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ANDEAN MAGMATISM: ITS PALEOGEOGRAPHIC AND STRUCTURAL SETTING IN THE CENTRAL PART (30°–35° S) OF THE SOUTHERN ANDES

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Abstract

In the central part of the southern Andes, three main paleogeographic periods (Geoliminal, Tardiliminal and Postliminal), preceded by an Embryonic Stage are recognized. These periods are characterized by intense sedimentary (mainly continental) and volcanic deposition and are separated and subdivided by five major orogenic and tectogenic phases: Araucanian (Late Oxfordian-Kimmeridgian); Meso-Cretacic or Subhercynian (Albian-Cenomanian); Laramic (Paleocene); Incaic (Late Eocene-Early Oligocene) and Quechuan or Pontian (Late Miocene). The effects of each phase are superimposed on those preceding and clearly indicate orogenic migration to the east. Orogenic phases are short and are followed by longer periods of "no compression" or of possible extension.

Geoliminal sedimentation is represented by two marine episodes separated by the Araucanian Phase. Sedimentary basins have a western or internal domain, essentially volcanic, and an eastern or external domain almost completely devoid of volcanics. Tardi-and Postliminal molassic basins were formed behind, in, or in front (back-, intra- and fore-deeps) of the paleoranges formed during each tectonic phase and were essentially filled with volcanic and volcanoclastic materials.

Volcanic activity is restricted to the longer periods between orogenic phases. Embryonic volcanism is of acidic composition and is concentrated along the western part of the studied region. Geoliminal volcanism is mainly acidic with some intermediate andesitic intercalations, near the top of the sequence. No ultrabasic rocks, common in other alpino-type mountains, are present. This volcanism was generated along an island arc. During subsequent paleogeographic periods volcanism began with rhyolites and ignimbritic rhyolites and was followed by andesitic flows and pyroclastics. It developed along paleovolcanic ranges superposed on older ranges formed during the preceding tectonic phase. Volcanic centers migrated eastward.

Andean volcanism is of a bimodal type (aluminous andesitic and rhyolitic); ophiolitic phases are absent. Volcanics are calcalkaline, rich in sodium and poor in potassium, except for a single Lower Cretaceous unit. Petrologic polarity is based on the increase in K_2O from west to east.

Plutonic-rock outcrops cover one third of the region. Field features correspond to postkinematic plutons. Granitoids belong to the calcalkaline series, with granodioritic, tonalitic, quartz-monzodioritic and granitic phases. Granodiorites and quartz-monzodiorites predominate. Both volcanic and plutonic rocks have an oversaturated calcalkaline character and no alkaline rocks are known in the studied region of the Andean Range. Plutonic activity is associated with important Cu, Fe, Mo and Zn mineral deposits.

Three main groups of intrusions are recognized on the basis of geochronological datings and stratigraphic relationships: Jurassic, Cretaceous and Tertiary. Their ages broadly correspond to the ages of the major tectonic phases. A clear polarity in time

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and space of the granitoid intrusions has been detected. This plutonic polarity has the same sense as the tectonic and volcanic polarities already described.

The Southern Andes have a rhythmic evolution. Short compressive phases are closely followed by postkinematic granitoid intrusions. Volcanism is concentrated in the longer periods of "no compression", in which initial acidic activity is followed by intermediate flows and pyroclastics. The close relationship in time between granitoid intrusions and acidic volcanic activity suggests a common origin for them.

The tectonic phases of the Southern Andes are synchronous with those of other regions of the Andes and other mountain ranges, but the absence of ultrabasic rocks and harmonious granitoids is an essential difference between Andean and alpinotype mountains. This difference may reflect their different geotectonic positions.

Introduction

The central part of the Southern Andes (between latitudes 30° and 35° S) reveal time and space relations between magmatism and the paleogeographic and tectonic evolution during the Andean Orogenic Cycle (Mesozoic-Cenozoic). The magmatic evolution of this part of the range is presented in relation to a previously established tectonic framework (CHARRIER and VICENTE, 1970). It deals exclusively with the development of the Andean Orogenic Cycle, which is the best known in this region of the Andes. The record of older cycles is scanty and scarcely studied.

Paleogeographic and Tectonic Evolution of the Central Part of the Southern Andes

GENERAL FRAMEWORK

Tectonic setting

Two principal sectors, with essentially different organizations and evolutions, are recognized in the Southern Andes during the Andean Orogenic Cycle (AUBOUIN and BORRELLO, 1966; VICENTE, 1970) (Fig. 1-A). A Geosynclinal Sector, lying south of 41° S, is principally constituted of sedimentary marine series deposited in an alpinotype geosyncline. Flysch sediments, ophiolites, nappes and high to intermediate pressure metamorphic series are present. A Geoliminal Sector, lying north of 41° S, consists mainly of a continental volcanic series, in which practically no flysch sediments, ophiolites, nor nappes and almost no regional metamorphism higher than greenschist facies are known. This sector has been proposed as a prototype for geoliminal-type of mountain ranges (AUBOUIN and BORRELLO, 1966; VICENTE, 1970, 1972; AUBOUIN *et al.*, 1973).

The contrast between sectors indicates a transition from a pericontinental position (*sensu stricto*) of the Geoliminal Sector to an intercontinental position (between the Patagonian and Antarctic Cratons) of the Geosynclinal Sector (AUBOUIN and BORRELLO, 1966). The region considered in this report lies within the Geoliminal Sector and is clearly pericontinental.

Morphostructural units

Late Miocene compressive basement folding and Plio-Pleistocene normal faulting produced five north-south trending morphostructural units from west to east (Fig. 1-B):

1. *Coastal Range*, corresponding essentially to a western Paleozoic axis with a back-land significance. On its eastern slope a thick Mesozoic series overlies unconformably Hercynian units.

2. *Central Valley*, lying between the Coastal and Main Ranges south of 33° S, and interpreted as a graben. This depression has been largely filled with Plio-Quaternary continental deposits.

3. *Main Range*, forming the boundary between Chile and Argentina. It is the highest morphostructural unit and is composed of a Mesozoic and Cenozoic series which form a western volcanic and volcanoclastic versant and an eastern sedimentary versant.

4. *Frontal Range*, representing a second (Late) Paleozoic axis. The Mesozoic series of the Main Range lies unconformably on its western versant.

5. *Precordillera*, representing a third (Early) Paleozoic axis, developed north of 33° S.

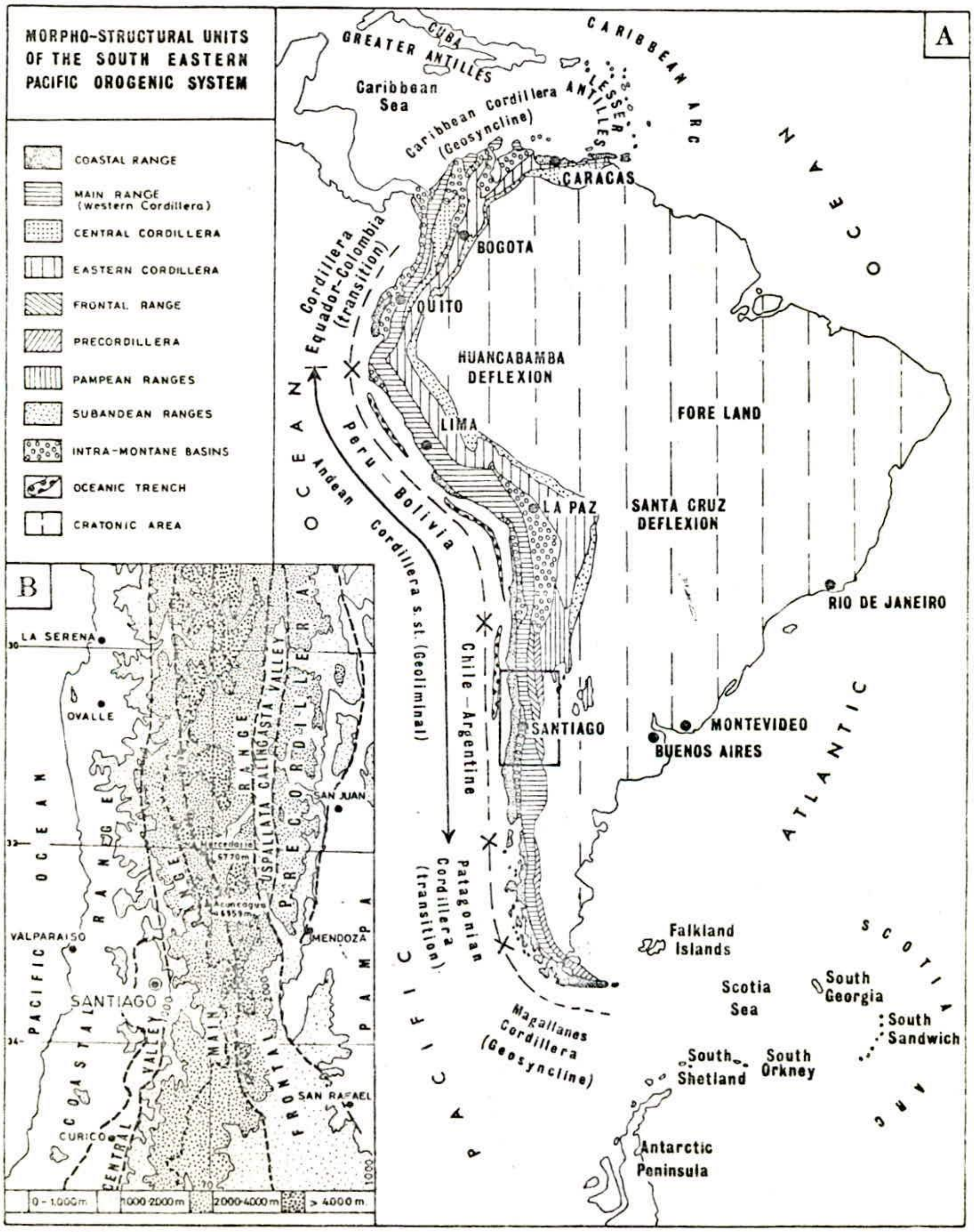

Fig. 1. A: Major morphostructural and geotectonic units of the Andean Range (modified from VICENTE, 1970). B: Morphostructural units of the studied region.

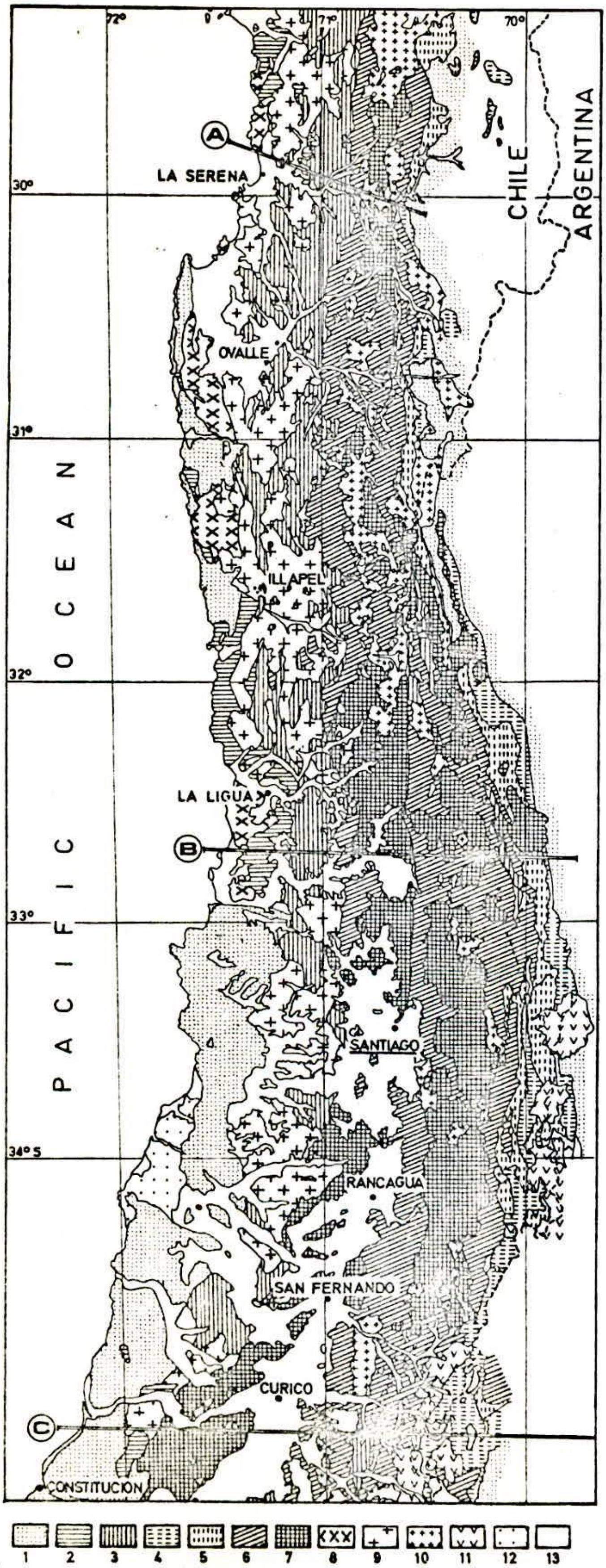

Fig. 2. General sketch of the stratigraphic-structural units of the central portion of the Southern Andes, between 30° and 35° S latitude (same area as in Fig. 1-B), after the Geological Map of Chile and recent work by the authors.

1, Basement (Pre-Andean units); 2, Triassic and Jurassic series of euliminal facies (internal zone); 3, Lower Cretaceous series of euliminal facies (internal zone); 4, Jurassic series of mioliminal facies (external zone); 5, Tithonian-Neocomian series of mioliminal facies (external zone); 6, Late Cretaceous series of the Abanico Paleovolcanic Range; 7, Paleogene series of the Farellones Paleovolcanic Range; 8, Jurassic granitoids; 9, Cretaceous granitoids; 10, Tertiary granitoids; 11, Plio-Pleistocene volcanics; 12, Tertiary marine molassic sediments (Navidad Fm.); 13, Plio-Pleistocene gravels.

A, B, C: location of profiles of Fig. 3.

If actually the deep-sea Peru-Chile Trench was formed by the sinking of a crustal block (graben), it should then be included in this morphostructural division. Its age is probably Plio-Pleistocene.

The north-south trend of these morphostructural units is oblique to the main paleogeographic elements which have a NNW orientation.

The studied region may also be divided into a northern part (north of 33° S) in which the Precordillera is present but the Central Valley is not developed, and a southern part (south of 33° S) in which the Central Valley is present concomitantly with recent volcanic structures on the Main Range and the Precordillera is not developed.

The Andean series (Mesozoic-Cenozoic), which crop out along the eastern versant of the Coastal Range and along the Main Range, forms a wide hanging synclinorium inserted between two basement anticlinoriums, namely, the western versant of the Coastal Range, and the Frontal Range (Fig. 2). These units crop out mainly along north-south stripes but are slightly deflected to the west at latitude 32° S.

