Tectonic Development of the North Chilean Andes in Relation to Plate Convergence and Magmatism Since the Jurassic

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Abstract. Since the early Jurassic the magmatic arc of the north Chilean Andes has been displaced from the Coastal Cordillera to the Western Cordillera. This eastward migration happened stepwise and four successive, ± stationary arc systems can be distinguished. The deformation history of the arc systems in relation to plate convergence and igneous activity shows that the magmatic arc, a zone of relative crustal weakness, reacted very sensitively to changing conditions of plate convergence. Both long-term continuous deformations and short-term tectonic events are recognized. They reflect periods of more or less steady state conditions and relatively sudden changes of subduction parameters respectively. Two major periods of different deformational styles, related to differing plate configurations and accompanying convergence obliqueness, can be distinguished: (1) 200-90 Ma (sinistral convergence obliqueness >45°) with general (trans-)tension during tectonic phases and interphases, and (2) since 90 Ma (dextral convergence obliqueness <45°) with transpression during phases and slight extension in interphases.

1 Introduction

The structural evolution of the Central Andes has largely been governed by the convergent motion between the South American upper plate and the subducting oceanic plate system of the Pacific. There is no doubt that the strain pattern within the edge of the upper plate is controlled by the parameters of plate convergence and, hence, if these parameters change with time, the strain pattern will change too. Therefore, it should be possible to ascribe the varying stages of geological evolution of the Andes to special and changing conditions of plate convergence.

Jarrard (1986) grouped the strain regimes within the overriding plates of modern subduction zones into seven strain classes ranging from the most extensional class 1 to the most compressional class 7 (Table 1). He showed that the best prediction of the strain regime occurs with a combination of the following three independent variables: (1) (trench-normal component of) convergence rate, (2) intermediate slab dip (from the trench to the 100-km depth), and (3) either slab age or absolute motion of the overriding plate with respect to the trench. All these variables operate in directions consistent with the hypothesis

Table 1. Strain classification of modern arc systems (after Jarrard 1986)

Strain Class	Description	Examples in modern subduction zones
1	active backarc spreading	Marianas, Tonga
2	incipient or very slow backarc spreading; high heat flow, thinned continental crust and thick sediment fill with growth-faulted grabens	Ryukyu, Izu-Bonin
3	mildly tensional, arc volcanism within an actively subsiding region, graben formation	Middle America New Zealand
4a	neutral, little evidence of either compression or extension	Lesser Antilles Cascades
4b	gradient: arc-forearc compression, backarc extension	Aleutians Alaska Peninsula
5	mildly compressional, gentle folds and thrusts	SW Japan, Java Sumatra, S Chile
6	moderately compressional, moderate folds, reverse faults	Colombia, Ecuador Peru, Alaska
7	very strong compressional, strong folding, imbricate thrusts	North Chile Central Chile

that the dependent variable coupling between the plates at their common boundary has the dominating influence on strain regime. As these strain regimes are considered a continuum, it should be possible to attribute a strain regime number between 1 and 7 to

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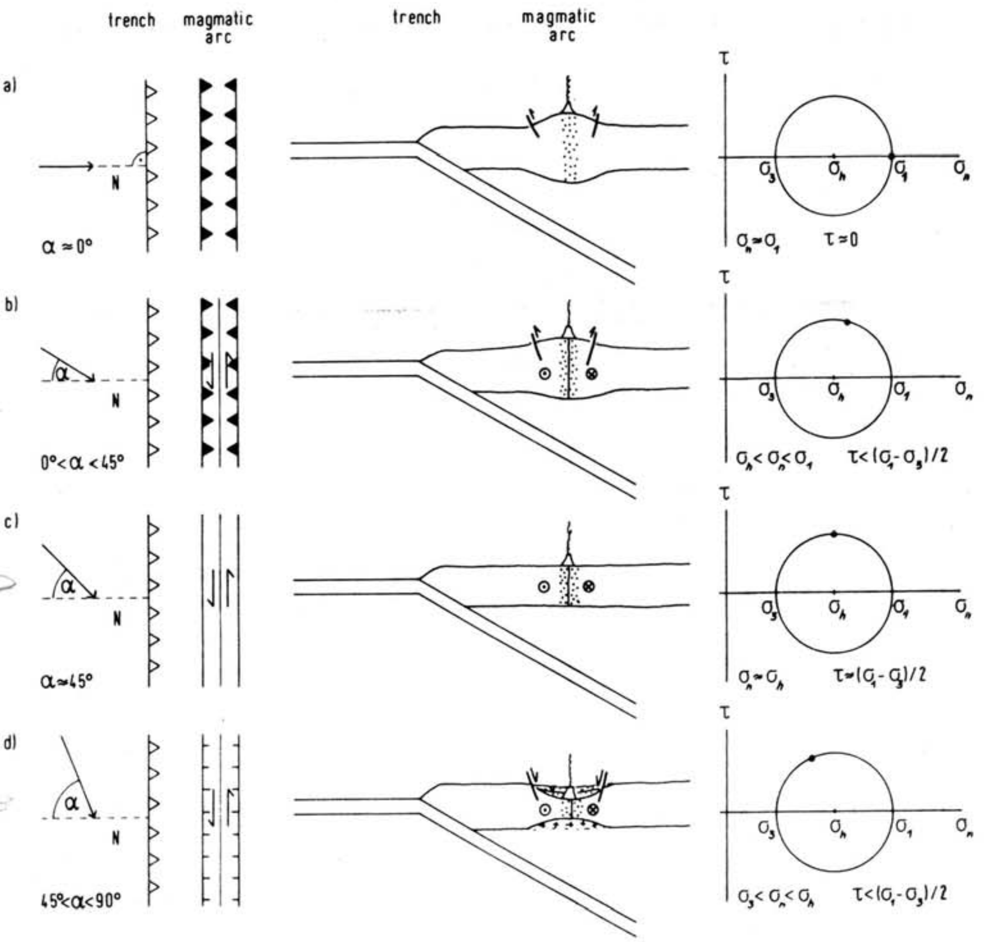

Fig. 1. The effect of subduction obliqueness on the deformational regime in the crust of the upper plate (prerequisites: convergence rate and plate coupling are sufficiently high). *Left column* map view; *middle column* cross section; *right column* Mohr circles showing the normal and shear stresses acting on the magmatic arc, which is reduced to a vertical plane oriented parallel to the plate boundary. In addition to arc-parallel shearing, obliqueness also leads to arc-normal movements: shortening occurs if obliqueness is <45° and extension if obliqueness is >45°. See text for explanation of **a-d**

all the different and transient palaeogeological situations in the evolution of the Central Andes and to draw conclusions about the effective parameters of convergence.

Another very important factor for the deformational regime operating within the upper plate is the angle between the plates' movement vector and the trench normal (convergence obliqueness) which, in the upper plate, may cause strike-slip movements parallel to the plate boundary (Fitch 1972; trench-linked strike-slip faults; Woodcock 1986). Such trench-linked strike-slip faults are indicative of the degree of coupling at the plate boundary, because weak coupling would cause lateral movements in the subduction zone (Beck 1983), while strong coupling produces strike-slip faulting within the forearc and/or arc of the upper plate. Such movements have occurred several times in the Central Andean history (Reutter and Scheuber 1988).

However, oblique convergence also causes movements normal to the plate boundary. Scheuber and Reutter (1992) have proposed a model according to which the angle of convergence obliqueness also determines compressive or tensional stress regimes in the upper plate (Fig. 1). If obliqueness is small ($\approx 0°$, Fig. 1a), the normal stress acting on the magmatic arc which represents a relatively weak vertical zone oriented parallel to the plate boundary, is about equal to σ_1 (parallel to the plate's motion vector); this results in orogen-normal shortening and crustal thickening. In the case of obliqueness between 0 and 45° (Fig. 1b), a shear stress is set up along the magmatic arc with τ_{max} at $\alpha = 45°$, while the normal stress is smaller than σ_1 but exceeds the hydrostatic stress. This setting should result in shortening plus strike-slip (transpression). The special case of $\alpha = 45°$ should produce pure trancurrence (Fig. 1c); obliqueness of $\alpha > 45°$ should lead to a normal stress that is smaller than the hydrostatic stress and also to a shear stress component so that extension plus strike-slip (transtension) are expected (Fig. 1d). The effects of oblique convergence, proposed in this model, probably add to the strain produced by the other parameters of plate convergence mentioned above.

