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Transpressive deformation in the southwestern part of the Sierra de San Luis (Sierras Pampeanas, Argentina)

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Abstract — In the southwestern part of the Sierra de San Luis, clastic sediments of the Phyllite Group are assigned to the Late Precambrian–Early Cambrian interval and contain acid meta-mamatic dykes. Deposits of the Micaschist Group are interpreted as deeper crustal equivalents. Lower Ordovician intrusions of the Bemberg and Las Verbenas Tonalites, as well as the Lower Devonian La Escalerilla Granite pluton, led to a thermal overprint in the Phyllite Group. A first deformation, pegmatitic injections, and amphibolite facies metamorphism in the Micaschist Group are of Famatinian (Ordovician) age. Post-Famatinian (Devonian) ~WNW–ESE compression affected all units under greenschist facies metamorphism, which locally reached amphibolite facies conditions, and is the second event in the Micaschist Group. Mostly sinistral, ductile shear zones within the granite, Las Verbenas Tonalite, and parts of the Phyllite Group were formed together with folds in the meta-clastic successions and an eastern mylonite zone along which the Micaschist Group was obliquely thrust northwestwards over the granite. They are related to the sinuous bending of the granite under sinistral transpression which probably was an important mechanism in this part of the sierra. Possible implications with respect to the collision of the Precordillera (Cuyania) Terrane are briefly discussed. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

In northwest Argentina, the basement complex of the Sierras Pampeanas underwent a complex tectonic, magmatic, and metamorphic history during Precambrian and Early Paleozoic times (e.g. Aceñolaza & Toselli, 1976; Aceñolaza *et al.*, 1978; Miller, 1984; Ramos, 1988; Rapela, *et al.*, 1992a,b; Ramos *et al.*, 1996). The half-horst structure of the Sierra (Grande) de San Luis is located in the southern part of the metamorphic complex (Fig. 1) and was lifted to a maximum elevation of more than 2000 m above sea level during the Andean (Late Tertiary to Quaternary) compression.

Mostly based on the type of metamorphism and distribution of granitoids, Caminos (1973, 1979) and Dalla Salda (1987) separated the Sierras Pampeanas basement into "Western and Eastern Sierras Pampeanas". The Sierra de San Luis is part of the latter and consists of ~NNE–SSW striking strips of the Phyllite Group and Micaschist Group (Fig. 2) within widely distributed injected micaschists, gneisses, and migmatites (e.g. Ortiz Suárez *et al.*, 1992). Isolated lenses of mafic to ultramafic rocks with granulites occur in the western part of the sierra (e.g. González Bonorino, 1961; Cucchi, 1964; Sabalúa *et al.*, 1981; Brogioni & Ribot, 1994) and follow the general structural trend.

The term "Famatinian cycle", stated by Aceñolaza & Toselli (1976), Aceñolaza *et al.*, (1978), and Aceñolaza & Miller (1982) for the different tectonic, magmatic, and metamorphic events within the Sierras Pampeanas, comprised the post-Middle Cambrian to Devonian time interval. New radiometric data from the Sierra de San Luis (Sims *et al.*, 1997) now allow us to broadly separate "Famatinian" (Ordovician) from "pre-" and "post-Famatinian" events. The structural style of deformation was described from single parts of the sierra by, e.g., Kilmurray (1982), Dalla Salda (1987), Ortiz Suárez (1988), Ortiz Suárez & Ramos (1990), Prozzi (1990), Carugno Durán *et al.* (1992), Sato (1993), v. Gosen & Prozzi (1996), and v. Gosen (1998), whereas many studies focused on ore deposits (e.g., Brodtkorb *et al.*, 1985, Hack, 1987; Delakowitz, 1988, Brodtkorb 1991). The metamorphic complex is intruded by several granitoids which are interpreted as pre-, syn-, and post-kinematic plutons (e.g., Kilmurray & Villar, 1981; Llambías *et al.*, 1991; Sato & Llambías, 1994; Varela *et al.*, 1994; Llambías *et al.*, 1996a; v. Gosen, 1998). Despite such separations, one major problem in the metamorphic complex of the sierra is related to the relative and absolute time relations between deposition of sedimentary sequences, magmatic activities, deformation(s), and metamorphic overprint(s).

The inferred boundary between the Eastern Sierras Pampeanas and the Precordillera (Cuyania) Terrane (Ramos et al. 1996; "Texas Plateau" of Dalziel 1997; present Fig. 1), west of the Sierra de San Luis, shows that the kinematic mode of contraction in the sierra is important with respect to the interpretation of terrane

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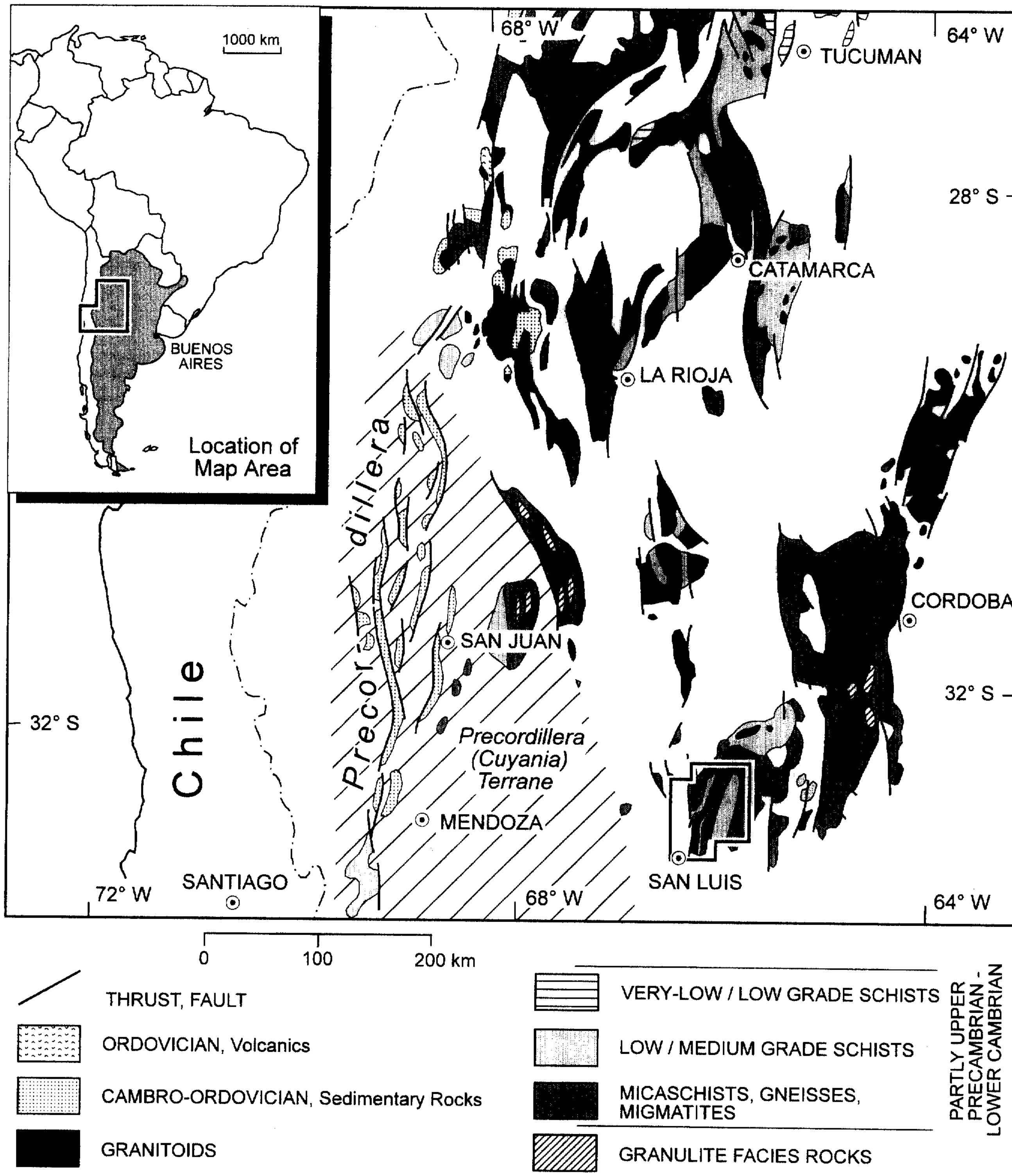

Fig. 1. Simplified sketch map of the W-Argentine Andes, based on the map of Willner *et al.* (1987). Outline of the Precordillera (Cuyania) Terrane modified from Ramos *et al.* (1996). Frame depicts location of map of Fig. 2.

collision. It has been postulated that collision took place during mid-Ordovician times (e.g. Astini *et al.*, 1995; Ramos *et al.*, 1996, Dalziel 1997). Several authors have shown that subduction and collision tectonics in general do not necessarily result in orthogonal compression with respect to plate margins, however, in many cases oblique convergence leads to a partitioning of contraction along thrusts and strike-slip faults (e.g. Fitch 1972, Jarrard *et al.* 1986, Oldow *et al.*, 1990, Reutter *et al.*, 1991; Lu & Malavielle, 1994; Tikoff & Saint Blanquat, 1997). Furthermore, terrane emplacement can be combined with, or caused by, transcurrent displacements (e.g. Williams &