Major orogenic phases

During the Andean Orogenic Cycle five major compressive phases have been recognized (CHARRIER and VICENTE, 1970): Araucanian (Late Oxfordian-Kimmeridgian); Subhercynian, Peruvian or Meso-Cretaceous (Albian-Cenomanian); Laramic (Paleocene); Incaic (Late Eocene-Early Oligocene); and Quechuan or Pontian (Late Miocene).

These phases show a remarkable synchronism along both sectors of the Southern Andes, for homologous zones (internal or external) of the range. All phases generated relief and structures (orogenic and tectogenic) and are recognized by pronounced angular unconformities and thick sequences of terrigenous deposits.

These phases separate six depositional periods which correspond to the different paleogeographic periods of no compression or of possible extension. These deposits were accumulated in basins formed after each tectonic phase and folded by the tectonic phase which closed the depositional period. The folded sequences constitute presently six different structural units which, according to their ages, are folded with variable intensity.

The profiles in Figure 3-A, B, C show the tectonic style of the Andean Range in the studied region. The Andean series, accumulated towards the western side of the range, form only broad warps because of their great thickness and competent behavior, whereas the eastern deposits are more strongly folded essentially because of the lack of competent volcanic intercalations. Normal faults of Plio-Pleistocene age, cut through the whole pile and correspond to a post-tectonic extension period. Angular unconformities which evidence the compressive tectonic phases, appear clearly in the profiles (indicated by the letter D).

PALEOGEOGRAPHIC AND STRUCTURAL EVOLUTION

In spite of some axial variations and other differences, the synchronism and similarities in the evolution of isopic zones of the studied region is remarkable. Three successive paleogeographic periods have been distinguished: Geoliminal, Tardiliminal and Postliminal (AUBOUIN and BORRELLO, 1966; AUBOUIN, 1972), which were preceded by a short Embryonic stage. Six profiles showing the paleogeographic organization at different periods of the Andean evolution are presented in Figure 4.

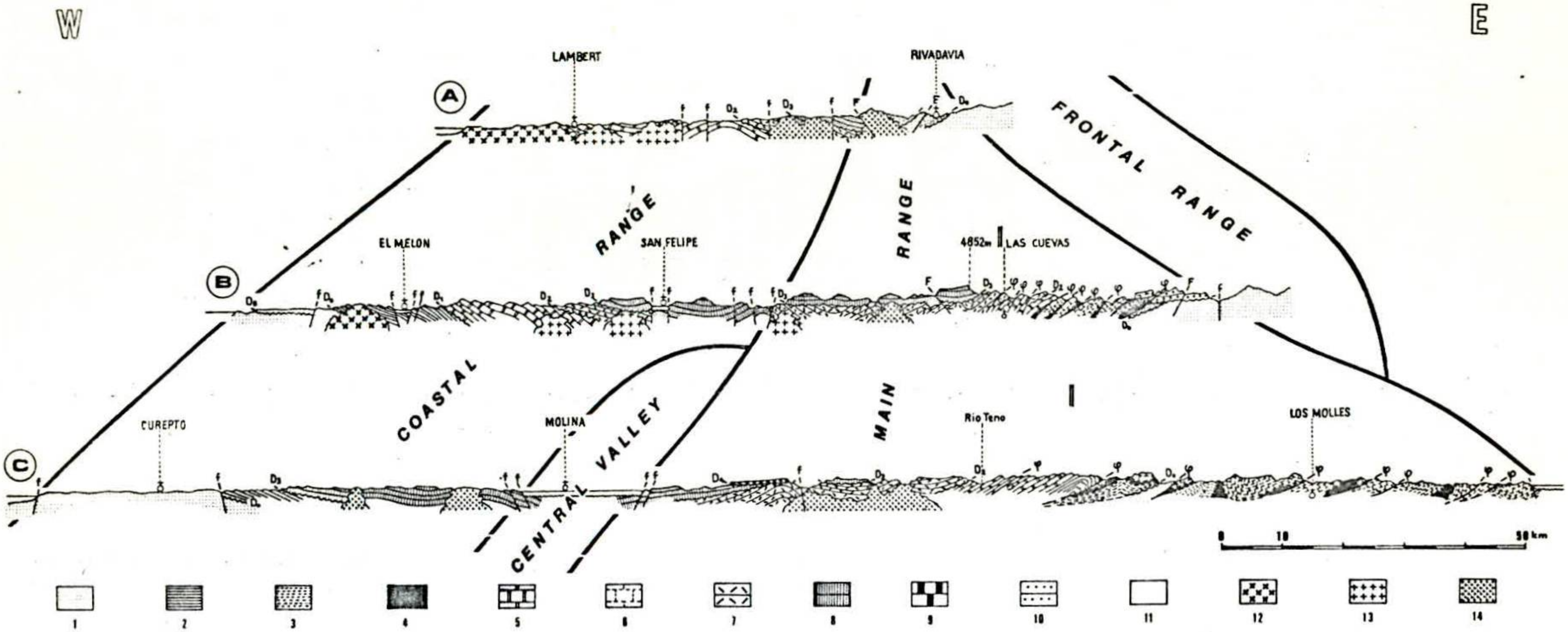

Fig. 3. Selected structural profiles across the Coastal and Main Ranges along the central portion of the Southern Andes (profiles without vertical exaggeration).
Lithology: 1, Basement (Pre-Andean units); 2, Late Triassic to Middle Jurassic internal series; 3, Late Liassic to Oxfordian marine series (external zone); 4, Upper Oxfordian evaporites (external zone); 5, Lower Cretaceous series (internal zone); 6, Tithonian-Neocomian marine series (external zone); 7, Late Cretaceous volcanic and volcano-clastic molasses (Abanico Fm.); 8, Paleogene volcanic and volcano-clastic molasses (Farellones Fm.); 9, Miocene volcanic plateau; 10, Oligo-Miocene red-beds (fore-deep); 11, Plio-Quaternary gravels; 12, Jurassic granitoids; 13, Cretaceous granitoids; 14, Tertiary granitoids.
Structure: f, normal faults; F, reverse faults; φ, Thrusts; D_0, Transgression (Unconformity) of andean marine series over the basement; D_1, Araucanian unconformity (Upper Jurassic); D_2, Mid-Cretaceous unconformity; D_3, Laramic unconformity (Paleocene); D_4, Incaic unconformity (Late Eocene-Early Oligocene); D_5, Quechuan unconformity (Late Miocene).

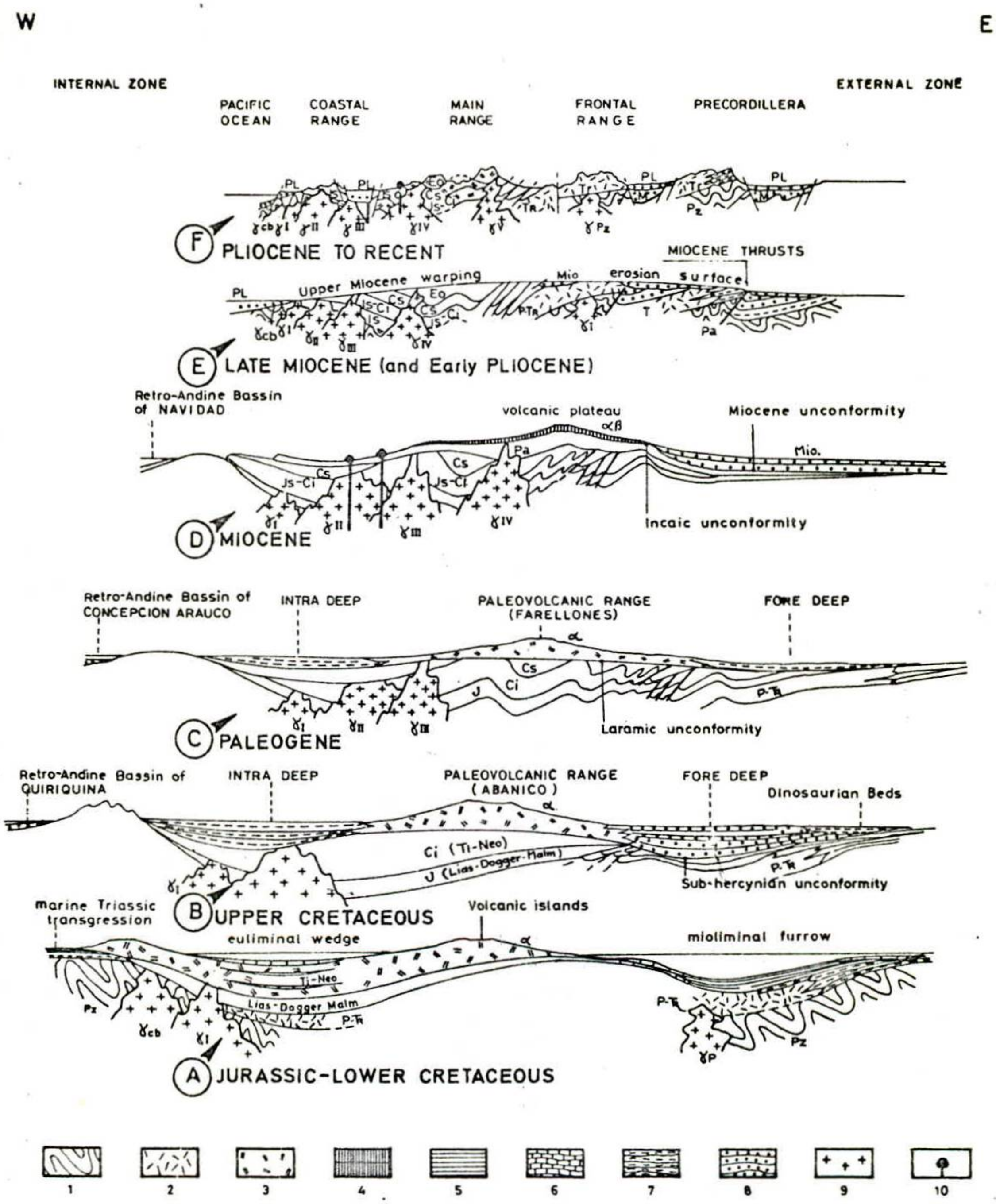

Fig.4. Schematic paleogeographic evolution of the central portion of the Southern Andes along 32° south latitude (according to AUBOUIN *et al.*, 1973).

1, Paleozoic metamorphic series (Pz); 2, Permo-Triassic acidic volcanism (P-Ŧ); 3, volcano-clastic deposits and andesite flows (α); 4, basaltic-andesitic plateau ($\alpha\beta$); 5, marls; 6, neritic limestones; 7, volcanic graywackes and conglomerates; 8, red-beds and sandstones; 9, granitoids (γ_{cb}: Carboniferous; γ_P: Permian; γ_I; Late Jurassic; γ_{II}: mid-Cretaceous; γ_{III} : Late Cretaceous to Lower Tertiary; γ_{IV} : Middle to Upper Tertiary; γ_V : Late Miocene).

Embryonic Stage (Upper Triassic: Anissic to Carnic)

In the Anissic a marine transgression covered part of the western versant of the present Coastal Range (32° S) (Fig. 4-A). Unconformably on folded Carboniferous sediments a marine series was deposited with basal breccias, followed by arkosic sandstones, turbidite deposits, lutites and again arkosic sandstones (El Quereo Formation; CECIONI 1964, 1970; CECIONI and WESTERMANN, 1968). These marine deposits are covered by a thick acidic volcanic sequence (Pichidangui Formation, CECIONI and WESTERMANN, 1968). This first tectonic and magmatic activity (subsidence, filling of a short-lived basin, upheaval and volcanic activity) heralded the intense orogenic activity which accompanied the evolution of the Andean Range. Rhythmic sedimentation (Flysch *S. Str.*, with solely a sedimentological connotation, CECIONI and WESTERMANN, 1968) is considered to be evidence for a Paleocimmerian or Palisade Orogenic Phase at the end of the Triassic (CECIONI, 1970).

Geoliminal period (Early Jurassic-Middle Cretaceous)

This first paleogeographic period (Fig. 4-A) is characterized by the geoliminal couple (VICENTE, 1972) that developed on the margin of the Gondwana Continent, or Andean foreland, and was formed by two main isopic zones roughly oriented NNW. In the western (Pacific) zone a very thick volcanic and volcanoclastic series accumulated and presently crops out in the Coastal Range and along the western or Chilean versant of the Main Range. The series is associated with two sporadic marine neritic sedimentary assemblages. The continental volcanic deposits constituted a subsiding volcanic ridge (island arc) with an internal position, i.e., an euliminal ridge. The eastern zone is characterized by a thinner and exclusively marine, sedimentary series, now cropping out along the eastern (Argentinian) versant of the Main Range. This zone was covered by the sea during two different subperiods and formed external or mioliminal furrows (the Aconcagüino-neuquino embayment of CECIONI, 1964; 1970).

First geoliminal subperiod (Liassic-Kimmeridgian). This subperiod began with an eastward marine ingression that covered the western margin of the Gondwana Continent. Although the main ingression took place at the beginning of the Lias, at some localities, such as, Los Molles (CECIONI and WESTERMANN, 1968; CECIONI, 1970) and Curepto (THIELE, 1965) it began earlier in Late Triassic (Norian). This ingression reached the more eastern regions of the present Main Range or the external zone only in the Late Lias (THIELE, 1964; VON HILLEBRANDT, 1970; VICENTE, 1970).

In the earlier developed internal zone, lutites, sandstones (in parts rhythmically sedimented, which were considered to be evidence for a Dunlap Orogenic Phase by CECIONI, 1970), and calcarenites were deposited (the Liassic Los Molles Formation and the Bajocian Melón Formation) intercalated with thick acidic volcanic sequences (the Upper Lias Ajial Formation and the Bajocian Melón Formation). No Jurassic formations, younger than Bajocian, are known along the Coastal Range. An Upper Jurassic hiatus is therefore admitted (MUÑOZ CRISTI, 1956; THOMAS, 1958) and is confirmed by an angular unconformity between Bajocian and Neocomian units (CARTER, 1963; CORVALAN and DAVILA, 1964; CORVALAN and MUNIZAGA, Fdo., 1972), caused by the Araucanian Orogenic Phase, the *first major Andean diastrophism*.

In the later developed external zone, marine carbonates with some volcanic intercalations in the northern part of the studied region were deposited from Sinemurian to Middle Oxfordian time (Nacientes del Teno, Upper Cuyano and Lotena Formation, La Manga and Tres Cruces Formations) and were followed by a characteristic evaporitic horizon (Yeso Principal). This horizon has no paleogeographic continuity north of 31° S where the Late Jurassic Algarrobal Formation lies unconformably on Middle Jurassic units (DEDIOS, 1967; MPODOZIS *et al.*, 1972). This 200-300 m thick evaporitic unit is overlain by very thick (up to 5000 m) terrigenous continental deposits, which gradually thin and become finer grained to the east (e.g., the Chilean Rio Damas Formation grades easterly into the Argentinian Tordillo Formation).

The external (mioliminal) furrow was short-lived because it was uplifted in the Late Oxfordian by the *first major Andean diastrophism* (MUÑOZ CRISTI, 1942; STIPANICIC and RODRIGO, 1970; CHARRIER and VICENTE, 1970; CHARRIER, 1973a). This phase is a local but slightly older (Late Oxfordian-Kimmeridgian) equivalent of STILLE's (1937) Andean or Nevadian Phase. Along the external zone almost no direct tectogenic effects of this phase have been detected, but indirect effects are the emergence of the furrow, evaporitic deposition, and terrigenous sedimentation, which are clear evidence for an important upheaval of the internal zones. An angular unconformity marking the disturbance, is restricted to the more internal zones.

