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PETROGRAPHY AND GEOCHEMISTRY OF FIVE GRANITIC PLUTONS FROM SOUTH-CENTRAL URUGUAY: CONTRIBUTION TO THE KNOWLEDGE OF THE PIEDRA ALTA TERRANE

(PÉTROGRAPHIE ET GÉOCHIMIE DE CINQ PLUTONS GRANITIQUES DU CENTRE-SUD DE L'URUGUAY: CONTRIBUTION À LA CONNAISSANCE DU TERRAIN PIEDRA ALTA)

NOVEMBRE 1993

Résumé

Les granitoïdes dans le centre-sud de l'Uruguay sont concentrés principalement en trois ceintures métamorphiques d'orientation est-ouest. Il s'agit (du sud vers le nord) des Ceintures de Montevideo, de San José et d'Arroyo Grande respectivement. Ces ceintures sont separées les unes des autres par des bandes de gneiss de composition granitiques. Toutes ces roches, les ceintures ainsi que les gneiss, constituent collectivement le Terrane de Piedra Alta.

Cinq de ces plutons granitiques, deux de la Ceinture de San José et trois de la Ceinture d'Arroyo Grande, ont été étudiés en détail. La composition chimique de 86 échantillons (éléments majeurs et traces) a été déterminée. Ces données, ainsi que des données isotopiques Rb-Sr, demontrent que, typiquement, ces plutons sont de nature composite et que l'âge des différéntes unités varie entre 1900 Ma à 2500 Ma. Les âges plus anciens proviennent des unités principales des plutons eux-mêmes tandis que les âges plus récents correspondent à l'âge de mise-en-place des dykes qui se sont injectés dans les plutons pré-existants et qui ne sont pas nécessairement associés à ces plutons. Les plutons sont généralement (mais pas exclusivement) du type calco-alcalin et sont typiquement syn-orogéniques tandis que les dykes sont post-orogéniques et sont de composition soit calco-alcaline soit alcaline.

Ces données sont incorporées en un modèle tectonique pour le Terrane de Piedra Alta qui est différent, à plusieurs

niveaux, que le modèle actuel. L'essentiel de l'évolution géologique de la région est:

1) développement d'un vieux «socle» de gneiss granitique

2) déposition, sur ou adjacent à ce «socle» de gneiss granitique, d'une séquence assez semblable à une complexe de schiste-verte archéen, bien qu'aucune komatiite n'a été découverte à date.

3) métamorphisme paléoprotérozoique, suivi par la mise-en-place des roches plutoniques syn-tectoniques à post-tectoniques.

4) développement d'accidents tectoniques importantes associés à l'orogenèse Tranamazonienne.

5) mise-en-place des dykes (post-orogéniques à anorogéniques) à la suite de l'orogenèse Transamazonienne.

Abstract

Granitoid rocks in south-central Uruguay are largely concentrated in three east-west trending metamorphic belts, known as (from south to north) the Montevideo Belt, the San José Belt and the Arroyo Grande Belt. These belts are separated from one another by intervening bands of gneisses of granitic composition. The whole assemblage, the gneisses as well as the metamorphic belts and their associated granites, collectively constitute the Piedra Alta Terrane.

Five of these granite plutons, two from the San José Belt and three from the Arroyo Grande Belt, have been studied in some detail and the chemical composition of 86 samples (major elements as well as a selected suite of trace elements) have been determined. These data, as well as Rb-Sr isotopic data, show that these plutons are typically composite in nature, and that the various units range in age from 1900 Ma to 2500 Ma. The older ages were obtained from the main units of the plutons themselves whereas the younger ages are from late dykes which were emplaced into the plutons and which are clearly not related to them. The plutons are predominantly, but not exclusively, of calc-alkaline affinity and are typically syn-orogenic whereas the dykes are post-orogenic and are either calc-alkaline or alkaline in composition.

These data have been incorporated into a tectonic model for the Piedra Alta Terrane which is considerably different

from that heretofore proposed. The essential features of the geological history of the area are:

1) development of an older "basement" of granitic gneisses

2) deposition, upon or adjacent to this gneisses basement, of a typical Archean greenstone belt assemblage (no komatiites so far reported)

3) Paleo-proterozoic metamorphism, followed by syn-tectonic to post-tectonic intrusion of the plutonic rocks

4) major tectonic dislocation(s) associated with the Transamazonian orogeny

5) dyke emplacement (post-orogenic to anorogenic) following the Transamazonian orogeny

Resumen

Las rocas granitoides del sur y centro del Uruguay se encuentran basicamente concentradas en tres cinturones metamórficos de direcciones regionales E - W, conocidos de norte a sur como Cinturon Montevideo, San José y Arroyo Grande. Estos cinturones estan separados unos de otros por fajas de neises de composición granitica. Todo el conjunto, los neises asi como los cinturones metamórficos y los granitos asociados, colectivamente constituyen el Terreno Piedra Alta.

Cinco de estos plutones graniticos, dos del cinturón San José y tres del cinturón Arroyo Grande han sido estudiados en detalle y la composición quimica de 86 muestras (elementos mayores, así como elementos trazas) han sido determinados. Estos datos, asi como las determinaciones geocronológicas Rb-Sr, muestran que estos plutones son de naturaleza compleja y que las distintas unidades varían en el entorno 1900 m.a. a 2500 m.a. Las edades mayores han sido obtenidas en las unidades principales de los plutones, mientras que las más jóvenes corresponden a filones tardíos emplazados en los mismos, no estando relacionados a ellos. Los plutones son predominantemente de afinidad calco- alcalina siendo tipicamente sin-orogénicos, mientras que los filones son post - orogénicos de composiciones alcalinas o calco-alcalinas.

Estos datos han sido incorporados a un modelo tectónico para el Terreno Piedra Alta, que considerablemente difiere del propuesto hasta el presente. Las principales caracteristicas de

la historia geológica del area son: 1) desarrollo de un basamento antiguo de neises graníticos. 2) deposición sobre o adjacentes a este basamento neísico de típicos conjuntos de cinturones arqueanos (greenstone belt) - komatiitas no han sido registradas. 3) metamorfismo paleo-proterozoico seguido por intrusiones de rocas plutonicas sintectónicas a postectónicas. 4) dislocaciones tectonicas mayores associadas a la orogénesis Transamazónica. 5)emplazamiento de filones (post-orogenicos a anorogénicos) siguiendo la orogénesis Transamazónica.

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Chapter 1 of this thesis was submitted to the Journal of South American Earth Sciences and has been accepted for publication. The author benefitted from two excellent reviews by Drs. Roberto Caminos and Carlos Rapela and their comments and suggestions have been incorporated into chapter 1. The writer would also like to thank Dr. Victor Ramos, regional editor of the Journal of South American Earth Sciences, for sheparding the manuscript through the review process so rapidly and so painlessly.

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Finally, I note that the computer program of Clarke (1990) greatly facilitated data analysis.

A note on the format of the thesis

The manuscript presented below is in the form of three largely autonomous chapters. Each chapter has its own title, introduction et cetera. The diagrams found in chapter one are labelled I-1, I-2 and so on. To avoid repetition, the references for all three chapters have been placed at the end of the thesis. The format style for the references is that required by the Journal of South American Earth Sciences.

It is acknowledged that, in adopting this format, there is an unavoidable duplication of some material, particularly among the introductory figures in each chapter. The writer can only express the hope that this does not cause unnecessary annoyance to potential users.

Each of these three chapters has been submitted for publication. Chapter 1 has been accepted for publication in the Journal of South American Earth Sciences. Chapter 2 has been submitted to the Revista de la Sociedad Brasileira de Geociencias and at the time of writing the author is awaiting the comments of the reviewers. Chapter 3 has been published by Bossi et al., (1993) in a publication of the Government of Uruguay, written in both Spanish and English, and entitled "El Predevoniano del Uruguay/The Predevonian of Uruguay".

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SOMMAIRE DETAILLE

La synthèse géologique de l'Uruguay, publié en 1991 par Bossi et Navarro était basée sur des documents publié jusqu'à 1986. Depuis, les connaissances sur la géologie des roches Précambriennes de l'Uruguay n'ont cessé d'augmenter, surtout grâce aux travaux de cartographie exectués par les équipes géologiques du Gouvernement de l'Uruguay ainsi que des études académiques effectués par des chercheurs Uruguaiens et de l'étranger. Ce document représente à la fois une contribution académique aux connaissances géologiques de l'Uruguay, et en même temps une tentative de synthèse ou d'intégration de toutes les données disponibles depuis de janvier, 1992.

Un survol de la géologie de l'Uruguay est présenté en Annexe 1. L'essentiel est répété içi comme introduction pour ceux et celles qui connaissent que très peu la géologie de mon pays. Essentiellement, il existe deux grands groupes de roches en Uruguay: (1) les roches déformés (une ou plusieurs fois) qui consistent en schistes et gneisses de composition et de faciès métamorphiques assez variés, et (2) des roches sédimentaires et volcaniques non-déformés qui reposent en discordance angulaire sur les roches du premier groupe. Toutes les roches du deuxième groupe sont d'âge dévonien ou plus jeunes. Pour cette raison, les roches du groupe 1 porte le nom de "pré-dévonien de l'Uruguay".

Les roches pré-dévoniennes ont été sub-divisées en trois groupes qui sont, de l'ouest vers l'est: (1) le terrane de Piedra Alta (2) le terrane de Nico Perez et (3) la ceinture Cuchilla - Dionisio.

Le terrane de Piedra Alta consiste en une vaste région de gneisses, schistes et roches intrusives, toutes les unités étant de composition variable. Selon Bossi et Navarro (1991), les roches du Piedra Alta ont été métamorphisées et déformées lors de l'orogénèse Transamazonienne (2000 Ma - 1800 Ma). Le but principal de cet travail est de démontrer que ce scénario est d'une part trop simpliste, et qu'il faut proposer l'existence d'au moins deux périodes de déformation pour expliquer les observations actuellement connues.

Le terrane de Nico-Perez est semblable, à plusieurs points du vue, aux roches du terrane de Piedra Alta. Par contre, les deux terranes sont séparés par une importante zone de mylonite de 15 km de puissance - le linéament de Sarandi del Yi - Piriapolis. Le déplacement horizontal le long de cette zone de faille étant inconnu, il est donc impossible d'affirmer que les roches des deux terranes étaient les mêmes à l'origine. La grande différence entre le Nico Perez et le Piedra Alta réside dans le fait que que les roches du Nico Perez ont été reprises plus tard par l'orogénèse Brésilien (1000 Ma - 650 Ma), ce qui complique l'interprétation géologique de ce terrane.

La ceinture Cuchilla - Dionisio contient également des gneisses, schistes et roches intrusives de diverses compositions. Les roches de cette zone ont été affectées seulement par l'orogénèse Brésilien et on ignore, du moins pour le moment, la présence des roches anciennes dans ce terrane.

Cette thèse consiste en une étude effectuée à l'intérieur du terrane de Piedra Alta (TPA) exclusivement. Afin que le lecteur puisse apprécier la contribution scientifique que représente ce travail, il est nécessaire de présenter quelques petites informations sur la géologie de cette zone.

Trois ceintures dit "volcano-sédimentaires" ont été identifiées à l'intérieur du TPA. Ils sont, du nord vers le sud: (1) la Ceinture de l'Arroyo Grande (métamorphisme schiste vert inférieur à moyen) (2) la Ceinture de San José (métamorphisme schiste vert supérieur) et (3) la Ceinture de Montevideo (métamorphisme dans le faciès amphibolite). La proportion des roches sédimentaires et volcaniques varient d'une ceinture à l'autre. Les trois ceintures sont séparées les unes des autres par deux domaines de gneiss, amphibolites et migmatites fortement métamorphisés et déformés dans le faciès amphibolite supérieur ou granulite.

Un certain nombre de roches plutoniques ont été cartographiées à l'intérieur des trois ceintures volcano-sédimentaires. La composition de ces roches intrusives varient entre gabbro et leucogranite et les textures varient de massive à folié.

L'étude géochimique et géochronologique de deux plutons du secteur oriental de la Ceinture de San José ainsi que trois plutons de la Ceinture de l'Arroyo Grande représente la partie principale de ce travail, (chapitres 1 et 2 respectivement). Une synthèse de toutes les connaissances géologiques de la région, incluant les résultats des premiers deux chapitres, est présenté dans le chapitre 3 qui a comme but de proposer un modèle cohérent pour expliquer les données géologiques connues.

Auparavant, le modèle tectonique expliquant l'évolution géologique du terrane de Piedra Alta était assez simple. Les datations sur quelques roches intrusives et métamorphiques, pris dans les ceintures volcano-sedimentaires ainsi que dans les gneiss, donnaient des âges entre 2100 Ma et 1900 Ma. En conséquence, on pensait que les roches de cette région avaient été affectées par l'orogénèse Transamazonienne exclusivement. Les données présentées ci-dessous compliquent légèrement ce modèle.

Les résultats de l'étude des Plutons de l'Arroyo de la Virgen et de Isla Mala, situés dans la Ceinture de San José, sont présentés en Chapitre 1. La cartographie de l'Arroyo de la Virgen dévoile la présence d'une intrusion zonée, qui passe de granodiorite dans le nord vers un leucogranite plus au sud. L'intrusion fut recoupé par une variété de dykes. Des datations de ces roches (toutes les datations citées dans ce texte ont été effectué par la méthode Rb-Sr sur roche totale) ont donné des âges de 2225 Ma pour le leucogranite et 1925 Ma et 1894 Ma pour deux dykes de composition légèrement différente. Ces résultats indiquent que les dykes sont beaucoup plus jeunes (d'âge tardi-Transamazonien) que l'intrusion - ils ne peuvent pas être le "dernier jus" associé à la mise en place de la partie principale du massif. L'âge du leucogranite était surprenant - le pluton est une roche massive et non-deformée, mais l'âge est PRE-Transamazonien.

La cartographie du Pluton de Isla Mala a également devoilé la présence de deux unités principales (granodiorite et leucogranite) recoupé par des dykes tardifs. L'âge déterminé pour un de ces dykes est 2040 Ma - tout à fait comparable aux dykes qui recoupent l'Arroyo de la Virgen. Par contre, l'âge de mise en place du granodiorite et du leucogranite ont été fixés à 2450 Ma et 2290 Ma respectivement. Ceci démontre que les deux unités principales de l'Isla Mala n'étaient pas contemporaines et qu'il s'agit d'un "pluton à l'intérieur d'un pluton". Pour cette raison, nous préférons le terme "Complèxe d'Isla Mala" pour décrire l'ensemble des unités.

Le leucogranite et le granodiorite sont tous les deux de texture massive et d'âge pre-Transamazonien. Ce résult confirme que l'âge pre-Transamazonien pour le leucogranite de l'Arroyo de la Virgen n'est pas abérrant.

Les résultats pour les plutons de Marincho, le South Granite (granite du sud) et l'Arroyo Grande, tous localisés dans la Ceinture de l'Arroyo Grande, sont présentés en Chapitre 2.
Le granodiorite de l'Arroyo Grande est le moins connu de ces trois amas intrusifs. Il est massif et, à l'état actuel de nos connaissances, de composition homogène. La composition légèrement subalcaline suggère un environnement distensif pour la mise en place. Aucune datation n'est disponible pour cette intrusion.

Le South Granite est un leucogranite massif de composition homogène. Une datation sur ce granite a donné un âge de 2180 Ma, ce qui est légèrement plus jeune que l'âge de 2225 Ma déterminé pour l'Arroyo de la Virgen.

Plusieurs unités cartographiables ont été identifiés dans l'intrusion de Marincho. Les trois unités les plus importantes sont une hornblendite (d'âge inconnu), un granodiorite (2291 Ma) et un leucogranite (2067 Ma). Il s'agit encore un fois d'un ensemble polyphasé, ce qui nous amène à appliquer le terme Complèxe de Marincho pour toutes ces roches. Un dyke de leucogranite qui recoupe le complexe, a été daté à 1969 Ma, semblable aux âges des dykes de la Ceinture de San José plus au sud.

La limite australe de la Ceinture de l'Arroyo Grande est la Faille del Paso de Lugo. Les gneiss granitiques sont situés au sud de cette faille. Quelques blocs de granite massif ont été découverts dans la zone de faille. Une datation sur ces blocs a donné un âge de 2544 Ma - la plus vieille roche reconnue à date dans la région. Cette datation laisse supposer que la déformation, qui a affecté les roches des ceintures volcano-sédimentaires, était antérieure à 2544 Ma - c'est à dire, d'âge archéen.

Le Chapitre 3 présente une synthèse qui intègre non seulement les résultats de ce travail mais aussi tous les travaux antérieurs effectués dans la région. Le but est d'utiliser toutes les informations disponibles afin de proposer un modèle tectonique qui concorde avec toutes ces données. La majeure partie de ce chapitre présente des données essentielles qui servent de base pour l'elaboration du modèle. Ces informations étant assez longues et détaillées, nous nous contenterons ici de présenter les éléments les plus importants du modèle qui en découle.

Etape #1

Il est plus ou moins certain maintenant que les roches les plus vieilles de la région sont d'âge archéen. Les évidences appuyant cette affirmation sont:

1) les roches des ceintures volcano-sédimentaires ont été déformées et métamorphisées au faciès schiste vert ou amphibolite.

2) des blocs du granite massif, échantillonnés à l'intérieur de la zone de faille de Paso de Lugo, (ceinture septentrionale) ont été datés à 2544 Ma.

3) le granodiorite d'Isla Mala, (ceinture centrale), qui est également massif, a été daté à 2450 Ma.

Le fait que ces derniers deux granites sont massifs indiquent que l'âge de la déformation affectant les ceintures volcano-sédimentaires était encore plus vieux. Si on accepte la date de 2500 Ma, proposée par la Geological Society of America comme limite entre l'archéen et le protérozoïque, alors la déformation qui a affecté les ceintures volcano-sédimentaires était certainement d'âge archéen dans le nord du TPA et probablement d'âge archéen également dans le centre du TPA.

On note aussi le rapport initiel de 0.734 obtenu sur le leucogranite du Complexe de Marincho (1969 Ma). Un tel rapport suggère que ce leucogranite est le produit de la fusion partielle d'une croûte continentale assez vieille (sans doute archéen), mais il est impossible d'être plus précis.

Etape #2

Un certain nombre des roches datées dans le cadre de ce projet se situent dans une intervalle de 2450 Ma jusqu'à 2180 Ma dont la plupart entre 2290 Ma et 2180 Ma. Les roches les plus vieilles sont caractérisées par une chimie calco-alcaline tandis que les plus jeunes sont plutôt de chimie alcaline - les leucogranites ne peuvent être classé par cette technique à cause de leurs particularités chimiques. Ceci suggère un passage graduel entre un environnement syn-tectonique à post-tectonique et ceci pendant une période d'environs 110 Ma. Des études géochronologiques effectuées au Brésil suggèrent que les importantes zones de failles et de mylonites, tels que le Paso del Lugo entre autres, se sont développées pendant cette période.

Etape #3

Un deuxième regroupement temporel de roches intrusives se situe entre 2040 Ma et 1894 Ma. Toutes ces roches sont des petits dykes qui recoupent les plus grands amas intrusifs développés lors du deuxième étape. Encore un fois, les roches les plus vieilles semblent être caractérisées par une chimie calco-alcaline tandis que les roches plus jeunes sont plutôt alcalines. Le pluton d'Arroyo Grande est définitivement à caractère alcalin, mais pour le moment aucune datation n'est disponible.

On note que le pluton de Mahoma, situé plus vers l'ouest en dehors du secteur considéré dans ce rapport, a été daté à 1935 Ma. Ceci démontre que les roches intrusives développées lors de cette troisième étape ne sont pas exclusivement des petits dykes.

Collage tectonique

La séquence de roches décrites ci dessus sont toutes situées à l'interieur de trois ceintures volcano-sédimentaires séparées, les unes des autres, par de vastes zones de "gneiss granitiques". Les datations Rb-Sr sur ces gneiss donnent des valeurs entre 2200 Ma et 2000 Ma. Ces âges, interprétés comme âges métamorphiques, représentent la date à laquelle la roche a refroidi à des températures inférieurs à la température de "blocage" pour ce système isotopique - vers 500°C selon la plupart des géochronologues. De tels datations sont traditionellement attribuées à l'orogénèse Transamazonienne.

Ces données sont très difficile à interpréter car ils amènent immédiatement à une contradiction. Les ceintures volcano-sédimentaires contiennent, surtout dans le nord (ceinture de Arroyo Grande) les assemblages métamorphiques qui caractérisent le faciès schiste vert. Les massifs granitiques, logés dans ces ceintures, semblent être non-déformés et d'âge 2290 Ma à 2180 Ma. Ces ceintures sont séparées des gneiss granitiques (d'âge 2200 Ma à 2000 Ma, donc post-granite) par des importantes zones de failles, qui sont également des zones de "discontinuité métamorphique". Il est peu probable que l'évènement métamorphique reponsable pour le développement des gneiss granitiques était la même que celui qui a donnée naissance aux assemblages métamorphiques dans les ceintures volcano-sédimentaires. Il s'agit donc de deux évènements métamorphiques distincts - un qui a affecté les ceintures volcano-sédimentaires (archéen ?) et l'autre qui a produit les gneiss granitiques, migmatites et granulites (2200 Ma - 2000 Ma). Le collage structurale de ces deux composantes en un grand terrane précambrien fut donc réalisée après que le deuxième métamorphisme soit, en grand partie, terminé. La grande contradiction mentionné ci dessus réside dans le fait qu'il existe aucune évidence supportant une hypothèse de collage tectonique post-2000 Ma. Au contraire, l'âge proposé pour le développement des zones de failles est de 2263 Ma - c'est à dire pre-Transamazonien. Cet âge est nettement en conflit avec l'âge du métamorphisme des gneiss granitiques. Des datations radiométriques additionelles seront nécessaires afin de régler ce problème. Une étude géochronologique approfondie représente la prochaiane étape pour améliorer nos connaissances du pré-dévonien de l'Uruguay.

Introduction

Two years ago, Bossi and Navarro (1991) published their benchmark article entitled "The Geology of Uruguay". The manuscript of this article was completed in 1988 and the geology therein described was up to date as of approximately 1986.

Since this article was completed, our knowledge of the "Predevonian Crystalline shield", one of the major components of Uruguayan geology, has been significantly improved - 1:100 000 scale mapping projects have been carried out on several key areas of the predevonian rocks. A university group (College of Agronomy) supported by I.R.D.C. (International Research Development Center) concentrated on the Middle Precambrian rocks. Similarily DI.NA.MI.GE. (Mining and Geology National Direction) staff of "Basic Geology Division" carried out an analogous work in the Late-Proterozoic - Cambrian igneous-metamorphic belt developed in the eastern part of the country. Finally, there have been a number of independent studies, such as that described in chapters 1 and 2 of this report, as well as several others, which have all contributed to our understanding of the pre-Devonian rocks of Uruguay.

A compilation of the above cited information was made in order to produce a synthesis of what is known of the predevonian rocks. It is hoped that this synthesis will prove useful not only for Uruguayan geologists but also for those who are interested in the geology of South American as a whole.

We note that, during the course of this synthesis, it was necessary to critically analyze the available data, to weigh its relevance and to evaluate them in the light of current hypotheses.

The goal was to construct a model which encompasses every valid opinion about such a difficult and vast subject.

Up to the present, the Uruguayan Predevonian Shield has only been studied on a small or local scale. The degree of available detail is variable and the models derived from these were also very different. Therefore, in order to produce a coherent whole, it was necessary to reinterpret almost all pre-existing work.

It is recognized that many readers, particularilly North American readers, may initially find the subject somewhat confusing due to a lack of familiarity with the geology of the area. To help overcome this obstacle, the writer has prepared a short overview of the Precambrian geology of Uruguay, which is included here as Appendix 1. Some of the material presented in this Appendix is discussed in considerably more detail in the body of the text, particularily in chapter 3. Although nothing which is presented in the Appendix is indispensable for an understanding of what follows, it should nevertheless provide a general basis for comprehension of the geology of this portion of South America.

The classic subdivision of the Precambrian of Uruguay of Ferrando and Fernandez (1971) was founded on the proposed existence of two orogenic events: a Limpopo-Kibali event dating from approximately 2000 Ma and a Baikalian event of approximately 500 to 600 Ma. This proposal was based on the geochronological data of Umpierre and Halpern (1971). Unfortunately this scheme is not adequate to explain the geology of the region as currently known. Nevertheless, their hypothesis represented a significant advance in the knowledge of Uruguayan (and South American) geology from a tectono-chronostratigraphic point of view. Both Bossi et al. (1975) and Preciozzi et al. (1985) accepted the validity of this subdivision. A new proposal involving three orogenic cycles by Bossi (1983) has not proven to be totally satisfactory for explaining the available data. Recently Bossi and Navarro (1991) proposed a new stratigraphic sequence for the Uruguayan Predevonian rocks which is outlined in Table i-1.

For a number of reasons it is now considered preferable to divide the Predevonian rocks into different terranes, each of which can be characterized by a number of distinctive features such as rock type, predominant structural trend et cetera. The three Predevonian terranes currently recognized are shown in Figure i-1. Two groups of plutonic rocks, one from southern Uruguay and the other from central Uruguay, are described in this report in chapters 1 and 2 respectively. These data have been incorporated, along with data from all other available sources, into a synthesis of the current state of geological knowledge of the Piedra Alta Terrane. This synthesis is presented here as chapter 3 of this thesis and it is the writer's hope that it is an accurate, coherent and meaningful synthesis of our current knowledge of the Piedra Alta Terrane.

TABLE i-1
Stratigraphic sequence proposed for the Uruguayan Predevonian rocks and Transamazonian - Brazilian tectonic events

Age (Ma)	Stratigraphic units	Rock types
485 - 545	Sierra de los Rios Fm	Rhyolites
	Sierra de las Animas Fm	Syenites, microsyenites, trachytes, basalts
515 - 550	La Paz and Illescas granites	
Late Orogenic Cycle		
	Sierra Ballena Fm	
blastomylonites		
	Barriga Negra Fm	
510 - 550	Post orogenic granites	
535 - 590	Syn orogenic granites	
610 - 670	Migmatites	
	Carapé Group	Medium grade ectinites
	Lavalleja and Rocha groups	Low grade ectinites
	Piedras de Afilar Fm	Sediments
900 +\- 50	Pre orogenic volcanism	Greenschists
Early Orogenic Cycle		
1930 +\- 35	Post and late orogenic granites	
1900 - 2050	Syn orogenic granites	
1930 - 2170	Migmatites, gneisses and pegmatites	
	Montevideo, Paso Severino and Arroyo Grande Fms.	Different grade metamorphic rocks with slight migmatization
Older Basement		
	Valentines Fm	Banded Iron Formation
	Cuñapiru-Vichadero crystalline region	

after Bossi (1983)

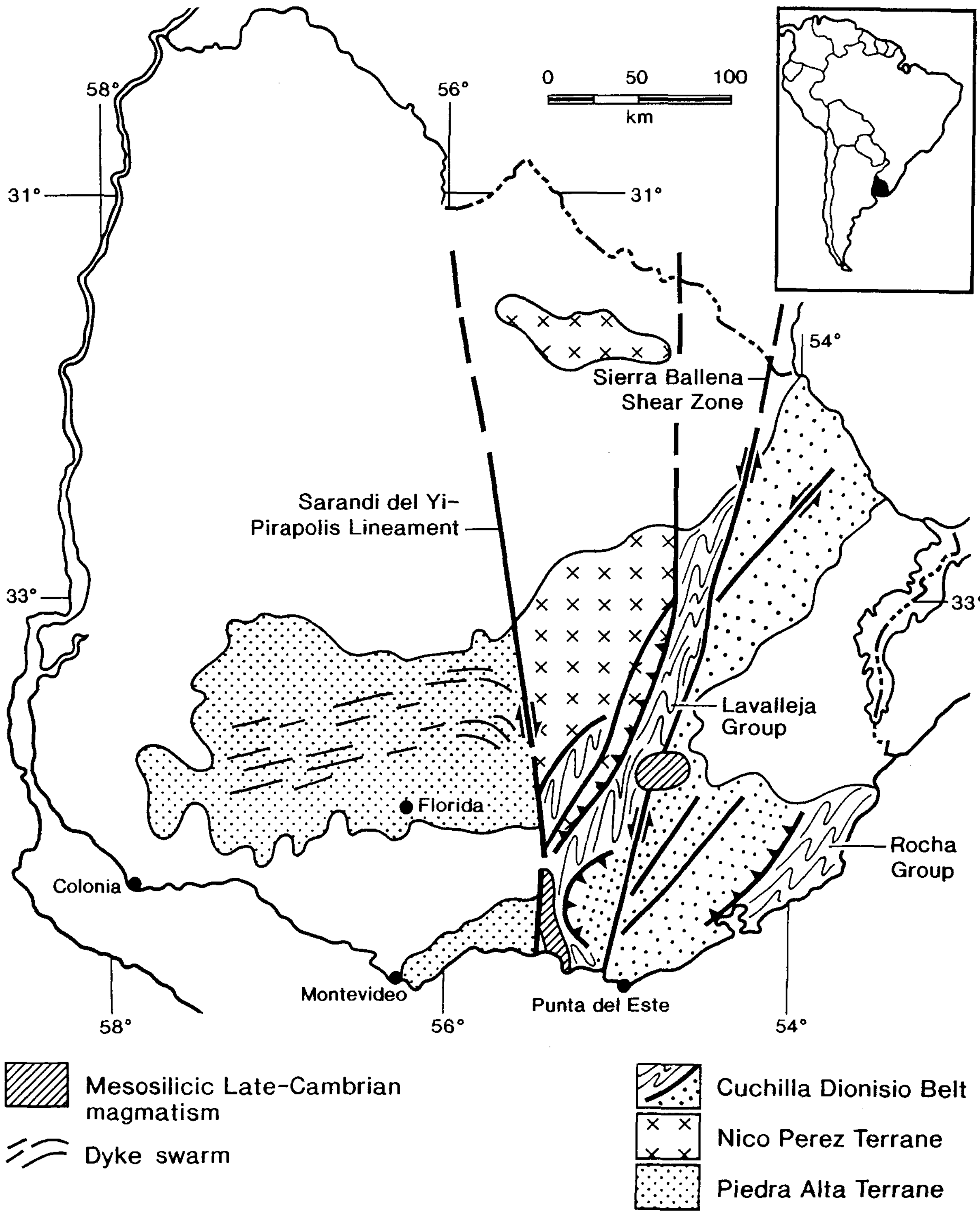


Figure i-1: Location of the three Predevonian terranes of Uruguay

<u>**Comment on Nomenclature**</u>

As seen on Figure i-1, the Piedra Alta Terrane occupies the western portion of the Predevonian Shield of Uruguay. This area has long been known as the "Rio de la Plata Craton", a term introduced by Almeida (1973, 1976) to replace the term "Zocalo de la Cuenca del Río de la Plata" (base of the Rio de la Plata Basin) proposed earlier by Ferrando and Fernandez (1971). The behaviour of this unit as a stable craton during the Brasilian orogenic cycle was surely the reason why Ferrando and Fernandez chose this term for these rocks. Nevertheless, an analysis of its geological evolution is more reasonably arrived at by considering the inherent characteristics of the belt itself, rather than only taking into account its age relationship with respect to the Late-Proterozoic - Cambrian mobile belt.

For reasons outlined below, the author proposes that the term Rio de la Plata Craton, with its associated geotectonic implication, be set aside and replaced by the more operational term <u>Piedra Alta Terrane</u>. Herve and Mpodozis (1991) define tectono-stratigraphic terranes as being those areas which have geological histories which differ from those of other neighbouring areas. We use the term Piedra Alta Terrane in the tectono-stratigraphic sense.

CHAPTER I

PETROGRAPHY AND GEOCHEMISTRY OF THE ARROYO DE LA VIRGEN AND ISLA MALA PLUTONS, SOUTHERN URUGUAY: EARLY PROTEROZOIC TECTONIC IMPLICATIONS

Foreward to Chapter 1

The largest of the three metamorphic belts referred to in the introduction is the San José Belt. The belt is host to a number of granitoid intrusions which are distributed more or less indiscriminantly along its entire length. Two of the larger intrusions, both of which are situated at the eastern end of the belt, were chosen for a geochemical and geochronological study. The goals of the project were:

1) to characterize the tectonic environment of emplacement of the granitoids

2) to determine their age of crystallization

3) to relate this information to currently available models for the tectonic evolution of southern Uruguay.

The results of this study are presented below as chapter 1.

Introduction

The southern half of Uruguay is underlain by a wide variety of Precambrian rocks which have been metamorphosed to grades ranging from greenschist to granulite. Two main age groupings have been identified based on the age of the deformation which later affected them. The two groupings are separated by a number of NNE trending mylonite zones up to 5 km in width which trend approximately parallel to the eastern coast of South America, (Figure I.1). Rocks east of the mylonite zones are mostly of Brazilian age in that they were influenced by the Brazilian orogeny which affected the area between 500 Ma - 650 Ma. Rocks west of the mylonite zones were deformed during the Transamazonian orogeny, which dates from 1900 Ma - 2100 Ma, as well as during earlier events, (Cordani et al., 1988). An overview of Uruguayan geology is available in Preciozzi et al., (1985).

Both the Transamazonian rocks, and to a lesser extent the Brazilian rocks, are hidden by extensive outcroppings of flat-lying sedimentary rocks ranging in age from Devonian to Quaternary and also by flat-lying volcanic rocks ranging in age from Jurassic to Cretaceous, notably the tholeiitic basalts of the Arapey Formation which underlie the central and northwestern portions of Uruguay, (Mantovani and Hawkesworth, 1991).

The predominant structural trend of the Transamazonian rocks is east-west except near the mylonite zones. The metamorphic grade of the different rock units often varies suddenly as lithologic contacts are crossed. These metamorphic discontinuities suggest the presence of stacked gneiss sheets (Davidson et al., 1982).

The fault zones which separate these metamorphic discontinuities are characterized by the presence of mylonitic rocks. Intrusive into these schists and gneisses are a number of plutonic bodies which are concentrated in four distinct areas. The largest of these is located between the town of Florida and the village of Conchillas in southern Uruguay and consists of 20 intrusions exposed over a strike length of approximately 160 km, (Figure I.1). The Arroyo de la Virgen Pluton (AVP) and the Isla Mala Pluton (IMP), located at the eastern end of this belt are the largest (80 km2 and 50 km2 respectively) and amongst the better exposed members of this suite of intrusions, the centre of which is located approximately 90 km north of Montevideo. Radiometric data, to be presented below, clearly indicates that the IMP is in fact a composite body, consisting of two units which are separated in age by approximately 150 Ma. To be consistent with earlier terminology, we refer to both of them as the IMP.

The purpose of this article is to describe the petrography and geochemistry of these plutons and to use this information to draw some inferences concerning the Middle Precambrian tectonic evolution of Uruguay.

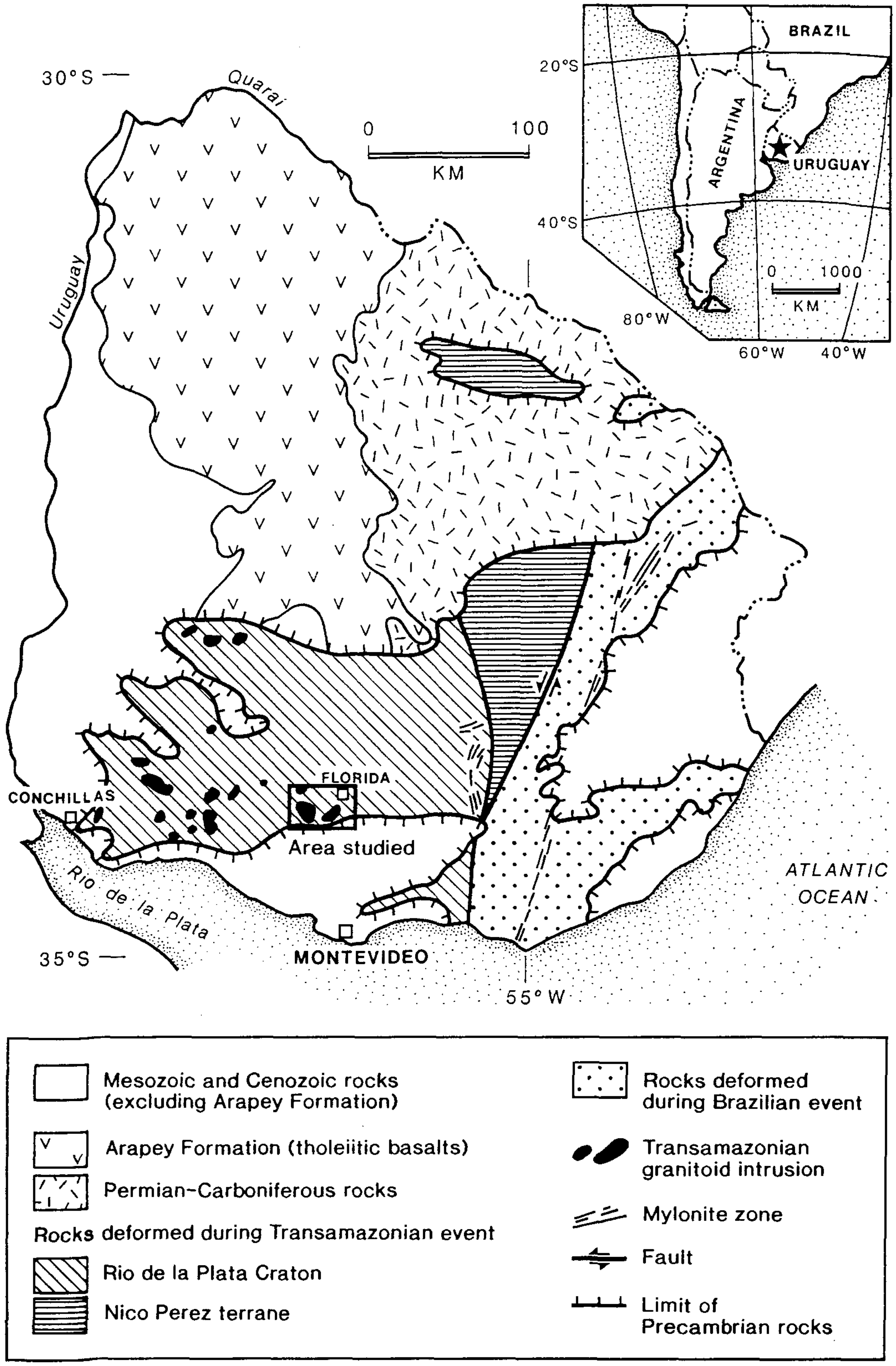


Figure I.1: Geological sketch map of Uruguay showing the location of the study area, southern Uruguay.

Geological Setting

Both the AVP and the IMP are intrusive into several different rock types, (Figure I.2). Low grade metamorphic rocks of the Paso Severino Formation (slates, phyllites, quartzites, meta-arkoses and metavolcanic rocks) are located along the southern and western margins of the pluton (Preciozzi et al., 1979; 1985). Ortho-amphibolitic rocks of the Berrondo unit and a lithologically complex suite of migmatites (the Pintado unit) are found along the northern and southeastern margins of the mass respectively.

Petrography

a) Arroyo de la Virgen Pluton (AVP)

The main portion of the intrusion consists of a massive, grey, coarse-grained, relatively homogeneous, biotite (rarely hornblende) granodiorite, (Figure I.3). A pinkish, coarse-grained, homogeneous leucogranite is located in the southern portion of the outcrop area of the complex and a homogeneous, porphyritic microdiorite has been observed locally within the main granodioritic unit. Finally, a series of late diorite, aplite and fine-grained pinkish granite dykes cross cut the main unit of the complex.

The AVP does not contain many enclaves, however the mylonitic nature of some of these enclaves suggests that the AVP is younger than the tectonic event which brought the low grade and high grade rocks into mutual contact. Furthermore,

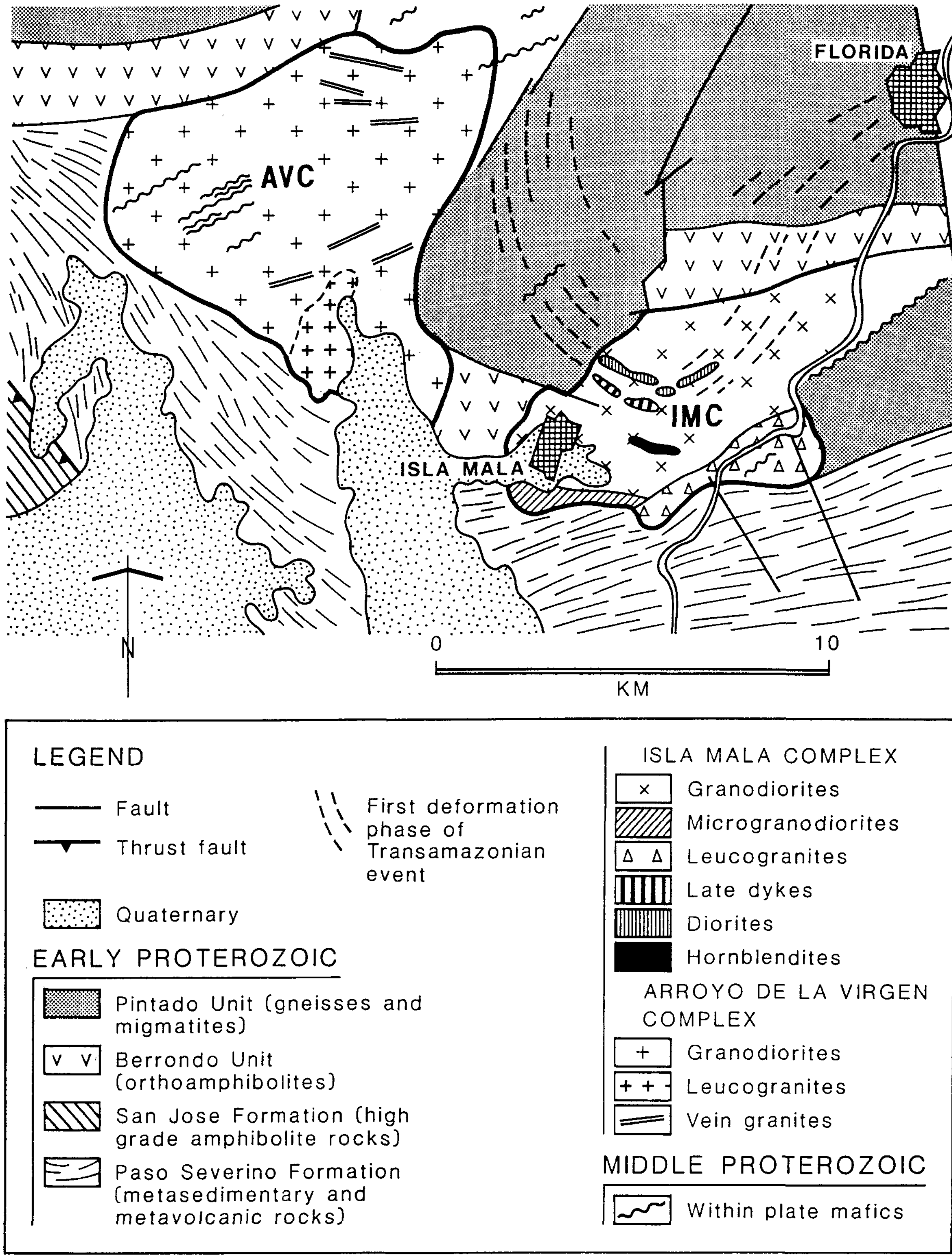


Figure I.2) Sketch map of the local geology in the vicinity of the AVP and the IMP.