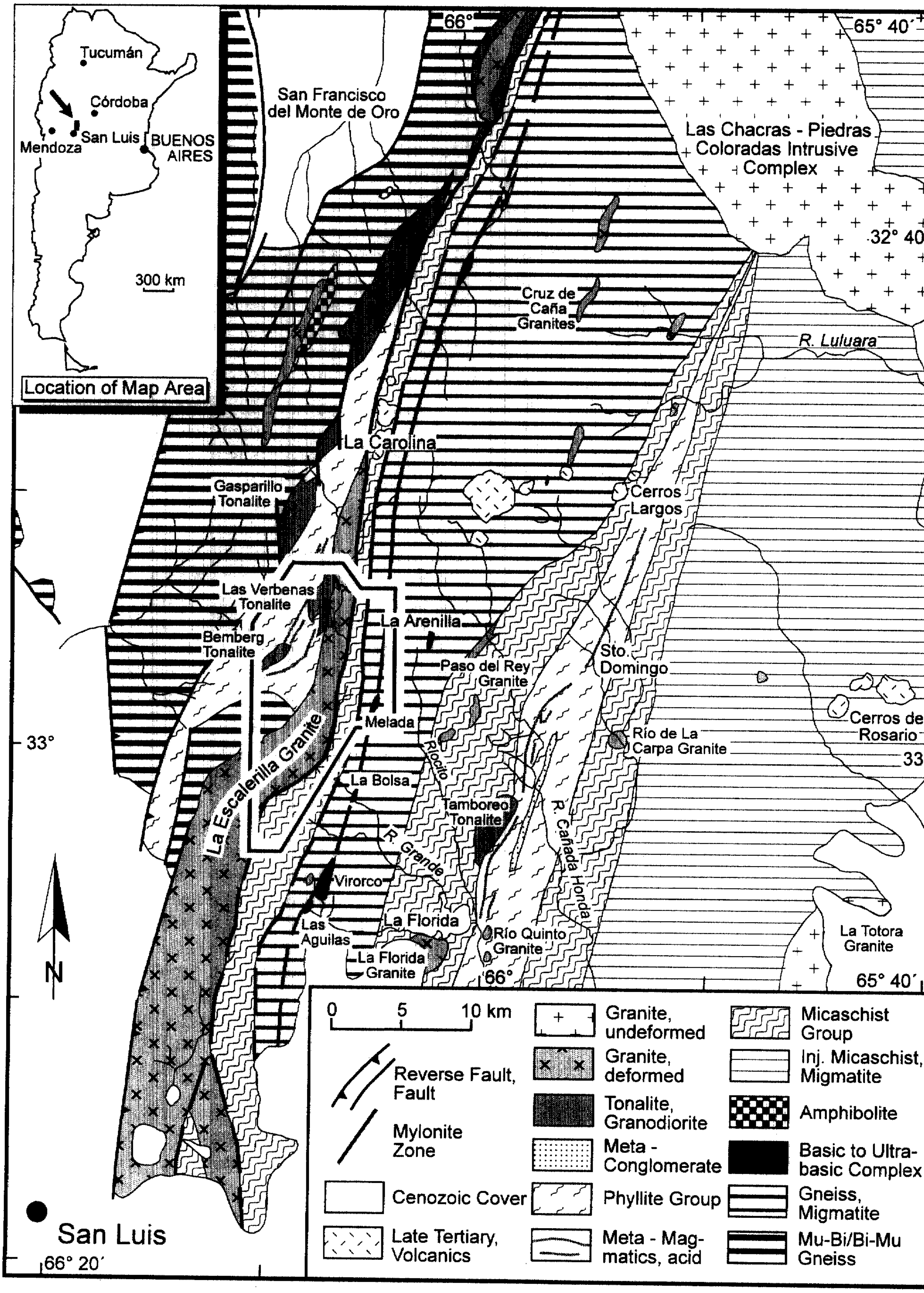

Fig. 2. Geological map of the southwestern part of the Sierra de San Luis, compiled and adapted after Ortiz Suárez & Sosa (1991), Ortiz Suárez *et al.* (1992), Brognioni *et al.* (1994), Llambías *et al.* (1996b), and own investigations. For location see Fig. 1; frame shows location of maps of Figs 3, 7 and 15.

Hatcher, 1983; Karig *et al.*, 1986; Hansen, 1989; Hooper & Hatcher, 1990).

In order to provide insight into the kinematic mode of compression, this study in the southwestern part of the Sierra de San Luis focuses on the structural evolution of the La Escalerilla Granite and surrounding units south of Valle de Pancanta (S of La Carolina: Fig. 2). The ~NNE–SSW trending and curved pluton extends through the southwestern part of the sierra over ~55 km. U–Pb dating of zircons from the granite has given an Early Devonian age of crystallization (403 ± 6 Ma: Sims *et al.*, 1997). Thus, fabrics within the granite and adjacent units give an insight into the kinematic mode and timing of compression. In the text, the structural, magmatic, and metamorphic evolution of the main lithologic units is described first in relative chronological order. It is based on fabric elements of the first deformation detected in the field. It will be shown that the sinuous bending of the granite and country rocks was the result of contraction under a transpressive regime. This will lead to some regional interpretations also with respect to the possible mode of terrane collision.

LITHOLOGICAL UNITS

To the west of the La Escalerilla Granite (Figs 2 and 3), the widely distributed Phyllite Group ("San Luis Formation" of Prozzi & Ramos, 1988) is a monotonous succession of alternating phyllites and quartzites which is interpreted as a turbiditic sequence (Prozzi 1990). The age of the meta-clastic sediments is not proved by fossil findings, however, it is compared with the timing of deposition of the Puncoviscana Formation s.l. of NW Argentina (Prozzi, 1990; v. Gosen & Prozzi, 1996; v. Gosen, 1998). In the Phyllite Group, layers of acid meta-magmatic rocks are widely distributed. In the La Florida area, they were interpreted as rhyolitic to dacitic volcanics (Brodtkorb *et al.* 1984, Fernández et al. 1991) while south of La Carolina they partly represent dykes (v. Gosen & Prozzi 1996).

In the northern part of the study area, the Las Verbenas Tonalite intrudes the Phyllite Group and is bordered to the east by the La Escalerilla Granite (see Sato 1993). North of the Ea. Pancanta, the pluton of the Bemberg Tonalite intrudes the Phyllite Group (Fig. 3). The western part of the oval-shaped intrusion consists of a quartz gabbro which, together with additional tonalites, also occurs around the Ea. Pancanta (Sánchez *et al.*, 1996). South of the Bemberg pluton, a fine-grained muscovite granite with a marginal facies of biotite granite is exposed. U–Pb dating of zircons from the Bemberg and Tamboreo Tonalites at 468 ± 6 and 470 ± 5 Ma, respectively (Sims *et al.*, 1997), suggests emplacements during the Early Ordovician together with other tonalites in the western part of the sierra. Between the Bemberg and Las Verbenas Tonalites, and extending toward the La Escalerilla Granite, the lithologies of the Phyllite Group grade into higher grade metamorphic rocks which can be described as "micaschists" but represent contact metamorphosed equivalents of the Phyllite Group clastics.

East of the granite, the ~NNE–SSW trending Micaschist Group (Fig. 3) consists of a monotonous succession of alternating biotite–muscovite schists and quartzites with widely distributed pegmatites. It can be compared with the meta-pelitic to psammitic lithologies of the Phyllite Group to the west of the granite. This is supported by relics of bedding and sedimentary structures in the western part of the micaschists.

Separated by a thin mylonite, the micaschists are followed by "injected schists, migmatites, and gneisses" to the east ("Eastern Basement Complex" of v. Gosen & Prozzi, 1998; partly "Pringles Metamorphic Complex" of Sims *et al.*, 1997). The continuation of the mylonite to the south could only be inferred. Within this complex, two larger, NNE–SSW trending lenses of meta-basic to ultra-basic rocks (compare Brogioni & Ribot, 1994) are referred to here as the La Melada Complex and a lot of others occur also outside the study area. The complex is cross-cut by a NNE–SSW trending mylonite zone (Brogioni & Ribot 1994) and thinner strips of mylonites occur to the west and north (Fig. 3).

Around the Ea. Pancanta (Fig. 3; see also Sánchez *et al.*, 1996), muscovite–biotite and biotite–muscovite gneisses and injected schists contain widely distributed and mm- to several meter-long and thick granitic and pegmatitic to aplitic sheets, layers, and lenses which record sharp boundaries toward the country rock. Due to injections of the muscovite granite and a poor outcrop situation, the contact with the Phyllite Group in the east is unclear (? fault). According to field observations, the central and southern parts of the gneisses were affected by at least three compressive deformations, injected, and metamorphosed prior to the intrusion of the tonalites, quartz gabbros, granites, and La Escalerilla Granite in the south. This unit is interpreted as part of the older, pre-Famatinian "Western Basement Complex" of the sierra (v. Gosen & Prozzi, 1998; "Nogolí Metamorphic Complex" of Sims *et al.*, 1997). Its evolution, as that of the Eastern Basement Complex, is beyond the scope of this paper and not treated in the text below.

FIRST STRUCTURAL AND METAMORPHIC EVENTS IN THE MICASCHIST GROUP

In the profiles studied, relics of the first recognizable deformation (D_1) are recorded by a planar and

