks of metamorphic rocks (chlorite schists, lenses of marble and hornblende-actinolite schists) are associated with the Serpentinite Breccia of Puerto Nuevo (FIGURE 20). The association is not that of blocks within a sedimentary (or metasedimentary) matrix that defines a real mélange. In spite of this, in previous literature several authors (Rangin, 1982; Kienast and Rangin, 1982; Kimbrough, 1985; Moore, 1986) have interpreted these blocks as blocks of what they called Puerto Nuevo Mélange (i.e., serpentinite breccia matrix plus metamorphic blocks) and as blueschists. Upon these assumptions they correlated their Puerto Nuevo Mélange with the actual mélange of Cedros Island., which consists (Rangin, 1982; Kienast and Rangin, 1982) of either a metamorphosed or unmetamorphosed sedimentary matrix and both Malm and Albian blueschist blocks. Furthermore, Rangin (1977, 1982) and Kienast and Rangin (1982) compared this unit with the Franciscan of California. Moore (1986) mentions amphibolitic “blocks” with Na-pyroxene replaced by barroisitic amphibole in some samples. Then, in the table of his FIGURE 7, he qualifies this Na-amphibole as omphacite, and the amphibolitic blocks bearing it as eclogites.

The rationale for this seems to have been only that in the greenschist paragenesis of another “block” (albite + actinote + epidote + white mica ± quartz ± titanite + rutile) “the presence of rutile suggests that the block may have had an epidote-amphibolite or eclogite facies mineral assemblage which was recrystallized to the greenschist assemblage”. It is beyond doubt that the blocks in question are polymetamorphic, as it is clearly shown by an undeformed, and therefore neogenetic, green amphibole that they often contain, and which most probably is the barroisitic amphibole and/or crossite mentioned by Moore (1986). But in fact neither glaucophane nor jadeite nor omphacite have ever been observed in the blocks of Puerto Nuevo Canyon.

Thus, such an idea of blueschist blocks in the area of Puerto Nuevo should be abandoned. It can be affirmed instead that said blocks are allochthonous upon the Puerto Nuevo sequence. The boundary between these metamorphic blocks and the underlying Serpentinite Breccia is always a well defined, generally low angle, tectonic surface. And this boundary, although disrupted by younger faults, can be followed over several km (FIGURE 20), which suggests that, prior to said younger faulting, the present-day blocks probably belonged in a single slab. With respect to the Serpentinite Breccia in the same area of Puerto Nuevo these metamorphic rocks occupy the same position as the San Hipolito Nappe. It is safe to conclude from these observations that these metamorphic bodies of Puerto Nuevo Canyon





**FIGURE 20.** Geologic map of the area of Puerto Nuevo Canyon.

The map shows the so-called “exotic metamorphic blocks” overlying the Serpentinite Breccia, which are, in fact, faulted slices of schists of the San Hipolito Nappe. See text for discussion.

1 – Quaternary; 2 – Valle Formation (Albian to Cenomanian);

3 – San Hipolito Formation (Nappe); 4 – Gabbro; 5 – Peridotite;

6 – Serpentinite Breccia; 7 – Faulted slices of the schists of the sole of San Hipolito Nappe.

correspond to a slice, or slices, of the San Hipolito Nappe, of which thus they constitute a tectonic sole.

Beside these metamorphic ones, other blocks that have been considered as blocks of the so-called Puerto Nuevo Mélange (Moore, 1986) are either boudinaged plagiogranite, or roughly vertical slices of peridotite and pyroxenite caught in the normal faults that skirt the western side of the Puerto Nuevo Canyon.

Thus, a Puerto Nuevo Mélange simply does not exist. What does exist there is the San Hipolito Ophiolitic Nappe, with its sole.