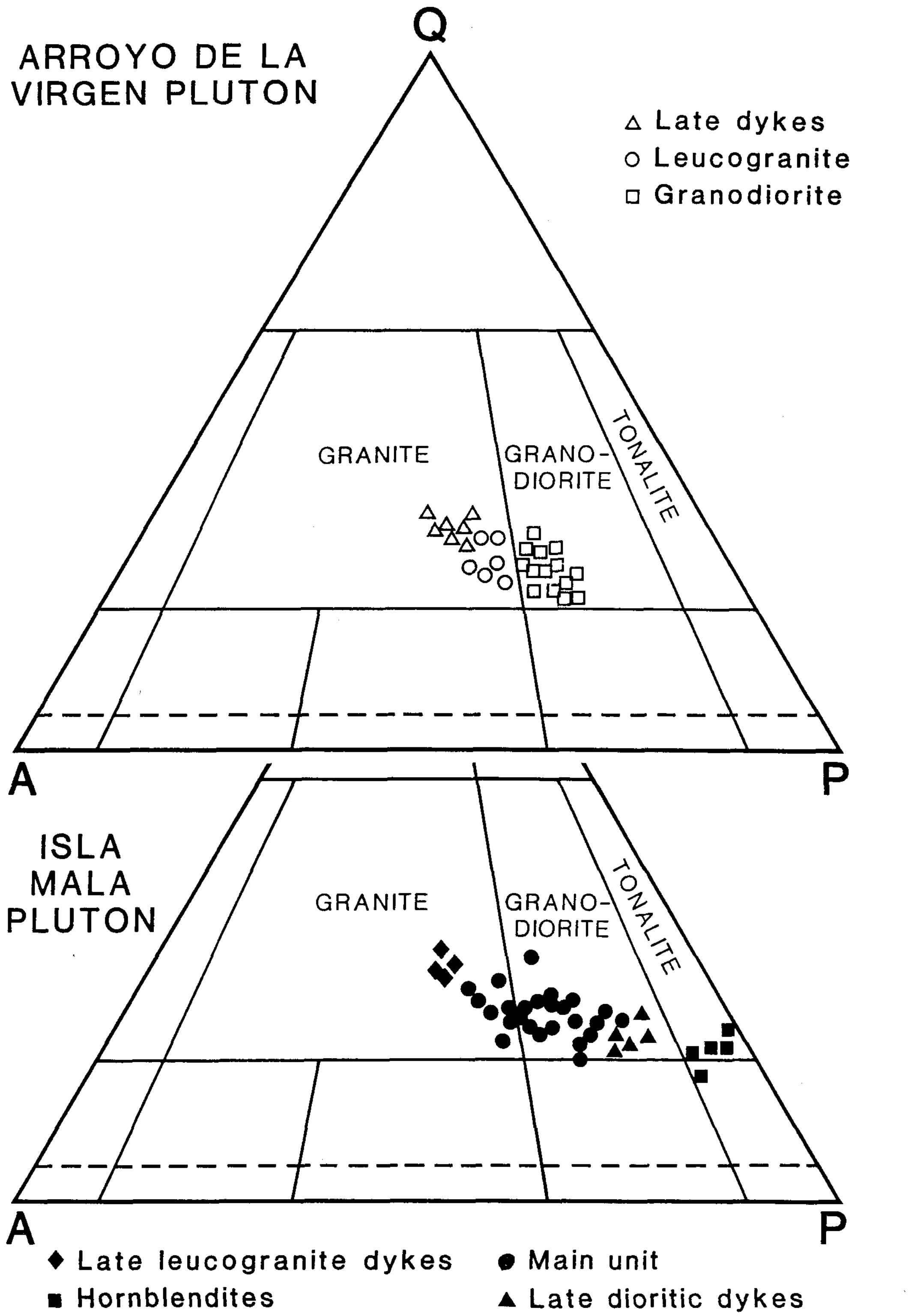


Figure I.3) Streckeisen (1976) diagram for the AVP and the IMP. After Preciozzi (1989a, 1989d) the fault zones observed in the country rocks do not cross the AVP.

Granodiorite (main unit)

Euhedral plagioclase crystals, situated within an hypidiomorphic granular matrix, is the texture typically encountered within the intrusion. The plagioclase crystals have been variably altered to secondary epidote and sericite.

The composition of the granodiorite is heterogeneous and is characterized by a well developed petrographic zoning, as revealed by the An content of plagioclase which varies systematically from An 20 values along the eastern, northern and western margins of the mass to An 0 values in the south-central portion of the complex.

The potassium feldspar phase is a microcline perthite in which the type of perthite ranges from acicular to vermiform to cryptoperthite and microperthite (Alling, 1938). The microcline is typically anhedral, although occasional subhedral crystal forms, and more rare poikilitic forms were also observed. Phyllic alteration phenomena are frequently present.

The quartz forms anhedral crystals which feature undulose extinction and numerous sub-grain boundaries. Two generations of quartz were observed depending on the tendency to form polygonal aggregates. This form of quartz tends to be found in those rocks which have the lower An values discussed above. The biotite is strongly pleochroic in shades of olive green, has been replaced by chlorite to a minor extent, and contains inclusions of zircon, apatite, sphene and opaque minerals.

Leucogranite

The rocks features a clear hypidiomorphic granular texture with subhedral albite. The albite shows several different styles of alteration, however the most important is phyllitization.

Microcline is abundant, being present in large anhedral to subhedral crystals which are occasionally poikilitic. Small veinlets of albite, of acicular and occasionally tabular form, are also present.

The quartz, which forms clear anhedral crystals comparable in size to the microcline crystals, has a well developed undulatory extinction.

Deep red biotite crystals, containing inclusions of radioactive minerals, are present. Muscovite forms subparallel laths in contact with the biotite. Accessory minerals include red garnet, bipyramidal zircon, sphene, apatite, and rarely iron oxides.

Aplite Dykes (vein granites)

The aplite dykes possess hypidiomorphic granular textures, however some rocks have clearly porphyritic tendencies. The plagioclases are subhedral, of oligoclase composition and are frequently altered. The potassium feldspar consists either of anhedral, granular perthitic microcline or of subhedral phenocrysts which may be slightly porphyritic. Phyllitic alteration is present to different degrees.

The quartz, which is relatively abundant, consists either of crystals of subhedral, equigranular quartz or forms part of the fine-grained matrix of the dykes along with microcline and plagioclase.

Red biotite crystals are relatively abundant. The accessory phases include zircon, apatite, sphene and iron oxides.

Porphyritic Diorite Dyke

The texture consists of microphenocrysts of euhedral basic plagioclase, (labradorite, An 56), which contain Carlsbad-albite twins. Evidence of secondary sausseritization and sericitization is present. The matrix of the dyke consists of microlites of plagioclase (An 42) and augite which have locally been altered to chlorite - actinolite assemblages. Opaque minerals and sphene are the most common accessory minerals - quartz and microcline are totally absent. No modal mineral data are available for this unit.

b) Isla Mala Pluton (IMP)

A medium-grained, hornblende + biotite granodiorite is the most important rock type encountered in the IMP, however the composition of the intrusion varies from "diorite" through to monzogranite, (Figure I.3). The hornblende and biotite are oriented parallel to the contact near the margin of the intrusion. A similar orientation, which is also parallel to the long axis of enclaves of schist and amphibolite, was observed near the western and southern contacts of the mass. In the centre of the pluton the rocks are massive.

A network of small E-W trending dykes of diorite and granite are found in the west-central portion of the complex. In addition, a small stock of porphyroblastic hornblendite was observed near the centre of the intrusion. Two distinct bodies of fine-grained diorite (microgranodiorite) and pale pink leuocogranite are found along the southern margin of the IMP. The age of the hornblendite and the microgranodiorite are not known. The chemistry of these units is similar to that of the main portion of the mass and it is assumed, for lack of evidence to the contrary, that the pluton developed by multiple injection from a deeper magma source. Age data for the leucogranite, presented below, suggest that this unit is substantially younger.

The slate unit of the Paso Severino formation has been converted into an andalusite-bearing hornfels at the contact with the leucogranite.

Granodiorite and related rocks

The granodiorite features a hypidiomorphic granular texture with abundant euhedral plagioclase which is typically calcic oligoclase in composition and is frequently altered. The potassium feldspar phase consists of anhedral to subhedral crystals of microcline. The biotite is greenish brown in colour and has been replaced by secondary chlorite to varying degrees as a consequence of late stage (deuteric) processes. The biotite is often spatially associated with an amphibole of a type typically found in intermediate plutonic rocks (Deer et al., 1966) which suggests that some of the biotite may have been formed by replacement of this mineral. Anhedral quartz featuring undulatory extinction is abundant. Accessory minerals include epidote, sphene, opaque minerals and secondary muscovite. The texture varies continuously from the dioritic to the monzogranite members of the unit.

Microgranodiorite

The rock features a fine-grained equigranular texture containing euhedral plagioclase crystals. Locally there is a tendency towards the development of a granophyric texture.

The plagioclase is zoned with a core composition of An 35 ranging outwards to a marginal composition of An 6. Typical compositions vary between An 16 and An 22. The granophyric texture (plagioclase intergrown with quartz) and more rarely a pegmatitic texture, are both developed at the margins of the plagioclase crystals.

Microcline is present as subhedral to anhedral crystals and is occasionally perthitic. Quartz is abundant and features a well developed undulatory extinction.

Mafic minerals consist of green-brown biotite, containing inclusions of sphene, zircon and epidote, which is spatially associated with a greenish hornblende.

A detailed textural study of this unit has been reported elsewhere (Preciozzi 1989a).

Leucogranite

This unit features a hypidiomorphic granular texture. The plagioclase composition averages An 12 and declines to An 5 at the margin of the crystals. The plagioclase frequently contains inclusions of microcline.

Microcline is typically perthitic. Wormlike, interpenetrating and tabular forms of perthite (Ailling, 1938) have been observed. Quartz features a well developed undulatory extinction.

The biotite is brown in colour and contains inclusions of zircon, sphene and opaque minerals.

Accessory minerals include garnet, sphene, bipyramidal zircon, epidote and opaque minerals.

Hornblendite

This porphyritic unit contains large, well-formed crystals of amphibole and smaller crystals of clinopyroxene which is probably augite.

The plagioclase composition ranges from An 56 to An 48. Most plagioclase has been severely altered to a fine-grained assemblage of epidote group minerals (sausseritization).

Microcline and quartz are both rare. The principal accessory minerals are sphene, opaque minerals and epidote.

Late dykes

Three distinct types of cross-cutting dykes were observed. Fine-grained leucogranite dykes, containing oligoclase, abundant microcline, quartz with undulatory extinction, green biotite and accessory zircon, sphene, large apatite and hematite. Aplite dykes contain oligoclase (An 14 to An 16) microcline and quartz with undulatory extinction. The biotite is pale brown in colour. Garnet is typically present as is bipyramidal zircon. The lack of epidote, colour of the biotite, presence of garnet and the fact that the plagioclase is typically unaltered enable this unit to be easily distinguished from the fine-grained leucogranite. Diorite dykes consist essentially of green hornblende, greenish-brown biotite and plagioclase (average composition An 42). Quartz and microcline are uncommon. The accessory minerals are opaque minerals, apatite and sphene.

Enclaves

Enclaves are very common in the IMP and consist of three different types. Fine-grained dioritic to gabbroic enclaves, of rounded shape, range in diameter from 5 to 35 cm. These enclaves are believed to be autoliths (previously solidified portions of the IMP which were stirred into the still liquid portion of the intrusion). Xenoliths of muscovite schist which are irregular in shape and are up to 1 meter in size, are very common. Finally, xenoliths of andalusite schist (Paso Severino Formation) are found near the southern margin of the IMP in both the granodiorite and the leucogranite units.

Geochemistry

A total of 32 chemical analyses of the AVP and 39 analyses of the IMP were carried out during the course of this study. A representative selection is presented in Tables 1 and 2 respectively. The granodiorite unit of both plutons (that is, granodiorite and related rocks) exhibit a range of SiO2 values, varying from 66% to 68% in the case of the IMP and 69.7% to 72.1% for the AVP. The leucogranite unit of the AVP features SiO2 values ranging from 73.8% - 77.8% whereas the same unit of the IMP has SiO2 values ranging from 70% to 77%. Both plutons are intruded by fine-grained leucogranite dykes which have SiO2 concentrations greater than 70%.

The AVP and IMP are mildly peraluminous and metaluminous respectively. The average value for the peraluminous index for

Table I.1

CHEMICAL ANALYSES OF THE ARROYO DE LA VIRGEN PLUTON

Sample	1	6	8	10	12	14	16
RockType	GDRT	GDRT	GDRT	GDRT	LGRA	LGRA	LGRA
SiO2	69.70	71.15	71.20	72.15	73.80	75.20	75.70
TiO2	0.45	0.55	0.50	0.50	0.30	0.40	0.05
Al2O3	15.10	15.00	14.90	14.50	13.80	13.00	13.80
Fe2O3	1.78	1.37	1.48	1.37	1.23	1.30	0.80
FeO	1.67	1.50	1.37	1.30	0.79	0.50	0.00
MnO	0.02	0.13	0.06	0.08	0.05	0.01	0.02
MgO	0.11	0.12	0.06	0.07	0.03	0.00	0.00
CaO	2.20	1.85	1.90	1.80	1.00	0.60	1.20
Na2O	4.10	4.15	4.15	4.10	3.85	4.15	3.65
K2O	4.15	3.80	3.95	3.75	4.30	4.30	4.30
P2O5	0.10	0.02	0.02	0.02	0.07	0.01	0.03
H2O	0.57	0.72	0.32	0.67	0.27	0.40	0.29
Total	99.95	100.36	99.91	100.31	99.49	99.87	99.84

TRACE ELEMENTS (PPM)

Ba	705	730	315	275	195	490	485
Rb	270	90	194	180	145	145	185
Sr	385	205	145	215	38	315	225
Li	105	20	72	56	35	45	78
F	60	35	85	2250	56	2240	65
Co	45	0	5	95	0	65	10
Cr	10	15	0	25	0	15	0
Ni	0	5	15	15	0	0	5
Cu	50	55	90	20	78	5	25
Zn				100		95	

Table I.1 (con't)

Sample	19	21	22	24	26	29	32
RockType	LGRA	GDRD	GDRD	LGRD	LGRD	LGRD	LGRD
SiO2	77.80	70.10	71.10	74.00	74.85	75.50	76.80
TiO2	0.05	0.25	0.25	0.25	0.15	0.05	0.15
Al2O3	12.20	15.30	15.20	13.20	12.95	13.70	12.00
Fe2O3	0.75	2.44	2.34	1.60	0.78	0.85	1.21
FeO	0.15	0.30	0.10	0.55	0.76	0.00	0.36
MnO	0.01	0.08	0.03	0.09	0.03	0.07	0.03
MgO	0.00	0.70	0.60	0.40	0.24	0.10	0.15
CaO	0.45	3.80	3.60	1.20	1.20	1.25	0.60
Na2O	4.15	4.80	4.75	3.70	3.65	3.80	3.55
K2O	3.60	1.85	1.75	4.40	4.05	4.40	4.80
P2O5	0.01	0.03	0.00	0.03	0.06	0.04	0.00
H2O	0.45	0.52	0.47	0.45	0.54	0.18	0.39
Total	99.62	100.17	100.19	99.87	99.26	99.94	100.04

TRACE ELEMENTS (PPM)

Ba	515	25	0	825	315	475	640
Rb	115	275	245	80	157	215	60
Sr	275	15	10	125	45	255	340
Li	55	35	40	25	55	85	32
F	2250	1680	85	60	980	65	65
Co	55	55	0	0	65	10	5
Cr	25	0	5	15	0	0	20
Ni	15	12	0	5	0	10	5
Cu	15	5	80	40	0	55	50
Zn	110	95			95		

Table I.2

CHEMICAL ANALYSES OF THE ISLA MALA PLUTON

Sample	1	2	3	4	5	6	7
Rocktype	GDRT	GDRT	GDRT	GDRT	GDRT	GDRT	GDRT
SiO2	66.00	66.60	67.00	67.30	67.40	67.70	68.00
TiO2	0.50	0.90	0.85	0.50	0.90	0.80	0.50
Al2O3	15.90	15.90	15.85	14.10	13.70	15.80	14.90
Fe2O3	1.15	1.35	1.30	2.70	3.96	1.25	2.25
FeO	1.95	3.70	3.65	2.20	0.22	3.55	2.39
MnO	0.05	0.16	0.15	0.10	0.06	0.10	0.40
MgO	2.50	2.00	1.90	2.10	1.85	1.80	1.00
CaO	3.95	4.60	4.50	3.55	2.70	4.40	2.80
Na2O	3.75	4.45	4.40	3.35	3.20	4.40	4.20
K2O	2.95	1.80	1.75	2.95	4.50	1.70	3.50
P2O5	0.10	0.30	0.25	0.15	0.00	0.20	0.15
H2O	0.30	0.12	0.20	0.25	0.69	0.10	0.16
Total	99.10	101.88	101.80	99.25	99.18	101.80	100.25
			TRACE ELEMENT (PPM)				
F	500	750	830	620	850	600	1120

Table I.2 (con't)

8	16	17	20	21	22	23	28
LGRA	LGRA	LGRA	LGRA	LGRA	LGRA	HORN	DIOD
71.10	73.00	73.50	76.00	76.60	76.90	55.40	62.80
0.35	0.10	0.15	0.00	0.30	0.20	0.80	0.80
15.10	15.00	15.00	13.50	11.80	11.70	11.80	15.50
0.88	1.07	0.88	0.75	1.08	0.82	4.03	3.77
0.75	0.58	1.01	0.15	0.29	0.43	3.48	2.46
0.10	0.05	0.07	0.10	0.01	0.02	0.15	0.15
0.50	0.40	0.40	0.00	0.12	0.11	9.00	2.90
2.40	1.90	2.10	1.10	0.74	0.74	10.70	4.70
4.80	5.00	4.80	4.30	2.90	3.20	2.50	3.60
3.20	3.00	2.00	3.80	5.10	4.80	0.80	2.80
0.01	0.05	0.50	0.00	0.01	0.01	0.20	0.20
0.76	0.58	0.28	0.16	0.51	0.31	0.92	0.42
99.95	100.73	100.69	99.86	99.46	99.24	99.78	100.10
TRACE ELEMENT (PPM)							
	860	350	200	900	585	660	880

Table I.2 (con't)

30	33	34	37	38	39
DIOD	LGRD	LGRD	LGRD	LGRD	LGRD
63.40	70.20	70.50	75.00	75.90	77.70
1.00	0.70	0.40	0.00	0.01	0.40
15.25	14.20	14.30	13.80	12.30	12.70
2.50	3.30	2.70	0.85	1.00	0.01
3.55	1.45	1.16	0.25	0.36	0.02
0.10	0.10	0.10	0.05	0.02	0.01
3.20	0.50	0.45	0.10	0.05	0.14
5.20	1.80	1.50	1.20	0.57	0.50
3.35	4.15	3.75	4.40	3.20	3.00
2.70	4.00	4.05	3.90	5.30	4.85
0.25	0.15	0.10	0.00	0.00	0.01
0.40	0.15	0.27	0.20	0.36	0.61
100.90	100.70	99.28	99.75	99.07	99.95

TRACE ELEMENT (PPM)

1000	930	900	420	1680	815

19 analyses of the plutonic component of the AVP and 13 analyses of the late dykes is 1.01 in both cases. The same index for 22 plutonic analyses of the IMP and for 14 analyses of the related dykes is 0.97 and 0.93 respectively.
Analyses of both plutons plot within the calc-alkaline domain on an igneous AFM plot as defined by Irvine and Baragar (1971), (Figures I.4a and I.4b). Two trends are seen on Figure I.4a, one defined by the dykes and the other by the plutonic host rocks. No such discrimination between dykes and host is obvious on Figure I.4b. The same two trends for the AV suite are apparent on an MgO - SiO2 plot (Figure I.5a). The dyke suite is distinctly more magnesian than is the plutonic host at intermediate SiO2 values. The dykes also have higher XFe (Fe*O/(Fe*O + MgO)) and possible slightly lower TiO2 values.

Fluorine is bimodally distributed in the AVP. Of the 31 analyses available, 21 have F values less than 100 ppm, whereas the F concentrations surpass 1000 ppm (up to 2300 ppm) in the other 10 analyses. No analysis show values between 100 ppm and 1000 ppm. Both the pluton and the dykes have low as well as high F values. In contrast, the F distribution in the IMP is unimodal. The F values in the 20 available analyses are all greater than 100 ppm and only two of these surpass 1000 ppm.

Discussion

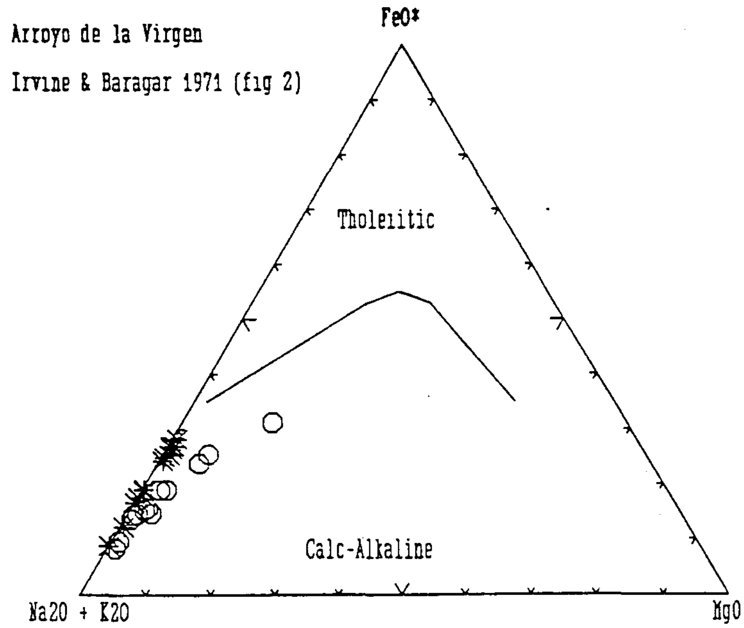
Geochronology and constraints on magma source

Six Rb-Sr whole rock age determinations are available - three from the AVP and two from the IMP (Table I.3). In addition, unpublished geochronological data (Bossi et al., 1993) indicate an age of 2450 ± 40 Ma (IR = 0.7003) for the main portion of the IMP. However the preliminary nature of this age determination means that the age difference between the main portion of the mass and the leucogranitic unit should be considered as suggestive but not proven.

The age of the late aplite and leucogranite dykes which are intrusive into the AVP are considerably younger than the AVP itself. As already indicated above, the geochemistry of the leucogranite dykes and the host pluton are strikingly different, thus corroborating the age difference between them.

A very similar situation is present in the Isla Mala Pluton. Both the granodiorite and the leucogranite units of the main portion of the pluton are considerably older than the late granitic dykes which are intrusive into them. The ages of the late dykes from both plutons are similar, although it appears that the Isla Mala dyke is a little older than the dykes which intrude the Arroyo de la Virgen Pluton.

The initial ratios of the main portions of both plutons are also rather similar, being 0.7076 and 0.7091 for the Arroyo de la Virgen and the IMP leucogranite respectively. Given the age of the plutons, it is probable that pure mantle derived



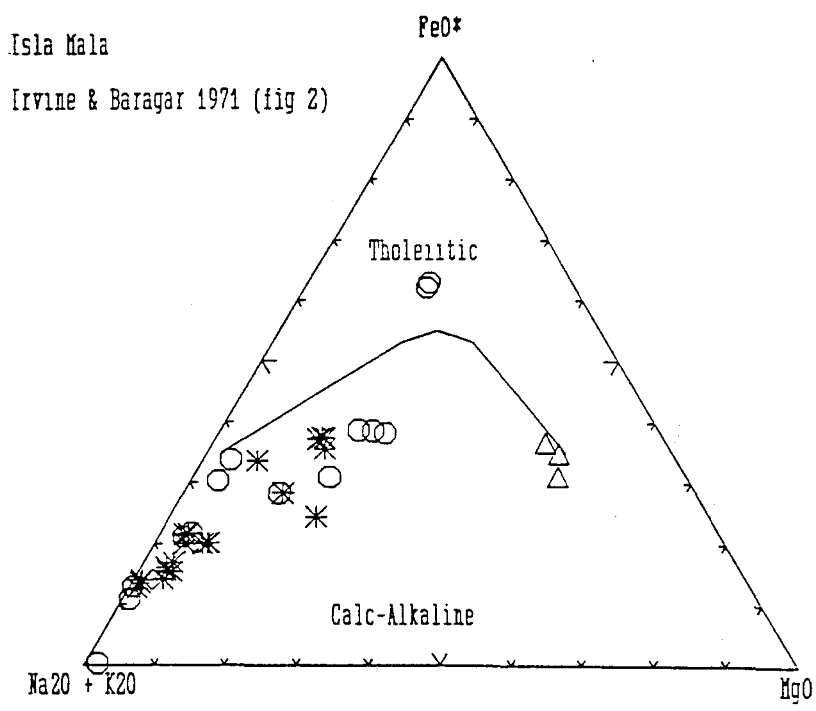
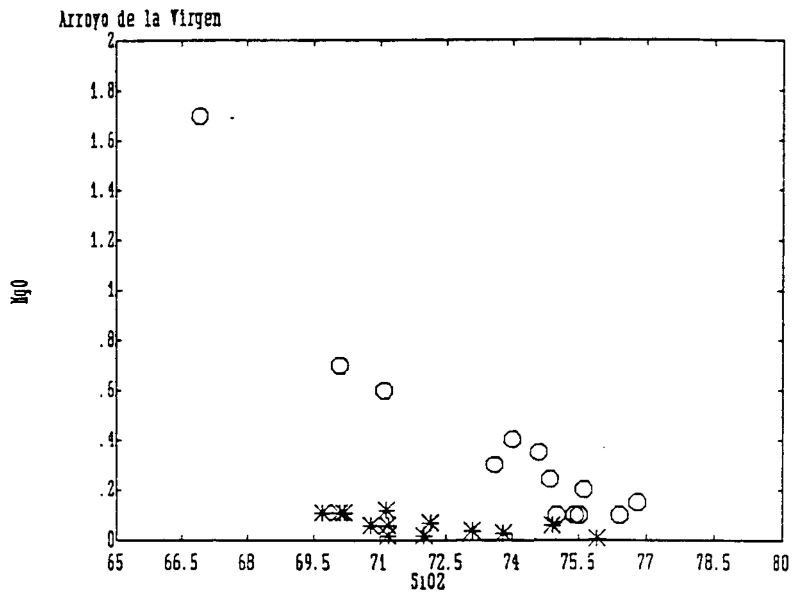


Figure I.4) AFM diagram for the AVP (4a) and the IMP (4b). Limit between calc-alkaline and tholeiitic fields taken from Irvine and Baragar (1971). Legend for figure 4a: * = late granitic dykes; o = granodiorite and leucogranite. Legend for figure 4b: * = late dykes; o = main unit of complex; triangle - hornblendite



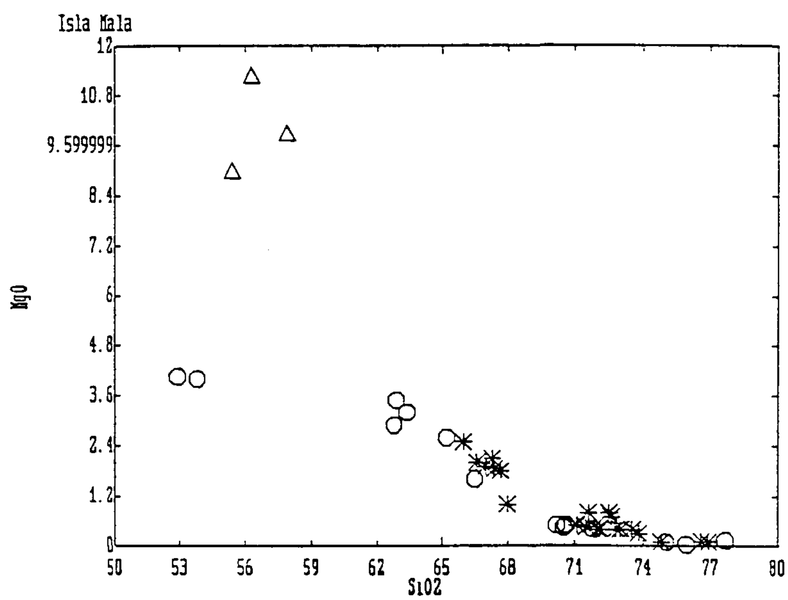


Figure I.5) MgO - SiO2 plot for the AVP (5a) and the IMP (5b). Symbols as on Figure I.4.

Table I.3
Geochronologial data for the
Arroyo de la Virgen and Isla Mala Plutons

Suite	Age (Ma)	1 sigma	init rat	1 sigma	MSWD	n
1	2225	25	0.7076	0.0009	12	5
2	1925	23	0.7109	0.0003	1.2	6
3	1894	75	0.7160	0.0011	4.5	5
4	2290	35	0.709	0.0012	7	5
5	2040	40	0.7064	0.0008	10	6
6	2450	40	0.7003	0.0016	6	5

1) AVP leucogranite. Main part of the intrusion
2) AVP granite dyke. Intrusive into suite 1
3) AVP aplite dyke. Intrusive into suite 1
4) IMP leucogranite. Main part of the intrusion
5) IMP granite dyke. Intrusive into suite 4.
6) IMP granodiorite

melts would have had an initial ratio of approximately 0.7018 (Cox et al., 1979, page 364). Thus the higher initial ratio for these rocks suggests either substantial contamination of a mantle melt by a crustal component, or possibly that the melts are totally of crustal origin.

Similar comments pertain to the dykes, however the elevated initial ratio of the aplite dyke intrusive into the AVP makes it relatively certain that it contains a large proportion of upper crustal component.

Depth of Emplacement

Several indirect lines of evidence all indicate a shallow to moderate depth of crystallization for most of the plutonic units. The presence of andalusite in the IMP contact aureole of the leucogranite unit of the IMP shows that the pressure of emplacement was less than that of the triple point in the aluminosilicate system (approximately 3.8 kb in the pure system - Holdaway, 1971). The presence of perthite is also suggestive of low water pressures (see Martin and Bonin, 1976) however there is no petrographic evidence in the form of abundant pegmatites or miariolitic cavities to indicate fluid saturation during the crystallization of even the most evolved members of either pluton. Third, a plot of the most evolved samples from each mass (those with a normative quartz + albite + orthoclase greater than 95% in Figure I.6 can be compared to experimental data for minimum melt compositions in the haplogranitic system.

The trajectory of minimum melt compositions in water saturated systems is a function of total pressure which is shown on Figure I.6 along with data points for each pluton. The data points fall slightly to the right of the minimum melt trajectory - which may be due to the small amounts of CaO present in the magma or to CO2 (Ebadi and Johannes, 1991) or both. Extrapolating to the left generates an intersection of approximately 2 and 0.5 kb for the AVP and the leucogranite unit of the IMP respectively. Since water saturation cannot be demonstrated to have been attained during the crystallization of either pluton, these values represent the minimum pressure of emplacement.

Chemical Classification of the Tectonic setting

A number of tectonic discriminant diagrams have been proposed in recent years. Application of these diagrams is somewhat confusing since there is no accepted terminology for the environments in which granitic rocks may develop. Furthermore, the discriminant functions which have been proposed are based on different data bases and use different elements to effect the discrimination. The comments which follow must therefore be viewed with some caution.

Maniar and Piccoli (1989) proposed a method based exclusively on major element data. Application of this approach suggests a major difference in the tectonic setting of emplacement of the two plutons. Figures I.7a and I.7b are

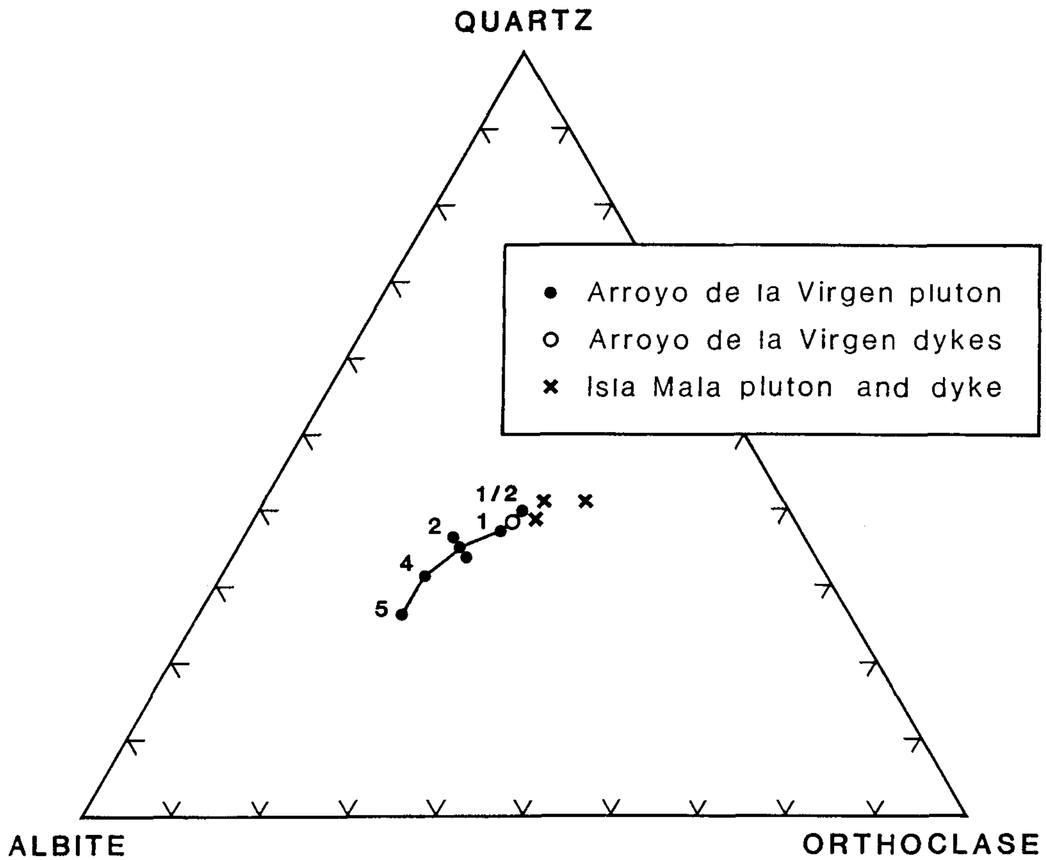


Figure I.6) Normative quartz - albite - orthoclase diagram for the most evolved plutonic analyses from the AVP. Location of minimum melt compositions taken from Winkler (1979).

FeO*/FeO* + MgO versus SiO2 plots for the AVP and the IMP. The main portion of the AVP (Figure I.7a) falls in the CEUG/RRG domain on this plot whereas the late dyke suite falls into the IAG/CAG/CCG/POG domain. In fact, the most chemically evolved members of both the main portion of the pluton as well as the dyke suite fall very close to one another on this plot. Only the intermediate members of either suite (less than 71% SiO2), can be successfully discriminated. An attempt to classify the main portion of the AVP as either CEUG or RRG using a TiO2 - SiO2 plot, as advocated by Maniar and Piccoli, was not successful. The same two groupings are apparent on Figure I.5a - the main portion of the AVP defines a trend featuring low MgO values.

Figure I.7b shows that both the IMP as well as the related dyke suite are most probably IAG, CAG, POG or CCG type plutons. The data points for all rock types define a broad band which crosses the central portion of the diagram. The low value for the peraluminous index of the pluton (less than 1.0) enables the CCG environment to be eliminated from consideration, however it is not possible to distinguish between the IAG, POG and CAG environments.

The above distinctions are also obtained using the method of Batchelor and Bowden (1985) who used the R1-R2 diagram (Figures I.8a and I.8b) of LaRoche et al. (1980) as a tectonic discriminant diagram. Data points for the AVP appear to define a trend which originates in the late-orogenic (sub-alkaline)

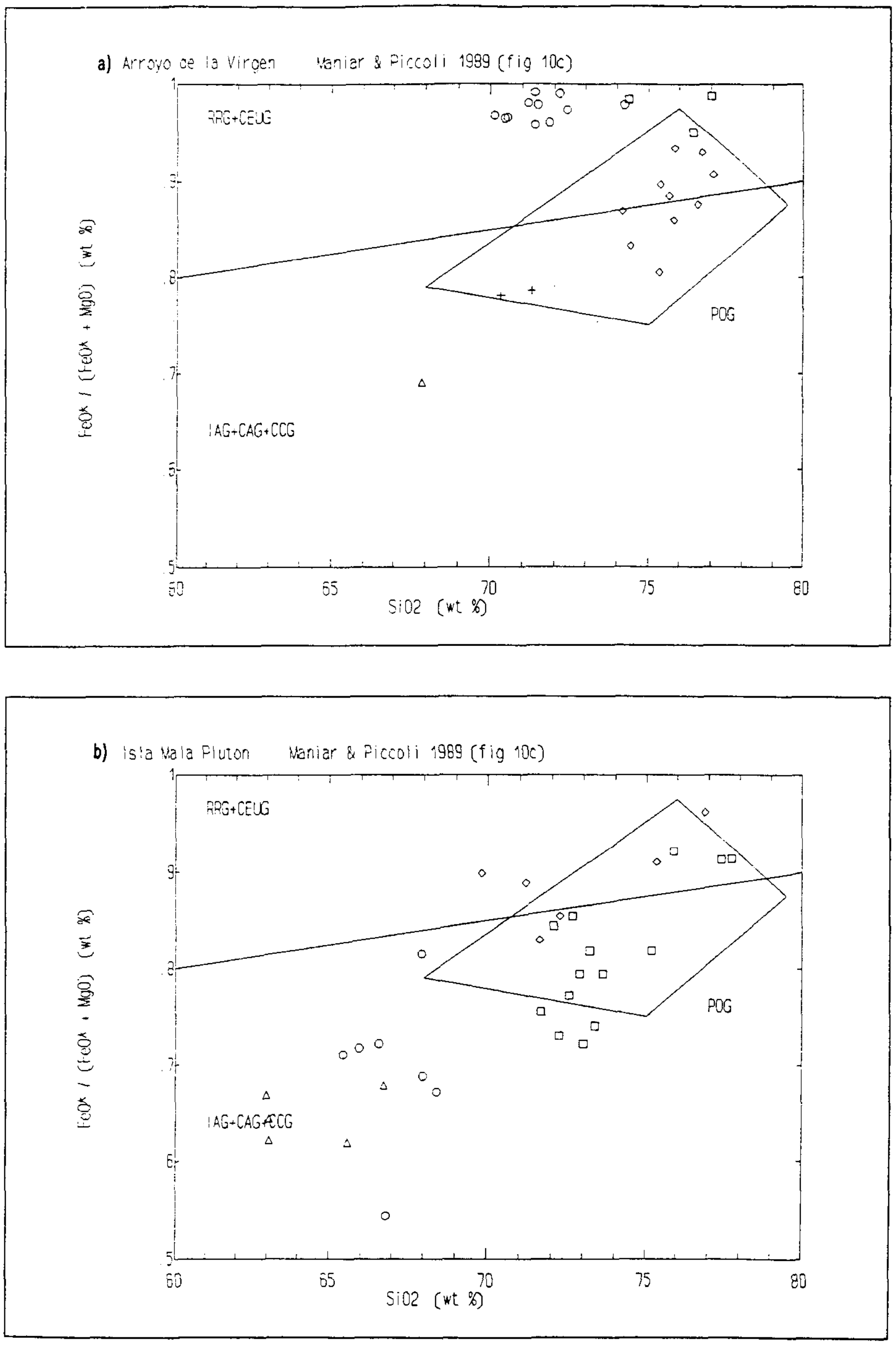


Figure I.7) FeO*/(FeO* + MgO) - SiO2 plot for the AVP (7a) and the IMP (7b).
circles = granodiorite and related rocks; squares = leucogranite; triangle = hornblendite and/or diorite; plus sign = granodiorite dyke; diamond = leucogranite dyke.
CEUG (continental epeirogenic uplift granite); RRG (rift related granite); IAG (island arc granite); CAG (continental arc granite); CCG (continental collision granite); POG (post orogenic granite).