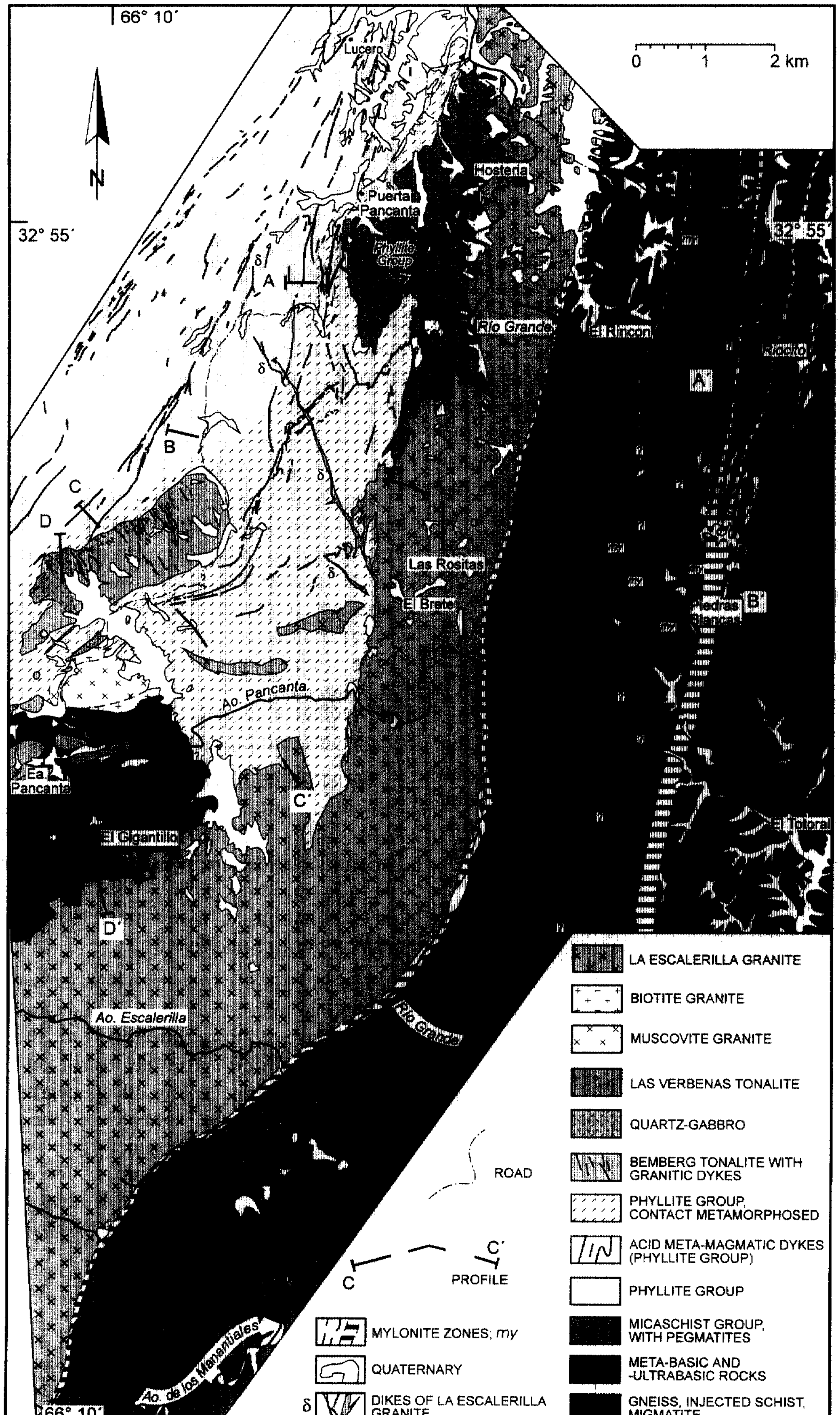

Fig. 3. Geological sketch map of the area south of Valle de Pancanta based on interpreted aerial photographs and local structural field mapping (see Fig. 2 for location); distribution of magmatics of the Bemberg pluton partly after Sánchez *et al.*, (1996).

penetrative S_1-foliation which is related to single tight or isoclinal, intrafolial F_1-folds. The grade of the accompanying metamorphism could not be determined precisely. Since no clear evidence for an amphibolite facies overprint was found, P/T conditions of the greenschist facies can only be assumed. After the D_1-deformation, widely distributed pegmatite dykes, pegmatitic, aplitic, and ±granitic layers, lenses, and pods were injected into the clastic sequence. The layers are oriented parallel to S_1-planes but cross-cutting, thick pegmatitic dykes under different angles are also widely distributed (Fig. 4a). This suggests that the injections were generated under overall extension within the clastic rock sequence.

The micaschists partly contain up to cm-long, lens-shaped muscovite plates and muscovite–sericite aggregates (? former andalusites). They grew pre-D_2 and can contain fibrolite needles (Fig. 4b). In biotite-rich layers, sillimanite needles and fibrolite could be detected in and between biotite plates. Fibrolite and dense fibrolite aggregates partly replace the latter, which is also described from other metamorphic complexes (e.g. Kerrick, 1987; Kerrick & Woodsworth, 1989). Groups of prismatic sillimanite can occur in optical continuity and probably derived from older porphyroblasts (? andalusite; compare e.g. Vernon, 1987).

Based on the structural evidence (see below) and the injections of widely distributed magmatics, it can be assumed that sillimanite grew after the D_1- and prior to the D_2-deformations. In addition, garnet porphyroblasts, muscovite plates, and muscovite–sericite aggregates (with enclosed fibrolite) are related to the metamorphic overprint. An increase in temperature could have led to the replacement of (?)andalusite by sillimanite plus muscovite/sericite, and the growth of fibrolite/sillimanite partly at the expense of biotite, indicating amphibolite facies conditions. Together with the widely distributed magmatic injections it can be related to an underlying pluton which probably intruded the clastic sequence in a deeper crustal level.

INTRUSIONS

Tonalites

As the Las Verbenas Tonalite, the Bemberg Tonalite pluton intruded the undeformed clastic sediments of the Phyllite Group (see also Sato, 1993; Sánchez *et al.*, 1996), and smaller intrusions are exposed in the basement to the south. At several localities, the exposed northern and southern intrusive contacts are steeply inclined to ~NW and no indication for an emplacement-related deformation was found. The tonalite contains single xenoliths of the country rocks and widely distributed, oval to lens-shaped mafic enclaves which are cm- to m-long. Only at a few points their alignment can be related to igneous flow. The quartz gabbro in the west of the tonalite pluton, as an equivalent in the south, can be interpreted as a second pulse of intrusion as no clear injection of the tonalite was found.

In the central part and along the northern margin of the pluton, mostly ~NW–SE striking dykes of granitic composition occur (Fig. 3) whilst tonalitic dykes were found in the south (Sánchez et al. 1996). They are several metres to tens-of-metres thick and up to ~500 m long, also cut across the quartz gabbro, and partly dissect it into angular fragments. Sharp contacts also with the tonalite indicate that the dykes were generated after cooling of the intrusion. As smaller dykes they fan into the northern country rocks and thin out.

At the steeply westward-inclined western contact of the Las Verbenas Tonalite (Fig. 5), several m- to tens-of-metres thick and up to ~100 m-long tonalite dykes cut through the country rocks and there fan and thin out. They suggest that during pluton emplacement brittle fracturing occurred indicating a high level of intrusion. Just west of the pluton margin (S of Ea. Puerta Pancanta), a few tight to isoclinal folds on a 10 m to 100 m size around steeply inclined to vertical axes do not fit with the regional F_1-structures within the Phyllite Group (see below) and can be related to local deformation during emplacement of the pluton.

Widely distributed, fine-grained mafic enclaves are cm- to several dm-long and mostly have oval to lensoid shapes whereas subangular enclaves in greater amounts only occur in some outcrops. In a few parts, the alignment of enclaves can be related to a magmatic foliation. In many cases, however, it is related also to the tectonic foliation.

The intrusion of the tonalites led to the formation of thermal aureoles in the clastic country rocks which were converted into hornfelses at the contacts (see also Sato 1993). To the north of the Bemberg Tonalite, the temperature effects decrease over a short distance. Near the contact of the Las Verbenas Tonalite, hornfelses contain former porphyroblasts (? andalusite or cordierite) which are entirely replaced by sericite. On a ~200 m wide strip to the west, the effects of heating are indicated by the growth of larger biotite and muscovite.

Muscovite granite

South of the Bemberg Tonalite, a fine-grained muscovite granite intruded the Phyllite Group in the north and the basement schists in the south and partly has a marginal facies of biotite granite (Fig. 3). At the southern margin, the granite encloses angular xenoliths of the basement rocks with different sizes. They display fabrics of at least three deformations and thus cannot be compared with the undeformed Phyllite

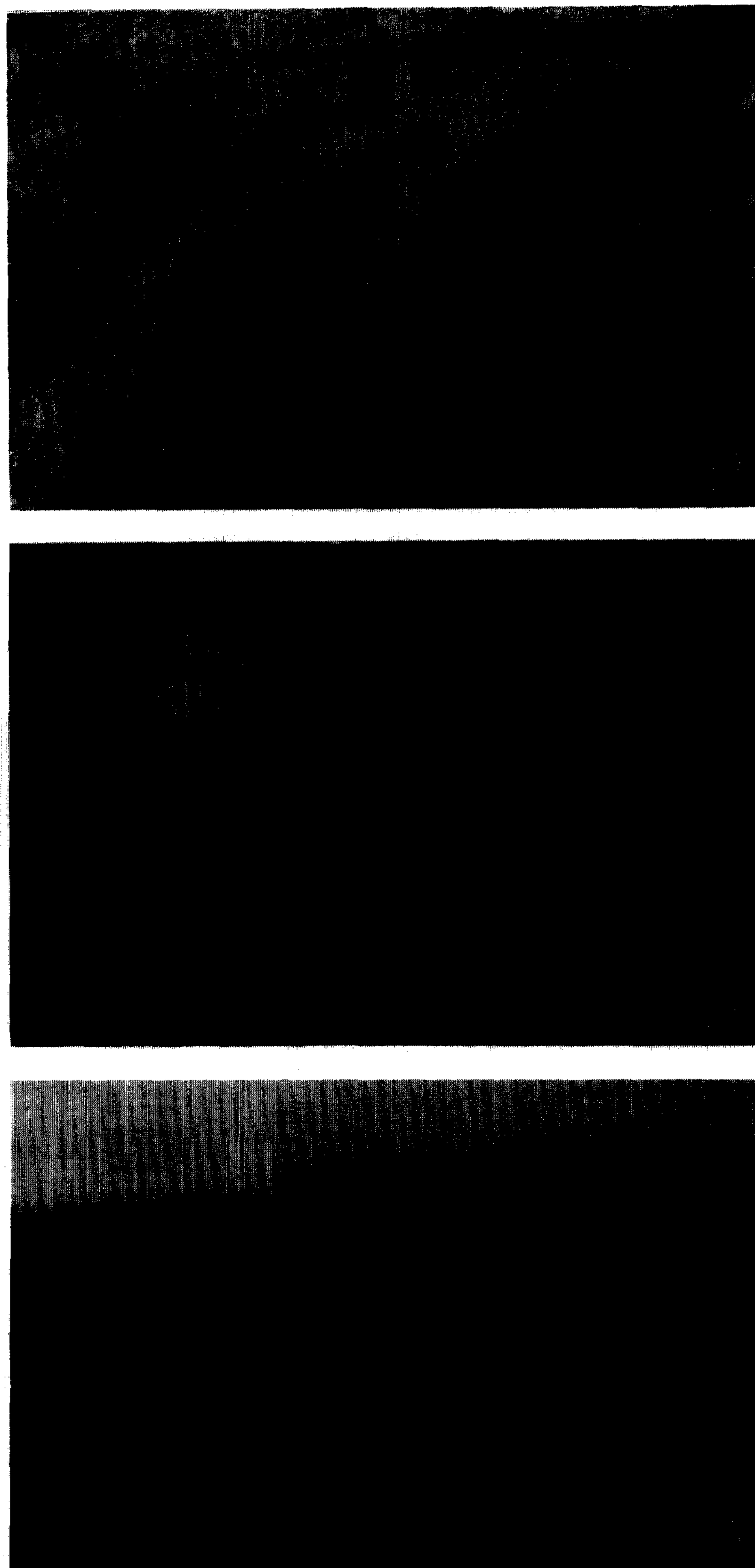

Fig. 4. (a) Pegmatite dykes and sills invading micaschists parallel and at different angles to the main S_1-foliation (Ao. de Los Manantiales, western part of the Micaschist group; scale bar = 35 cm). (b) Photomicrograph of poikiloblastic muscovite plate with enclosed fibrolite (arrows) and quartz grains. Muscovite is bent within S_2-foliation and partly replaced by sericite (upper part of photograph; micaschist east of La Escalerilla Granite, scale bar = 1 mm, crossed polarizers). (c) View toward south-southwest of contact metamorphosed Phyllite Group with acid meta-magmatic dykes (light layers, arrows). At different angles the dykes cut across bedding of the phyllites and intersect each other (left side). The cliffs in the background consist of the La Escalerilla Granite (ESE of Bemberg pluton).

