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Structural overprint of a late Paleozoic accretionary system in north-central Chile (34°-35°S) during post-accretional deformation

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ABSTRACT. In the Coastal Cordillera of central Chile a coherently preserved architecture of a late Paleozoic accretionary prism is exposed at 36°-35°S in close spatial association with a neighbouring area at 34°-35°S, where it is strongly modified by post-accretional processes. Syn- and post-accretional structures can be distinguished relatively easily in this region studying the deviations from the original architecture. South of 35°S a transitional contact between two major units is observed, which reflects a continuous change of the mode of accretion in the accretionary wedge before ~305 Ma: the structurally overlying metagreywacke of the Eastern Series exhibits structures typical of frontal accretion, *i.e.,* subvertical chevron folds of bedding planes with an axial-plane foliation S_1. With increasing finite strain structurally downwards, open F_2 folds develop associated with a S_2-foliation which becomes gradually flattened as it rotates into a subhorizontal orientation. S_2 is the penetrative transposition foliation in the structurally underlying Western Series. It affects the continent-derived metagreywacke series as well as metabasite intercalations of oceanic origin and was formed during basal accretion. This principal evolution of the accretionary system places firm constraints on the original architecture also in regions where it was destructed after accretion. Accretion ceased at ~225 Ma, when a major tectonic change from a convergent to an extensional/strike-slip regime occurred. Although the development of the margin in central Chile is largely characterized by extension during Mesozoic and Cenozoic times, two pronounced episodes involving shortening of the forearc particularly affected the Western Series north of 35°S: **1.** Expressions of strike-slip activity during Jurassic times involve local steepening of the originally flat S_2-foliation planes, local rotation of the stretching lineation L_2 into the N-S direction, tight upright folding of the S_2 foliation and refolding about steep axes with associated vertical cataclastic left-lateral shear zones. **2.** The left-lateral reverse Pichilemu-Vichuquén fault at the boundary between both units is a prominent brittle structure that formed at ~100 Ma concomitant with basin closure and acceleration of exhumation rates in the forearc. Similar contractional structures occur along the coast further north, where both units partly disappeared by subduction erosion most likely during these deformation episodes. The transition between nearly unaffected accretion systems in the south and disrupted and partly subducted ones in the north occurs at 35°S.

Keywords: Accretionary prism, Late Paleozoic, Frontal accretion, Basal accretion, Post-accretional deformation, Strike-slip, Reverse fault, Subduction erosion.

RESUMEN. Modificación estructural de un sistema acrecional del Paleozoico tardío en el centro-norte de Chile (34°-35°S), durante deformación posacrecional. En la Cordillera de la Costa de Chile, de 36° a 35°S, se encuentra expuesta la arquitectura coherentemente preservada de un prisma de acreción del Paleozoico tardío, en cercana vecindad a un área entre los 34° y 35°S, donde el mismo está fuertemente modificado por procesos postacrecionales. Estudiando las desviaciones de la arquitectura original, en esta región pueden ser perfectamente distinguidas estructuras sin- y post acrecionales. Al sur de los 35° se observa un contacto transicional entre dos unidades mayores, el cual refleja un cambio continuo en el modo de acreción de la cuña acrecional antes de ~305 Ma: las metagrauvacas estructuralmente suprayacentes de las series orientales muestran estructuras típicas de una acreción frontal, pliegues chevron subverticales de planos de estratificación con una foliación de plano axial S_1. Con el aumento de la deformación finita hacia su base, se desarrollan pliegues abiertos F_2 asociados con una foliación S_2, la cual se va tornando cada vez más achatada y subhorizontal. En las series occidentales estructuralmente subyacentes, S_2 es la foliación de transposición penetrativa que afecta a las metagrauvacas derivadas de un continente e intercalaciones de metabasitas de origen oceánico. Las estructuras fueron formadas durante acreción basal. Esta evolución principal del sistema acrecionario pone firmes restricciones sobre la arquitectura original, también en regiones donde éste fue destruido luego de la acreción. La acreción finalizó cerca de los 225 Ma, cuando ocurrió un cambio mayor en las condiciones geodinámicas hacia un régimen extensional. Aunque el desarrollo del margen en el centro de Chile está ampliamente caracterizado por extensión durante el Mesozoico y Cenozoico, dos episodios pronunciados que involucran acortamiento del antearco afectaron las series orientales al norte de 35°S: **1.** Las expresiones de actividad de deslizamiento de rumbo durante el Jurásico son planos empinados de foliación penetrativa S_2, rotación local de la lineación de estiramiento L_2 a una dirección norte-sur, plegamiento apretado vertical de la foliación principal y replegamiento alrededor de ejes empinados, con zonas de cizalla verticales, semifrágiles y sinistrales asociadas. **2.** La falla inversa Pichilemu-Vichuquén, levemente sinistral, en el límite entre ambas unidades, es una prominente estructura frágil formada hace cerca de 100 Ma, concomitante con el cierre de cuencas y aceleración de la exhumación en el antearco. Estructuras compresivas similares ocurren a lo largo de la costa hacia el norte, donde ambas unidades desaparecieron parcialmente por subducción, probablemente durante estos eventos de deformación. La transición entre sistemas acrecionales casi sin afectar y sistemas afectados, parcialmente subductados al norte, ocurre a los 35°S.

Palabras claves: Prisma de acreción, Paleozoico tardío, Acreción frontal, Acreción basal, Deformación posacrecional, Deslizamiento de rumbo, Falla inversa, Erosión por subducción.

1. Introduction

Accretionary systems at long-lived convergent continental margins such as those in the circum-Pacific region are time-restricted phenomena and are usually strongly disrupted by post-accretional deformation processes, when activity at these margins continued under changing plate geometries and kinematics. Hence it is a general problem to distinguish between syn- and post-accretional structures in order to provide better data for tectonic models describing the formation of accretionary systems and other plate configurations at active margins. Here we present an example from central Chile, where a nearly coherent accretionary wedge architecture occurs in close vicinity to one strongly modified by post-accretional processes.

The formation of the metamorphic basement within the Coastal Cordillera of Chile between 26° and 55°S marks the last increment of lateral growth of the continental margin of South America during late Paleozoic times in the north and Mesozoic times at its southernmost end. In the area between Pichilemu and Constitución (34°-35°30'S; Fig. 1) González-Bonorino (1971) and Aguirre *et al.* (1972) first proposed that this basement represents deep-seated parts of a palaeo-accretionary wedge within a paired metamorphic belt, which was active in late Paleozoic times (Hervé *et al.,* 1984). Whereas the architecture of this accretionary system was strongly overprinted in northern Chile during Mesozoic times, it is largely well preserved in central Chile, where its characteristics have recently been studied in detail (Glodny *et al.,* 2005, 2006; Willner, 2005; Willner *et al.,* 2005; Richter *et al.,* 2007). Traditionally two units of contrasting structural evolution are recognized in central Chile (Hervé *et al.,* 1984): The Western Series of mixed oceanic and continental rocks is regarded as a high pressure/low temperature unit, whereas the Eastern Series composed of metagreywackes only experienced a low pressure/high temperature metamorphic overprint related to intrusion of an arc batholith. The concept developed in this region was later adapted to the entire basement of the Chilean Coastal Cordillera between 26° and 55°S defining it as a collage of accretionary prisms of diverse origin and age (Hervé, 1988). Revisiting the original type