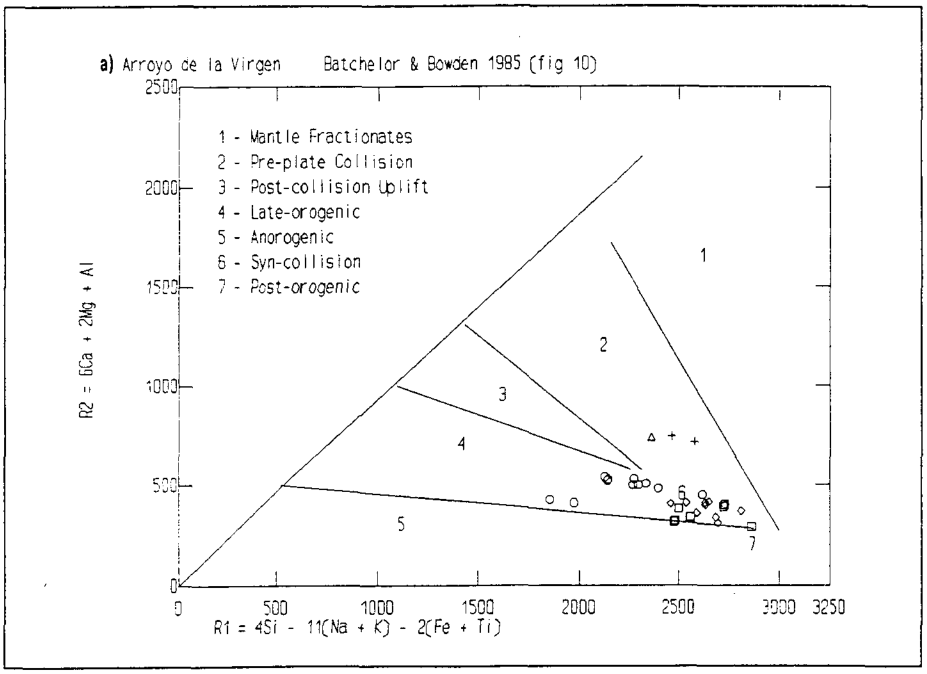
field. The fact that the data points indeed define a trend which originates in one of the fields numbered 1 to 5 argues against the possibility that these rocks are syn-collisional in nature. The trend for the AV dykes, as well as for both the IM dykes and pluton define trends that are largely in the pre-plate collision field which includes destructive plate margins such as the Cordillera.

Implications for Tectonic History

The geochronological data clearly reveal the presence of two, and possibly three, groups of granitoid plutons in southern Uruguay. (1) the main portion of the IMP (2450 Ma - Bossi et al., 1993); (2) the leucogranitic unit of the IMP and the AVP (2290 Ma and 2225 Ma respectively - see Table I.3); (3) the late dykes intrusive into both complexes (roughly from 1900 Ma to 2000 Ma - Table I.3).

None of these plutonic rocks appears to have been metamorphosed, although all have been altered, particularly the main portion of the IMP. We conclude, therefore, that the metamorphic event which developed the greenschist facies assemblages in the Paso Severino Formation and the upper amphibolite to granulite facies assemblages in the gneisses is definitely older than 2290 Ma and possibly older than 2450 Ma - that is, the regional metamorphism is likely of Archean age. This tentative conclusion is in agreement with Cordani et al., (1988) who suggested that almost all of the continental crustal material in this portion of Uruguay formed prior to 2500 Ma. It is possible that the main portion of the IMP formed near the end of this deformational event, and therefore escaped the most intense periods of the metamorphism, however there is no independent evidence to support this hypothesis. The IMP leucogranite and the AVP are both considerably younger than the main portion of the IMP. The IMP leucogranite is the older, and features a chemistry suggestive of a pre-plate collision/active continental margin type of tectonic environment. The AVP is slightly younger and has a chemistry suggestive of a late-orogenic environment.

Soliani (1986) dated a granitic body located in northern Uruguay which is located <u>within</u> one of the fault zones. The age of this granite (2263 Ma) corresponds to the age of fault development. Thus it is possible that the period 2290 Ma to 2225 Ma (data Table I.3) records a major deformational event, during which time significant differential movement occurred. Previously metamorphosed low grade and high grade rocks were tectonically juxtaposed, the contact between these zones being occupied by mylonitic rocks. We associate this period of tectonic activity and associated plutonism with the Transamazonian orogeny. Similar abrupt metamorphic transitions were noted in the Superior Province of the Canadian Shield by Card (1990) who suggested that this might be the result of the assembly of "suspect terranes" such as those of the North American Cordillera (see Coney et al., 1980; Gabrielse, 1991).



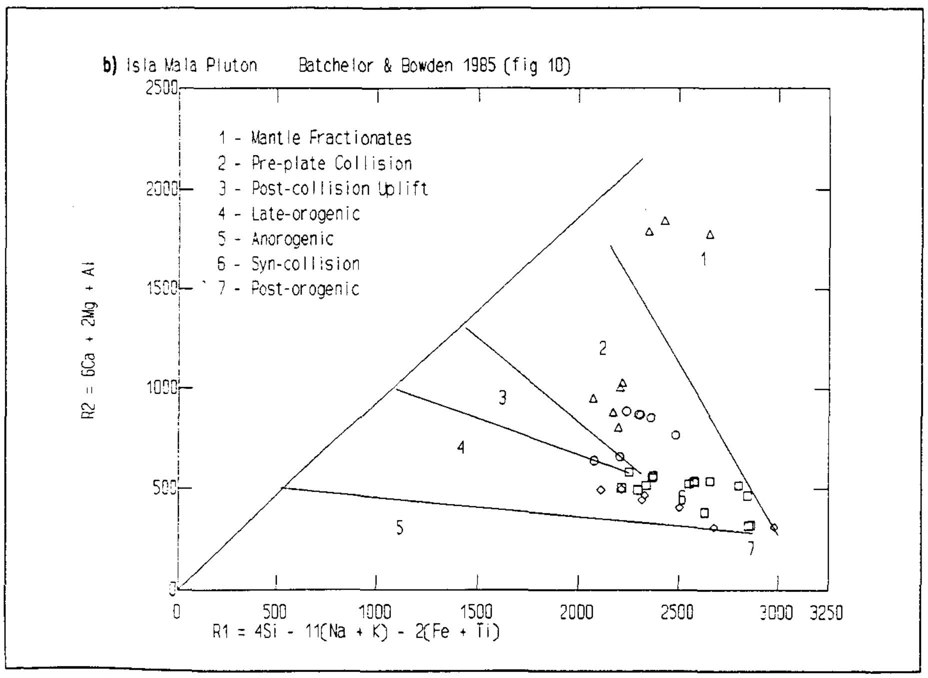


Figure I.8) Tectonic discriminant diagram for the AVP (8a) and the IMP (8b). Diagram based on the method of Batchelor and Bowden (1985). Symbols as on Figure I.7.

Thus it is reasonable to propose, as a working hypothesis, that a period of tectonic subduction occurred between 2290 Ma (pre-collision phase) and 2225 Ma (post-collision phase) which brought previously metamorphosed, possibly Archean rocks into contact with one another. If the subduction were oblique, significant horizontal (as well as vertical) displacements may have occurred, and the crust may have been fragmented into a number of lens-shaped lithotectonic blocks of different metamorphic grade (Sylvester, 1988). We consider this event to be the main phase of the Transamazonian orogeny in southern Uruguay.

The late dykes feature a chemistry which once again is typically calc-alkaline. Although these dykes are volumetrically insignificant, the dates obtained from these dykes are similar to that reported for the Mahoma Pluton, which is located 50 km to the west and which has been dated at 1979 ± 35 (Rb-Sr whole rock - recalculated from data of Umpierre and Halpern, 1971). Thus there is reason to believe that the period of roughly 1900 Ma to 2000 Ma was also a period of significant plutonic activity in the region. We are not certain how these relatively young plutonic rocks are related to the Transamazonian orogeny, and until a detailed geochemical study of the Mahoma Pluton, or another pluton of similar age, is carried out, we can only speculate that the Transamazonian was a poly-deformational event and that these plutons were formed during the terminal stages of this orogenic episode.

<u>Conclusions</u>

1) Age data reveal the presence of two or possibly three groups of intrusive rocks in southern Uruguay (2450 Ma; 2290 Ma to 2225 Ma; and 1894 Ma to 2040 Ma respectively - data from Bossi et al., 1993; Preciozzi (1990) and Table I.3 of this work).

2) The leucogranitic unit of the IMP (2290 Ma) has not been metamorphosed and has imposed an andalusite-bearing contact aureole on the schists of the Paso Severino Formation, thus demonstrating that the Paso Severino is of still older, possible Archean age.

3) The leucogranitic unit of the IMP appears to have formed in a pre-plate collision/continental margin type of environment whereas the slightly younger AVP (2225 Ma) features a chemistry suggestive of a late-orogenic environment. Hence the period from 2290 Ma to 2225 Ma may correspond to the period during which time a number of discrete lithologic blocks were tectonically assembled to form this portion of the Brazilian Shield. We believe that this event represents the main phase of the Transamazonian orogeny in southern Uruguay.

CHAPTER II

GEOCHEMISTRY AND GEOCHRONOLOGY OF THREE PLUTONS FROM CENTRAL URUGUAY: TECTONIC IMPLICATIONS FOR THE TRANSAMAZONIAN OROGENY

Introduction to Chapter 2

The Arroyo Grande Belt is the smallest of the three metamorphic belts recognized in south-central Uruguay and is located along the northern margin of the Piedra Alta Terrane. Geological mapping has suggested a striking similarity between the rocks of this belt and those found in the San José Belt to the south, both in terms of structural development and the metamorphic grade of the rocks. However these two belts are separated from one another by an east-west trending band of gneissic rocks of considerable width. Thus is was not sure to what extent the observed similarities between the two metamorphic belt might by superficial and coincidental.

As in the case of the San José Belt, the Arroyo Grande Belt has also acted as host to a number of granitoid intrusions. Thus, to further examine the similarities (or possible differences) between the San José and the Arroyo Grande metamorphic belts, it was deemed useful to carry out a geochemical and geochronological study of the Arroyo Grande Belt granitoids in order to compare them to the San José granitoids described in chapter 1. The results of this study, the comparison with the San José granitoids, and the tectonic implications of the results, are presented as chapter 2.

Introduction

From a geotectonic standpoint, Uruguay is a part of the South American Platform which became tectonically stable at the end of the Proterozoic era. This vast area consists of a number of cratonic regions which became stable at the end of the Transamazonian Cycle, separated by a number of fold belts of different ages.

The very few radiometric dates available enable the Precambrian rocks of Uruguay to be subdivided into a number of different age groupings as follows:

pre-Transamazonian rocks	<2200 Ma
Transamazonian rocks	2200 - 2000 Ma
post-Transamazonian rocks	1900 - 1700 Ma
pre-Brazilian rocks	1400 - 1000 Ma
Brazilian rocks	1000 - 500 Ma

The Transamazonian rocks can be subdivided into two main groupings: a) upper amphibolite to granulite facies metamorphic rocks including large areas of granitic rocks and gneissic granites. b) either greenschist facies (Minas de Corrales, (Preciozzi et al., 1985), Paso Severino, Cerros de San Juan and Arroyo Grande Formations) or amphibolite facies (San José and Montevideo Formations) rocks which are found as thin bands intercalated with the granitic gneiss complex.

The Arroyo Grande Formation (AGF) (Ferrando and Fernandez, 1971; Fernandez and Preciozzi, 1974; Preciozzi et al., 1979) is located along the northwestern margin of the Uruguay

Crystalline Terrane (Figure II.1), which forms the basement to the Rio de la Plata Basin. The AGF has been intruded by a number of bodies of granitic rocks, three of which are the Marincho Complex (MC), the South Granite (SG) and the Arroyo Grande Pluton (AGP). The purpose of this article is to present petrographic, geochronologic and whole rock geochemical data for these three intrusive suites and to discuss the implications of these findings for the Proterozoic evolution of this portion of the South American Platform. A detailed microprobe study of the minerals present in the MC has been presented elsewhere (Preciozzi 1989c).

Geological Setting

The AGF consists of greenschist facies metasedimentary and metavolcanic rocks which are exposed in a lozenge-shaped area approximately 40 km in length with a maximum width of 13 km. Detrital metasedimentary rocks (with minor metavolcanic units) constitute the lower and middle sections of the formation and are exposed along the northern and central portions of the outcrop area of the AGF, (Figure II.2). The metavolcanic rocks, the uppermost portion of the AGF, are exposed along the southern margin of the lozenge. Both rock types typically have an overall east-west strike except near the margins of the granites where the schistosity tends to be oriented parallel to the contact of the intrusion. The Paso de Lugo fault, a major

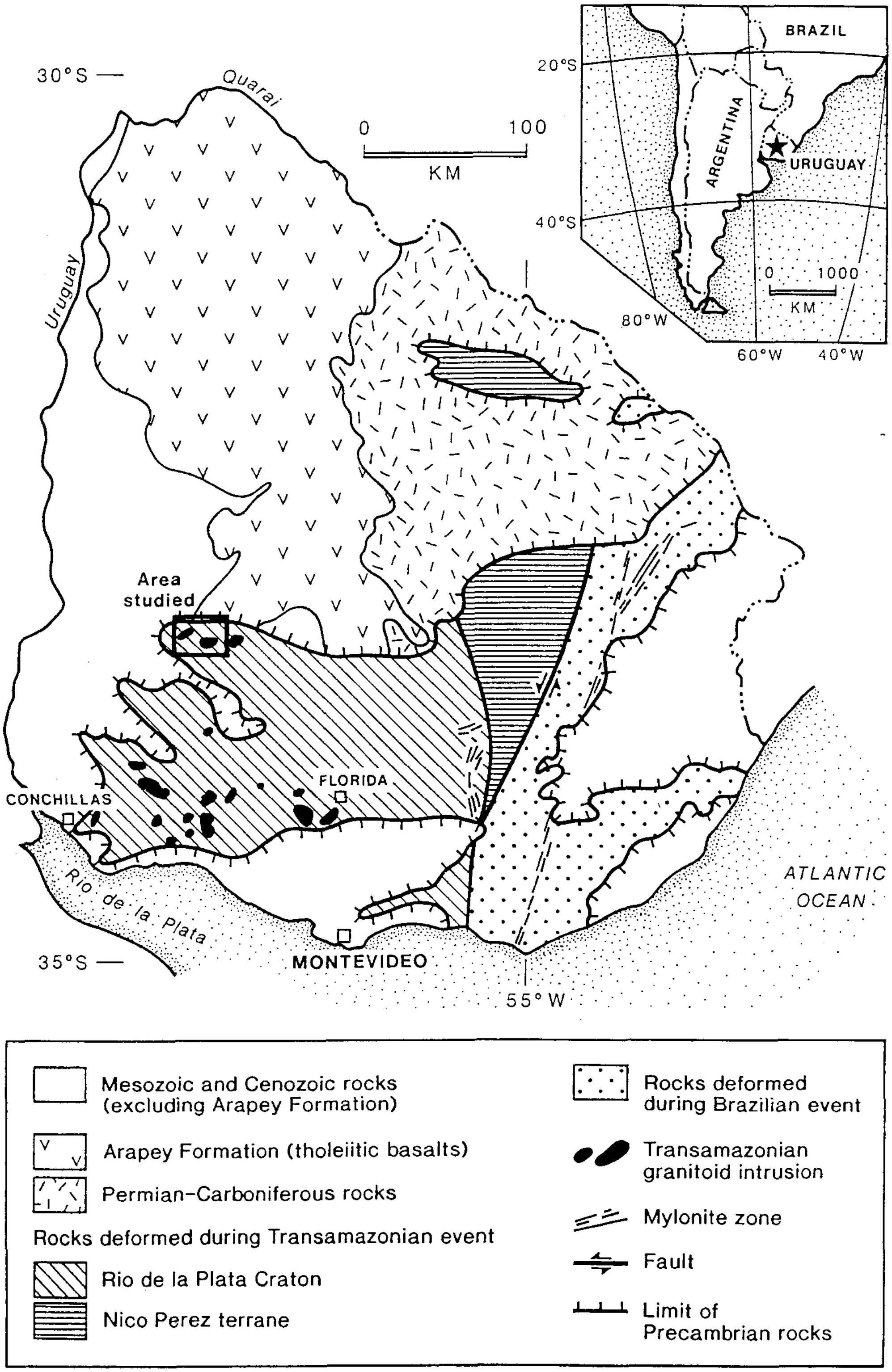


Figure II.1) Geological sketch map of Uruguay showing the location of the study area, central Uruguay.

structure of considerable linear continuity and east-west orientation, forms the southern boundary of the lozenge, separating it from granitic gneisses and related granitic rocks to the south. The Paso del Puerto fault forms the northwestern boundary of the AGF - the boundary has not been studied in detail in the northeast. It is likely that the whole of the AGF is fault-bounded since the metamorphic grade increases suddenly from greenschist facies to upper amphibolite facies once these faults are crossed. A similar feature has been noted in the Canadian Shield by Card (1990) who suggested that the fault bounded nature of the contacts and the metamorphic discontinuity might be explained by an accreted assemblage of different tectonic terranes.

Six different granitic bodies have been intruded into the AGF, the largest of which are the MC and the SG (50 km2 total for both plutons) and the AGP (20 km2). Of the remaining three plutons, the Yi and Feliciano granites feature well developed planar structures indicating that they have been deformed. The observed foliation in these two plutons appears to correspond to the D1 structures present in the surrounding AGF. We therefore consider these plutons to be syn-tectonic in character with respect to the first major episode of deformation.

It is probable that the Feliciano mass is older than the Yi since the Feliciano has been intruded by a swarm of acid dykes which have not been observed to cross-cut the Yi Pluton. The

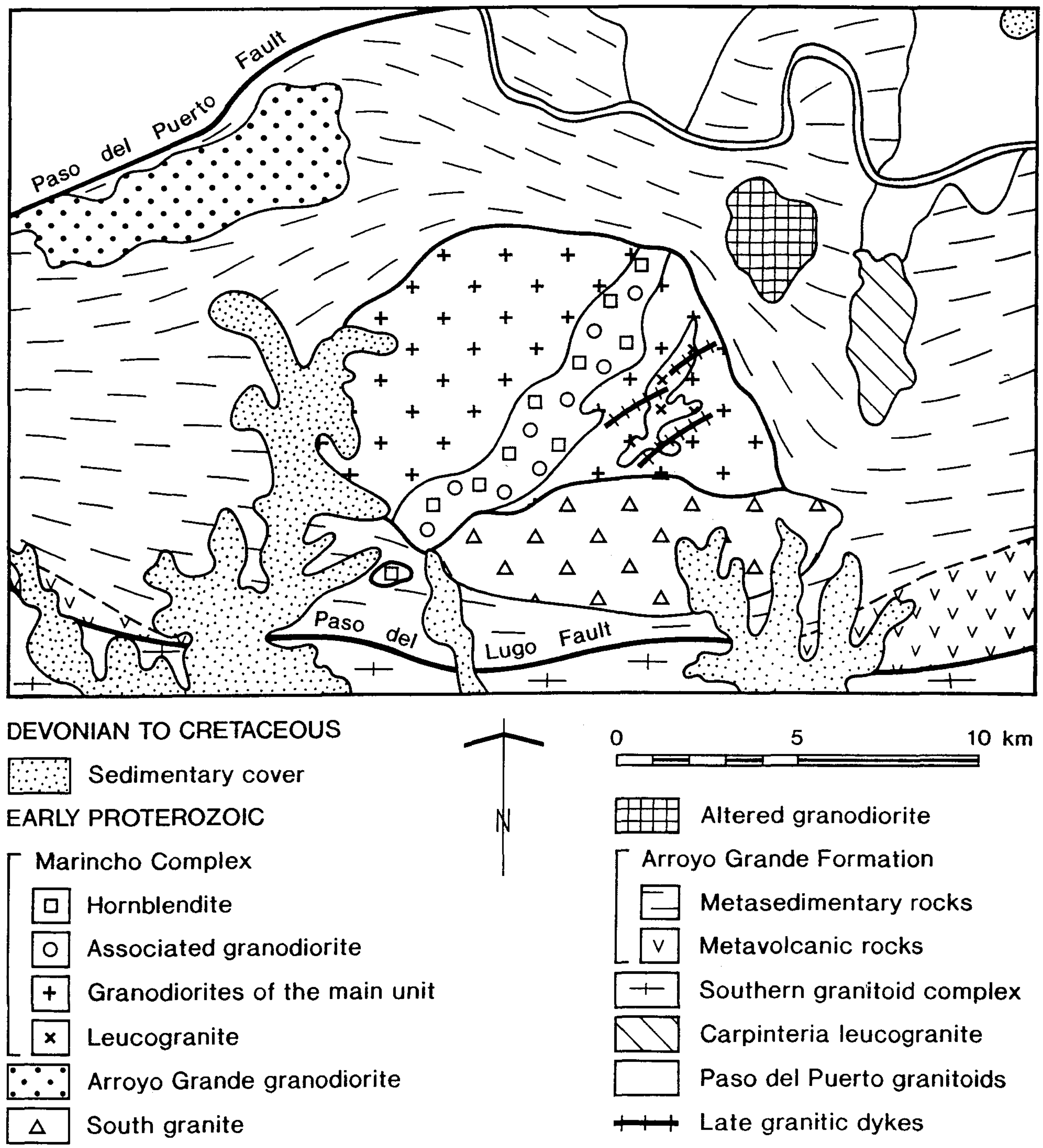


Figure II.2) Sketch map of the local geology showing the locations of the Marincho Complex, the South Granite and the Arroyo Grande Granodiorite. Location of sketch map is shown on Figure II.1. After Preciozzi (1989c).

Carpinteria Pluton is a very small mass of garnetiferous, two-mica leucogranite which is located to the east of the Marincho Complex (Figure II.2). None of these three plutons will be considered further in this report.

Petrography

Marincho Complex

The MC is a crudely circular mass, approximately 8 km in diameter which is located in the centre of the AGF. It is a composite pluton consisting of three distinctly different components:

a) the main unit, which consists typically of grey, biotite-hornblende granodiorite, but which ranges in composition from diorite to monzogranite. Both the texture and mineralogy vary rather noticeably from outcrop to outcrop. Plagioclase compositions range from An42 in the diorite to An19 in the monzogranite. Plagioclase in the more mafic members of the unit are often altered to epidote and sericite. The potassium feldspar is a perthitic microcline. Myrmekitic intergrowths are frequently observed at the contacts between plagioclase and potassium feldspar. The quartz crystals typically have undulatory extinction. The amphibole is a green hornblende typical of intermediate plutonic rocks (Deer et al., 1966). Biotite contains numerous inclusions of zircon, apatite, titanite and opaque minerals and is spatially associated with hornblende.

The main unit contains enclaves of fine-grained basic material as well as xenoliths derived from the surrounding AGF. The rock is typically massive and there is no evidence of an igneous foliation being present.

b) <u>the hornblendite and associated granodiorite</u> forms a NE trending band which crosses the centre of the complex, with rocks of the main unit being located both to the west and to the east. The hornblendite is typically a porphyritic rock containing coarse-grained, euhedral dark green hornblende and also medium-grained subhedral pale green hornblende. Clinopyroxene is present, either as independent grains or as relicts surrounded by the dark green hornblende. A concentration of opaque minerals is frequently observed at the contact between the relict clinopyroxene and the amphibole. Plagioclase compositions vary from An52 - An56. The plagioclase is typically altered to a fine-grained assemblage of pistachite (pleochroic yellow epidote) and clinozoisite.

A "granodioritic" unit, whose composition ranges from diorite to monzogranite, is intimately associated with the hornblendite. Although superficially similar to the main unit granodiorite, Fernandez and Preciozzi (1974) observed that the plagioclase compositions are systematically more sodic in the main unit granodiorites. The plagioclase compositions vary from An52 in the dioritic members of this unit to An25 in the monzogranitic members. The mineralogy and textures exhibited by this unit are comparable to those observed in main unit rocks.

The rocks of this unit clearly are intrusive into the rocks of the main unit described above. A well developed igneous foliation, defined by aligned hornblende crystals, is present near the contact with the rocks of the main unit.

c) a leucogranite unit forms a mappable mass of irregular form in the east central portion of the complex. It is completely surrounded by main unit rocks and appears to be intrusive into it. The plagioclase is zoned and varies in composition from An8 in the core of the crystals to An2 at the margin. The potassium feldspar is a perthitic microcline and the quartz features undulatory extinction. Biotite, generally associated with muscovite, is the main mafic mineral present. The accessory minerals include garnet, prismatic apatite and bypyramidal zircon. Small pegmatitic segregations were observed in the field which suggests that this particular unit of the MC was fluid saturated during crystallization.

d) a set of leucogranite dykes featuring hypidiomorphic granular textures. They are intrusive into the eastern portion of the MC (leucogranitic member as well as the main unit). They contain oligoclase, perthitic microcline and quartz as the main minerals. The principal accessory minerals are biotite, garnet (relatively abundant), zircon, sphene, apatite and opaque minerals.

The South Granite (SG)

The SG, which is located immediately adjacent to the MC, features massive, granitic to porphyritic textures except at the contact between either the AGF or the rocks of the main unit where cataclastic to mylonitic textures are observed. Biotite forms irregular crystals which have been partially replaced by chlorite. Potassium feldspar is a perthitic microcline and the plagioclase is sodic oligoclase in composition. Quartz crystals typically feature undulatory extinction and have mortar texture developed along intergrain contacts. Enclaves and xenoliths of the surrounding rock types are notably absent.

Arroyo Grande Pluton (AGP)

The AGP exhibits a much more restricted petrographic range than does the MC, varying in composition from granodiorite to monzogranite. Biotite is deep brown in colour and is spatially associated with hornblende. The plagioclase composition varies from An_{32} in the granodiorite to An_{16} in the monzogranite. The potassium feldspar is a perthitic microcline.

The pluton is somewhat elongate in form and appears to be spatially related to the Paso del Puerto Fault.

The difference in both the ages, and to a lesser extent the initial ratios, suggest that all these rocks should be considered to have evolved relatively independently of one another.

The data for the granitic blocks found within the Paso de Lugo Fault Zone (2544 ± 38 Ma; initial ratio 0.7073) demonstrate the presence of Archean crust in the area at this time. Furthermore, the initial ratio is rather high, and therefore it is reasonable to propose that crustal material was incorporated in the magma at some point. This crustal material must obviously have been older than the age of the granitic blocks. Another late Archean age determination on blocks in a similar tectonic setting has been reported by Preciozzi (1992) (2501 ± 112 Ma; initial ratio 0.7003). In this latter case, the low initial ratio suggests that the primary magma was derived by partial melting of previously depleted mantle material (previously melted between 2800 and 3000 Ma?).

Table II.1

RESULTS OF RADIOMETRIC AGE DETERMINATIONS FOR THE MARINCHO COMPLEX (MCL) AND THE SOUTH GRANITE (SG) SUITES

Suite	Rb87/Sr86	1 sigma	Sr87/Sr86	1 sigma	age
MCL-1	2.907	0.0027	0.81995	0.00012	1969 ± 25 Ma
MCL-2	2.709	0.0056	0.81436	0.00011	
MCL-3	1.457	0.0021	0.78017	0.00026	MSWD = 26
MCL-4	1.725	0.0012	0.78421	0.00019	
MCL-5	2.082	0.0027	0.79725	0.00032	IR = 0.734
MCL-6	1.809	0.0036	0.78871	0.00013	
MCL-7	1.302	0.0052	0.77391	0.00007	
LGR-1	0.512	0.0021	0.73505	0.00021	2067 ± 24 Ma
LGR-2	0.623	0.0017	0.73601	0.00031	
LGR-3	0.751	0.0024	0.74008	0.00022	MSWD = 28
LGR-4	1.756	0.0016	0.77152	0.00011	
LGR-5	3.532	0.0033	0.82561	0.00013	IR = 0.719
GRS-1	0.496	0.0032	0.72657	0.00026	2180 ± 50 Ma
GRS-2	0.802	0.0012	0.73365	0.00009	
GRS-3	1.596	0.0024	0.75801	0.00032	MSWD = 76
GRS-4	2.250	0.0015	0.77854	0.00011	
GRS-5	2.489	0.0021	0.78851	0.00015	IR = 0.709
GDP-1	0.273	0.0025	0.72017	0.00017	2291 ± 65 Ma
GDP-2	0.387	0.0013	0.72631	0.00027	
GDP-3	0.611	0.0018	0.73512	0.00011	MSWD = 73
GDP-4	0.767	0.0027	0.74007	0.00041	
GDP-5	1.965	0.0033	0.77814	0.00023	IR = 0.714
GDP-6	2.026	0.0012	0.78024	0.00017	
BGR-1	0.251	0.0015	0.71605	0.00021	2544 ± 38 Ma
BGR-2	0.374	0.0022	0.71960	0.00019	
BGR-3	0.501	0.0031	0.72517	0.00043	MSWD = 76
BGR-4	1.126	0.0011	0.75008	0.00010	
BGR-5	1.655	0.0014	0.76651	0.00017	IR = 0.7073
BGR-6	2.887	0.0017	0.81350	0.00009	

Data from Preciozzi (1992).
MCL: late leucogranite dykes cross-cutting the Marincho Complex
LGR: leucogranite unit of the Marincho Complex
GRS: South Granite
GDP: Main portion of the Marincho Complex
BGR: Granite blocks located within the Paso de Lugo Fault Zone

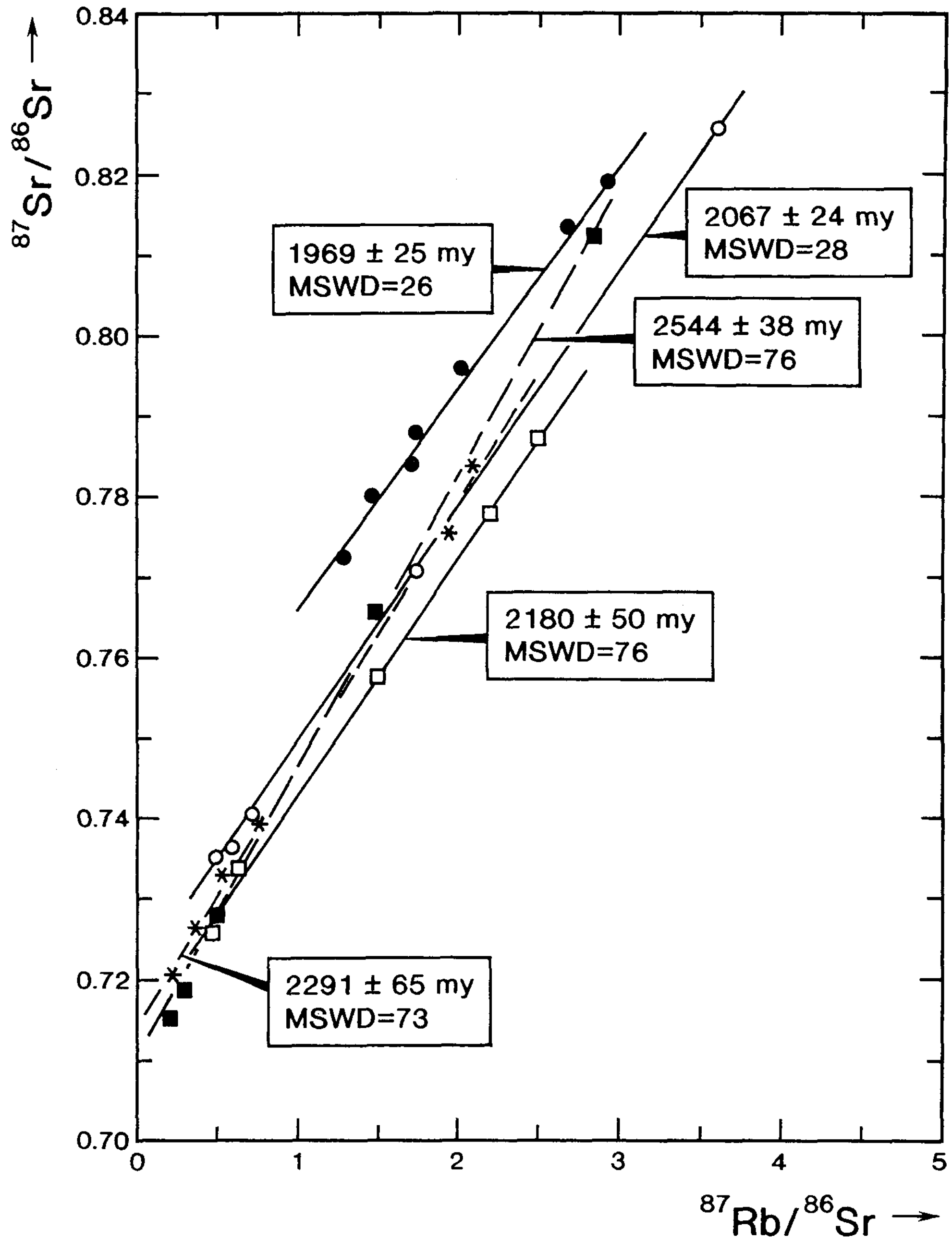


Figure II.3) Isochrons for the various members of the Marincho Complex, the South Granite, and granitic blocks.

Geochemistry

A total of 41 analyses of the MC and 10 of the AGP are presented in Table II.2.

The validity of the petrographic terms applied to the samples of both suites is apparent on the P-Q plots (Figures 4a and 4b) proposed by Debon and Lefort (1983). The MC suite defines a broad band of data points which sweeps across the diagram from the quartz diorite to the syenogranite fields with the majority of samples falling in the granodiorite or monzogranite domains. Two trends are crudely apparent on the diagram, the first defined by the hornblendite and associated granodiorites as well as the granodioritic rocks of the main unit. The Q values for these rocks increase from 50 in the quartz diorites to approximately 150 in the granodiorites and then decline to 100 in the more evolved granitic rocks. The second trend is defined by those rocks which were mapped in the field as "leucogranites" (and related rocks). The data points for these rocks define a trend parallel to the second part of the first trend however it is situated at much higher Q values, which fall from 225 in the granodioritic members of the unit to 180 in the more evolved members. This observation is mirrored in the normative mineral contents of these two groups of rocks. The leucogranites have normative quartz contents which decline from 40% to 35% in the more evolved members whereas the rocks defining the first trend rarely have normative quartz values

Table II.2
CHEMICAL ANALYSES OF THE MARINCHO COMPLEX

#	R	SiO2	TiO2	Al2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O	H2O	Total
1	A	60.00	0.60	17.80	4.22	5.21	0.18	1.50	4.60	4.10	1.70	0.67	100.58
2	A	61.90	0.60	17.50	2.98	2.90	0.07	2.30	4.70	3.85	2.40	0.58	99.78
3	A	62.00	0.50	17.10	4.02	2.01	0.10	1.40	4.30	3.80	1.55	0.38	100.16
4	L	74.60	0.01	14.10	0.51	0.36	0.09	0.20	0.80	4.16	2.20	1.32	98.35
5	L	74.90	0.01	13.50	0.49	0.73	0.18	0.15	0.90	4.25	3.16	0.52	98.79
6	L	75.00	0.01	13.70	0.80	0.01	0.09	0.14	0.40	3.75	4.70	0.62	99.22
7	L	75.00	0.05	13.40	0.59	0.63	0.12	0.05	0.95	4.05	3.36	0.6	98.80
8	L	75.00	0.05	13.20	0.95	0.15	0.08	0.30	0.50	3.70	4.60	0.68	99.21
9	L	75.30	0.05	13.00	0.92	0.08	0.08	0.35	0.45	3.85	4.50	0.65	99.23
10	L	75.60	0.01	12.80	0.90	0.01	0.08	0.20	0.60	3.75	4.60	0.62	99.17
11	H	50.10	0.85	12.70	3.83	6.37	0.16	11.00	10.00	2.45	1.10	1.14	99.70
12	H	52.20	0.60	10.40	4.82	4.49	0.16	10.70	10.90	2.00	1.00	2.17	99.44
13	H	52.80	0.60	11.80	3.67	5.07	0.16	10.60	10.40	2.35	1.10	0.69	99.24
14	H	56.70	0.50	9.00	2.79	5.50	0.23	11.30	10.70	2.20	0.70	0.86	100.48
15	H	62.00	0.50	10.00	2.87	2.82	0.14	9.40	7.80	2.30	2.10	0.83	100.76
16	G	61.90	0.85	16.50	1.61	3.16	0.12	2.45	5.15	4.80	1.30	0.53	98.37
17	G	62.90	0.80	16.30	1.41	3.06	0.09	2.35	5.05	4.70	1.20	0.51	98.37
18	G	63.00	0.80	16.20	1.21	3.26	0.08	2.55	4.85	4.80	1.10	0.56	98.41
19	G	66.00	0.70	14.80	2.57	1.74	0.04	2.30	3.60	3.70	3.60	0.61	99.66
20	G	66.50	0.60	14.50	2.40	2.61	0.05	2.30	3.40	3.60	4.10	0.58	100.64
21	G	66.50	0.70	14.30	2.47	1.84	0.04	2.40	3.70	3.90	3.40	0.71	99.96
22	G	66.50	0.80	15.60	1.38	2.12	0.10	1.40	3.00	3.70	4.90	0.7	100.20
23	G	66.80	0.70	14.60	2.47	1.70	0.07	2.00	3.44	3.75	3.40	0.25	99.18
24	G	67.10	0.75	14.50	2.37	1.54	0.02	2.15	3.45	3.60	3.55	0.73	99.76
25	G	67.30	0.80	14.70	1.58	1.92	0.10	1.50	2.90	3.90	4.70	0.68	100.08
26	G	67.50	0.55	13.50	2.60	2.41	0.10	2.40	3.30	3.75	3.95	0.78	100.84
27	G	67.50	0.78	14.60	1.48	2.02	0.08	1.45	2.82	3.85	4.00	0.72	99.30
28	G	67.86	0.70	14.60	1.68	1.82	0.05	1.55	3.20	4.15	3.55	0.48	99.64
29	G	67.96	0.70	15.30	1.58	1.62	0.05	1.55	3.30	3.85	3.20	0.47	99.58
30	G	68.70	0.75	14.30	1.38	1.82	0.05	1.30	2.80	3.70	3.90	0.72	99.42
31	G	68.96	0.65	14.30	1.58	1.72	0.05	1.45	3.10	4.05	3.25	0.47	99.58

Table II.2) Chemical analyses of the Arroyo Grande, South Granite and Marincho Complex intrusions. Code for Maricho analyses: G = main portion of the MC; L = leucogranite; H = hornblendite; A = associated granodiorite

Table II.2 (CON'T)

CHEMICAL ANALYSES OF THE SOUTH GRANITE

#	SiO2	TiO2	Al2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O	H2O	Total
1	71.80	0.60	14.80	1.38	0.85	0.05	0.72	2.10	4.05	3.60	0.72	100.67
2	72.50	0.50	14.60	1.28	0.75	0.10	0.70	2.05	3.95	3.50	0.25	100.18
3	73.00	0.20	14.70	1.48	0.60	0.05	0.65	2.10	3.40	3.75	0.42	100.35
4	73.20	0.30	14.70	1.38	0.65	0.01	0.60	2.00	3.75	3.40	0.56	100.55
5	73.50	0.45	14.30	1.33	0.24	0.01	0.50	2.00	4.30	3.20	0.71	100.54
6	73.80	0.40	14.40	1.18	0.65	0.01	0.52	1.90	3.75	3.30	0.52	100.43
7	74.50	0.25	14.40	1.18	0.45	0.05	0.50	1.75	3.60	3.20	0.57	100.45
8	75.20	0.05	14.20	0.25	0.15	0.01	0.21	0.30	3.45	6.10	0.48	100.40
9	75.40	0.01	14.00	0.40	0.01	0.01	0.11	0.40	3.65	5.90	0.36	100.25
10	76.00	0.05	13.80	0.30	0.10	0.01	0.05	0.36	3.60	5.85	0.27	100.39

Table II.2 (CON'T)

CHEMICAL ANALYSES OF THE ARROYO GRANDE PLUTON

#	SiO2	TiO2	Al2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O	H2O	Total
1	65.50	0.95	15.00	1.81	5.94	0.09	1.00	4.05	3.00	3.00	0.25	100.59
2	66.00	0.90	14.50	1.91	5.84	0.14	0.90	4.15	3.15	2.85	0.27	100.61
3	66.30	0.85	14.00	1.53	5.29	0.08	0.80	4.10	3.00	3.10	0.29	99.34
4	66.80	0.70	13.70	1.43	5.39	0.09	0.70	3.95	3.15	3.25	0.35	99.51
5	66.80	0.75	13.60	1.05	5.47	0.15	1.05	3.60	3.45	2.75	0.48	99.15
6	67.00	0.80	13.40	1.20	5.32	0.10	0.90	3.85	3.30	2.90	0.38	99.15
7	67.10	0.80	13.30	1.09	6.05	0.10	0.85	3.55	3.25	3.90	0.30	100.29
8	67.50	0.75	13.40	1.29	6.25	0.21	0.95	3.45	3.45	3.70	0.45	101.40
9	68.50	0.55	14.90	2.54	1.99	0.05	0.93	3.70	3.75	2.30	0.89	100.10
10	69.60	0.50	15.00	2.34	1.59	0.05	0.93	3.50	3.70	2.20	0.89	100.30

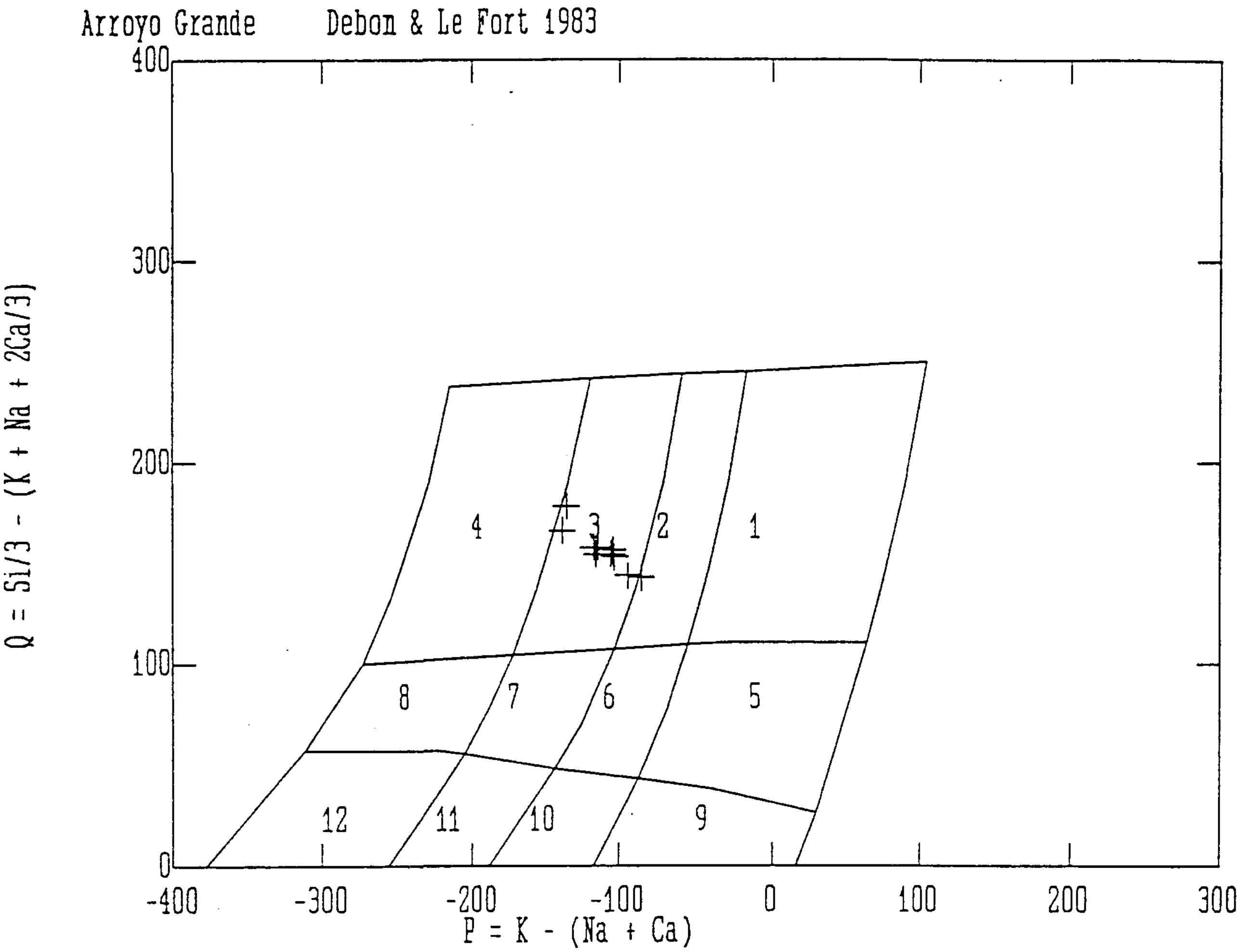


Figure II.4a) P-Q classification diagram for the Arroyo Grande Pluton. Diagram after Debon and Lefort (1983). 1 = syenogranite; 2 = monzogranite; 3 = granodiorite; 4 = tonalite; 8 = quartz diorite;

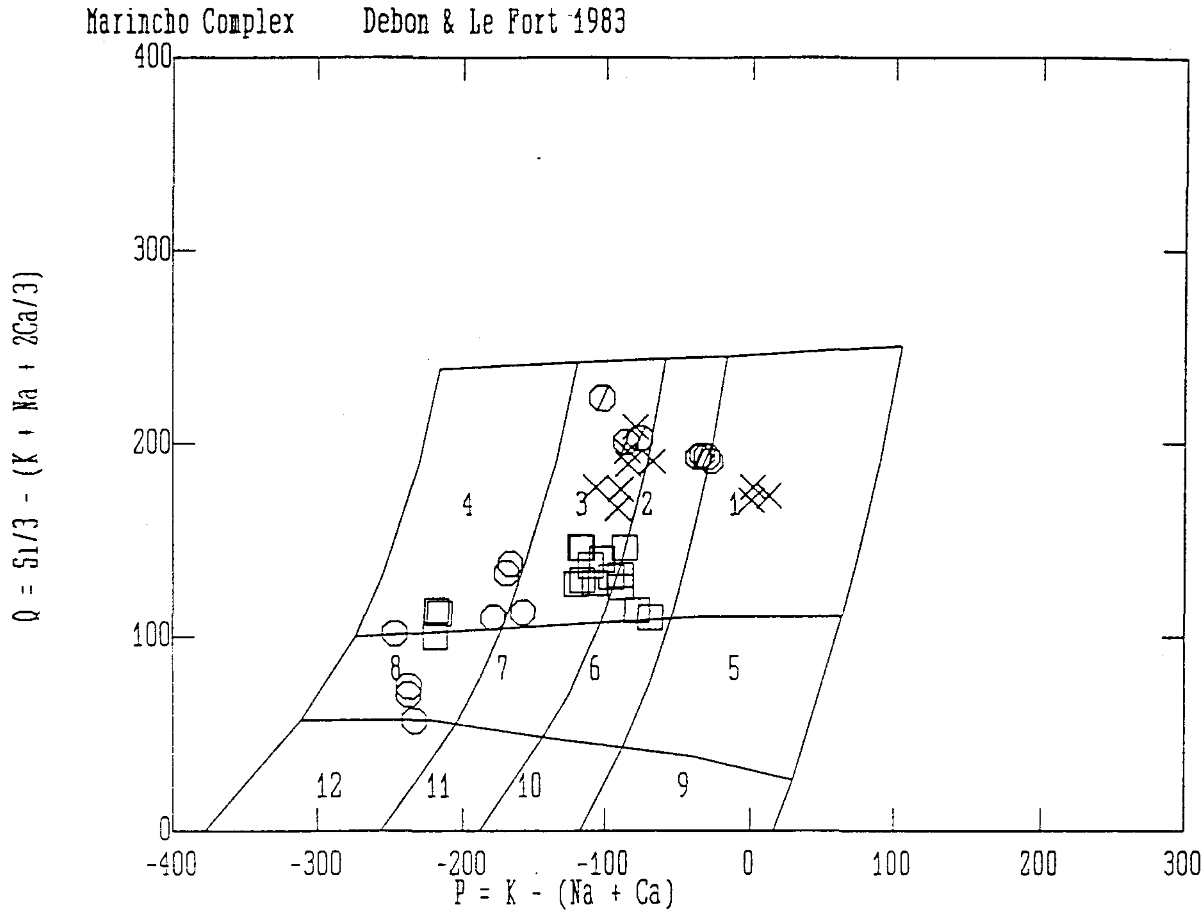


Figure II.4b) P-Q classification diagram for the Marincho Complex and the South Granite. Diagram after Debon and Lefort (1983). 1 = syenogranite; 2 = monzogranite; 3 = granodiorite; 4 = tonalite; 8 = quartz diorite;
X = SG; open circle with diagonal slash = MC leucogranite; open box = MC main unit; open circle = MC hornblendite and related rocks.

which surpass 25%. The SG rocks define a crudely triangular area on Figure II.4a and no trend is apparent. In common with the leucogranites, the SG is also characterized by relatively high Q values.