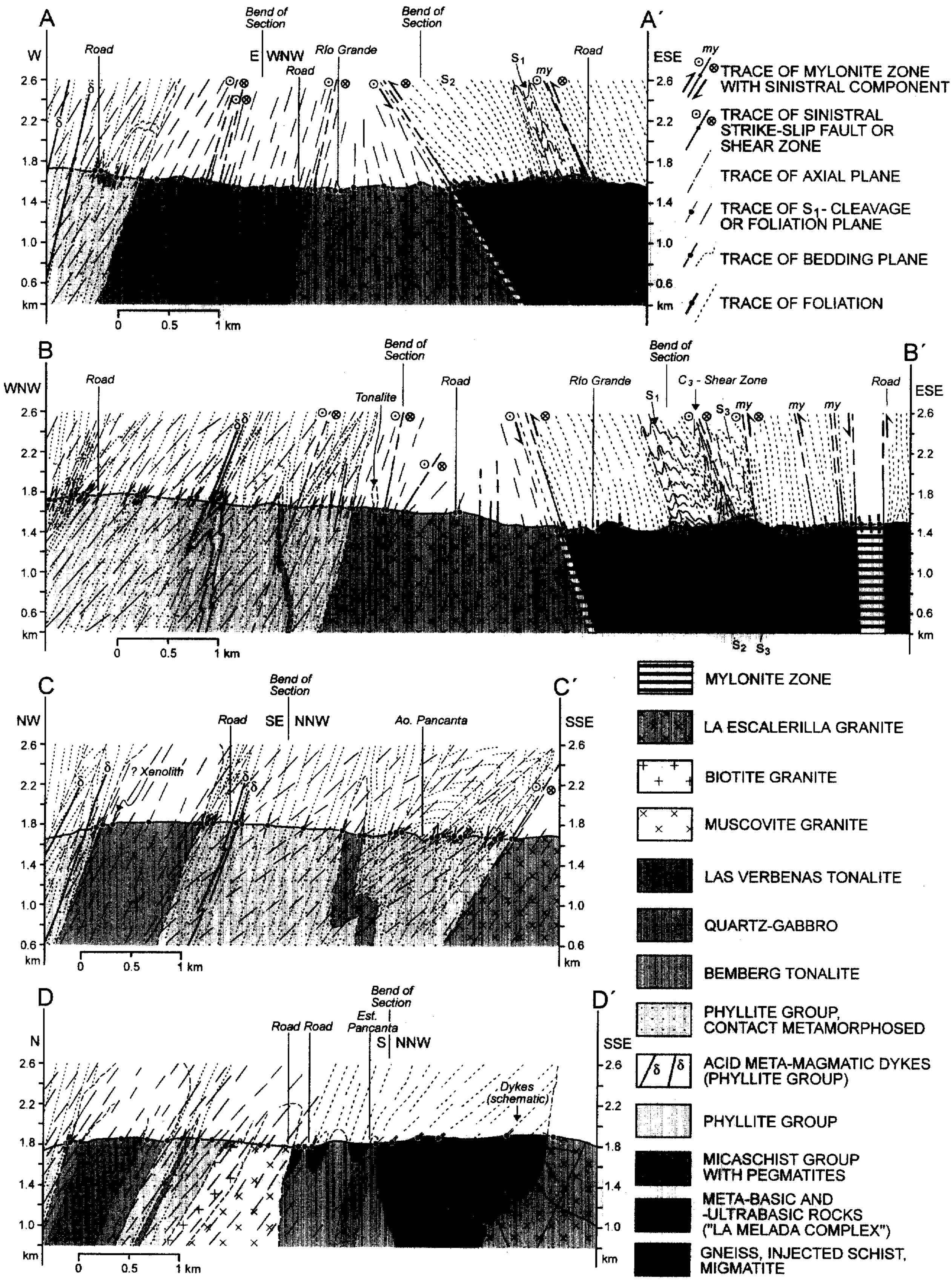

Fig. 5. Geological profiles across the different metamorphic units and intrusions in the study area (for locations see Fig. 3). Traces of cleavage and foliation planes are given as a trend. Subsurface continuations of intrusive contacts are inferred.

Group clastics in the north. This suggests that the granite intruded a high crustal level by stoping after uplift of the basement. Since exposed contacts with the tonalite were not found, a younger age of the granite intrusion can only be assumed.

Acid meta-magmatic dykes

In the clastic meta-sediments of the Phyllite Group, fine-grained, cm- to tens-of-metres thick and up to km-long layers of acid meta-magmatic rocks can contain macroscopic quartz and feldspar phenocrysts, as well as single muscovite and/or biotite on a mm-size. Based on the mineral content, they can be assigned to have a rhyolitic to dacitic composition. The layers cut across bedding (S_0) of the sediments at small to great angles (Fig. 6). At several localities they intersect at different angles (Fig. 4c) or branch off and then trend parallel to each other. Some of them split off and apophyses thin out into the country rocks. These observations suggest that the layers represent dykes and, according to the geometric dyke-fracture classification of Hoek (1991), their display can be described as irregular, braided, and partly en échelon. Clear indications for a volcanic origin were not found anywhere. Isolated layers, which are parallel to bedding, could either represent sills or volcanics, however, no relics of chilled margins and/or igneous flow textures could be detected. As in the area south of La Carolina (v. Gosen & Prozzi 1996), the dykes intruded the consolidated but undeformed sediments.

These cross-cutting dykes were not found either at the contacts nor within the tonalites. This suggests that the dykes are older than the tonalite intrusions. In the La Florida area, however, a comparable dyke cuts across the southwestern margin of the Tamboreo Tonalite (v. Gosen, 1998). At a few localities within the clastic sequence at the northern margin of the Bemberg Tonalite, younger granitic dykes cut the acid dykes.

The acid dykes are older than the intrusion of the La Escalerilla Granite. This is recorded, for example, at the western margin of the pluton where dykes of the granite cut across the clastic sediments and acid magmatic dykes (Fig. 6). Some of the dykes contain lens-shaped muscovite–sericite aggregates which represent converted porphyroblasts related to the contact metamorphism.

La Escalerilla Granite

In the western part of the study area, the multiply-deformed basement rocks are intruded by the La Escalerilla Granite. They are cross-cut by a dense swarm of granite, pegmatite, and aplite dykes with variable thicknesses, lengths, and orientations (not indicated on the map of Fig. 3, schematically depicted on Fig. 5: profile D–D′). Aplite and pegmatite dykes also cut through the granite. To the east and northeast of Ea. Pancanta, the La Escalerilla Granite intruded the undeformed clastic succession of the Phyllite Group along an irregular contact (Figs 3 and 6). Also at the ~N–S trending part of the granite margin, m- to tens-of-metres thick and up to km-long, ~NW–SE trending dykes are injected into the clastic sediments and are clear apophyses of the pluton. Thus, the granite intrusion took place under brittle conditions within the country rocks and no emplacement-related folding at the pluton margin could be detected. The eastern margin of the Las Verbenas Tonalite is either an intrusive contact of the granite or an important NNW–SSE trending shear zone (see also Sato 1993). Up to tens-of-metres thick granite and dm- to m-thick aplite and pegmatite dykes cut through the tonalite. The length and small width of the La Escalerilla Granite, and the fact that it intruded different units of different age, make it reasonable to assume that pluton emplacement followed a pre-existing fault (zone). Up to now, no clear evidence for a syn-kinematic intrusion was found.

Southeast and east of the Bemberg Tonalite, phyllites with larger biotite and muscovite dominate. Toward the southeast, up to 1 cm long relics of chiastolite porphyroblasts occur within dark phyllites. Up to the contact with the granite, muscovite and biotite increase in abundance and size and are accompanied by sericite-($\pm$quartz) aggregates (converted porphyroblasts). The rocks appear as micaschists, however, simple deformational fabrics (see below), the increase of mineral growth toward the granite contact, and the comparable lithology suggest that they are contact metamorphosed parts of the Phyllite Group. This is also supported by the fact that on map scale they record along-strike transitions into phyllites. To the north of Ao. Pancanta, two ~W–E trending granites within the clastic country rocks point to a wider extent of the pluton in the subsurface to the west of its exposed contact, and contact metamorphism in most parts of the Phyllite Group between Ao. Pancanta and south of Ea. Puerta Pancanta can be related to the granite intrusion.