### ***Significance of the Serpentinite Breccia***

The San Hipolito Nappe lies on every one of the units of the Puerto Nuevo Complex and the metamorphic sole of the San Hipolito Nappe lies on the lowermost unit of the Puerto Nuevo Complex, the Serpentinite Breccia of Puerto Nuevo. Thus, the metamorphic sole of that Nappe occurs (FIGURES 2, 4, 20) at the core of the Puerto Nuevo Laramide antiform. It necessarily follows that, prior to the

Liassic emplacement of the San Hipolito Nappe, the Puerto Nuevo Complex underwent a strong extensional event, that exhumed and exposed its different units. The dolerite and the plagiogranite dykes are dated  $\pm 220$  Ma, an age corresponding to the Carnian-Norian limit (Odin and Odin, 1990). The age of the San Hipolito basin is Carnian (?) - Norian. The appropriate conclusion to be drawn from these facts is that said extensional event began at the Carnian-Norian limit, to remain in force during the Norian, allowing first the emplacement of the dykes in discussion, as well as the opening of the San Hipolito basin. Then, *the Serpentinite Breccia appears as a detachment zone*, a product of the Upper Triassic listric fault system along which that extensional event occurred. And it seems at least permissible to think, in this context, that La Pintada Sequence (cyclic units, gabbro, diorite), which is the highest part of the intrusive Vizcaino Layered Complex, and its roof, the San Pablo Metamorphic Complex, were also displaced then to their present position along a higher detachment zone, buried at present under the Cainozoic basin dividing the Sierra of Puerto Nuevo from that of La Pintada.

## VIZCAINO LAYERED COMPLEX

(Puerto Nuevo plus La Pintada Sequences)

The continuity between the facies (harzburgite - dunite - cyclic units - gabbros and diorite) of this Complex, and therefore its oneness, have been established above on geological, structural and petrographic grounds. This conclusion is confirmed by the results of the geochemical analyses (major elements; trace elements including Cr, Ni, Co, Cu; RRE and Rb, Sr, Ba, Y, Zr, Nb, Cs, Ta, Th, U, Hf; and Platinum Group Elements - a total of 1352 individual element analyses) of samples collected systematically along the sections of El Tigre (FIGURE. 12), San Miguel (FIGURE. 13) and La Pintada (Castro-Leyva, 1992; Vatin-Perignon et al., 1998). These results show: (a) continuous, concomitant variations of the content of all of the elements from the dunites to the doleritic dykes; (b) a pattern of precipitation of the PGE consistent with the differentiation of the ultrabasic-basic pile; and (c) congruent chondrite-normalized REE abundance, and MORB-normalized high-field-strength element (considered as relatively immobile) diagrams for the gabbros, diorites there. All of these characteristics are consistent with, and to be expected only in, a *pile produced by a magmatic differentiation*. The conclusion of the intrusive character of the Vizcaino Layered Complex into the San Pablo Metamorphic Complex is based on field evidence. Thus, for this character and for its very geological and petrographic nature the *Vizcaino Layered Complex appears as the product of a magma underplating of a continental crust (sensu Fyfe, 1992)*.

From its main petrographic association discussed here above it can be inferred that the Puerto Nuevo Layered Complex was emplaced within a Supra Subduction Zone (SSZ) setting. This is confirmed by the already mentioned geochemical results. The dunites have a TiO<sub>2</sub> content, 0.01%, that compares with that  $\geq 0.04\%$  of those of a MORB sequence. Cumulate gabbros have a low-K tholeiitic signature. The gabbros and diorites are from arc tholeiitic to calc-alkaline in character.

As said, during the Late Triassic the San Hipolito marginal sea was opened behind the region of that intrusion. It becomes then a matter of consequence to conclude that *the Vizcaino Layered Complex, and thus the magma underplating that gave way to it, took place at an active margin, in a magmatic arc, the Puerto Nuevo-La Pintada continental magmatic arc, constituting now the Puerto Nuevo - La Pintada Zone*.

## CONCLUSIONS

The ultrabasic-basic rocks of the Vizcaino Peninsula, above the so-called Puerto Nuevo *mélange*, had been considered as a single obducted slab of an Upper Triassic oceanic