The AGP exhibits a much more restricted compositional variability and is largely confined to the granodiorite field. The trend defined by the data points is parallel to that defined by the granodiorites of the main unit of the MC.

Both the AGP and the main unit of the MC are metaluminous intrusive rocks which show very little variation in the peraluminous index, (PI = A/CNK = 0.90 in both cases). All but two of the 26 analyses for these two groups of rocks have values less than 0.95 and all have values less than 1.01. The SG is mildly peraluminous - PI ranges from 1.03 to 1.15 and increases with increasing SiO_2. The leucogranitic unit of the MC is considerably more peraluminous - PI values range from 1.04 to 1.32 and decline with increasing SiO_2. The high PI values are related to relatively low K_2O contents in some of the leucogranites.

The MC suite of rocks appears to collectively define a typical calc-alkaline trend on the igneous AFM diagram of Irvine and Baragar (1971, Figure II.5b). All but two samples are either within or very close to the line separating the calc-alkaline and tholeiitic domains. Data for the AGP define a trend which straddles the tholeiitic and calc-alkaline fields.

Discussion

a) Pressure of Emplacement

Experimental studies in the water saturated haplogranitic quartz - albite - orthoclase system can be used to estimate the pressure of emplacement of granitic plutons since the position of the experimental minimum in this system varies as a function of pressure. Only the most evolved compositions can be used in order to reduce uncertainty due to the presence of Ca in plagioclase. In addition it is required that fluid-saturated conditions were attained during crystallization (ie that PH2O = P total). The presence of pegmatitic segregations in the leucogranite unit indicates that the assumption of fluid-saturated conditions is reasonable for this unit, however no such supporting evidence was observed in the SG. We have retained only those analyses for which the normative quartz + albite + orthoclase contents surpass 95%. Results are shown on Figure II.6. The MC leucogranites all plot very close to the 1 kb minimum which can be taken as the pressure ofcrystallization of this mass, and therefore of the MC as a whole.

The analyses of the South Granite are not close to the trajectory of minimum melt compositions. This may be due to the fluid-undersaturated nature of the magma combined with the presence of another component, such as CO2, in the fluid phase. Ebadi and Johannes (1991) have shown that addition of CO2 displaces minimum melt compositions to more orthoclase-rich values. In any case the pressure of emplacement cannot be

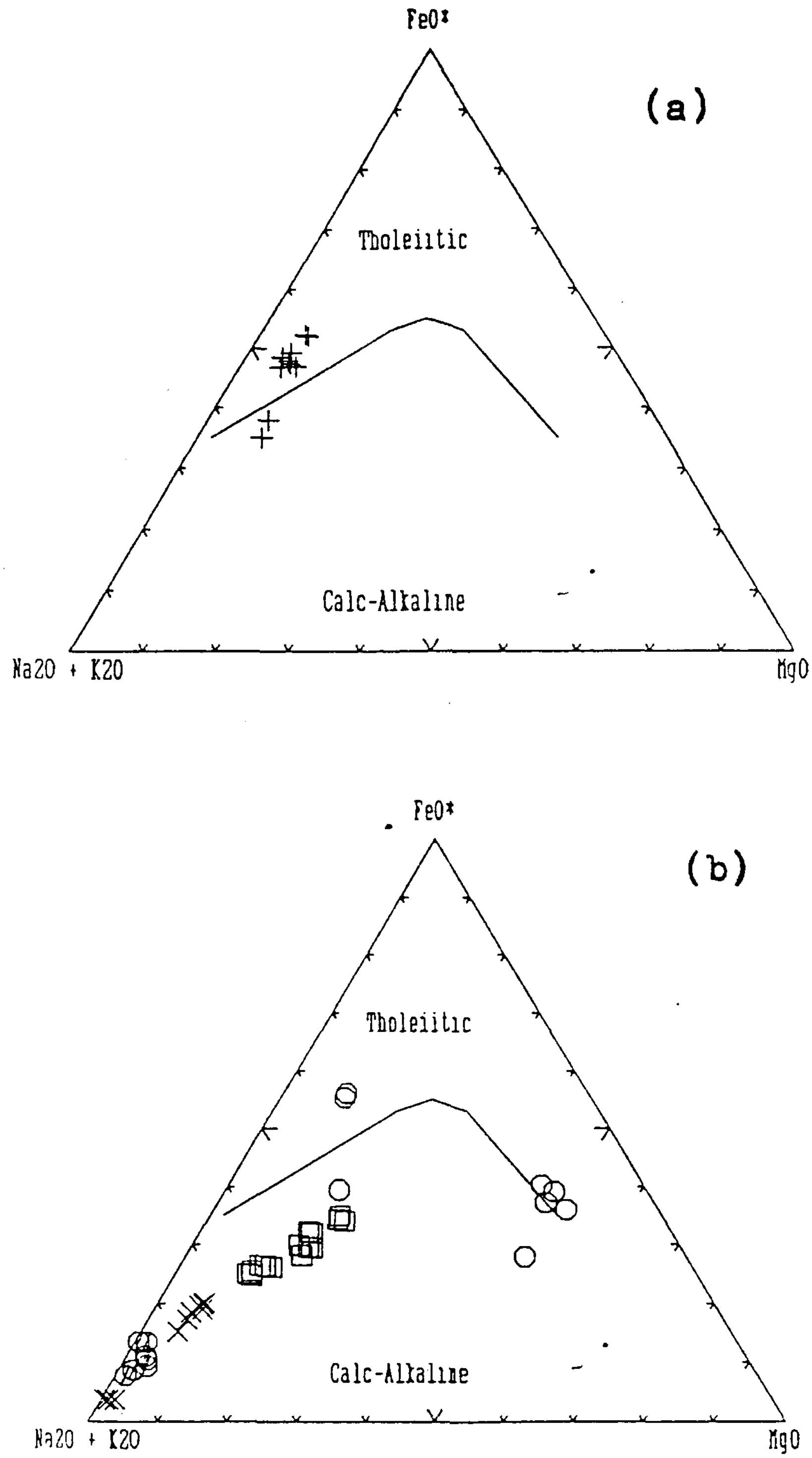


Figure II.5) AFM diagram for the AGP (5a) and the MC and SG (5b). Limit between calc-alkaline and tholeiitic fields taken from Irvine and Baragar (1971). Legend as on Figure II.4.

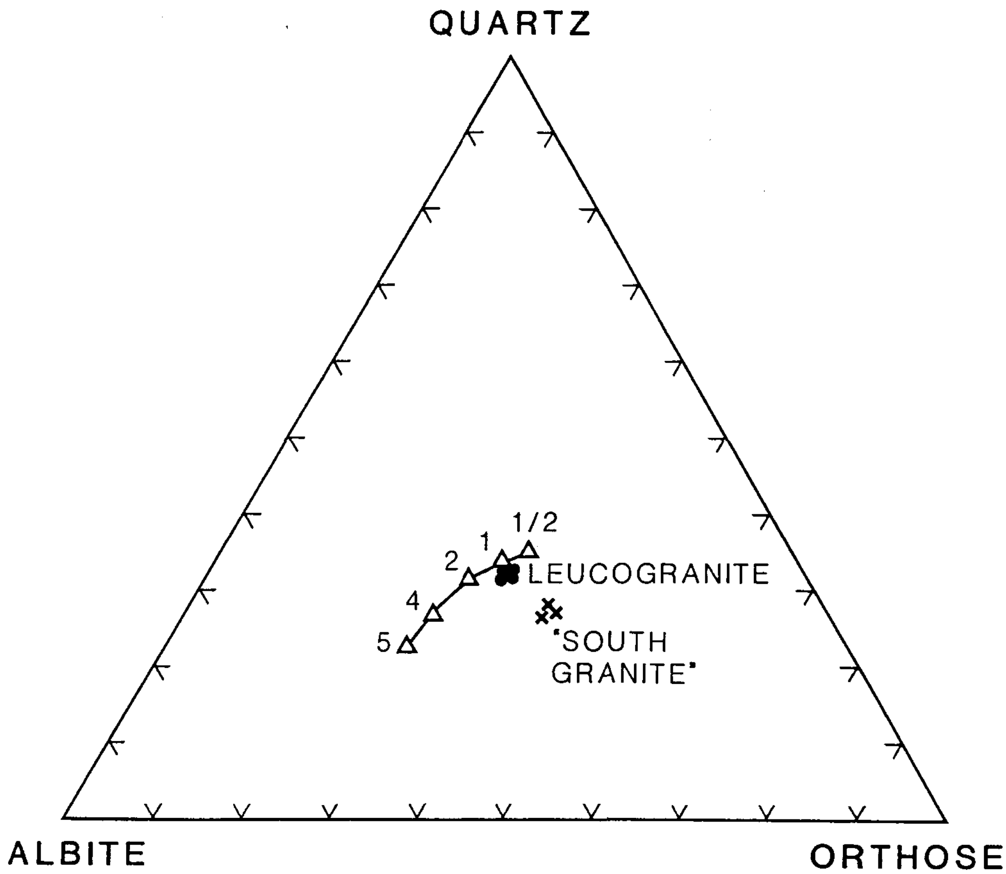


Figure II.6) Normative quartz - albite - orthoclase diagram for the most evolved plutonic analyses from the Marincho Complex and the South Granite). Location of minimum melt compositions taken from Winkler (1979).

determined in this manner, although the presence of perthitic alkali feldspar in the SG suggests that the pressure of emplacement was also relatively low (Martin and Bonin, 1976).

b) Chemical Classification of the Tectonic Setting

A number of tectonic discriminant diagrams for granitic rocks have been proposed in recent years, however only two make use of the major element data. Application of the approach of Maniar and Piccoli (1989) suggests a fundamental difference in the environment of emplacement of the AGP and the MC rocks, (Figures 7a and 7b). The AGP analyses mainly fall above the crudely horizontal line which crosses the diagram, placing them in the extensional granite field. The MC hornblendites and associated granodiorites, as well as the main unit granodiorites, all fall below this line in the collisional granite field. The low value of the peraluminous index for the MC rocks enables the CCG environment to be eliminated from further consideration, however the data do not permit discrimination between the IAG and CAG environments using the Maniar and Piccoli method.

Analyses of both the leucogranite and the SG fall either within or very close to the post-orogenic granite field. It is commonly observed that the evolved members of granitic suites of whatever origin tend towards this field. Since neither of these two plutons has an associated basic component, they cannot be uniquely associated with a specific tectonic

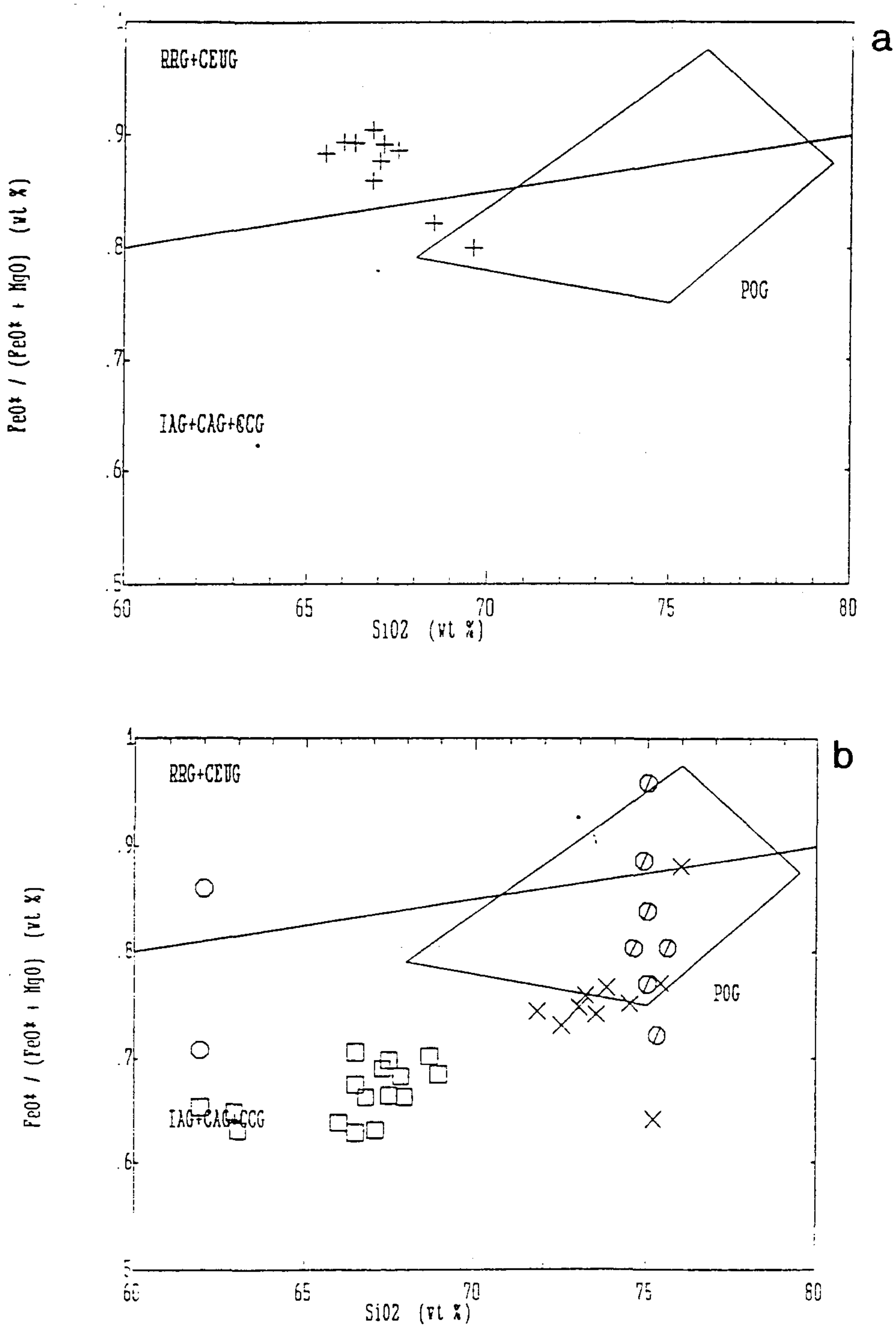
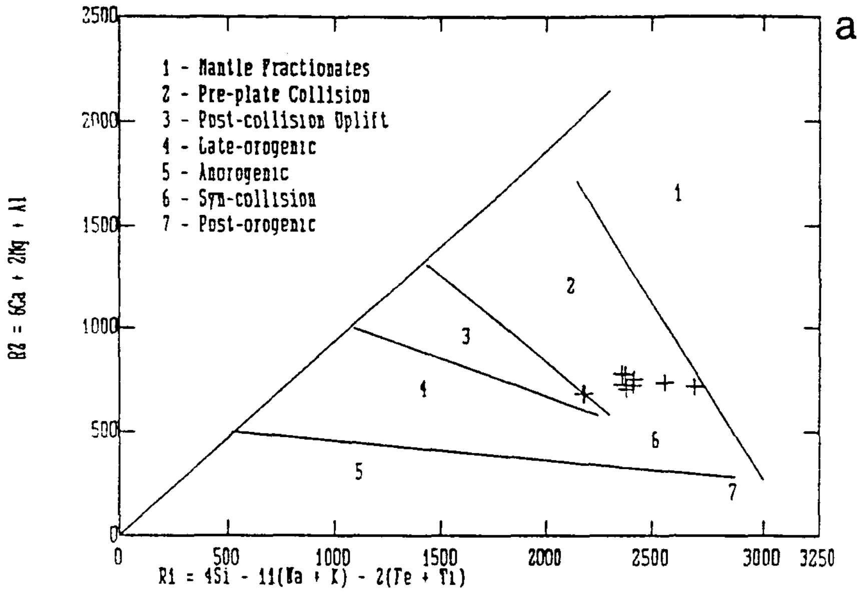


Figure II.7) FeO*/(FeO* + MgO) - SiO2 plot for the AGP (7a) and the MC and SG (7b). Legend as on Figure II.4. CEUG (continental epeirogenic uplift granite); RRG (rift related granite); IAG (island arc granite); CAG (continental arc granite); CCG (continental collision granite); POG (post orogenic granite).

environment. The almost vertical trend defined by the leucogranite analyses is attributed here to the crystallization of magmatic garnet which rapidly depletes the iron content of the residual liquid.

Batchelor and Bowden (1985) used the R1-R2 diagram originally proposed by LaRoche et al., (1980) as a tectonic discriminant diagram (Figures 8a and 8b). Analyses of the AGP plot near the limit between the pre-plate collision field and the syn-collision field. The problem is thus similar to that discussed with reference to Figure II.7; the evolved members of any of the chemical trends which originate in field 2 through 5 all plot in field 6. Thus samples which only plot in or very near to field 6 could belong to any chemical trend, and therefore to any one of the associated tectonic environments. We note that a pre-plate tectonic environment is not favoured by the field evidence - the massive nature of the plutons suggests a late-tectonic to post-tectonic timing of emplacement although there are numerous exceptions to this statement.

The MC analyses (excluding the hornblendites) plot in a crudely circular area on the diagram which straddles the pre-plate collision and post-collision uplift domains and is therefore not definitive. The SG and the leucogranites plot in the syn-collision to post-orogenic fields which is in agreement with their positions on Figure II.7.



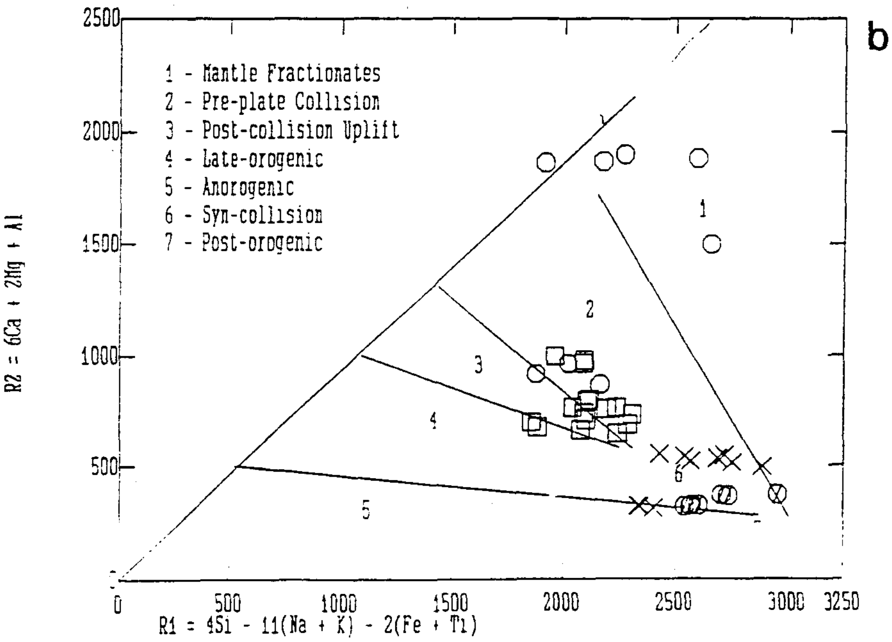


Figure II.8) Tectonic discriminant diagram for the AGP (8a) and the MC and SG (8b). After Batchelor and Bowden (1985). Legend as on Figure II.4.

c) timing of intrusion

The proposed ages for the SG, the AGP, and the different units of the MC clearly indicate that none of these intrusions are in any way related. The cataclastic nature of the contact between the SG and all surrounding rocks indicates a faulted contact for this particular mass. However the contact between the hornblendite, the rocks of the main unit and the leucogranite are all demonstrably intrusive with no evidence of faulting being present between them.

Two possible models can be proposed to explain the relationship between the hornblendite and the main unit of the MC. The first is that the hornblendite and the associated granodiorites are in no way related to the main unit. The field evidence, which clearly indicates that the hornblendite is younger than the main unit supports this hypothesis. However there are many examples in the geological literature of multiphase intrusions in which a partially evolved, relatively high-level magma chamber is invaded by a second surge of more primitive, but co-magmatic material from depth, followed by mixing between the two components. This possibility cannot be discounted here, and additional isotopic data will be required to resolve this dilemma.

The high initial ratio of the leucogranite (0.737) clearly indicates that this unit crystallized from a melt which was derived by partial melting of middle to upper crustal level material. It is possible that the heat necessary to provoke partial crustal melting originated from a source other than the main portion of the MC itself, and that the age of the leucogranite is significantly younger than the main portion of the MC.

d) Analogies with the Abitibi Belt of Canada

The nature of the plutonic rocks from this area, as well as their tectonic setting and contained structural elements, greatly resemble the Archean plutonic rocks from the Abitibi area of Quebec, Canada. These similarities can be summarized as follows:

1) the plutonic rocks of both areas were emplaced into greenschist facies metamorphic rocks which contain both metasedimentary and metavolcanic units which have undergone more than one period of deformation.

2) the greenschist facies rocks and their associated plutons are exposed within fault-bounded, lozenge-shaped areas. Higher grade rocks are encountered once the bounding faults are crossed.

3) the predominant intrusive rock types range in composition from granodiorite to monzogranite and feature a calc-alkaline chemistry. 4) hornblendites are found associated with the granodiorites, as are muscovite-garnet leucogranites.

5) the primary mafic mineralogy has been substantially modified, being replaced by secondary epidote, chlorite and sericite. The quartz grains found in the plutons from both areas are typically strained.

6) contact metamorphic aureoles surrounding the plutonic rocks are typically rather difficult to identify.

Detailed study of the Abitibi intrusions has also revealed the following information which may be pertinent to the area under consideration.

1) a number of <u>well-foliated</u> intrusive bodies, also of granodiorite to tonalite composition (analogous to the Feliciano and Yi intrusions?) are believed, on chemical grounds, to be contemporaneous with the surrounding metavolcanic rocks.

2) high-precision U-Pb geochronology suggests that the massive granitoids, such as those described here, are only a few million years younger than the foliated plutons. The associated leucogranites are of the same age as the massive granodiorites.

3) A number of shoshonitic, alkaline plutons, which are massive, have well defined contact aureoles, and which consist of syenite and co-existing pyroxenite, are situated <u>within</u> the bounding fault zones. These rocks, which are believed to be related to a number of calc-alkaline lamprophyres and possibly ultramafic lamprophyres found throughout the area, are definitately related to gold mineralization. The span of time between the emplacement of the foliated granitoids and the shoshonitic rocks is approximately 30 Ma.

4) Card (1990) has proposed that the sudden change of metamorphic grade observed when crossing the limiting boundary faults may be related to the assembly of a number of discrete terranes, each of which has its own distinct geologic history,

during the Archean orogenic event. This has been discussed in more detail in chapter 1.

e) Comparison with the southern portion of the Uruguay Crystalline Belt

The plutonic rocks described in this article are very similar to those in southern Uruguay described in chapter 1. In both areas, granitoid rocks have been emplaced into a series of greenschist facies schists. Additionally, three periods of pluton emplacement appear to have occurred in both areas. The age of the South Granite (2180 ± 50 Ma) is similar to the reported ages of 2225 ± 25 Ma for the leucogranite member of the Arroyo de la Virgen Pluton and 2290 ± 35 Ma age for a granitic member of the Isla Mala Pluton, (Preciozzi and Bourne, 1993). All three of these rocks have moderate initial ratios which range from 0.707 to 0.711). Furthermore, all three plutons have been slightly deformed (granulated grain boundaries - see criteria presented by Paterson et al., 1989) and are largely non-foliated, which suggests that they were emplaced after the peak of the greenschist facies metamorphic event had been attained. By contrast, the Feliciano and Yi granites feature a well developed foliation; a date on either of these rocks will enable a maximum age for the greenschist facies metamorphism to be established. Foliated plutons such as the Feliciano and the Yi intrusions have also been identified in the San José Belt of southern Uruguay.

The age of the leucogranitic member of the Marincho Complex (2067 ± 24 Ma - Preciozzi, 1992) is considerably younger than any of the abovementioned plutons, however it is similar in age to the 2040 ± 40 Ma Isla Mala granite dyke discussed by Preciozzi and Bourne (1993). The ages of the late granitic dykes are also comparable with those from southern Uruguay (1925 ± 23 Ma and 1894 ± 75 Ma - Preciozzi and Bourne, 1993). Since the petrographic data indicate that these plutons have also been slightly deformed to some degree, this suggests that a mild metamorphic event (less intense than greenschist facies) affected the whole area after the emplacement of these younger intrusive bodies, and probably resulted in the development of the extensive secondary sericite and epidote seen in all these rock units.

f) Contributions to a tectonic model

Bossi (1983) proposed a sequence of events for the pre-Devonian rocks of Uruguay as follows:

1) development of a cratonic area of rocks older than 2050 Ma located to the north of the AGF.

2) deposition of the AGF (and other similar units such as the Paso Severino Formation further south) in ENE trending zones

3) metamorphism of variable intensity and granite intrusion between 2050 Ma and 1800 Ma. He suggested that syn-tectonic granites developed in the high-grade zones whereas post-tectonic intrusions were contemporantously emplaced into the

low-grade zones. This period of deformation and intrusion is known as the "Ciclo Orogénico Antiguo" (COA).

The data presented here and elsewhere (Preciozzi and Bourne, 1993) suggest that the sequence of events proposed by Bossi must be somewhat modified. In particular, the geochemistry and available geochronology of the granitoid rocks suggest that the COA may be subdivided into three phases.

The **first phase** (of inferred Archean age) is believed to be related to the greenschist facies metamorphism. The marked planar structures and other structural elements observed in the Feliciano and Yi granites suggest that they should be considered as syn-tectonic with the main deformational phase of the AGB. The Marincho granodiorite is related to the end of this first episode, that is, the geological setting is late-tectonic. The available geochronological/isotopic data for this intrusion (2386 ± 120 Ma; initial ratio 0.7113 and 2291 ± 65 Ma; initial ratio 0.7136 - Preciozzi 1992) suggest the existence of an older basement. This hypothesis is supported by the presence of alkali granite blocks which are found **within** the Paso de Lugo fault zone and which have been dated at 2501 ± 112 Ma (initial ratio 0.7003) and 2544 ± 38 Ma (initial ratio 0.7073) (data from Preciozzi, 1992). Field observations have shown that the MC granodiorite is present on both sides of the Paso de Lugo Fault, thereby suggesting that this brittle deformation event is younger that the 2291 Ma age of the granodiorite.

The <u>second phase</u>, as determined by field observations, is the emplacement of the hornblendite intrusion. The characteristic of the AGP suggest a late-tectonic setting for the emplacement of this phase. The South Granite, dated at 2180 ± 50 Ma (Preciozzi, 1992) can be related to the Paso de Lugo Fault. This granite is contemporaneous with the well-foliated granitoids which are found to the south of the San José Belt, whose ages range from 2176 ± 146 Ma (initial ratio 0.719) and 2290 ± 130 Ma (initial ratio 0.712) -both ages from Bossi et al., (in press). These ages (Preciozzi, 1992) are considered as indicative of Transamazonian activity.

The <u>third phase</u> consists of the post-tectonic leucogranite units (2067 ± 24; initial ratio 0.719) and a number of granitic dykes (1969 ± 25 Ma; initial ratio 0.737). They represent the very latest stages of Transamazonian activity.

<u>Conclusions</u>

1) The age of emplacement for five granitoid intrusions were determined as follows:

- granitic blocks in the Paso de Lugo fault: 2544 ± 38 Ma
- Marincho Complex granodiorite: 2291 ± 65 Ma
- South granite: 2180 ± 50 Ma
- Marincho Complex leucogranite: 2067 ± 24 Ma
- leucogranite dykes cutting Marincho Complex: 1969 ± 25 Ma

2) The tectonic environment of emplacement of these rocks were determined as follows:

- syn-collisional environment for the Marincho Complex
- extensional environment for the Arroyo Grande Pluton

3) These data, combined with the data presented in chapter 1 of this report, suggest that there are three distinct periods of emplacement of granitoid rocks in the Precambrian of southern and central Uruguay as follows:

- Archean rocks. The massive alkaline granite blocks, dated at 2544 Ma, prove that the greenschist facies metamorphism and associated deformation is older than this age.

- 2290 - 2180 Ma: Intrusion of small to medium-sized plutonic rocks, some of which are composite in nature. The older intrusions are calc-alkaline whereas the younger are alkaline.

- 2040 - 1894 Ma: Intrusion of a number of small dykes which cross-cut the plutons formed at stage 2.

CHAPTER III

AN OVERVIEW OF THE GEOLOGY OF THE PIEDRA ALTA TERRANE SOUTH-CENTRE AND SOUTHWESTERN URUGUAY WITH A PROPOSED MODEL FOR ITS TECTONIC EVOLUTION

Foreward to Chapter 3

Having presented geochemical and radiometric age data as well as a preliminary tectonic interpretation for some of the Piedra Alta Terrane granitoids in chapters 1 and 2, it is now useful to see to what extent these interpretations coincide with the currently popular models for this area. It will be seen below that these models, which are largely based on previous studies of the other types of rocks which are found in the Piedra Alta Terrane, must be modified in order to accomodate the tectonic and geochronological data provided by a study of the granitoids.

In order to do this, it is first necessary to provide an overview of the geology of the Piedra Alta Terrane. This overview is presented in the first 2/3 of this chapter. The geological information presented for the five granites in chapters 1 and 2 are sufficiently detailed for our requirements and are not repeated here. The remaining 1/3 of the chapter presents a model for the tectonic evolution of the Piedra Alta Terrane.

Many references are made to place names throughout this chapter. For readers unfamiliar with the geography and political divisions of Uruguay, a sketch map showing the locations of the various Departments (Provinces), as well as many of the place names mentioned in the text, is presented in Figure III.1.

Figure III.1): Location map of the departments as well as many of the place names mentioned in the text.

Introduction

The Piedra Alta Terrane (see Figure i-1) consists of a litho-tectonic assemblage with a predominantly EW trend. The region can be subdivided into three subparallel, narrow, metamorphic belts, of varying metamorphic grade, which are separated from one another by granite-gneissic areas (Figure III.2). Magmatic rocks of different composition, age and tectonic environment of emplacement have intruded the whole terrane.

The three metamorphic belts will be described separately, followed by descriptions of the granite-gneiss complex and the intrusive rocks. In all cases, each unit will be described presenting all the data currently available.

I: THE VOLCANO-SEDIMENTARY BELTS

ARROYO GRANDE BELT

A metamorphic belt known as the Arroyo Grande Belt (AGB) is located at the northern border of the Piedra Alta Terrane, near the Yi River (Department of Durazno). Several different plutons, two of which have been described in some detail in Chapter 2, are intrusive into the metamorphic suite, (see Figure III.3). The main area of the metamorphic rocks, which trend E-W, extends from Paso de Lugo in the west to several kilometers east of Arroyo Malo del Yí in the east.

Variations of the main strike are frequently observed, particularly near the plutonic bodies. Dips are subvertical and towards the south. Primary structures preserved in the metasedimentary rocks (cross-bedding), reveal that the bottom of the series is in the north and abuts against the Paso del Puerto granite (see Figure III.3). A fault of significant lateral extent (Paso de Lugo fault) forms the southern boundary of this sequence and tectonically separates the metamorphic belt from a large area of undifferentiated granitic rocks to the south.

Generally speaking, detrital rocks predominate near the base of the sequence, however amphibolites and amphibolites with quartzites are locally intercalated with them. Basic metavolcanic rocks predominate along the southern margin of the belt. Locally they have been metamorphosed to either chlorite schists or amphibolites. The detrital sequences have been intruded by several granitoids bodies eastwards. The contacts of the Feliciano and Yí granites are mylonitic in nature.

Petrography of the detrital sequence

The most volumetrically important rocks of this sequence are impure (feldspathic) or pure quartzites. They are associated with metaconglomerates that have a phyllitic or sandy matrix, which has been recrystallized to different degrees, surrounding pebbles which range in diameter from 1 to 20 cm. The quartzites are slightly bedded and have grains which can be observed with the naked-eye (0.5 to 1 mm.). Some of the quartzites are of low metamorphic grade, having preserved

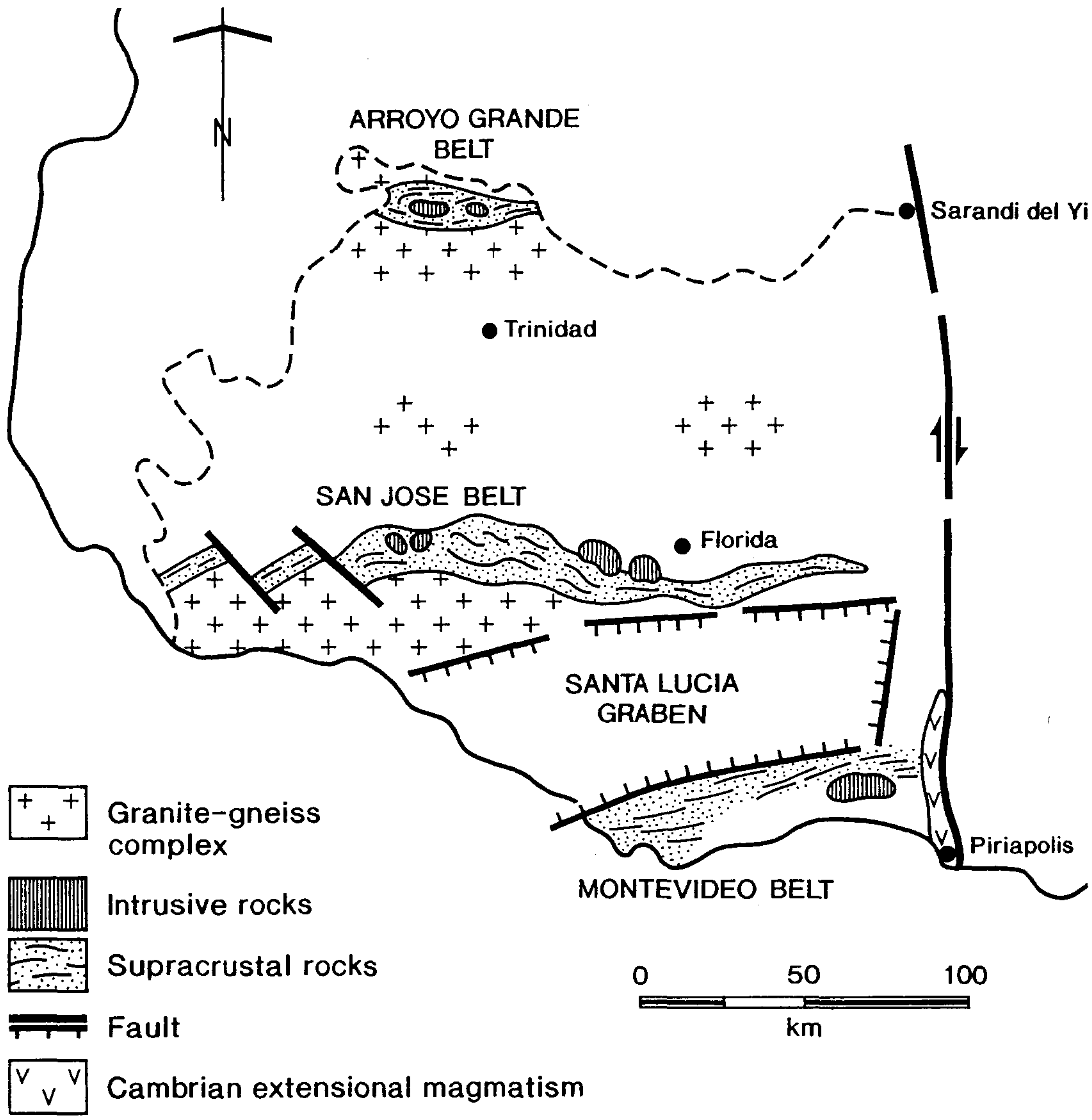


Figure III.2: Sketch map showing the location of the three metamorphic belts of southern Uruguay. After Bossi et al., (1993)

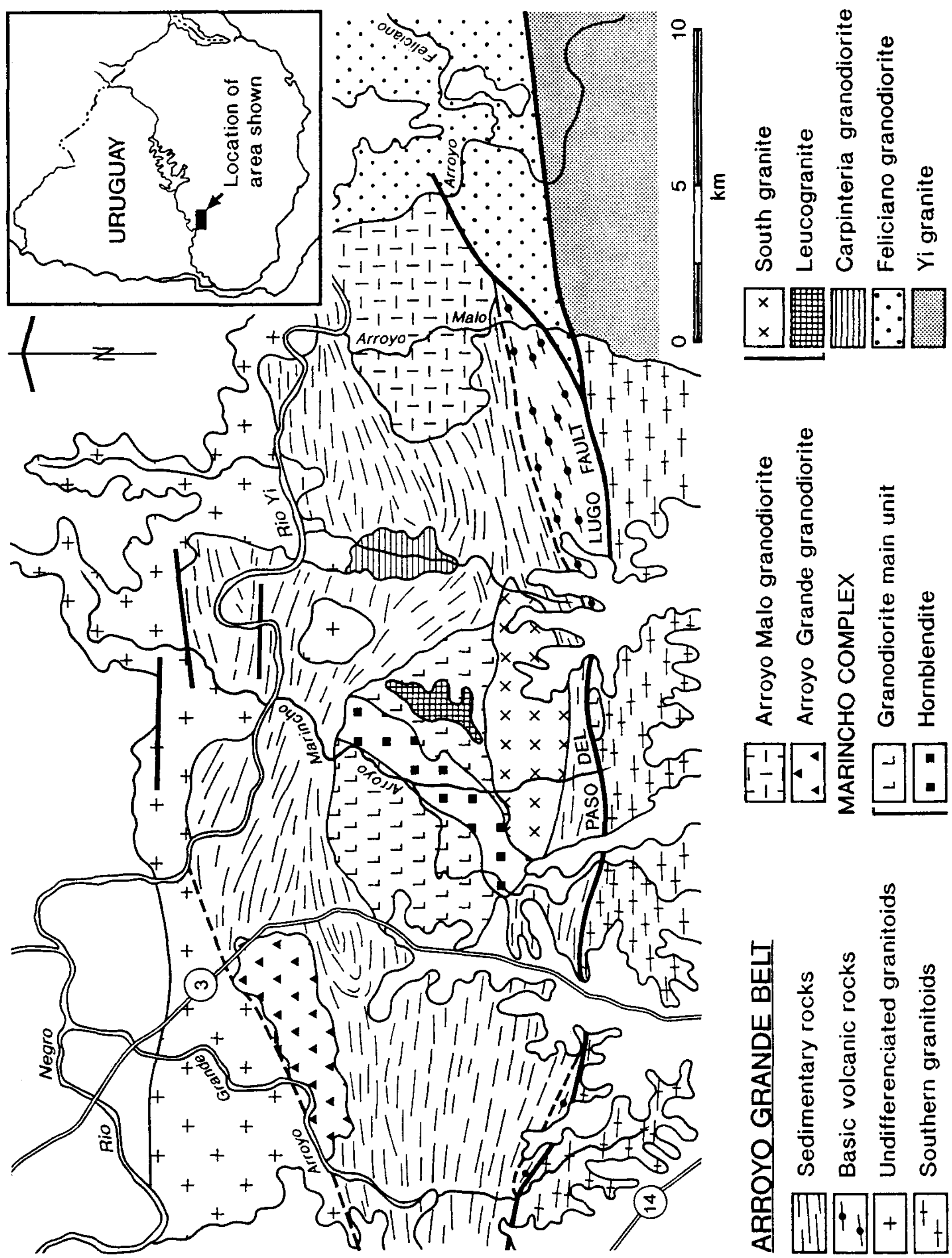


Figure III.3: Geological map of the Arroyo Grande Belt quartzites are locally present. Basic metavolcanic rocks, sometimes transformed into amphibolites and chlorite schists, predominate in the southern portion of the outcrop area of the belt, near the summit of the volcano-sedimentary pile.
The detrital sequences have intruded by several granitoid plutons in the eastern portion of the belt.