In this first subperiod two subsidences are recognized in the external zone; one in the Upper Liassic-Late Oxfordian resulting in marine sedimentation and another in Kimmeridgian time resulting in continental sedimentation.

Second geoliminal subperiod (Tithonian-Middle Cretaceous). This second subperiod is reiterative of the first one and its features are even more clearly developed. It began with a marine transgression which entered first, in Early Tithonian (CORVALAN, 1956, 1959; KLOHN, 1960; DAVIDSON, 1971; VICENTE, 1972) and even in Late Kimmeridgian (CHARRIER, 1973a), along the mioliminal furrow. Calcareous-pelitic marine sediments, devoid of volcanics, were deposited along its axial zone (Leñas-Espinoza and Baños del Flaco Formations and Lo Valdés Formation).

In the internal zones the first marine deposits are only as old as Valanginian age and are intercalated with acidic volcanics (THOMAS, 1958; MUÑOZ CRISTI, 1960; ALISTE *et al.*, 1960; LEVI, 1960; CORVALAN and DAVILA, 1964; VERGARA, 1965; 1969). This internal zone is composed of thick volcanic and volcanoclastic deposits intercalated with pelitic and calcareous neritic sediments (Arqueros, Lo Prado and La Lajuela Formations). These very thick volcanic deposits have, thus, a clear euliminal (internal) character in contrast to those of the mioliminal furrow. They were accumulated in a marine basin bounded on the west by a subsiding island arc (euliminal ridge) (GERTH, 1931; BRÜGGEN, 1934; HERM, 1967; MUÑOZ CRISTI, 1968). In this interval the isopic zones of the geoliminal couple were best developed.

At the end of the Barremian the whole Andean domain was distinctly emergent. Along the external zones a regression took place and some evaporites accumulated (Huitrín Formation). Terrigenous continental and lacustrine deposits were laid down during Aptian-Albian time. Their thickness and coarseness diminish clearly towards the east (Colimapu Formation to Diamante Formation). Meanwhile along the internal zones, volcanism continued and its products were deposited interlayered with continental volcanoclastic series (upper part of La Lajuela and Quebrada Marquesa Formations, and Veta Negra Formation).

This widespread regression and the associated terrigenous deposits heralded the tectogenic events of the *second major Andean diastrophism* (CHARRIER and VICENTE, 1970), the Meso-Cretaceous Orogenic Phase, an equivalent of STEINMANN's (1929) Peruvian Phase, GROEBER's (1952) Intersenonian Phase and STILLE's (1937) Subhercynian Phase. The upheaval in the western or internal zones caused intensive erosion there and deposition in the external zones which were finally tectonized by this same phase. The time-lapse between the upheaval of the internal zone and the tectonization of the resultant terrigenous deposits in the external zone is evidence for the migration of the orogenic wave eastward. The tectonism in the internal zone may be correlated to the Austrian Phase of Europe.

The Meso-Cretaceous Phase marks the end of the geoliminal period (VICENTE, 1972; VICENTE *et al.*, 1972) and a widespread tectonization of the whole Andean domain. Along the paleogeographic transition between the internal and external series the more competent volcanic series are repeatedly thrust over the less competent external series (AUBOUIN and BORRELLO, 1966; VICENTE, 1970, 1972; DAVIDSON, 1971; THIELE, in press). The internal series form broad warps of several kilometers, which correspond to an induced folding style, whereas the tectonic style of the external series is the result of folding and *décollement* along the Late Oxfordian evaporitic horizon. All these structures were fossilized by the unconformable deposition of the Late Cretaceous volcanic sequence (Abanico Formation) (Figs. 3; 4-B). The great importance of this phase may be realized by comparing the highly deformed structures it generated with those produced by the younger phases (VICENTE, *et al.*, 1972).

In this second subperiod, also, two subsidences are recognized in the external zone; that in the Tithonian-Neocomian resulted in marine sedimentation and that in the Aptian-Albian lapse resulted in continental sedimentation.

Tardiliminal Period (Senonian to Miocene)

The Meso-Cretaceous diastrophism determined fundamental paleogeographic changes: starting in the Upper Cretaceous new paleogeographic units completely unrelated to the former were developed. Although these units had almost the same NNW orientation they were filled with very thick molassic series. Two diastrophisms, the Laramic Phase (Paleocene) and the Incaic Phase (Late Eocene-Early Oligocene) separate three subperiods which repeat the same paleogeographic sequence but each depositional basin shifted to the east of the precedent (Fig. 4-B, C, D). Marine basins, almost devoid of volcanics, developed along the western versant of the present Coastal Range. They are called retro-andine basins and have a back-deep significance (AUBOUIN, *et al.*, 1973). One continental basin formed on the axis of the Coastal Range, designated an epi-andine basin, with an intra-deep significance, and another along the eastern margin of the Main Range, designated a peri-andine basin, with a fore-deep significance (AUBOUIN *et al.*, 1973).

First Tardiliminal Subperiod (Late Cretaceous) (Fig. 4-B). During the Senonian marine molassic detritic sediments were deposited along the eastern side of the retro-andine basin (Quiriquina Formation). These deposits unconformably overlie the crystalline basement of present Coastal Range. Because of the NNE trend of the present Pacific coast this unit crops out only south of Valparaiso (33° S latitude). To the north the Quiriquina Formation disappears beneath the sea.

The most important deposits of this period are the very thick volcanic series from a volcanic range (Abanico Paleovolcanic range, AUBOUIN *et al.*, 1973) located along the western versant of the present Main Range. These volcanics extended west over the internal zone and east where they covered wide parts of the external zone of the precedent subperiod. The deposits accumulated on the present Coastal Range are mainly volcanoclastic (Las Chilcas and Viñita Formations), whereas those accumulated on the Main Range are essentially volcanic (Abanico = Coya-Machalí Formation and part of Viñita Formation).

In a more external position, along the fore-deep, and principally south of 33° S, a thin red continental series accumulated (Neuquén Group).

The Late Cretaceous deposits were folded during the Paleocene by the Laramic Orogenic Phase (CHARRIER and VICENTE, 1970; CHARRIER, 1973a). This phase generated open folds on the Coastal Range and along the western versant of the Main Range but the amplitude of folding diminishes considerably towards the axis of the Main Range. The thrusting of the Meso-Cretaceous Phase along the paleogeographic transition (along the axis of the Main Range) between competent internal volcanic series and incompetent external sedimentary series, was reactivated by this new compressive phase. In the more external areas the folding effects are considerably attenuated (Fig. 3-C).

Second Tardiliminal Subperiod (Paleogene) (Fig. 4-C). Thick volcanic sequences poured out from a new volcanic range (Farellones Paleovolcanic range, AUBOUIN *et al.*, 1973), east of the Abanico Paleovolcanic range, and covered unconformably the Late Cretaceous series. Pyroclastic and volcanoclastic deposits predominate to the west (Lo Valle and Los Elquinos Formations) whereas lava flows (Farellones Formation) dominate to the east. These flows reached locally very external regions where they overlay unconformably the basement rocks of the Frontal Range.

These deposits were deformed in the Late Eocene-Early Oligocene by the Incaic Orogenic Phase (CHARRIER and VICENTE, 1970), but the folds are gentle and dips of limbs do not exceed 10° to 15°.

Third Tardiliminal Subperiod (Oligo-Miocene) (Fig. 4-D). After the Incaic Phase, which caused the regression of the sea from the marginal regions of the continent, a new transgression took place as a response to the tectonic relaxation that followed the compressive phase. On the eastern margin of a retro-andine basin (back-deep), marine molassic sediments (Navidad Formation) accumulated.

On the mountainous terrain formed by the Incaic Phase plateau volcanic activity took place (Coastal Range Miocene volcanism).

East of the present Main Range, along what was the foreland until the Paleogene, an extended peri-andine basin with a N10°E orientation formed, and thick red continental terrigenous deposits accumulated (Mariño Formation). These deposits covered completely the present Frontal Range and Precordillera domain.

The tardiliminal period came to an end in the Late Miocene with the Pontian Phase, equivalent to STEINMANN's (1929) Quechuan Phase, which generated broad basement compressive folds. During this phase, the whole Andean system assumed a shape very similar to its present form (Fig. 4-E). These orogenic movements have been named the "orographic phase" (VICENTE, 1972).

The intensive compressive folding in the basement caused an impressive thrusting along the foreland of Precambrian and Paleozoic rocks over continental Miocene strata. Rocks in the Coastal and Main Ranges were only gently warped. The sea regressed along the retro-andine basin (back-deep) and a hiatus separates the Miocene molassic deposits from the overlying Pliocene series (HERM, 1969; CECIONI, 1970).

Postliminal Period (Plio-Pleistocene) (Fig. 4-F)

In the Early Pliocene, immediately after the Quechuan Phase, an extension period began with a N-S and E-W normal faulting. These faults undercut the huge mountain volumes formed during the Quechuan Phase. Blocks separated by these faults form the present morphostructural division of the range. For this reason this extension phase has been termed "geographic phase" (VICENTE, 1972).

Some marine deposits accumulated on the western versant of the Coastal Range (La Cueva, Horcón, Coquimbo Formations). Their thicknesses increase towards the west, on what is presently the continental shelf.

On other depressed areas of the range (Central Valley of Chile, Uspallata-Calingasta Valley and Bolsón de la Travesía in Argentina) thick continental terrigenous deposits accumulated.

South of 33° S a volcanic range parallel with the Central Valley has formed along the axis of the Main Range. Between latitudes 27° S and 33° S both the Central Valley and the volcanic range are absent (PEREZ and AGUIRRE, 1970).

Deposits accumulated during this period maintain their original horizontal position. They are cut only by normal faults as may be easily distinguished on the Pleistocene marine terraces (BORDE, 1966; PASKOFF,1970). Some very recent strike-slip movements along some of the faults has also been recognized.

Summary

The following are the main features of the paleogeographic and tectonic evolution of the studied region.

Paleogeography. (1) a typical evolution(geoliminal type) with prevailing volcanic and continental sedimentary facies. (2) no deep-sea sedimentary facies like radiolarites, associated with flysch deposits, are known. (3) superposition of successive paleogeographic periods. (4) a geoliminal couple with internal (west) volcanic series and external (east) sedimentary series is recognized during the Geoliminal Paleogeographic Period. (5) a gradual shifting to the east of the terrigenous sedimentary basins (paleogeographic polarity). (6) decrease in thickness and coarseness of the terrigenous deposits towards the east (sedimentary polarity).

Tectonics. (1) superposed effects of five compressive orogenic and tectogenic phases. (2) orogenic polarity towards the east displayed by each phase. (3) alternate (rhythmic) tectonic evolution with short periods of compression and longer periods of "no compression" or of possible extension.

Volcanism

Volcanism was very important in the development of the studied region. Volcanic activity is concentrated in the paleogeographic periods of probable extensional tectonism.

UPPER TRIASSIC VOLCANISM (EMBRYONIC)

During the Embryonic Paleogeographic Stage volcanism was mainly of acidic character and is represented by thick continental formations intercalated with marine sediments.

Triassic volcanics are exposed throughout the western part of the studied area (Fig. 2). The best exposed series is in the Los Vilos area (32° S), where approximately 4500 meters of rhyolitic volcanics (Pichidangui Formation) are intercalated with marine sediments containing Triassic fauna (MUÑOZ CRISTI, 1942) (Fig. 5). This volcanic sequence possibly poured out through deep fractures. Ignimbritic and rhyolitic flows formed wide plateaus. No mineralogic and chemical data are available for this Triassic volcanic sequence.

EARLY JURASSIC-MIDDLE CRETACEOUS VOLCANISM (GEOLIMINAL)

Liassic-Kimmeridgian Volcanism

The volcanic activity of the Jurassic represents the initial magmatism of the Andean

MAJOR OROGENIC PHASES	Age	Unit	Lithology
	Pleisto-cene Recent	CENTRAL VOLCANISM	Basaltic andesite subordinate rhyolite volcanic rocks.
	Plioce-ne 2,45 m.y	PLATEAU ANDESITIC SERIES	Mainly andesitic volcanic rocks. Rhyolitic volcanic rocks
		UNCONFORMITY	
PONTIAN PHASE	Miocene 22,7 m.y	COAST RANGE Miocenic Volcanism 800-1400 m.	Mainly andesitic volcanic rocks. Subordinate marine clastic rocks. Rhyolitic volcanic rocks. Subordinate marine clastic rocks.
		UNCONFORMITY	
INCAIC PHASE	Lower Tertiary	FARELLONES FORMATION 850-2000 m.	Mainly andesitic volcanic rocks. Rhyolitic volcanic rocks.
		UNCONFORMITY	
LARAMIAN PHASE	Upper Cretaceous	ABANICO FORMATION 4000-6000 m.	Mainly andesitic volcanic rocks; subordinate in the lower part rhyolitic volcanic rocks.
		UNCONFORMITY	
SUB-HERCYNIAN PHASE	Lower to "middle" Cretaceous	VETA NEGRA FORMATION 5.500 7.500 m.	Mainly andesitic volcanic rocks.
		LO PRADO FORMATION = =LA LAJUELA FORMATION 4.500-13.000 m.	Mainly rhyolitic volcanic rocks; subordinate marine clastic rocks.
		HIATUS-UNCONFORMITY	
ARAUCANIAN PHASE	Lower to middle Jurassic	MELON FORMATION 2.100-5.500 m.	Mainly andesitic volcanic rock; subordinate marine clastic rocks.
		AJIAL FORMATION 750-1.300 m.	Mainly rhyolitic rocks
		QUEBRADA DEL POBRE FORMATION 300-1.250 m	Marine clastic rocks and rhyolitic rock
		UNCONFORMITY ?	
PHASE	Middle to upper Triassic	± 4.500 m PICHIDANGUI FORMATION	Marine clastic rocks Rhyolitic rocks. Marine clastic rocks.

Fig. 5. Column presenting lithology, thickness and structural relations of the stratigraphic-structural units of the central portion (Geoliminal Sector) of the Southern Andes.

Orogenic Cycle. The volcanism was aligned along continuous strips (Fig. 2), parallel to the continental margin, and corresponds roughly to the orientation of the original basins of deposition. In the El Melón-La Ligua area (32° 30′ S) the principal sequences of this period are exposed. They represent the lithological types deposited along what has been called the Internal Zone or Eugeoliminal margin of the basin of deposition. There a 8050 m thick sequence of volcanics principally (Ajial and El Melón Formations) is intercalated at different levels with some marine sediments (Fig. 5). Liassic and Lower Bajocian volcanics are mainly rhyolites but in the upper Bajocian andesitic intercalations are present.

