Jurassic and Early Cretaceous island arc volcanism, extension, and subsidence in the Coast Range of central Chile

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ABSTRACT

More than 2000 km^3 of acid and 9000 km^3 of basic volcanic rocks formed during the Jurassic and Early Cretaceous in the Coast Range of central Chile, between 32°30′S and 34°S. These rocks, which constitute the major part of an ~15-km-thick pile of alternately marine and continental deposits, issued from volcanic arcs situated between a land area with Paleozoic basement in the west and a marginal sea in the east. Asthenospheric upwelling led to extension and bimodal volcanism; the volcanic products were deposited in intra-arc basins subsiding at high rates (100–300 m/m.y.). The source of the magmas became more depleted with time due to an increase in degree of partial melting, and their compositions were modified by subduction-related fluids and contamination with a progressively thinner and younger crust. The basic lavas are of high-K calc-alkaline to shoshonitic affinity, chemically resembling the lavas found in some mature island arcs in the western Pacific. The extension and subsidence resulted in a low-relief topography close to sea level, in contrast with the present-day convergent type of Andean volcanism at the same latitude where calc-alkaline intermediate lavas erupt from volcanoes at great height above a thick crust.

INTRODUCTION

Jurassic and Lower Cretaceous stratified sequences form two north-trending belts that can be followed along the entire length of central Chile (SERNAGEOMIN, 1982; Åberg et al., 1984; Aguirre, 1985). The thickest sequences, composed mostly (>90%) of volcanic and volcaniclastic rocks with a cumulative thickness of 10 to 20 km, are located in the western part of the Andes, the Coast Range (Fig. 1A). They form the homoclinal western limb of a synclinorium where the lithochronological units dip 20°–70° to the east and become successively younger toward the Central Valley Graben (Fig. 1B). The rocks are intruded by Mesozoic epizonal granitoids, which also decrease in age toward the east. Thinner (2–4 km) Jurassic and Lower Cretaceous units with a higher proportion of sedimentary rocks are found in the High Andes, constituting the eastern limb of the synclinorium upon which a Quaternary volcanic arc is built. The western and eastern basements of the synclinorium consist of predominantly magmatic Paleozoic-Triassic rocks (Hervé et al., 1987). Late Cretaceous to Neogene units in volcano-tectonic graben structures (Thiele et al., 1991; Vergara et al., 1993) occupy the center of the synclinorium.

Several models, usually based on sparse data, have been proposed in order to explain the presence of the two Jurassic–Lower Cretaceous belts in central and northern Chile. They involve one wide basin (Levi and Corvalán, 1968), splitting of an arc or back-arc (Levi and Aguirre, 1981; Åberg et al., 1984), and an arc (intra-arc)/back-arc pair (Coira et al., 1982; Thiele and Nasi, 1982; Charrier, 1984; Jensen, 1984; Ramos, 1989; Mpodozis and Ramos, 1989; Charrier and Muñoz, 1994).

This paper treats a representative sector of the Coast Range of central Chile (32°30′–34°S) where the Mesozoic formations crop out as semicontinuous belts (Fig. 1B) in a mountainous region at altitudes of 500–3000 m. Two stratigraphical-structural superunits of Jurassic and Early Cretaceous age, respectively, are described here (Table 1). They are separated by a major unconformity and rest unconformably on a Paleozoic basement, which extends to the coast line; the Lower Cretaceous rocks are unconformably overlain by subaerial sequences of Late Cretaceous age. Both the Jurassic and Lower Cretaceous superunits are characterized by a lower part with acid volcanic rocks deposited in a marine environment and an upper part dominated by basic subaerial lavas. Many dikes and normal faults, coeval with the units they intrude and affect, respectively, parallel the trend of the belts (Levi, 1973; Nasi and Thiele, 1982). Mesozoic thrust faults have not been observed (Cenozoic thrust faults complicate the structure of the High Andes in Argentina and Chile; Ramos et al., 1991). The Jurassic and Cretaceous granitoids in the studied region are coeval with a decline in volcanism and subsequent uplift (Drake et al., 1982; Aguirre, 1985).

The purpose of this paper is to show that the Jurassic and Lower Cretaceous formations in the Coast Range of central Chile were deposited in a setting quite different from the present Andean-type continental margin. Extension and progressive crustal attenuation led to generation of large volumes of bimodal high-K calc-alkaline to shoshonitic volcanic rocks. They erupted from Jurassic and Early Cretaceous island arcs situated between an emerged Paleozoic basement in the west and a marginal sea in the east.

THE BASEMENT

The basement in the studied region (Fig. 1) consists of granitoids belonging to the late Paleozoic Coastal Batholith of central Chile (age ca. 290–305 Ma; Hervé et al., 1988) and isolated outcrops of late Paleozoic marine volcaniclastic rocks (Corvalán and Dávila, 1964). Toward the west the basement extends to the present coastline. The granitoids, which have initial $^{87}Sr/^{86}Sr$ ratios of ca. 0.706 (Hervé et al., 1988), are

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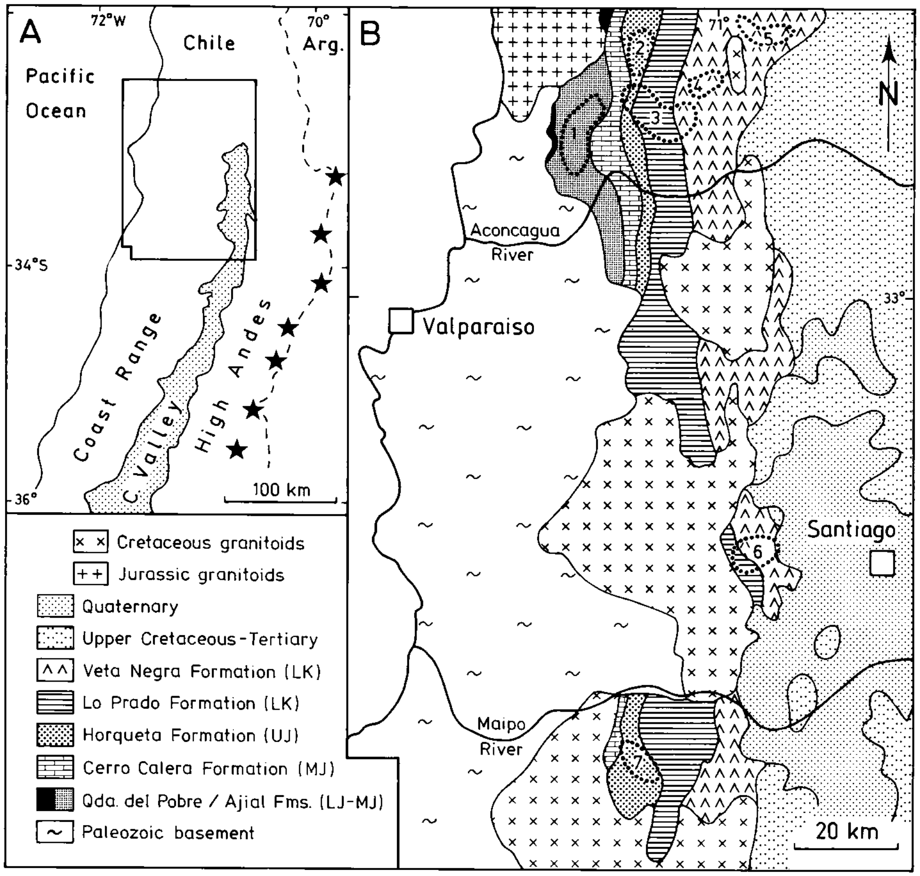

Figure 1. The studied region in central Chile. A. Location map and main physiographic features (Arg. = Argentina; C. Valley = the Central Valley Graben; Qda. del Pobre = Quebrada del Pobre). The stars represent Quaternary volcanic complexes belonging to the northern part of the Southern Volcanic Zone. A nonvolcanic zone extends north from 33°S to 27°S. B. Simplified geologic map of the Coast Range between 32°30′S and 34°S. LK = Lower Cretaceous; UJ, MJ, and LJ = Upper, Middle, and Lower Jurassic (see Table 1 for lithology and stratigraphic relationships). Based on Thomas (1958), Carter and Aliste (1961–1963), Levi (1968), Piracés (1976, 1977), Piracés and Maksaev (1977), Thiele and Nasi (1982), and observations by the authors. Triassic sequences crop out immediately north of the studied region. The numbered areas are the sample localities of volcanic rocks collected for chemical analysis.

calc-alkaline, coarse-grained tonalites, granodiorites, and granites, in part with a gneissic structure. As a rule their quartz has strong undulatory extinction and is locally granulated. The plagioclase commonly shows curved twinning planes, and the K-feldspar is microcline (Muñoz Cristi, 1964). Hervé et al. (1981) suggested that the Coastal Batholith represents a deeper crustal level of the late Paleozoic magmatic arc that occurs in the central and eastern parts of the High Andes in Argentina.

From the coast and up to 20 km inland, the basement immediately north of the studied region is composed of predominantly marine sedimentary sequences of Middle to Upper Triassic age with intercalations of bimodal, low-K volcanic rocks, mostly of acid composition (Vergara et al., 1991). Paleocurrent data (Charrier, 1979) indicate a southeastern source of the sediments and paleoslopes facing southwest to northwest. Forsythe et al. (1987) considered that the Triassic sequences represent an allochthonous terrane. However, Thiele and Nasi (1982) and Hervé et al. (1987) suggested that they were formed in a fore-arc region with a young arc at a continental margin. According to Vergara et al. (1991) the volcanic arc was floored by a quasioceanic crust.