In this chapter, based on field studies in northern Chile within the segment between 21° and 25°S, we

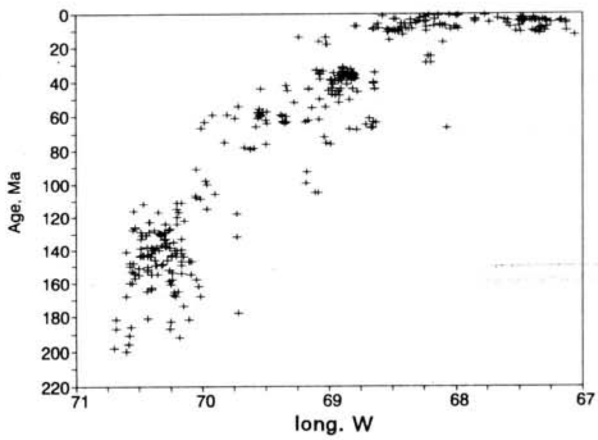

Fig. 2. Compilation of available isotope age data from north Chile between 21° and 26°S (406 age values included). The diagram shows the eastward migration of igneous activity since the early Cretaceous. Data from: compilation by Maksaev (1990): 297 age values (from various authors, 1965-1989); datings by Maksaev (1990), 58 age values; datings by Döbel et al. (1992), 18 age values; datings by Scheuber and Hammerschmidt (1991), 23 age values; datings by Pichowiak (this Vol.), 3 age values; datings by Andriessen and Reutter (this Vol.), 7 age values

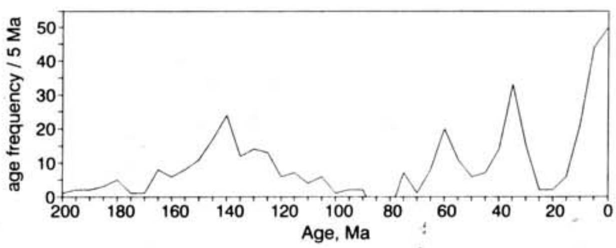

Fig. 3. The frequency of isotope age data in classes of 5 Ma (data base same as in Fig. 2)

consider only the deformations which have affected the active continental border since the early Jurassic (Andean Cycle, Coira et al. 1982). From that time to the Holocene, plate convergence was probably continuous, although its parameters have been subject to considerable variations. These variations influenced the strain regime and, hence, the tectonic setting of the magmatic arc and its respective forearc and backarc areas. In the study area, the wellknown (e.g. Coira et al. 1982) and well documented shift of the axis of the magmatic arc from west to east during the Andean Cycle is perhaps the best example of changing conditions at the active continental margin.

The compilation of all available isotope age data for northern Chile (Fig. 2) suggests that this migration was not characterized by jumps, but was a gradual process. Nevertheless, times of accelerated migration of igneous activity and separations of high and low activity periods (Fig. 3) allow the distinction of at least four arc systems (Fig. 4): (1) a Jurassic-early Cretaceous arc in the Coastal Cordillera, (2) a mid-Cretaceous arc in the Longitudinal Valley, (3) a late Cretaceous-Palaeogene arc in the Chilean Precordillera, and (4) the modern arc in the Western Cordillera.

These arc systems and their adjacent forearc and backarc areas had a specific and gradually developing tectonic evolution, which was sometimes interrupted by short-term events either during the lifetime of an arc system or between one arc system and the next one. Figure 5 gives a synopsis of the structural evolution of the north Chilean magmatic arc system since the Jurassic. In the following sections, this tectonic history will be reviewed and the attempt will be made to characterize the prevailing strain regimes and draw conclusions about the changing conditions of plate convergence.

2 The Jurassic-Early Cretaceous Arc System

The centre of igneous activity of the Jurassic-early Cretaceous arc system was situated in the Coastal Cordillera. Isotope ages range between 200 and 90 Ma, indicating that there was some areal overlapping with the 110 to 90 Ma old mid-Cretaceous arc system, whose activity was centred farther to the east in the Longitudinal Valley. To the east the Jurassic-early Cretaceous magmatic arc was bounded by a backarc basin which was installed upon an older continental crust. Subsidence started in the late Triassic and its deposits were marine until the

Table 2. Amount of rock units in the Coastal Cordillera between 20°15'-25°S

rock unit	km2	per cent
volcanic rocks	9436	37
plutonic rocks	10222	40
total igneous rocks	*19658*	*77*
pre Andean units	4171	16
younger units	1652	7
total	25481	100

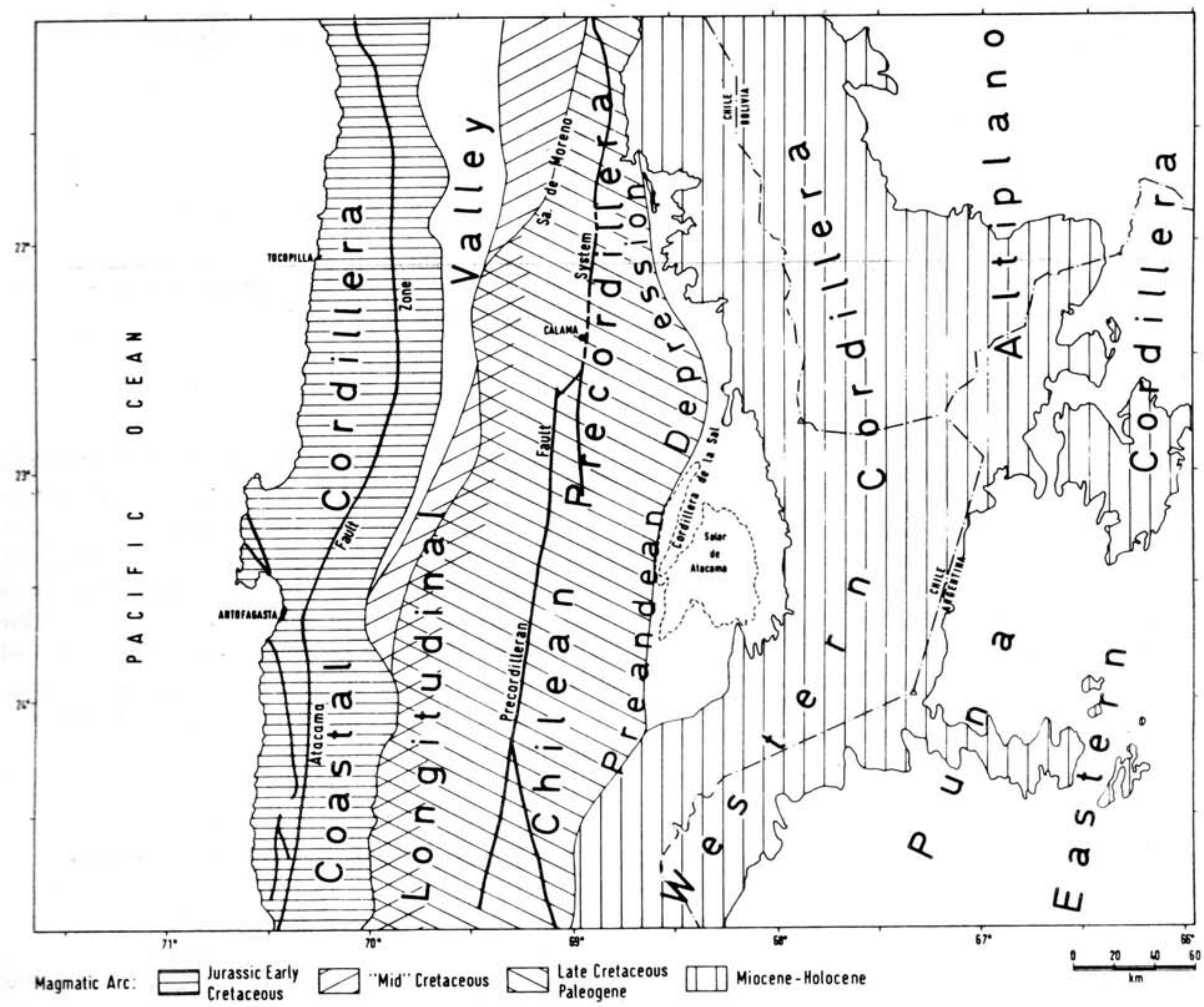

Fig. 4. The distribution of the four magmatic arcs that developed in the southern Central Andes (20°-26°S) since the early Jurassic (Andean Cycle, Coira et al. 1982)

Kimmeridgian when they gradually became continental. The forearc lies offshore and is possibly made up of Palaeozoic accretionary complexes.