The Upper Lias-Lower Bajocian Ajial Formation (THOMAS, 1958, p. 28) is principally constituted by rhyolites and ignimbritic rhyolites with thicknesses up to 1300 m. The Bajocian Melón Formation (THOMAS, 1958, p. 31), which overlies the forementioned formation, has in its upper part intercalations of andesitic lavas and pyroclastics. GERTH (1931), BRÜGGEN (1934), HERM (1967) and MUÑOZ CRISTI (1968) suggested the possibility that this intensive volcanism had been generated along island arcs, facing the continent, which partly closed the intervening basin.

The acidic volcanic rocks are rhyolites with albite phenocrysts and quartz in a fluidal matrix and ignimbrites of similar composition (THOMAS, 1958; LEVI, 1960). The andesites consist of intermediate plagioclase and pyroxenes. All volcanic rocks are altered principally to chlorite minerals, quartz, epidote, actinolite and biotite (LEVI, 1970, p. 1004).

Average chemical analyses recalculated to 100% free of volatiles of two intermediate rocks and three acidic rocks of this Jurassic sequence are presented in Table I (Analyses 1, A and B). Acidic rocks have a rhyolitic composition with a higher

Table 1. Average chemical analyses of volcanic rocks of the Jurassic (1), Lower Cretaceous (2), Upper Cretaceous (3), Lower Tertiary (4), Miocene (5), Pliocene (6), Quaternary (7), CHAYES' (1968) andesites (8) and DALY's (1933) rhyolites (9).

	1		2		3		4		5	6	7	8	9
	A	B	A	B	A	B	A	B					
SiO_2	59.21	70.17	54.19	68.61	56.78	71.22	58.16	70.11	58.37	57.64	54.46	58.17	72.90
Al_2O_3	17.47	15.43	17.90	15.41	17.89	15.15	18.15	15.34	17.15	17.98	17.89	17.26	14.18
Fe_2O_3	1.60	3.09	5.04	3.10	5.14	2.23	3.84	2.50	2.68	2.74	2.87	3.07	1.65
FeO	5.38	0.42	4.51	2.54	3.92	1.67	3.60	1.00	3.60	3.03	5.35	4.17	0.31
CaO	5.61	0.36	6.10	1.13	5.28	2.13	6.08	2.36	6.87	7.52	7.62	6.93	1.13
MgO	3.24	0.04	3.66	0.67	2.89	0.64	3.02	0.82	4.73	2.28	4.11	3.23	0.14
Na_2O	4.73	6.01	4.22	3.37	4.76	3.19	4.27	3.54	3.73	4.95	4.56	3.21	3.54
K_2O	1.53	3.71	2.56	3.89	1.15	3.43	1.54	3.53	1.42	1.94	1.08	1.61	3.94
TiO_2	0.81	0.69	0.99	0.53	0.95	0.29	0.79	0.59	0.79	0.83	1.16	0.81	0.48
MnO	0.16	0.02	0.24	0.08	0.19	0.07	0.14	0.09	0.14	0.13	0.17	–	0.13
P_2O_5	0.25	0.04	0.34	0.21	0.27	0.10	0.34	0.13	0.15	0.13	0.29	0.02	0.01
H_2O	–	–	–	–	–	–	–	–	0.84	1.24	0.65	1.24	1.33
Na_2O+K_2O	6.26	9.72	6.78	7.26	5.91	6.62	5.81	7.07	5.15	6.89	5.64	4.82	7.48
Na_2O/K_2O	3.09	1.62	1.70	0.87	4.14	0.93	2.78	1.00	2.63	2.58	4.22	1.99	0.90

NOTES:

(1) Jurassic volcanic rocks (OYARZUN and VILLALOBOS, 1969, p. 10-12). A = average of two intermediate volcanic rocks and B= average of 3 acid volcanic rocks.

(2) Lower Cretaceous volcanic rocks. (OYARZUN and VILLALOBOS, 1969, p. 6-7-8-10-11-12-16 to 23). A= average of 83 intermediate volcanic rocks and B= average of 8 acid volcanic rocks.

(3) Upper Cretaceous volcanic rocks (OYARZUN and VILLALOBOS, 1969, p. 10-11-18-21-27-28). A= average of 12 intermediate volcanic rocks and B= average of 5 acid volcanic rocks.

(4) Lower Tertiary volcanic rocks. (OYARZUN and VILLALOBOS, 1969, p. 10-11-24-25-27). A= average of 19 intermediate volcanic rocks and B= average of 9 acid volcanic rocks.

(5) Andesite from Coast Range Miocene volcanism (VERGARA, 1972b).

(6) Plateau andesite (Pliocene) (VERGARA, 1972b).

(7) Average of 6 volcanic rocks from Antuco Volcano (VERGARA and KATSUI, 1969).

alumina and alkali (especially K_2O) content than the DALY type rhyolite (1933) (Table I, No. 9). Intermediate volcanic rocks are aluminous andesites with higher total alkali percent than the CHAYES andesites (Table I, No. 8).

In parts of the Main Range some andesitic flows are intercalated in a Kimmeridgian red continental sequence (KLOHN, 1960; DEDIOS, 1967; MPODOZIS *et al.*, 1972).

Tithonian-Middle Cretaceous Volcanism

The marine sequence of the Lower Cretaceous is separated from that of the Middle Jurassic by a hiatus and a gentle angular unconformity (Fig. 5). Sedimentation was similar to that of the Jurassic. Marine sediments are intercalated in thick volcanic sequences of principally rhyolitic composition in the initial stage and of andesitic composition in the final stage.

Lower Cretaceous volcanics of the studied region crop out in an almost continuous north-south strip (Fig. 2). As in the Jurassic, the volcanic activity developed mainly along the western margin of the geoliminal basin (internal zone). The Lo Prado or La Lajuela Formation and the Veta Negra Formation represent the main volcanic units (volcanoclastic and volcanic) of this period (Fig. 5). These formations range in thickness southward from 4,500 (THOMAS, 1958) to 13,000 m (VERGARA, 1969).

The Lo Prado or La Lajuela Formation consists principally of rhyolitic volcanics intercalated with lenses of calcareous marine sediments. Volcanic rocks are mainly rhyolitic flows and rhyolitic ignimbrites associated to volcanoclastic sediments. Sedimentation took place in shallow, short-lived, marine basins, separated by long-lived volcanic barriers which permitted the huge accumulation of volcanics and volcanoclastic sediments (VERGARA, 1969).

The Lo Prado Formation is overlain in the central and northern part of the studied area by the continental volcanic Veta Negra Formation, which consists mainly of porphyric andesitic flows with clino-and orthopyroxenes and large plagioclase phenocrysts (locally named ocoites) and scarce clastic continental sediments.

All volcanic rocks of these formations generally present some alteration, mainly with chlorite, quartz, albite and epidote (VERGARA, 1969). Average chemical analyses recalculated to 100% free of volatiles of 8 rhyolites of the Lo Prado Formation and 83 andesites of the Veta Negra Formation are presented in Table I (analyses 2B and 2A).

Intermediate volcanic rocks are aluminous andesites with higher alkali (especially K_2O) and alumina content than the type CHAYES' andesite. Acidic volcanic rocks (2B) are very similar to the DALY-type rhyolite except for the total iron content.

LATE CRETACEOUS-MIOCENE VOLCANISM (TARDILIMINAL)

Late Cretaceous Volcanism

After the Meso-Cretaceous Orogenic Phase (Subhercynian) a continental volcanic and volcanoclastic sedimentary cycle took place. The Abanico Formation (Coya-Machalí or Viñita) is the most important volcanic sequence of this period. It is widely distributed and continuous outcrop; it forms a north-south strip which covers almost all the area considered herein. The median line of this formation appears located to the east of the older volcanic formations (Fig. 2, symbol 6).

The Abanico Formation reaches its greatest thickness in the area of the Tinguiririca River, 34° 30′ S. In this region it is composed of 500 meters of basal rhyolitic ignimbrites and rhyolitic breccias and 5,500 m of mainly andesitic volcanoclastic rocks and rare andesitic flows. The basal ignimbrites are generally welded and consist of crystalloclasts of sodic plagioclase and quartz, with a vitroclastic matrix, generally welded. The upper levels of this formation consist mainly of andesitic volcanic graywackes, formed by fragments of andesite, feldspar and clinopyroxene in a matrix of volcanic dust. Most rocks in this formation show alteration to calcite, chlorite, epidote, sericite, albite and prehnite (VERGARA, 1969). Table I (analyses 3A and 3B) presents the average chemical composition of the two rock types of this formation. Intermediate rocks are aluminous andesites with more alkali than the average of the CHAYES' andesite.

The basal acidic rocks have a higher alumina and total iron content than the average rhyolite of DALY.

Paleogene Volcanism

The Lower Tertiary is represented by the Farellones Formation (Fig. 5) which consists of continental volcanic rocks that overlie unconformably the Abanico Formation. It forms a continuous north-south strip mainly along the axis of the Main Range (Fig. 4-C). This formation thickens from south to north from 850 m (VERGARA, 1969) to 2,000 m (AGUIRRE, 1960).

The base of the Farellones Formation is principally sodic rhyolite and ignimbritic rhyolite flows. The upper levels consist of andesitic pyroclastics and flows. The volcanic rocks of this formation, in contrast to older formations are less altered. The principal secondary minerals are: zeolites, chlorites, quartz and albite. The recalculated chemical averages to 100% free of volatiles of its intermediate and acidic rocks are given in Table I(analyses 4A and 4B). The intermediate rocks are aluminous andesites with more alkali than the average andesite of CHAYES. The acidic rocks are similar to the average rhyolite of DALY, except for higher alumina, total iron and calcium.

Oligo-Miocene Volcanism

The distribution of Miocene volcanic rocks breaks the structural pattern that prevailed since the Jurassic. The best known Miocene volcanic sequence crops out south of the studied area (between 37° and 40° S). In the Coastal Range the volcanic sequence is highly eroded. The Miocene age is based on radiometric determinations (VERGARA and FCO. MUNIZAGA, 1974). Some volcanic formations of the Main Range in the studied area have been assigned to this volcanic period by structural and lithological correlation (Fig. 4-D).

The lower part of the Miocene Coastal Volcanic Belt (VERGARA, 1972b), is characterized by rhyolitic pyroclastics and andesitic lava flows with two pyroxenes. Amphibole-bearing andesites, and pyroclastics of similar composition, form the middle and upper parts. These rocks crop out in horizontal or gently dipping layers, or form volcanic necks. In most of the area, these rocks were deposited in a continental milieu, and along the Coastal Range they overlie a metamorphic basement of Paleozoic age. The top of the unit corresponds to the present erosion surface. Its thickness has been estimated at more than 200 meters (Fig. 5).

The rocks of this unit are generally fresh and free of alteration minerals. Table I, No. 5, presents a chemical analysis of a two-pyroxene andesite of this formation. This andesite has more alkali (higher Na_2O and lower K_2O) than the CHAYES andesite.

PLIO-QUATERNARY VOLCANISM OR NEOVOLCANISM (POSTLIMINAL)

This volcanism appears to be concentrated along the Andean Volcanic Belt. Two volcanic units have been distinguished, the andesitic Plateau Series and the strato-volcanoes of the central type superimposed on top of the Plateau Series.

The name andesitic Plateau Series is given to an extensive sequence of horizontal and sub-horizontal andesitic lava flows and pyroclastics of continental origin which rest unconformably on Mesozoic and Lower Cenozoic basement. This series locally displays gentle folding, deep glacial erosion and intense block-faulting. Its thickness varies from 800 to 100 meters and available radiometric data demonstrate a Pliocene age (VERGARA and MUNIZAGA, FCO., 1974).

The andesitic Plateau Series consists mainly of orthopyroxene andesitic flows, amphibole trachiandesites and, lesser amounts of olivine basaltic andesites. Acidic pyroclastic flows form the lowest part of this formation (Fig. 5).

The strato volcanoes of the central type are very young and normally superimposed on the andesitic Plateau Series. Active volcanoes are located along the western border of the Andean Volcanic Belt (Fig. 3, Symbol 11).

Recent volcanic rocks of the studied region are intermediate in composition and some samples of the Marmolejo and Tupungato Mounts correspond to trachiandesites and andesites, with common hornblende phenocrysts. These rocks belong to the calcalkaline series and are similar to those of the Cascade Range (THIELE and KATSUI, 1969, p. 18).

The petrological characteristics mentioned for the recent volcanic rocks do not seem, however to be the rule for the Andean Range because south of the herein considered region studied samples constitute a petrographic series mainly composed by basaltic andesites and andesites. The most basic rocks contain olivine phenocrysts with reaction rims, clinopyroxenes (subcalcic augites and augites) and bytownite-labradorite. Clinopyroxenes are present in the groundmass. In the most acidic rocks, which constitute a very significant fraction of the whole volume, orthopyroxene phenocrysts are present and in the groundmass there are also amphiboles and biotites associated with microphenocrysts of iron oxides. Trydimite and interstitial anorthoclase form part of the groundmass of almost all the rocks of this series (VERGARA, 1972b).

According to VERGARA and KATSUI (1969, p. 45) this series of volcanic rocks has a remarkable chemical and mineralogical similarity with the Japan "high-alumina basalt series".

The volcanic rocks of this period are generally completely fresh and unaltered. Table I, No. 6 and 7, presents a chemical analysis of a plateau andesite and the average composition of six basaltic andesites of the presently active Antuco Volcano (37° 30′ S). In comparison with the CHAYES' andesite, both types are aluminous andesites, richer in Na_2O and poorer in K_2O.

SUMMARY OF THE VOLCANIC EVOLUTION

The huge thickness of volcanic rocks accumulated on the western region of the Andean Range emphasizes the great importance of volcanic activity in the evolution of this orogen. The Andean volcanism is of a bimodal type (aluminous andesitic and rhyolitic) and devoid of ophiolitic phases. Volcanic products are calcalkaline (VERGARA, 1972a), rich in sodium and poor in potassium (OYARZUN and VERGARA, in press). An exception is the Lower Cretaceous Veta Negra Formation where Na_2O/K_2O of its andesites is 4.14. This unit constitutes a peculiar volcanic sequence of the Andean Range.

The stratigraphic relations between volcanic flows and sedimentary deposits of the Jurassic and Lower Cretaceous indicate that the volcanic centers formed an island arc facing the continent.

Volcanic activity, younger than the Lower Cretaceous, was principally continental (Abanico and Farellones Formations) and superposed on mountainous relief formed by the immediately precedent tectonic phases.

The increase in K_2O from the Andean series to the alkaline volcanic series of the foreland, in both Mesozoic and Cenozoic rocks (VERGARA, 1972b), is evidence for volcanic activity along a continental margin. The volcanic activity of each structural stage is characterized by initial rhyolitic (principally ignimbritic) volcanism followed by an andesitic volcanism which closes each structural-magmatic cycle. The rhyolitic volcanics correspond to the first post-orogenic or extensional magmatic activity of each paleogeographic period.

From the Jurassic to the Lower Tertiary each active volcanic belt gradually migrated towards the east (volcanic polarity).

From the Miocene to the Plio-Pleistocene and Present the active volcanic belt abruptly shifted (100 km approximately) to the east (VERGARA and MUNIZAGA, FCO., 1974). The Andean volcanic focus has continuously oscillated gradually at some periods and abruptly at others.