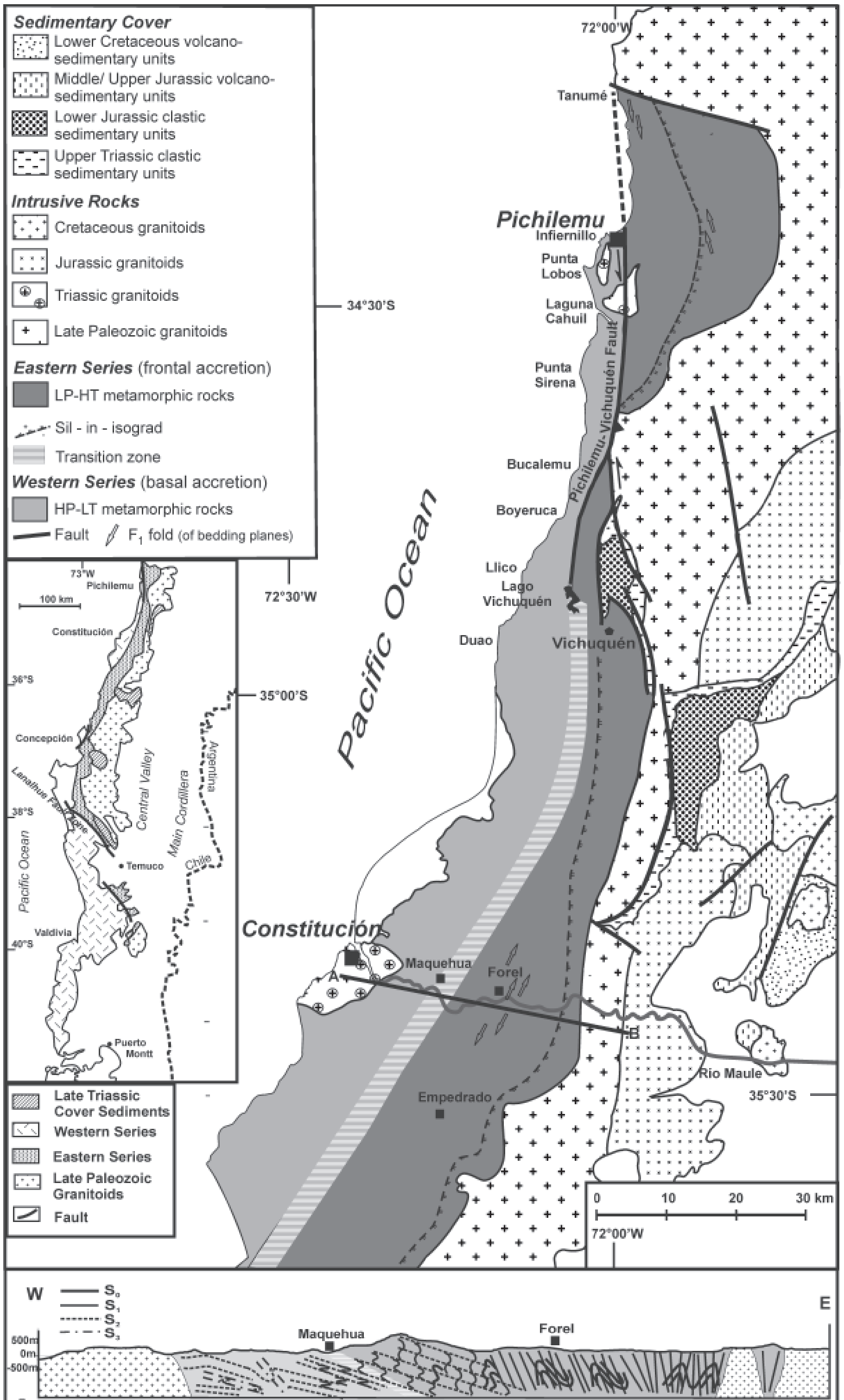

FIG. 1. Geological map of the Coastal Cordillera at Pichilemu and Constitución (34°-35°40'S) with cross section AB. Mapping information in this paper was also compiled from Godoy (1970), González-Bonorino (1971), Moraga (1981), Gana and Hervé (1983), Hervé *et al.* (1984), Klähn (1999) and Bravo Espinosa (2001).

area in north-central Chile (Fig. 1) it was shown that accretion activity was restricted to about 100 Myrs duration (319 Ma to 224 Ma) being exhumed at a rate of 0.2-0.6 mm/yr with erosion as the major agent of exhumation during continuous cyclic mass flow (Willner *et al.,* 2005). Both series have Carboniferous depositional ages (Willner *et al*., 2008). The Western Series was overprinted at high pressure greenschist facies apart from local blueschist facies conditions (350-420°C, 7-11 kbar), whereas the Eastern Series was contemporaneously overprinted at 3 kbar with progressively rising temperature of 400°-720°C towards a batholith in the east that intruded in the east representing the Late Palaeozoic magmatic arc (Willner, 2005). It was shown by Richter (1977) and Richter *et al.* (2007) that the two major units represent two different principal modes of accretion: initial frontal accretion in the Eastern Series that gradually changes to basal accretion (underplating to the base of the wedge) in the Western Series. Particularly, the traverse east of Constitución (35°30'S) was shown to represent a complete and coherent architecture of the accretionary system (Willner, 2005; Richter *et al.,* 2007).

Particularly in northern Chile, episodic destruction of the continental margin by shortening-related subduction erosion during Mesozoic times is supposed to have affected the metamorphic basement (*e.g.,* Scheuber *et al.,* 1994; Scheuber and González, 1999). Kay *et al.* (2005) proposed that subduction erosion affected the margin at 34°S during late Tertiary times. Glodny *et al.* (2006) argued that the entire margin of north-central Chile north of the Lanalhue fault at 38°S was affected by subduction erosion already around 270 Ma, *i.e.,* during the time of accretion. In this paper, we challenge these contrasting views and reassess the nature of the link between processes leading to destruction and shortening of the outermost margin and structures actually observed in the field. We consider subduction erosion as tectonic removal of continental forearc crust from the toe of the accretionary wedge.

The aim of this paper is to distinguish original accretionary structures and their orientations, from later structures that reorientated these original structures. The later structures are related to a stepwise destruction of the accretionary system and were caused by episodic events during continuing activity along the convergent margin and possibly by subduction erosion. We will show that the type region where the characteristics of the metamorphic basement of the Coastal Cordillera were originally described, also represents a transition between the largely coherent architecture exposed in south-central Chile and strongly disrupted and overprinted occurrences in north-central and northern Chile.

2. The original subduction system

2.1. The Eastern Series

The Eastern Series represents the structurally upper unit of the accretionary system in central Chile, which is entirely composed of metagreywacke and metapelite of turbiditic origin with well preserved sedimentary structures such as graded and convolute bedding, load casts and crossbedding. The characteristic structures are best observed in the eastern part of the entire outcrop area, but become continuously obliterated by increasing deformation intensity toward the west: an orthostratigraphic coherence at outcrop scale and upright to slightly west-vergent chevron folds of bedding planes on a meter to decameter scale with a pronounced axial-plane cleavage S_1 (Fig. 2A) F_1 fold axes strike NE-SW in the southern part of the study area and NNW-SSE in the northern part. This is consistent with a prominent change of strike of bedding/S_1-planes as well as of the transition zone to the Western Series (Fig. 1).

Along two prominent traverses from E to W, *i.e.,* the Río Maule transect (Godoy, 1970; Richter *et al.,* 2007) and along the abandoned railway line east of Pichilemu, it can be observed that a second foliation S_2 continuously evolves from a widely spaced foliation parallel to subhorizontal west-vergent open F_2-folds (Figs. 2A, B) with a penetrative transposition foliation S_2 that becomes increasingly flattened towards the west, where it becomes the dominant regional foliation in the Western Series. A SW-NE-trending stretching lineation L_2 is expressed on early formed quartz veins, which were transposed parallel to the subhorizontal S_2-planes. The D_2 fabrics indicate substantial vertical flattening and ductile thinning. The shortening axis rotated from a subhorizontal to a subvertical position from the eastern area where D_1 structures are dominant towards deeper structural levels in the west where D_2 becomes pervasive.

At shallow crustal levels the entire Eastern Series was intruded by the batholith of the Late Paleozoic magmatic arc and overprinted by a pervasive high temperature/low pressure metamorphism at about 300 Ma (Willner, 2005; Willner *et al.,* 2005). The batholith had its main intrusive pulse at that time, but its activity continued until ~250 Ma (Willner *et al.,* 2005). Statically grown porphyroblasts (biotite, andalusite, staurolite) in the metapsammopelitic rocks of the Eastern Series may locally be slightly rotated and stretched (Fig 2C). Stretching as evidenced by quartz-filled tension gashes in the porphyroblasts is generally in the direction of the regional stretching lineation L_2, which can be observed with similar orientation in the Eastern and Western Series. This means that during and after HT-metamorphism of the Eastern Series the structural development was continuously influenced by the same deformation field as during deformation of the Western Series. This observation is in line with previous Ar/Ar dating (Willner *et al.,* 2005) indicating that HT-metamorphism in the Eastern Series was contemporaneous with accretion and high-pressure metamorphism in the Western Series.

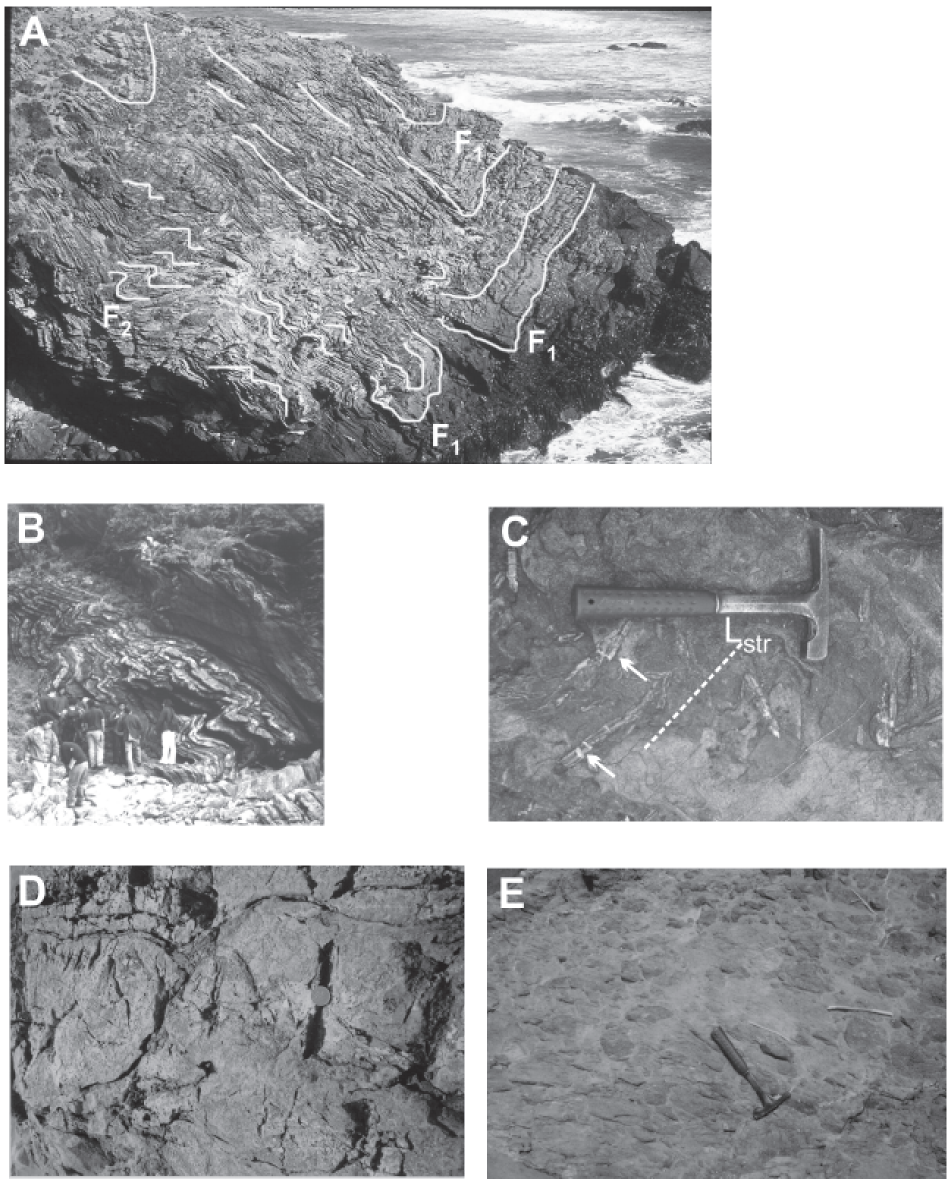

FIG. 2. **A.** subvertical F_1 chevron folds strongly overprinted by subhorizontal F_2- folds at the coast of Tanumé (34°13'S) in the Eastern Series; **B.** close view of subhorizontal F_2-folds near A; **C.** late-tectonic andalusite porphyroblasts stretched parallel to the regional stretching lineation with quartz-filled tension gashes (see arrows) at locality B; **D.** relic pillow lava fabric at Infiernillo (34°24´S) in greenschists of the Western Series; **E.** relic hyaloclastite fabric near locality D.