The Jurassic-early Cretaceous magmatic arc is composed of large quantities of basic to intermediate igneous rocks consisting of lavas (La Negra Formation), large and small plutons and of numerous andesitic to dacitic subvolcanic stocks and dykes. The Jurassic-early Cretaceous volcanic and plutonic rocks cover some 77% of the area of the Coastal Cordillera (37% volcanics, 40% plutonic rocks, Table 2), although dykes and smaller sheet-like intrusions are not considered. The volcanics are calc-alkaline basalts to andesites. Their average thickness is about 3800-5000 m (Boric et al. 1990), however, in some places, e.g. near Antofagasta, it may exceed 10 km (Buchelt and Tellez 1988). There are several facts that indicate a deposition of the volcanics more or less at sea level: Early Sinemurian and Bajocian marine intercalations are found within the volcanics of the Coastal Cordillera north of 21°S and south of 25°S (Davidson et al. 1976; Naranjo and Puig 1984). Near Arica (18°30'S) the volcanics are conformably overlain by marine upper Oxfordian to lower Kimmeridgian sediments (García 1967). The deposition of the volcanics was thus coupled to strong subsidence of at least parts of the arc crust, which may be attributed to graben structures and pull-apart basins. The constant lateral thickness of the single lava flows of some 10 m, and the fact that volcanic breccias have not been described, points to an extrusion of the volcanic products by fissure eruptions

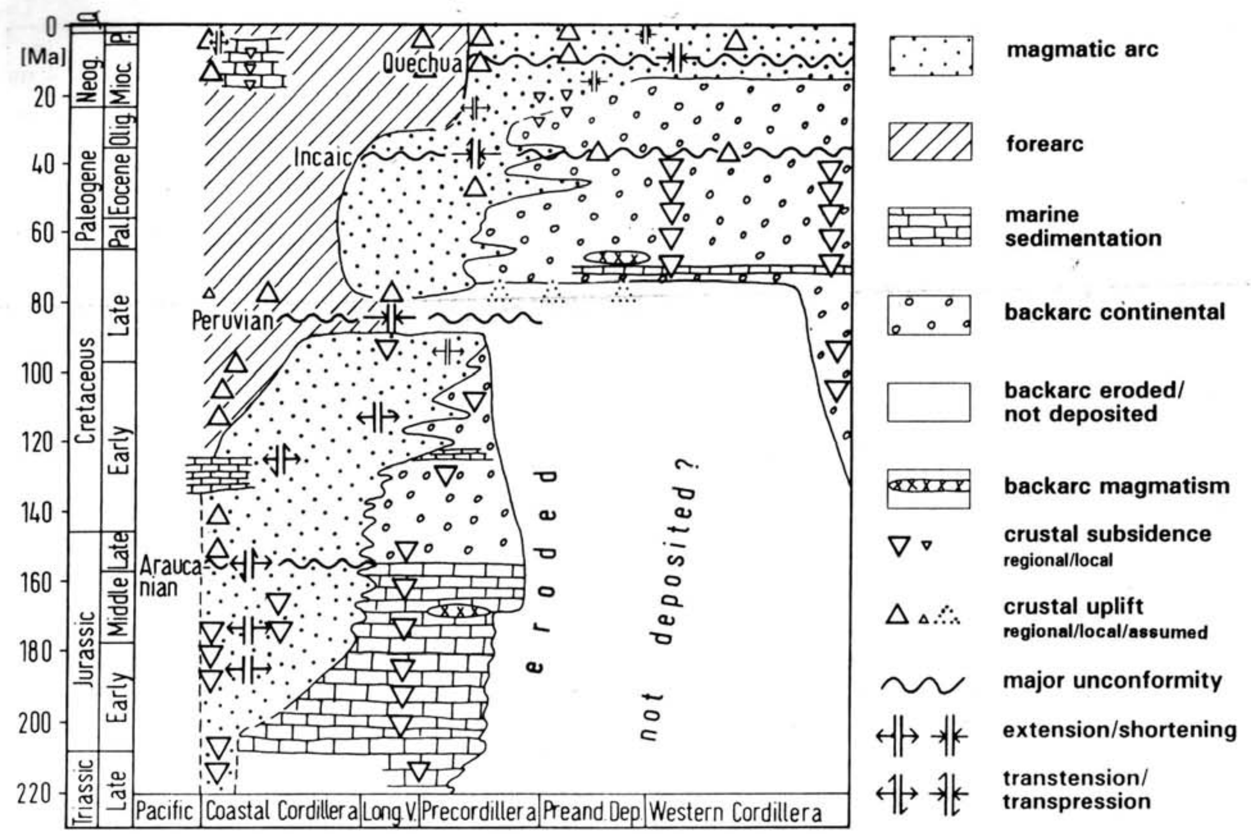

Fig. 5. Major aspects of the geological and structural development of the north Chilean Andes since the early Jurassic

rather than by single feeders. Volcanism was contemporaneous with the intrusion of huge batholiths. Geochemical data show that the plutonics are deep-level equivalents of the volcanics (Pichowiak et al. 1990). Throughout the Jurassic-early Cretaceous igneous rocks are mantle derivates without or with extremely little contamination by continental crust (e.g. Sr_i of about 0.703, Pichowiak this Vol.).

2.1 Deformation history of the Jurassic-early Cretaceous magmatic arc

The magmatic and tectonic activity were contemporaneous in this arc system. In the arc itself, extension normal to the arc and strike-slip movements parallel to the arc can be detected, to such a degree that a transtensional stress and deformation pattern becomes evident.

Arc-normal extension does not directly manifest itself in tectonic structures, but can be deduced from the following features:

(1) In some places numerous mafic to felsic dykes and subvolcanic stocks cover >40% of the area between the main branches of the Atacama Fault Zone (Fig. 6). Most of the dykes are oriented parallel to the trace of this fault zone (NNE-SSW).

(2) Frequent N-S linearity of plutonic intrusives (Rössling 1988: see geological map) points to an extensional regime at the time of their emplacement.

(3) The presence of mantle-derived gabbroic to dioritic intrusions at rather shallow levels is indicative of crustal thinning. The large Coloso Gabbro south of Antofagasta shows cumulate layering. Phanerozoic layered gabbros are normally related to rift zones or spreading centres (cf. Hyndman 1985), where they represent the pulses of opening of the magma chamber.

(4) Outcrops of Preandean rocks which show that the Coastal Cordillera was built up by continental material before the Jurassic make up only some 15% of the area of the Coastal Cordillera (Table 1) whereas Jurassic-early Cretaceous igneous rocks constitute some 77%. As these igneous rocks do not

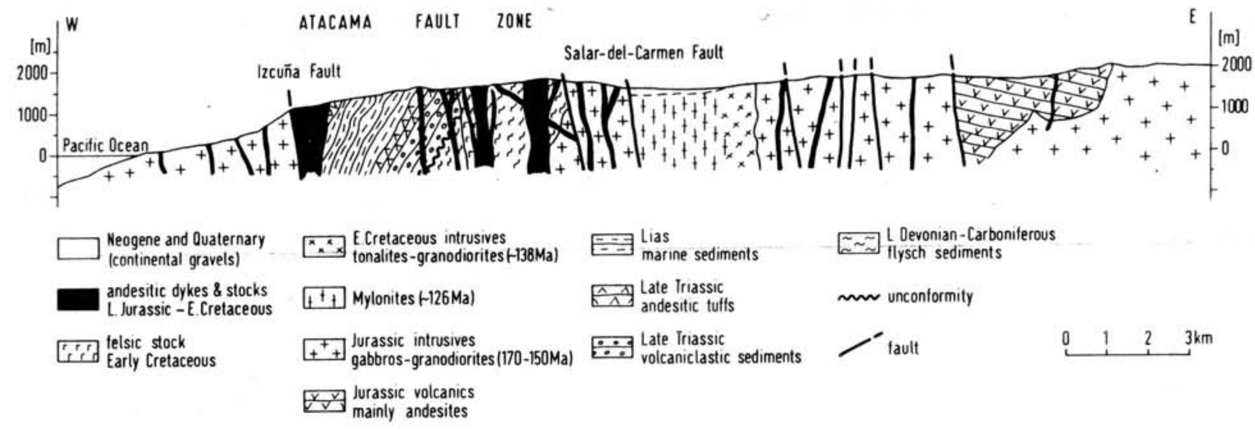

Fig. 6. Cross section through the Coastal Cordillera at 24°53'S showing the concentration of dykes and smaller sheet-like intrusions to the area of the Atacama Fault Zone

show a significant contamination by continental material it can be concluded that the originally existing continental crust has been replaced by this mantle derived material. Even where deep levels are exposed (e.g. south of Antofagasta) no remnants of the basement are found. High P-wave velocities of about 6.8 km/s in the Coastal Cordillera extending to depths of about 30 km (Wigger 1988) also exclude a normal continental basement beneath the Jurassic-early Cretaceous igneous units.

(5) In the western part of the Coastal Cordillera Palaeozoic-early Jurassic strata are homoclinal and dip steeply to the west or east (Fig. 6), but they are completely devoid of tight or even isoclinal folds and/or repetitions of strata successions that would be necessary to explain the steep dips by shortening. Thus the homoclinal dip of the beds can only be interpreted by block rotation due to crustal extension.

(6) Strong crustal subsidence affected not only the arc but also the backarc, implying that crustal thinning as a consequence of an extensional stress regime affected an area at least 200 km wide.