Plutonism

Mesozoic and Cenozoic granitoids crop out all along the studied area (Fig. 2) where they occupy approximately 33% of the region as large batholiths, massifs, minor stocks and scattered bodies. Several petrological phases are represented, the most common being granodiorite, tonalite and granite. Quartz monzonite, adamellite, gabbro and different types of porphyry are also present. These granitoids intrude rocks ranging in age from Paleozoic metamorphic basement to the Upper Tertiary series of the Main Range.

Contact relationships indicate a postkinematic character for these plutonic rocks. In most places they clearly cut across the structures; transitional margins and migmatitic borders being absent or rare. Contact metamorphic aureoles are well developed around several of these bodies and hydrothermal alteration is common in some of them. Mineral deposits of economic significance are closely related to these intrusives, especially copper, iron, molybdenum and zinc.

Geochronological studies carried out in recent years permit the identification of at least three main cycles of emplacement with ages broadly corresponding to the Jurassic, Cretaceous and Tertiary. The majority of the determinations available for the region (38 out of 57) are based on the lead-alpha method, which precludes any refined correlation with the geotectonic evolution of the area. Nevertheless, a general agreement between plutonic activity and known tectonic dynamic episodes in the Andean Orogenic Cycle can be obtained.

As very few detailed studies have been carried out on the granitoids it is difficult to distinguish well- defined petrological phases on the basis of petrographic, chemical and mineralogic data.

Geochronological determinations and known stratigraphical relations permit three groups of granitoids to be defined, Jurassic, Cretaceous, and Tertiary.

JURASSIC GRANITOIDS

These rocks outcrop as scattered bodies surrounded by marine Pliocene rocks and Quaternary sediments along the coast between latitudes 29° S and 30° S (Fig. 2). Main outcrops in the studied area form a belt comprising a major part of the Coastal Range between rivers Limarí and Choapa (30° 45′ - 30° 30′ S latitude).

The Jurassic granitoids cut across the Paleozoic metamorphic basement (Fig. 3-A,B,C) at Damas Island (latitude about 29° S just outside the studied area) (AGUIRRE, 1967) and are, in turn, intruded by Cretaceous granitoids along most of the eastern boundary of the belt south of latitude 30° S (THOMAS, 1967). A tectonic contact with the Paleozoic metamorphic basement has been established along most of the western boundary of the Jurassic intrusive belt south of latitude 30° S (THOMAS, 1967).

Different petrographic types are present in this plutonic complex from north to south. At Damas Island (AGUIRRE, 1967) the only outcrop, with an exposed area of 0.1 km^2, the rock is a gneissic granite consisting of wavy quartz, perthite, zoned oligoclase, biotite and amphibole. In the La Serena region, near latitude 30° S recently K-Ar-dated Jurassic intrusives (G. CURTIS, written communication, 1972) consist of quartz-monzodiorite. Its modal composition is represented in Table 3, No. 1 and Fig. 6.

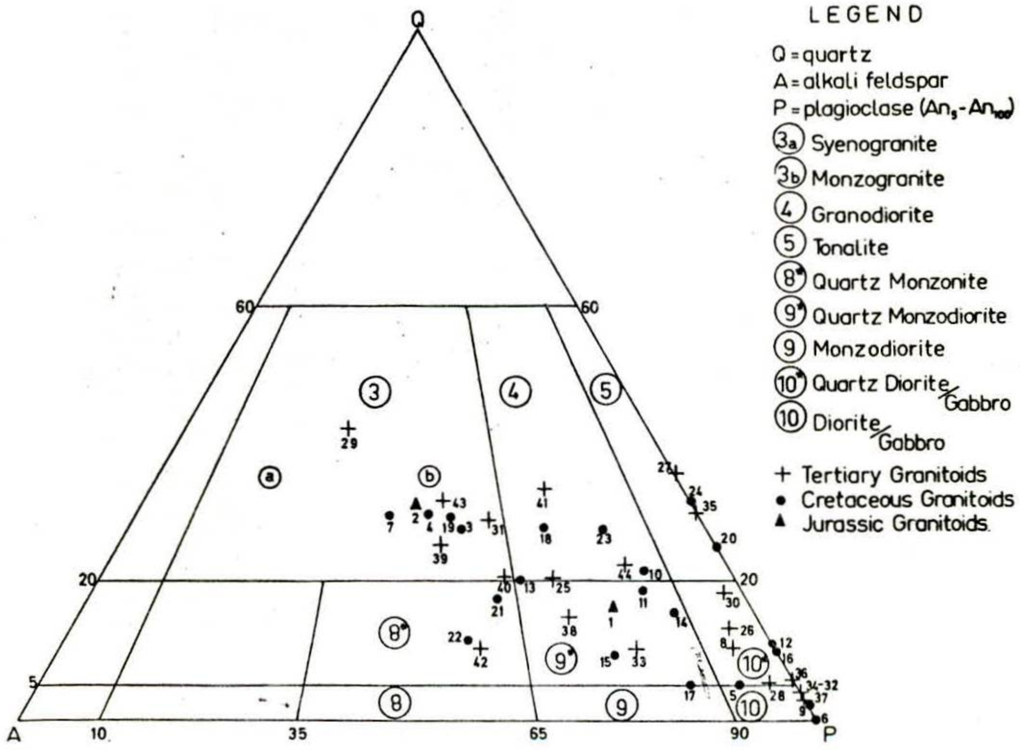

Fig. 6. QAP triangle with location of granitoids of different ages presented in Table 3.

Rocks present at Punta Lengua de Vaca (30° S latitude) and in the Coastal Range between Limarí and Choapa Rivers are coarse-grained, medium to dark gray tonalite and granodiorite (THOMAS, 1967), cut by a great number of andesitic dykes.

A metamorphic aureole developed around these Jurassic intrusives has been described only for Damas Island where the Paleozoic metamorphic basement has been transformed in a narrow zone around the granite into a hornfelsic rock with minor to abundant crystals of andalusite.

Nine lead-alpha and two K-Ar ages have been obtained for these rocks. They range from a maximum of 173 my. to a minimum of 147 my. Highest values correspond to the Damas Island gneissic granite and to the diorite and granodiorite south of the Limarí River, whereas lowest values correspond to the coastal region around latitudes 30° S (Herradura Bay and Lambert Quadrangle) and latitude 31° 30′ S (Mincha) (*see* Fig. 7 and Table 2).

Mineral deposits related to the Jurassic granitoids have not been described in the studied region. According to RUIZ, *et al.*, (1965) Jurassic granites in Chile would be associated with hydrothermal deposits of copper and cobalt in the form of dykes cutting across diorites.

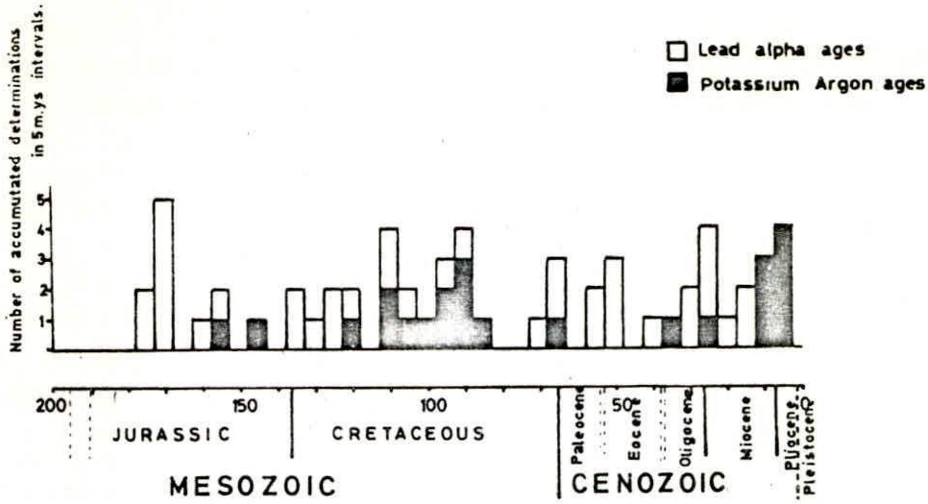

Fig. 7. Histogram showing number of radiometric determinations (Lead-Alpha and Potassium/Argon) versus geologic age for granitoids of the studied region. Major accumulations coincide broadly with the orogenic phases.

Table 2. Radiometric ages for Jurassic Granitoids between 30° and 35° S latitude.

Locality	Rock Type	Age my.	Method	Author
Damas Island 29°13′ S/ 71°31′ W	Gneissic granite	171±20	Lead-alpha	AGUIRRE, L. (1967)
Lambert Quadrangle 29°47′ S/ 71°09′ W	Quartz monzodiorite	156.8	K/ Ar biot.	CURTIS, G. (written communication, 1972)
Herradura Bay 29°57′ S/ 71°32′ W	Granodiorite	156±15	Lead-alpha	MUNIZAGA. Fdo. (1972)
Fray Jorge 30°36′ S/ 71°32′ W	Granodiorite	171±20	Lead-alpha	THOMAS, H. (1967)
Limarí River 30°40′ S/ 71°32′ W	Diorite	171±20	Lead-alpha	THOMAS, H. (1967)
Peña Blanca 30°55′ S/ 71°35′ W	?	169±20	Lead-alpha	THOMAS, H. (1967)
Huentelauquen 31°19′ S/ 71°35′ W	Granodiorite	173±20	Lead-alpha	MUNIZAGA, Fdo. (1972)
Mincha 31°35′ S/ 71°24′ W	Tonalite	173±20 147.0	Lead-alpha K/Ar biot.	MUNIZAGA, Fdo. (1972)
Papudo 32°29′ S/ 71°25′ W	Monzogranite	160±20	Lead-alpha	LEVI, B. *et al.* (1963)
Catapilco 32°36′ S/ 71°23′ W	Granodiorite	170±20	Lead-alpha	LEVI, B. *et al.*, (1963)

CRETACEOUS GRANITOIDS

They are present as a continuous belt along the west-central part of the studied area (Fig. 2). Large roof pendants of Mesozoic stratified formations are enclosed in these batholiths. These granitoids cut across formations ranging in age from Lower Jurassic to mid Cretaceous. In several places they also intrude Jurassic and Paleozoic granitic masses (Fig. 3-A).

Cretaceous granitoids correspond with topographic heights in many places of the Coastal Range as, for instance, the Tamaya Ridge (latitude 29° S), La Campana Hill (1910 m), El Roble Hill (2222 m) and others located west of Santiago.

Granodiorite, diorite, granite and tonalite are the most common petrographic types;

Table 3. Modal analyses of Mesozoic and Tertiary granitoids between 30° and 35° S latitude.

Sample No.	Locality	Qtz	K-feld	Plag	Biot	Amph	Pyrox	Opaque Min.	Acce-sories	Ser Clor Ep	Name of Rock (after Streckeisen)
1	Lambert	12.3	13.9	52.6	6.9	11.3		2.2			Qtz Monzodiorite
2	Papudo	26.0	29.0	29.0	6.0	7.0	–	–	–	–	Monzogranite
3	La Higuera	21.8	24.4	32.5	1.6	3.8	12.3	4.0	0.6	0.6	Monzogranite
4	Sta. Gracia	27.3	32.0	33.6	3.0	2.5	–	1.0	–	–	Monzogranite
5	Sta. Gracia	3.6	5.0	62.9	1.0	22.9	0.9	2.6	0.7	–	Diorite
6	Lambert	–	–	61.3	30.6	–	8.0	–	–	–	Diorite
7	LaLigua River	28.7	37.8	31.0	–	1.3	0.3	0.4	0.5	–	Monzogranite
8	LaLigua River	7.9	3.8	64.4	–	22.9	–	–	0.3	0.7	Qtz Diorite
9	La Campana	1.0	–	65.2	–	24.1	3.7	2.7	6.3	2.8	Gabbro
10	La Campana	14.9	7.2	46.0	15.0	8.5	1.9	0.9	0.4	5.0	Granodiorite
11	La Campana	15.2	9.6	54.3	6.8	7.9	2.7	1.5	0.3	1.6	Qtz Monzodiorite
12	La Campana	7.1	–	64.0	7.0	14.1	–	2.0	0.5	3.1	Qtz Diorite
13	La Campana	16.6	21.9	42.3	8.4	1.9	4.1	1.5	0.7	2.5	Granodiorite
14	La Campana	10.8	7.1	52.3	4.9	14.8	3.6	1.7	0.5	4.0	Qtz Monzodiorite
15	La Campana	8.5	19.1	64.1	–	5.5	1.3	0.6	0.7	0.1	Qtz Monzodiorite
16	La Campana	7.0	–	67.9	4.6	2.3	14.1	2.7	1.2	0.1	Qtz Diorite
17	La Campana	4.0	10.2	64.1	7.6	1.5	10.0	2.3	–	–	Monzodiorite
18	La Campana	24.0	17.6	45.0	0.7	5.3	–	1.4	–	6.0	Granodiorite
19	La Campana	22.5	24.1	39.6	–	–	–	2.1	0.1	11.1	Monzogranite
20	Valpo San Antonio	20.0	–	60.0	5.0	15.0	–	–	–	–	Tonalite
21	Valpo San Antonio	15.0	28.0	45.0	–	12.0	–	–	–	–	Qtz Monzonite
22	Valpo San Antonio	9.0	29.0	39.0	22.0	–	–	–	–	–	Qtz Monzonite
23	Valpo San Antonio	24.0	11.0	51.0	7.0	5.0	–	–	–	–	Granodiorite
24	Peñaflor	27.4	–	59.5	–	5.2	–	0.8	–	7.1	Tonalite
25	High Limarí	16.7	18.1	45.9	4.5	14.8	–	–	–	–	Granodiorite
26	High Limarí	10.2	3.1	62.3	11.5	8.1	–	2.0	1.5	–	Qtz Diorite
27	High Limarí	29.3	–	52.7	7.4	8.0	–	0.6	–	2.0	Tonalite
28	Tascadero	3.1	1.9	53.9	–	30.6	4.1	–	6.3	–	Qtz Diorite
29	Tascadero	41.7	36.8	18.9	0.5	–	–	–	1.0	–	Syenogranite
30	Campo deAhumada	15.0	2.0	64.7	4.0	10.5	0.2	4.0	0.2	–	Qtz Diorite
31	Putaendo River	27.4	24.5	41.1	–	6.3	–	0.5	0.2	–	Monzogranite
32	Putaendo River	2.9	0.1	83.9	–	10.2	0.2	2.3	0.5	–	Diorite
33	Rocín River	8.1	13.1	54.9	–	19.8	0.6	3.0	0.5	–	Qtz Monzodiorite
34	El Toro Brook	2.9	–	68.0	–	–	24.2	4.9	–	–	Diorite
35	Pan de Azúcar	27.8	–	65.3	6.2	–	–	0.7	–	–	Tonalite
36	Juncal River	4.4	–	71.3	–	–	19.4	3.9	1.0	–	Qtz Diorite
37	Est. San José	2.4	–	72.7	–	–	21.5	0.1	3.3	–	Diorite
38	Riecillos	13.0	20.5	55.0	3.5	7.5	–	–	0.5	–	Qtz Monzodiorite
39	Riecillos	24.0	32.0	38.0	3.0	4.0	–	–	–	–	Monzogranite
40	Riecillos	13.0	26.0	46.0	–	6.0	–	–	–	2.1	Monzogranite
41	La Obra	30.0	15.6	44.4	6.7	2.8	–	0.7	–	–	Granodiorite
42	San Gabriel	7.6	27.2	39.2	–	19.5	–	6.0	0.5	–	Qtz Monzonite
43	Rio Colorado	28.6	28.0	34.3	4.1	3.8	–	–	1.2	–	Monzogranite
44	Portillo	20.8	11.2	59.1	3.7	1.8	–	–	3.4	–	Granodiorite

quartzmonzonite, adamellite and gabbro are more restricted. From north to south, the principal regions known can be summarized as follows:
a) *La Higuera* (MUÑOZ CRISTI, 1950), latitude 29° 30′ S. Most granitoids consist of tonalite and granodiorite accompanied by marginal facies corresponding to granites, quartz-monzonite and gabbro. One modal analysis is shown in Table 3, No. 3, and Fig. 6.
b) *Santa Gracia* (AGUIRRE and EGERT, 1970; CHAVEZ, 1972), latitude 29° 45′ S. A centered, roughly elliptical body of monzogranite with a maximum diameter of 6.5 km is partly surrounded by a minor zone of gabbro. The monzogranite is a medium grained, light yellowish gray rock, mainly formed by quartz, K-feldspar, oligoclase and biotite. One average modal analysis of this rock based on seven different samples is presented in Table 3, No.4 and Fig. 6.