South of the studied region the Paleozoic granitoids intrude metamorphosed lower Paleozoic fore-arc sequences (quartzites, schists, and gneisses), which have been interpreted as a subduction complex (paired metamorphic belts according to González-Bonorino and Aguirre, 1970) accreted to the western margin of Gondwana (Hervé et al., 1981, 1987).

JURASSIC AND LOWER CRETACEOUS SEQUENCES

The following description of the lithology and petrography of the Jurassic and Lower Cretaceous sequences in the Coast Range is based on unpublished theses from the Universidad de Chile, Santiago, and observations by the authors, in addition to the references in the text. The terms *basic* (basalts and basaltic andesites) and *intermediate* (andesites) refer to lavas and flow breccias with maximum SiO_2 contents of 53, 57, and 63 wt%, respectively, recalculated to 100% anhydrous; acid lavas, ignimbrites, and tuffs contain more than 63% SiO_2 (dacites up to 68%, and rhyolites >68%). The investigated sequences are affected by regional alteration (burial metamorphism of predominantly prehnite-pumpellyite facies), which is pervasive in the upper, amygdaloidal parts of the basic to intermediate flows but is only incipient to weak in many places in the massive, lower parts (Levi, 1969, Fig. 2; Levi et al., 1982, 1989; Vergara et al., 1994). There, the primary phenocrysts are well preserved (plagioclase, pyroxene, and Fe-Ti oxide); the same minerals are found in the groundmass (Levi, 1969, Fig. 1 and passim; Levi et al., 1982, 1989). In the acid rocks, however, the volcanic plagioclase is replaced by sodic albite (less than An_5, no Or component) of low structural state, the original K-feldspar is recrystallized to an intermediate- to low-temperature variety, and the glassy matrix is completely devitrified.

The Lower to Middle Jurassic

Three units conformably overlying each other, the Quebrada del Pobre, Ajial, and Cerro Calera Formations, represent the Early to Middle Jurassic age span (Table 1). Their lithology, starting with the oldest, is as follows.

Quebrada del Pobre Formation. This formation (Thomas, 1958) is a marine sedimentary unit that in its type locality immediately north of the studied region rests unconformably on Triassic volcanic rocks.

TABLE 1. GENERALIZED JURASSIC TO LOWER CRETACEOUS LITHOSTRATIGRAPHIC COLUMN FOR THE COAST RANGE OF CENTRAL CHILE BETWEEN 32°30′ S AND 34° S

Upper Cretaceous continental volcanic and sedimentary rocks	
Veta Negra Formation *(Lower Cretaceous) continental, partly marine (littoral) at the base* Basic to intermediate lavas and flow breccias, and eolian sandstones; scarce acid ignimbrites. Peperites and brackish–water sedimentary rocks at the base of the unit	5000–15000 m
Lo Prado Formation *(Lower Cretaceous) marine (bathyal to littoral) and continental* Upper member (1800–4500 m): acid ignimbrites and deltaic sedimentary rocks; subordinate basic lavas, partly peperites, and sublittoral clastic sedimentary rocks with limestone lenses and water–laid tuff intercalations Lower member (700–1800 m): Sublittoral–littoral conglomerates at the base of the unit, covered by bathyal volcaniclastic rocks (turbidites), limestones, and cherts. Water–laid tuffs and ignimbrites in the upper part	3000–6000 m
Horqueta Formation *(Upper Jurassic) continental* Basic to intermediate lavas and debris flows. Beach and/or eolian sandstones and acid lavas predominate in the lower part	1800–4300 m
Cerro Calera Formation *(Middle Jurassic) marine (sublittoral to littoral)* Marine clastic sedimentary rocks with limestone intercalations; scarce submarine acid tuffs. Beach and/or eolian sandstones in the upper part	350–1400 m
Ajial Formation *(Lower – Middle Jurassic) marine (littoral to sublittoral) and continental* Acid lavas, pyroclastic fall deposits (partly submarine) and ignimbrites, and marine clastic sedimentary rocks with minor limestone intercalations; subordinate basic lavas	750–2000 m
Quebrada del Pobre Formation *(Lower Jurassic) marine (sublittoral to littoral)* Marine clastic sedimentary rocks with limestone intercalations; scarce submarine acid lavas and ignimbrites, and basic lavas	0–1250 m
Basement *(upper Paleozoic)* Tonalite, and microcline–bearing granodiorite and granite; Triassic marine sedimentary and volcanic rocks immediately north of the studied area	

Note: The Veta Negra Formation is considered in the sense of Levi (1968) and the other units are described in the sense of Piracés (1976). Lithologies and depositional environments are based on unpublished observations by the authors and data from Thomas (1958), Levi (1968, 1973), Piracés (1976), Piracés and Maksaev (1977), Dávila and Galatzán (1979), and Nasi and Thiele (1982). Unconformities are indicated by dashed lines and conformities by dotted lines.

However, it lies with an unconformity directly on the Paleozoic basement in our region, north of the Aconcagua River (Fig. 1B). The Quebrada del Pobre Formation consists of greenish gray quartzo-feldspathic sandstones and fine-grained conglomerates with subrounded pebbles made up of aggregates of quartz with strong undulatory extinction, interlayered with dark gray siltstones and silty limestones. An abundant fauna of pelecypods, corals, and rare ammonites defines an Early Jurassic (Sinemurian) age. The lithology and fossil content indicate deposition on a shelf in a littoral to sublittoral environment. The existence of a western land area during the deposition of the upper part of the unit is suggested by intercalations of pinkish brown ignimbrites in the westernmost outcrops that toward the east grade into or interfinger with calcite-cemented sandstones with clasts of perlitic texture and bioclastic remains.

Ajial Formation. This formation (Thomas, 1958; modified by Carter and Aliste, 1961–1963, and Piracés, 1976, 1977) is predominantly volcanic, deposited under alternately marine and continental conditions. It crops out in the northern part of the studied region (Fig. 1B) and consists of a lower sequence dominated by acid lavas and an upper sequence composed of acid pyroclastic fall deposits and some ignimbrites grading into and interfingering with sedimentary rocks toward the east. The sedimentary rocks are composed of light gray to green volcaniclastic sandstones, conglomeratic sandstones (with subangular clasts of acid volcanic rocks), and marls and limestones with corals, equinoderms, plant remains, belemnites, pelecypods, and relatively sparse ammonites of earliest Middle Jurassic age (Aalenian). In the north, grayish red cross-bedded sandstones, similar to those in the Cerro Calera Formation mentioned below, are present in the upper part of the unit. The marine sediments and their faunas indicate a littoral to sublittoral environment. The interfingering of marine and continental volcanic rocks and paleocurrent measurements (Piracés, 1977) suggest that there was a land area in the west.

The acid lava flows are 50 to 100 m thick, pink, brownish gray, or violet in color, and have a fluidal texture that partly is granophyric due to devitrification. They contain phenocrysts of plagioclase, minor orthoclase, and bipyramidal quartz. Several of the flows are submarine, strongly vesicular, and autoclastic; toward the east some of them pinch out and/or grade into matrix-rich hyaloclastite deposits containing rhyolitic clasts with curviplanar margins. There are intercalations of well-laminated 10- to 20-cm-thick grayish green tuffs, siltstones, sandstones, scarce limestone lenses, and a few 10- to 30-m-thick flows of basic lava with large phenocrysts. These lavas have a hyalophitic groundmass and phenocrysts of labradorite (unzoned An_{60} with an outermost edge of andesine) and unzoned augite ($Wo_{[41 \pm 1]}En_{[46 \pm 1]}Fs_{[13 \pm 1]}$).

The pyroclastic fall deposits are generally light gray to greenish gray in color and occur as alternating beds of centimeter-thick vitric and crystal tuffs and 10- to 20-m-thick beds of lapilli-tuffs and tuff-breccias with up to 15-cm-large clasts of pumice, vesicular acid lavas, and pyroxene-phyric basic volcanic rocks. The grain size of the pyroclastic deposits is coarsest and their bedding is most diffuse 1–10 km north of the Aconcagua River. Farther north there are reverse grading and intercalated beds of fine-grained tuff with accretionary lapilli. The presence of accretionary lapilli suggests but is not conclusive evidence of subaerial explosive eruptions (cf. McPhie et al., 1993, and references therein).

Cerro Calera Formation. This formation (Piracés, 1976) is a predominantly marine unit composed of gray to greenish, brownish, and yellowish gray polymictic conglomerates and well-bedded, 1- to 10-m-thick well-sorted volcaniclastic sandstones and siltstones, with intercalations of limestone. At the base of the unit and in its central part there are a few 1- to 10-m-thick intercalations of tuff with perlitic fragments and calcite cement and 10- to 20-m-thick flows of autoclastic basic lava flows that pinch out toward the east. The top of the unit is marked by well-sorted, cross-laminated sandstones that we interpret as beach or eolian deposits. The thickness of the Cerro Calera Formation increases southward from about 500 m at 32°30′S to 1300 m at the Aconcagua River. At the same time, there is an increasing proportion of volcaniclastic intercalations and a decrease in limestones (Piracés, 1976).