Arc-parallel strike slip movements generated a belt of foliated rocks that is linked to the Atacama Fault Zone (AFZ). The AFZ is considered to be the major and most continuous structure of the Coastal Cordillera (Arabasz 1971) and can be traced over more than 1000 km from ≈20° (Iquique) to ≈30°S (La Serena). Naranjo et al. (1984) reported the existence of mylonite zones from the AFZ north of Chañaral, with early Cretaceous K-Ar ages (hornblende: 126 ± 10 Ma). Scheuber et al. (1986) mentioned mylonite zones which contain S-shaped vertical folds indicating sinistral strike-slip movements to have occurred along the AFZ. Hervé (1987) mapped plutons which show a sinistral displacement along some branches of the AFZ (K-Ar whole rock age of a mylonite: 139 ± 5 Ma). In a study of high to low grade mylonites from the AFZ Scheuber (1987), and Scheuber and Andriessen (1990) showed that microstructural features such as S-C fabrics, S-bands, asymmetric porphyroclast systems, and quartz-c axes preferred orientation reveal a uniformly sinistral sense of shear. South of Antofagasta two sets of ductile shear zones are found along the AFZ, a Jurassic one deformed under amphibolite facies conditions and an early Cretaceous one formed in the greenschist facies. For both sets of shear the age of deformation has been determined using the Rb-Sr and the $^{40}Ar/^{39}Ar$ methods (Scheuber and Hammerschmidt 1991). For the late Jurassic shear zones two deformation steps could be determined, one before 152 ± 1 Ma (hornblende $^{40}Ar/^{39}Ar$, biotite Rb-Sr) and one at 143 ± 0.3 Ma (biotite Rb-Sr and $^{40}Ar/^{39}Ar$). The deformation age of the early Cretaceous greenschist facies shear zone is 125.3 ± 0.3 Ma (biotite Rb-Sr and $^{40}Ar/^{39}Ar$). The ages are contemporaneous to the period of major intrusive activity in the Coastal Cordillera (Fig. 3) illustrating the combined action of magmatism and tectonism. The close temporal relationship between intrusion and deformations can also be inferred from transitions of magmatic flow structures to structures of plastic deformation in late Jurassic shear zones as described by Gonzalez (1990).

The deformation ages of the late Jurassic shear zones (Araucanian tectonic event, Riccardi 1990, and references therein) correspond to a major angular unconformity and the beginning of coarse conglom-

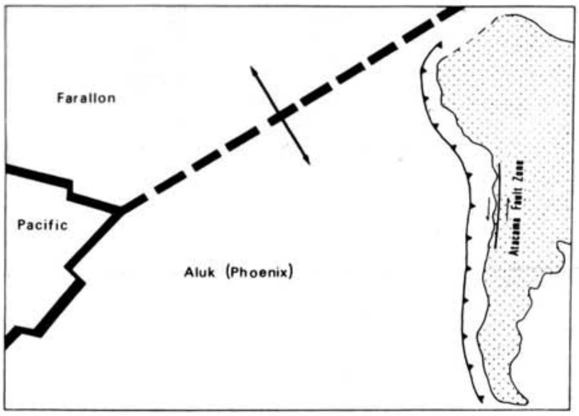

Fig. 7. Reconstruction of the plate configuration in the SE Pacific at ≈150 Ma. (After Larson and Pitman III 1972; Zonenshayn et al. 1984) Sinistral subduction obliqueness exeeded 45° resulting in a transtensional regime (cf. Fig. 1 d)

eratic sedimentation in the Coastal Cordillera (Fm. Caleta Coloso, Tithonian-Valanginian) north of 24°. The 125 Ma deformation of the greenschist facies shear zone occurred at the beginning of strong and rapid uplift of the Coastal Cordillera starting between 130 and 120 Ma ago (Maksaev 1990; Scheuber and Andriessen 1990; Andriessen and Reutter this Vol.).

In contrast to the magmatic arc, the narrow marine backarc basin was characterized by tectonic quiescence to some very slight backarc rifting which is indicated by minor occurrences of middle Jurassic basalts in the Chilean Precordillera. Early Cretaceous alkaline igneous rocks from northwest Argentina also point to foreland rifting (Galliski and Viramonte 1988). The thickness distribution of Jurassic backarc deposits indicates two periods of greater subsidence rates, one in the Sinemurian-Toarcian corresponding to the installation of the magmatic arc, and one in the Kimmeridgian during which a gradual change from marine to continental deposition took place (Prinz et al. this Vol.). In the magmatic arc this change corresponds to the culmination of intrusive and tectonic activity at ≈152 Ma. For the strong 125 Ma strike-slip movements no corresponding tectonic features have been described from the backarc basin. In summary, during the Jurassic-early Cretaceous, tectonic activity was largely restricted to the area of the magmatic arc which accommodated most of the imposed regional strain rate, due to a strongly reduced strength as a consequence of heating and intrusion of liquids. The backarc area only reflected, by subsidence, the crustal extension of the arc.

The deformations in the Jurassic-early Cretaceous arc system are consistent with available data of plate configurations of that time (Larson and Pitman III 1972, Zonenshayn et al. 1984). The Aluk (Phoenix) plate moved with a very high angle of obliqueness (≈60°) against South America (Fig. 7). From this, according to the model outlined above, the transtensional regime (normal stress < hydrostatic stress) can be deduced, and this is in agreement with the observed structures. The high angle of obliqueness also corresponds to the Jurassic tectonics of Peru (Jaillard et al. 1990), north of the Bolivian orocline. Here a subduction-related volcanism is only locally developed and sinistral strike-slip movements and extensions normal to the plate boundary are the prevailing deformations. Jaillard et al. (op.cit.) suggest that these tectonics are consistent with a sinistral transform plate boundary.

3 The Mid-Cretaceous Magmatic Arc System

During the early Cretaceous, the centre of igneous activity shifted eastward to a position in the previous backarc basin and the present Longitudinal Valley, although it extends into the adjacent parts of the Coastal Cordillera and Chilean Precordillera. A sequence of andesitic lavas about 2000 m thick (Empexa-Fm., Galli 1957; Estratos del Río Seco, Quebrada-Mala Fm., Charrier and Muñoz this Vol.), was deposited conformably upon a sequence of clastic sediments up to 3000 m thick with marine and some volcanic intercalations (Kimmeridgian-Barremian: Western Sequence, Bogdanic 1990). The migration of the arc from the Coastal Cordillera towards the Longitudinal Valley was a gradual process. Towards the south, where both arcs overlap, there is no unconformity between the extrusive products of the two arcs, and thus, the distinction from the former arc becomes somewhat arbitrary. The same is true for the character of magmatism which shows great similarities with the Jurassic-early Cretaceous one (Pichowiak this Vol.).

The lavas frequently alternate with sediments that are partly marine to the south of the segment considered here (Formación Aeropuerto, Naranjo and Puig 1984). The lower age limit of the mid-Cretaceous volcanics is given by underlying partly marine sediments of Hauterivian-Barremian age, while the upper limit is constrained by the 76 to 78-Ma San Cristobal intrusive complex (Maksaev 1990, Pichowiak this Vol.) and unconformably overlying volcanics of the late Cretaceous-Palaeogene arc (Fm. Chile-Alemania,

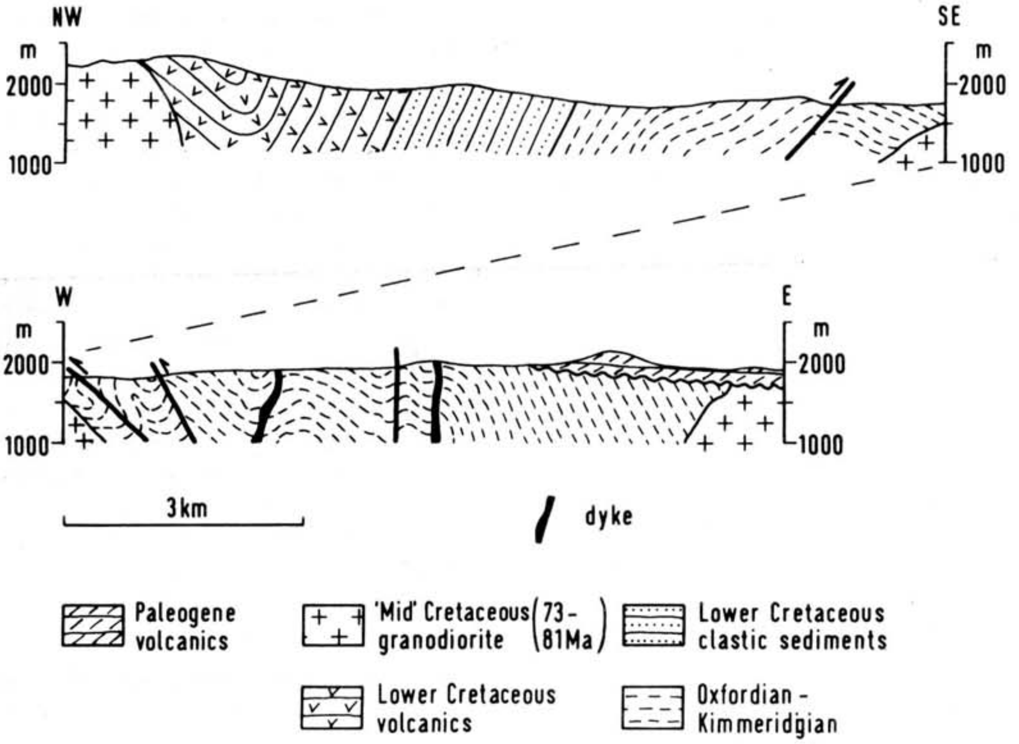

Fig. 8. Cross sections of the Longitudinal Valley east of Antofagasta at 23°45'S, 69°30'W showing the tectonics of the mid-Cretaceous magmatic arc. Lower Cretaceous volcanics and sediments were deposited conformably upon Jurassic-Lower Cretaceous sediments. The whole sequence was folded during the Peruvian phase (between 90 and 80 Ma)

oldest isotope age: ≈72 Ma, Naranjo and Puig 1984; Herrmann and Zeil 1989). This stratigraphic position corresponds to geochronological data of ≈115-90 Ma for the igneous rocks (Ulriksen 1979; Marinovic and Lahsen 1984; Rogers 1985; Döbel 1989; Andriessen and Reutter this Vol.). The mid-Cretaceous magmatic arc was followed by a gap in igneous activity that lasted some 10 Ma. For the time between 90 and 80 Ma, no isotope ages are reported from either the study area or the neighbouring areas in north Chile, northwest Argentina or southwest Bolivia. The gap in igneous activity may be due to the passing by of the Aluk-Farallon spreading centre (see below).