2.2. The Western Series

The Western Series, which structurally underlies the Eastern Series north of 35°S, is dominated by two contrasting lithotypes: predominant continental metapsammopelitic phyllites and intercalated lenses of oceanic origin (metabasite with occasionally associated metachert, Fe- or Mn-rich quartzite and serpentinite). In spite of their different rheological properties both major rock types show the same deformational overprint and the same sequence of fabric formation, although with differing intensity. Primary structures are mostly erased in the metapsammopelitic rocks, but are locally present in the intercalated metabasites as pillows and hyaloclastitic fabrics (Fig. 2D, E). Further relics are a transposed S_1-foliation, and abundant quartz veins of a first generation formed during prograde dissolution. Both are folded by rootless intrafolial isoclinal F_2 folds during formation of the predominant transposition foliation S_2 (Figs. 3A, B). Early formed planar structures as bedding, S_1-relics and prograde quartz veins are transposed into parallelism with S_2. Pressure solution and intracrystalline plasticity are regarded as the principal deformation mechanisms (Richter *et al.,* 2007). A stretching lineation L_2 marked by elongated quartz grains is associated with the S_2-foliation that generally plunges perpendicular to the strike of the foliation planes in the E-W direction (Fig. 4) except for a zone north of Lago Vichuquén, where it prominantly deviates to a N-S-direction. The S_2-transposition foliation becomes continuously more closely spaced in the transition zone between the Western and Eastern Series, where F_2-folds continuously become rootless or destroyed. Tightening of F_2 is associated with rotation of F_2 axial planes and S_2 into a shallowly east-dipping position. F_2-fold axes are consistently subparallel to the stretching lineation L_2 (Fig. 4). There is no evidence that this parallelism was caused by rotation during noncoaxial deformation. Where the S_2-transposition foliation is locally rotated away from its original subhorizontal position within the metapsammopelites, a further crenulation foliation S_3 is formed that may locally become the penetrative foliation (Fig. 3D). The corresponding stretching lineation L_3 is subparallel or at a small angle to L_2 (Fig. 4). The penetrative transposition foliations S_2 and S_3 are subhorizontal to moderately inclined south of 35°S, but generally steeply dipping north of 35°S (Fig.4).

During both deformation episodes omnipresent mineral phases like phengite, chlorite, epidote and Na-Ca-amphibole depict a preferred orientation that indicate peak metamorphic PT conditions at 350-420°C, 7-11 kbar (Willner, 2005). However, subsequently all fabrics recrystallized statically with retrograde growth at the rims of these minerals as evidenced, for instance by mimetic growth of oriented minerals in F_2-crenulation fold hinges (Willner, 2005). This proves that the penetrative fabrics were formed at maximum depth and during the earliest stage of exhumation. Post-D_2 quartz veins of a second generation crosscut the S_2-foliation and were deformed during the D_3 episode. A third generation of quartz veins developed as tension gashes (Fig. 3E) at the end of crystal growth and recrystallisation under static conditions during exhumation of the Western Series rocks. The tension gashes formed perpendicular to the stretching lineation and are the locally last deformation structure formed under the deformation field related to the accretion process.

2.3. Processes at the end of accretion

Three concomitant features mark the end of accretion and a major tectonic change. Upper Triassic sediments were unconformably deposited onto the Eastern Series and the late Paleozoic batholith (Thiele and Morel, 1981). According to Charrier (1979) tectonic development during the late Triassic and Jurassic was controlled by a simple morphology of locally subsiding basins and broad rising elevations that formed a NNW-SSE-trending en echelon pattern oblique to the present margin. The oldest zircon FT ages in the basement at 220 Ma (Willner *et al.,* 2005) coincide with the time of deposition of the oldest overlying clastic sediments (Corvalán, 1976). However, cooling under 280°C is regionally remarkably uniform at ~200 Ma coinciding with a pronounced drop of the exhumation rate from 0.2-0.6 mm/yr to 0.04-0.06 mm/yr as evidenced by fission track data of zircon and apatite between 232 and 98 Ma (Willner *et al.,* 2005). Similar tectonic conditions with a long-term crustal stability also prevailed in south-central Chile (Glodny *et al.,* 2006)

At 224 Ma the granite of Constitución intruded the Western Series (Willner *et al.,* 2005). This is an indication for the end of accretion, because it requires decoupling of the subducting and overriding plate. Similar granites have been described by

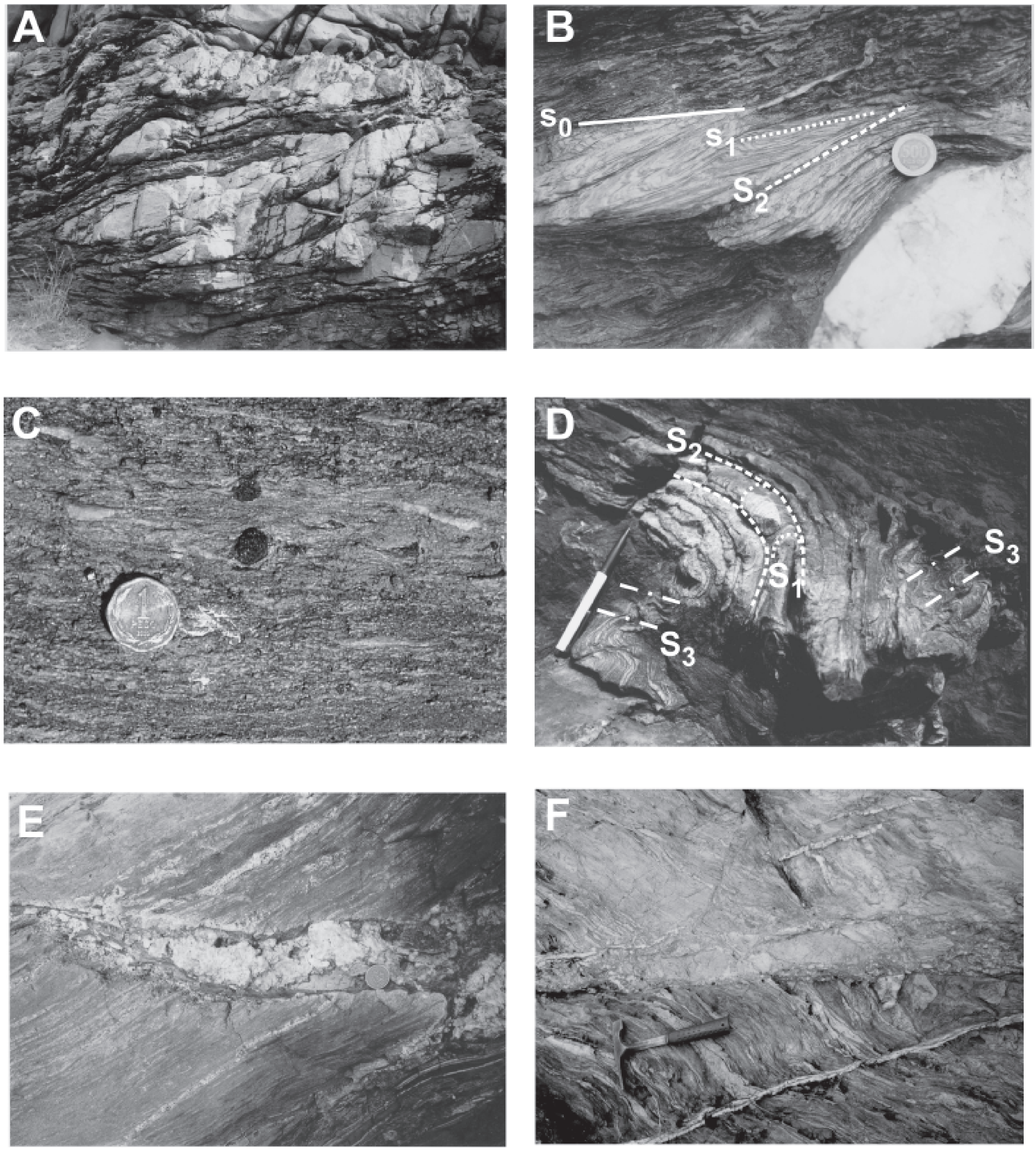

FIG. 3. **A-E.** Deformation features in the Western Series: **A.** subhorizontal isoclinal rootless intrafolial F_2-folds at Punta Lobos (34°26'S); **B.** subhorizontal S_1-and S_2-foliation transposed subparallel to relic bedding s_0 ; **C.** garnet σ clasts south of Punta Sirena (34°32'S) in deeply subducted garnet micaschist; **D.** s_2-crenulation foliation deformed by F_3-folds and s_3-foliation planes; **E.** quartz-filled tension gashes cross-cutting s_2-foliation as latest deformation during exhumation; also note the first generation of quartz veins transposed parallel to the penetrative foliation; **F.** post-accretional cataclastic sinistral shear zone at Infiernillo cliffs in Pichilemu (34°24'S).