The limestone beds are commonly oolitic, with nuclei of plagioclase crystals or rhyolite fragments in the oolites. The graywackes contain subangular fragments of acid lavas and tuffs, rounded quartz with undulatory extinction, and subrounded perthitic feldspar. The clasts of the conglomerates are up to 15 cm across in the westernmost exposures and diminish in size toward the east, and they consist of subrounded acid volcanic rocks, rounded quartzites (made up of fractured quartz with a strong undulatory extinction), and leucogranites (a mosaic of microcline-perthite, calcian albite, and quartz with undulatory extinction). The latter are similar to the Paleozoic leucogranites in the basement to the west described by Muñoz Cristi (1964). Sublittoral to littoral conditions are indicated by the occurrence of conglomerates, oolitic limestones, and a fauna rich in pelecypods and gastropods. Three horizons containing ammonites demonstrate a Middle Jurassic age (Aalenian to late Bajocian) for the lower part of the unit. The beach/eolian deposits at the top of the unit constitute a transition to the continental rocks of the Horqueta Formation. The decreasing size of conglomerate clasts and pinching out of lavas toward the east indicate a land area in the west.

The Upper Jurassic

Horqueta Formation. The Late Jurassic is represented by the Horqueta Formation (Thomas, 1958; modified by Piracés, 1976), a sedimentary-volcanic unit deposited under continental conditions. It conformably overlies the Cerro Calera Formation (or the Ajial Formation where the former is absent; Piracés, 1976). The lower part consists of acid lavas and a few ignimbrites (locally, with basal sandstones resembling the beach/eolian deposits of the underlying unit), and its upper part is composed of red continental volcaniclastic rocks (breccias, sandstones, and subordinate siltstones with mud cracks) and lavas of mainly intermediate and basic types. The formation is thickest south of the Maipo River (Fig. 1B) and in the northernmost part of the studied region (the type locality), where lavas are more abundant and the intercalated clastic rocks are coarser than in the central part of the region. A 0.2-m-thick intercalation of limestone was observed ~20 km north of the Aconcagua River in the lower part of the sequence. Because no fossils or age determinations of the volcanic rocks have been reported from the Horqueta Formation, the Late Jurassic age attributed to it is merely inferred from the ages of the underlying and overlying units.

The acid lavas are gray to reddish gray with flow banding and are partially brecciated. They have porphyritic texture with albite phenocrysts and a few pseudomorphs after amphibole in a trachytic or granophyric groundmass. The intermediate lavas are typically autobrecciated and vesicular; their texture is generally aphanitic, but some flows are porphyritic with phenocrysts of stepwise normally zoned plagioclase (An_{50} to An_{35}, with melt inclusions), unzoned augite ($Wo_{[39 \pm 1]}En_{[45 \pm 1]}Fs_{[16 \pm 1]}$), and, in some samples, pseudomorphs after amphibole in an intersertal groundmass. The basic lavas are slightly porphyritic with phenocrysts of stepwise normally zoned plagioclase (An_{65} to An_{50}), altered olivine, and unzoned augite ($Wo_{[42 \pm 3]}En_{[46 \pm 1]}Fs_{[14 \pm 4]}$) in a hyalophitic groundmass.

The volcaniclastic rocks consist of brownish to grayish red siltstones and sandstones in beds ranging from a centimeter to several meters in thickness, and 10- to 30-m-thick sedimentary breccias with up to 10-cm-large fragments. The sandstones and breccias are very poorly sorted and matrix-supported (except the well-sorted sandstone at the base of the formation) and contain subangular clasts of acid to basic volcanic rocks similar to those in the formation. In addition to the volcanic components, clasts of aplite and quartzite are present, especially in the southern exposures. The large variation of rock types among the clasts and the poor sorting suggest that the volcaniclastic rocks were deposited as debris flows.

The Lower Cretaceous

The Lower Cretaceous section consists of two conformable sequences: the Neocomian Lo Prado Formation, a bathyal marine sequence covered by ignimbrites interfingering with littoral and continental sedimentary rocks, and the post-Neocomian Veta Negra Formation, which is characterized by basic to intermediate subaerial lavas.

Lo Prado Formation. This formation (sensu Piracés, 1976) is separated from the Jurassic units or the western Paleozoic basement by an unconformity (Carter, 1963; Corvalán and Dávila, 1964). It is divided into a lower marine sedimentary member previously known as the Patagua Formation (Carter et al., 1961), and an upper, alternately marine and terrestrial member (defined by Piracés, 1976, as being composed of the Pachacama and Lo Prado Formations of Thomas, 1958).

The *lower member* of the Lo Prado Formation is a bedded sequence of gray to greenish gray marine graywackes, siltstones, and limestones. The thickness of the different lithological types varies from some centimeters to 60 m, and they extend for hundreds of meters to kilometers. Typically, there is a repetition consisting of a basal part with well-developed graded bedding (graywacke, or even sedimentary breccia, to siltstone), followed by siltstone with intraformational folds, faults, and slumps, which passes upward into laminated siltstone and locally into limestone (cf. Bouma sequence). This indicates deposition by turbidity currents (Levi, 1968), probably within a bathyal environment. The slump-fold orientations measured in several outcrops west of Santiago (area 6 in Fig. 1) suggest a continental slope facing east. Lenses of polymictic pebble and cobble conglomerates overlain by beds of coquina at the base of the member, and some ignimbrites in its upper part, indicate that the initial and final depositional environments were sublittoral to littoral.

The graywackes are poorly sorted and commonly contain bioclastic remains. They have angular to subangular grains, which consist almost exclusively of volcanic rocks and their mineral components, except south of the Maipo River, where many granitoid clasts are found. The volcanic clasts are composed of acid volcanic and subvolcanic rocks (or their mineral components) with phenocrysts of saussuritized albite and embayed quartz in a pilotaxitic, hyalopilitic, or cryptocrystalline groundmass. The sedimentary breccias are poorly sorted and matrix-supported and have angular to subrounded clasts (up to 4 cm in size) of limestone and siltstone. The limestones, which are more common north of the Aconcagua River, are generally interstratified with silicified siltstones or cherts. About 10-m-thick intercalations of green tuff and volcaniclastic sandstone occur in some of the limestones. A scarce fauna composed mainly of ammonites and some pelecypods has been observed in the limestones and calcareous sandstones. The fauna defines a Neocomian age for this member (Valanginian north of the Aconcagua River and Upper Berriasian south of the Maipo River) and supports a bathyal to sublittoral environment as suggested by the lithology.

The *upper member* of the Lo Prado Formation consists of alternately marine and continental sedimentary rocks with voluminous volcanic intercalations of bimodal chemistry: acid ignimbrites and subordinate basic lavas. Vertical and lateral facies changes from volcanic rocks to terrestrial and marine sedimentary rocks are numerous and abrupt at a small scale (Herm, 1967); terrestrial beds tend to interfinger with marine strata toward the east (Levi, 1968). There are abundant acid dikes and subvolcanic intrusions that probably represent feeders for the acid volcanic rocks, as suggested by an often close spatial relationship and petrographic similarity between the intrusive and extrusive rocks of the member (Levi, 1973; Klohn et al., 1990).

The acid volcanic rocks occur throughout the member but are more frequent in its lower part, where they form an up to 1-km-thick monotonous unit composed of 10- to 20-m-thick violet to greenish gray welded ignimbrites with porphyritic texture in the lower and middle part of each sheet. The ignimbrites have a eutaxitic texture defined by fiamme, and phenocrysts/phenoclasts of plagioclase, minor K-feldspar, embayed quartz, and pseudomorphs after mica. Some ignimbrites, especially at the base of the member, overlie or interfinger with limestones and grade into green volcaniclastic sandstones and breccias with perlitic fragments and abundant bioclastic remains, consistent with deposition under water (Levi, 1968; Nasi and Thiele, 1982).

The basic lava flows are about 20 m thick, greenish gray, and aphyric to slightly porphyritic with reddish brown autobrecciated and/or vesicular tops. The flows become more abundant and porphyritic in the uppermost part of the member toward the contact with the Veta Negra Formation, especially south of the Aconcagua River. The phenocrysts are labradorite with oscillatory zoning around An_{65}, and zoned augite ($Wo_{[44 \pm 3]}En_{[45 \pm 1]}Fs_{[9 \pm 1]}$) with Fe-enrichment in the outer part and in the groundmass grains ($Wo_{[43 \pm 3]}En_{[40 \pm 1]}Fs_{[15 \pm 4]}$). Some of the strongly autobrecciated lavas have been described as peperites, because they contain a sedimentary matrix and show an interfingering relationship with siltstones and sandstones (Dávila and Galatzán, 1979). Development of pillows was observed in one locality 40 km north of the Aconcagua River.

The marine clastic sedimentary rocks are greenish-gray, moderately well sorted, and calcite-cemented sandstones; they commonly contain plant remains. In addition to the predominant volcanic clasts (acid ignimbrites and basic lavas), many of the clasts are granitoids with microcline, calcian albite, and quartz showing undulatory extinction. The clasts of granitoids (and of scarce quartzites and schists) are similar to corresponding rock types in the Paleozoic basement and increase in frequency southward (Levi, 1960, 1968; Nasi and Thiele, 1982). There are lenses of micritic to biosparitic limestone with faunas composed mostly of algae, corals, rudists, crinoids, echinoids, pelecypods, and rare ammonites. The marine fauna and the interfingering of marine and terrestrial/deltaic beds indicate a littoral to sublittoral environment (Levi, 1968; Nasi and Thiele, 1982). The Neocomian age assigned to the member is based on ammonites (Valanginian in the lower part and Hauterivian in the upper part).