Information about the tectonics related to this arc system is rather scarce because most parts of the mid-Cretaceous arc are covered by younger formations of the Chilean Longitudinal Valley. As the mid-Cretaceous magmatic arc was installed within a subsiding basin without any marked angular unconformity between the sedimentary substrate and the lavas (Fig. 8), it may be concluded that extensional tectonics of the arc area (and former backarc area) continued up to the mid-Cretaceous. An internal angular unconformity within the volcanic-sedimentary sequences (between Fm. Quebrada Mala and Estratos del Rio Seco: Charrier and Muñoz this Vol.) can be attributed to the extensional tectonics. Large scale extensional tectonics of probably Aptian to Cenomanian age (124.5-90.4 Ma, Harland et al. 1990) have also been described by Mpodozis and Allmendinger (1991) for the Chilean Precordillera east of Copiapó (≈27°S).

In contrast to the preceding arc system, no directly adjoining backarc basin was developed. It is probable that, to the east, the arc bordered on hilly lowlands which did not receive any sedimentation during that time. However, about 400 km to the east, in the Bolivian Altiplano and the Puna of northwestern Argentina, a sedimentary basin developed, where mostly continental and marine (Cenomanian, Bolivia) sediments were deposited (Marquillas and Salfity 1988). The extensional nature of these depocentres is documented by mid-Cretaceous basaltic extrusions (120-90 Ma, Bossi and Wampler 1969, Valencio et al. 1976).

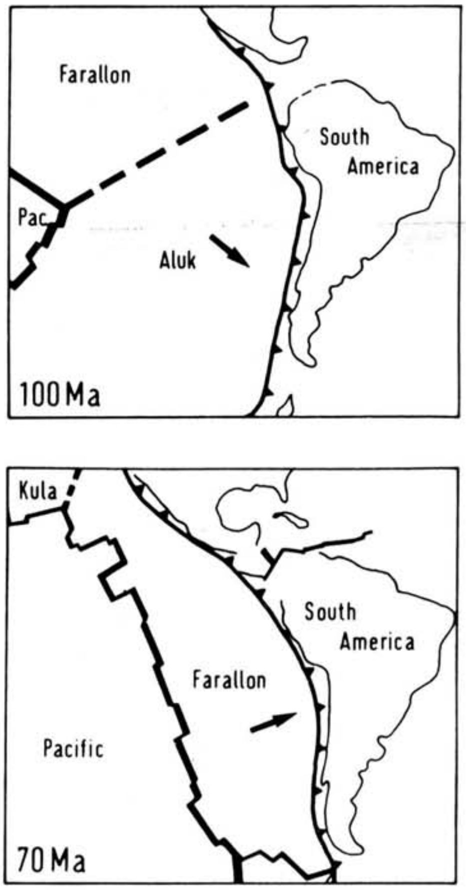

Fig. 9. The change in the SE Pacific plate configuration in the late Cretaceous. (After Zonenshayn et al. 1984)

The extensional strain regime was replaced by a compressional one with a tectonic event during the late Cretaceous. Deformation affected an area about 100 km wide corresponding more or less to that of the magmatic arc whose volcanic activity was terminated. The whole Jurassic-early Cretaceous sequence was subject to strong orogen-normal shortening which led to intense folding and thrusting, partly affecting also the pre-Jurassic basement (Fig. 8, Jensen 1985). In some places, e.g. east of Antofagasta, mid-Cretaceous volcanic rocks developed a foliation and axial plane cleavage is observed in upright folded Jurassic sediments. Strike-slip deformations within the arc have not yet been reported either in relation to the mid-Cretaceous extensional tectonics or in relation to the late Cretaceous compressional tectonics, but this may be due to the poor knowledge of this arc area. However, along major structures strike-slip movements may have occurred within the arc.

Similar to the late Jurassic events, the backarc area of the mid-Cretaceous system was not affected by the compressional tectonics, in either its elevated or its basinal parts. This is evidenced by the lack of definite angular unconformities with overlying late Cretaceous to Palaeogene sediments and volcanics to the east of the Chilean Precordillera. However, it is probable that the widespread stratigraphic gaps between these younger formations and the underlying Triassic to Palaeozoic rocks are related to mid-Cretaceous crustal uplift and erosion (cf. Fig. 5).

The deformational age is constrained by the upper age limit of the deformed rocks (≈90 Ma) and by the postdeformational emplacement of granitic-monzonitic plutonic bodies (78-76 Ma, Maksaev et al. 1988a; Pichowiak, this Vol.), as well as by an angular unconformity between the deformed sequence and the overlying volcanic sequence of the subsequent late Cretaceous-Palaeogene arc system (starting at ≈72 Ma, Naranjo and Puig 1984, Herrmann and Zeil 1989). All these events are correlated and are comparable with the effects of the Peruvian tectonic phase which was first described for Perú and western Bolivia as a compressive phase (Steinmann 1929); its age was described as Santonian (86.6-83 Ma, Harland et al. 1990) by Mégard (1987).

In contrast to the preceding and the following arc systems, deformations affected the mid-Cretaceous arc system only after its magmatic activity had ceased, i.e. during the 90 to 80-Ma magmatic quiescence. However, as deformation concentrated on the terminating magmatic arc, it can be concluded that the arc was a hot, still weak zone in the crust of the upper plate. The change in the deformational regime at the end of the mid-Cretaceous arc reflects the major change in the plate configuration in the southeast Pacific between 110 and 70 Ma (Fig. 9). During this time span the spreading centre between the Aluk and the Farallon plates (possibly a continuation of the Tethyan rift, Jaillard et al. 1990) migrated towards the south, and, as a result, the Aluk-South America convergence was replaced by one between the Farallon and the South American plates. While the Aluk-South America convergence was at a very high angle of sinistral convergence obliqueness, the convergent plate motion between Farallon and South America had a dextral component at a lower angle of obliqueness. Thus, a completely different stress and strain regime can be inferred for the time following the change in plate movements. During the Aluk-South America convergence,

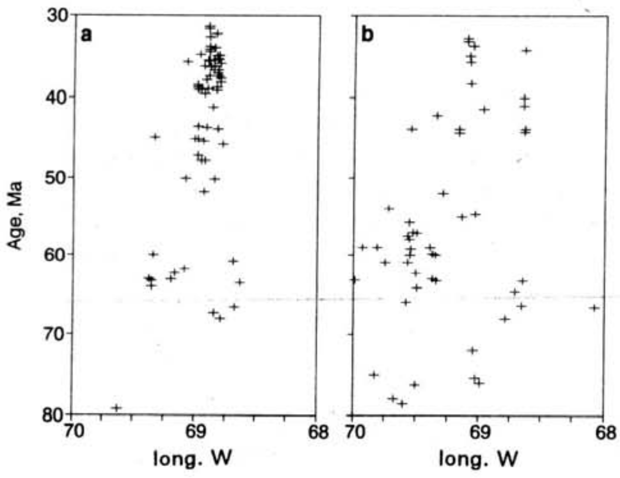

Fig. 10. Distribution of isotope age values in the Chilean Precordillera, *a* north of the line Calama-Antofagasta; *b* south of the line Calama-Antofagasta (Source of data same as in Fig. 2)

orogen-normal extension occurred, whereas orogen-normal shortening is assumed to have occurred during the Farallon-South America convergence. The period of igneous quiescence between 90 and 80 Ma (Figs. 2 and 3b), which coincides with the reorganization of Pacific plates during the mid-Cretaceous, may be a result of subduction of the southward migrating spreading axis. A modern example of a gap in igneous activity due to the subduction of an oceanic ridge is the subduction of the Chile ridge underneath the southern Andes at 50°S; this also produces a gap in the volcanic chain (Herron et al. 1981; Ramos et al. 1991).

4 The Late Cretaceous-Palaeogene Arc System

This magmatic arc system, which was again emplaced to the east of the preceding magmatic arc system, was active from the late Cretaceous to the Oligocene. Isotope age determinations of volcanic and plutonic rocks fall between 80 and 30 Ma. Figures 3 and 10 show two maxima of igneous activity, one at 75-55 Ma, more distinct in the Longitudinal Valley south of the line Antofagasta-Calama, and the other one at 48-35 Ma centred on the Chilean Precordillera north of Calama. As both parts of this magmatic arc show differences in their tectonic setting they will be dealt with separately.