STRUCTURE

Phyllite Group and contact metamorphosed equivalents

Within the Phyllite Group, the first deformation (D_1) found in the field is indicated by widely distributed F_1-fold structures (Figs 5 and 6). These folds could also be detected on aerial photographs or reconstructed by S_0 /S_1-cross-cutting relationships. The tight folds reach wavelengths on a tens-of-metres to several hundred-m scale or more. In the western part of the Phyllite Group, they verge toward S to SE (Fig. 5) and can be followed up to the contact with

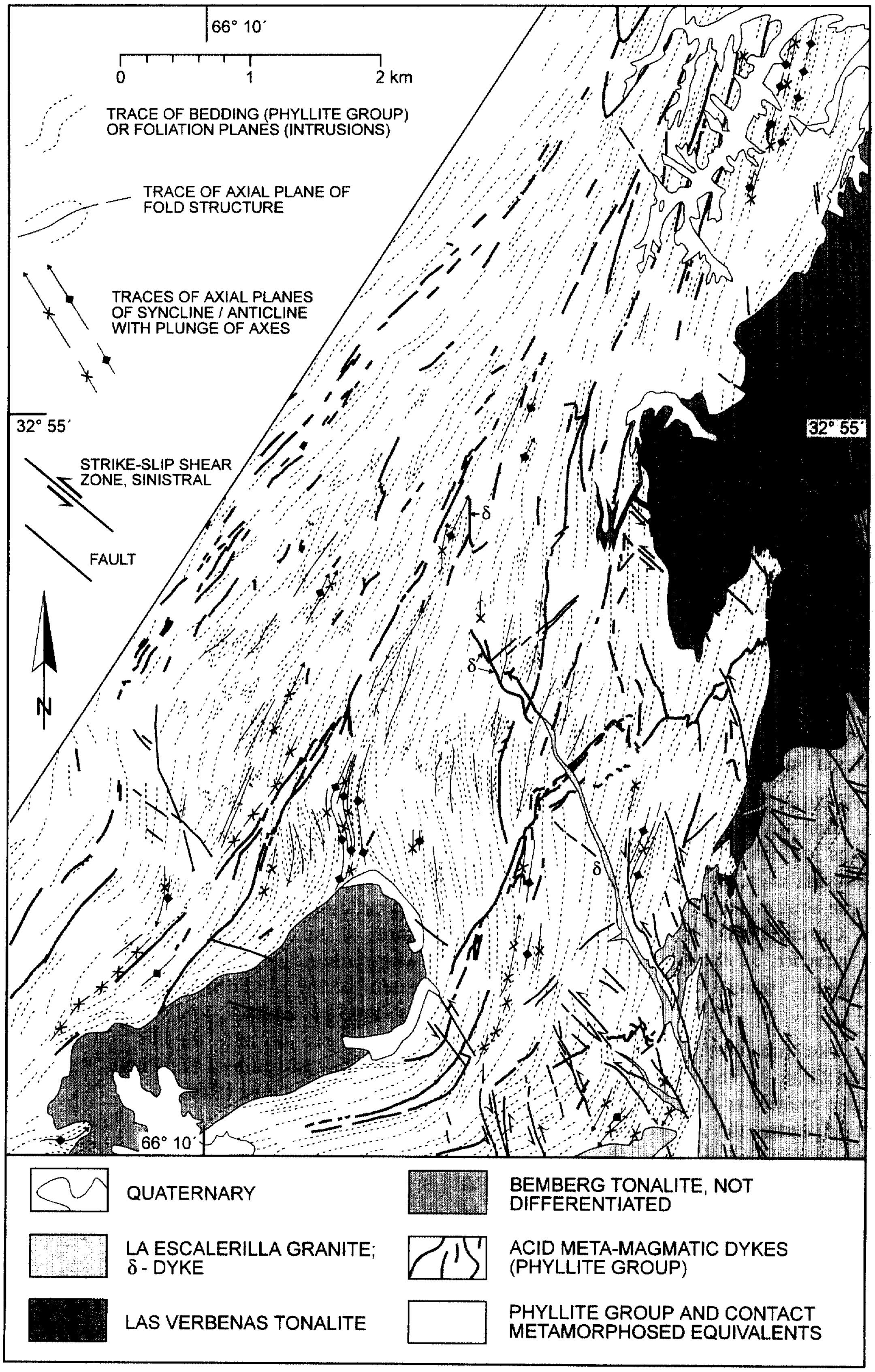

Fig. 6. Simplified map of the Phyllite Group (white) to the west of the La Escalerilla Granite with acid meta-magmatic dykes recording different orientations with respect to the trend of bedding planes (based on interpreted aerial photographs and local field mapping).

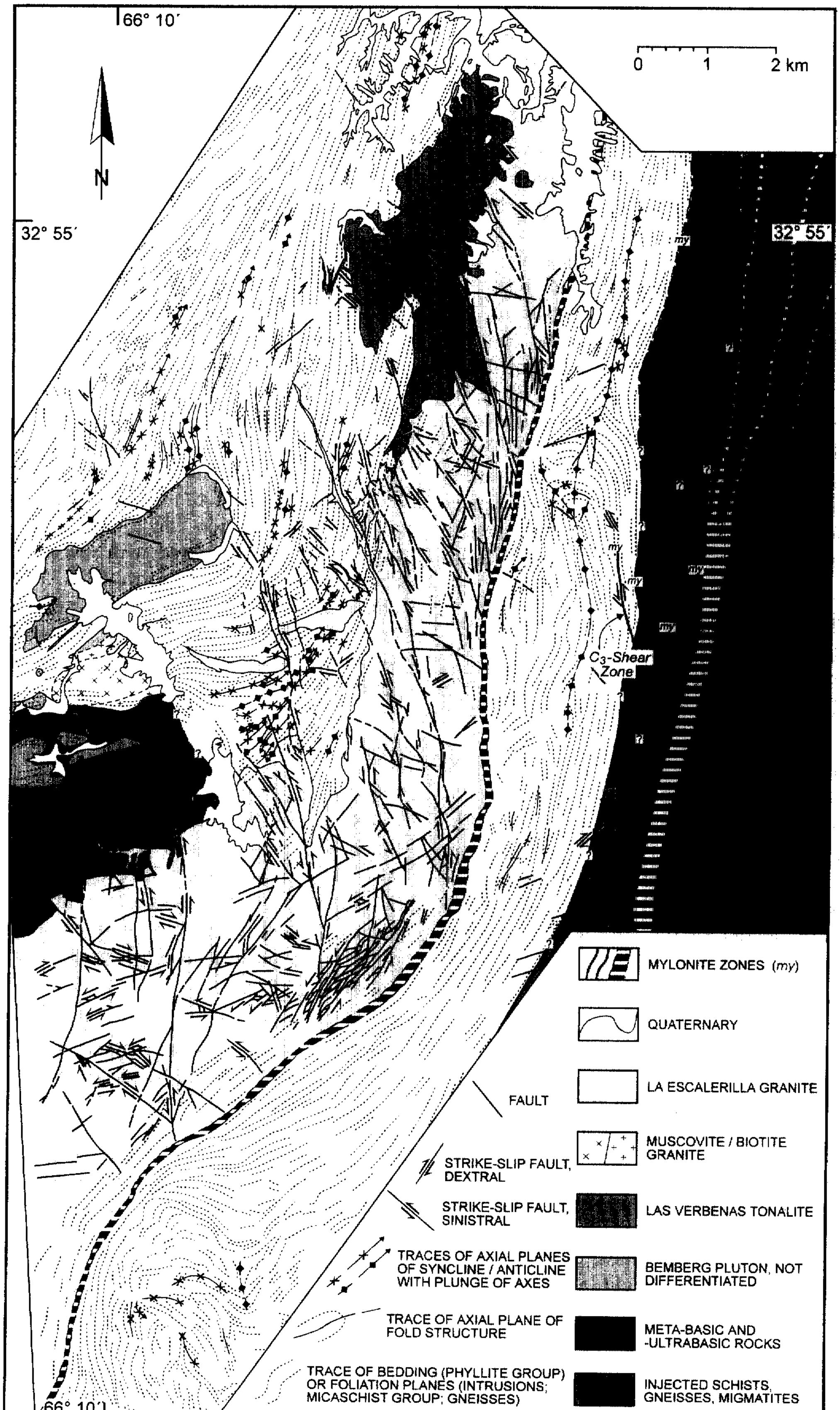

Fig. 7. Tectonic sketch map of the area south of Valle de Pancanta based on interpreted aerial photographs, local structural field mapping, studied profiles, and selected outcrops. White areas of Phyllite and Micaschist Group to the west and east of the La Escalerilla Granite, respectively, are not differentiated. See Fig. 2 for location.

the La Escalerilla Granite. From north to south the geometries change from tight structures to more open geometries in the competent, contact metamorphosed rocks. Near the granite contact, folding is condensed and ~SE-verging structures dominate.

To the north and southeast of the Bemberg pluton, the ENE–WSW trend of the F_1-folds turns into a NNE–SSW strike which can be traced northwards up to La Carolina. The bending of the entire Phyllite Group succession (Figs 6 and 7) can locally be related to the more stiff rocks of the Bemberg pluton, however, it also follows the trend of the bent La Escalerilla Granite. According to this curvature, the F_1-folds verge towards ~ESE in the north. The B_1-axes record a gentle to steep plunge to different directions (Fig. 8). The folds are combined with a penetrative, axial-plane S_1-cleavage which statistically dips toward N to NNW in the western and W to WNW in the northern part of the Phyllite Group. The L_1-lineation is mostly defined by aligned sericite, biotite, muscovite, and elongated sericite aggregates. It plunges to ~NW to N in the western and to ~W to WSW in the northern part of the study area.

In the Phyllite Group, minor fabrics of a second deformation (D_2) occur only at a few localities. These are crenulations on cm-scale combined with an incipient S_2-crenulation cleavage. The B_2-axes mostly plunge to NE to ENE.

The acid meta-magmatic dykes are cross cut by a penetrative S_1-foliation which, together with the L_1-lineation, can be traced across the contacts into the S_1-cleavage and L_1-lineation of the clastic country rocks. Dykes at a greater angle to S_0-planes of the country rocks are bent or folded (Fig. 6), and S_1-foliation planes are related to the fold structures. The fold axes mostly record a steep plunge to different directions.

Tonalites

During the D_1-deformation, the Bemberg Tonalite was foliated along the margins. On S_1-foliation planes, the L_1-lineation is indicated by aligned biotite and elongated quartz and feldspar. Both fabric elements could be traced across the ~NW-inclined contacts into the S_1-cleavage planes and L_1-lineation of the country rocks (Fig. 5). They have the same orientations (Fig. 8), and S_1-planes cut at small angles across the contacts.

The intensity of the S_1-foliation decreases towards the center of the pluton over a distance of several tens-of-metres. S_1-planes are replaced by single C_1-shear planes or shear zones indicating heterogeneous deformation. Due to the competence contrast with the tonalite the quartz gabbro only records a few C_1-shear planes. In the northern part of the pluton, the granitic dykes are also cross-cut by S_1-planes with an L_1-lineation recorded by aligned sericite and muscovite. The northern continuations of the dykes within the country rocks are bent around F_1-folds and cross-cut by S_1- cleavage planes.