The continental sedimentary rocks that become more abundant toward the upper part of the member were probably deposited in a deltaic environment (Levi, 1968). They consist of up to 30-m-thick reddish gray sandstones, commonly with cross bedding, and conglomerate lenses with clasts up to 30 cm across of granitoids similar to those in the basement, and acid ignimbrites.

Veta Negra Formation. This formation (sensu Levi, 1968) is a thick pile of basic to intermediate lava flows erupted in a continental environment. Morphologically, they are flood basalts (Åberg et al., 1984). Thin intercalations of sandstone occur between many flows. Strongly autobrecciated lavas with a sandstone matrix, hyaloclastitic breccias, and peperites similar to those in the upper member of the Lo Prado Formation occur especially in the lowermost part of the Veta Negra Formation, suggesting deposition under water or on wet sediments. Brackish water claystone, with ostracods, and vertebrate and plant remains are sparsely intercalated in the lower part of the unit north of the Maipo River. South of the river marine intercalations of greenish gray calcareous sandstone and reddish gray, micritic and bioclastic limestone are found throughout most of the unit (Nasi and Thiele, 1982). However, the fossils are not useful for dating purposes. The Barremian to Albian age assigned to the formation in the studied region is bracketed by the Hauterivian age of the underlying Lo Prado Formation and the Cenomanian age of the oldest granitoids intruding the upper part of the unit (K-Ar age is 94 Ma; Munizaga and Vicente, 1982). This is consistent with the Albian age of primary plagioclase separated from a flow in the middle part of the Veta Negra Formation (K-Ar age is 105 Ma; Vergara and Drake, 1979), and a dating of the regional alteration (Rb-Sr age of samples from the amygdaloidal tops of the flows is 102 Ma; Åberg et al., 1984). The thickness of the formation varies along the belt, partly due to erosion, as shown by the existence of Upper Cretaceous conglomerates unconformably overlying different stratigraphic levels of the Veta Negra Formation.

The basic lava flows are 10 to 40 m thick. Typically, there is an upward gradation from a nonvesicular dark gray to brownish gray lower part, through a dark greenish to reddish gray slightly amygdaloidal central part with large phenocrysts of plagioclase (up to 3 cm) and pyroxene (up to 1 cm), to a dark grayish red strongly amygdaloidal upper part with a dark red autobrecciated top. The rocks in the lower part of flows tend to be unaltered and have small phenocrysts of calcian labradorite ($An_{[64.2 \pm 2]}Ab_{[33.4 \pm 2]}Or_{[2.4 \pm 0.2]}$), augite ($Wo_{[40 \pm 4]}En_{[39 \pm 3]}Fs_{[21 \pm 3]}$; commonly with pigeonite cores of $Wo_{[9 \pm 1]}En_{[58 \pm 3]}Fs_{[31 \pm 3]}$), titanomagnetite, and scarce (altered) olivine. The labradorite is of high structural state, unzoned (or with a weak oscillatory zoning) except for an outermost edge of An_{50}. The augite is unzoned to slightly zoned, without iron enrichment at the rim and in the groundmass crystals. The groundmass, which is intergranular to hyalopilitic with intergrowths of K-feldspar and quartz, is composed of the same minerals that occur as phenocrysts, although the plagioclase here is calcian andesine.

Flow breccias of intermediate composition are common in the middle and upper parts of the Veta Negra Formation. They are 40 to 160 m thick and have a nonbrecciated base (2–8 m thick) of dark brownish red, almost aphyric lava with well-developed parting parallel to flow. Upward there is a change to greenish red brecciated lava with 10- to 30-cm-large subangular reddish green blocks (exceptionally, angular blocks up to 1 m are seen) elongated parallel to the overall stratification of the unit. The small scattered phenocrysts consist mostly of unzoned calcian andesine to labradorite, augite with a composition similar to that in the basic lavas described above, and corroded pseudomorphs after amphibole.

Acid volcanic rocks are rather uncommon except in the uppermost levels of the formation. They include 10- to 20-m-thick, light gray to pinkish gray ignimbrites with pumice fragments in their tops and scarce brownish to violet gray fluidal and slightly porphyritic lavas with amygdules.

The intercalations of sedimentary rocks in the Veta Negra Formation are from 0.5–2 to rarely 30 m thick and include easily eroded red to brownish red well-sorted eolian and beach sandstones with cross-bedding (and ripple marks at the base of the unit), poorly sorted sandstones with subangular clasts (debris flow deposits), and lacustrine shales with mud cracks and raindrop imprints. Most of the clasts are basic volcanic rocks similar to those in the formation, but the well-sorted sandstones contain many rounded grains of microcline-perthite, myrmekite, and quartz with undulatory extinction. Their provenance is probably the Paleozoic granitoids in the western part of the Coast Range (Levi, 1968). These grains increase in amount south of the Maipo River where they also occur in the intercalations of marine sandstone.

SOME GEOCHEMICAL FEATURES OF THE VOLCANIC ROCKS

Seventy-five samples of Jurassic and Lower Cretaceous volcanic rocks from the Coast Range of central Chile between 32°30′S and 34°S (40 from basic to intermediate lava flows and 35 from acid volcanics) were analyzed for major and some trace elements by inductively coupled plasma atomic emission spectrometry (ICP-AES), and for H_2O^+, CO_2, and FeO by wet chemical methods at the Centre de Recherches Pétrographiques et Géochimiques, Nancy, France. Among these samples, 31 of the basic to intermediate lavas can be considered as unaltered due to a minimum amount of secondary minerals as checked by microscopy and X-ray diffraction, presence of phenocrysts and groundmass crystals of the original plagioclase and pyroxene, and a CO_2 content of <0.4 wt%; veinlets and amygdules are absent in thin sections. In addition, 16 of the sampled acid volcanic rocks can be regarded as only slightly altered due to absence of veinlets and low CO_2 contents (<0.5 wt%); the devitrification of these samples led to mobility of Ca, Mg, Na, and K, but the total alkali content apparently remained constant (cf. Levi, 1969). Trace elements were determined by inductively coupled plasma mass spectrometry (ICP-MS) at the same laboratory in 14 of the unaltered basic to intermediate lavas and 7 of the less altered acid volcanics. Representative analyses are given in Table 2, and some geochemical features of the basic volcanic rocks of the formations treated here are summarized in Table 3; the data given in tables and figures represent unaltered to weakly altered samples. Tables 2 and 3 also include initial $^{87}Sr/^{86}Sr$ ratios, Sr(i), based on determinations with a Finnegan MAT 261 multicollector mass spectrometer at the Swedish Museum of Natural History.

The chemical similarities between the Jurassic and Lower Cretaceous volcanic rocks are remarkable, given the great length of time they represent. According to the lithologic and petrographic descriptions above,

TABLE 2. CHEMICAL ANALYSES OF REPRESENTATIVE SAMPLES OF JURASSIC – LOWER CRETACEOUS LAVAS AND IGNIMBRITES IN THE COAST RANGE OF CENTRAL CHILE BETWEEN 32°30' S AND 34°S

	Ajial Formation Lower–Middle Jurassic		Horqueta Formation Upper Jurassic			Lo Prado Formation Lower Cretaceous		Veta Negra Formation Lower Cretaceous			
Sample	CAL-7	CAL-16	MEL-21	MEL-22	CAL-33A	SOL-52	SOL-59*	BUS-19	BUS-35	CER-73	BUS-14
Area†	1	1	7	7	3	3	3	6	6	4	6
Type§	BA, HK	R, ig	BA, HK	A, HK	R, ig	B	R, ig	B	BA, SH	A, SH	R, ig
(wt %)#											
SiO_2	55.94	69.35	55.10	58.54	73.67	49.28	74.65	51.59	53.19	57.60	68.68
TiO_2	1.61	0.88	0.81	0.89	0.45	0.97	0.34	0.87	0.98	1.20	0.57
Al_2O_3	17.38	14.05	17.56	17.76	13.95	20.60	12.85	19.87	18.10	15.27	15.00
Fe_2O_3	4.49	3.06	2.90	2.65	2.27	3.01	0.86	5.98	3.86	4.64	4.91
FeO	4.31	3.64	5.01	4.76	0.16	6.09	0.53	3.81	5.79	4.55	0.29
MnO	0.16	0.03	0.18	0.22	0.03	0.28	0.11	0.18	0.31	0.25	0.04
MgO	3.07	0.79	4.40	3.24	0.30	5.57	0.34	3.36	3.98	2.55	0.10
CaO	7.00	0.48	7.39	4.41	0.02	9.63	4.89	8.03	8.25	6.83	0.27
Na_2O	3.26	7.15	3.81	3.94	3.23	3.24	1.29	3.75	2.85	2.75	4.80
K_2O	2.45	0.36	2.73	3.32	5.70	1.18	4.07	2.34	2.43	3.90	5.10
P_2O_5	0.33	0.20	0.11	0.27	0.22	0.15	0.07	0.21	0.28	0.45	0.24
(ppm)											
Rb	79	4	148	91	222	44	184	68	113	165	107
Sr	445	84	366	343	83	528	58	621	694	429	53
Ba	565	32	728	589	677	386	748	434	609	514	639
V	281	56	226	199	23	364	17	313	334	200	63
Ni	25	7	22	11	2	32	3	7	47	11	3
Co	21	7	22	15	2	86	1	22	22	16	4
La	29.7	18.5	18.6	21.8	36.8	7.7	10.8	9.9	14.6	19.2	20.7
Ce	69.2	39.2	41.6	50.8	65.7	26.2	20.6	22.1	33.6	44.8	45.3
Nd	39.0	23.7	22.1	24.8	39.7	16.7	11.3	14.8	20.5	24.4	25.7
Sm	8.37	4.72	4.98	5.35	8.21	3.45	2.74	3.93	4.93	6.36	5.79
Eu	2.15	0.78	1.36	1.18	1.32	1.20	0.81	0.99	1.38	1.26	1.07
Gd	7.47	3.69	4.05	4.19	6.30	3.12	2.61	2.81	4.57	5.10	5.12
Dy	7.04	3.31	3.80	3.96	6.12	2.89	3.63	3.03	4.76	5.18	5.82
Er	4.12	2.16	2.26	2.51	3.64	1.61	2.35	1.75	2.67	2.90	3.98
Yb	4.03	2.83	2.36	2.72	4.00	1.81	2.66	1.93	3.09	3.27	4.44
Lu	0.66	0.49	0.39	0.46	0.59	0.19	0.46	0.31	0.44	0.44	0.70
Y	44.4	21.7	23.7	23.4	33.9	15.8	25.8	18.7	29.3	33.9	35.5
Zr	257	271	116	190	349	43	186	58	113	206	204
Hf	8.3	7.1	4.10	6.2	10.2	2.06	4.83	2.03	4.10	5.98	6.4
Nb	9.4	8.9	3.2	4.45	10.2	1.18	4.79	1.48	2.56	5.9	5.0
Ta	0.73	0.68	0.27	0.39	0.92	0.10	0.44	0.13	0.21	0.45	0.42
Th	7.0	10.9	6.2	9.8	29.6	1.60	9.2	2.00	4.69	7.0	9.4
U	1.63	1.79	1.72	2.81	5.94	0.43	2.42	0.58	1.36	1.96	2.32
Eu/Eu*	0.82	0.55	0.90	0.74	0.54	0.98	0.92	0.87	0.88	0.66	0.59
$^{87}Sr/^{86}Sr(i)$	0.70428		0.70505	0.70472	0.70512	0.70385	0.70455	0.70378	0.70370	0.70380	0.70385