Glodny *et al.* (2005), Vásquez and Franz (2008) and Irvine *et al.* (1988) in other parts of central Chile. According to Vásquez and Franz (2008), these granitoids are not related to the late Palaeozoic magmatic arc. A migration of the magmatic arc can be excluded. It is remarkable that apparently no structures can be related with the major tectonic change at the end of Triassic times.

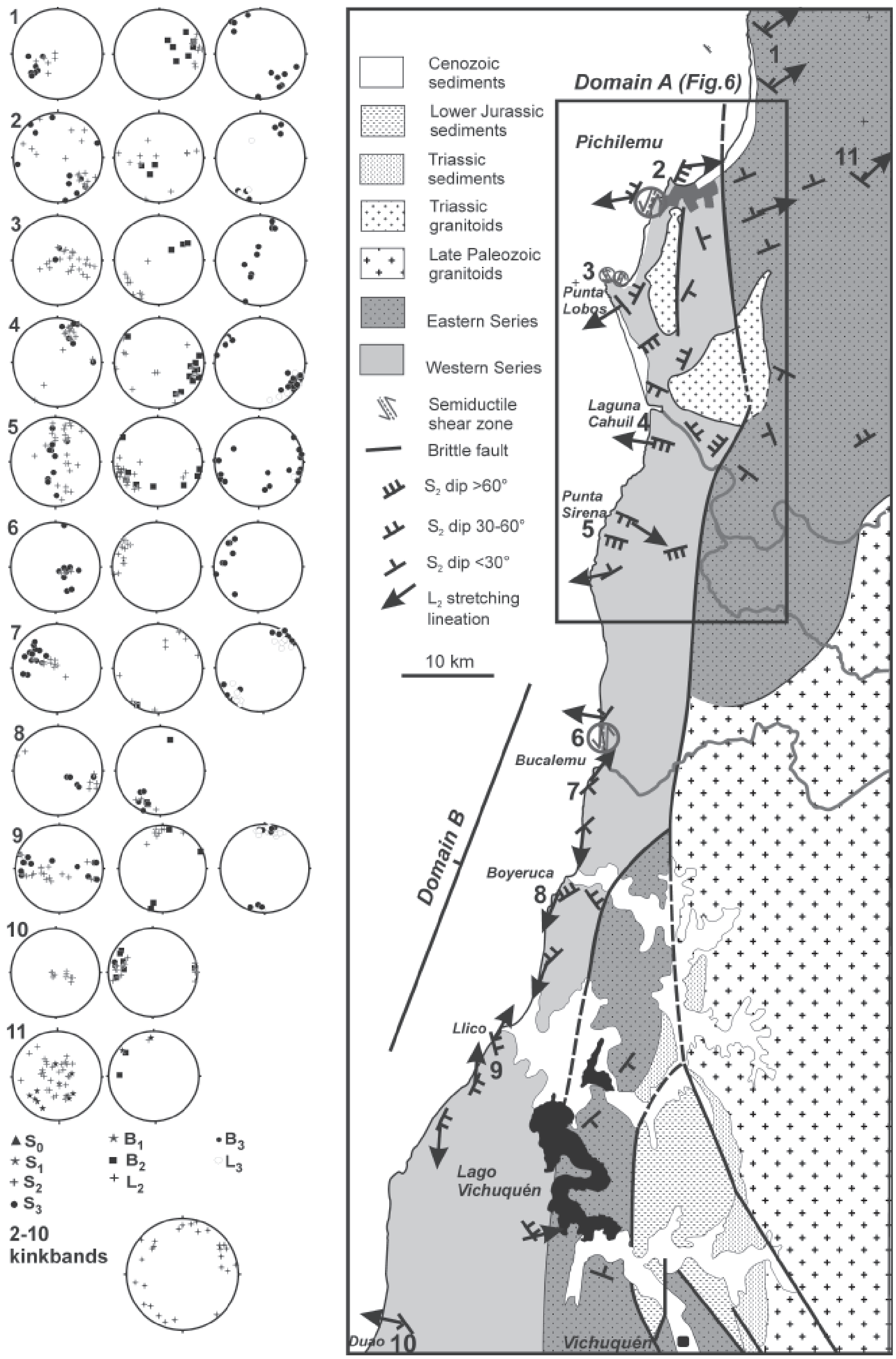

FIG. 4. **A.** Detail map and lower hemishere, equal area stereoplots showing the local orientation of mesoscopic structures in anomalous domains **A** and **B** within the Western Series north of 35°S. Note the cataclastic subvertical shear zones associated with these domains. Domains **A** and **B** represent areas with anomalous orientation of structures within the Western Series that do not correspond to their original orientation during accretion. Stereoplot of kink bands summarizes data from domains **A** and **B**.

3. Overprinting of the original system

3.1. Variation of finite strain data: a tool for small scale resolution

To estimate finite strain variation in rocks of the Western and Eastern Series, R_f/Φ analyses in metagreywackes and X-ray texture goniometry (XTG) on phyllosilicate-rich rocks were carried out. For comparison of the results of both methods the conventional octahedral shear strain γ_{oct} was determined. Both methods and their application are described in detail in Richter *et al.* (2007). Along the Río Maule traverse in the southern part of the study area, these authors documented a continuous structural transition between the Eastern and Western Series caused by continuous variation of the strain parameters. This finding was interpreted to reflect a gradual change of the mode of accretion. For this study we apply this approach also to the northern part of the study area (Fig. 5A) to get further hints for its partly discontinuous structure. The combination of these data with those in Richter *et al.* (2007) is given in figure 5B. In figures 5A and 5B the conventional octahedral shear strain, $\gamma_{oct.}$, has been plotted and contoured.

Phyllosilicate-rich rocks and metagreywackes show no differences in strain symmetry. The rather smooth westward increase in strain magnitude suggests a continuous transition from the Eastern into the Western Series for the entire southern part of the area south of Lago Vichuquén. The magnitude

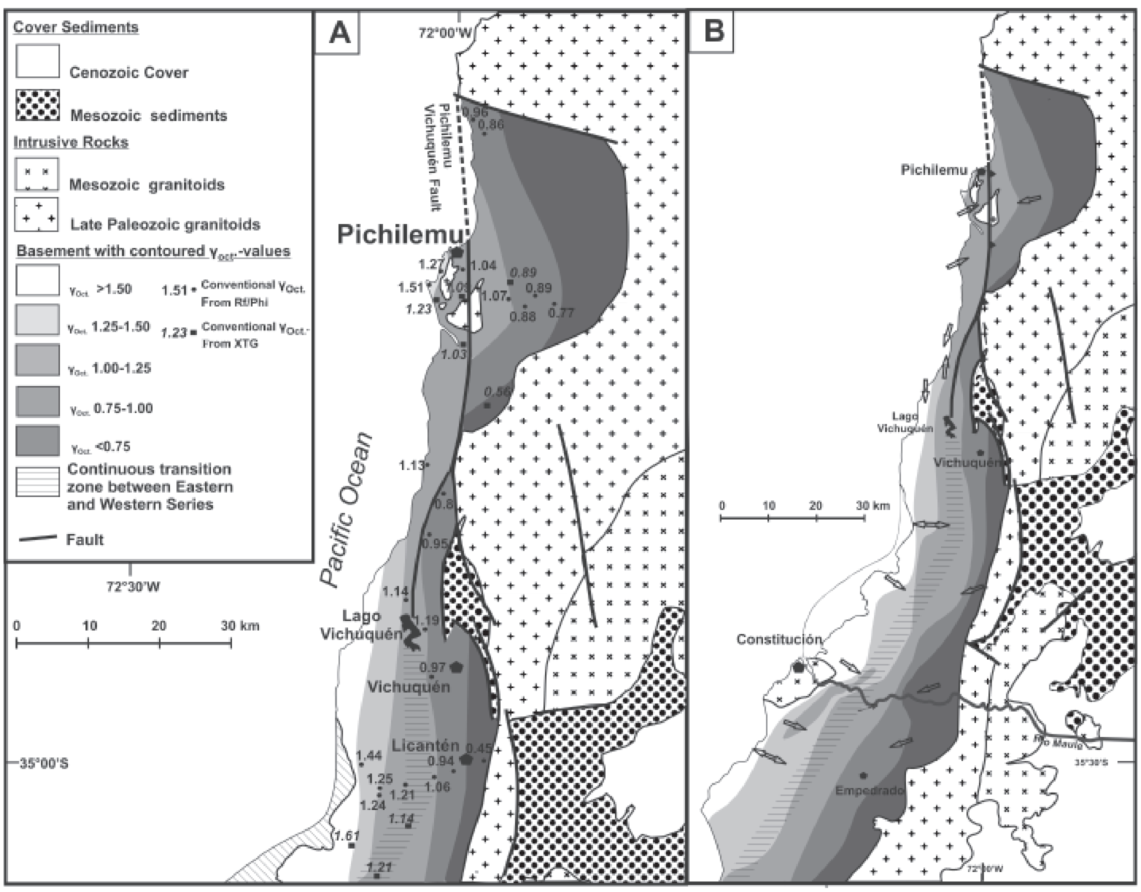

FIG. 5. **A.** Map showing values of the conventional octahedral shear strain, $\gamma_{oct.}$, as obtained from R_f/Φ and XTG measurements and contouring of their distribution for the northern part of the study area. Note the offset of contours by the Pichilemu-Vichuquén Fault; **B.** Map compilation including the data of Richter *et al.* (2007) showing: **1.** the contouring of the conventional octahedral shear strain, $\gamma_{oct.}$, for the entire study area and **2.** observed transport directions of local noncoaxial structures (arrows).

of strain progressively and gradually rises from the eastern part of the Eastern Series ($\gamma_{oct.}$ as low as 0.56) towards the Western Series at the coast ($\gamma_{oct.}$ values up to 1.61). Contours of $\gamma_{oct.}$ values are subparallel to the boundary between both units and the mean strike of the predominant foliation planes. A considerable change from a general NE-SW to a NNW-SSE direction again becomes conspicuous. A slight break in the strain distribution pattern by the Pichilemu-Vichuquén Fault in the northern part of the study area becomes apparent that can now be shown for the entire length of the fault between Pichilemu and Lago Vichuquén. However, west of the fault the number of data do not allow a good resolution.