After Fernandez and Preciozzi (1974)

primary structures. Recrystallization is better developed at the base of the sequence as well as immediately adjacent to the intrusive rocks. Microscopic observations of the less recrystallized quartzites reveal that the quartz grains, having their original shapes, are set in a microcrystalline sericitic matrix. Such rocks also contain chlorite, muscovite, garnet, biotite and opaques. Also present are only slightly recrystallized anhedral quartz lenses. The most recrystallized quartzites have a very fine granoblastic groundmass of anhedral quartz and biotite, with larger poikiloblastic albite, chlorite and garnet crystals. Pyroxenes have been found within the quartzites near the contacts and within granodiorite enclaves however as a whole the observed parageneses are consistent with low grade metamorphism.

Petrography of the volcanic sequence

The most important rock type of this sequence is a basic metavolcanic rock featuring a palimpsestic texture. Phenocrysts (1-8 mm. of euhedral labradorite) are set in a fine-grained actinolitic nematoblastic matrix. Less common plagioclase-amphibolites, intercalated within the detrital sequence described above, feature recrystallized amygdules which have been transformed into quartz lenses of 1 to 8 mm. length.

Along the southern border of the basic sequence, where the dynamic effects of Paso de Lugo fault were very intense, the volcanic sequence develops a variety of textures ranging from lepidoblastic to cataclastic. The main minerals in this area are chlorite, epidote (pistacite), albite, quartz, opaques minerals and calcite (perhaps secondary).

Metamorphic Mineral Assemblages

No systematic study of the mineral assemblages present within the Arroyo Grande Belt has yet been carried out. The data currently available indicate that the The AGB consists low to medium grade metamorphic rocks as mentioned above. Mineral assemblages which have been noted in the AGB rocks are indicated in Table III.1.

Chlorite and biotite are present in both detrital and volcanic rocks. It is probable that the local presence or absence of these minerals is compositionally controlled. The presence of garnet co-existing with chlorite in some of the detrital rocks suggests that the metamorphic conditions approached those of the greenschist facies - amphibolite facies boundary, (Winkler, 1970). The difficulties of working on greenschist facies rocks are well known (see comments in Will et al., 1990) and it is unlikely that a significant improvement in our knowledge of the metamorphic petrology of these rocks can be made easily.

Tectonic evolution

Conclusions concerning the tectonic and stratigraphic evolution of this region are based on an analysis of the behaviour of the metamorphic rocks. Analysis of schistosity, folding lineation, and maximum deformation axes in the metaconglomerate pebbles (stretching direction) reveal the presence of at least three phases of deformation. Relations detected between linear elements, such as the opposite plunge sense observed in the eastern and western portions of the AGB (Figure III.4), as well as the central position of the Marincho complex, can be related to the first two deformational episodes.

The first one (of inferred Archean age), of regional extent, generated isoclinal folds. Its presence has been recorded by the deformation in pebbles of some conglomerate layers. The Arroyo Grande mafic sequence probably formed subsequently by injection along the southern structural discontinuities during the late stage of the evolution of the metamorphic belt. This kind of evolution is also suggested by the presence of basic metavolcanic rocks which are located along the contact between the Yí and Feliciano granites. The marked planar structures and other structural elements observed in these two granites suggest that they should be considered as syntectonic, contemporaneous with the main phases of deformation in the AGB.

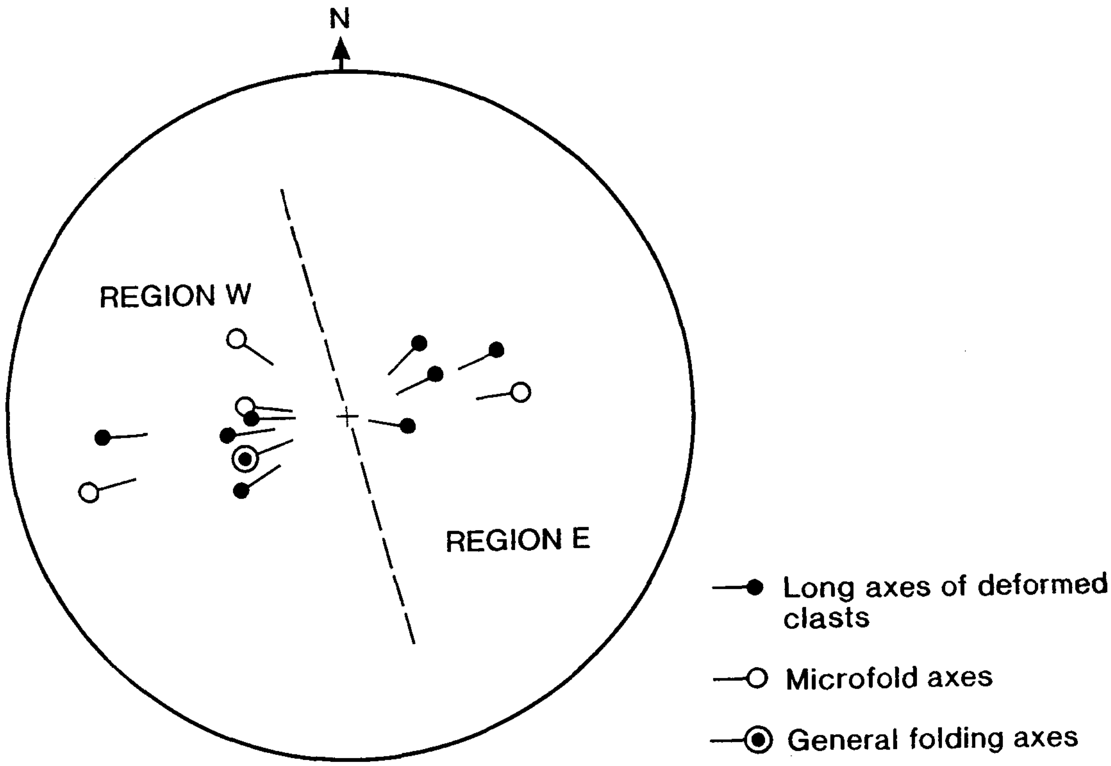


Figure III.4: Stereonet (upper hemisphere projection) showing the contrast between the eastward and westward plunge of stretching lineations and microfold axes in the eastern and western portions of the Arroyo Grande Belt.

After Fernandez and Preciozzi (1974)

Table III.1
MINERAL ASSEMBLAGES OBSERVED IN THE ARROYO GRANDE BELT

Sequence	Num	QZ	PL	CH	MU	BI	GA	EP	ZO	CA	OM	AM	SP
Detrital	1	x	x	x		±	±				x		
(in north)	2	x	x	x	x	x	x	x			x		
	3	x	x	x				x		±	x		
Volcanic	4	x	x						x		x	x	
(in south)	5	x	x			x					x	x	
	6	x	x						±		±	x	x

Assemblages 1 and 2 were recorded in the detrital rocks in the northern portion of the AGB. Assemblages 3 - 6 were observed in the volcanic rock situated in the southern portion of the belt. QZ = quartz; PL = plagioclase; CH = chlorite; MU = muscovite (undifferentiated white mica); BI = biotite; GA = garnet; EP = epidote (pistachite); ZO = zoisite; CA = calcite (undifferentiated carbonate); OM = opaque minerals (undifferentiated); AM = amphibole; SP = sphene (titanite)

The Marincho complex intrusive granodiorite is related to the terminal stages of this first episode of plastic deformation. Tectonic evidence, such as the elongated form of the intrusion which is concordant with the regional structure, suggests a late-tectonic character for this intrusion. Two different whole rock (Rb/Sr method) age determinations for this granodiorite (Preciozzi, 1992) have yielded values of 2386 ± 120 Ma (Ro = 0.7113) and 2291 ± 65 Ma (Ri = 0.714). This intrusion produced an important variation in the spatial orientation of rocks in both eastern and western zones.

The metavolcanic and metasedimentary rocks were intruded by this granodiorite and therefore they are obviously older. The existence of an even older basement is supported by the presence of allocthonous blocks of alkaline coarse-grained biotite granite observed in the Paso de Lugo fault. This fault formed during a period of brittle deformation which followed deformational episodes described above. The granitic blocks have yielded Archean ages: 2501 ± 112 Ma (Ro= 0.7003) and 2544 ± 38 Ma (Ro= 0.7073) - Preciozzi (1992). Presumably they represent exotic fragments which have been tectonically incorporated into the fault zone. The fact that there is an elongated outcrop of the Marincho granodiorite on the southern side of the Paso de Lugo Fault suggests an age younger than 2291 Ma for this brittle tectonic event.

The second deformational event formed in response to an E-W compressional stress. This event modified the orientation of the D1 linear structural elements, generating N-S to NE-SW axial planes. The Marincho granodiorite is situated in this axial plane. An extensional event near the end of this phase is believed to be responsible for the intrusion of the hornblendite band which cuts across the Marincho complex.

The emplacement of the Arroyo Grande granodiorite appears to have been controlled by NE-trending (ie D2) structural elements, and we therefore believe that this intrusion is late-tectonic with respect to this deformational episode.

The South Granite, (2180 ± 50 Ma - Preciozzi, 1992) is quartz-rich muscovite- bearing granite with mylonitic textures. Its mineralogical and textural features and its shape suggest an emplacement simultaneous with the major activity of Paso de Lugo Fault. This granite can be correlated with the foliated granites developed at the south of San José belt with reported ages between 2176 ± 146 (Ro= 0.7090) and 2290 ± 130 Ma (Ro= 0.7120), Bossi et al., (in press).

The <u>third deformation phase</u> is associated with post-tectonic leucogranites (2067 ± 24 Ma; Ro= 0.719) and granitic dykes of 1969 ± 69 Ma (Ro= 0.7345). Such ages, both from Preciozzi (1992), are normally considered as indicative of Transamazonian activity.

The sequence of tectonic events which are currently believed to have affected the AGB are presented in Table III.2.

San José Belt

This name was proposed by Preciozzi et al. (1991) to designate a belt which forms a roughly east-west trending band across southern Uruguay (Figure III.1), and which extends from Cerros de San Juan (Department of Colonia) to Fray Marcos (Department of Florida). The belt consists of rocks of both volcanic and sedimentary origins. The metamorphic grade increases from low to medium grade in a southerly direction.

Figure III.5b shows the regional lithological distribution after Bossi and Navarro (1991) in order to point out the structural style of this metamorphic belt. An enlargement (Figure III.5a) is presented for the most complex sector (Department of San José).

The term "San José Belt" was proposed to group together several metamorphic units including the Paso Severino Formation (Bossi et al., 1965), the San José and the Cerros San Juan Formations (Preciozzi et al., 1985). This name is retained here, because it eliminates several obscure points in previous lithostratigraphic separations.

The Francis and Mones (1965) and Andreis and Mazzoni (1967) definitions of the San José Formation, which they used for naming the upper part of the Kiyú klippe which is a continental sedimentary infra-Pampean unit, was not accepted by later authors. Hence, this proposal is not an obstacle for using this geographic term to name a Precambrian metamorphic belt.

Table III.2

TECTONIC EVENTS RECORDED IN THE ARROYO GRANDE BELT

Age (Ma)	Units	Events	Domain
1969	leucogranite dykes		
2067	leucogranite	3rd. deformational phase	Transamazonian
2180	South Granite	contemporaneous with Paso de Lugo Fault	
2275	Arroyo Grande grano-diorite	extensional environment	pre-Transamazonian
	hornblendites	2nd. deformation phase	
2291-2386	Marincho main granodiorite		
2501-2544	Alkaline-granite blocks		
	Arroyo Grande belt metamor-phic rocks	metamorphism and 1st. deformation phase	Archean

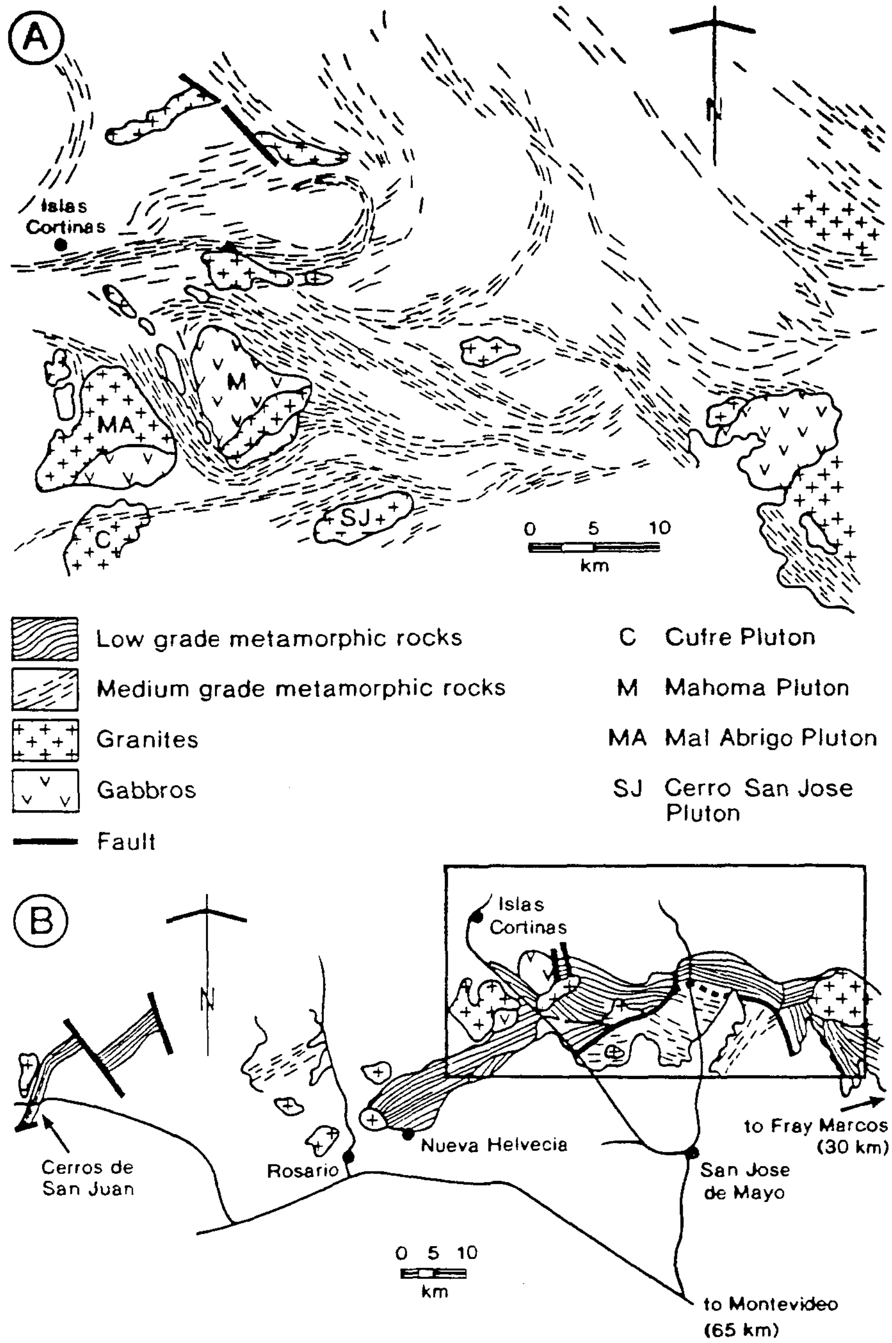


Figure III.5: (5b) Geological sketch map of the San José Belt. The rectangular area shown on Figure III.5b has been enlarged and presented as Figure III.5a, on which regional structural trend lines have also been shown.

Outline of the Petrography of the San José Belt

A considerable lithologic variation has been observed within this tectonostratigraphic unit both along the strike of the belt as well as across the belt. Between Paso Severino and Fray Marcos, the rocks are typically low grade varities and include carbonaceous shales, sericitic phyllites, and graphitic quartzites.

In Department of San José (currently the type locality) the same lithologies have been recognized as those described by Bossi et al. (1965) and Bossi and Navarro (1991) from Paso Severino (Department of Florida). However these authors also noted the presence of extensive areas of basic metavolcanic rocks, (greenschist facies chlorite schists) interbedded with the metasediments at Paso Severino.

Westwards, in Department of Colonia, thick accumulations of metakeratophyre have developed, and this fact allowed Preciozzi et al. (1985) to subdivide the Cerros San Juan Formation into two major units. This separation was considered inconvenient in later interpretations and will not be employed in this work. The volcano-sedimentary sequence in the western section of San José belt includes dolomites, talcschists, chloritic phyllites and the aforementioned metakeratophyres. Manganiferous horizons associated with this volcanism were described by Serra (1945).

Tectonic History of the San José Belt

Campal (1990) recognized at least two plastic deformation phases in this belt: the first one, syn-metamorphic, generated tight folding with subvertical ENE axial planes; the second one is associated with open folding with N45W axial planes. Interference structures and the emplacement of granite-gabbro are associated with this second phase. A brittle deformation episode between these two periods of plastic deformation has been recognized by Campal (1990) and surveyed in some detail by Garat (1991) in the Guaycurú area. Mylonitic rocks generated during this phase were folded during the second period of plastic deformation. This information is presented in summary form in Table III.3. The similarity between the sequence of events proposed for the San José Belt and that for the previously described Arroyo Grande Belt is striking.

Some authors interpreted these associations as a greenstone belt of possible Archean age (Fragoso et al., 1987; Feselfeldt, 1988) but the absence of komatiites and other ultrabasic rocks, and the predominance of non-pelagic sedimentary sequences, suggests that this hypothesis should be disregarded.

Different authors have interpreted the talcschist of Pietracaprina (Department of San José) and Paso del Pelado (Department of Colonia) as having formed by metamorphism of pre-existing ultrabasic rocks. However the talcschists are always associated with dolomites, and tremolite is present in every paragenesis where talc appears (Bossi, 1978). This belt

Table III.3

TECTONIC EVENTS RECORDED IN THE SAN JOSE BELT

Age Ma	Units	Events	Domain
1800	doleritic dykes	extensional environment	POST TRANSAMAZONIAN
----------------------CRATONIZATION----------------------			
1894 - 1925	Aplites and granitic dykes of A. Virgen		
			TRANSAMAZONIAN
2000	granite-gneiss complex		OROGENESIS
2040	granitic dyke of Isla Mala		
2070-2100		Metamorphism, migmatization, granitization and folding	
2100---			
2225	A. Virgen Leucogranite	late-orogenic	
		Development of very important mylonite zones	
2290	Isla Mala leucogranite		PRE TRANSAMAZONIAN
2450	Isla Mala granodiorite		
2500+	Development of the San José belt with first major phase of deformation older than 2500 Ma		ARCHEAN

contains meta-dolomitic lenses in several places but to date no meta-limestones have been recognized.

Metamorphic Assemblages

The metamorphic grade of the rocks in the northern portion of the San José belt is low to very low. Primary metavolcanic amygdules can be recognized in spite of the deformation. Amygdules in basic metalavas are indicative of gas elimination and consequently, shallow water depth during development of the volcano-sedimentary sequence. Some higher-grade greenschist facies rocks exhibit complete metamorphic recrystallization and are characterized by the presence of actinolitic amphiboles and intensively saussuritized plagioclases.

In Department of San José, rocks grade gradually southward into medium grade metamorphic rocks (San José Formation, Preciozzi et al., 1985). According to these authors, the metamorphic belt in this area consists of interbedded gneisses, amphibolites, leptinites, quartzites and micaschists. Quartzites and leptinites are very scarce while amphibolites are common. Gneisses are leucocratic and well foliated, containing quartz, microcline, plagioclase, biotite and muscovite. Two-mica schists contain quartz - kyanite - staurolite and garnet. This assemblage is univariant in the model system SiO_2 - Al_2O_3 - FeO - MgO - K_2O - H_2O and requires pressures considerably in excess of that of the aluminosilicate triple point in order to form. Sillimanite has also been recently recognized in these rocks. In the same micaschists and in carbonaceous shales, andalusite (chiastolite variety) is frequently found, usually in close relation with granitic intrusive bodies. These observations require that a significant amount of erosion occurred between the time of the development of the regional metamorphic mineral assemblages and those developed in the contact aureoles of the granites. The presence of the talc + tremolite assemblage in the enigmatic talcschists mentioned above is also indicative of relatively high pressures of metamorphism. Several authors including Skippen (1971, 1974) and Slaughter et al., (1975) have proposed on the basis of experimental evidence that this assemblage should not develop at low pressure and should be comparatively rare at medium pressure. According to these authors, only at relatively high pressure (approximately 5 kb) does talc + tremolite become a common assemblage.

Montevideo Belt

This roughly east-west trending metamorphic belt is situated along the extreme southern margin of the Piedra Alta Terrane in the Departments of Montevideo and Canelones (Figure III.2). Walther (1948) has provided some detailed petrographic information on the rocks of the Montevideo crystalline basement, however very little additional lithologic information has been accumulated during the intervening 45 years. Consequently the present knowledge about this lithologic unit, named the Montevideo Formation by Bossi et al., (1965) is quite scarce.

The three main lithologies so far identified are: oligoclase gneisses, amphibolites, and micaschists. The structural conformity and homogeneity of metamorphic facies were the main criteria used to define the formation. Cardellino and Ferrando (1969) included every crystalline rock outcropping in this department within the Montevideo Formation except the much younger "La Paz" granite. The authors described different kinds of migmatites and anatectic granites but at the same time they proposed to disregard the concept of migmatization when defining this unit.

The following comments pertain to those models so far presented concerning the rocks of this formation.

- although the "La Paz" granite is correctly excluded, the inclusion of "all the Department of Montevideo crystalline rocks" into Montevideo Formation is not geologically reasonable. This proposal is in fact a geographical grouping and does not have a lithostratigraphic meaning.
- without a particular geological context or frame of reference, the term "anatectic granite" is not a useful descriptor because all magmatic rocks, are, in fact, of anatectic origin.
- if migmatization processes may be disregarded, the inclusion of migmatites by Cardellino and Ferrando (1969) among the lithologies is not understandable.
- the recognition of the "Pajas Blancas" banded amphibolites as paragneissic rocks with preserved primary layering should be considered as an important contribution.

Later authors like Bossi et al., (1975); Preciozzi et al., (1985); Bossi and Navarro (1991) didn't change the previous geological interpretations, accepting them without discussion. Consequently these authors didn't present a reasonable explanation for the observed coexistence of medium-grade muscovite-bearing metamorphic rocks and high grade granitized areas. The study of the Mosquitos quartzites and adjacent migmatites made by Oyanthçabal in Preciozzi et al. (1985) may be considered the only exception to this statement. Yet even here the study is far from satisfactory since these two different lithologies were incorrectly mapped as being structurally concordant. The original criteria of structural concordance as a main feature for grouping lithologies into the Montevideo Formation is in fact, not essential, and is very hard to verify with outcrop which is not only scarce but also of poor quality. Furthermore, this concordance can only be applied to the paragneisses and doesn't necessary exist between the paragneisses and the rocks which have an igneous protolith.

As a result of an imprecise lithostratigraphic definition, the boundaries of the Montevideo Formation have not yet been precisely determined. The northward and westward extents of the formation are unknown, and the Santa Lucía graben conceals its structural relationship to the metamorphic rocks which are exposed along the northern margin of this rift-valley.

The name Montevideo Belt is proposed here for designing only the metamorphic rocks whose main lithologies were described by Bossi et al. (1965) as representing the Montevideo Formation (see Figure III.6).

The lithologies included in Mosquitos Formation (Campal et al., 1988) are proposed here as the northern limit of the Montevideo belt, since the rocks of this formation are situated along a very important tectonic boundary. According to these authors, the Mosquitos Formation can be defined as consisting of strongly deformed peraluminous granitic rocks which were emplaced in an east-west trending structural lineation which is situated between Toledo and Solís Grande rivers. This lineation abruptly separates a medium grade metamorphic belt to the south, from a granitic-gneissic domain to the north. Anatectic conditions were frequently attained in this northern domain.

In the southern belt two-mica oligoclase gneisses, ortho- and para-amphibolites, micaschists and graphite paragneisses have been recognized. Ortho-amphibolites (described in considerable detail by Walther, 1948) crop out in both prominent hills within the Montevideo city limits. Its nephritic textures gives a high weathering resistance that explains the resulting geomorphology.

Reasonable exposures of the para-amphibolites and micaschists can only be observed in coastal outcrops or in

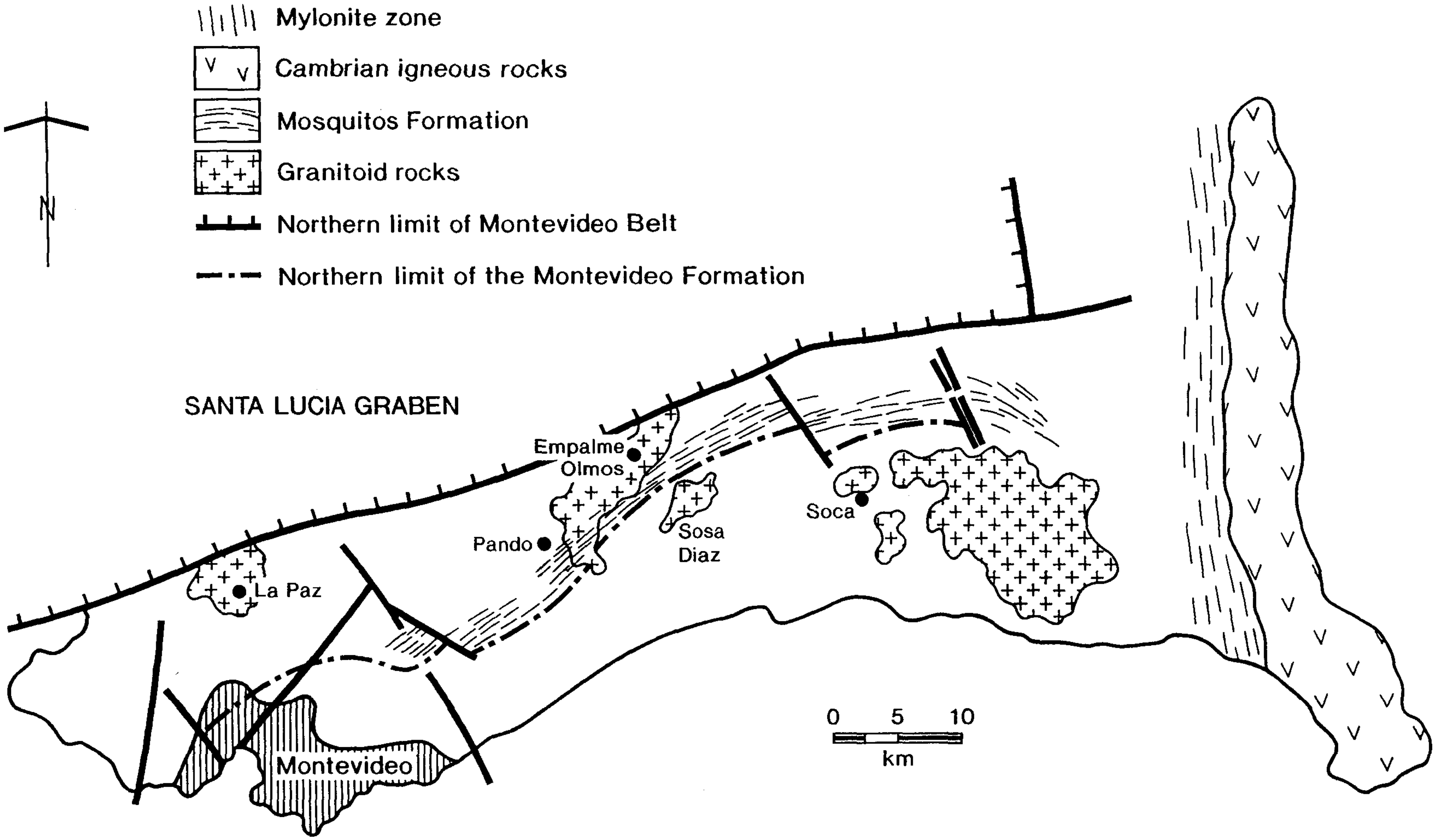


Figure III.6: Geological sketch map of the Montevideo Belt quarrys. They are structurally concordant and the best exposures are at Pajas Blancas for the amphibolites and Frigorífico Nacional for the micaschists.

Metamorphic observations

Professor N. Campal (pers. comm., 1991) has made the following observations:

1) metamorphic assemblages developed in the micaschist include muscovite, biotite, almandine garnet, staurolite, andalusite, plagioclase, quartz. The andalusite and staurolite form centimetre-scale crystals.

2) The texture displayed by the andalusite in outcrop and the lack of neighbouring granitic stocks suggest that this mineral formed as a consequence of regional metamorphism.

Graphitic paragneisses which are exposed near Soca are clearly discordant with respect to the peraluminous granites belonging to Mosquitos Formation. These kinds of gneisses are local facies in lithologies with quartz, oligoclase, and biotite as essential minerals.

In this metamorphic belt a typical medium- to high- grade assemblage of andalusite-muscovite-staurolite-garnet-biotite-quartz has been recognized, and in addition migmatites are locally present. The metamorphic assemblage suggests that the pressure of metamorphism must have been relatively low, and therefore suggests that the contact between these rocks and the anatectic granite is probably tectonic, an hypothesis which has been confirmed by field study.

Tectonic History

From the structural point of view, the medium-grade metamorphic rocks develop N 70E - N 70W axial planes in tight folds with subvertical axes (first plastic deformation phase). Variation in the strike of the axial plane strike can be related to at least one north-south regional compressional phase which generated a dextral shear strain with the general strike orientation of N20W - N40W. This last episode of shearing affected all rocks belonging to the Montevideo Belt.

II: GRANITIC-GNEISS COMPLEX

The granitic-gneissic complex and related migmatites occupy the entire area between the Arroyo Grande and San José belts (see Figure III.2). The complex consists mainly of anatectic foliated and porphyritic granitoids. These kind of granitoids are oval in shape and they have been emplaced into different kinds of gneisses. Ages close to 2000 Ma have been determined by the Rb-Sr method on granitoids and migmatites belonging to this complex.

Two plastic phases and one brittle phase of deformation have been recognized in this granitic complex (Campal, 1990). The first one is a plastic deformation phase which generates tight folds with subvertical axes, and N 70E trending axial planes. A second thrusting phase is associated with peraluminous muscovite granites and related mylonite development.

East-west structural lineations, particularly well developed near the village of Ismael Cortinas (Figure III.5), (Campal, 1990; Garat, 1990), can be related to this phase. Open folds and NW structures were generated during a third deformation phase. Anatectic phenomena and intense bimodal magmatic activity developed contemporaneously. The main structural lineations (Campal, 1990) are illustrated in Figure III.7. These kinds of structures were surveyed at 1/100.000 scale by Campal and Chulepin (1991) and Garat (1991).

Figure III.8 is a geological map for a small area near the village of La Cruz (Department of Florida). Several relict S1 schistosity planes, trending N 70E, are shown, Also visible is a slightly convex mylonitic S2, and a second plastic NW trending deformation phase (S3). Also indicated on the map are areas of massive (isotropic) granodioritic rocks.

The first plastic deformation phase is presumed to be contemporaneous with the primary metamorphism of the volcano-sedimentary pile - that is, the rocks which constitute the different metamorphic belts previously described. The second deformation phase is associated with a dynamic tectono-thermal event generating mylonitic S-surfaces. The third phase, again of plastic deformation, generates tectonic transposition

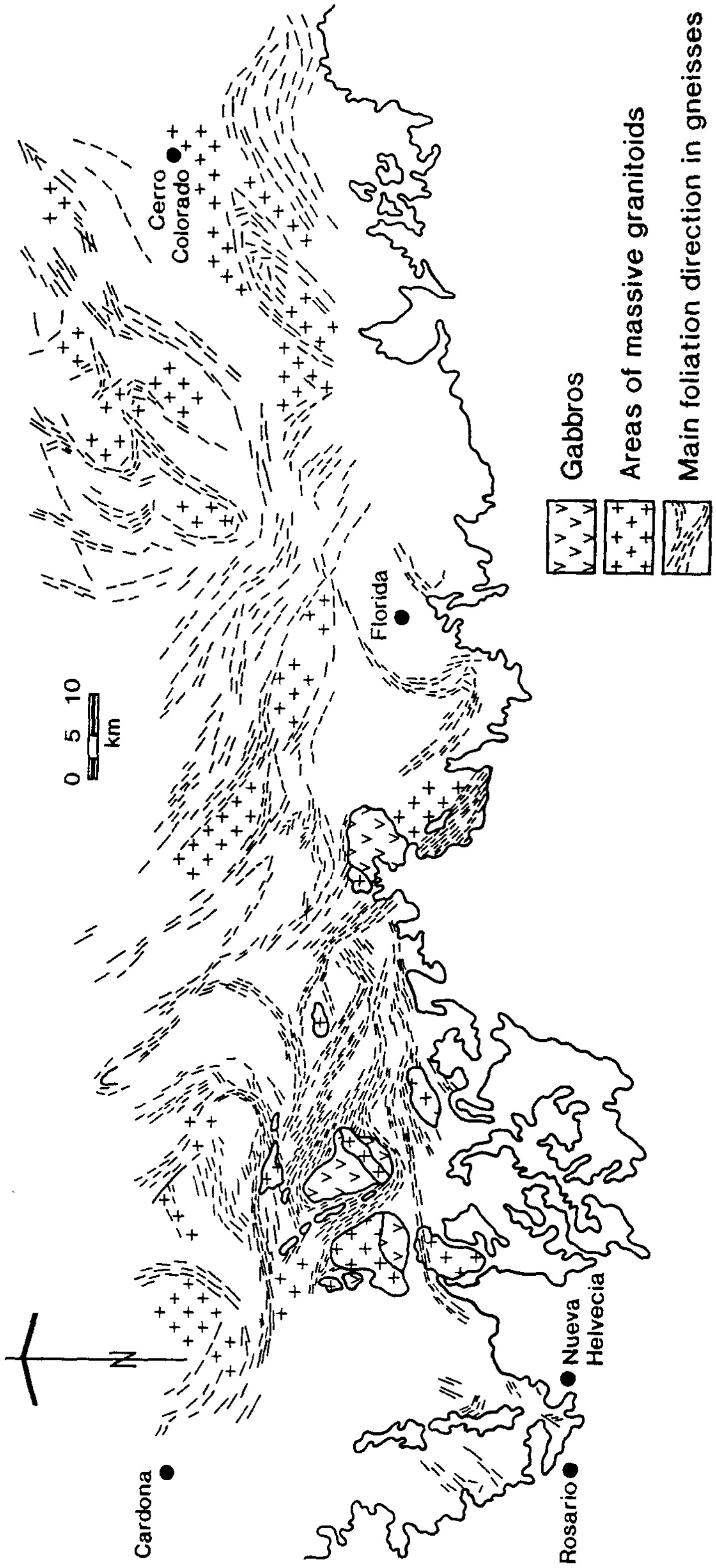
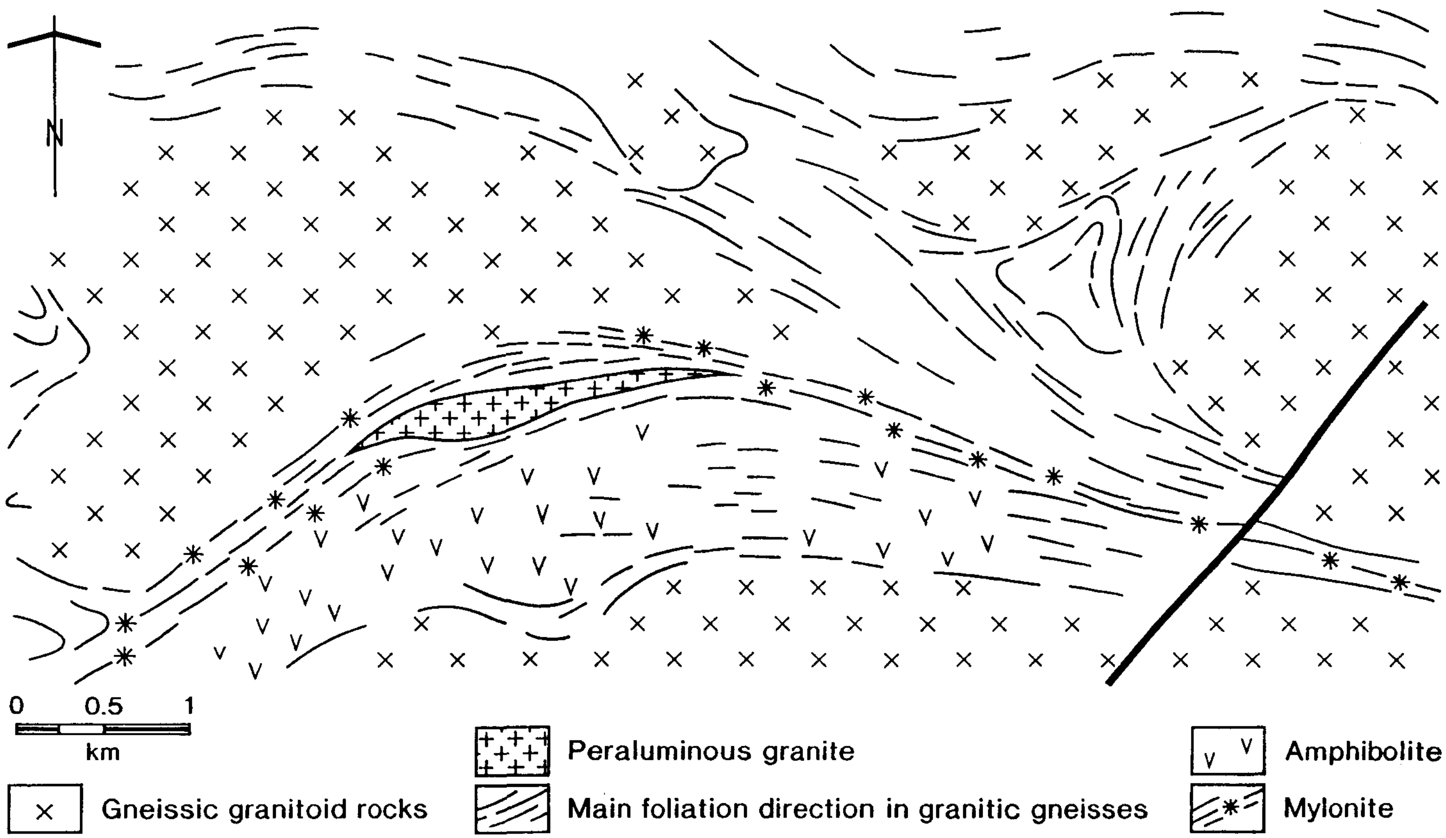


Figure III.7: Trend lines for the granitic gneiss complex and the San José Belt, southern Uruguay (after Campal, 1990)

Figure III.8: Detailed trend surface map for gneisses and related rock near the town of La Cruz, Department of Florida After Campal and Chulepin (1991)



phenomena on the S1 and S2 planes. This phase may be recognized by an intense thermal activity. Quartzofeldspathic remobilization has taken place in shallow metamorphic rocks and anatexis in lower crustal level areas. According to Campal (1990), the simultaneous evolution of basic and acid magmas is the main magmatic feature associated with this plastic phase.

Anatectic granitoides are found at the lowest crustal levels. They are more or less allochthonous and strongly related to basic magmas (dioritic). Mixing and mingling phenomena are frequently observed (Piedra Alta and Cerro Colorado; Department of Florida). At shallower crustal levels the metamorphic rocks are intruded by granite-gabbro complexes (Mahoma, Department of San José).