* Altered sample with 3.6 wt % CO_2 (high CO_2 is common in the Lo Prado Formation).

† Refers to sampling area in Figure 1B.

§ B = basalt, BA = basaltic andesite, A = andesite, and R = rhyolite; HK = high–K calc–alkaline series and SH = shoshonite series. All the samples are lavas except those marked ig (= ignimbrite).

\# Recalculated anhydrous.

the formations show a bimodal distribution, which also can be seen in a total alkali versus silica diagram (TAS; Fig. 2). Basaltic andesites and rhyolites predominate; andesites are less common except in the Horqueta Formation. The rocks of the four formations plot close to the boundary line between the subalkalic and alkalic fields in the TAS diagram (Fig. 2). The alternative use of the boundary line of Le Bas et al. (1986) in the diagram would only increase the number of samples plotting in the alkaline field. There is a trend toward more alkalic (shoshonitic) compositions with time (Fig. 2; Table 3), as pointed out in a reconnaissance study by Levi et al. (1988). The basic lavas are rich in Al_2O_3 and poor in MgO (Table 2).

A common feature of the rocks is an over-

TABLE 3. SOME GEOCHEMICAL FEATURES OF JURASSIC TO LOWER CRETACEOUS BASIC LAVAS IN THE COAST RANGE OF CENTRAL CHILE BETWEEN 32°30' S AND 34°S

	Rock type	Ajial Fm. Lower–Middle Jurassic	Horqueta Fm. Upper Jurassic	Lo Prado Fm. Lower Cretaceous	Veta Negra Fm. Lower Cretaceous	NSVZ Quaternary
K_2O vs. SiO_2	BA	High–K calc–alkaline	High–K calc–alkaline	High–K calc-alk. to shoshonitic	Shoshonitic to high–K calc-alk.	Medium–K
La/Yb	B and BA	8.2 ± 1.2 (3)	6.8 ± 1.9 (4)	6.5 ± 2.1 (3)	6.1 ± 1.3 (11)	13.6 ± 2.9 (7)
Ta/Yb	B and BA	0.16 ± 0.04 (2)	0.12 ± 0.01 (2)	0.11 ± 0.08 (3)	0.10 ± 0.04 (6)	0.31 ± 0.06 (4)
Zr/Y	B	4.4 (1)	3.9 ± 0.8 (3)	3.1 ± 0.6 (2)	3.4 ± 0.8 (3)	N.D.*
	BA	5.6 ± 0.7 (3)	5.2 ± 0.4 (2)	5.2 (1)	4.7 ± 0.8 (9)	8.5 ± 1.4 (7)
$^{87}Sr/^{86}Sr(i)$	B and BA	0.70428 (1)	0.70424 (2) ± 0.00113	0.70405 (3) ± 0.00057	0.70379 (11) ± 0.00020	0.70485 (8) ± 0.00032

Note: Average and standard deviation followed by number of samples in parentheses for the ratios. Rock type: B = basalts and BA = basaltic andesites (grouped together when they show similar values); K_2O vs. SiO_2: most frequent chemical type. Data for basaltic andesites from Quaternary volcanoes in central Chile between 33°20' S and 34°10' S are included for comparison (NSVZ; from López Escobar et al., 1985; Hickey et al., 1986; and Hildreth and Moorbath, 1988).
*N.D. = no data (no basalts observed).

all similarity in trace element distribution, well illustrated in a MORB-normalized spider diagram of the most common lava type, basaltic andesite (Fig. 3A). The contents of Rb, K, Ba, and Th are relatively high and Ta-Nb constitute a marked trough, with even lower contents of heavy rare earth elements (HREE) and Y. In the smaller number of basalts the incompatible elements Ta, Nb, Zr, Hf, Y, and Yb occur in levels roughly parallel to the MORB-normalizing values (Fig. 3B). Some trace element ratios of petrogenetic interest show systematic changes with time, in spite of overlap by individual samples. For example, Zr/Y, La/Yb, and Ta/Yb in the basic lavas decrease in value passing from the Ajial to the Veta Negra Formations (Table 3). A trend of decreasing values with time can also be discerned for the initial $^{87}Sr/^{86}Sr$ ratios of the rocks, which are relatively low (Tables 2 and 3).

DISCUSSION

A Western Land Area During the Jurassic and Early Cretaceous

The various Jurassic and Lower Cretaceous formations in the Coast Range, up to and including the Lo Prado Formation, rest directly on the western Paleozoic basement in several places. This shows that the elongated north-south marine and continental basins where the rocks were deposited were bounded by a western land area (Levi, 1960). Granitoid clasts up to 30 cm across are found in both marine and subaerial sedimentary sequences. The presence of microcline and strained quartz in the granitoid clasts supports a basement source, because the Jurassic and Cretaceous granitoids of the Coast Range generally contain orthoclase instead of microcline and their quartz has, as a rule, at most only a weak undulatory extinction, in contrast to the Paleozoic granitoids. For the Lo Prado Formation there is a good correlation between frequency of apparent basement clasts and vicinity to the basement.

The transition from marine strata in the east to subaerial beds in the west occurring repeatedly in the stratigraphic sequence also supports the existence of a western land area. Moreover, paleocurrent observations, size distribution of conglomerate clasts, and sedimentary structures in different formations indicate transportation from the west, in contrast to an eastern source for the Trias-

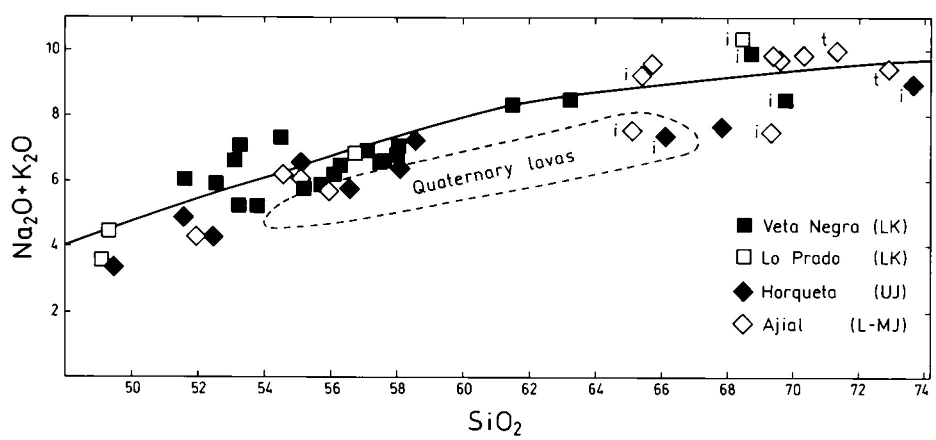

Figure 2. Total alkali vs. silica variation (TAS; wt%, recalculated to 100% anhydrous) in Jurassic to Lower Cretaceous volcanic rocks from the Coast Range of central Chile (32°30′–34°S; all lavas, except i = ignimbrites and t = tuffs; LK = Lower Cretaceous; UJ, MJ, and LJ = Upper, Middle, and Lower Jurassic). The boundary line separates the subalkaline (below) and alkaline series (above; after Irvine and Baragar, 1971). The field for Quaternary lavas from central Chile between 33°20′S and 34°10′S is included for comparison (dashed line; data from López-Escobar et al., 1985; Hickey et al., 1986; and Hildreth and Moorbath, 1988).