4.1 Maastrichtian-early Eocene

During this time the magmatic arc was more than 100 km wide (Fig. 10a). In contrast to the preceding arc systems of the Andean Cycle, the volcanics of this time (basaltic and rhyolitic lavas, acid tuffs and ignimbrites; Chile Alemania Fm.) were deposited in the western parts of the arc, directly upon Palaeozoic to Cretaceous rocks, with a marked angular unconformity at the base. The substrate of the arc, which had been subject to shortening after the extinction of the preceding arc system, was located above sea level. At its eastern side the arc was bordered by a broad backarc basin which extended to the east as far as the Eastern Cordillera of southwest Bolivia and northwest Argentina. Here, crustal extension can be inferred from Maastrichtian to lower Palaeocene marine sedimentation (Salta Group, Marquillas and Salfity 1988), and strongly alkaline basic volcanics of 78-76 Ma (Reyes et al. 1976; Valencio et al. 1976) and 65-60 Ma (Omarini et al. 1988). In the north Chilean part of the backarc basin mainly continental red sandstones and conglomerates up to 2 km thick were deposited (north of Calama: Eastern Sequence (Bogdanic 1990); east and southeast of Calama: Tonel Fm. of the Purilactis Group (Charrier and Reutter this Vol.)) indicating the

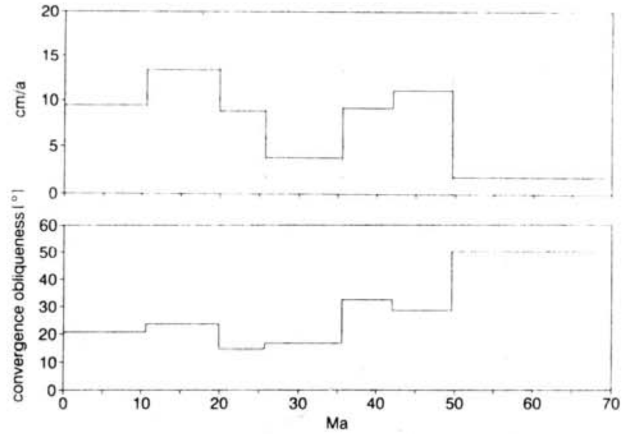

Fig. 11. *Above* convergence rate (cm/a) and *below* convergence obliqueness between the Farallon/Nazca and the South American plates since the uppermost Cretaceous. (After Pardo-Casas and Molnar 1987.) For the convergence rate the error range is also shown (*light lines*), for the convergence obliqueness only the roughly determined mean value has been used (cf. Pardo-Casas and Molnar 1987: Figs. 4 and 5). Data have been interpolated for 25°S between the values for 20° and 30°

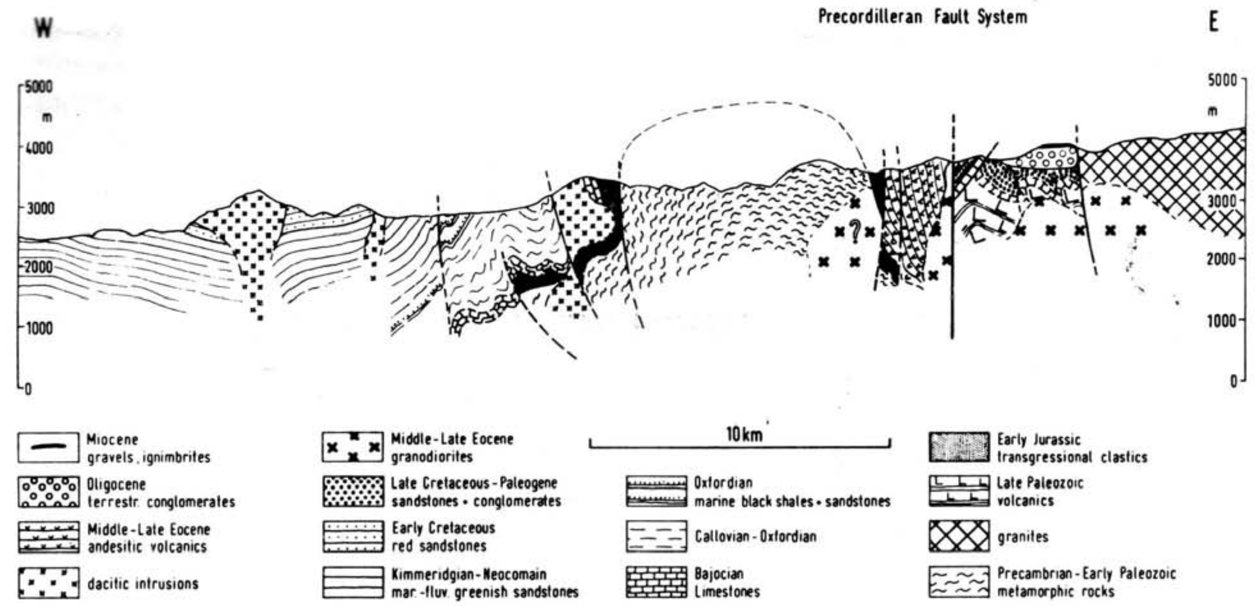

Fig. 12. Cross section through the Chilean Precordillera at 21°S (Quebrada Choja). The section shows the incorporation of the Preandean basement (Precambrian-late Palaeozoic) into an anticlinal structure which originated during the Incaic phase (~38 Ma). The structure is intruded by granodioritic to dacitic stocks of Eocene age. The Precordilleran Fault System is also shown

transition between the elevated arc and the backarc area. Extensional stress conditions for this backarc area are recorded by a Maastrichtian marine ingression, and by alkali-basaltic flows of ~68 Ma (Döbel et al. 1992).

During the Maastrichtian-early Eocene the deformational regime was characterized by relative tectonic quiescence to slightly extensional conditions in the arc and, in the backarc/foreland, by the described strong crustal extension. In the magmatic arc some extension can be inferred from the presence of early Eocene calderas in the Longitudinal Valley at 24°30'S (Herrmann and Zeil 1989) and in the Chilean Precordillera east of Copiapó (27°45'S, Rivera and Mpodozis 1991). Large scale arc-parallel strike-slip faults have not been described from this arc.

The time interval Maastrichtian-early Eocene was characterized by a low convergence rate of <5 cm per year (Fig. 11). A rather low degree of coupling between the plates is expected which, in turn, should produce an extensional strain regime in the upper plate. The relatively high degree of convergence obliqueness may have increased the extensional regime (cf. Fig. 1).

4.2 Late Eocene-early Oligocene

During this time the magmatic arc became narrower and the centre was situated in the Chilean Precordillera north of Calama (Fig. 10b) where calc-alkaline volcanics up to 2000 m thick were deposited. Volcanic activity extended to the south along the western border of the Maastrichtian-Eocene backarc basin where the lavas interfinger with sediments. Volcanism was accompanied by the emplacement of mainly acid plutons. The onset of igneous activity was linked with uplift of the arc's crust as is documented in the deposition of >3000 m of conglomerates in the backarc basin (Purilactis Fm. s. str. of the Purilactis Group, Charrier and Reutter this Vol.). In contrast to the Maastrichtian-early Eocene, there are no indications of backarc/foreland extension.

In late Eocene times the arc was affected by the strong deformations known as the Incaic tectonic phase (Steinmann 1929; Noble et al. 1979). The deformation history is initially governed by a transpressional regime of arc-normal shortening and arc-parallel dextral strike-slip faults. Shortening is well illustrated in the Chilean Precordillera (Fig. 12) which is built up by long more or less upright anticlines (Chong and Reutter 1985: 25% of shortening) with Preandean basement cores consisting of Precambrian to Palaeozoic sedimentary, metamorphic and plutonic rocks. Smaller fold structures are developed in the sedimentary and volcanic cover rocks. Döbel et al. (1992) could establish the ages of folding during the Incaic phase by $^{40}Ar/^{39}Ar$ datings of volcanic rocks located immediately below and above a 50° angular unconformity. As both ages (38.45 ± 0.61 and 38.54 ± 0.87 Ma respectively) are identical, it can be concluded that folding took place during a period of < 1.5 Ma.

During the Incaic phase, arc-parallel strike-slip movements started along the Precordilleran Fault System (Reutter et al. 1991). A contemporaneous activity of shortening and transcurrent movements can be inferred from the observation that some of the Precordilleran folds and thrusts are oriented en echelon, obliquely (NW-SE) to the prevailing N-S trend of the orogen, and normally to the direction of shortening in the dextral system. On the other hand, strike-slip movements lasted until at least 35 Ma. This has been shown by Maksaev et al. (1988b) who reports a 34 Ma age in mylonites from shear zones cutting through a 35 Ma old pluton. The longer duration of transcurrent movements compared with folding can also be inferred from the observation that second order vertical folds were generated in stratified rocks, where strike-slip faults cut through vertically dipping flanks of first order horizontal folds (Reutter et al. 1991).