The extensional direction derived from the strain analyses fits well in all cases with the stretching lineation measured in the field. Orientation of the stretching lineation L_2 does not change along traverses from the Eastern into the Western Series. The sense of local shear parallel to the stretching lineation within the S_2-foliation (derived from S-C relationships, σ-clasts and shear bands) is consistently top-to WSW in the Eastern Series in the entire study area. In contrast in the Western Series the shear sense is alternating top-to west and top-to east with the exception of the anomalous area north of Lago Vichuquén with N-S transport directions (domain B in Fig. 4).

3.2. Cataclastic processes during destruction of the accretionary wedge

The most striking characteristic of the study area is a prominent contrast in the structural setting of the Western Series north and south of 35°S which reflects different intensity of the deformational overprint after the end of accretion. Whereas in the entire Eastern and Western Series south of 35°S the accretionary structures largely occur in their original position, most effects of post-accretionary deformation are restricted to the Western Series north of 35°S. Deformational processes which caused these late deformational structures severely displaced the original orientation of the accretionary structures. Cataclastic deformation structures, observed only in the Western Series of the northwestern part of the study area, involve **1.** megascale tight subvertical folds of the predominant foliation; **2.** local subvertical kink bands in more pelitic schists; **3.** local cataclastic strike-slip shear zones, and **4.** megascale open folds with steep axes. For better resolution we distinguish two domains within the Western Series north of 35°S (Fig. 4): Domain A is mainly characterised by a steep dip of the principal foliation that originally formed horizontally as it is preserved in the southern study area. Domain B is also characterised by this subvertical predominant foliation, but additionally by a N-S-orientation of the principal stretching lineation, which deviates markedly from its normal E-W trend (see above).

South of 35°S the dominant transposition foliation in the Western Series is subhorizontal (Richter *et al.,* 2007). This can also be observed in the entire western part of the Eastern Series where S_2 becomes prominent (Fig. 4, areas 1, 11) as well as at Punta Lobos in the Western Series (Fig. 4, area 3). Local undulation of dip in opposite directions can be explained by open folding. Such a megascopic open fold is prominently exposed at Punta Lobos (Fig. 6). Widespread late post-accretionary upright open folding of the similarly predominantly subhorizontal foliation within the Western Series was widely recognized in south-central Chile at 40°S by Martin *et al.* (1999). These authors relate this phenomenon to an episode of post-Permian transpression. Yet in domains A and B the general dip of the penetrative foliation planes is mostly subvertical (Fig. 4; areas 2, 4, 5, 7, 8, 9). This may be explained by tightening of these late large scale folds with subhorizontal fold axes. Prominent exposed megascopic examples where such megafolds may be reconstructed by regional mapping of metabasite intercalations are tight megafolds southwest of Pichilemu and at Punta Sirena (Figs. 6, 7). The distribution of foliation poles in stereoplots (Fig. 4, areas 2, 5 and 9) also reflects such tight F_4-megafolds.

Furthermore, kink bands are randomly observed in more pelitic lithologies, but only within domains A and B. They are invariably steep (65°-80° dip; Fig. 4) and mostly conjugate. The predominant foliation within these up to 5 cm thick kink bands is always rotated antithetically with respect to the dip of the kink bands. This means that they formed during episodes of subhorizontal shortening. However, the distribution of their strike (Fig. 4) indicates that they were partly rotated into an E-W-strike by folding around steep axes by a further deformation event. Both the tight upright folding of the transposition planes and the kink bands require local subhorizontal shortening incompatible with the deformation field during basal accretion, where the last deformation structures after exhumation to upper crustal levels are represented by tension gashes.

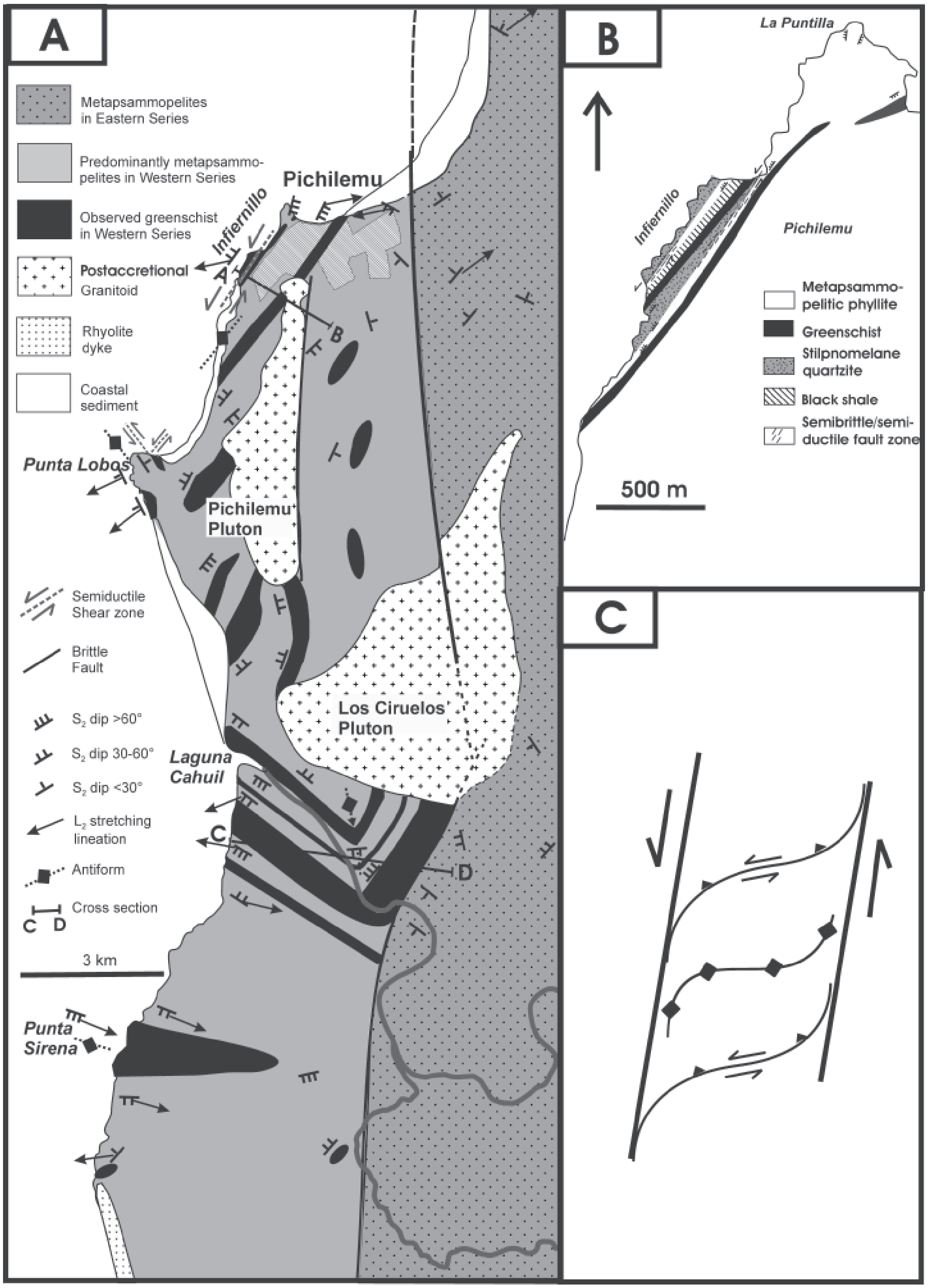

FIG. 6. **A.** Detail map of domain A showing mesoscopic structures using exposed greenschist as tracer horizons; **B.** Detail map of the area at Infiernillo west of Pichilemu affected by left-lateral cataclastic strike-slip zones; cross sections AB and CD are shown in Fig. 7; **C.** Schematic sketch of presumed mega-scale left-lateral strike-slip system active during formation of the Jurassic cataclastic structures. Earlier formed tight megascopic folds were refolded.