A geological and geochronological study of the Cerro Colorado granite (see location map, Figure III.1) has recently been carried out by Cingolani et al. (1990). The Cerro Colorado granitoids feature a nucleus which is typically several hundreds of meters in diameter and which is characterized by the presence of prismatic megacrysts. North-west trending amphibolitic migmatites surround these granitic nucleii (see Figure III.9). Under the microscope, slightly perthitic microcline megacrystals are surrounded by a biotite, quartz, oligoclase (An 25) matrix. Textural evidence suggests that microcline crystallization was a late stage phenomenon. Local anatexis of pre-existing rocks is the origin suggested by the authors for this granitic body. A Rb/Sr whole rock age of 2071

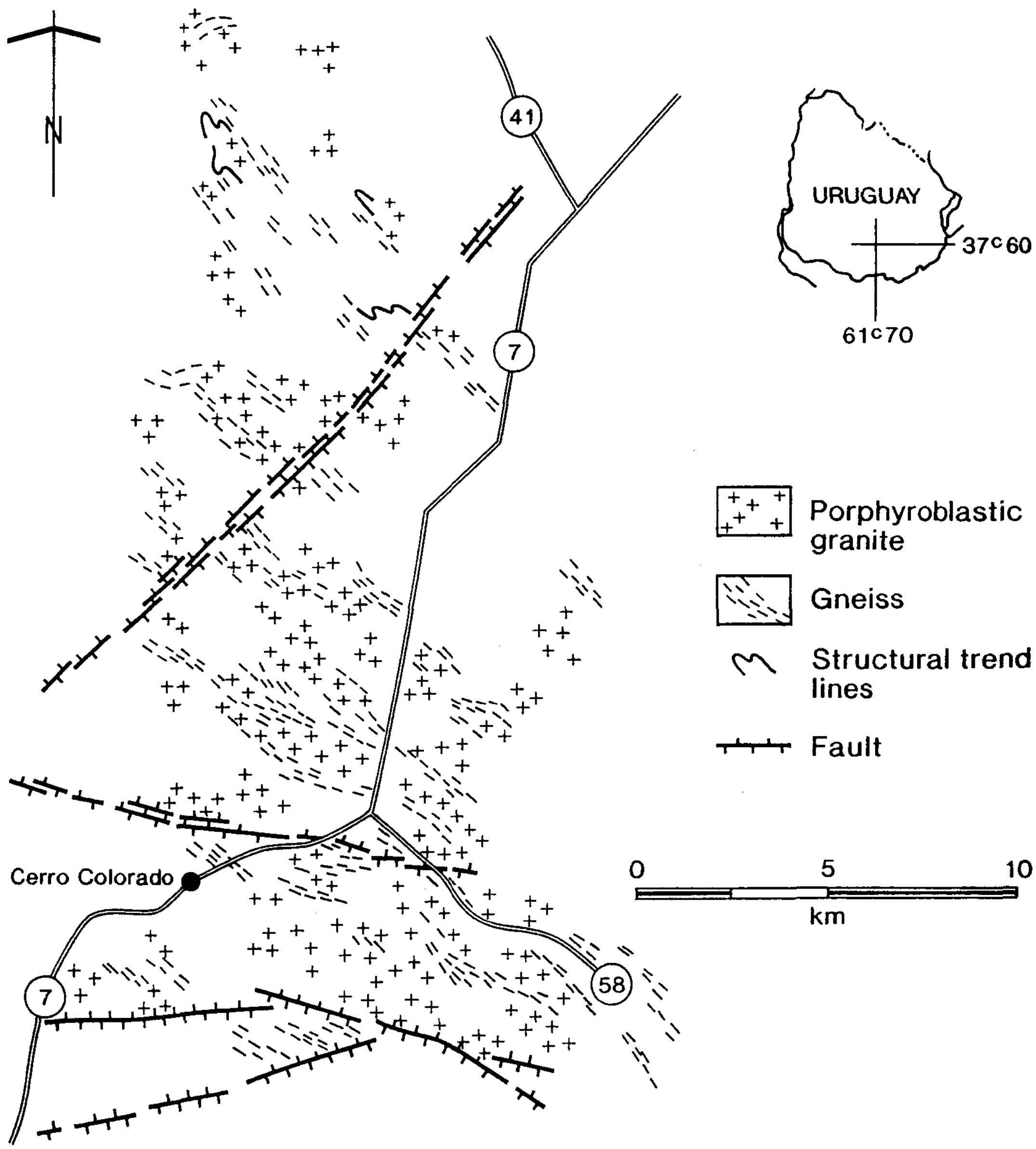


Figure III.9: Structural sketch map of the gneisses and related rocks near the town of Cerro Colorado

± 71 Ma with Ro= 0.7011 (Cingolani et al., 1990) was obtained based on seven cogenetic samples. The age is one typically associated with the Transamazonian deformation, and the isotopic data are consistent with mantle values for Archean times (initial ratios between 0.7000 and 0.7003).

The granitic body located near the city of Florida, in particular at the Piedra Alta and El Prado quarries, show the characteristics of the deepest level of the Transamazonian domain dated at 2030 ± 75 Ma (Rb/Sr whole rock, recalculated from Umpierre and Halpern, 1971). The quoted authors described the intrusion as consisting of granitic and granodioritic rocks, with subhorizontally layered structures and a sharp contact between them (Figure III.10). They are crosscut by granodioritic and microdioritic dykes, and there was significant late-magmatic (hydrothermal) activity. In the upper portion of the intrusion there is a leucocratic granular rock with turbulent flow structure lacking a preferred orientation. It shows grain size variation ranging from coarse-grained (centimetre scale) to medium-grained. Sometimes this leucocratic rock contains miarolitic or pegmatitic "bubbles". The main minerals are oligoclase, microcline, quartz and biotite, with amphibole, epidote, sphene, apatite and muscovite being present in smaller amounts.

Also identified in the area are syn-magmatic dykes that were folded and "boudinaged" by movement within the magma chamber with different stress and dragging directions. The main

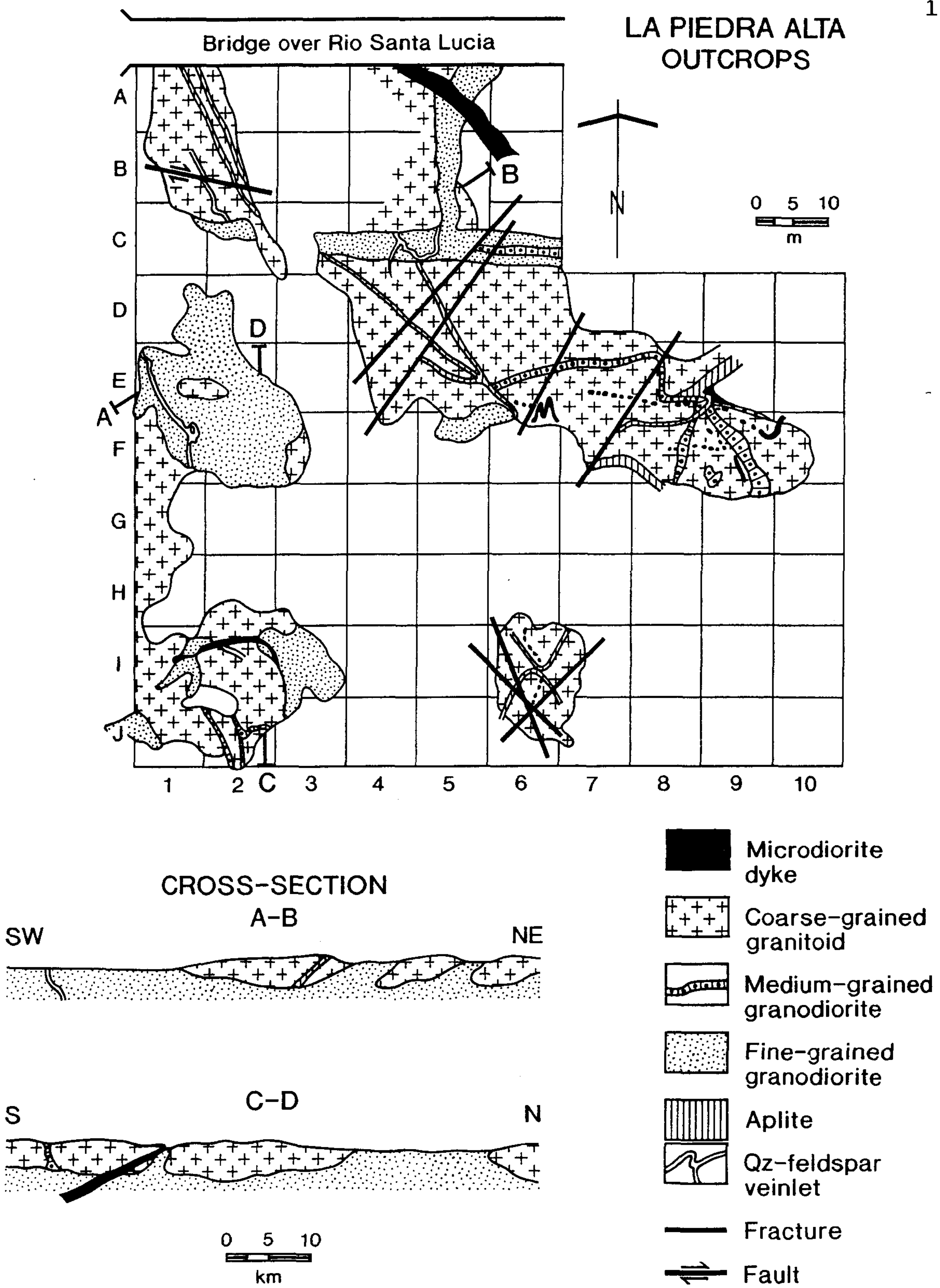


Figure III.10: Outcrop-scale map of the granitoid intrusions in the Piedra Alta Quarry, near the city of Florida. A 10 meter grid system is shown for reference.

rock in the basement is melanocratic, fine-grained, and isotropic. Volumetrically, the most important minerals are plagioclase, K-feldspar, quartz, hornblende and biotite with lesser amounts of apatite, sphene and epidote. It is classified as granodiorite.

Quartz-feldspar dykes and veinlets intruded the basement rocks under both plastic and brittle conditions. Syn-magmatic dykes flexured and folded by the magma motion have also been described. Considering the existence of continuous interpenetration and diversity of structures generated, we think that the leucocratic and melanocratic components have evolved as two melts without great thermal contrast between them. This would explain the fact that there are not important compositional variations, although chilled margins are present. Besides this there are also mutual inclusion phenomena and interpenetration among the rocks. This zone was supersaturated with respect to water. During the end- magmatic stage fluid pressure could produce fracturing in a melt which has crystallyzed more than 50 %. Microdiorite dykes such as the ones located at co-ordinates A-5 and I-2 of Figure III.10, which show lobate boundaries and interpenetrate the host rock, seem to have be emplaced with viscosity contrast into an incompletely crystallyzed host rock (50 % crystals). Magma mingling is the phenomenon considered for this rock assemblage.

This kind of granitic stock may be considered as a locus of melting within the metamorphic complex. These metamorphic rocks (mainly gneissic granites, amphibolites, and gneisses) have been described by Campal and Chulepin (1990) in the 1/100.000 Talita Sector Geological Map.

Gneissic-granites are only exposed in quarries. They have inequigranular texture, in which feldspathic megacrysts are set in a matrix consisting of quartz, plagioclase and biotite. Foliated gneisses envelop these granitic nucleii. Amphibolites appear as enclaves within the granitoids or as lenses in the gneisses which range in size up to several tens of meters. In some cases the amphibolites are foliated and folded while most of outcrops are isotropic in nature. This strongly suggests that the amphibolites have experienced a previous tectonic history.

One of the outstanding features of this area is the scarcity of metasedimentary rocks which form discontinous bands and contain significant volumes of remobilized quartzo-feldspathic material. These features are the main differences between the gneiss terranes and the metamorphic belts described above. The quartz-feldspar remobilizations are present in the form of microgranites, aplites and pegmatite dykes.

These main lithologies are systematically cut by microgranite dykes which have no preferred values of either strike or dip. They have homogeneous fine grained textures and consist of quartz, oligoclase, K-feldspar and biotite. Biotite is present as strongly undulated pleochroic plates and is very similar to that found in the granodiorites.

Pegmatites with very simple mineralogy, and with only biotite as an accessory mineral, are intimately associated with microgranites cutting amphibolites, gneisses, and foliated granites. Lenticular shapes are specially developed by these pegmatites in the Departments of Florida and Flores. The major axes of these lenses are subhorizontal and are several tens of meters in length and up to 3 meters in thickness.

The band developed between the San José and Montevideo Belts must be tentatively included into this granite-gneiss complex. The exposed area of this sub-zone is of limited extent since a large part of it forms the floor to the Santa Lucía graben. The most informative outcrops of these rocks are found in the vicinity of Ecilda Paullier, Estación Gonzales, and Carreta Qumada The Bocas del Rosario quarries and the AFE quarry at the town of Suarez also have good exposures of these rocks.

The AFE quarry, which may be taken as a typical example, was described by Coronel and Oyhantçabal (1988) as consisting of heterogeneous migmatites with dictyonitic and stromatic structures (sense Mehnert, 1968) which vary laterally into gneisses or granitic rocks consisting of oligoclase, K-feldspar, quartz, biotite, epidote, apatite and sphene. Granites with gneissic border facies are intimately associated with the above-mentioned rocks.

The variations in structural direction underscore the plastic nature of these rocks during deformation. A Rb/Sr whole rock age of 2233 ± 107 Ma with Ro= 0.7020 (Preciozzi, 1992) was obtained on migmatites from this quarry. Deformed granitoids exposed near Estación Gonzalez and Carreta Quemada in the

Department of San José also belong to this complex. They have been affected by one or more tectonic events frequently showing different types of planar structures. Rb/Sr whole rock ages have also values near 2200 ± 100 Ma

Geochronological data for the granitic gneisses of this belt are presented in Table III.4. These ages are intimately related to the brittle tectonic phase which developed across the whole terrane. To differenciate between intrusive granitic rocks and pre-existing gneissic granites belonging to the basement is one of the most difficult problems in studying this granite-gneissic complex. The situation can be complicated even further by the presence of planar structures in the intrusive granitoids as a result of post-magmatic tectonic activity. This kind of problem can only be partially solved by detailed mapping. Isotopic data (at least K/Ar and Rb/Sr geochronology) don't define the emplacement age because the subsequent tectono-thermal events led to a resetting of the isotopic system.

III: INTRUSIVE ROCKS

Different kinds of magmatic intrusive bodies are intrusive into the Piedra Alta Terrane and a variety of emplacement mechanisms and lithological contexts can be defined for these rocks. The plutonic bodies in question are shown on Figure III.11 from which the basic dykes have been excluded for simplicity. The nature of the country rock can be taken as a first-order classification criterion for these plutonic bodies.

Granitic bodies associated with the three metamorphic belts can be distinguished from those geometrically related with the granite-gneissic complex which have been described above.

Detailed descriptions of several of these intrusions have already been provided in chapters 1 and 2 and will not be repeated here. Emphasis will be placed on a description of the remaining plutons, however the tectonic implications derived from the study of these rocks will make use of all available data.

Plutonic rocks associated with metamorphic belts

Arroyo Grande belt.

Four main intrusions, the Marincho, Arroyo Grande, Carpintería and Arroyo Malo plutons, have been identified in this belt, (Figure III.3). The Marincho and Arroyo Grande plutons have been described in some detail in Chapter 2, and the description is not repeated here. The brief description below represents all that is known of the other two plutons.

The Carpintería granodiorite is a fine grained rock with poecilitic K-feldspar, oligoclase (An 22-25), anhedral quartz, epitactic biotite-muscovite intergrowth, pistacite and ilmenite with sphene and/or leucoxene haloes. It has a clearly cross

Table III.4

SUMMARY OF RB-SR AGE DETERMINATIONS FROM THE SOUTHERN GRANITIC GNEISS COMPLEX

Place	Age(Ma)	Ro
AFE Quarry Suarez	2233 ± 107	0.7020
Estación Gonzalez	2176 ± 146	0.7090
Carreta Quemada	2290 ± 130	0.7120

Data from Preciozzi (1992).

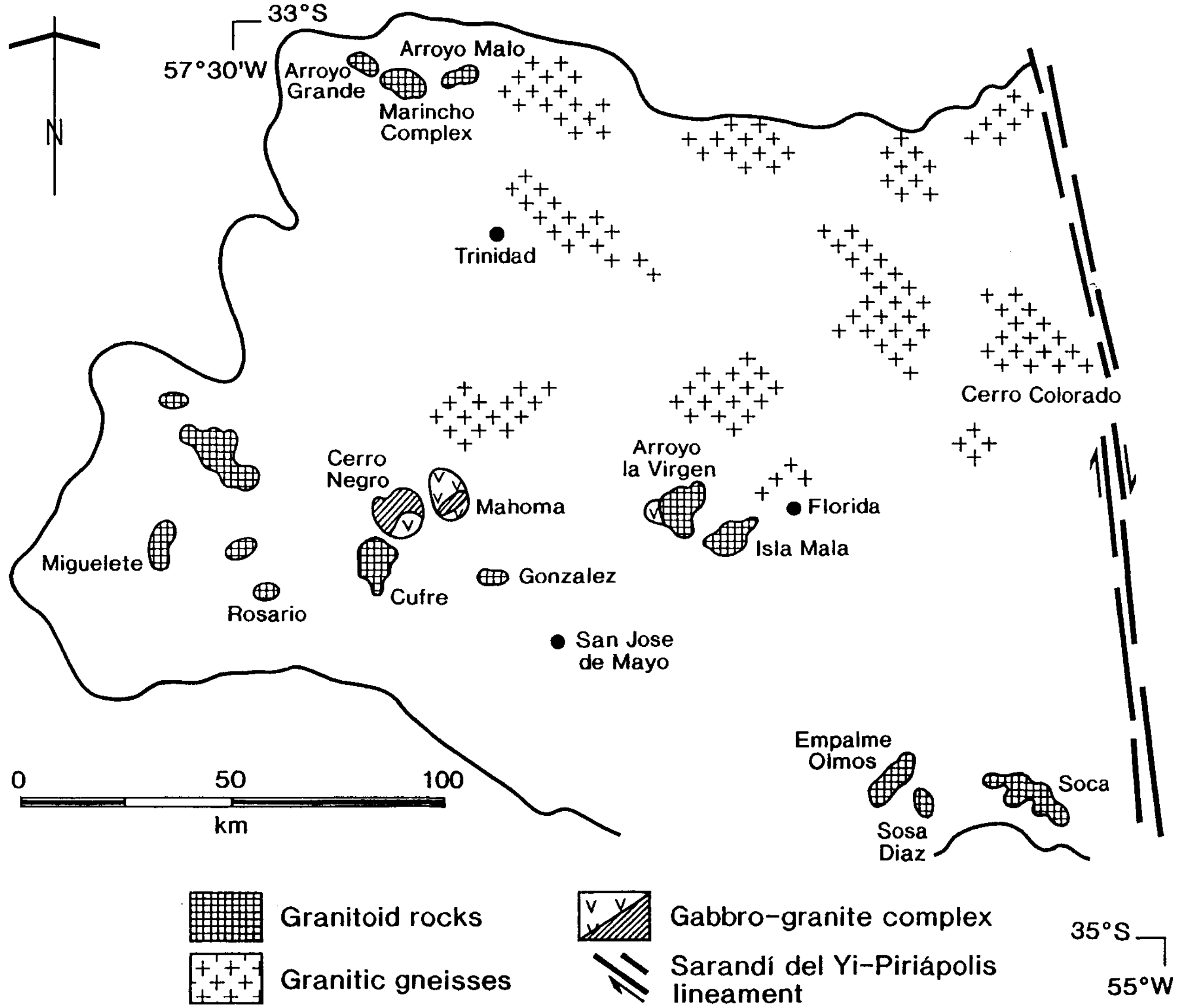


Figure III.11: Distribution of granitoid intrusions in the Piedra Alta Terrane, southern Uruguay cutting (discordant) relationship with respect to the surrounding country rock.

The Arroyo Malo granodiorite was described by Fernandez and Preciozzi (1974) as a medium to coarse gray rock with biotite-rich enclaves. Biotite and hornblende are the mafic minerals present. Zircon, sphene, garnet, apatite, ilmenite and pistacite are the accessory phases.

Classification diagrams

Chapter 2 discusses the geochemistry of the Arroyo Grande and Marincho suites in some detail. Not discussed in this chapter are modal mineral data, which are only available in reasonable quantity for the Marincho Complex. These data are shown on a Streckeisen diagram (Figure III.12 - upper half) as well as a plagioclase - alkali feldspar - ferromagnesian mineral (PAFM) plot (Figure III.12 - lower half).

Porphyroblastic hornblendites are situated near the plagioclase-rich end of a trend which terminates in the granite field. However on the PAFM diagram it can be seen that the hornblendite unit defines a trend which is completely separate and distinct from the trend defined by the granodiorites and related rocks - thereby suggesting that the hornblendite should be considered as a separate intrusive phase. The leucogranite unit should also be considered as a separate intrusive episode for the same reason. Thus, when both modal mineral plots are considered together, the subdivision of intrusive episodes is

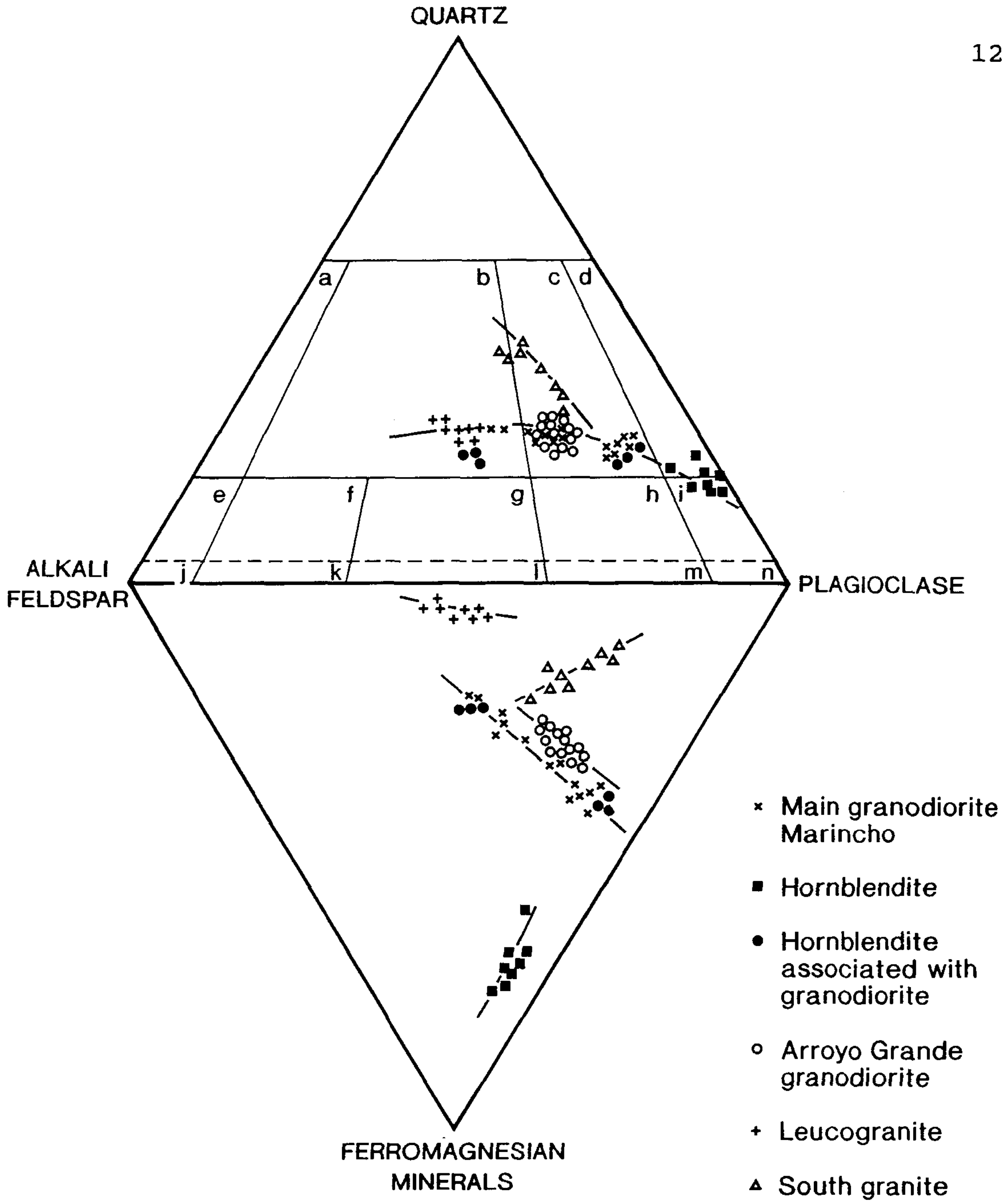


Figure III.12 Modal mineral data for the Marincho Complex plotted on classification diagram of Streckeisen (1976). (a) alkali-feldspar granite (b) granite (c) granodiorite (d) tonalite (e) alkali-feldspar quartz syenite (f) quartz syenite (g) quartz monzonite (h) quartz monzo-diorite (i) quartz diorite (j) alkali-feldspar syenite (k) syenite (l) monzonite (m) monzo-diorite (n) diorite/gabbro

After Preciozzi (1989b)

the same as that derived at from a consideration of the whole rock geochemistry (Chapter 2).

The Arroyo Grande Pluton and the South Granite also define distinct trends on this pair of diagrams. Thus it is reasonably certain that neither the Arroyo Grande intrusion nor the South Granite should be considered as satellitic apophyses of one of the phases of the Marincho Complex.

San José Belt

Several plutons, concentrated basically in three areas, are spatially or genetically associated to this belt. These are the Isla Mala-Arroyo de la Virgen, Mahoma-Cufré and Cerros de San Juan areas, (see Preciozzi et al., 1985).

These plutons are generally "granites" (in the large sense), with the exception of Mahoma-Cerros Negros-Mal Abrigo, where gabbro-granite complexes are present. The gabbroic members of these suites are considered below in the section on basic magmatism.

The distribution of the granitoids in the San José Belt is shown in Figure III.13. The geochemistry of the Arroyo de la Virgen Pluton and the Isla Mala Plutons were discussed in some detail in Chapter 1 and are not reconsidered here. The composition of the feldspars in the Arroyo de la Virgen Pluton vary in a systematic manner, ranging from An20 at the margins to An0 in the south. The distribution of the various compositional zones resembles a somewhat dismembered normal zoning pattern (Figure III.14).

Field evidence

Observations made during geological mapping suggests the following sequence of events. In the south, the Isla Mala pluton with isotropic, massive textures, generated thermal metamorphism in its contact with San José Belt slates. Northwards, a transitional evolution to syn-magmatic foliated structures is observed. This kind of structure suggests a late-tectonic emplacement of the main granodiorite body.

Planar structures have been observed within the Isla Mala Complex. The observed planar structures developed in the northern portion of the mass have been deformed as shown in Figure III.15. Younger leucogranite dykes with isotropic textures have been injected into these deformed structures and consequently are interpreted as late-tectonic in relation to this deformational phase.

Diorite dykes also have a sinuous map pattern, but they show internal structures concordant with their contacts. They are interpreted either as pre-existant magmatic bodies or syn-deformational intrusions. Independent plutons of leucogranite are also intrusive into the San José Belt and they cut the main granodiorite. They are also structurally massive, suggestive of a post-tectonic timing for emplacement.

The Arroyo de la Virgen pluton ranges in composition from leucogranite to granodiorite. All the developed textures are isotropic, indicative of a post-tectonic timing of emplacement. Brittle discontinuities with rough EW trend, traverse the Isla Mala pluton but are cut by the Arroyo de la Virgen body.

A series of sketches depicting the evolution of the Isla Mala Pluton, as visualized by the author, is presented in Figure III.16.

Mahoma Cufré region

Four plutons, known as the Cufré, Cerro San José, Mal Abrigo and Mahoma plutons, crop out in the Mahoma-Cufré region, (see Figure III.5). The last two are associated with gabbro material. Modal analyses of these plutons are presented in Figure III.17. Heterogranular hornblende-biotite granites and granodiorites of the Cufré stock contain deformed microcline megacrystals. Fine-grained mafic enclaves are very common and are probably of magmatic origin.

Petrography of the plutons of the Mahoma - Cufré region

The Mal Abrigo granite has sharp contacts along its southern border however this contact is diffuse in the north. The pluton is a biotite-hornblende granodiorite. In the eastern portion of its outcrop area it is coarse grained with well-developed planar structures. Under the microscope the plagioclase is euhedral near the core of the intrusion and

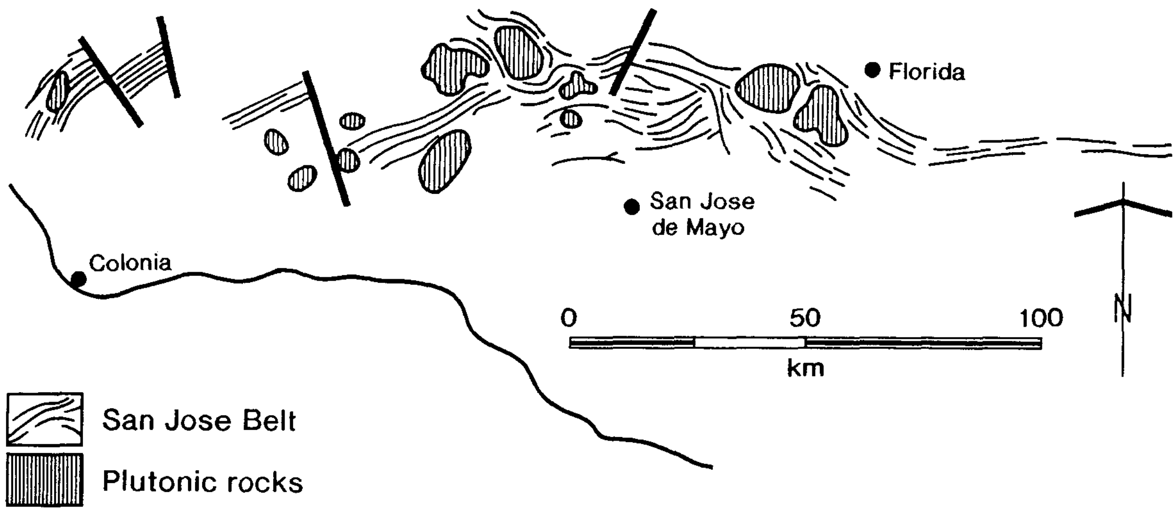


Figure III.13: Distribution of granitoid plutons in the San José Belt

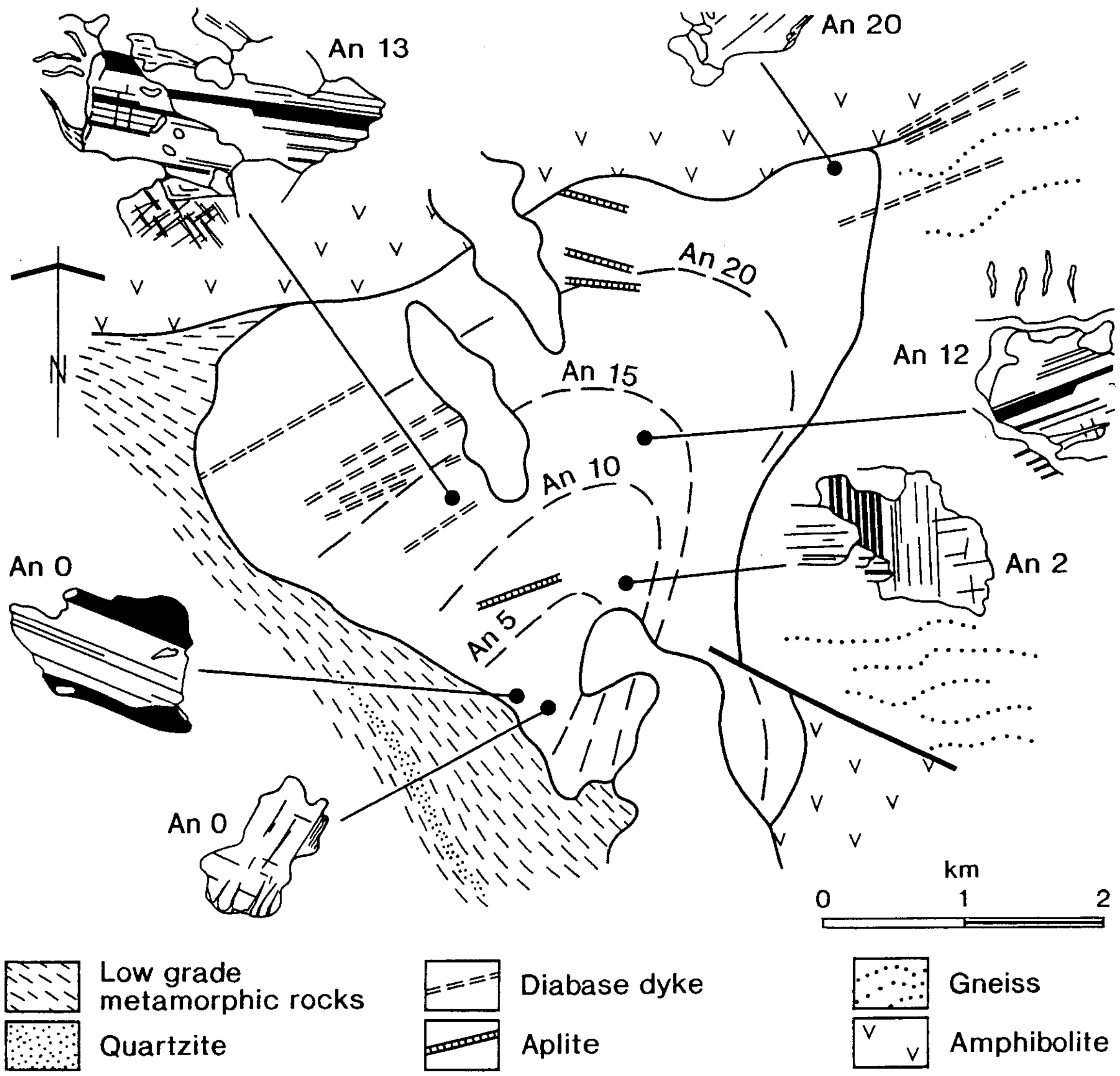


Figure III.14: Chemical zonation in the Arroyo de la Virgen as revealed by variation in plagioclase compositions

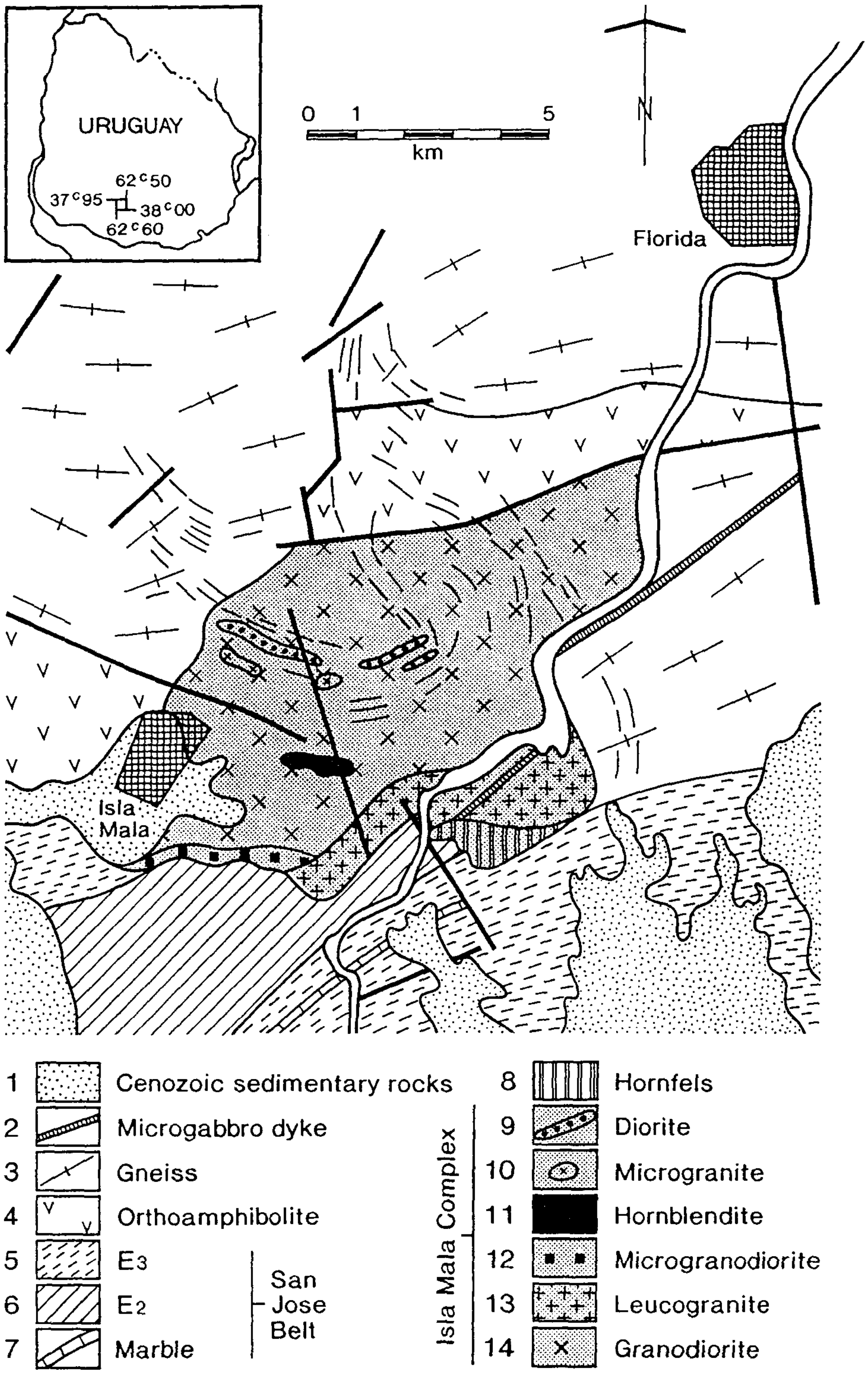


Figure III.15: Structural elements within the Isla Mala Complex becomes progressively more cataclastic towards the northern border. Subeuhedral perthitic microcline, heterogranular quartz and An 24 plagioclase are the most important minerals. Biotite and minor hornblende and muscovite are the accesory phases.

The Mahoma granite has discordant contacts with the country rocks. Rounded enclaves of a fine-grained basic rock are commonly found in this homogeneous, leucogranitic biotite granite. Under the microscope this rock shows anhedral quartz, perthitic microcline, zoned oligoclase, biotite and pink garnet. Zircon, sphene, rutile and abundant fluorite (750 ppm F in the whole rock chemical analyses) are the main accessory minerals.

The Cerro San José granite is a small, coarse-grained leucogranite intrusion. It is white in colour with bluish-green minor mica. Subeuhedral albite and big microcline and quartz crystals are the main minerals of the rock. Muscovite is the main accesory mineral. It also contains abundant fluorite (1600 ppm F) and Li (average of 500 ppm).

The Mahoma granite is the only one of these intrusions which has been dated by isotopic methods (Rb/Sr whole rock). The age, recalculated fron the data of Umpierre and Halpern (1971) is 1979 ± 35 Ma with Ro= 0.7075. In fact, the Mahoma granite forms a part of a gabbro-granite suite, the mafic component of which is discussed in some detail below.