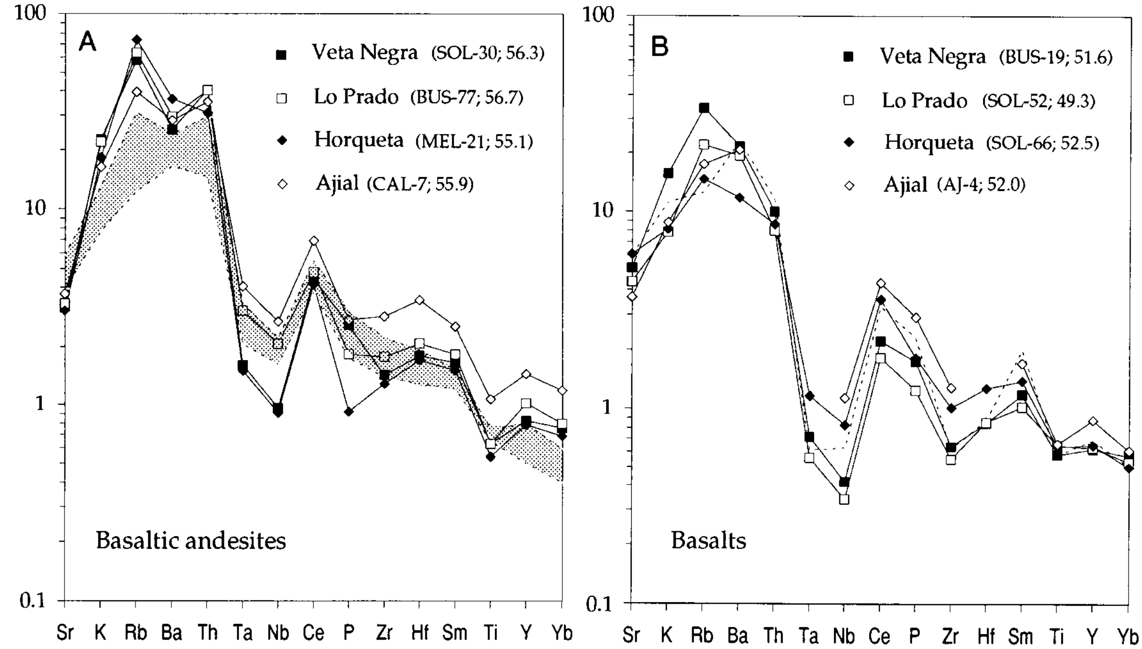

Figure 3. MORB-normalized variation diagrams for representative basaltic andesites (A) and basalts (B) from Jurassic and Lower Cretaceous formations in the Coast Range of central Chile (32°30′–34°S; sample number and SiO_2 content in parentheses; ICP-MS data except for sample AJ-4 which was analyzed by ICP-AES and lacks Th, Ta, and Hf data). The shaded field in A shows basaltic andesites from Quaternary volcanoes in central Chile between 33°20′S and 34°10′S (average SiO_2 = 55.5 ± 0.9 wt%; data from López-Escobar et al., 1985; Hickey et al., 1986; and Hildreth and Moorbath, 1988). The dashed line in B represents a Quaternary high-K calc-alkaline basalt from New Hebrides (after Pearce, 1983). Note that the curve for Lo Prado probably is shifted toward lower values due to the relatively low SiO_2 content of the plotted sample. Normalization values (ppm; oxides in percent): Sr = 120, K_2O = 0.15, Rb = 2, Ba = 20, Th = 0.2, Ta = 0.18, Nb = 3.5, Ce = 10, P_2O_5 = 0.12, Zr = 90, Hf = 2.4, Sm = 3.3, TiO_2 = 1.5, Y = 30, Yb = 3.4 (Pearce, 1983).

sic sedimentary rocks in the basement immediately north of the studied region. The Paleozoic land area represented by the western basement extended west of the present coast line, as revealed by the occurrence of metamorphosed rocks of a probable early Paleozoic age as far as to the inner slope of the Chile-Peru trench (Mordojovich, in Hervé et al., 1988).

Near-Shore Deposits and Low-Relief Topography

A near-shore shallow-water environment is evident for the marine deposits from the littoral and sublittoral faunas and plant remains, deltaic intercalations, and alternations with continental sequences. The only exception is the bathyal conditions inferred for most of the lower member of the Lo Prado Formation, as suggested by the presence of turbidites with scarce, predominantly ammonite-bearing faunas. A near-shore environment can also be inferred for the continental deposits, based on the presence of brackish-water or even marine intercalations. It seems that the coast line on the whole was linear except for a probable embayment in the southern part of the studied region during the deposition of the Veta Negra Formation (Nasi and Thiele, 1982), because the various lithochronological facies show a notable north-south continuity.

The continuity over long distances of the sedimentary facies suggests deposition on a flat basin floor. For example, many of the turbidites in the lower member of the Lo Prado Formation can be followed north-south for many kilometers. A low-relief topography is indicated by the continuity of the subaqueous tuffs and ignimbrites in the upper member of the same formation, and the extensive subaerial piles of ignimbrites, basic lavas, and flow breccias of the Lo Prado and Veta Negra Formations. The one exception, the Horqueta Formation, has longitudinal facies changes between sequences dominated either by lava flows with intercalated sedimentary breccias or debris flow deposits, features consistent with a volcanic topography of relatively high relief.

Volcanic Vents and Proximal Volcanic Facies

The interfingering volcanic and sedimentary sequences represent a proximal facies with respect to the source vents, as shown by the large thickness of the volcanic components. In addition, the presence of vents and feeders is suggested by the occurrence of subvolcanic intrusions and dikes petrographically and chemically similar to the hosting and immediately overlying volcanic units (Levi, 1973; Piracés, 1976; Nasi and Thiele, 1982; Klohn et al., 1990). The lower member of the Lo Prado Formation, where volcanic rocks are virtually absent, is an exception.

The combination of a great thickness, maximum abundance of acid lavas, and coarse-grained pyroclastic deposits in the widest part of the Ajial belt strongly suggests vicinity to the source vents. Two volcanic centers that appear to be remnants of stratovolcanoes have been recognized in the Horqueta Formation (areas 2 and 7 in Fig. 1B), based on high concentrations of thick lava

TABLE 4. VOLUMES OF VOLCANIC ROCKS

Formation	Average thickness (km)	Percentage of volcanic rocks	Total volume (km^3)
Ajial	1.5	80	320
Horqueta	1.5	50	740
Lo Prado	3	60	2100
Veta Negra	10	90	9000

flows with intercalated sedimentary breccias of debris flow character. Calderas are a likely source for the pile of welded ignimbrites in the upper member of the Lo Prado Formation. The local concentration of acid subvolcanic intrusions and dikes in areas with normal faults coeval with the intruded rocks is consistent with the presence of calderas. In addition, the alteration gradients here are in the range typical of geothermal fields (measured from fluid inclusions; Klohn et al., 1990), that is, much higher than the temperatures inferred from the regional alteration assemblages in surrounding areas (Aguirre et al., 1989; Vergara et al., 1994). Local dike swarms in the Veta Negra Formation are evidence for fissure eruption; the dikes are feeders for the basic lavas constituting this unit.

Volume of the Volcanic Rocks

A calculation of the volume of volcanic rocks formed during the Jurassic and Early Cretaceous in the present Coast Range between 32°30′S and 34°S involves the thickness of each stratigraphic unit, the proportion of volcanic rocks within each unit (disregarding the volumes now occupied by granitoid intrusions and removed by erosion in the mountainous terrain), and their lateral and longitudinal continuations. Because proximal volcanic deposits and inferred vents are found in all the formations except the lower Lo Prado member, it is reasonable to assume that the outcropping belts (Fig. 1) correspond to the central parts of volcanic arcs. As a consequence, the formations should pinch out laterally toward the west (eroded) and east (their down-dip underground continuation). The along-dip distances from mountain crests to valley floors within each unit are 1.5–4.5 km. The inferred lateral continuations should at a minimum be equal in magnitude to the volumes present in the Coast Range above valley floors, disregarding erosion and granitoids. The along-strike length of the formations in the studied section is 165 km, with the exception of the Ajial Formation, which merely can be followed for 45 km; probably it was deposited only in the northern part of the region. The Ajial and Lo Prado volcanic rocks are largely acid and those of the Horqueta and Veta Negra Formations are predominantly basic. Table 4 shows the volumes that are obtained (the figure for the Lo Prado Formation refers to its upper member).

More than 2000 km^3 of acid magmas and 9000 km^3 of basic magmas erupted in the studied sector of the Coast Range. These estimates are conservative because they do not take into account the upper parts of the Horqueta and Veta Negra Formations, which were eroded during the Late Jurassic and mid-Cretaceous uplifts, respectively, before the deposition of younger units. The more than 11 000 km^3 of volcanic rocks formed during the Jurassic and Early Cretaceous gives a minimum eruption rate of 140 km^3/m.y., which is comparable with the rate for the Quaternary volcanism in the High Andes at corresponding latitudes (33°20′–34°10′S; ~130 km^3/m.y. according to data in Hildreth and Moorbath, 1988, their Table 1). However, the eruption rate was three to four times higher (~500 km^3/m.y.) during the formation of the Veta Negra lavas. If the calculation is extended to the entire length of the units treated here and their equivalents to the north (25°S) and south (36°S), without including the much thinner coeval volcanic sequences in the High Andes (Aguirre, 1985; Levi et al., 1988; Vergara et al., 1994), then a figure of about 100 000 km^3 is obtained.