At three localities (Infiernillo cliffs of Pichilemu, cliffs east of Punta Lobos and along the coast north of Bucalemu; Fig. 4, 6) prominent subvertical tabular cataclastic shear zones are exposed that can be traced for about 200 m in outcrop. In the damage zone, within about 50 m width to either side of the discrete shear zones, minor cataclasite zones of dm-thickness are observed which cause a 'mélange'-like appearance in the country rocks (Fig. 3F). The cataclasites show a subhorizontal lineation expressed by the alignment of fractured quartz grains and the preferred orientation of mica and clay minerals that formed during cataclasis. The deformed S_2-foliation of the country rocks is generally subvertical and shows open folding around steep axes associated with movement along the semi-brittle shear zones. Prominent examples are steeply dipping decameter scale folds in stilpnomelane quartzite along the Infiernillo shear zone (Fig. 6A, B). Shearing is subparallel to the local strike of the S_2-foliation in the country rock. The strike slip shear zones mainly developed in metapsammopelites and in the vicinity of rocks with contrasting lithology/competence. The shear sense along the three exposed semi-brittle shear zones, depicted from local rotation of neighbouring S_2-planes and subvertical Riedel shears, is consistently left-lateral.

Unfortunately good outcrops only exist along the coast and it was so far impossible to find similar semi-brittle shear zones inland for reconstruction of a major strike-slip system. However, prominent folds with steep axes that are presumably related to strike slip zones can be observed or reconstructed indirectly. A large-scale fold with a steep axis can be observed along the road east of Cahuil. In this zone mapping of the greenschist (Fig. 6, 7) reveals refolding of the subvertically dipping predominant foliation. Also the megafold at Punta Sirena (Fig. 6) has an unusual E-W strike presumably caused by rotation during refolding around steep axes. Furthermore, the stretching lineation L_2 is rotated from a regional NE-SW direction, as observed in the Eastern Series, into directions around E-W. The entire eastern flank of the Cahuil megafold was later overthrust by the Eastern Series along the Pichilemu-Vichuquén Fault (Figs. 4, 6, 7).

In the same way the narrow zone of domain B with the unusual N-S strike of the stretching lineation L_2 (Fig. 4, 5, 6) can be explained by localized rotation of the subvertical predominant foliation planes into parallelism with a major strike-slip zone. Further east these structures are obliterated by late brittle thrusting of the Eastern Series over the Western Series.

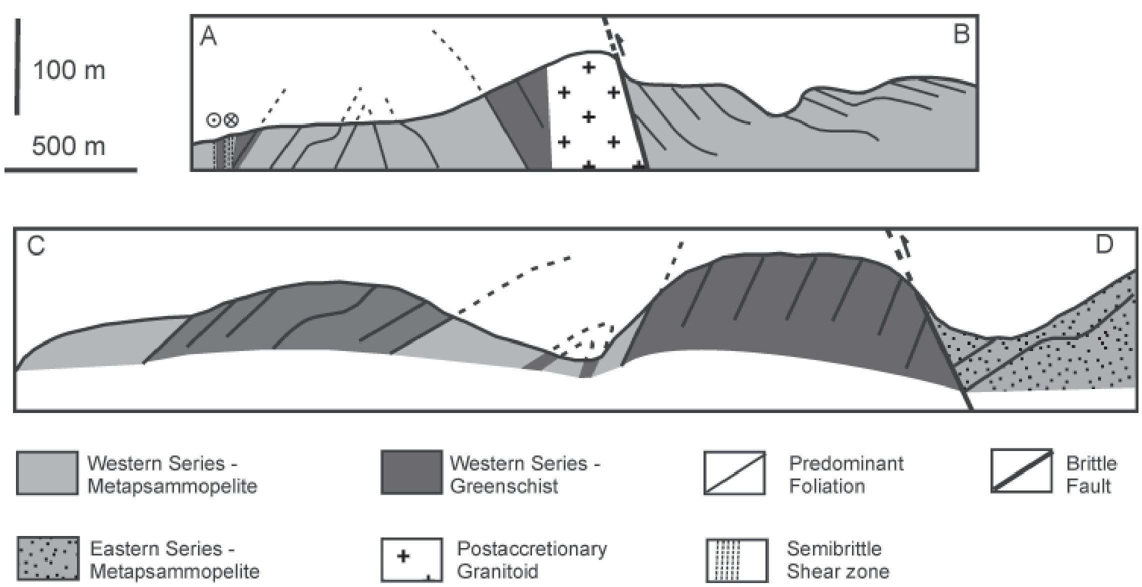

FIG. 7. Cross sections **A-B** and **C-D** in domain A (for locations see Fig.6) showing megascopic structures originated after the cease of accretion.

The described cataclastic structures may be best explained as being related to a megascale left-lateral strike-slip system of presumable N-S-strike (Fig. 6C) during a strike-slip episode with a subhorizontal maximum shortening axis oriented NW-SE. Early formed tight upright folds, kink bands and also minor shear zones were rotated into E-W and N-S directions, respectively. Both flanks of the mega-shear zone are not exposed, but might be submerged offshore or buried beneath the Pichilemu-Vichuquén Fault (see below).

3.3 The Pichilemu-Vichuquén Fault: brittle destruction processes

The Pichilemu-Vichuquén Fault (PVF) in the northern part of the study area (Figs.1, 4-8) was first shown by Hervé *et al.* (1984) as a prominent brittle structure which cuts isogrades produced during the high temperature metamorphic overprint of the Eastern Series (Fig.1) and which separates biotite-bearing schists of the Eastern Series from biotite-free phyllites of the Western Series. Earlier, Ernst (1975) referred to the PVF as the 'Coast Range Suture' prolonging this tectonic contact between both series along their entire boundary in central Chile and thus implying plate tectonic dimensions. However, the distribution of strain data (Fig. 5) shows that the fault only continues southward to Lago Vichuquén as it was already mapped by Moraga (1981). Hitting the contact with the late Paleozoic batholith, the PVF splits into three branches at its southern end: The eastern branch cuts into Triassic and Jurassic cover sediments showing a slight apparent left-lateral separation (Figs 1, 8). The intermediate branch cuts off the lowermost Triassic cover sediments and places Jurassic sedimentary rocks in direct contact with the metamorphic basement. The western branch, at the boundary between both series, cuts the strike of the predominant foliation, the megascale deformation pattern in the Western Series, produced during Jurassic times (Fig. 6), as well as the strain contour lines (Fig. 5). Left-lateral strike slip also becomes apparent by the displacement of the sillimanite-in isograde (Fig. 1) and possibly the strain contours (Fig. 5), although resolution of the latter is low. On the other hand, the PVF appears not to be fully continuous along its length, but presumably splits into two separate faults both starting within the Los Ciruelos granite pluton north of the village of Cahuil. Although boundaries of the pluton are difficult to map due to poor outcrop conditions, no major displacement by the fault becomes apparent. Cataclastic fabrics in the prolongation of the fault within the granite body suggests that it was affected by faulting (see below). The prominent difference of the strike of the PVF rather suggests two separate branches starting at the pluton. Parallel to the northern branch a repetition of the fault is observed further W, which cuts the eastern boundary of the Pichilemu granite pluton near the town of Pichilemu (Figs. 1, 6-8).

To obtain further information about the nature of the fault, we carried out a fault-slip analysis at six localities along the PVF (Fig. 8). The cataclastic rocks in the vicinity of the main trace of the Pichilemu-Vichuquén fault have a rubbly to fragmental appearance and show numerous mesoscopic brittle faults. The fault planes are characterized by anastomosing clayey gouge layers with thin zones of cataclasite, breccia and hematite-clay-coated fractured rock. Bleaching and alteration of intact rock occurs in the vicinity of faults. Weakly oriented phacoid-shaped tectonic slivers of country rock within the fault zone are in the centimetre to decimetre scale. The fault-surfaces contain Riedel shears which caused lunate and crescentric structures at their intersections with the fault plane. In sections parallel to the striation and perpendicular to the fault plane the Riedel surfaces are characterized by fine seams of greyish-brown material. In addition to the Riedel planes, linear fibre growth features formed in dilatant areas of sliding fault blocks and extension-rack arrays occur.

To evaluate the kinematics of the PVF the orientation of primary and secondary fault and foliation planes, plunging directions of striations, and the sense of relative displacement on these planes were mapped in order to determine principal strain axes (Marrett and Allmendinger, 1990). The scale of observation was usually held small (*i.e.,* outcrop scale). The direction and sense of shear on these surfaces can be deduced from the orientation of associated fibres and Riedel shear planes. The displacement of the measured fault planes was generally in the centimetre to decimetre range. The main argument for relating these minor faults to the kinematic evolution of the Pichilemu-Vichuquén fault is their spatial relationship to the trace of the main fault plane. Away from the main trace