The Las Verbenas Tonalite and associated dykes within the Phyllite Group were affected by a penetrative foliation (S_1) which steeply dips towards ~WNW or is vertical. It can be traced across the contacts into S_1-cleavage planes of the clastic country rocks (Fig. 5). The L_1-lineation is displayed by aligned biotite and elongated quartz. Its plunge to southwestern directions can be compared with that of the L_1-orientations in the adjacent Phyllite Group (Fig. 8a, b), however, it is also related to the formation of shear zones (see below).

Muscovite granite

The muscovite granite south of the Bemberg tonalite, as well as its biotite-rich, marginal facies, is cross-cut by an S_1-foliation which dips toward ~NNW and can be directly compared with the S_1-cleavage of the Phyllite Group in the north (Fig. 5: profile D–D′). This also accounts to the L_1-lineations in both units. To the south, the effects of the D_1-event die out, and within the gneisses plus intrusions only single C_1-planes could be detected.

La Escalerilla Granite

In the western part of the La Escalerilla Granite (~ESE of Ea. Pancanta), S_1-foliation planes are combined with distinct shear zones (see below). North of Ao. Pancanta, the ~W–E trending granite occurrence within the contact metamorphosed succession is locally cross-cut by S_1-foliation planes which are directly related to the S_1-cleavage in the country rocks.

The southern tip of the Las Verbenas Tonalite together with the western margin of the granite are affected by a penetrative S_1-foliation which moderately to steeply dips toward WNW and can be traced across the contact into the S_1-cleavage of the Phyllite Group. In this ~N–S trending part of the granite, the S_1-foliation is heterogeneously distributed and by this differs from the penetrative foliation within the adjacent tonalite. Fine-grained parts of the granite are foliated while coarse-grained areas are less deformed or do not record foliation or shear plane fabrics. The L_1-lineation is indicated by aligned mica and elongated quartz and feldspar. A varying plunge to ~S and SW (Fig. 8c, e) is also related to different shear zones (see below).

Micaschist Group

After D_1-deformation and metamorphism, the meta-clastic succession was affected by a penetrative

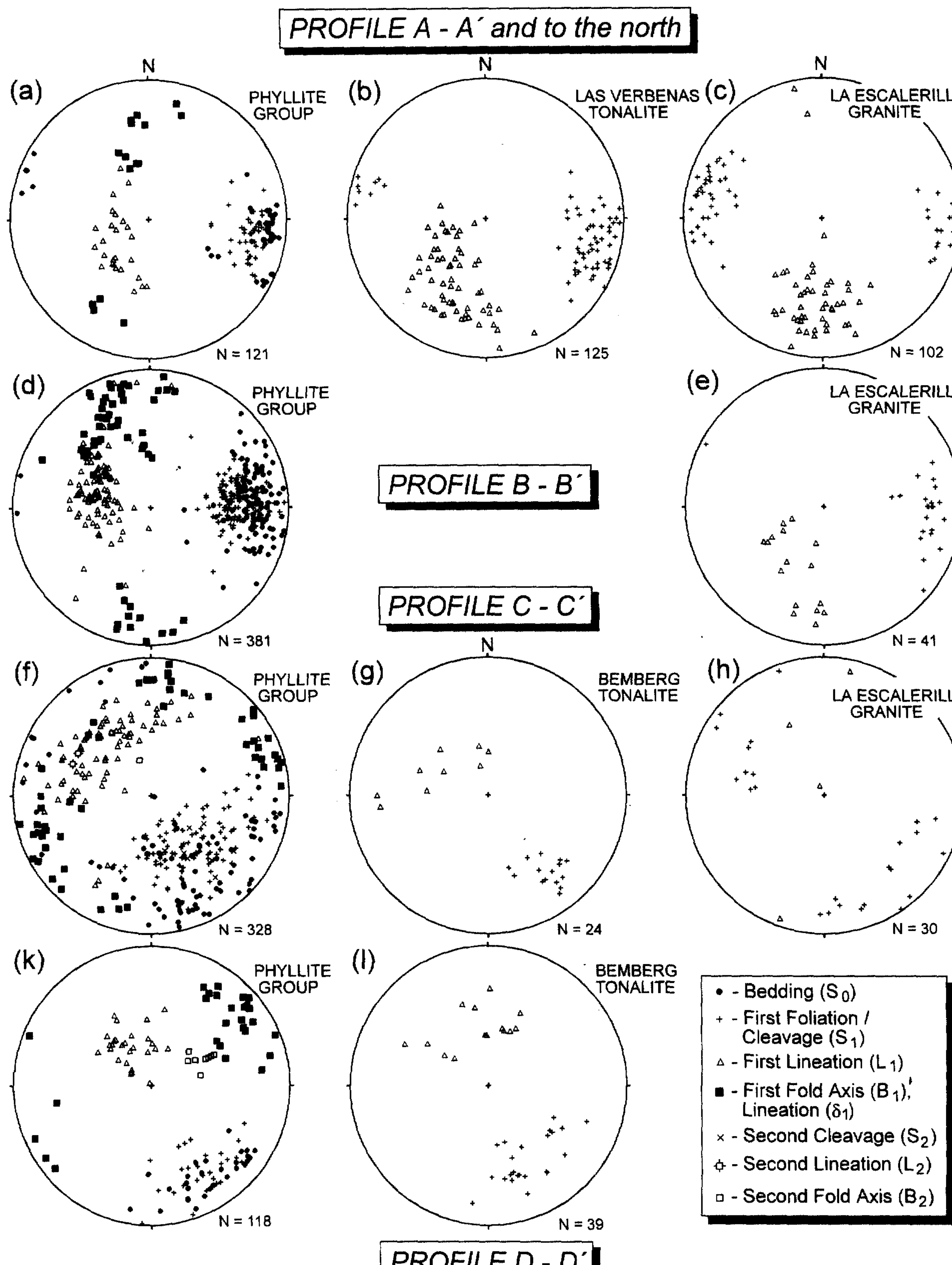

Fig. 8. Lower hemisphere, equal area stereoplots of fabric elements within the Phyllite Group (not differentiated), tonalites, and La Escalerilla Granite. Horizontal arrangements of diagrams follow the profiles A–A′ (top) to D–D′ (bottom). See Fig. 3 for location of profiles.

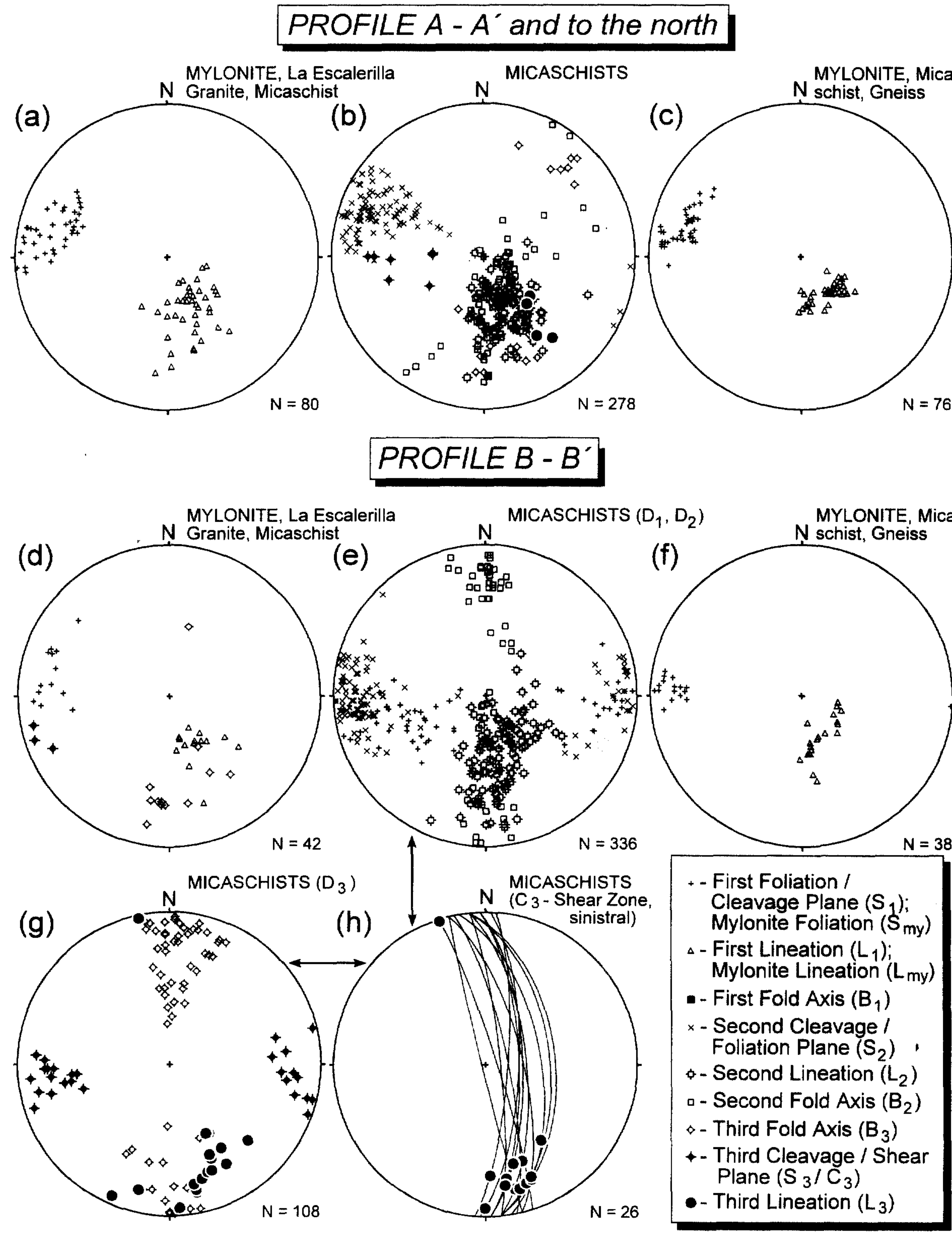

Fig. 9. Lower hemisphere, equal area stereographic projections of fabric elements in the mylonite at the eastern margin of the La Escalerilla Granite, Micaschist Group, and mylonite zone between Micaschist Group and gneisses to the east.