A fine to mediumgrained, dark gray diorite consists mainly of hornblende, subordinate biotite, magnetite and sphene and has been interpreted (CHAVEZ, 1972) as the final product of contact metamorphism and metasomatism of stratified Lower Cretaceous andesites produced by the adamellite intrusion. One average modal analysis of this diorite based on thirteen different samples is shown in Table 3, No. 5 and Fig. 6.

Agmatitic migmatites interpreted as magmatic breccias are present in many places in the outer part of the adamelite body.
c) *Tambillos* (MÜNCHMEYER, 1972). Latitude 30° 08′ S. Aplitic granite (quartz, orthoclase, albite, perthite, and magnetite), granodiorite (andesine, orthoclase, quartz, hornblende, magnetite) and diorite (oligoclase- andesine, orthoclase, perthite, augite, epidote, chlorite, sphene, rutile) correspond to the main phases present in this locality.
d) *Coastal Range* between latitudes 32° 20′ S and 33° S. (THOMAS, 1958). Diorite is the most characteristic type of intrusive there. It is a light gray, medium-grained rock formed by amphibole, biotite and minor amounts of quartz, magnetite, sphene and zircon. There are transitions of this diorite to tonalite, granodiorite, monzonite, granite and finer grained types such as aplitic granites and microgranites. Darker varieties (gabbric diorite and gabbro) are also present in reduced amounts. Several types of dykes are related to the batholith in this region, among them aplites, granitic and dioritic porphyries and lamprophyres are the most common.
e) *La Ligua* (VICENTE, in prep.). Latitude 32° 25′ S. Monzogranite and quartz diorite have been sampled along the La Ligua River, near Cabildo. Monzogranite, a light gray, fine-grained rock, consists of orthoclase, plagioclase, quartz, amphibole, pyroxene and sphene as accessories. Quartz diorite, a light gray, fine-grained rock, is made up of plagioclase, amphibole, quartz, orthoclase, opaque minerals and sphene and apatite as accessories. Modal analyses of both rocks are given in Table 3, No. 7, 8; and Fig. 6.
f) *La Campana* (TIDY, 1970). Latitude 32°56′ S. In the La Campana Hill mining district sedimentary and volcanic rocks of Lower Cretaceous age are intruded by a batholith of approximately 360 km^2 which crops out along the eastern border of the studied area. This batholith consists of a nearly circular mass about 18 km across. Most of it is a light gray, medium-grained granodiorite composed of quartz, orthoclase, plagioclase, biotite, augite, hornblende, magnetite, apatite and sphene. There are local transitions to monzogranite, diorite, gabbro and other minor phases. A marginal and approximately circular body of medium to dark gray, medium-grained gabbro, 2.5 km in diameter, constitutes the upper part and summit of Campana Hill. This gabbro is petrographically very homogeneous and is composed of labradorite, diopsidic augite with characteristic exolution lamellae, ilmenite and apatite. One average modal analysis of this gabbro based on twelve different samples is given in Table 3, No. 9 and Fig. 6. Ten modal

analyses corresponding to granodiorite, quartz-diorite, monzogranite, monzodiorite and quartz-monzodiorite are also represented in Table 3, No. 10 to 19 and Fig. 6.

g) *Coastal Range* between latitudes 33° S and 34°S (CORVALAN and MUNIZAGA, FDO., 1972). Quartz monzonite, tonalite and granodiorite, all containing amphibole and biotite, are the main petrographic types mentioned by CORVALAN and MUNIZAGA, FDO., (1972) for the region between 33° S and 34° S. Five modal analyses of these rocks are shown in Table 3 No. 20 to 24 and Fig. 6.

Thirteen K-Ar ages on biotite, hornblende, and plagioclase and ten lead-alpha ages (Table 4) have been obtained from Cretaceous granitoids of this region. K-Ar ages vary from a maximum of 118 my. and a minimum of 66 my., most of the values clustering between 90 my. and 110 my. Lead-alpha ages move from a maximum of 136 my. and a minimum of 89 my. (Fig. 7).

Table 4. Radiometric ages for Cretaceous granitoids between 30° and 35° S latitude.

Locality	Rock Type	Age my.	Method	Author
Balboa Creek 29°43′ S/ 71°10′ W	Granodiorite	105.0 107.0	K/Ar biot. K/Ar hornbl.	CURTIS, G. (written communication, 1972)
Santa Gracia 29°45′ S/ 71°05′ W	Monzogranite	89±06 98.0	K/Ar biot. K/Ar biot.	CURTIS, G. (written communication, 1972)
Lambert Quadrangle 29°47′ S/ 71°09′ W	Hornblende gabbro	90.4	K/Ar biot.	CURTIS, G. (written communication, 1972)
Santa Inés Mine 29°48′ S/ 71°10′ W	Diorite	108.5	K/Ar biot.	CURTIS, G. (written communication, 1972)
Punta de Piedra 29°57′ S/ 71°06′ W	Granodiorite	95.0 93.8	K/Ar biot. K/Ar biot.	CURTIS, G. (written communication, 1972)
Las Rojas 29°59′ S/ 71°21′ W	Granodiorite	136±15	Lead-alpha	MUNIZAGA, Fdo. (1972)
Pan de Azúcar 29°59′ S/ 71°21′ W	Granodiorite	109±10	Lead-alpha	MUNIZAGA, Fdo. (1972)
Tamaya 30°04′ S/ 71°20′ W	Granodiorite (?)	134±20	Lead-alpha	MUNIZAGA, Fdo. (1972)
Montepatria 30°41′ S/ 71°03′ W	Granodiorite	125±15	Lead-alpha	THOMAS, H. (1967)
Punitaqui 30°56′ S/ 71°19′ W	Granodiorite	128±15	Lead-alpha	MUNIZAGA, Fdo. (1972)
Illapel 31°41′ S/ 71°09′ W	Granite	104±10 92.0	Lead-alpha K/Ar biot.	MUNIZAGA, Fdo. (1972)

Salamanca 31°45′ S/ 70°57′ W	Granite	109±10	Lead-alpha	MUNIZAGA, Fdo. (1972)
Salamanca 31°49′ S/ 70°54′ W	Granodiorite	89±10	Lead-alpha	MUNIZAGA, Fdo. (1972)
Pedegua 32°19′ S/ 71°05′ W	Granodiorite	123±20	Lead-alpha	MUNIZAGA, Fdo. (1972)
Cuesta El Melón 32°35′ S/ 71°16′ W	Monzogranite	120±20	Lead-alpha	LEVI, B. *et al.*, (1963)
La Campana 33°05′ S/71°01′ W-32°57′ S/ 71°07′ W	Granodiorite Gabbro	83.0 66.0	K/Ar biot. K/Ar Plg.	TIDY, E. (1970)
Puangue 33°20′ S/ 71°08′ W	Tonalite	118.0	K/Ar biot.	CORVALAN, J. and MUNIZAGA, Fdo. (1972)

Eleven additional lead-alpha determinations given by CORVALAN and MUNIZAGA, FDO. (1972), covering the interval 130-170 my., were obtained from a batholith cutting across Lower Cretaceous stratified formations. Disagreement between the stratigraphic relationship and the isotopic ages could be attributed to the fact that the analysed samples correspond to possibly contaminated rocks in the vicinity of the contact with the coastal Paleozoic batholith.

Contact metamorphic aureoles have been described from some of the previously mentioned areas. At La Higuera, andesitic flows of Lower Cretaceous age have been metamorphosed to hornfels in an aureole 1 to 2 km wide. The hornfels has been classified (MUÑOZ CRISTI, 1950) into three types; plagioclase-diopside, plagioclase-hornblende and plagioclase-hornblende-diopside.

At Santa Gracia (AGUIRRE and EGERT, 1970; CHAVEZ, 1972) an aureole with an average width of 2 km has developed in andesitic flows and calcareous sedimentary rocks of the Lower Cretaceous Arqueros Formation. Metamorphic facies correspond to albite-epidote hornfels and hornblende hornfels.

At Tambillos (MÜNCHMEYER, 1972) an aureole 1.7 km wide has developed also on the Arqueros Formation. Garnet hornfels and amphibole hornfels are the predominant petrographic types.

At La Campana (TIDY, 1970) a metamorphic aureole has formed mainly in volcanic rocks of Lower Cretaceous age. This aureole is wider where developed around granodiorite (1.0 km) than around gabbro (0.3 km). Metamorphic facies represented correspond to albite-epidote hornfels, hornblende hornfels and pyroxene hornfels, this last with a very reduced development.

Mineral deposits related to the Cretaceous granitoids (OYARZUN, 1971) are iron and apatite mainly developed by contact metamorphism in andesite. Hydrothermal deposits of silver have developed in limestone, shale and andesite under the influence of these intrusives.

TERTIARY GRANITOIDS

They form discontinuous outcrops in the east-central part of the region (Fig. 2).

Compared to the Cretaceous intrusives, the Tertiary bodies are smaller and clearly become smaller from north to south between the latitudes of this study.

These granitoids cut across formations with ages ranging from Paleozoic to Lower Tertiary. Most of them intrude volcano-sedimentary continental formations of the Upper Cretaceous and Lower Tertiary, as in the Main Range between 31°-33° S (Fig. 3-A, B, C). Borders are well defined and sharp and most of the bodies seem to have been emplaced high in the epizone.

Petrographically, the commonest types are granodiorite, diorite, tonalite and porphyries. Representative regions in which these intrusives have been described can be summarized as follows from north to south:

a) *Vicuña* (DEDIOS, 1967). Latitude 30° 15′ S. Two intrusive belts are distinguished in relation to a continuous north-south thrust present in the area. In the western intrusive belt, diorite (oligoclase, andesine, clynopyroxene, magnetite, quartz, apatite, epidote), tonalite (oligoclase, andesine, augite, quartz, epidote, apatite, magnetite) and tonalitic porphyries are the predominant rock types. In the eastern intrusive belt, light gray, medium-grained granodiorite (oligoclase, orthoclase, quartz, clinopyroxene, biotite, magnetite, apatite) and tonalite (oligoclase, quartz, microcline, hornblende, augite, biotite, sphene, zircon, apatite, epidote, magnetite) are the petrographic phases present.

b) *Quebrada Marquesa* (AGUIRRE and EGERT, 1965). Latitude 29° 45′ S to 30° S. Main types are greenish gray diorite and medium-grained granodiorite. The diorite is composed of zoned plagioclase (An_{60} core, An_{30} rim) partly albitized, amphibole, minor quartz and interstitial K-feldspar. Relicts of biotite in chlorite are also present; accessories are magnetite and apatite. Myrmekitic and micrographic intergrowths are present. The granodiorite is composed of andesine, hornblende, quartz and biotite.

c) *High Limarí River* (MPODOZIS, in prep.). Latitude 30° 50′ S. Three belts are distinguished from west to east. In the western belt, an extension of the western intrusive belt of the Vicuña area, the predominant petrographic type is a light gray, medium-grained granodiorite composed of plagioclase, partly perthitic interstitial orthoclase, hornblende, biotite, quartz and magnetite. One modal analysis of this rock is shown in Table 3, No. 25 and Fig. 6. This rock forms relatively large bodies (maximum diameter 20 km). In the central belt, typical intrusives are a light gray, medium-grained, partly porphyritic diorite and quartz diorite. Minerals present in these rocks are zoned plagioclase, quartz, hornblende (partially altered to actinolite and epidote), biotite and magnetite. A modal analysis of the quartz diorite is given in Table 3, No. 26 and Fig. 6. These rock types appear as small circular bodies (diameter less than 0.5 km) emplaced along faults or thrust zones. The eastern belt corresponds with a composite batholith having a porphyritic tonalite core and an equigranular tonalite border. A gradual transition between the two types has been observed. Maximum diameter of this body is about 15 km. The mineralogy of these tonalites comprises plagioclase, hornblende (with crystals up to 3 cm in the core of the batholith), quartz, biotite and iron ore. A modal analysis of this rock is shown in Table 3, No. 27 and Fig. 6.

d) *Tascadero and Turbio Rivers* (RIVANO, in prep.). Latitude 31° 10′ S. Main petrographic types are syenogranite and minor quartz diorite. The syenogranite is composed of quartz, K-feldspar (perthite and microcline), plagioclase, and rare biotite, chlorite and sphene as accessories. The quartz diorite is formed of plagioclase, amphibole, clinopyroxene and minor quantities of quartz, K-feldspar and iron ores. Modal analyses of both rock types are given in Table 3, No. 28 and 29 and Fig. 6.

e) *Pelambres* (UNITED NATIONS REPORT, 1970). Latitude 31° 50′ S. The main rock type is a medium-grained tonalite composed of andesine, quartz, hornblende and biotite in minor amounts, and apatite, zircon and sphene as accessories. A transition to tonalitic porphyries has been observed. The intrusive body has a maximum diameter of 4.5 km and shows a well defined contact and numerous apohysis.

f) *Main Range* between latitudes 32° 20′ and 33° S (VICENTE, in prep.). Diorite, quartz diorite, monzogranite, quartz monzodiorite, and tonalite have been sampled in this region. All of these rocks contain plagioclase, quartz and opaque minerals, Orthoclase is present in the monzogranite, quartz monzogranite and diorite. Augite is present in almost all types but in diorites and quartz diorites it is the only ferromagnesian mineral present, reaching in one sample (Table 3, No. 37) 21.5%. Biotite and amphibole are sporadic. Modal analysis of these rocks are given in Table 3, No. 30 to 37 and Fig. 6.

g) *Riecillos* (AGUIRRE, 1960; LEVI *et al.*, 1963). Latitude 32° 50′ S. Monzogranite (oligoclase, orthoclase, quartz, hornblende and biotite), quartz monzodiorite (oligoclase, microperthite, quartz, hornblende, sphene and magnetite) and diorite are the three patrographic types present in the area. Modal analyses are given in Table 3, No. 37 and 40 and Fig. 6.

h) *Rio Colorado,* Aconcagua Province, latitude 32° 45′ S. Fine to medium-grained, light gray monzogranite (oligoclase, perthite, quartz, biotite, amphibole, magnetite, sphene, tourmaline, epidote) is present at this locality. Modal analysis is given in Table 3, No. 43 and Fig. 6.

i) *Portillo,* latitude 32° 45′ S. Fine to medium-grained, light gray granodiorite (plagioclase, quartz, partly perthitic K-feldspar, biotite, amphibole, calcite, sphene, apatite and chlorite) is present in this locality. Ferromagnesians are generally altered to chlorite; a porphyritic texture is formed in places by regularly distributed megacrysts of plagioclase with an average size of 5 to 7 mm. One modal analysis is given in Table 3, No. 44 and Fig. 6.

j) *Main Range* between latitudes 33° S and 34° S. (URQUETA, 1969; ALFARO, 1970; SAAVEDRA, 1971; OYARZUN, 1971).