Subsidence, Uplift of Rocks, and Erosion

A feature that is not typical of the present Andes but is characteristic of the Early to Middle Jurassic and Early Cretaceous in the Coast Range of central Chile is subsidence, especially during times of vigorous volcanic activity. The evidence for subsidence includes the large thicknesses of the formations and the recurrence of marine facies noted already by Darwin (1876) and the inferred low relief close to sea level during the deposition of the subaerial sequences (with the exception of the Horqueta Formation). The rates of subsidence that can be calculated for the different formations treated here are at best crude approximations due to several uncertainties, for example, the exact age of the formations and the influence of extension. A straightforward division of the thicknesses of the units by their ages gives figures of the order of 50–100 m/m.y. for the Early to Middle Jurassic and >250 m/m.y. for the Early Cretaceous. The coincidence between areas of subsidence and accumulation of proximal volcanic deposits indicates that the basins where the volcano-sedimentary piles accumulated were volcano-tectonic depressions (intra-arc basins).

The large thickness of the Jurassic and Lower Cretaceous formations in the Coast Range (Table 1) is remarkable. The estimated thickness of a sequence deposited during an extensional regime tends to be inflated. On the other hand, large portions of the original pile can be removed by erosion. The Horqueta and Veta Negra Formations were certainly eroded before the deposition of overlying units, judging from the fact that the upper parts of these formations, which should be altered at zeolite facies, largely are missing. The low paleothermal gradients here (Vergara et al., 1994, and references therein) imply that a considerable thickness of zeolite-facies rocks has been removed from the tops of both units by erosion. Less-eroded (and younger) formations elsewhere in Chile are made up of thousands of meters of volcanic rocks at zeolite facies (Levi et al., 1989). Moreover, at least 5–10 km of the Veta Negra Formation must have been removed locally before the deposition of the overlying Upper Cretaceous unit, because clasts derived from lower sequences, reaching even down to the upper member of the Lo Prado Formation, are found in the up to 1100-m-thick Las Chilcas conglomerate deposited above the Veta Negra Formation (Carter and Aliste, 1961–1963; Levi, 1968).

A rate of erosion exceeding 300 m/m.y. is obtained by dividing the eroded thickness (at least 5 km) by the time span (~15 m.y.) between the final deposition of the Veta Negra Formation and the Las Chilcas conglomerate above it. This figure is similar in magnitude to that given for the Neogene-Pleistocene erosion in the High Andes east of the studied area (Skewes and Holmgren, 1993, and references therein). This rate and the erosion of the Horqueta Formation suggest that considerable uplift of rocks took place during the mid-Cretaceous (the late

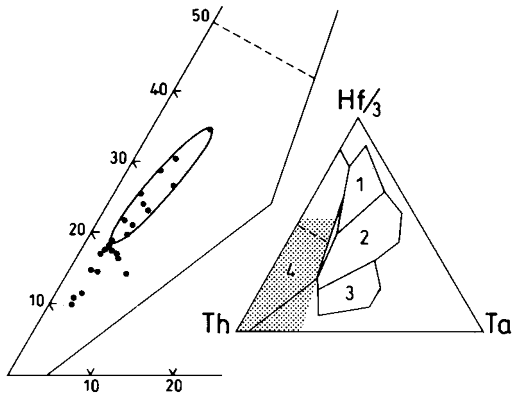

Figure 4. Jurassic–Lower Cretaceous volcanic rocks of basaltic to rhyolitic composition from the Coast Range of central Chile (32°30′–34°S) plotted in the Th-Hf-Ta discrimination diagram of Wood (1980; 1 = N-type MORB; 2 = E-type MORB and within-plate tholeiites; 3 = alkaline within-plate basalts; and 4 = volcanic-arc basalts; tholeiites above and calc-alkaline basalts below the dashed line). The shaded corner of the diagram is shown enlarged; the basalts fall within the elliptical field.

part of the Early Cretaceous) and Late Jurassic in the present Coast Range. However, rates of uplift cannot be calculated because many relevant factors are unknown (cf. England and Molnar, 1990). Aguirre and Thomas (1964) reported a large mid-Cretaceous uplift in the continuation of the Lower Cretaceous belt at about 27°S, which indicates that this uplift is a regional phenomenon (see also Vicente et al., 1973, and Aguirre, 1985).

Extension

Extension is indicated by the high rates of subsidence inferred from the thick piles of predominantly volcanic rocks deposited in elongated basins, probably volcano-tectonic graben structures, which remained close to sea level. An extensional regime is also consistent with the abundance of normal faults and dikes parallel with the strike of the coeval volcanic sequences they affect. Besides the major normal faults reported on regional maps there is a large number of smaller faults with displacements of the order of meters or less. These small normal faults explain why the apparent dips of key beds inferred from outcrop patterns as a rule are significantly lower than the dips of the same beds measured in individual outcrops. The homoclinal structure of the Coast Range is consistent with an extensional regime, but concomitant uplift of the western basement (Thiele and Morel, 1981) might be a contributing factor.

Other, independent lines of evidence consistent with extension are the bimodal character of the volcanic rocks and the lack of high-pressure metamorphism in the thick volcanic piles that were affected by burial metamorphism at low thermal gradients soon after their deposition (Åberg et al., 1984). In a scenario of extension-subsidence as proposed by Levi and Aguirre (1981), the subsiding volcanic rocks would not experience long periods at high temperatures and pressures. An alternative explanation for the Jurassic and Lower Cretaceous geology of the Coast Range, eastward migration of volcanism with time and deposition of the products in a succession of basins (Levi, 1973; Nasi and Thiele, 1982), cannot account for the overall symmetry of the synclinorium in central Chile.

Volcanic Arcs

The formations treated here were deposited on an ensialic basement consisting of the exposed root of a late Paleozoic arc, and Triassic fore-arc/arc sequences. The stratigraphic record (Table 1) shows that periods dominated by sedimentation in a shallow marine environment alternated with periods characterized by volcanism. The volcanic activity increased with time during the Jurassic, and subaerial conditions became prevalent toward the end of the period. A similar history, although starting with a bathyal marine environment, took place during the Early Cretaceous. The volcanic rocks issued from arcs located between the uplifted basement area in the west that represents the old continental margin and a marginal sea in the east. The development between this sea and the continent farther to the east is not known.

Åberg et al. (1984) suggested that the Lower Cretaceous volcanic rocks erupted in an aborted marginal basin, and in recent literature the setting is often referred to as a back arc. However, an arc (intra-arc) setting as postulated by Vergara (1972), Thiele and Nasi (1982), and Charrier and Muñoz (1994) for the Jurassic–Lower Cretaceous rocks is more consistent with the geological data than a back arc is. Batholiths composed of Jurassic and Cretaceous granitoids emplaced in the volcanic sequences of the Coast Range represent deeper levels of the arcs (Parada et al., 1991, 1992). The low thermal gradients obtained from burial metamorphic mineral assemblages (20–30 °C/km; Aguirre et al., 1989; Vergara et al., 1994) and the geochemistry of the volcanic rocks support the existence of an arc and argue against a back arc. On the other hand, a back-arc setting is the best explanation for the coeval volcanic (and sedimentary) rocks in the High Andes to the east, based on the geology (Charrier and Muñoz, 1994; Mpodozis and Ramos, 1989), preliminary geochemical data (Vergara and Nyström, unpub. information), and high paleothermal gradients (Vergara et al., 1994).

The geochemistry of the volcanic rocks in the Coast Range indicates that they originated in arcs. For example, all the rocks, from basalts to rhyolites, plot well inside the field of volcanic-arc basalts in the Th-Hf-Ta diagram (Fig. 4). Diagrams used to discriminate between oceanic and continental volcanic arcs illustrate a trend from a continental to an oceanic character with time (e.g., Zr/Y vs. Zr; Fig. 5). Some trace element ratios of petrogenetic significance record the same trend. For example, the Ta/Yb ratio is

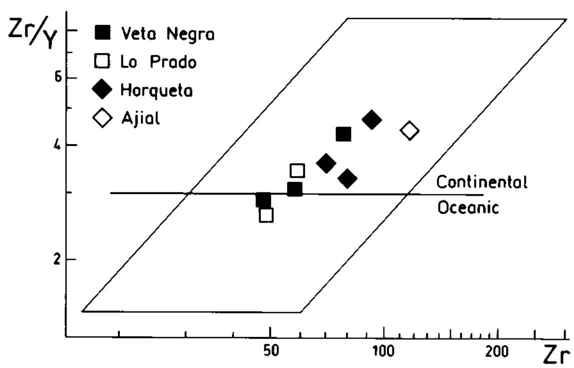

Figure 5. Jurassic–Lower Cretaceous basalts from the Coast Range of central Chile (32°30′–34°S) plotted in the Zr/Y vs. Zr (in ppm) diagram of Pearce and Norry (1979), which discriminates between continental and oceanic volcanic-arc basalts.

higher than 0.11 for the Jurassic basic lavas and lower than this value for most Lower Cretaceous ones (Table 3); Pearce (1983) used 0.11 as the boundary value between continental and oceanic settings.