In contrast to the preceding arc systems deformation at the end of the Eocene (Incaic phase) was not restricted to the magmatic arc. The backarc region of the late Cretaceous-Palaeogene arc was also subject to strong shortening so that the backarc sediments and parts of their substrate were involved in east-vergent folds and reverse faults. Crustal shortening that extended to the Eastern Cordillera of Bolivia and Argentina (Reutter et al. 1988) must have contributed to an important crustal thickening in the arc area.

Reconstructions of plate movements during the Eocene are consistent with the observed structures (Fig. 11). Around 48 Ma there was a sharp increase in the Farallon-South America convergence rate and this coincides with the onset of igneous activity after the early to mid-Eocene. This increase must have resulted in an intensified coupling between the plates. Together with the 30° dextral obliqueness the plate configuration corresponds to the transpressional regime observed in the arc.

5 The Miocene-Holocene Arc System

Around the Oligocene-Miocene boundary, the modern magmatic arc (Central Volcanic Zone of the Andes) was installed in the Western Cordillera, east of the preceding extinct arc system. In the segment considered the arc is very wide as it extends as far as the western reaches of the Eastern Cordillera. Although isotope ages indicate igneous activity since 28 Ma (Figs. 2 and 3), ages older than 17 Ma are very rare, and there is a further remarkable increase in the number of data since 10 Ma which corresponds to the Quechua tectonic phase (Steinmann 1929; Mégard 1984).

The lavas and ignimbrites of the new arc overlie unconformably different Palaeozoic to Oligocene rocks of the shortened backarc area of the late Cretaceous-Eocene arc system. It can be supposed that where the new arc was installed the crust was relatively thick due to the late Eocene shortening. However, slowing convergence rates during the Oligocene (Fig. 11, Pardo-Casas and Molnar 1987) and the resulting decrease in the compressive stress in the upper plate led to some crustal collapse and crustal thinning in the course of isostatic adjustments. The formation of intramontaneous basins (e.g. Salar de Atacama (probably along preexisting structures), Upper Loa Valley, and the probably still active depressions within the Puna), and the rapid uplift of Eocene-Oligocene plutons and older rocks during the Oligocene (Maksaev 1990; Andriessen and Reutter this Vol.) give evidence of the tectonics of this interarc stage. Geologically this period is well marked by the formation of a broad peneplain over the whole segment of the Andes, and by a pronounced angular conformity beneath a thick cover of unconsolidated continental gravels (Gravas de Atacama) of late Oligocene to early Miocene age, which interfinger with the volcanic products near the Western Cordillera.

The deformations in the modern arc system are largely governed by arc-normal shortening. Miocene and younger structures of intense crustal shortening can be observed in the Western Cordillera and its border regions. In the Western Cordillera deformations occurred at ~23, ~10 Ma and ~4-5 Ma (Lahsen 1982). According to Kussmaul et al. (1975), in the Altiplano of southwest Bolivia shortening took place during the early Miocene (23-24 Ma), the late Miocene (13-14 Ma) and the late Pliocene (~3 Ma). In the Puna of northwestern Argentina, west and east vergent conjugate reverse fault systems developed in the early Miocene, in the middle Miocene, in the Pliocene and in the Quaternary (Schwab 1970, 1985). In the southeastern border of the Puna plateau Allmendinger (1986) has documented the youngest deformations. He could define a late Pliocene deformation (after ~2.35 Ma ago, before early Quaternary) with NW-SE shortening (vertical extension), and a Quaternary deformation dominated by strike-slip movements (E-W shortening, N-S extension). Allmendinger attributed this Quaternary kinematic change to a change in either the geometry of the subducted Nazca plate or plate convergence. To the west of the Western Cordillera, on the border of the Salar de Atacama depression (Cordillera de la Sal, Cordon de Lila), after Oligocene extension and collapsing, reverse faults (Megafalla Tucucaro, Niemeyer 1984) and anticlines (Cordillera de la Sal, Wilkes 1991; Wilkes and Görler this Vol.) developed from the Miocene to the present. To summarize, the structures of the modern magmatic arc indicate more or less continued deformations (mainly arc-normal shortening) from the Oligocene-Miocene boundary until the present. However, deformations were strongest during the Quechua (~10 Ma) and the Diaguita (5-3 Ma) tectonic phases.

The most important deformation related to the modern arc system is the development of the fold-and-thrust belt of the Subandean Ranges of Bolivia and northwestern Argentina since the late Miocene. Strong crustal shortening of up to 140 km (Kley et al. 1991) leads to the underthrusting of the Andean foreland (corresponding to the Brazilian Shield) beneath the Andes. Generally, the backarc deformations started later than those of the arc (Jordan and Gardeweg 1989; Mégard 1989). This can be explained by Isacks' (1988) model which proposes two stages for the Neogene compressive deformations: (1) a pervasive and widespread horizontal shortening, and (2) a concentration of deformation along the eastern side of the orogen (Eastern Cordillera, Subandean Ranges) triggered by an increased convergence rate in the late Miocene. The later phase resulted in the strong uplift of the present arc to a height of some 4000 m.

In contrast to the shortening in the arc and backarc regions the western part of the forearc is characterized by steep fractures. For the Coastal Cordillera Armijo and Thiele (1990) ascribed these faults to an E-W extension caused by subduction-related underthrusting and the existence of east-dipping ramps.

In the modern magmatic arc system orogen-parallel strike-slip displacements seem to be of minor importance. This is due to the low angle of convergence obliqueness (<20°). Nevertheless, on the eastern scarp of the Salar de Atacama depression right-stepping Riedel shears indicate local left lateral strike-slip movements with a throw unlikely to exceed 100 m. Orogen-parallel sinistral strike-slip movements have also been reported by Armijo and Thiele (1990) from the forearc region where a reactivation of the Atacama Fault occurred in the Coastal Cordillera. These authors interpret the sinistral movements, which are in contradiction with the present minor right lateral component of Nazca convergence, as due to the clockwise rotation of the Central Andes south of the Arica bend.

The more or less continuous deformations in the modern magmatic arc system correspond to special conditions of plate convergence since the early Miocene: (1) convergence rates are very high (Fig. 11), (2) the subducting Nazca plate is relatively young (~40 Ma at the trench, Herron 1972), resulting in a low slab-dip angle of <30°, (3) the motion of the South American plate in a direction opposite to that of the Nazca plate overcompensates subduction rollback, and (4) a convergence obliqueness of <20°. All these factors lead to strong compressional stresses at the interface of the plates, a good coupling between the plates and, thus, to an intense stress transmission to the upper plate. As a consequence, the modern Central Andes have the world's strongest compressional strain regime which resulted in a crustal thickness of some 70 km and a very broad zone of crustal shortening.

6 Discussion

6.1 Continuous Deformation and Tectonic Events

The tectonics of the active continental margin of the Central Andes is an expression of the changing conditions of plate convergence. Both long-term continuous deformations, and short-term tectonic events can be recognized, which should respectively reflect periods of more or less steady state conditions and relatively sudden changes of subduction parameters (e.g. Fig. 11). Some of the events can be correlated with global tectonic phases whereas other deformations are only of regional or local significance.

Examples of long-term continuous deformation, which may pertain to the stress pattern induced by a uniform plate movement, are: (1) the Jurassic and early Cretaceous crustal subsidence under growing lava formations and a probable contemporaneous crustal uplift of deeply intruded plutons in the arc area; (2) the Maastrichtian-early Eocene tectonic quiescence to mild extension in the arc, coupled with long-term subsidence and extension in the backarc; and (3) superimposed on the Quechua and Diaguita tectonic phases, the continued Miocene to recent shortening and uplift in the modern magmatic arc.

Short-term tectonic events are better known because of their marked structural expression, and they can be better appreciated in terms of plate tectonics and global events than can the long-term deformations.

The tectonic event that affected the Jurassic arc during the Kimmeridgian (Araucanian phase) corresponds to a worldwide tectonic phase which is probably linked with major changes in the plate configurations. For the Peruvian and Colombian segment of the Andes, Jaillard et al. (1990) have attributed these late Jurassic events to a geodynamic revolution which is marked by the end of the Tethyan breakup, and by the beginning of the Atlantic rifting. The Araucanian deformations of northern Chile are also contemporaneous with the ≈155±3 Ma Nevadian phase in western North America as dated by Schweickert et al. (1984). The early Cretaceous (126 Ma) movements along the Atacama Fault Zone have no correspondence with other areas of the arc system. On the other hand, these deformations mark the beginning of uplift and termination of the arc, and the beginning of the eastward displacement of igneous activity. The 126 Ma movements may, thus, be related to the dynamic evolution of the arc rather than to the result of an externally imposed tectonic phase.

The late Cretaceous tectonic event (Peruvian phase, between 90 and 80 Ma), induced by the major plate reorganization in the southeast Pacific, as shown in Fig. 9, is prominent in the many parts of the Andean domain (Vicente et al. 1973; Coira et al. 1982; Mégard 1987), although in some segments it is not present (e.g. Godoy 1991) In northern Chile, this phase not only terminates the generally extensional tectonics of the previous arc systems but also initiates the slightly extensional to compressional conditions governing the active continental margin since the very late Cretaceous (see below).