S_2-foliation which also cuts across pegmatite dykes and there represents the first deformational fabric. The foliation is related to F_2-folds around ~N–S to NNE–SSW striking and gently to steeply inclined B_2-axes. They are part of a NNE–SSW trending F_2-anticline which could be traced for several kms on aerial photographs (Fig. 7). The cross-section of profile B–B′ (Fig. 5) has shown that it is a WNW-vergent structure. Long–short fold limb relationships of smaller F_2-folds are related to the larger structure with S_2-planes representing an axial-plane cleavage.

In the northern profile A–A′ (Fig. 5), the F_2-anticline is a condensed, tight structure which is modified by several folds on a 10 m scale. The limbs are steeply inclined toward ESE. The B_2-axes steeply plunge toward ~NNE to NE or SSW or are vertical. Toward the west, the fold structures grade into F_2-sheath fold geometries. East of the anticline, tight F_2-folds with steeply inclined to subvertical axes are combined with a penetrative S_2-axial-plane cleavage. Since many fold axes are parallel to the pronounced L_2-lineation, the folds could represent parts of larger sheath fold structures. Elongated quartz and feldspar, as well as aligned muscovite and biotite, indicate the L_2-lineation. It mostly has a steep plunge to ~SE to S (Fig. 9b, c). In the Ao. de los Manantiales section, tight to isoclinal F_2-folds record gradual transitions into sheath fold geometries on a dm- to several metres-scale.

Shear and mylonite zones

La Escalerilla Granite and Phyllite Group. At the ~W–E trending northern margin of the La Escalerilla Granite, a local S_1-foliation is restricted around NNW–SSE striking ductile shear zones which displace the contact with the contact metamorphosed Phyllite Group (Fig. 7). S_1-foliation planes within the granite and S_1-cleavage planes of the Phyllite group are cross-cut by steeply inclined to vertical C-planes. These grade into S/C-fabrics parallel to a central and steeply inclined strip of mylonites (Fig. 10a) which consists of sheared granite and phyllite. North of the granite contact, ~NNW–SSE trending, ductile shear zones within the Phyllite group are several tens-of-metres wide (Figs 7 and 11a). S_1-cleavage planes of the phyllites sinistrally curve toward a central, dm- to m-wide strip of mylonites with condensed S/C-fabrics along both sides (Fig. 10b).

S_1-planes represent the S-plane set of the S/C-fabrics in the shear zones within the granite and Phyllite Group. On C- and S-planes, and on the mylonite foliation within the center of the shear zones, an L_1-lineation gently plunges toward SSE and partly also NNW. It is recorded by aligned mica and elongated quartz and feldspar. The curvature of S_1-planes toward the ductile shear zones, S/C-fabrics, asymmetric (σ-) feldspar clasts, and displaced more competent quartzite layers (Fig. 11b) indicate a sinistral sense of shear parallel to the L_1-lineation. On S_1-planes, the orientation of L_1 continuously changes from a steep plunge, being related to the F_1-folds in the phyllites, to a gentle plunge toward and within the shear zones. SSE to SE verging F_1-fold structures could not be traced across the shear zones (Fig. 10b). This is supported by observations in the eastern part of the Phyllite group: east of a long, NNW–SSE trending dyke of the La Escalerilla Granite, F_1-fold structures are bounded by a NNW–SSE striking, sinistral shear zone (Fig. 11c) which steeply dips toward WSW. The folds have no equivalents on the opposite side of the shear zone which continues south-southeastwards and cuts through the La Escalerilla Granite.

Las Verbenas Tonalite and La Escalerilla Granite. The Las Verbenas Tonalite and La Escalerilla Granite are cross-cut by widely distributed and steeply inclined to vertical shear planes and shear zones with different lengths and strike (see also Sato, 1993). 0n map scale, ~NNW–SE trending sinistral shear zones which partly cut through the entire granite dominate (Fig. 7). ~NNE–SSW to ENE–WSW trending dextral shear zones occur to a minor extent. On aerial photographs, the sense of shear could be detected by displaced and/or bent dykes or vein sets, bending of the foliation fabric and/or shear/fault planes, as well as displaced contacts between both plutons or between the intrusions and rocks of the Phyllite Group.

Toward ductile, sinistral shear zones, which are cm- to several tens-of-metres wide, an S_1-foliation is intensified (tonalite) or develops (granite). On S_1-planes, the steeply westwards plunging L_1-lineation is defined by aligned sericite and biotite (tonalite) or muscovite and biotite (granite) along with elongated quartz and feldspar. As the S_1-foliation sinistrally curves toward the center of the shear zones, L_1 turns into a gentle plunge toward ~SSE or ~NNW which is comparable with that of L_1 on the C-plane set (Fig. 12).

Within one sinistral shear zone of the Las Verbenas Tonalite, a dm-thick quartz vein cuts through S_1-foliation planes (Fig. 10c). In the center of the shear zone, thin quartz layers only record incipient flattening with boudinage and suggest that they were generated *during* shear zone deformation and affected only by the final stage of compression. This probably also accounts for a quartz vein within one sinistral shear zone south of Ao. Pancanta (Fig. 10a). Comparable quartz veins were found in the western part of the tonalite where systematic mining (? tungsten) has directly followed the center of sinistral shear zones.

The eastern margin of the Las Verbenas Tonalite against the La Escalerilla Granite is partly marked by an important sinistral shear zone (Fig. 12; see also Sato 1993). Within the central, tens-of-metres thick tonalite mylonite (Fig. 10d), a pronounced mylonite lineation (L_{my}) on the mylonite foliation (S_{my}), defined by elongated quartz, stretched pencil-like feldspar, and aligned biotite, plunges gently towards the SSE. To the west, a tens-of-metres wide zone with dominant S/C-fabrics continuously grades into the S_1-foliation. The zone of intense shearing within the

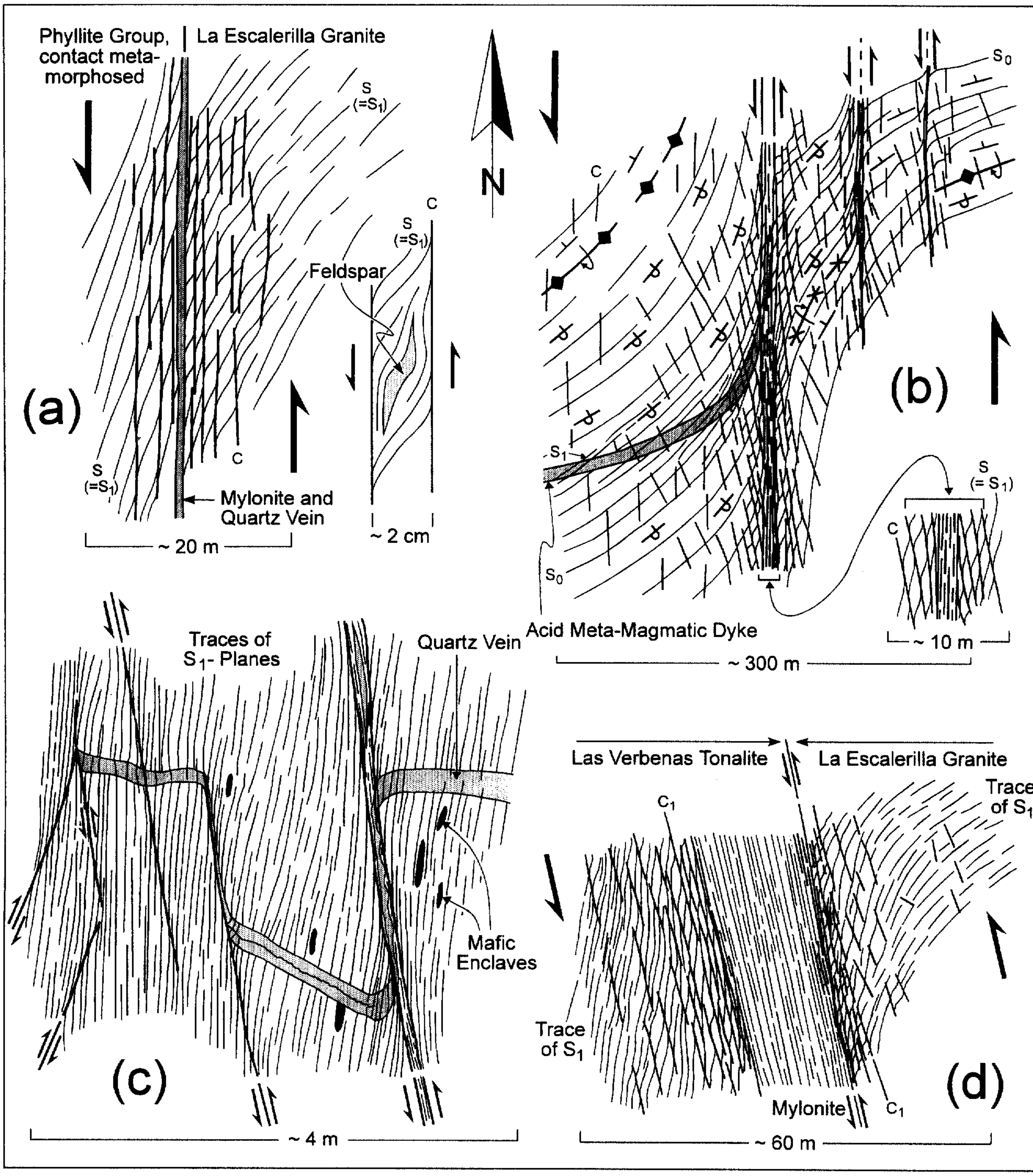

Fig. 10. (a) Sinistral shear zone between contact metamorphosed rocks of the Phyllite Group and La Escalerilla Granite with *S/C*-fabrics along both sides of the central mylonite. In the sheared granite, *S/C*-fabrics contain asymmetric feldspar clasts (small sketch; northern margin of the La Escalerilla Granite south of Ao. Pancanta). (b) Sinistral shear zones in the Phyllite Group southeast of the Bemberg Tonalite. *S/C*-fabrics are concentrated in the central parts (small sketch). Sinistrally dragged phyllites, with an acid meta-magmatic dyke in the western part, record different SE- to SSE-vergent F_1-fold structures which could not be traced across the shear zones. They also suggest the direct connection between folding and shear zone formation. (c) Sinistral shear zone in the Las Verbenas Tonalite with small conjugate dextral planes. Syntectonic quartz vein cuts across S_1-foliation planes and is locally affected by minor shearing and flattening in the shear zones (outcrop in valley south of Ea. Puerta Pancanta, profile A–A′). (d) Sinistral shear zone separating the Las Verbenas Tonalite from La Escalerilla Granite. The tonalite is intensely sheared in a thick mylonite zone and a western strip with *S/C*-fabrics whereas deformation in the granite is concentrated only within a small strip east of the tonalite mylonite. In the granite, the sinistrally bent S_1-foliation dies out to the east (eastern margin of Las Verbenas Tonalite south of hosteria Las Verbenas, road to Ea. Las Rositas). All sketches are plan view.