An R1-R2 classification diagram (LaRoche, 1980) is shown in Figure III.18. It can be seen that the Cerro San José pluton

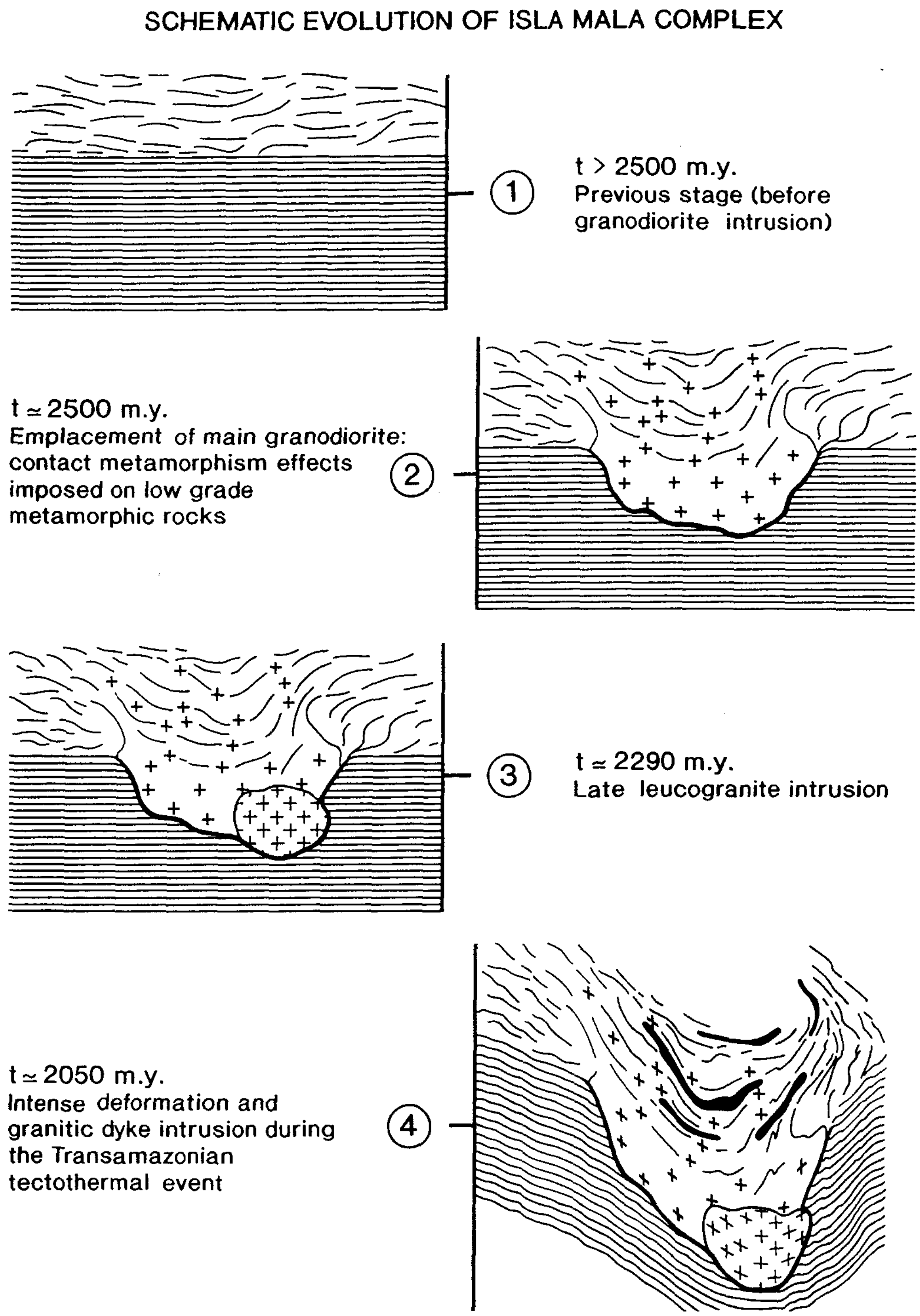


Figure III.16: Series of sketches showing the proposed evolution of the Isla Mala Complex

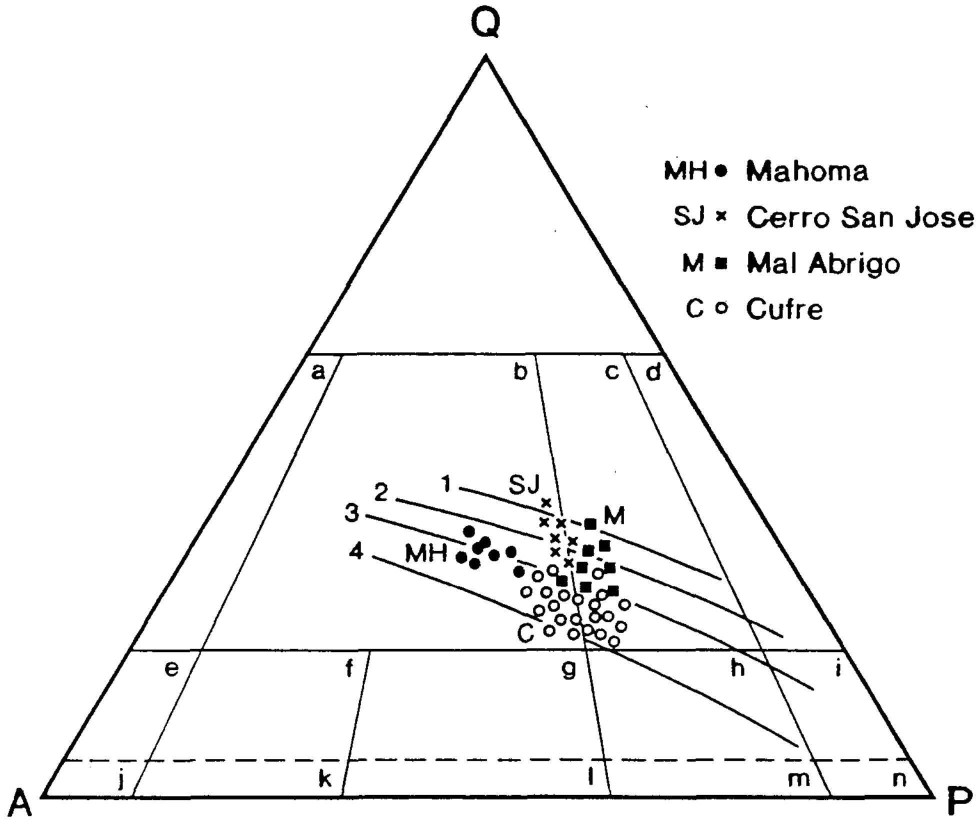


Figure III.17: Modal mineral plot of the Cufré, Cerro San José, Mal Abrigo and Mahoma Plutons. After Preciozzi (1989g). See legend of Figure III.12 for the names of the different compositional fields. The four lines represent four different calc-alkaline trends as reported by Lemeyre (1987).

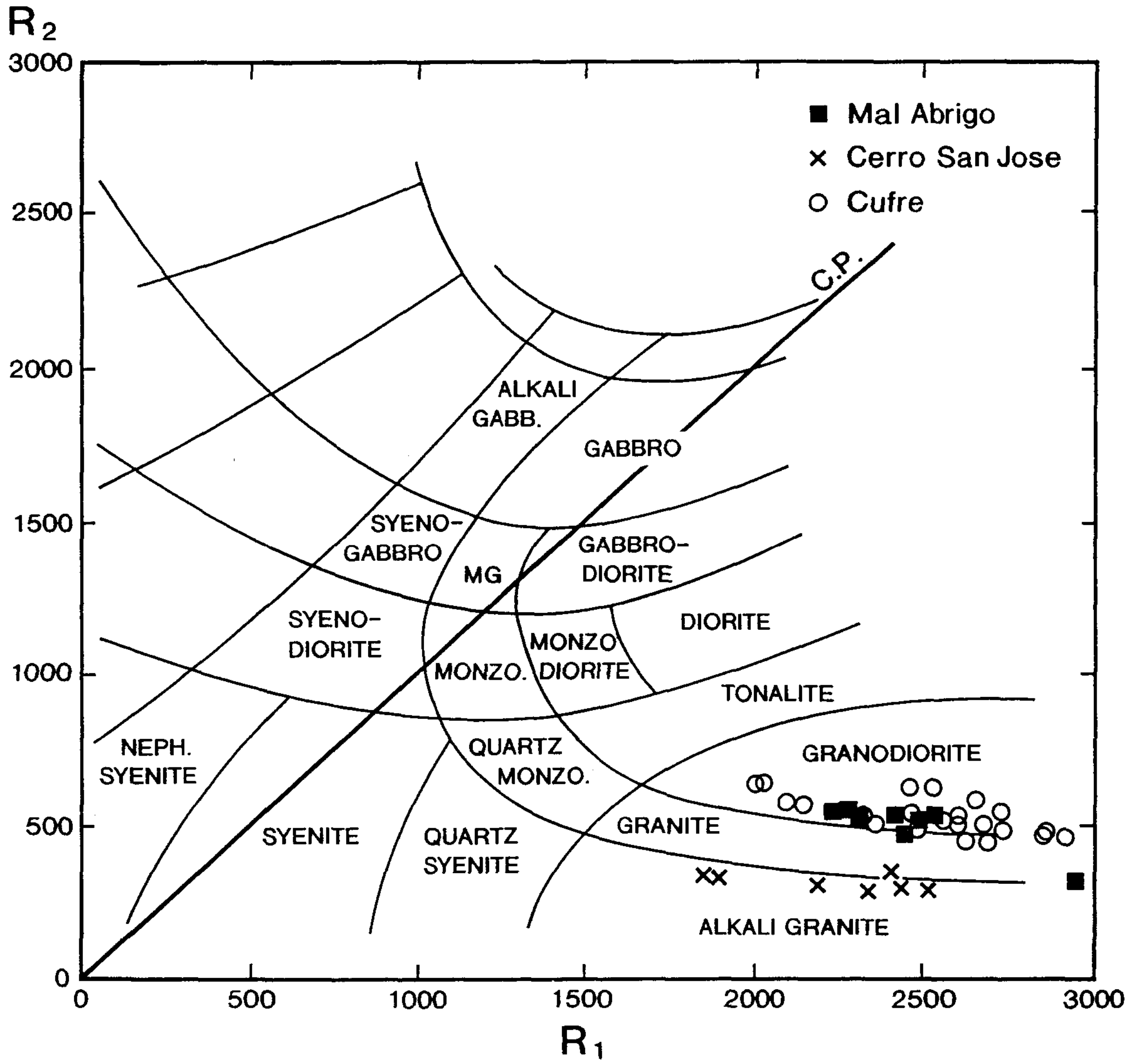


Figure III.18: R1-R2 classification diagram for the Cufré, Cerro San José and Mal Abrigo Plutons. After Bossi et al., (1993).

plots just over the limit between true granites and alkali-granites, while the Mal Abrigo and Cufré bodies plot into granodiorite field.

The Batchelor and Bowden (1985) geotectonic discriminant diagram (Figure III.19) shows a clear distinction between the Cerro San José granite and the Mal Abrigo-Cufré plutons. The first one falls in the anorogenic field while the others form linear trends which originate in either the late-orogenic or post-collision uplift fields. Although many of the data points fall near the syn-collision field typical of S-type granites, the fact that both plutons define linear trends which originate in other domains enables this possibility to be rejected.

A similar result is obtained from the Maniar and Piccoli (1989) diagram, (Figure III.20). The San José granite falls within the anorogenic granite (RRG-CEUG) field whereas the Mal Abrigo and Cufré granodiorites plot in the orogenesis-related field. The data points for the Mal Abrigo pluton fall within the post-orogenic subfield of the orogenic field, however this may only be a reflection of the geological sampling procedure and may not be of tectonic significance.

The San José granite has isotropic texture and has imposed a narrow low-pressure metamorphic contact aureole on the country rock. Field observations are thus in agreement with the interpretation derived from the geotectonic discriminant diagrams.

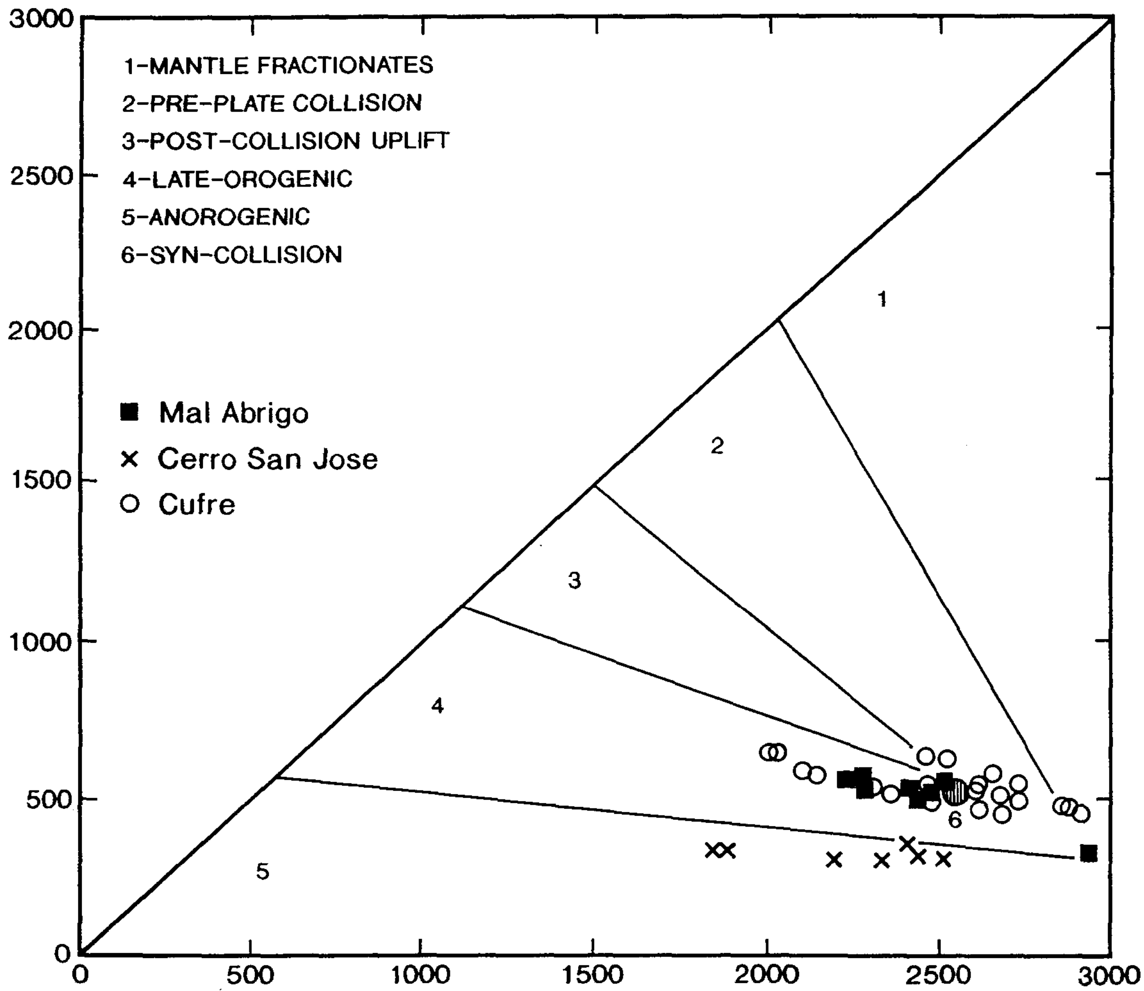


Figure III.19: Tectonic discriminant diagram for the Cufré, Cerro San José and Mal Abrigo Plutons. Diagram taken from Batchelor and Bowden, (1985). Data from Bossi et al., (1993).

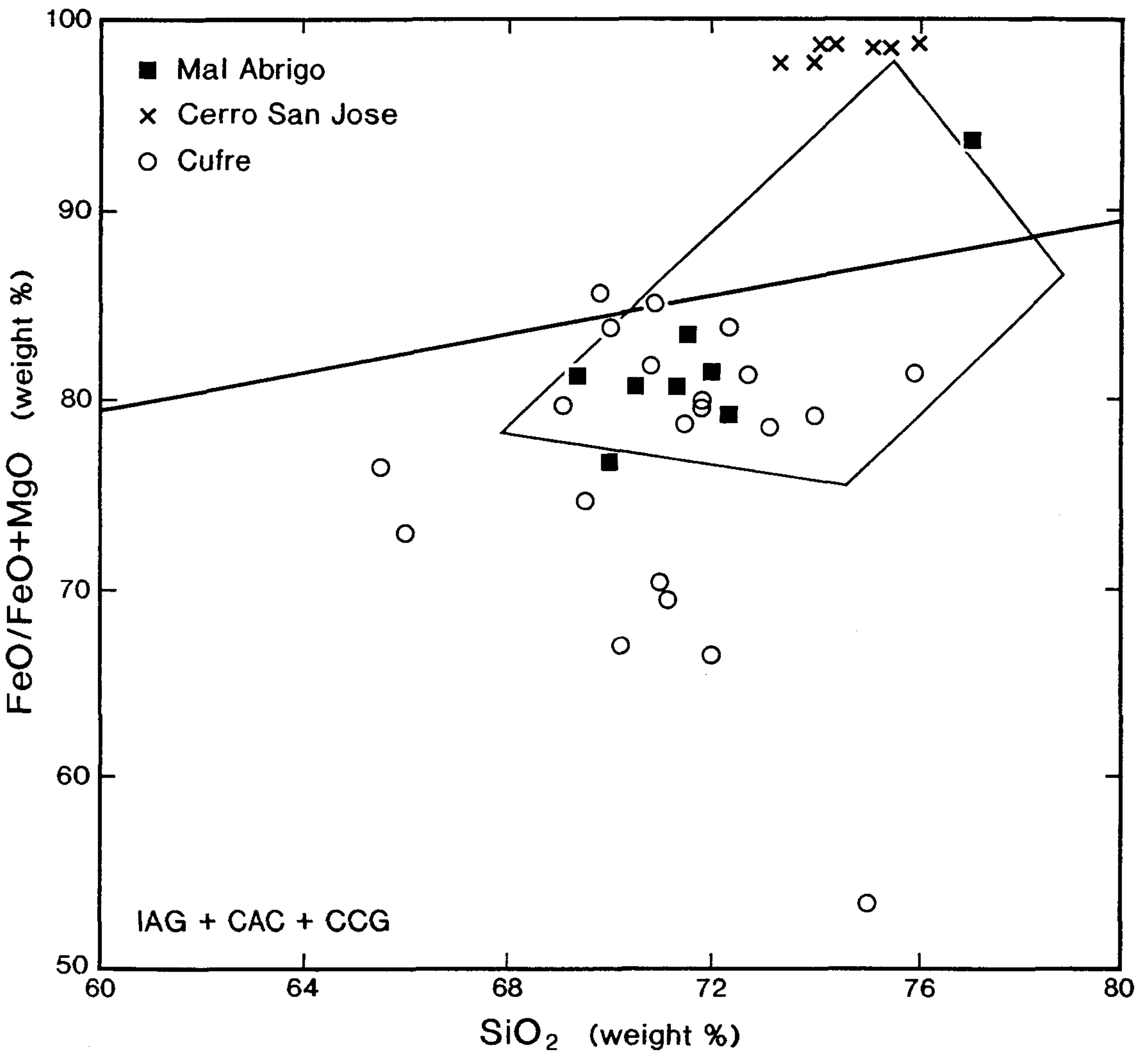


Figure III.20: Tectonic discriminant diagram for the Cufré, Cerro San José and Mal Abrigo. Diagram based on the method of Maniar and Piccoli (1989). Data from Bossi et al., (1993) The Mal Abrigo granodiorite shows field evidence of a syn-tectonic character in the north, where syn-magmatic foliated structures have developed.

The Cufré pluton, which varies in composition from leucogranite to granodiorite, has only been affected by late brittle deformation. The intensity of this brittle deformation features inceases towards the north. This deformation is related to the brittle phase which has an inferred age of about 2200-2300 Ma. Field evidence thus suggests that the Cufré pluton was intruded during the very Early Proterozoic as a late-orogenic body.

The granitic bodies in the western portion of the San José belt have not been examined in any detail. The Arroyo Miguelete granite (Department of Colonia) which is intrusive into low grade metamorphic rocks of the San José Belt is the best known. It is a heterogranular leucogranite containing perthitic microcline crystals up to 3 mm. in size and anhedral quartz with a normal, as opposed to an undulose, extinction.

Montevideo Belt.

Several plutons are considered to be associated with this metamorphic belt. Some of these intrusions (La Teja, Santander, Capurro) have been described by Walther (1948) and are not now accesible for study due to subsequent building development. Others, such as the Empalme Olmos, Sosa Díaz and Soca plutons are still available for follow up work.

The schematic regional distribution of the Montevideo Belt and its associated plutons is shown in Figure III.6. The Empalme Olmos pluton was described by Coronel and Oyantçabal (1988) as being a porphyritic granite featuring a planar distribution of microcline megacrysts oriented N50E (the same strike as the long axis of the oval shaped massif).

The texture is heterogranular anhedral with subhedral zoned oligoclase. The microcline crystallized relatively late, including the other minerals. Quartz, biotite, and an unremarkable variety of accessory minerals complete the mineralogy. It must be emphasized that this pluton, though geometrically related to the Montevideo Belt, was intruded to the north of Mosquitos Formation, which itself forms the northern limit of the Montevideo Belt.

The Sosa Díaz biotite granite, although situated only 7 km SE of the aforementioned intrusion, is definitely situated within the Montevideo Belt. According with Coronel and Oyantçabal (1988), it contains basic enclaves, some pegmatites and, locally, planar structures oriented N50E.

The Soca pluton is an elongated body that crops out in Department of Canelones, east of the town of Soca where it has been quarried for dimension stone. Two varieties have been recognized within the quarries, based on the colour (green or pink) of the microcline megacrysts. The first one (green) has finely perthitic microcline megacrysts including little euhedral quartz grains which feature a bipyramidal shape. A second generation of microcline, oligoclase and euhedral quartz are the most important minerals found in the matrix. Accessory minerals include pyroxene, poecilitic amphibole, biotite, apatite and zircon. Zoning in the megacrysts is defined by variation in the size and shape of the perthite. An ovoidal nucleus, in which the perthitic plagioclase is oligoclase, is always present. This variety has a spatial association with an orthopyroxene-plagioclase rock with amphibole and minor quartz. Irregularly shaped bodies and dykes of these rocks can be observed in some of the quarry walls.

The pink microcline variety never contains pyroxene and has euhedral to subeuhedral blue iridiscent quartz with abundant very fine rutile needles.

Angular shaped metamorphic blocks, ranging up to 1 metre in diameter, are included within the granite. A muscovite leucogranite, similar to the one emplaced in the Mosquitos Formation, is also present as xenoliths. Except for the presence of the pyroxene in the green variety and the blue quartz in the pink variety, no other petrographic differences have been identified.

Primary K-feldspar megacrystal crystallization can be inferred from the described petrographic features. The perthitic composition (oligoclase) and the nature of quartz (beta) indicate that high pressure and temperature conditions prevailed during megacryst growth. The only available geochemical analysis features a high K_2O/Na_2O ratio which is consistent with the early crystallization of the microcline megacrystals. The rigid nature of the country rock during emplacement, anhydrous nature of the intrusion, iron rich chemistry and lack of planar features are suggestive of an anorogenic setting.

BASIC MAGMATISM

Numerous bodies of basic material, not necessarily associated with the metamorphic belts, have been recognized in the Piedra Alta Terrane. These basic magmatic rocks intruded at different tectonic stages of evolution. Some of them show evidence of plastic deformation and metamorphic modification whereas others are undeformed. These differences were used for tectono-stratigraphic purposes and leads to the following grouping of the basic rocks.

1.- Orthoamphibolites affected by the earliest metamorphic phase of supposed Archean age. These rocks are located within the metamorphic belts. The Cerro and Cerrito of the Montevideo Belt are considered as prototypes.

2.- Orthoamphibolites later than first metamorphic phase but which were affected by the subsequent tectono-thermal events. Outcrops located in the Berrondo area (Department of Florida) are typical of this group.

3.- Hornblendites, with up to 50 % hornblende or other Ca-Mg amphibole. These rocks can have either equigranular or porphyritic textures with euhedral amphibole megacrystals up to 1 cm. Sometimes a magmatic foliation can be seen near the contact with surrounding units.

4.- Fine- to medium-grained stratified gabbros associated with later epizonal granite intrusions.

5.- A microdiorite to microgabbro dyke swarm, which is the last regional magmatic episode to have affected the Piedra Alta Terrane.

Montevideo Belt orthoamphibolites (group 1)

These rocks have been described by Walther (1948) and this description is not repeated here.

Berrondo orthoamphibolites (group 2)

This unit is poorly known. Detailed information concerning its map pattern and its relationships with the country rocks are lacking because of poor exposure and also because all observed contacts are tectonic. At the type locality several younger aplitic and pegmatitic dykes intrude the amphibolitic bodies.

Numerous micaschist xenoliths, very similar to those found within the main granodiorite of Isla Mala Pluton (2500 Ma), have been observed near the town of Berrondo. Structural analysis at this locality indicates that these rocks were affected by at least the last (plastic) phase of Transamazonian tectonic activity. The Berrondo rocks have been metamorphosed and now consist of assemblages containing hornblende + plagioclase (andesine) ± secondary chlorite/actinolite ± epidote ± relict pyroxene.

The average chemical composition of the Berrondo amphibolites is as follows:

SiO_2	51.0 %	FeO	6.2 %	Na_2O	1.3 %
Al_2O_3	13.5 %	MgO	6.0 %	K_2O	0.2 %
Fe_2O_3	6.1 %	CaO	14.2 %	H_2O	0.6 %
TiO_2	1.1 %	MnO	0.2 %		

This composition was plotted on several discriminant diagrams (not shown) and all suggest that these rocks are tholeiitic in character. However this finding must be treated with considerable caution since the concentations of Na and K, and possibly other elements, may have been modified during the metamorphic event, and these elements are used in many of the tectonic classification schemes. Trace element data would be more useful in this situation since those elements which are used for tectonic classification are often HFSE (high field strength elements) which are considered to have been relatively immobile under low-grade metamorphic conditions. Unfortunately such data are not available.

Hornblendites (group 3)

The hornblendites are typically massive rocks which feature a slight magmatic foliation towards the contact with the country rock. Porphyritic textures with euhedral amphibole megacrystals are very common. Equigranular textures are scarce (Preciozzi, 1989c).

The modal composition of these rocks is as follows:

amphibole	50-60 %	augite	8-2 %
andesine	24-14 %	pistacite	3-1 %
quartz	12- 4 %	microcline	0-4 %

Several features of these rocks are described in some detail below because they appear to be relatively rare, not only in southern Uruguay but around the world.

Two different generations of hornblende crystals can be recognized based on textural and morphological features: subhedral crystals with bluish pleochroism and euhedral crystals with green pleochroism. The optical characteristics of these two types of amphibole are quite different.

Plagioclase with An 52-56 has been partially altered to a fine-grained intergrowth of pistacite-clinozoisite. Microcline and quartz are interstitial while, sphene, apatite, epidote and opaques are the main accessory phases.

The primary pyroxene (augite) has been partially replaced by a green amphibole with the same cleavage traces. Pyroxene inclusions or relicts are common within the amphibole crystals. A primary origin for the blue amphibole can also be deduced from petrographic observations.

Preliminary electron microprobe data show that both the blue and green amphiboles are relatively magnesian, (Preciozzi, 1989c). A magmatic origin, in which pyroxene phenocrysts were partially replaced by magmatic reaction to form two generations of amphibole, seems to be the most reasonable explanation for this unit.

Numerous outcrops of this group of rocks were identified in the Piedra Alta Terrane, particularily in the Marincho and Chamanga areas (Department of Flores) and in the Isla Mala complex (Department of Florida).

Gabbros (group 4)

Members of this unit have been described from 3 localities (Arroyo de la Virgen, Mahoma and Cerros Negros), all located in Department of San José.

At Arroyo de la Virgen, bedding structures have been preserved within the gabbro, which is cross cut by a set of microgranite dykes. Deuteric alteration is more evident near the margin of the mass, generating intense uralitization and saussuritization of the component mineral.

The Arroyo Mahoma intrusion is shown in Figure III.21. This intrusion also features compositional layering. The layers dip at a pronounced angle, thereby allowing the observation of different lithologies. Oyantçabal et al. (1990) and Villar and Segal (1990) presented abundant petrographic data for this stock. The main texture is medium-grained, typically cumulus,

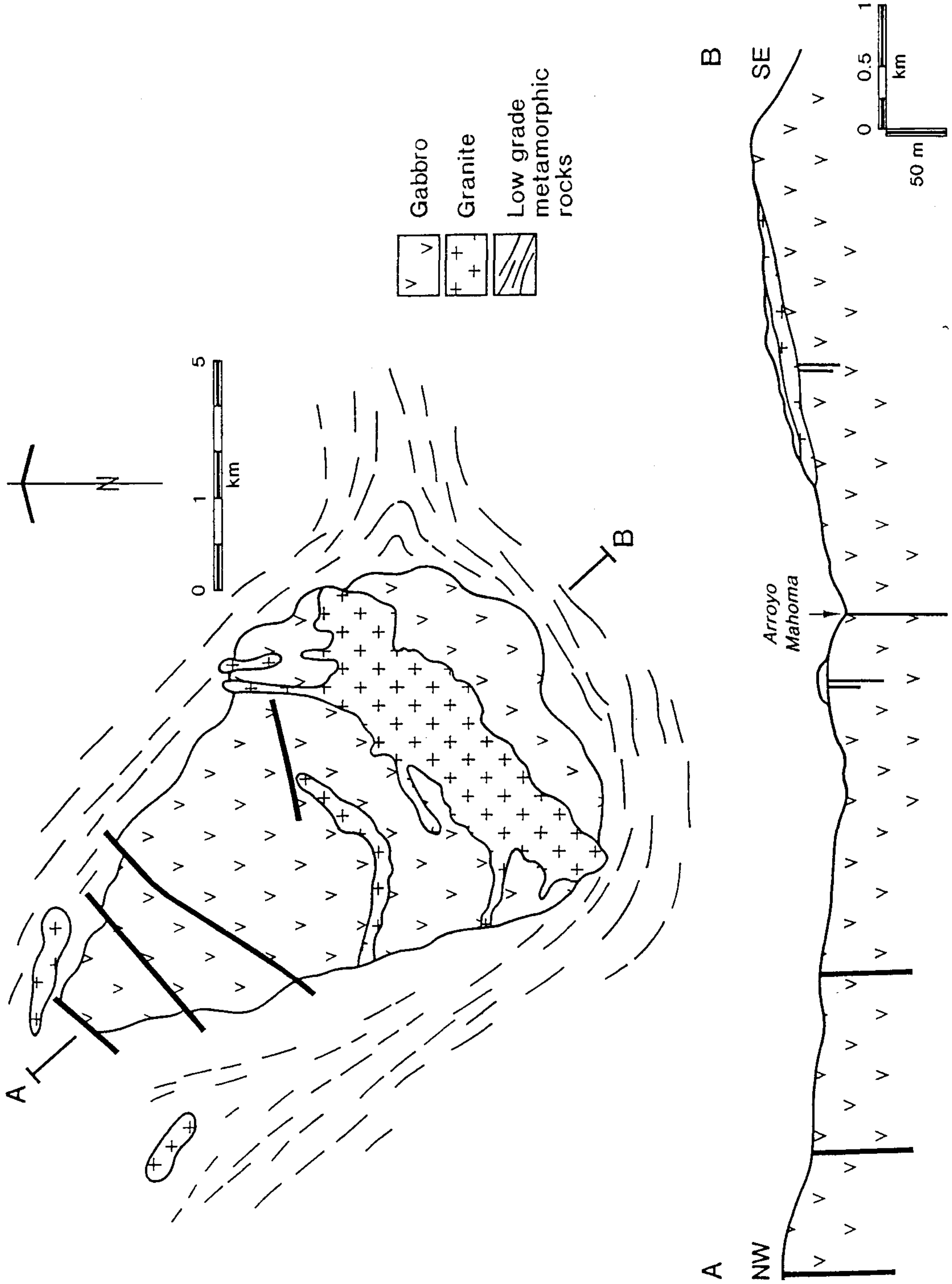


Figure III.21: Geological sketch map of the Mahoma Pluton, San José Belt and may or may not contain olivine. Plagioclase, normally a cumulus mineral in this intrusion, ranges in composition between An 55-65. Orthopyroxene, the composition of which ranges between En 50-75 (hyperstene-eulite) is also cumulus in nature and contains laminar exolutions of clinopyroxene. Primary post-cumulus amphibole with brownish-green to brown pleochroism and secondary amphibole with green pleochroism, were observed. According to these authors, this intrusion has undergone a slight differentiation. Primary hornblende throughout the mass would indicate a minimal pressure of 2 Kb at the roof of the intrusion (depth not less than 6 km.)

Villar and Segal (1990) proposed that the Cerros Negros gabbro/anorthosites suite was emplaced into upper crustal rocks during the Transamazonic event, before intrusion of the Mahoma granite and the related pegmatitic microgranitic dykes. Oyantçabal et al. (1990) have given a radiometric age of 2033 ± 44 Ma (K/Ar on plagioclase) for this gabbro.

Mafic dyke swarm (group 5)

The mafic dyke swarm (Bossi and Campal, 1991) is found exclusively in the Piedra Alta Terrane. Rocks which collectively constitute the swarm are unknown east of the Sarandi del Yi-Piriapolis lineament. This lineament is thus proposed here as the eastern limit of the terrane. Members of this swarm have not been recognized either in the Arroyo Grande nor in the Montevideo belts (Figure III.22).

The gabbro-diorite dyke swarm displays a constant ENE structural trend with a mean strike direction of approximately N 70E. The width of the swarm is 150 km. as measured perpendicular (N 20W) to the mean trend. The eastern edge of the swarm has been subjected to a southward displacement for about 40 km, and as a result, dykes have been flexured in a simple shear regime which becomes more intense eastwards.

Most dykes are more than 1 km in length. The most common length is about 5 km, but they range up to 26 km. Dyke thicknesses range from 2 to 50 m. The thickness is practically constant along the dyke, and decrases only at the extremities of these intrusions. The walls are planar and parallel. In quarries, and other localities where the topography permits them to be observed easily, it is clear that they are subvertical but rarely they can dip up to 70 to the south. Longitudinal discontinuities of dykes can be related to: a) progressive thinning, b) dyke coalescence, or c) faulting at some orientation oblique to the trend of the dyke.

Geochemical data shows that there are two different groups of dykes, namely andesites and basaltic andesites (Bossi et al., 1990). The R1-R2 diagram of LaRoche (1980) shows the distribution of the samples (Figure III.23). Group A dykes (basaltic andesites) show "mg" values (MgO/ MgO + FeO), ranging from 0.25 to 0.31 whereas group B dykes have both higher "mg" values as well as a greater variation of "mg" than Group A: (0.40 to 0.56). Such differences indicate distinct stages of

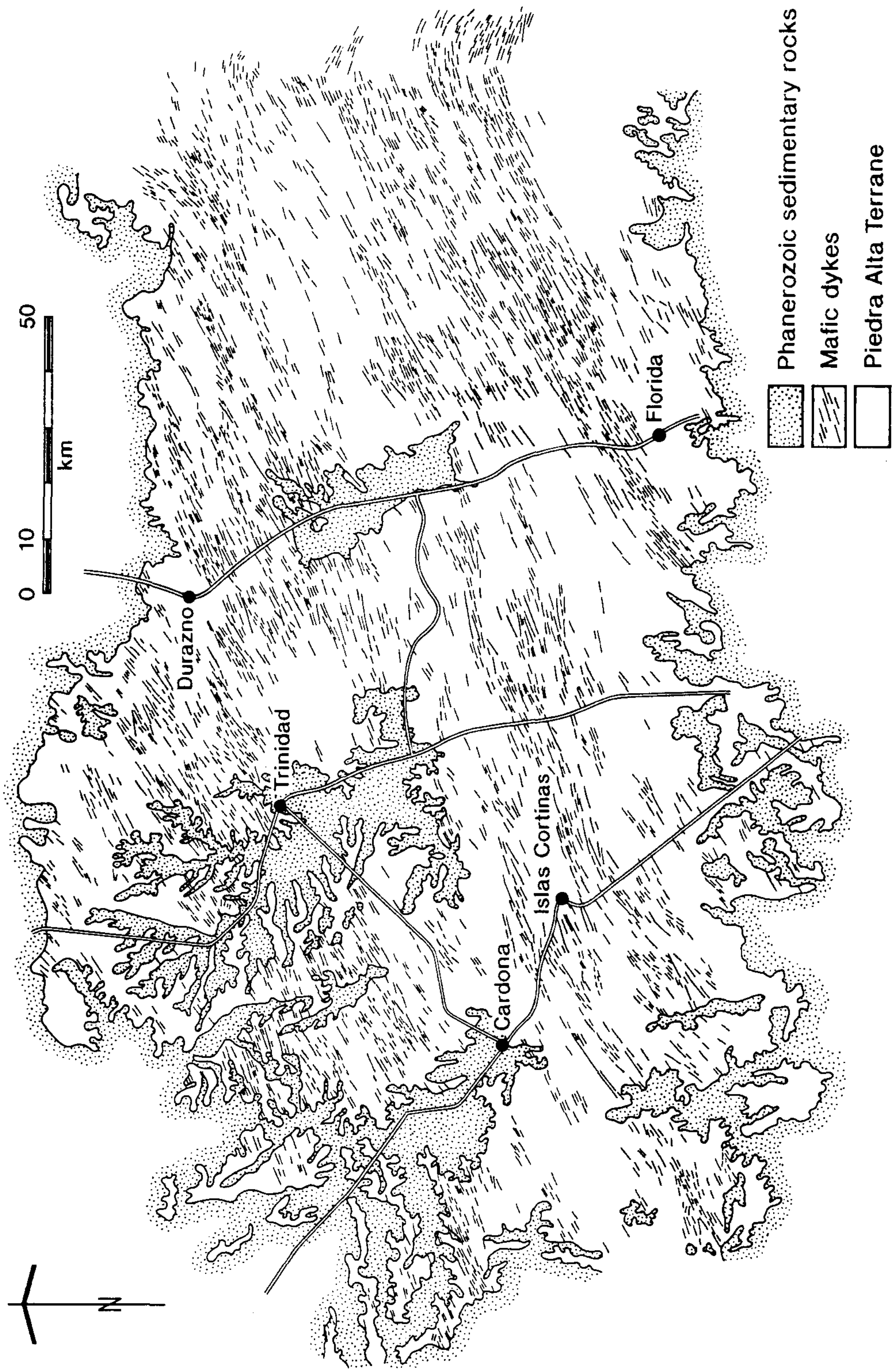


Figure III.22: Distribution of late basic dykes in the Piedra Alta Terrane. After Bossi et al., (1993).

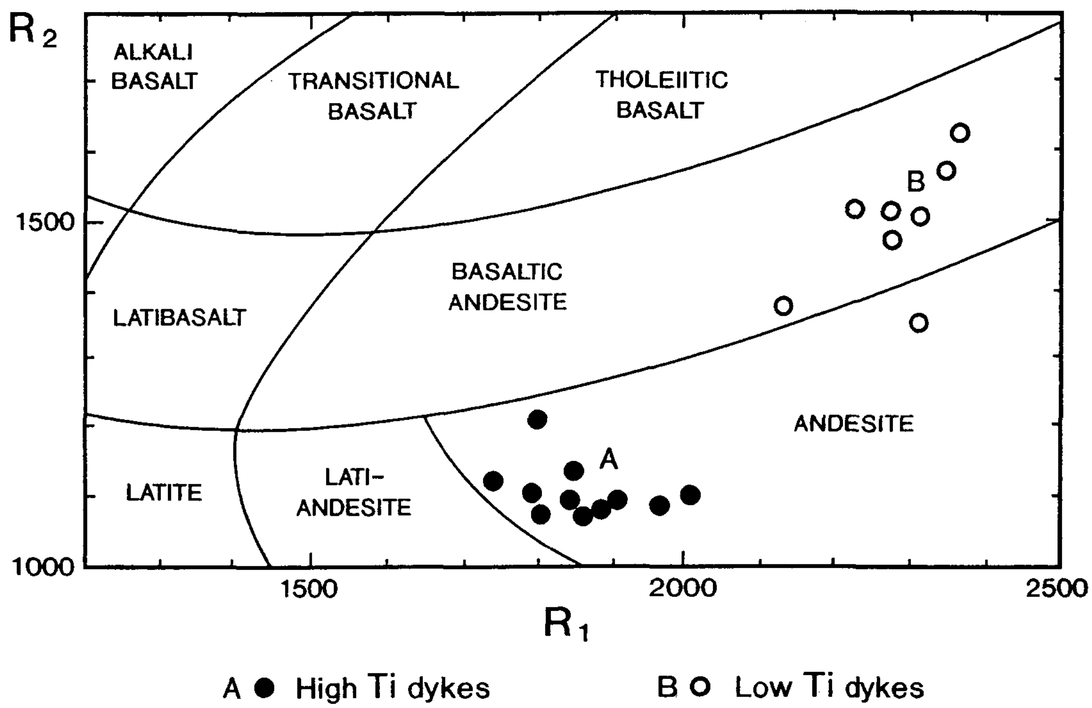


Figure III.23: R1-R2 classification diagram for the late dyke swarm, showing the presence of two distinct groups of basic dykes. After Bossi et al., (1993).

magmatic evolution which are closely related to the variable TiO_2 and incompatible element contents. The TiO_2 content has been used simply by itself to distinguish between the two geochemical groups of mafic dykes, (Piccirillo and Melfi, 1988). The grouping arrived at by this method coincides with that arrived at based on petrographic considerations and is as follows:

A) High titanium rocks, with weight percentage of TiO_2 between 1.5% and 2.4%.

B) Low titanium rocks with weight percentage of TiO_2 less than 1.05%.

Both groups of dykes also have important differences in trace element concentrations, suggesting origins from melts of different compositions. These two groups are closely associated in the field, however definitive cross-cutting relationships have not been observed to date.

Campal and Garat (1990) have carried out a detailed petrographic study of the dykes, both qualitative and quantitative. The dykes are holocrystalline, with plagioclase and pyroxene as the dominant minerals. Also present are essential or accesory quartz - feldspar intergrowths (micropegmatite) and opaques. The accessory minerals are apatite, amphibole and biotite. The most common texture is subophitic. Grain size of mafic rocks ranges from 0.1 mm. to 2.0 mm. in samples from the centre of the dyke.

Petrographic features (Table III.5) indicate the presence of two different petrologic groups.

The composition of the plagioclase crystals changes from core to rim (composition ranging from An 42 to An 65) and there are two compositional modes (An 45 and An 52-54) corresponding to the two groups. The main pyroxene is a non pleochroic subcalcic augite. In samples of Group B, orthopyroxene constitutes at least 10 % of the total amount of pyroxene. They are classified as "bronzite" based on their optical properties.

Opaque minerals are magnetite, ilmenite, pyrite and chalcopyrite, the last two representing just 5 % of the total volume of opaque phases. Intergrowths of magnetite and ilmenite occur, forming equidimensional euhedral to subeuhedral crystals. This kind of intergrowth is common in Group A and is situated within the pyroxene. Skeletal ilmenite is dominant in Group B.

Pyroxene-amphibole transformation (uralite) and biotite have been observed in rocks of Group A. Long, thin crystals of apatite, associated with micropegmatite, are always present. These dimensional relations of crystals, suggest a fast cooling, in accordance with their setting conditions.

Umpierre and Halpern (1971) originally determined whole-rock K/Ar ages of 1580 and 1640 Ma on two of the dykes. Gomez Rifas (1988) obtained K/Ar (whole-rock) ages of 1600 and 1400 Ma Teixeira (in Bossi et al., 1990) obtained two K/Ar biotite ages of 1790 Ma and 1830 Ma for samples taken at the contact between

TABLE III.5

PETROGRAPHIC CHARACTERISTICS OF THE TWO GROUPS OF MAFIC DYKES

CRITERION	GROUP A	GROUP B
plagioclase nucleus	An 42-An50	An52-An64
plagioclase (vol %)	35 - 43	47 - 56
micropegmatite (vol %)	15 - 26	2 - 10
opaques (vol%)	5 - 10	2 - 5
opaque shape	cubic like	skeletal
opaque type	magnetite-ilmenite	ilmenite
orthopyroxene	not present	rare

the host rock and the microgabbro dykes. Based on the probably better Ar retentivity of the biotite than the whole rocks, this author believes that the 1.8 Ga. age represents the approximate age of development of the thermal contact phenomenon due to dyke intrusion. An age of 1860 ± 120 ma (Rb/Sr method, whole rock isochron) was obtained for several dykes with an 87Sr/86Sr initial ratio of 0.7031 (Bossi et al., 1990). Recent 39Ar/40Ar determinations by P.Renne (pers. comm.) have yielded an age of 1790 ± 10 ma. The Sr isotope evidence combined with geochemical data suggest that the dykes are derived from a slightly enriched mantle or that they have a minor crustal contamination.