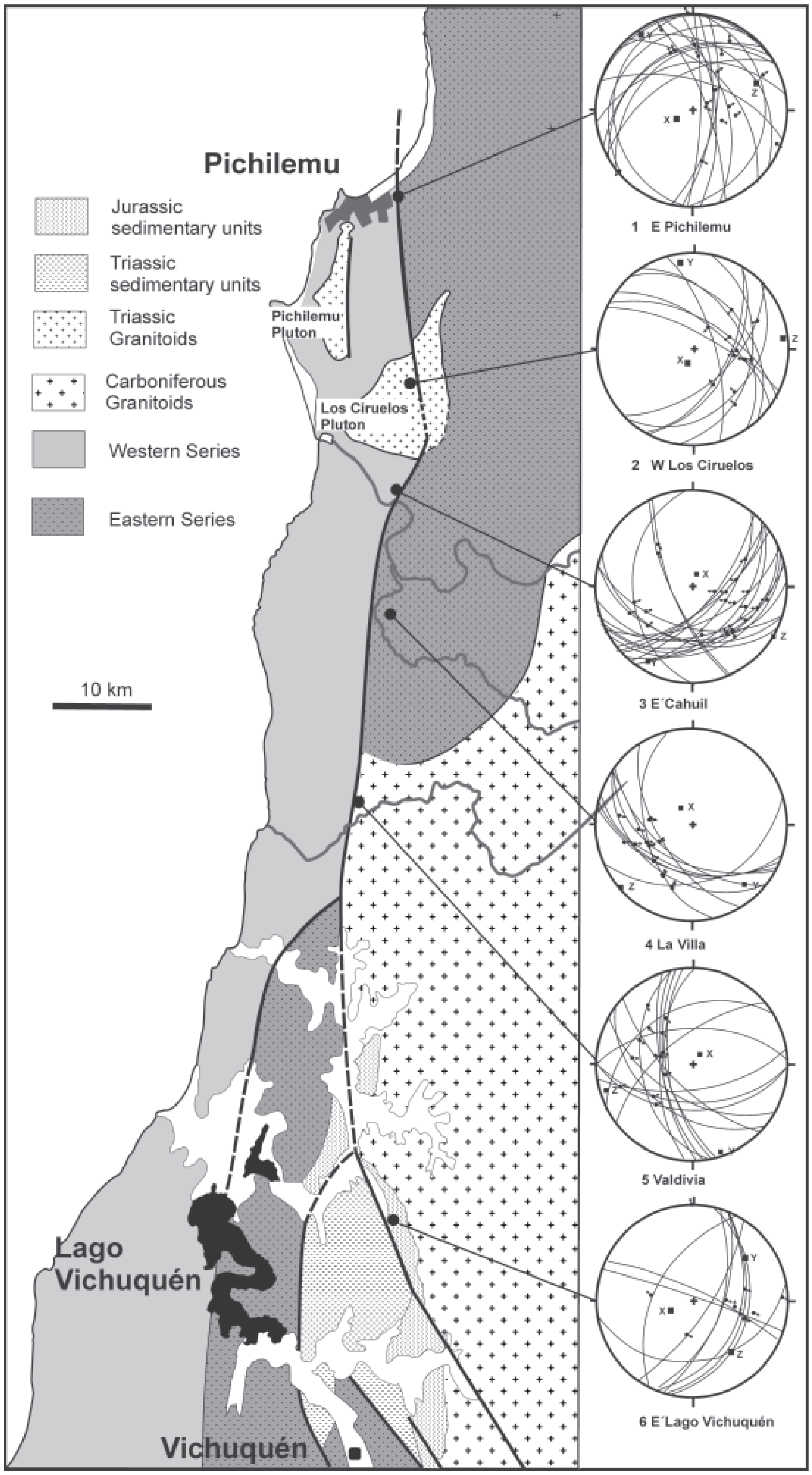

FIG. 8. Detail map of the Pichilemu-Vichuquén Fault with kinematic analyses of minor faults along the principal fault. Lower hemisphere, equal area stereograms show the fault surfaces and striae as well as the calculated principal strain axes. Note the splitting of the fault into three branches at its southern termination.

of the Pichilemu-Vichuquén fault usually no minor fault planes were observed. Hence the increasing number of secondary faults in the vicinity of the Pichilemu-Vichuquén fault is thought to imply a genetic link between the minor faults and the PVF. A simple method has been used to determine the principal strain axes from these crosscutting faults and associated slickensides (program 'Fault Kinematics' written by R. Allmendinger). This method graphically constructs the principal incremental shortening and extension axes for a given population of faults. Each pair of axes lies in the movement plane of the fault (*i.e.,* a plane perpendicular to the fault plane that contains the unit vector parallel to the direction of accumulated slip, and the normal vector to the fault plane). Furthermore, each pair of axes makes angles of 45° with each of both vectors. For distinguishing between the shortening and extension axes, information on the relative sense of slip is needed. Since the method converts the measurements into a fault-plane solution, the kinematic axes of a fault only portray a different and visually more convenient presentation of the original data. Bingham distribution statistics for axial data were used to optimize clusters of kinematic axes of a fault array (Mardia, 1972).

Riedel structures, fibres and extension cracks indicate consistent up-dip displacements on the minor fault planes. The consistently subhorizontal shortening (Z) axes and subvertical extension (X) axes indicate E-W to SE-NW reverse faulting. Hence the resulting deformation field completely differs from the one during formation of the accretionary structures. At locations 1, 2, 3, and 5 the Z axes are subnormal to the trace of the fault, whereas their oblique orientations at locations 4 and 6 might be due to some local rotation during strike-slip movements. Although the main fault is nowhere clearly exposed we infer that the eastern block (Eastern Series, the batholith, and the oldest cover sediments) is thrust-over the western block along a steeply E-dipping main fault plane (Fig. 7). Although the maximum vertical displacement can only be estimated not to have exceeded 3-4 km, the PVF is an expression of a regionally important contractional episode.

4. Discussion and Conclusions

4.1. The accretionary system

The two main structural units of the metamorphic basement of the Chilean Coastal Cordillera that may be traced over entire central Chile (Hervé, 1988) are fundamental features of a deep-seated accretionary system. Following the flow-field concept of Freehan and Brandon (1999) and Ring *et al.* (1999) and analogue experiments of Glodny *et al.* (2005), Richter *et al.* (2007) interpreted the structural characteristics of the Eastern Series rocks as frontally accreted sediments. Frontal accretion represents one of the two principal end members of accretion modes which is characterized by subhorizontal shortening and largely subhorizontal initial particle flow. This original architecture is preserved north and south of 35°S. Changes of the strike of F_1-fold axes and S_1-foliation are interpreted as an original change of the strike of the accretionary system.

Within the Western Series, the origin of the subhorizontal S_2-foliation during ductile thinning at depth is thought to result from underplating of material to the base of the wedge. The observed structures formed by basal accretion following the flow-field concept of Freehan and Brandon (1999) and Ring *et al.* (1999) and analogue experiments of Glodny *et al.* (2005). Basal accretion is characterised by subvertical shortening and a mainly subvertical particle flow path. Because both lithotypes of the Western Series have a similar structural inventory, tectonic intermingling of oceanic and continental rocks must have occurred during an early stage of subduction prior to basal accretion.

According to Willner *et al.* (2005) maximum burial of the accreted rocks of the Western Series was reached at 292-305 Ma at the same time when the bulk of the arc batholith intruded into the Eastern Series at around 300 Ma causing high temperature/ low pressure metamorphism that statically overprinted the high level accretionary prism architecture. Thus a truly contemporaneous paired metamorphic belt originated in Central Chile. The change of the mode of accretion must have occurred before that time at ~305 Ma. The beginning of accretion processes was slightly before 320 Ma as indicated by exotic local garnet-bearing schist in the Western Series at Punta Sirena exhibiting maximal PT-conditions of 10-15 kbar, >600°C, an anticlockwise PT-path and the oldest (retrograde) metamorphic ages (Ar/Ar; phengite) of 320 Ma (Willner, 2005; Willner *et al.,* 2005).

An originally continuous transition between the structurally overlying frontally accreted rocks (similar to the Eastern Series) and the structurally underlying basally accreted rocks (similar to the

Western Series) can be assumed as a fundamental feature of the metamorphic basement along the entire Chilean coastal Cordillera between 26° and 55°S irrespective of the depositional or metamorphic age of the accretionary systems. However, this transition was clearly demonstrated at two localities only: in the Constitución area (35°30'S) by Richter *et al.* (2007) and in the Chonos Archipelago (43°S) by Davidson *et al.* (1987). All other basement complexes are isolated and exhibit either structures typical of frontal accretion or basal accretion. For instance, structures similar to those of the Eastern Series were observed in Southern Chile *e.g.,* in the Eastern Andean Metamorphic Complex or the Madre de Dios Accretionary Complex, structures equivalent to those of the Western Series in the Diego de Almagro Metamorphic Complex (Hervé *et al.,* 2000). Hence it is of importance to unravel structures related to postaccretional processes that isolated these partial metamorphic complexes. Some of these structures are overprinting the accretionary complexes themselves during their exhumation.

Based on the consistent orientation of underplating related stretching lineations in the lowermost parts of the Eastern Series and within the Western series, as well as associated shear-sense indicators in the lower part of the accretionary wedge (Fig. 5B), we propose that there was a relatively high degree of coupling between the subducting and the overriding plate. Due to the relatively high degree of plate coupling the direction of subduction of the oceanic plate may be deduced from the mean orientation of the stretching lineations. Subduction was mainly from westerly directions with neglegible oblique components, from WNW south of 35°S to WSW north of 35°S. It is notable that the strike (1) of the F_1-folds in the Eastern Series, (2) of the transition zone between the series, (3) of the penetrative foliation, and (4) of the magmatic arc is perpendicular to these directions. These relationships can be regarded as primary in the entire study area.

4.2. The Jurassic post-accretion development

The orientation of the subhorizontal maximum shortening axis of the cataclastic phenomena in the Western Series north of 35°S strongly deviates from that during accretion in the Western Series. Therefore the cataclastic phenomena are unrelated to the accretion process and are thought to relate to a deformation episode which severely destroyed the original structure of the accretionary system. However, they are confined to the narrow zones of domains A and B only.