The late Eocene change of plate-motion directions and velocities (well documented by the bend in the Hawaii-Emperor ridge) is recorded in the Andes as the Incaic phase. In the segment under study it produced strong transpressional deformations, consisting of folding in arc and backarc, and dextral strike slip restricted to the magmatic arc area. The Incaic compressional event was replaced by an Oligocene period of minor compressional stress and consequent isostatic relaxations with the formation of intramontaneous basins perhaps as a consequence of a decreased convergence rate and/or less effective plate coupling. For the Oligocene deformations no corresponding structures have been reported in other parts of the Andes; it may thus be interpreted as a local event.

Finally, the late Miocene Quechua and the Pliocene Diaguita phases, which again coincide with tectonic events in other parts of the world, interfere in the activity of the Miocene-Holocene arc, but they accelerate this activity rather than intercept it. They only cause an increase in the compressional strain regime (again up to the Jarrard strain class 7) and initiate the uparching of the Central Andes to their present height, as well as initiating the apparently continuously ongoing development of the Subandean foreland fold-and-thrust belt.

6.2 Development of the strain regime

Due to the changing conditions in plate convergence the structural development of the Central Andes described in the previous sections shows a wide range of different strain regimes. In order to obtain a more quantitative idea of the deformation history of the Central Andean segment, an attempt has been made to group the deformations into Jarrard's (1986) strain classes (Table 1). The strain regime of tectonic phases and of interphases is shown in Table 3 and Fig. 13. In order to show the relation between deformation and igneous activity. Fig. 13 also shows the frequency of isotope ages. Obviously, from the observed structures the strain regime for the tectonic phases is far better known than the one for the interphases. The classification of the interphases is thus somewhat uncertain. According to their strain classification it is possible to distinguish two main periods with contrasting types of tectonics: (1) between 200 and 90 Ma a general extensional to transtensional strain regime during tectonic phases and interphases, and (2) since 90 Ma a period of strong transpression/compression during tectonic phases and slight extension to compression in interphases.

The differences in tectonic style between the periods can be attributed to different plate configurations (Fig. 9). For period (1) the convergence obliqueness was always >45°, whereas for period (2) the angle was <45°.

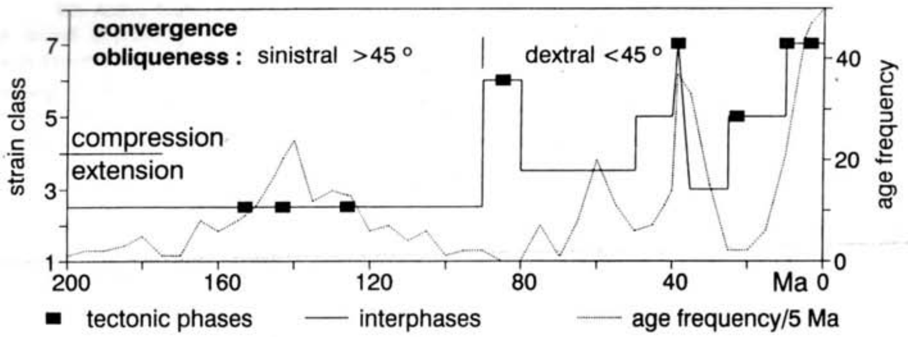

Fig. 13. The tectonic evolution of the north Chilean Andes in terms of Jarrard's (1986) strain classes and the frequency of isotope ages (5 Ma classes; data source same as in Fig. 2). Two periods with contrasting tectonics can be distiguished: (1) before 90 Ma with a sinistral convergence obliqueness of >45° and (2) after 90 Ma with a dextral convergence obliqueness of <45° to nearly trench-normal convergence. During period (1) deformations are (trans-)tensional in phases and interphases, while period (2) is characterized by (trans-)pression in phases and tectonic quiescence to extension in interphases

For period (1) arc-normal extension is expected for: (i) high convergence rates and/or a high degree of plate coupling, and also for (ii) low convergence rates and/or low plate coupling. In case (i), which should correspond to tectonic phases, extension should be produced according to the model outlined in Fig. 1 (normal stress is less than the hydrostatic stress at obliqueness >45°, Fig. 1). Case (i) can be applied to the tectonic phases of the Jurassic and early Cretaceous. Here, the existence of trench-linked strike-slip faults (e.g. the Atacama Fault Zone) implies that there was good coupling between the plates, and this, in turn, implies that extension was not the result of suduction rollback, very steep slab dip, and/or movement of the upper plate in the same direction as the subducting plate. Case (ii), which can be applied to the interphases, also led to crustal extension. The reason is that a decreasing convergence rate leads to a decoupling of the plates, which also operates in the direction of extensional strain. However, low convergence rates may be the reason for the lower tectonic activity during interphases.

For the period (2) the development of plate convergence rates and obliqueness is rather well constrained (Fig. 11). Tectonic phases can be correlated with times of increased plate convergence rate (Incaic, Quechua). It can be concluded that a high convergence rate leads to an increased coupling between the plates and, thus, to the observed structures of shortening. During the interphases the convergence rate, together with the horizontal stress, decreases, leading to a decoupling to some extent and thus to crustal extension. This effect has been described by Daly (1989) for Colombia where low angle faults in the forearc operated as reverse faults during periods of high convergence rates and as normal faults when convergence rates decreased.

Figure 13 also shows that there is no simple relationship between igneous activity and deformations in the magmatic arc. Some maxima in igneous activity can be correlated with deformational phases, while other phases are related to igneous quiescence; one maximum in igneous activity occurred during tectonic quiescence. Clearly related to maxima in isotope age frequency, and thus to increased convergence rates and plate coupling, are the late Jurassic-early Cretaceous phases, the Incaic phase and the Quechua events. In contrast to these phases, the mid-Cretaceous (Peruvian phase, 90-80 Ma) and late Oligocene (~23 Ma) deformations are more related to periods of magmatic quiescence, although they can be correlated to reorganizations of the plate system and/or a displacement of the magmatic arc. During both phases the centre of igneous activity had been offset to the east, during the Peruvian phase a complete plate reorganization took place in the southeast Pacific, and during the late Oligocene the Farallon-South America convergence rate started to increase and may thus have influenced the deformational regime. The 60 Ma maximum in igneous activity occurred during tectonic quiescence and this is consistent with the low convergence rate at that time.

Table 3. The development of strain classes in the Central Andes since the early Jurassic

Time	strain class	indication	strike-slip
Sinemurian - Oxfordian (200-153 Ma)	2-3	arc volcanism in subsiding region, arc-normal extension (dykes,layered gabbro), backarc basalts	?
Late Jurassic events(~153 and ~143 Ma): Araucanian Phase	2-3	arc-normal extension (dykes), graben formation	strong sinistral (Atacama Fault Zone)
Kimmeridgian - Barremian (153-126 Ma)	2-3	arc-normal extenison (e.g. dykes)	?
Early Cretaceous event (~126 Ma)	2-3	arc - normal extenison (e.g. dykes), beginning of alkaline backarc/foreland magmatism	strong sinistral (Atacama Fault Zone)
Aptian - Cenomanian (126-90 Ma)	2-3	arc volcanism in subsiding region, strong alkaline backarc/foreland magmatism	?
Peruvian Phase (90-80 Ma)	6	strong folding, thrusts	?
Late Campanian - early Eocene (80-48 Ma)	3-4	slight extension in the arc (calderas), partly marine backarc/foreland basin with alkaline magmatism	not present
Middle - Late Eocene (48-39 Ma)	4	increased arc uplift, continental sedimentation in backarc, no alkaline backarc magmatism	?
Incaic Phase (39-38 Ma)	7	thrusting and folding in arc and backarc	str. dextral (Precordilleran Fault S.)
E.- M. Oligocene (35-25 Ma)	3	basin formation (collaps structures)	(sinistral)
L. Oligocene - L. Miocene (25-10 Ma) (deformational event at ~23 Ma)	5	continued but gentle folding, reverse faults	(sinistral)
Quechua Phase (~10 Ma)	7	onset of very strong shortening in the backarc (fold and thrust belt), continued shortening in the arc	weak sinistral
Late Miocene - present (10-0 Ma), including Diaguita Phase (~4.5 Ma)	7	continued shortening in arc and backarc, some	weak sinistral

6.3 Magmatic arc tectonics

The geological record of the Andean segment between 21° and 25°S shows that especially the magmatic arc areas within the active continental margin were very sensitive to the prevailing strain regime, which was apparently expressed in the quantity and composition of the magmas produced as well as in the tectonic development. In comparison with the adjacent forearc and backarc areas, the strength of the magmatic arc is necessarily greatly reduced by the much higher heat flow and temperature level, and by the presence of liquid magmatic bodies at different levels in the crust, so that a concentration of the deformation can be expected here. Indeed, arc-parallel shear movements caused by oblique subduction ran longitudinally through the respective arcs at least during the Jurassic, early Cretaceous and Eocene-Oligocene. Special extensional and compressional tectonics within the arc area have also been described (Reutter and Scheuber 1988; Scheuber and Reutter 1992). It can now be added that the concentration of important tectonic events to the magmatic arc proves again that in this area the contemporaneous strain and its variations are well registered.

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