lithosphere and that so-called *mélange* of Puerto Nuevo as a Lower Cretaceous unit of Franciscan affinity (Rangin, 1977). This cannot be maintained any longer. In fact, in the Vizcaino Peninsula there are two ultrabasic-basic rocks-bearing units: the *Puerto Nuevo Layered Complex* (harzburgite - dunite - cyclic units including pyroxenite, gabbros and diorites of the Puerto Nuevo and La Pintada Sequences), and the overlying *San Hipolito Zone* (serpentinites, microgabbros, spilitic pillow lavas, ophicalcites, radiolarites, tuffs, graywackes, interbedded limestones and dolomites, siliceous sandstones, and volcanosedimentary strata). The *Puerto Nuevo Layered Complex, product of a magma underplating, is intrusive into the San Pablo Metamorphic Complex* (amphibole-biotite gneiss with lenses of granite, migmatitic amphibolitic gneiss, orthoamphibolites, and hornblende-actinolite schist). The *San Hipolito Zone* is an allochthon, the *San Hipolito Nappe*, which lies upon every one of the units of the Puerto Nuevo Sequence, including the so-called Puerto Nuevo *mélange*, which in fact is a Serpentinite Breccia only. The San Hipolito Zone corresponds to a former marginal basin, opened behind the *Puerto Nuevo-La Pintada Zone* (Vizcaino Layered Complex plus its roof, the San Pablo Metamorphic Complex), which appears to have been part of a continental magmatic arc.

The extensional event that gave way to the San Hipolito basin began at the Carnian-Norian boundary (at  $\pm 220$  Ma), and continued during the Norian. During this event, plagiogranitic and doleritic dykes were first emplaced (about 220 Ma) into the peridotites of the Puerto Nuevo Complex. During this same event the different units of the Puerto Nuevo Complex were exposed, and the block of La Pintada and its metamorphic roof (constituting together the upper part of Puerto Nuevo-La Pintada Zone) displaced to its present position. This occurred along low angle, listric faults, that gave way to zones of detachment, one of which corresponds to the *Serpentinite Breccia* of Puerto Nuevo, the lowermost known unit of the Puerto Nuevo Complex.

During the Liassic a phase of contractional deformation ensued. The *San Hipolito Nappe* was emplaced upon everyone of the terms of the Puerto Nuevo Complex, already exposed by the Upper Triassic extensional event, and the plagiogranite dykes were boudinaged.

During its translation the San Hipolito Nappe passed upon the Puerto Nuevo-La Pintada Zone. Disrupted as it has been by younger faults, its sole (the actinote schists) may appear as separate "blocks" - hence the previous misinterpretation of the "Serpentinite Breccia plus exotic blocks" as a *mélange*, mistakenly correlated with that of Cedros Island.

*By all evidences, the San Hipolito Nappe is a real ophiolitic unit, in the sense that it contains ultrabasic-basic rocks of*

*a former marine floor, that of the San Hipolito marginal basin. But this is not the case of the Puerto Nuevo Complex. This Complex has never been part of the floor of either an ocean or a marginal sea : it is an Ultrabasic-Basic Layered Complex intrusive into a pre-existing crust, the San Pablo Metamorphic Complex, and related to a magma underplating.*

Based on sound paleontological data, the San Hipolito corresponds to a Upper Triassic paleogeographic unit. Direct data are lacking to determine the geological age of the Puerto Nuevo Complex. Being crossed by 220 Ma plagiogranites it is certainly pre-Late Triassic. Pending some radiometric measurements, if it can be assumed that said plagiogranites are the product of its ultimate differentiation, it might be permissible to think that its differentiation was probably occurring during the Early and/or Middle Triassic. In a way, this is a minor matter. What does matter is that, according to both geological and petrochemical data, the *Puerto Nuevo Complex was emplaced in a Supra Subduction Zone tectonic setting, that is, at an active margin* .

The learned reader will have already noted the similitudes existing between the Puerto Nuevo-La Pintada Zone and the Ivrea-Verbanò (or first diorítico-kinzigite) Zone of the Western Alps, the Vizcaíno Layered Complex corresponding to the Ivrea ultrabasic-basic body (peridotite, cyclic units, gabbros and diorite), which is an outstanding example of magma underplating (cf., for instance, Ivrea-Verbanò Zone Workshop, 1992).

Although this point shall be the object of a future inquiry, it seems interesting to point out since now that the foregoing confirms that the magma underplating can be a fundamental process of the active margins (Radelli et al., 1992; Radelli et al., 1995) and it also suggests that other similar ultrabasic-basic occurrences, axiomatically related to a rifting, and therefore considered as obducted oceanic lithosphere, could be in reality autochthonous bodies, generated by a magma underplating of the crust of an active margin.

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