Some considerations concerning the age of the cataclastic phenomena are possible: the temperature during formation of the cataclastic structures has to be below 280°C, which is the annealing temperature of fission tracks in zircon. Cooling of the rocks of the study area below the zircon annealing temperature was dated at 206-218 Ma in the study area (Willner *et al.,* 2005) giving an upper age limit for the cataclastic deformation. On the other hand, the local semi-brittle shear zones are cut by undeformed basalt and rhyolite dykes. A rhyolite dyke in the study area was dated at 138 Ma (Willner *et al.,* 2005) consistent with Jurassic to Lower Cretaceous ages of the widespread bimodal magmatism in the forearc further north (Irvine *et al.,* 1988). Hence, the cataclastic deformation episode is largely confined to Jurassic times. Similar semi-brittle strike-slip zones of considerable size cross-cut by Jurassic dykes are widely observed further north along the coast of north-central Chile (Rebolledo and Charrier, 1997; Irvine *et al.,* 1988). Summarizing the cataclastic structures may be best explained as related to a left-lateral strike-slip system (Fig. 6C) formed during a Jurassic time-restricted episode of strike-slip movement. Most likely this represents the southernmost occurrence of similar phenomena widespread in northern Chile during Jurassic times. Left-lateral strike-slip during Jurassic times, causing stretching of the outermost continental margin, becomes prominent in northern Chile known as the Atacama fault system (*e.g.,* Scheuber *et al.,* 1994; Scheuber and González, 1999). On the other hand, the strike-slip system may have commenced during late Triassic times and thus could be related to the marked tectonic change throughout central Chile, which involved basin formation in the former accretionary wedge and granitoid intrusion into the Western Series. Yet granitoid intrusion into the Western Series involves plate decoupling. A marked change in the tectonic setting from a convergent to an extensional regime with a characteristic accompanying magma productivity (as observed in Chile) was recently studied by numerical modeling (Gorczyk *et al.,* 2007). Their results show that the change from a high degree of plate coupling during accretion to plate decoupling during slab retreat was mainly controlled by the convergence rate.

4.3. Cretaceous shortening episode

The PVF represents a late brittle reverse fault system with a minor left lateral component. It must be younger than Jurassic because it cuts the Jurassic sediments. Willner *et al.* (2005) associated this young shortening event with an episodic acceleration of cooling and hence exhumation as deduced from the interpretation of apatite fission track ages (80-113 Ma) and modeling of track lengths. Bravo Espinosa (2001) proposed the closure of Mesozoic intra-arc basins in the area by mid-Cretaceous times. Arancibia (2004) dated ductile reverse shearing along the prominent Silla del Gobernador shear zone further north (32°S) at 109±11 Ma (Ar/Ar; white mica grains). Due to widespread apatite fission track ages in north-central Chile around ~100 Ma a mid-Cretaceous shortening event, responsible for the closure of Mesozoic basins and associated with an increased erosion rate, is now widely accepted (*e.g.,* Parada *et al.,* 2005). Thus, the mid-Cretaceous shortening episode affected a wider part of the forearc causing closure of the Mesozoic basins and acceleration of exhumation (Willner *et al.,* 2005; Belmar *et al.,* 2004). Accelerated exhumation must be due to enhanced erosion, which was probably caused by crustal thickening and the associated development of topography.

4.4. The possible role of subduction erosion

'Subduction erosion' as a mechanism of subduction of continental crust is frequently proposed in northern, but also in central Chile to explain missing structures beyond the present coastline (*e.g.,* Glodny *et al.,* 2006; Kay *et al.,* 2005). Only at 35°30´S the entire width of the exposed late Paleozoic accretionary wedge onshore and its extension to about 50 km offshore allows to reconstruct a coherent model for the convergent margin during late Paleozoic times (Willner, 2005). This contrasts to the suggestion of Glodny *et al.* (2006) that north of the Lanalhue Fault Zone at 38°S (Fig. 1, inset map) the accretionary wedge was shortened by subduction erosion during late Paleozoic times, because the width of the accretionary wedge doubles south of the fault. Yet no structures can be related to this proposed omission of the continental margin and accretion was definitely continuing in the north during the proposed time of the subduction erosion during Permian times (Willner *et al.,* 2005). Furthermore, magmatic activity in the late Paleozoic arc continued. We argue that the Lanalhue Fault Zone can be much better explained as a transform fault between two segments of contrasting slab geometry during formation of the Late Paleozoic accretionary systems.

However, north of 35°S the late Paleozoic forearc becomes narrower and nearly disappears between 34° and 30°S, where the late Paleozoic arc is directly exposed at the coast. Kay *et al.* (2005) pointed to this effect and proposed a latest Tertiary time for the observed omission of the forearc to explain eastward migration of the magmatic arc at that time, however, without presenting corresponding structures in the forearc. In contrast, we propose that this effect must rather be related to the two episodes of strike-slip faulting and shortening, because distribution of their structures coincides with the area of presumed cut-off of the fore-arc. The Jurassic episode of strike-slip faulting did apparently not involve any crustal thickening. On the one hand, considerable acceleration of exhumation was proposed by Willner *et al.* (2005) for the study area for the mid-Cretaceous event suggesting some crustal thickening. This shortening episode seems to have affected the entire forearc at least up to 30°S (Arancibia, 2004; Parada *et al.,* 2005). On the other hand, no marked crustal thickening evidently occurred in the forearc since latest Tertiary times. The last marine sediments overlying the metamorphic basement in the study area at its northernmost end, the Miocene Navidad Formation, was merely uplifted by ~100-200 m at the coast (Encinas *et al.,* 2006). Evidently deformation and shortening during the latest Andean orogeny was rather confined to the magmatic arc (Kay *et al.,* 2005) and the eastern foreland leaving the forearc in the Coastal Cordillera as a rigid block or ram. Hence it is unlikely that subduction erosion in the fore-arc occurred as late as the latest Andean orogeny.

5. Summary

The basement area in the Chilean Coastal Cordillera between Pichilemu and Constitución represents an ideal type region, where the development of the late Paleozoic accretionary wedge can be studied. Structures related to a strike-slip and a later shortening event in the forearc during Mesozoic times are exposed in the northwestern part of the area providing clues to the type of destruction of the accretionary system. These destructive events made any reconstructions of the original late Paleozoic accretionary wedges so far difficult along the coast of north-central and northern Chile north of 35°S.

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APPENDIX

SUMMARY OF STRAIN DATA.

Sample	x-direction	y-direction	z-direction	Sx	Sy	Sz	Rxy	Rxz	Ryz	γ_{oct},
CH-02-51	292°/16°	26°/14°	156°/68°	2	0.8	0.6	2.51	3.35	1.34	1.25
CH-02-52	329°/39°	100°/39°	224°/28°	2.04	0.97	0.51	2.11	4.04	1.91	1.45
CH-02-56	93°/13°	01°/14°(-Y)	223°/70°	1.29	0.7	0.47	1.84	2.77	1.51	0.96
CH-02-67	350°/18°	78°/24°	216°/60°	1.76	1.22	0.44	1.44	4	2.78	1.51
CH-02-70	230°/03°	332°/210°	131°/68°	1.88	0.77	0.7	2.44	2.71	1.11	1.03
CH-02-84	213°/15°	304°/02°	36°/76°	1.27	0.58	0.43	2.06	2.72	1.33	0.96
CH-02-85	288°/05°	198°/06°	45°/83°	1.35	0.8	0.53	1.68	2.56	1.52	0.86
CH-02-91	336°/23°	234°/28°(-Y)	100°/52°	1.77	0.66	0.62	2.68	2.85	1.06	1.14
CH-04-132	-	-	-	1.82	0.72	0.53	2.54	3.41	1.34	1.28
CH-04-133	195°/05°	290°/51°	100°/39°	1.18	0.72	0.5	1.64	2.36	1.44	0.77
CH-04-134	53°/01°	145°/23°	319°/50°	1.66	0.95	0.63	1.74	2.65	1.52	0.9
CH-04-135	35°/34°	300°/07°	199°/54°(-Z)	1.7	0.89	0.66	1.9	2.58	1.36	0.89
CH-04-136	304°/24°	196°/34°	60°/47°(-Z)	1.7	1.06	0.55	1.6	3.07	1.92	1.08
CH-04-138	-	-	-	1.76	0.71	0.61	2.47	2.88	1.16	1.09
CH-04-139	-	-	-	1.2	0.82	0.57	1.61	1.71	1.44	0.56
CH-04-140	308°/18°	212°/21°	75°/62°(-Z)	1.66	0.88	0.56	1.88	2.97	1.58	1.03
CH-04-142	254°/31°	147°/26	24°/48°	1.27	0.86	0.49	1.47	2.62	1.78	0.89
CH-04-143	25°/20°	113°/02°	212°/68°	2.05	0.74	0.66	2.76	3.13	1.14	1.23
CH-04-144	-	-	-	1.45	0.72	0.64	2.02	2.28	1.13	0.8
CH-04-146	25°/20°	113°/02°	212°/68°	1.79	0.98	0.51	2.43	2.75	1.93	1.14
CH-04-150	102°/06°	191°/01°	289°/84°	1.62	1.08	0.57	1.49	2.82	1.89	0.98
CH-04-151	56°/03°	147°/30°	320°/60°	1.83	0.74	0.62	2.48	2.95	1.19	1.12
CH-04-212	106°/02°	16°/02°	262°/88° (-Z)	1.67	1.19	0.5	1.4	3.32	2.37	1.22
CH-04-215	273°/09°	183°/07°	50°/79°(-Z)	2.38	0.68	0.61	3.49	3.88	1.11	1.61
CH-04-216	130°/04°	222°/22°	38°/68°(-Z)	1.95	0.8	0.64	2.43	3.06	1.26	1.14
CH-04-217	104°/25°	205°/21°	329°/55°	1.96	0.9	0.57	2.19	3.47	1.58	1.25
CH-04-218	301°/34°	207°/08°	102°/54°(-Z)	2.03	0.75	0.66	2.7	3.1	1.15	1.21
CH-04-219	296°/05°	213°/42°	31°/48°	1.76	0.98	0.58	1.79	3.06	1.71	1.07
CH-04-220	68°/02°	158°/20°	325°/74°	1.76	0.86	0.66	2.04	2.69	1.32	0.95
CH-04-221	65°/62°	165°/08°	258°/27°	1.15	0.99	0.68	1.17	1.69	1.45	0.46