–*Rio Blanco and Disputada*, Latitude 33° 90′ S.
Granodiorite and quartz porphyry are present in this area. The granodiorite is composed of plagioclase (sericitized/albite-oligoclase), quartz, orthoclase, biotite, amphibole and accessories such as apatite and sphene. The quartz porphyry is a light gray rock formed by phenocrysts of quartz, albite, K-feldspar and biotite in a microcrystalline groundmass of quartz, feldspar, epidote, calcite and chlorite.

–*La Obra,* Latitude 33° 35′ S.
The main rock is equigranular, medium-grain, light gray granodiorite composed of plagioclase, quartz, orthoclase (perthitic), amphibole and biotite. One modal analysis of this rock is given in Table 3, No. 41.

–*Tupungato Volcano area*, Latitude 33°20′ S.
Tonalitic porphyry (quartz, plagioclase, biotite, epidote, chlorite, sericite) and dioritic porphyry are the phases present.

–*Rio Colorado*, Santiago Province, Latitude 33° 30′ S.
Quartz tonalite (quartz, plagioclase, biotite, amphibole, apatite and iron ores) is the principal rock.

–*San Gabriel*, Latitude 33° 50′ S.
Quartz monzonite composed of plagioclase (An_{30}), K-feldspar, hornblende, quartz, magnetite and accessories is the predominant phase (Table 3, No. 42).
Olivinic gabbro and diorite have been emplaced in small bodies at higher levels than the quartz monzonite.

Seventeen lead-alpha ages (Table 5) are available for the Tertiary granitoids of this

Table 5. Radiometric Ages for Tertiary Granitoids between 30° and 35° S latitude.

Locality	Rock Type	Age my	Method	Author
Las Ñipas 30°06′ S/ 70°41′ W	Granodiorite	50±10	Lead-alpha	DEDIOS, P. (1967)
Vicuña Quadrangle 30°12′ S/ 70°43′ W	Diorite	56±10	Lead-alpha	DEDIOS, P. (1967)
Loica 31°04′ S/ 70°41′ W	(?)	34.5±5	K/Ar hydro-thermal biotite	QUIRT, E.S. *et al.*, (1971)
Salamanca 31°42′ S/ 70°47′ W	Porphyritic Granite	65±10	Lead-alpha	MUNIZAGA, Fdo. (1972)
Salamanca 31°43′ S/ 70°48′ W	Granodiorite	64±10	Lead-alpha	MUNIZAGA, Fdo. (1972)
Los Pelambres Mine 31°45′ S/ 70°28′ W	(?)	9.96±0.18 9.74±0.16	K/Ar hydr. biot.	QUIRT, E.S. *et al.*,
Cuncumén 31°53′ S/ 70°42′ W	Granodiorite	52±10	Lead-alpha	MUNIZAGA, Fdo. (1972)
Putaendo River 32°30′ S/ 70°34′ W	Dioritic porphyry	55±10	Lead-alpha	MUNIZAGA, Fdo. (1972)
Putaendo River 32°30′ S/ 70°37′ W	Granodiorite	68±10	Lead-alpha	MUNIZAGA, Fdo. (1972)
Riecillo Brook 32°59′ S/ 70°21′ W	Quartz-monzodiorite	50±20	Lead-alpha	LEVI, B. *et al.*, (1963)
Riecillo Brook 33° S/70°21′ W	Monzogranite	30±20	Lead-alpha	LEVI, B. *et al.*, (1963)
Disputada Mine 33°09′ S/ 70°18′ W	Granite	23±10 10.0	Lead-alpha K/Ar biot.	RUIZ, C. *et al.*, (1965)
Pérez-Caldera 33°12′ S/ 70°18′ W	Granodiorite	18±10	Lead-alpha	MUNIZAGA, Fdo. (1972)
Rio Blanco Mine 33°09′ S/ 70°18′ W	Quartz porphyry	4.59±0.8 3.92±o.10	K/Ar biot K/Ar biot	QUIRT, G.S. *et al.*, (1971)
La Obra 33°35′ S/ 70°29′ W	Granodiorite	24.0	K/Ar biot.	RAVICH, M.G. (written communication, 1967)
Colorado River 33°30′ S/ 70°13′ W	Tonalite	14±10	Lead-alpha	RUIZ, C. *et al.*, (1965)

Yeso River 33°46′ S/ 70°13′ W	Granite Granodiorite Granodiorite	30±10 15±10 23±10	Lead-alpha Lead-alpha Lead-alpha	RUIZ, C. *et al.*, (1965)
Yeso River 33°47′ S/ 70°13′ W	Granodiorite	40±10	Lead-alpha	MUNIZAGA, Fdo. (1972)
El Teniente Mine 34°55′ S/ 70°20′ W	(?)	4.32±0.08 5.62±0.11	K/Ar on whole rock hydro-therm. sericite	QUIRT, G.S. *et al.*, (1971)
Las Lajas 35°3′ S/ 70°38′ W	Granodiorite	27±10	Lead-alpha	MUNIZAGA, Fdo. (1972)

region. They vary from a maximum age of 68 my. (Cretaceous-Tertiary boundary) to a minimum of 14 my. Four K-Ar determinations on magmatic biotite have been carried out on the youngest porphyry bodies; they gave values between 10 my. (Disputada) and 4 my. (Rio Blanco).

Age determinations on hydrothermal biotite from some Tertiary intrusives (QUIRT *et al.*, 1971) have been made. They should indicate the age of the hydrothermal alteration related to the emplacement of these bodies. They give values of 34.5 my. for the Loica alteration zone (latitude 31° 10′ S) and 9.96 and 9.74 my. for the Pelambres alteration. For the El Teniente alteration zone, ages of 4.32 my. and 5.62 my. have been obtained on K-Ar whole rock hydrothermal sericite.

Taken as a whole (*see* Table 5 and Fig. 7) age determinations show a general clustering in the intervals 60-70 my., 50-55 my., 20-30 my. and 4-17 my.

No metamorphic aureoles have been described for the Tertiary granitoids of this region but hydrothermal alteration is widespread and has been studied in several places in relation with prospecting.

At Doña Ana (THIELE, 1964), at the northern boundary of the studied region, hydrothermal alteration is characterized by strong sericitization, limonitization and epidotization.

In the Quebrada Marquesa quadrangle (AGUIRRE and EGERT, 1965) alteration is fairly extensive; in the northeast part of the area it is superimposed on Lower Teriary stratified volcanic and sedimentary rocks. A well-developed zonation from the core to the border includes a silicified central zone, sericitic and argillic zone, sericitic zone with secondary quartz, chorite-sericite zone and chlorite zone. This alteration extends north of the quadrangle where several areas with similar characteristics have been studied (KENTS, 1963).

In the Vicuña region a widespread alteration zone is present, mainly west of the Vicuña Fault. It is characterized by sericite, chlorite, quartz and extensive silicification.

Between this last region and the southern boundary of the Coquimbo Province (latitude about 32° 20′ S) several areas of alteration are present, most of them characterized by extensive zones of silicification, sericitization and argillization. A typical example is the Pelambres locality (UNITED NATIONS REPORT, 1970) where a zonal concentric pattern of alteration has been developed with the following sequence from the center to the periphery: a potassic zone, sericitic zone, argillic zone, silicic zone and a propylitic zone.

In the Disputada region, at the Los Bronces copper mine (ALFARO, 1970) the hydrothermal alteration is represented by two zones, an inner zone with sericite, pyrite and quartz and a propylitic outer zone with epidote, chlorite and calcite. A similar zoning has been described by URQUETA (1969) for the Rio Blanco copper district, closely related to the Disputada region.

The most important copper and molybdenum deposits of the country are genetically associated with the Tertiary intrusives, especially the porphyry types. This is the case of Chuquicamata, El Salvador and El Teniente copper mines, the largest copper deposits known in the world. Tourmaline breccia-pipe deposits containing copper, tungsten and gold are also related to shallow Tertiary intrusives. Dykes mineralized with silver, lead, zinc, quicksilver, antimony and gold are often present cutting across volcanic and sedimentary rocks at the periphery of the main copper and molybdenum mineralization.

SUMMARY OF PLUTONIC EVOLUTION

The geographic distribution of the different intrusive cycles in the region shows a general reduction in age from west to east. Jurassic granitoids occupy the westernmost position, Cretaceous granitoids form a central belt and Tertiary intrusives of the same nature are confined to the Main Range on the east. A similar migration of granitoids has been observed in a northern region (27° 20′ S) near Copiapó (FARRAR *et al.*, 1970). A plot of all available geochronological ages against longitude (Fig. 8) clearly illustrates this relationship. The interpretation of this diagram should take into account the fact that geological units and structures have some curvature and depart from a strict north-south orientation.

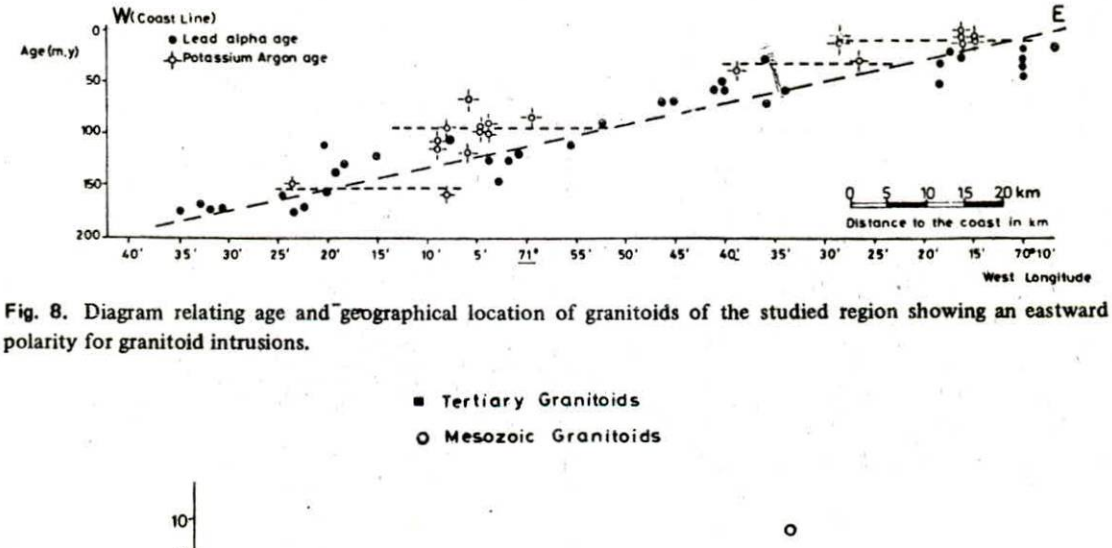

Fig. 8. Diagram relating age and geographical location of granitoids of the studied region showing an eastward polarity for granitoid intrusions.

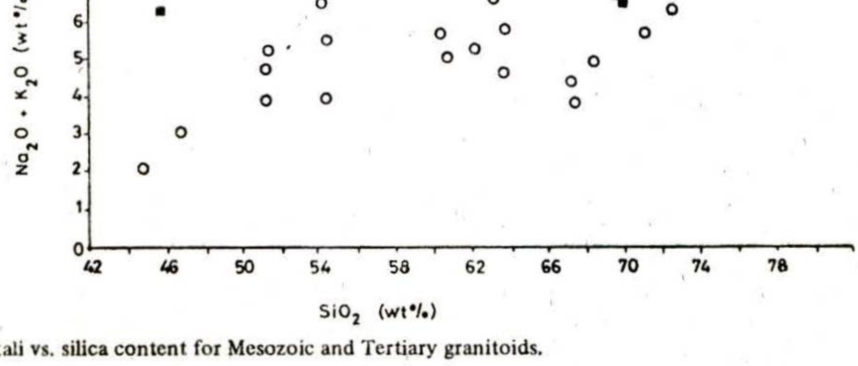

Fig. 9. Alkali vs. silica content for Mesozoic and Tertiary granitoids.

Table 6. Average of available chemical analyses of Mesozoic and Tertiary granitoids between latitudes 30° and 35° S.

	Mesozoic (1) Granitoids	Tertiary (2) Granitoids
SiO_2	61.20	62.79
TiO_2	0.57	0.74
Al_2O_3	15.83	16.60
Fe_2O_3	2.32	1.93
FeO	4.01	2.84
MgO	2.96	2.15
CaO	8.35	3.58
Na_2O	3.48	5.14
K_2O	1.93	2.41
Na_2O+K_2O	5.41	7.55
Fe^{+3}/Fe^{+2}	0.52	0.61

NOTE:
(1) This average is based on 18 analyses, one of which is an average of 9 diorites.
(2) This average is based on 11 analyses.

Chemical analyses for major elements of intrusive rocks that crop out between parallels 30° and 35° latitude south are as yet scarce. Eighteen analyses of Mesozoic intrusives (one of them an average of 9 diorites) and eleven corresponding to Tertiary intrusives, scattered through the literature, have been compiled. The analyses of Mesozoic intrusive rocks correspond mainly to granites, granodiorites, tonalites, diorites and gabbros, and those of Tertiary intrusives to granodiorites (trondhjemites), porphyritic tonalites, diorite porphyry and gabbro.

Comparison of the general averages of these two groups of analyses show that Tertiary intrusives are much richer in alkalis (Fig. 9), and that Mesozoic intrusive rocks are higher in lime, both ferric and ferrous iron, and magnesia. Silica and alumina are slightly more abundant in the younger rocks. The Fe^{+3}/Fe^{+2} ratios are higher in Tertiary intrusive rocks (Table 6).

Data on ages indicate a general postkinematic relationship between plutonic cycles and tectonic evolution of the Andean Orogenic Cycle. Figure 7 shows the location of geochronological ages (K-Ar and lead-alpha methods) in relation to the geological time scale recommended by the Time Scale Symposium (1964). Clustering of isotopic ages in certain intervals is not always in accord with other knowledge on the geologic evolution of the Andean Orogene.

–Interval between 173 my. and 167 my. does not correspond to any known geological episode, but all of the ages in this interval are from lead-alpha determinations which are known for a tendency to give older ages.

–Interval between 142 my. and 133 my., corresponding to the Jurassic-Cretaceous boundary, may represent postkinematic plutonic activity known as the Late Jurassic or Araucanian Phase. This phase is documented by unconformity and hiatus in several regions especially in the western part of the country.