Progressive Crustal Attenuation

The enrichment in K, Rb, Ba, and Th and the marked trough for Ta-Nb displayed by the basic lavas (Fig. 3) are typical of subduction-related magmas in convergent plate margins. However, the inferred setting does not resemble the present Andean-type margin that is characterized by a thick continental crust. The chemistry is more in agreement with an arc built on moderately thick crust that became more attenuated with time, from the Early Jurassic to the end of the Early Cretaceous. Crustal attenuation is consistent with the extensional regime; the rate of extension seems to have been highest during the Early Cretaceous with the formation of the many-kilometers-thick pile of Veta Negra lavas, which morphologically resemble flood basalts.

The REE fractionation, which can be expressed as the La/Yb ratio, is often related to the thickness of the continental crust. This ratio decreases with time for the basic lavas (Table 3), consistent with a progressively thinner crust. Among the basalts there is a clear tendency for highly incompatible elements like Ta and Nb to become more depleted with time relative to somewhat less incompatible elements (Y and Yb; Fig. 3B). The same tendency, although less pronounced, can be discerned among the basaltic andesites (Fig. 3A). In addition, both diagrams show that the incompatible elements as a group become more depleted, passing from the Ajial to the Veta Negra Formation. These patterns for the predominantly mantle-derived incompatible elements can be explained by an increase in degree of partial melting and source depletion (cf. Pearce and Parkinson, 1993), leading to the formation of more immature volcanic arcs with time. The relatively high abundances of HREE (low La/Yb ratios in Table 3; see also Fig. 3A) suggest a reduced role for garnet during the generation of the magmas.

Progressive crustal attenuation is not obvious from the values of K, Rb, Ba, and Th for the basalts, because the Cretaceous ones and especially those from the Veta Negra Formation are generally richer in these elements than the Jurassic basalts (Fig. 3B). However, high contents of alkalis and alkaline earths combined with low contents of incompatible elements, like in these lavas, have been recorded for some oceanic island arcs. For example, the high-K calc-alkaline basalts of New Hebrides (Pearce, 1983), which originated during crustal rifting (Gorton, 1977) above a steeply dipping Benioff zone (Monzier et al., 1993), resemble chemically the basalts in the Coast Range (Fig. 3B). This suggests that influx of K, Rb, and Ba from the subducted lithospheric slab could be responsible for the high levels of these elements in the latter. Since basalts are subordinate to basaltic andesites, and silicic volcanism at times was intensive during the Jurassic–Early Cretaceous, assimilation–fractional crystallization processes and crustal melting must have played important petrogenetic roles.

Crustal attenuation leading to the formation of a more immature volcanic arc during the Early Cretaceous than during the Jurassic is supported by the trend of decreasing initial $^{87}Sr/^{86}Sr$ ratios with time for the volcanic rocks (Tables 2 and 3). These ratios are consistent with increasingly depleted magma sources and a decrease in crustal contamination. The upper crust is a suitable contaminant that would leave the Sr isotope ratios of the magmas essentially unaffected. It is dominated by Paleozoic granitoids with 200–500 ppm Sr (López-Escobar et al., 1979) and initial $^{87}Sr/^{86}Sr$ ratios of about 0.706 (Hervé et al., 1988). The Triassic basic lavas floored by a quasioceanic crust in the basement just north of the studied region (the Pichidangui Formation) also could have influenced the magmas; the lavas contain about 200 ppm Sr (Vergara et al., 1991) and have initial $^{87}Sr/^{86}Sr$ ratios of about 0.7034 (Nyström, unpub. information). The crust below the Early Cretaceous arc, situated east of the old Jurassic arc, was thinner and probably included a larger proportion of young rocks of rather uniform $^{87}Sr/^{86}Sr$ ratios (the Jurassic rocks have lower initial ratios within a more restricted range than the Paleozoic rocks of the basement; Parada et al., 1992).

Parada et al. (1991, 1992) reached a similar conclusion, that the arcs became more immature with time, based on geochemistry and Sr-Nd isotope data for Jurassic and Cretaceous granitoids in the region studied by us and to the north of it. Their interpretation is that asthenospheric upwelling led to generation of magmas from a progressively more depleted mantle, in combination with a decreasing magmatic fertility of the lower crust that had become more and more refractory due to earlier magmatic events.

The maximum attenuation of the crust was reached during the Late Cretaceous–Oligocene in the part of central Chile treated here, with volcanism occurring in graben structures along the center of the synclinorium that now is occupied by the Central Valley and the western foothills of the High Andes (Thiele et al., 1991; Nyström et al., 1993; Vergara et al., 1993).

A Non-Andean Setting

The large silicic provinces with bimodal volcanism of Jurassic age in southern South America have been attributed to crustal anatexis, extension, and formation of volcano-tectonic graben structures; the rifting is related to the breakup of Gondwana (e.g., Gust et al., 1985; Dalziel, 1986; Dalziel et al., 1987; Kay et al., 1989; Hanson and Wilson, 1991). The Jurassic arc volcanism in the Coast Range was probably also connected with this breakup. The thick Lower Cretaceous pile in the Coast Range, coeval with the opening of the South Atlantic, occupies a structure that was one link in a string of extensional basins stretching from Antarctica to Colombia (Dalziel et al., 1987; Aguirre et al., 1989; Stern et al., 1991; Atherton and Aguirre, 1992). Their setting varied with latitude from arc and intra-arc to back arc; at some latitudes more than one basin in different tectonic settings existed side by side (Stern et al., 1991; Mpodozis and Allmendinger, 1993), with extension as a common factor.

A relationship between a mid-Cretaceous superplume, high spreading rates in the southeast Pacific (Larson, 1991), and extension in northern Chile was proposed by Mpodozis and Allmendinger (1993). Åberg et al. (1984) suggested that the basic lavas of this age in the Coast Range of central Chile (the Veta Negra Formation) formed during an episode of slow sea-floor spreading, based on data in Larson and Pitman (1972). However, the imprecise ages of the lavas do not permit a detailed correlation with the spreading rates in the Pacific.

The Jurassic–Early Cretaceous history of the Coast Range of central Chile resembles the Early Mesozoic intra-arc basin development in the southwestern United States described by Busby-Spera (1988) and Riggs and Busby-Spera (1990). Bimodal calc-alkalic to mildly alkalic volcanic rocks formed in an extensional ensialic setting, with deposition of alternately marine and low-relief continental sequences; a rapidly subsiding arc-graben depression acted as a long-lived trap for craton-derived clastic rocks. In central Chile, Jurassic and Early Cretaceous graben structures were traps for volcanic rocks that became more alkalic with time, with admixture of erosional products from the western basement.

The geochemical differences between the Jurassic–Lower Cretaceous basic lavas in the Coast Range and Quaternary lavas of corresponding composition occurring at the same latitude in the High Andes (Fig. 1) emphasize the difference in tectonic setting clearly reflected in the geologic record. The rocks studied by us have a bimodal chemistry where basaltic andesites of high-K calc-alkaline to shoshonitic affinity and rhyolites predominate (Table 3), whereas the Quaternary rocks define a continuous, more narrow range of andesites and dacites of medium- to high-K type (Fig. 2; cf. Hildreth and Moorbath, 1988, and references therein). A comparison of basaltic andesites from the two groups demonstrates that the Mesozoic lavas are richer in HREE, K, Rb, Ba, and Th and poorer in Sr (Fig. 3A). They show no within-plate chemical character (expressed by high contents of Ta and Nb relative to Zr and Hf, and of Zr and Hf relative to Y and Yb; Pearce, 1983) that is typical of lavas from continental margins of Andean type. Moreover, there is no evidence that the present segmentation of the Andes with a major break at ca. 33°S corresponding to the northern limit of the Southern Volcanic Zone (Fig. 1) existed during the Jurassic and Early Cretaceous, because the formations of the Coast Range continue without interruption north and south of the Aconcagua River valley.

The non-Andean setting of the formations in the Coast Range has been recognized for some time from geologic evidence. Levi (1960) compared it to the present setting of Japan, where a volcanic arc is separated from the continent by a marginal sea. A situation similar to the present-day western Pacific margin was suggested by Chotin (1981), Coira et al. (1982), and Mpodozis and Ramos (1989) for different parts of Chile on the basis of the presence of a volcanic arc/back-arc pair, and by Munizaga et al. (1985) on the basis of the presence of strata-bound deposits of Kuroko type. Up to now, the chemical evidence for an oceanic island arc has been the large proportion of shoshonites among the Lower Cretaceous lavas of the Coast Range, suggesting a steeply dipping Benioff Zone, as in the case of some oceanic island arcs (Levi et al., 1988), and chemical similarities between intermediate Jurassic intrusive rocks immediately north of the studied region and oceanic island-arc andesites (Parada et al., 1988). The geochemical data given here are consistent with formation in island arcs floored by a moderately thick continental crust that became thinner with time.

In summary, asthenospheric upwelling below the present Coast Range of central Chile during the Jurassic and Early Cretaceous led to extension, crustal attenuation, and bimodal volcanism from arcs situated between a land area with Paleozoic basement in the west and a marginal sea in the east. The volcanic products were deposited in rapidly subsiding intra-arc basins. The source of the magmas became more depleted with time and their compositions were modified by subduction-related fluids and contamination with a progressively thinner and younger crust. The basic lavas are of high-K calc-alkaline to shoshonitic affinity, chemically resembling the lavas found in some mature island arcs in the western Pacific. The extension and rapid subsidence generated a low-relief topography close to sea level, in contrast with the present-day convergent type of Andean volcanism at the same latitude where calc-alkaline intermediate lavas erupt from volcanoes at heights of 5000–6500 m.

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