The nature and geometric relations of this dyke swarm suggest a regional extensional episode during the Statherian period which was related to the stabilization (cratonization) of the Piedra Alta Terrain. It is possible that the crustal thinning and lithospheric thickening proposed by Introcaso and Huerta (1982) are related to this extensional event.

TECTONICS

In this section we will only describe the most important structural features recognized in the Piedra Alta Terrane. The effects of successive deformations can be more easily studied within the metamorphic belts than in the granite-gneiss complex. In fact, when So is still identifiable, an indicator of the original spatial position is available. In brief, the analysis of the different tectonic phases affecting all the rocks of the area, based on the observed deformations within these belts, suggest that all the component regions of the terrane (the metamorphic belts as well as the gneissic terranes) have experienced an identical or similar evolution. At present, geochronological data do not enable the age of the metamorphic events to be established precisely within the belts, because all the available data record the age of crystallization of the magmatic rocks.

The San José Belt (mainly low grade metamorphic rocks) was first deformed into regionally continuous E-W folds. A second period of deformation, of major importance, overprinted the early E-W tectonic grain of this belt, either breaking it up into discrete units limited by faults in the western portion of the belt (Department of Colonia) or generating a plastic deformation as in the Department of San José (see Figure III.13). Medium and low-grade lithologies as well as tectonic contacts between them, were all affected by this later phase of deformation, and therefore the discontinuities are older than this phase.

A tectonic phase which overprinted the different grades of metamorphic rocks was subsequently recognized. This phase occupies an intermediate stratigraphic position between metamorphism and associated folding (the first deformation mentioned above) and the second phase related to the flexure and segmentation of the belts. The granite-gneissic complex and the San José belt are also separated by tectonic limits, in this paper assigned to the same phase.

Similar structures can be detected (with difficulty) in the granite-gneiss complexes. In these areas, gneissic peraluminous granites are present which are of an enlongated shape (see Figure III.8). The available data indicate a similar tectonic evolution for the granite-gneiss complex and the Arroyo Grande and San José belts, at least with respect to the two main tectonic phases of deformation referred to above. An extrapolation of this kind of deformation across the whole Terrane seems to be reasonable.

Granitic bodies associated with the San José belt can be divided in two main categories, based on the observed plastic deformation. Two typical examples will be considered, the Isla Mala granodiorite and the Mahoma granite. The first one shows intrusive relations with low-grade metamorphic rocks along its southern margin whereas progressive deformation and concordant structures are developed along the north side of the intrusion where it is in contact with the granite-gneiss complex. On the other hand, the Mahoma granite is clearly post-tectonic, without any evidence of having experienced plastic deformation.

Although a similar evolution for the granite-gneiss complexes and the metamorphic belts may be accepted, at least for the two last tectonic phases, based on the available data, the origin and early history of the granite-gneiss complexes remains obscure. These rocks may be primitive basement which experienced a complex evolution and metamorphism which attained anatectic conditions during the last tectono-thermal event (Transamazonian event).

Summary of Pertinent Data for the Model

If the Piedra Alta Terrane may be considered as a tectono-stratigraphic unit, then a model for the geological events determining its whole architecture may be tentatively proposed.

A Transamazonian age for the main deformational phenomena was the preferred model for the area prior to 1986. The presence of granitic pebbles in meta-conglomerates of Arroyo Grande Belt (Ferrando and Fernandez, 1971) argued in favour of the existence of older basement in the area. Nevertheless, its geometry and the location of this old basement were unknown.

Recently obtained isotopic age data (some of which were presented in chapters 1 and 2) for a number of intrusive bodies emplaced into the San José and Arroyo Grande metamorphic belts now clearly indicate that the metamorphism and main folding events are pre-Transamazonian in age.

Consequently any tectonic model for the Piedra Alta Terrane must take into account the following facts:

1) Existence of 2500 ma magmatic rocks intruding the metamorphic belts

2) Granitic bodies intruding these metamorphic belts as well as the adjacent granite-gneiss complexes having Transamazonian radiometric ages (2000 ma).

3) Some intermediate radiometric ages showing isochrons with highly scattered data points.

4) Existence of structures which suggest the tectono-thermal evolution originally proposed by Campal (1990), namely:

a) E-W trending structures with plastic tight folding associated with the main metamorphic episode.

b) thrust structures superimposed on folded metamorphic rocks.

c) a late stage of open folding which caused a NW trending reorientation of the main foliation direction of the San José belt.

Pre-Transamazonian ages obtained from some intrusive granitoids suggest that the metamorphism of the San José and Arroyo Grande belts occurred either in the very early Proterozoic or possibly in the upper Archean.

Available geochronological data supporting the existence of at least two domains, are presented in Figure III.24. Between the pre-Transamazonian ages (greater than 2300 Ma) and Transamazonian ones (1900-2100 Ma), a third group of intermediate radiometric ages can be recognized.

The first group, in the 2400-2500 Ma range, corresponds to the Isla Mala granodiorite. The granitic blocks inside the Paso de Lugo Fault have Archean ages (2544 and 2501 Ma).

The second group (2100-2300 Ma) corresponds to the Marincho granodiorite, the Isla Mala and Arroyo de la Virgen leucogranites, to the other lithologies associated with the

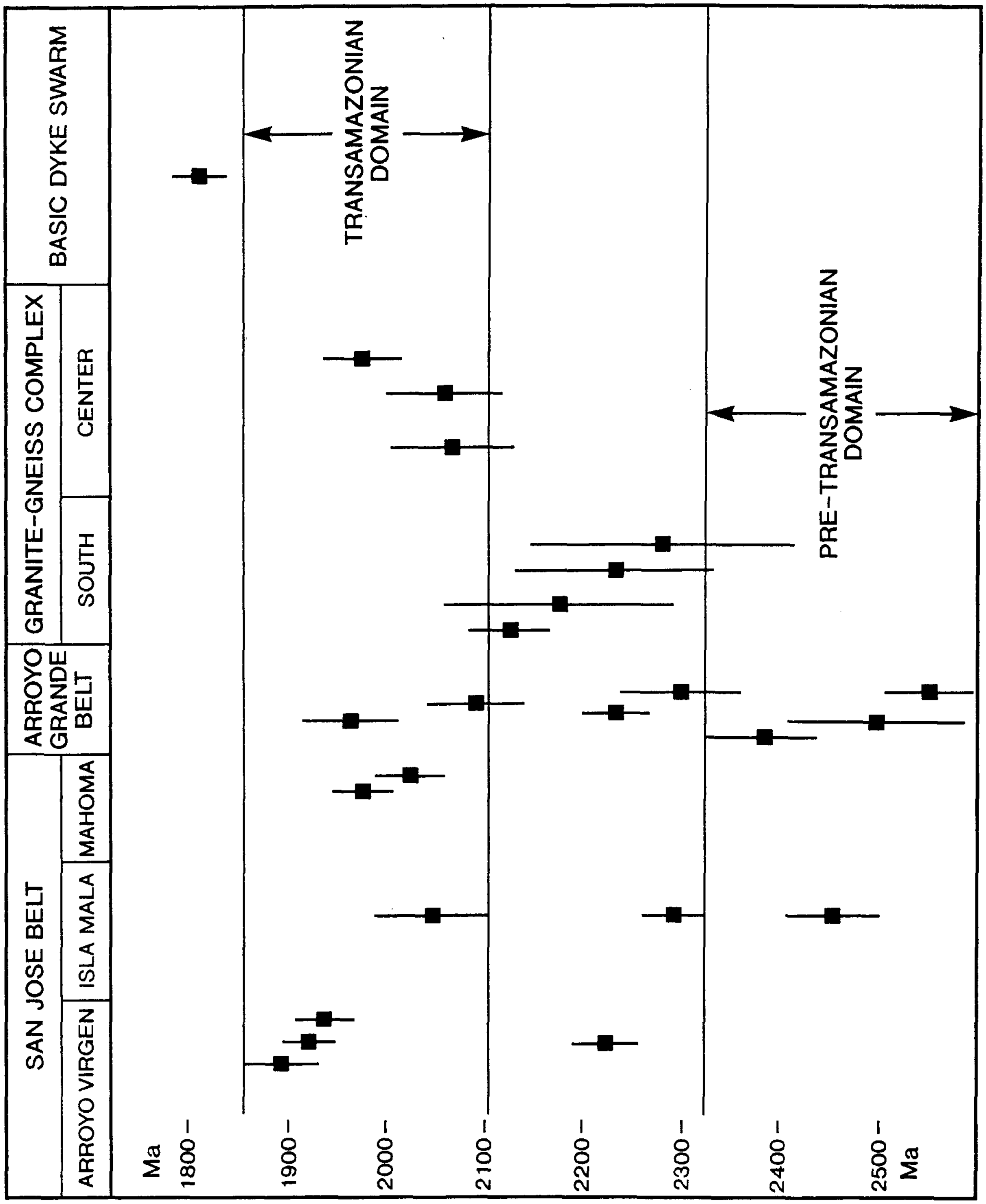


Figure III.24: Summary of the available radiometric age data for rocks of the Piedra Alta Terrane

Marincho complex, and to the southern portion of the granite-gneissic complex: Carreta Quemada, Pueblo Gonzales and the migmatites of the AFE quarries (near the town of Suarez).

The third group (1900-2100) is clearly related to Transamazonian granitic activity: Arroyo de la Virgen, Isla Mala and Marincho late dykes; Marincho leucogranite; Cerro Colorado (Department of Florida), Cerros de San Juan (Department of Colonia) and Mahoma (Department of San José) granites.

In the granitic-gneiss complex a group of intermediate ages have been determined which have large uncertainties. Considering that the Transamazonian event could thermically affect the primary age of pre-existing rocks (opening the Rb/Sr system for some of the component minerals), the large uncertainties are not in factsurprising and the whole rock ages obtained from these rocks should be viewed with caution. The youngest values obtained, considering the error interval, suggest that these ages might be syn-tectonic to the last tectono-thermal event.

The Proposed Model

The above data can be integrated into a model which applies to at least the SJB and the AGB, and which consists of the following sequence of events:

1) development of an "old" cratonic basement somewhere in the area. Evidence favouring such a basement includes the very high

initial ratio of the 1969 Ma dykes which are intrusive into the Marincho Complex (0.737) which can only have been derived by partial melting of much older upper crustal material. Also considered significant is the presence of cobbles of granitic material within the meta-conglomerates of the AGB. The source of these cobbles, and the location of the presumed old basement, remain unknown. Cordani et al. (1988) have suggested that, in Brazil, there exist two preponderant ages of older rocks, one of approximately 2700 Ma and another at approximately 3100 Ma. However these rocks are located to the north of the area considered here, and there is no evidence to suggest that the rocks that yield these ages are in any way representative of the hypothetical "old basement" of Uruguay.

2) development of the two volcano-sedimentary sequences (the SJB and the AGB). Metamorphism of these rocks to greenschist facies conditions. These metamorphic belts are dominated by the presence of mafic volcanic rocks, suggesting some similarity, possibly only superficial, to Archean greenstone belts in other parts of the world.

3) emplacement of at least one syn-tectonic granitoid intrusion (the main portion of the Marincho Complex) which does not appear to have been deformed but most certainly has been altered, sometimes rather strongly. The age of this intrusion is approximately 2450 Ma. There exists several "older" plutonic

bodies (Feliciano and Yí granites - age unknown) which have clearly been deformed.

It must be noted that this sequence of events is VERY similar to that recognized in the Abitibi area of Quebec (see discusion in chapter 2). Thus, by analogy, it is reasonable to suggest that the age of the plutonic rocks may by only slightly younger than the age of the metamorphic belts themselves. Carrying the anology further, it is possible that the lens-shaped distribution of rock types observed here is analogous to those observed in the Abitibi Belt. Such a lens-shaped distribution can form as a result of oblique subduction (Sylvester, 1988).

4) emplacement of the major portion of the plutonic granitoid rocks which are situated WITHIN the metamorphic belts. The age of these plutons range from approximately 2300 MA to 2200 Ma. The older of these intrusions have a chemistry suggestive of a syn-tectonic environment of emplacement, whereas the younger intrusions have a post-tectonic chemistry.

5) tectonic juxtaposition of all the above rocks with areas of high-grade granitic gneisses and migmatites. The contact between these two major assemblages of rocks are major fault zones with significant mylonite development. Numerous Rb-Sr age determinations on the gneissic rocks suggest that the metamorphism occurred between 2200 Ma and 2000 Ma - an event

known as the Transamazonian orogeny. The primary age of the gneisses is not known. The tectonic juxtaposition must have occurred after the metamorphism of the gneisses was completed and the gneisses has cooled to some extent - otherwise the greenschist facies mineral assemblages in the "greenstone-like" metamorphic belts would not have been preserved. The elongated (oblong) shape and massive texture of the Arroyo Grande Pluton, which was emplaced into one of the major fault zones and which has been dated at 1969 Ma, suggests that tectonic assembly had been completed by this time (ie during Transamazonian time)

6) emplacement of a number of granitoid dyke rocks into the pre-existing plutons. Available Rb-Sr age data suggest that these dykes are post-Transamazonian, ranging in age from 1900 Ma to 2050 Ma. The chemistry of these rocks is variable, however some are clearly Fe-rich post-orogenic rocks. As yet, these dykes have not been observed in the gneissic rocks

7) emplacement of a mafic dyke swarm into both the metamorphic belts and the gneissic rocks. These mafic dykes have been dated by several different methods and have yielded a variety of ages, however the author believes that the most reasonable for the age of intrusion is approximately 1800 Ma.

8) development of a major fault zone (the Sarandi del Yí - Piriapolis Lineament) along the eastern margin of the Piedra Alta Terrane, separating it from the adjacent Nico Perez

Terrane. The mafic dyke swarm is not present in the Nico Perez Terrane, thereby indicating that the tectonic activity which juxtaposed these two terranes is post-dyke (post 1800 Ma) in age.

The relationship of the Montevideo Belt

The Montevideo belt represents the only assemblage that could have been metamorphosed during the Transamazonic orogeny only, but the absence of geochronological data in the metamorphic rocks makes this statement speculative. The age of the muscovite pegmatites of Arroyo Pando and 101 Road range between 1900-2100 Ma, (Hart, 1966) and are consistent with a Transamazonian age, however this should not be considered as definitive because the relationship of the dated material to the Montevideo belt as a whole is not clear. Campal (pers. comm) thinks that this type of pegmatite is genetically related to the "S" type granite injections which are found in the Mosquitos Formation. Thus, with the possible exception of this belt (with a doubtful age) it can be definitely stated that supracrustal rocks of Transamazonian age have not yet been recognized within the Piedra Alta Terrane.

Possible correlations on a larger scale

Other areas of either Archaean or Early Proterozoic rocks have been identified in the southern portion of South America, however their relationship to the Piedra Alta Terrane is largely speculative.

The Tandilia region of Argentina is the centre of a long sliver of Proterozoic rocks which is approximately 400 km in length and 50 km in width, (see Figure III.25). The centre of this band of rocks is located about 400 km southwest of Montevideo. Dalla Salda et al. (1988) suggest that the Piedra Alta Terrane and the Tandilia rocks have numerous features in common, including the age and nature of the plutonic rocks, the metamorphic grade of the host gneisses and the orientation and sequence of development of the observed structures. For this reason, they propose that the rocks of the two areas form a common geotectonic unit. However Ramos (1988) proposes the presence of suture zone along the northern margin of the Tandilia rocks (see Figure III.25), thereby casting doubt on the validity of this correlation.

The fact that the mafic dyke swarm mentioned above is not found east of the Sarandi del Yí - Piriapolis Lineament clearly shows that the Nico Perez Terrane evolved independently of the Piedra Alta Terrane in spite of their superficial similarities. Therefore the Piedra Alta Terrane can only be correlated with rocks which are located to the west of this fault zone. The closest rocks to the north of the Piedra Alta Terrane which

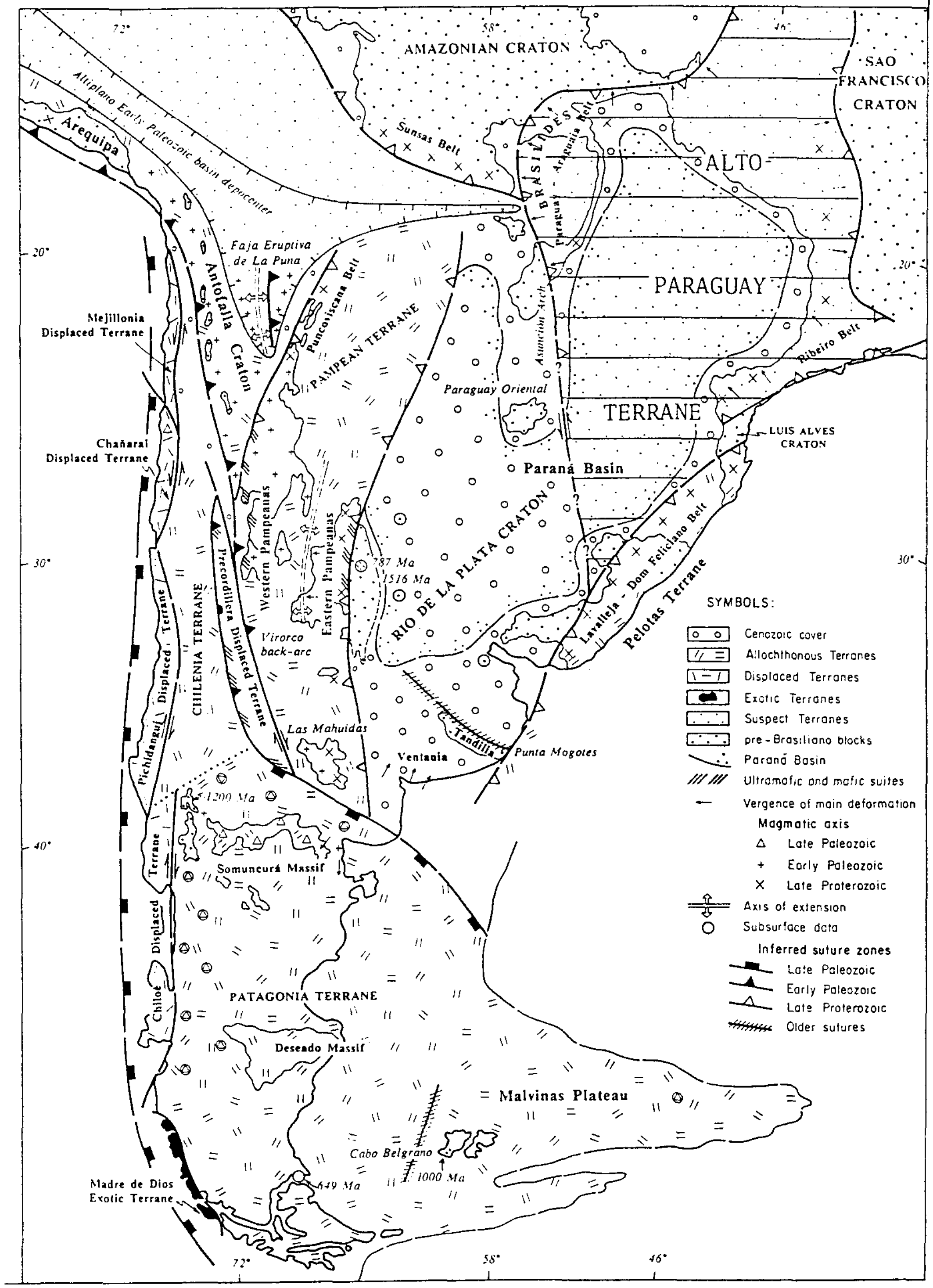


Figure III.25) Main cratonic blocks and allochthonous terranes of southern South America. Horizontal lines indicate the extent of the Alto Paraguay Terrane (after Ramos, 1988).

satisfy this requirement are located 1000 km north of Montevideo in eastern Paraguay (the Paraguay Oriental exposures), the intervening area being covered by younger rocks. The Paraguay Oriental rocks may themselves belong to the much larger Amazonian Craton which is located even further north in Brazil, however this also is speculative, since the area between these two is also covered by younger material. Thus, for the moment, the Piedra Alta Terrane must be considered as an entity unto itself, not demonstrably related to any other Precambrian rocks of South America. Porada (1989 and earlier papers) has written extensively on the striking similarity between the Precambrian rocks of southern Africa and those discussed above. He has proposed that a large area of Precambrian rocks, with underwent a complicated geotectonic evolution, was fragmented at approximately 1000 Ma only to undergo continental collision and reassembly at approximately 600 Ma (the Brasilian orogeny). While this may be a useful model on a grand scale, it has been emphasized above that even the South American portion of this larger area of Precambrian rocks consists of a number of terranes which are distinct either because of the lithology, metamorphic grade or structural orientation of the observed units or because of the age of the deformation. This hypothesis must therefore be continuously revaluated, and possibly modified, as more information becomes available and as the relationship between the different areas of Precambrian rocks of southern South America, and adjacent Africa, become better understood.

Closing Comment

Finally the author offers a closing comment concerning the apparent absence of Lower Proterozoic volcano-sedimentary belts in the area described above. Three hypotheses can be proposed to explain this observation:

1) No such volcano-sedimentary basins developed in the interdomain period (2500-2100 Ma) in the Piedra Alta Terrane.

2) The Piedra Alta Terrane originally contained such rocks, but they were subsequently completely eroded - in spite of the preservation of low-grade supracrustals rocks of the pre-Transamazonian domain.

3) The rocks are in fact present but they have not yet been recognized at the present.

Additional geological and geochronological information, which hopefully will become available in the next few years, will enable meaningful choices between these alternatives (or possibly other alternatives as yet unenvisaged) to be made, and in addition should shed some light on the nature, age and regional significance of the Transamazonian orogeny in Uruguay.

Conclusions

The three periods of intrusion of granitoid rock discussed in chapters 1 and 2 are consistent with a model involving two distinct periods of orogenic activity.

1) The first orogenic episode is of Archean age (earlier than 2544 Ma) and is associated with the development of the volcano-sedimentary belts and the deformed plutons located within them.

2) The second orogenic episode is of Early Proterozoic age (2290 - 2180 Ma) and is associated with the emplacement of most of the massive granitoid rocks described in the report. At approximately the same time, the area underwent a tectonic assembly - different blocks of crustal material, of different metamorphic grade and possibly different primary age, were welded together to form the Piedra Alta Terrane. This episode is considered to be the Transamazonian orogeny. The relationsip between the timing of metamorphism in the granitic gneisses and the intrusion of the granitoids is not clear and will require additional age determinations.

3) A number of granitic dykes and small intrusions were emplaced into the pre-existing granitic rocks between 2040 Ma and 1894 Ma. They are either very late Transamazonian or possibly post-Transamazonian.

4) The whole area was intruded by a swarm of gabbroic dykes at approximately 1800 Ma. They are undeformed and unmetamorphosed - therefore the Transamazonian event had definitately ended by this time.

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APPENDIX 1

AN OVERVIEW OF THE PREDEVONIAN SHIELD OF URUGUAY

The Uruguayan crystalline basement may be subdivided in three major structural provinces: Piedra Alta Terrane, the Nico Perez Terrane and the Cuchilla Dionisio Belt (see Figure 1). The last two provinces belong to the Brasilian cycle sensu Almeida (1973) because they contain lithostructural units which were deformed during Late Proterozoic time, and also a number of 500-700 Ma granitoid intrusions. The boundaries between these provinces are major shear zones. Studies of kinematic indicators in these shear zones reveal that the Nico Perez Terrane moved southwards from its original position relative to the other two provinces. The western shear zone with regional trends N 10 W is called the Sarandi-Piriapolis lineament and had a dextral movement over 40 kms. The eastern shear zone contains syndeformational type "S" granites with subvertical planar structures in the north and subhorizontal ones in the south with vergence indicators to the SE. Basic and ultrabasic rocks have been observed along this boundary.

PIEDRA ALTA TERRANE

This structural province (Bossi et al., 1993) is the westernmost of the three and belongs to the Transamazonian Cycle sensu Almeida (1973), This event, which in Uruguay has previously been named the Ciclo Orogenico Antiguo after Bossi (1983), has been renamed here as the Piedra Alta Terrane. A synthesis of this unit was made by Campal (1990) who recognized three deformation phases predating 2000 Ma followed by cratonization during the Estaterian (1900 Ma) and the development of an exceptionally intense microgabbro dyke swarm during Calymmian times (1700 - 1800 Ma).

New radiometric data indicate that the age of the intrusive leucogranites with ENE structures is 2290 ± 35 Ma (initial ratio of 0.7113) using the Rb/Sr method on the whole rock. Therefore it is reasonable to place the metamorphism near the beginning of the Early Proterozoic.

Four different elements may be recognized in this terrane: Arroyo Grande Belt, San José Belt, Montevideo Belt and the Granitic-gneissic complex.

The Arroyo Grande Belt is located along the northwestern margin of the Uruguayan Crystalline terrane, which forms the basement of the Piedra Alta Terrane. The AGB consists of greenschist facies metasedimentary and metavolcanic rocks which are exposed in a lozange-shaped area approximately 40 km in length with a maximun width of 13 km. Detrital metasedimentary rocks (with minor metavolcanic units) constitute the lower and middle sections of the formation and are exposed along the northern and central portions of the outcrop area of the AGB. The metavolcanic rocks, the uppermost portion of the AGB, are exposed along the southern margin of the lozange. Both rock types typically have overall east-west strike. The Paso de Lugo fault, a major structure of considerable linear continuity and east- west orientation, forms the southern boundary of the lonzage, separating it from granitic-gneisses and related

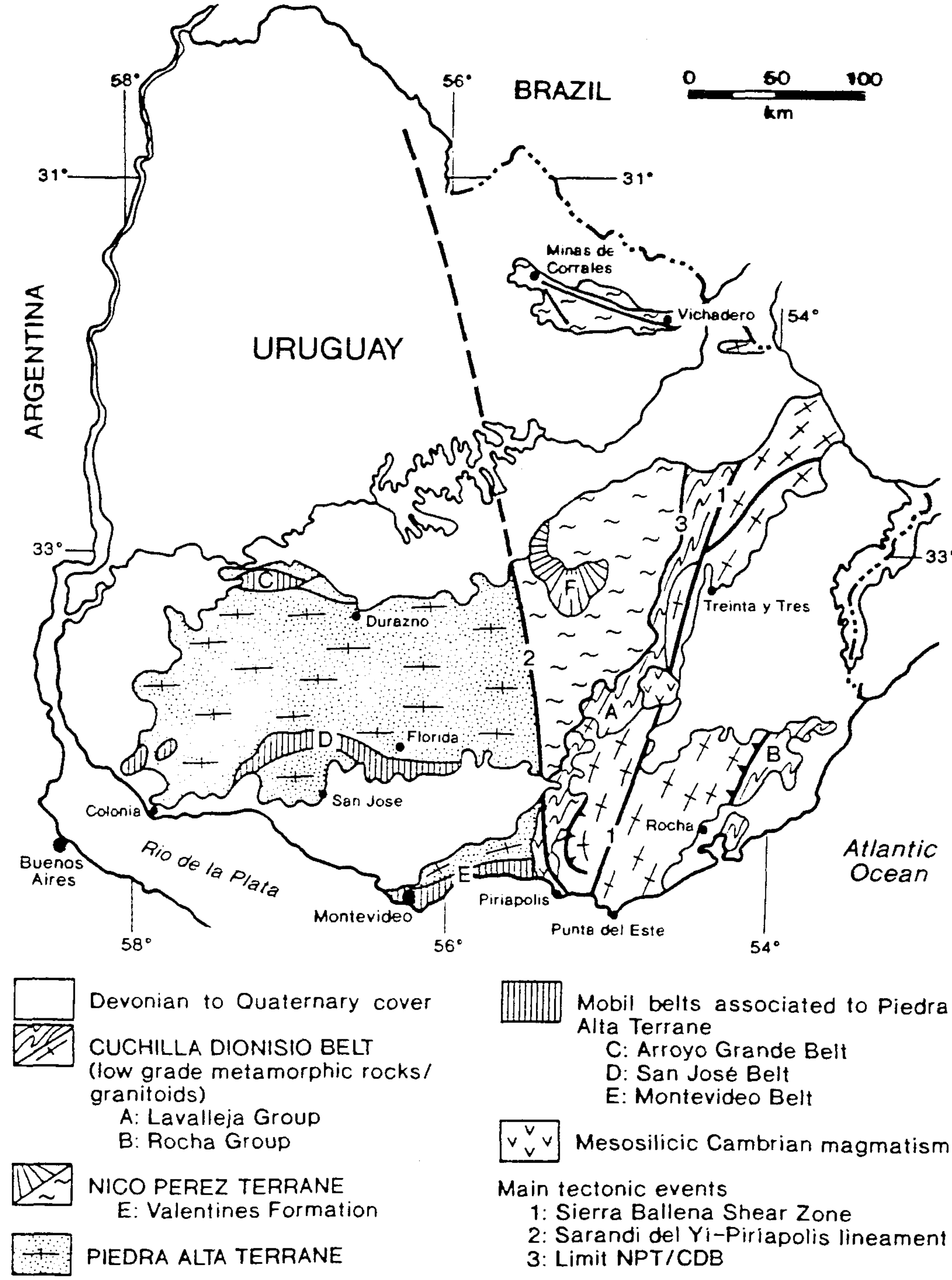

Figure A-1: Geological sketch map of southern Uruguay, showing the location of the different "terranes". After Preciozzi et al., (1991).

granitic rocks to the south. The Paso del Puerto fault forms the northwestern boundary of the AGB. Several granitic bodies have been intruded into AGB.

The San Jose Belt is an east-west trending belt consisting of a low- to medium-grade volcano-sedimentary series. The northern limit of the belt is a tectonic contact with high-grade orthoamphibolites whereas in the south the rocks are transformed into a sequence of amphibolites, gneisses amd kyanite-sillimanite micashists. At least two demormational phases have been recognized in this belt. The first phase, syn-metamorphic, is folded about vertical axes whereas the second generation of folds are of large amplitude and have a horizontal axis. The second phase affected the late tectonic 2300 Ma granitoids and yet have controlled the emplacement of a 2000 Ma gabbro-granitic-complex which are preferentially located in the cores of these structures, (Mahoma, Guaycuru).

Some authors have interpreted these associations as greenstone belts (Fragoso et al., 1987; Fesefeldt, 1988) of possible Archean age, but the absence of komatiites and other ultrabasic rocks, and the clear predominance of a non-pelagic sedimentary sequence, argues against this hypothesis. The belt really has the same lithologic and tectonic features as those of the surrounding rocks, so it is preferable to consider them as metamorphic relicts of a typical ensialic volcano-sedimentary sequence.

The Montevideo Belt is a roughly west trending metamorphic belt and it is situated along the extreme southern margin of the Piedra Alta Terrane in the departments of Montevideo and Canelones. The three main lithologies so far identified are: oligoclase gneisses, amphibolites and micaschist. The structural conformity and homogeneity of metamorphic facies were the main critria used to define this belt.

The granitic-gneissic complex (and related migmatites) is exposed along both sides of the San José belt and consists mainly of a series of foliated anatectic porphyritic granitoids associated with different types of gneisses.

To the south of the San José belt, syntectonic granites and migmatites have been dated at 2200-2300 Ma and are contemporaneous with a number of late tectonic, shallow-level intrusive granites (eg. Isla Mala and Arroyo de la Virgen plutons).

North of the San José belt, the granitoids and migmatites have been dated at 2000 Ma. Campal (1990) demonstrated that these gneisses have been affected by three periods of deformation. Included in this unit are a number of intrusive rocks, ranging from shallow intrusive gabbro-granitic complexs (eg. Mahoma) to anatectic deep seated granites (Florida, Cerro Colorado).

A very large swarm of microgabbro-diorite dykes is the last manifestation of magmatic activity recorded in the Piedra Alta Terrane. It consists of a large number of subparalell dykes, trending N 60- 80 E, which range in length up to 20 kms and are typically about 20 meters in width. Recent geochronological studies have yielded values of about 1780 ± 30 Ma (K-Ar on biotite from the country rock where it is in contact with the dyke). This E-W continuity of the swarm has been interrupted by a N 10 W dextral shear zone known either as the Sarandí del Yí fault (Preciozzi et al., 1979) or the Sarandí del Yí lineament (Bossi and Navarro, 1987).

SARANDI DEL YI - PIRIAPOLIS LINEAMENT

This regional mylonite zone ranges in width up to 15 km. Within this zone, the rocks have been deformed to varying degrees, and now range from cataclastites to ultramylonites. Bands of intensive recrystallization are commonplace. Locally, partial melting phenomena have been observed, generating lens of rhyolite with euhedral beta quartz, implying temperatures higher than 580°C at shallow depth. This lineament, which played a major role during the evolution of the Uruguayan Shield, may have been (re)activated a various times. Certain recrystallization phenomena, which were probably related to the latest movement within the belt, have been dated at 535 ± 15 Ma (Rb-Sr whole rock values recalculated from the data of Umpierre and Halpern, 1971). This date is from a mylonite located southeast of the village of Nico Perez, the protolith of which has dated at 1760 ± 30 Ma by the same authors. The temperatures which would have been attained due to friction as well as the grade of recrystallization observed in the rocks strongly suggest that the K-Ar isotopes would have been reset by such an event. Kinematic indicators at different scales all agree in showing dextral shear movement without a significant vertical component.

NICO PEREZ TERRANE

This structural unit consists of Transamazonian Shield rocks which were intensively affected by the Brazilian orogenic event, as well as supracrustal relicts and granitic intrusions. The Transamazonian rocks of this area contain lithostructural features which are completely different from those of the Piedra Alta Terrane. The Nico Perez rocks consist of high-grade metamorphic rocks such as the Valentines Formation (Bossi et al., 1965), a granitic-gneiss complex (dated 2100-2200 Ma, Cordani and Soliani, 1990) and related metamorphic rocks (Minas de Corrales -Vichadero region of northern Uruguay) which have been intruded by several Brazilian plutons (680 to 530 Ma).

During the Brazilian orogeny these lithologies were intensely deformed and intruded by plutonic rocks which locally modified the radiometric ages. Supracrustal rocks have been deformed and metamorphosed to variable degrees. In general, these relict outliers have been either little or not at all affected by metamorphic events in the Transamazonien Craton. It is believed that the Nico Perez Terrane was the foreland zone during the later Brazilian deformation.

CUCHILLA - DIONISIO BELT

This name has been proposed to describe the Brazilian mobile belt in Uruguay. It is defined by several subparallel N-E trending bands, each one of which is separated from its neighbours by shear bands along which displacements of several tens of kilometers has taken place. Figure A-2 is a geological-structural map of the southern part of the Dionisio Belt. From W to E, four distinct bands have been recognized (Bossi, 1983; Preciozzi et al., 1985; Preciozzi 1989f).

In the Lavalleja Group, supracrustal rocks of sedimentary origin and volcano-sedimentary rocks predominate. The metamorphic grade of both types of rocks is low, however the tectonic setting is completely different. The volcano-sedimentary rocks seem to have formed in an unstable graben setting, with thicknesses ranging up to 2100 m. The sedimentary rocks, which are possibly younger, constitute a typical platform sequence and attain maximum thicknesses of 1100 m. (Preciozzi, 1989e). Unmetamorphosed molasse, which is of Upper Cambrian age, unconformably overlies the Lavelleja Group.

The Carapé Group, consists of greenschist to lower amphibolite facies metamorphic rocks which locally reach the kyanite isograd. (Preciozzi, 1989e). These rocks consist mainly of gneisses, amphibolites and marble. A SW thrust has tectonically placed this unit over Lavalleja Group. Hypersthene orthogneisses are present as tectonic sheets within these

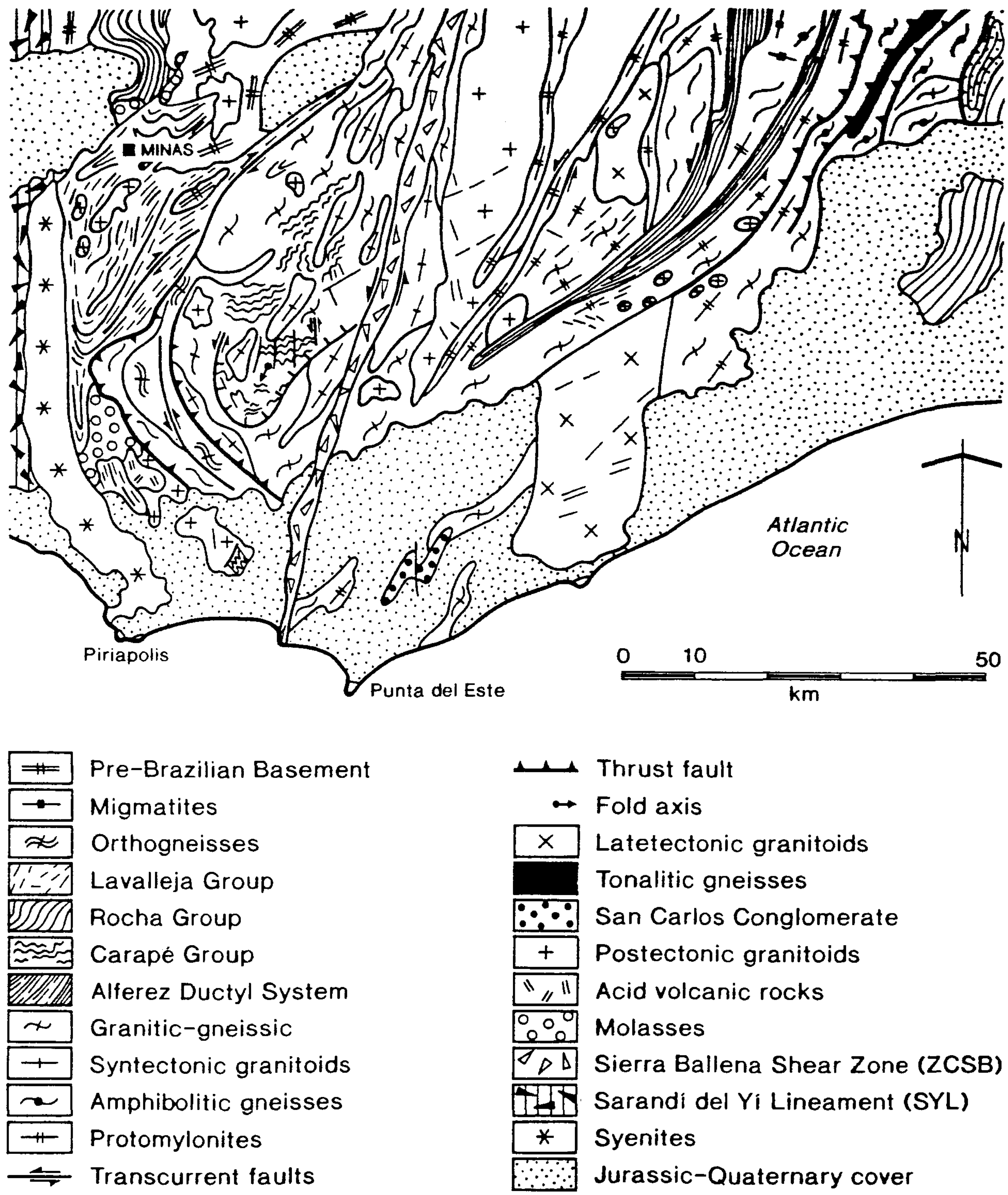

Figure A-2: Geological-structural map of the southern part of the Dionisio Belt metamorphic rocks. The origin of these granulite facies rocks is not understood, since they apparently formed during the Brazilian Orogeny. The Sierra Bellena Shear Zone (SBSZ) separates this group of rocks from the mainly granitic area which is located to the east. The SBSZ consists of cataclastic rocks, protomylonites and blastoylonites which are variable in nature. A subvertical foliation (N 20 E to N 30 E dipping 80 E) has developed as a consequence of significant sinstral displacement coupled with simultaneous inverse faulting.

The Central Gnessic-Granitic Band (CGGB) is the zone featuring the highest concentration of granitoid plutons. Different discrete intrusive events, of possibly different ages, are intrusive into one another to form a batholith "collage". Many of the intrusions are potassic alkaline rocks. Brazilian supracrustal rocks can still be recognized within the CGGB, (eg. the Paso del Dragon Formation, Preciozzi et al., 1985, and the metaconglomerates of the San Carlos Formation, Masquelin, 1990).

The major transcurrent mylonitic belts traverse the CGGB. Generally they are associated with thrusts, but here the vergence of the thrusts is the opposite of those described above (Masquelin, 1990).

The Rocha Group consists mainly of low- to very low-grade metamorphic pelitic supracrustal rocks. They have been subjected to the same sequence of deformational events as the Lavalleja Group. The macrostructural tectonic style is characterized by tectonic sheets and mylonites which dip steeply to the NW. The deformed Cerros Aguirres volcano-sedimentary succession overlies the Rocha Group. The contact between the two is possibly tectonic.

A summary of the tectonic evolution of the rocks which are currently considered to belong to the Dionisio Belt has been presented in Preciozzi et al. (1991).

BRAZILIAN MAGMATOGENESIS

Tectonic classifications of the setting of emplacement of granitic rocks has enabled the intrusions to be subdivided into a number of different groups. It was during the second deformational phase of the Brazilian Orogeny that the main structural trend (N-E) was developed and the oldest granites are syntectonic to this phase "2". They are of alkaline composition with a ratio of Na/K = 1.0. The Roche Granite is a typical representative of this group. Ages of approximately 680 Ma have been reported for these granites (Cordani and Soliani, 1990).

Late-tectonic granitoids were emplaced during phase "3" (eg. the Dionisio, Florencia, José Ignacio Plutons among others) and available data indicate whole rock ages of about 610 Ma. Typically the margins of these plutons contain a protomylonitic foliation which formed at approximately 570 Ma. The alkaline nature of the rocks and the Na/K ratio was not affected by the development of these protomylonites.

Post-tectonic granites (eg. the Aigua, Pan de Azucar, Minas, Santa Teresa Plutons among others) were not affected by Brazilian deformational events. Whole rock Rb/Sr data show a range of ages between 550 Ma and 580 Ma. They are still geochemically alkaline granitoids, however the post-tectonic rocks are potassic in nature.

DISTENSIONAL MAGMATISM

Several volcanic and hypabyssal units of somewhat diverse composition (basalts, syenites, trachytes and rhyolites...)have been dated between 500 and 530 Ma. Field observations show that the syenitic magmatism is later than the late-Brazilian molassss and blastomylonite zones, suggesting an extensional setting for emplacement. The Sierra de Animas, Sierra de los Rios and Valle Chico Formations are the only rocks which have, to date, been classified into this group.