–Interval between 110 my. and 90 my. (middle-Cretaceous) closely agrees with the age assigned to the Subhercynian Phase documented by the unconformity separating the Colimapu and Abanico Formations in the Main Range.

–Interval between 70 my. and 62 my. (Cretaceous-Paleocene boundary) corresponds well with the Laramic Phase that folded the Abanico Formation in the Central Andes of Chile.

–Interval between 57 my. and 47 my. (Eocene) corresponds to the Incaic Phase documented by the folding of the Farellones Formation.

–Interval between 32 my. and 22 my. (Late Oligocene-Early Miocene) may correspond to young intrusives that followed the Quechuan Phase which folded the Coastal Range Miocene volcanics, but younger ages would have been expected.

Relations between Tectonics and Magmatism

DISCONTINUITY OF TECTONIC AND MAGMATIC EVENTS

Between each compressive phase, recognized by strong angular unconformities, sedimentary or volcanic formations were deposited. These formations constitute six structural units which, according to their ages, are folded with variable intensity. During deposition no compression took place since each structural unit has a unique tectonic style. It is not possible to affirm whether extension actually took place. The extension which has been taking place in orogenic regions (Alps, Andes, Island Arcs) since the end of the Late Miocene compressive phase suggests that the same probably occurred in older epochs after each compression while similar thick volcanic deposits (rhyolitic and andesitic) were accumulating.

On the basis of this evidence CHARRIER (1973b) stated that the tectonic evolution of the Southern Andes is rhythmic and that each cycle is composed of two periods, a long period of "no compression"or relaxation or of possibie extension, and a short period of compression.

Volcanism is clearly related to the periods of "no compression" and may itself even be evidence for extension, whereas plutonism is more closely related to the periods of compression. Radiometric ages of plutonic rocks coincide fairly well with the ages of the compressive phases but since the granitoids have sharp borders and lack of foliation a postkinematic origin should be accepted. Plutonism is, however, the first magmatic manifestation after each compressive phase and is followed by longer volcanic events. The close chronologic relation between batholithic intrusions and the acidic volcanism at the beginning of each volcanic cycle suggests a related origin for both phenomena.

It may thus be concluded that the tectonic and magmatic evolution of the Southern Andes is clearly discontinuous (rhythmic) and that it has an orogenic beat of approximately 20 to 40 my. The time relations between the different tectonic and magmatic processes discussed in this article are shown in Fig. 10.

GLOBAL MAGMATIC EVOLUTION

One of the most striking features in the geotectonic evolution of the Andean Belt is a clearly shown migration of the volcanic units and granitoids of the same age from west to east.

Jurassic volcanic and plutonic outcrops in the studied region are smaller in total area than those of the Cretaceous and Tertiary. Nevertheless, both plutonic and volcanic rocks of the Jurassic occupy a westernmost position, generally in the Coastal Range. The largest bodies of Jurassic granitoids crop out between latitudes 30° S and 31° 31′ S where no Jurassic volcanics are present. On the other hand, the most important Jurassic volcanic units are located in the western part between latitudes 32° and 33° where the age of the associated granitoids has not been positively confirmed as Jurassic.

Cretaceous and Tertiary volcanics and granitoids, in contrast, generally outcrop in the central and eastern belt respectively. Cretaceous granitoids are mainly spatially

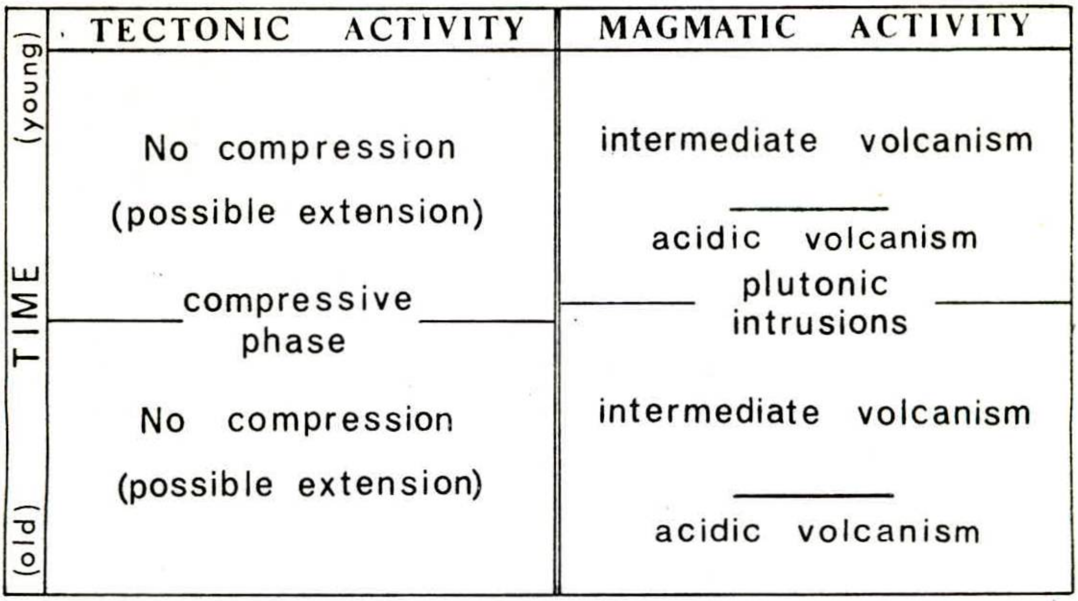

Fig. 10. Time relations between tectonic and magmatic events in each period of the Andean (Geoliminal) Orogenic Cycle showing a rhythmic evolution for both activities.

associated with Lower Cretaceous volcanoclastic formations, whereas Tertiary granitoids are coincident with Upper Cretaceous and Lower Tertiary volcanoclastic formations.

Plutonic and volcanic rocks associated with the Andean Orogen are of an oversaturated calcalkaline character. No ultrabasic or alkaline rocks have been described.

Volcanic rocks are mainly rhyolitic in composition in the early stage and andesitic in the final stage in each volcanic cycle.

Cretaceous and Tertiary granitoids range regularly from diorite to granite with most concentrated around the granodiorite and quartz monzodiorite composition (Fig. 6). Information about Jurassic granitoids is very limited.

OYARZUN (1971) studied the Rb-and Sr-contents and Rb/Sr ratio for the granitoids and volcanics of Cretaceous and Tertiary age, mostly for rocks in the area covered by this report. A close relationship in Sr-and Rb-content between the Tertiary intrusives and the Pliocene andesitic flows was pointed out by OYARZUN. A genetic connection between these magmatic products could be inferred according to this author (Table 7).

Table 7. Rb–and Sr–contents and ratio for granitoids and volcanics of Cretaceous and Tertiary age. After OYARZUN, J. (1971)

	Sr (p.p.m.)	Rb (p.p.m.)	Rb/Sr
Cretaceous Granitoids	425	54	0.127
Cretaceous Andesites	395	70	0.180
Tertiary Granitoids	700	63	0.090
Tertiary Andesites	340	63	0.16
Pliocene Andesites	630	69	0.109

The predominant character of the magmatic processes during the evolution of the Andean Orogenic Cycle is clearly illustrated by the fact that almost one third of the area is covered by plutonic outcrops and that the maximum thickness of the volcanic pile for the Mesozoic and Tertiary reaches 42,450 m (Fig. 5).

As a final conclusion, there is a marked similarity in the direction of migration and composition of the plutonic bodies and volcanic products of the Andean Range.

GLOBAL PLUTONIC-TECTONIC SYNCHRONISM

The compressive tectonic phases determined for the Southern Andes are not new nor unique to the studied region and all have been reported, though sometimes separately, from other areas.

Along the Southern Andes the effects of each phase are synchronous and are associated with granitoid intrusions (CHARRIER and VICENTE, 1970).

STEINMANN (1929) defined in Perú three orogenic phases, a Peruvian (Early Senonian), and Incaic (Paleocene or Oligocene) and a Quechuan Phase (Late Miocene). Recently, MEGARD (1972) determined an early Oligocene age for the Incaic Phase.

In Ecuador three phases have been precisely dated by means of foraminiferal determinations by FAUCHER and SAVOYAT (1973), a Subhercynian (Senonian), a Laramic (Paleocene) and a Quechuan Phase (Late Miocene).

Four phases have been recognized in Colombia by BÜRGL (1967), a Peruvian (Santonian-Campanian), a Laramic (Early Tertiary), an Incaic (Middle Eocene) and a fourth phase of Miocene age. The same author stated that the Peruvian and Incaic Phases are accompanied by granitoid intrusions.

Although some ages determined for some phases in different parts of the Andean Range differ slightly depending on whether the dating was done in the internal or external domain of the range, a tectonic synchronism is clearly shown. Age determinations for granitoids along the range are too scanty to permit a clear correlation between intrusions and tectonic phases in regions other than the Southern Andes.

In other orogenic regions, such as, the Alps and Island Arcs, the Upper Miocene phase is well known. A similar tectonic calendar is also known in North America. In the Alpine region and its foreland all five phases recognized in the Southern Andes are represented and are associated with granitic intrusions. These data suggest a synchronism for widely separated orogenic regions.

Finally, published data on sea-floor spreading for the different oceans (CHARRIER, 1973b), show a close correlation between interruptions in spreading and the compressive tectonic phases of the Southern Andes and between the periods of spreading activity and the periods of "no compression". This suggests, not only a synchronic teconic evolution of orogenic belts, as first postulated by STILLE (1924), but also a world-wide dynamic model of generalized compressions and extensions.

COMPARISON BETWEEN GEOLIMINAL AND GEOSYNCLINAL MAGMATISM

Magmatism in the two types of pericontinental mountain ranges (Geoliminal and Geosynclinal) is differenciated by the composition of the initial magmatism and the relationship between plutonism and the tectonic phases. Initial magmatism must be separated from Triassic volcanic activity (Embryonic Stage of the Southern Andes). In mountain ranges of the Geosynclinal type initial magmatism refers to the synsedimentary volcanic activity of the first paleogeographic period (Geosynclinal Period). There exists a remarkable difference between the classic ophiolitic (basic to ultrabasic) initial magmatism in the Geosynclinal type of mountain ranges and the mainly acidic initial volcanism of the Southern Andes (Geoliminal type). More specifically no ultrabasic bodies, serpentinites associated with radiolarites, nor 'green-rocks' have been found in the internal zones of Geoliminal-type ranges. If ophiolitic volcanism actually has an oceanic origin, geoliminal initial volcanism clearly has another origin.

Syntectonic plutonism, which generates conformable bodies, seems to be exclusive to geosynclinal mountain ranges, where they constitute deep or intermediate massives (*sensu* GUITARD, 1958) with abundant migmatites, showing both anatexis and injection. These plutons have diffuse migmatitic borders (harmonious granitoids of WALTON, 1965) and are closely related to high-grade regional metamorphism. None of this has been observed in the Southern Andes. Granitoids of the studied region are typically late or post-tectonic and have sharp discordant borders (disharmonious granitoids of WALTON, 1965). They are shallow massives (*sensu* GUITARD, 1958) similar to the late and post-tectonic plutons of Geosynclinal ranges.

The absence of syntectonic plutonism in Geoliminal ranges seems to be closely related to the very low grade of metamorphism present (burial metamorphism between zeolite and greenschists facies, (LEVI, 1969, 1970), which indicates that thermodynamic conditions were not high enough to generate migmatites (WINKLER, 1967).

Geoliminal plutonism seems to confirm the independence between discordant massives of granitoids and direct anatexis phenomena (AUTRAN *et al.*, 1970) and supports a deep magmatic origin, probably infracrustal (GAGNY, 1968; AUTRAN *et al.*, 1970).

Apart from these two essential characteristics of the Geosynclinal magmatism that are not present in Geoliminal magmatism, there are other differences which seem to be more quantitative. Early (since Early Cretaceous) calcalkaline volcanism which shows a clear tendency to migrate towards more external positions in the Andean Geoliminal Range, compared to the calcalkaline volcanism of Alpine Ranges, which begins only in the late geosynclinal period (Oligo-Miocene) and is restricted to internal zones.

Thick (10,000 to 15,000 m) sequences of essentially andesitic volcanics and a large number of recent, active volcanic centers characterize the Andean Geoliminal Range.

Great extension and continuity of batholiths in the Geoliminal Ranges and the apparent scarcity of granitoids in the Alpine Ranges has been usually taken as an essential difference between the two types of ranges. Nevertheless, this difference seems to be more apparent than real (AUBOUIN *et al.*, 1973), since there are important granitic bodies in the Alpine internal zones which have been given little attention (MERCIER, 1966). Moreover, the continuity of outcrops of huge granitic masses along Geoliminal and Geosynclinal (Patagonian Range) sectors of the Southern Andes is evidence against this distinction.

This comparison between Geoliminal and Geosynclinal magmatic activities indirectly supports the close relationships between tectonics and magmatism in the orogenic regions. Magmatic differences seem to point to tectonic differences. The absence of ultrabasic magmas during initial volcanism in Geoliminal Ranges could be explained by weaker extension tectonic processes than those of Geosynclinal Ranges. The absence of anatectic magmatism and high-grade metamorphism in Geoliminal Ranges could be the result of weaker tectonic compressions than those active in Geosynclinal Ranges.

These differences between types of mountain ranges seem to be related to their different geotectonic positions, monoliminal (pericontinental, *s.s.*) for the Geoliminal Sector of the Andes and biliminal (intercontinental) for the Geosynclinal Ranges.

General Conclusions

The tectonic and magmatic evolution of the studied region is rhythmic; five short and superposed compressive phases are followed by longer periods of "no compression" or of possible extension. Compressive phases are closely followed by postkinematic intrusions of granitoids. Volcanism took place during the periods of "no compression" and in each period it began with an acidic composition followed by intermediate flows and pyroclastics. Five tectonic phases separate six paleogeographic periods.

Close geographic and compositional similarities between Mesozoic and Cenozoic granitoids and volcanics exist for each paleogeographic period. Plutonic and volcanic rocks are of an oversaturated calcalkaline composition. No ultrabasic rocks are known in the studied region, and alkaline volcanics are present only east of the range, on the Andean foreland. Mesozoic granitoids are richer in lime and both ferric and ferrous iron and Tertiary granitoids are richer in alkalis.

A sedimentologic, paleogeographic and tectonic migration to the east, associated with a similar migration of the volcanic centers and granitoid intrusions, has been demonstrated. This migration is strong evidence for an eastward polarity in the evolution of the Andean Range.

Radiometric datings on Andean granitoids show a close relationship between intrusive activity and compressive tectonic phases. Granitoids are postkinematic but were emplaced immediately after cessation of compression.

The five compressive tectonic phases are remarkably synchronous with the tectonic phases of other Andean regions (Patagonian Andes, Perú, Ecuador, Colombia) and other orogenic belts.

Magmatism of the studied region (Andean Geoliminal Sector) differs from Alpinotype (Geosynclinal) magmatism by the absence of basic or ultrabasic rocks and of harmonious granitoids. Different geotectonic positions, monoliminal for the studied region and intercontinental or biliminal for Alpinotype ranges, may account for this difference.

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