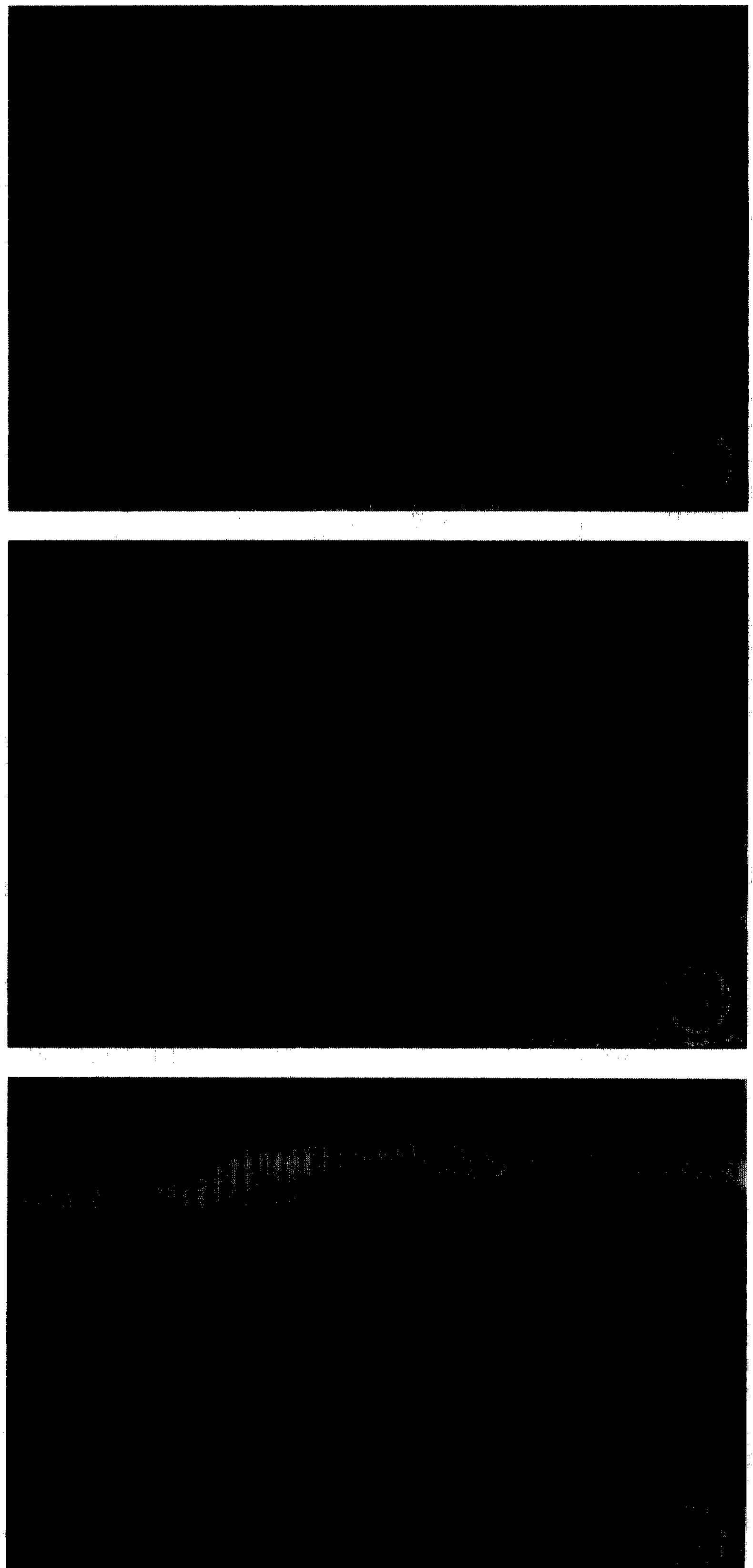

Fig. 11. (a) View toward southwest on sinistral shear zones (small valleys, arrows) in contact metamorphosed Phyllite Group. Note curvature of bedding planes (left and right sides) toward the shear zones (SE of Bemberg pluton). (b) Oblique view toward west–southwest on part of sinistral shear zone in contact metamorphosed phyllites with quartzite layers (lower part). Note sinistral shear planes (schematically indicated on top left side) which displace the different layers (SE of Bemberg pluton). (c) View toward north–northeast on tight F_1-folds in the contact-metamorphosed Phyllite Group indicated by quartzite layers. The fold structures are cut by a sinistral shear zone and the cliffs in the foreground represent its displaced southwestern block (ENE of Bemberg pluton, height of the hill in the background is ~50 m).

coarse-grained granite is a few metres wide and recorded by sinistral S/C-fabrics which grade into a dm-wide mylonite. Further east, the sinistrally bent S_1-foliation dies out.

In outcrops of the La Escalerilla Granite, m-wide sinistral shear zones with and cm-thick shear zones without macroscopic S/C-fabrics are concentrated within up to tens-of-metres wide strips. In most cases they could be related to larger shear zones which were detected on aerial photographs. On S_1-planes, the orientation of the L_1-lineation coincides with that on C-planes and single shear planes.

Intersections of sinistral and dextral shear planes and shear zones suggest that both represent a conjugate set indicating ~WNW–ESE compression. On map scale, the L_1-lineation generally records a gentle plunge to ~SSE or ~NNW (sinistral) and ~SSW or~NNE (dextral; Fig. 12). The main sinistral zones do not cut across the eastern margin of the granite. On aerial photographs, sinistral shear zones parallel to the ~NE–SW trending part of the margin (Fig. 12), as minor ~NW–SE trending dextral zones, probably accommodated the sinuous bending of the granite. The amounts of displacement along the shear zones within the different units could not be determined. In general, sinistral zones represent the dominant set and in many cases, the eastern units were obliquely lifted parallel to their SSE-plunging L_1- lineations (5–35°).

Eastern margin of the La Escalerilla Granite. The eastern margin of the La Escalerilla Granite against the Micaschist Group is marked by a thick mylonite zone representing the southern continuation of its equivalent in the area of La Carolina and to the south (see v. Gosen & Prozzi, 1996). On aerial photographs it could be traced southwards up to Ao. de los Manantiales (Fig. 3), which is supported by observations of Sales (1996), and marks the entire eastern margin of the granite pluton. Further southwards, a faulted contact was described by Costa (1983).

The mylonite zone consists of a platy granite mylonite. The S_{my}-foliation moderately to steeply dips toward ~ESE. The L_{my}-lineation is defined by aligned sericite, muscovite, elongated quartz and feldspar, and plunges toward ~SE to S (Fig. 9a, d). Toward the west, mylonitic shearing continuously dies out. At the contact with the granite mylonite zone, the eastern micaschists are converted into mylonite quartzites and phyllonites within a small strip. Their S_{my}-foliation is related to the S_2-foliation with crenulated S_1-foliation planes and isoclinal F_2-fold structures of the micaschists in the east. The L_{my}-lineation is recorded by aligned biotite, muscovite, sericite, and elongated quartz. It moderately plunges toward ~SE. As the L_2-lineation, it can directly be compared with the lineation of the granite mylonite. The above fabrics are the same as those in the northern along-strike continuation of the mylonite zone and eastern micaschists (v. Gosen & Prozzi, 1996).

S/C-fabrics on a cm-scale develop from single sinistral shear planes and shear zones to the east of the contact. As single asymmetric (σ-) feldspar clasts in the granite mylonite they indicate an oblique, ~NW-directed uplift of the micaschists with respect to the La Escalerilla Granite along the S_{my}-foliation and parallel to the L_{my}-lineation. Thus, the relative displacement of both units took place with a sinistral component. Parts with S/C-fabrics also contain minor dextral shear planes which are conjugate to the sinistral plane set. NW-vergent fold structures on a cm- to dm-scale overprint the L_{my}-lineation and indicate continuing compression. Both sets of shear planes and S/C-fabrics can be compared with the sinistral and dextral shear zones in the La Escalerilla Granite and suggest that the granite and micaschists were deformed under the same kinematic regime.

Mylonite zones east of the La Escalerilla Granite. In the basement rocks to the east of the La Escalerilla Granite, one thick mylonite zone cuts through the "La Melada Complex" (Fig. 7; see also Brogioni & Ribot, 1994) and to the north splits into several branches. The mylonites consist of intensely sheared relics of migmatitic schists and gneisses. The subvertical S_{my}-foliation is oriented parallel to the older foliation fabric and compositional layering and contains asymmetric feldspar clasts (σ- and partly δ-types), shear bands, and S/C-fabrics. They indicate an uplift of the eastern block parallel to the steeply southeast- to eastwards plunging L_{my}-lineation defined by aligned sericite, biotite, and sillimanite as well as elongated quartz and feldspar.

To the west of this mylonite zone, additional mylonite zones up to tens-of-metres thick (Fig. 7) are steeply inclined to the ESE. Asymmetric feldspar clasts (σ-types) indicate an uplift of the eastern blocks parallel to the L_{my}-lineation. The westernmost east-dipping mylonite zone led to uplift of the migmatitic schists and gneisses over the micaschists in the west during their D_2-event and could be traced to the north (Figs 3 and 5: profile B–B′, and 7) whereas the southern continuation could be only inferred. The L_{my}-lineation steeply plunges toward ESE to S (Fig. 9c, f). Asymmetric feldspar σ-clasts indicate an oblique, reverse displacement of the eastern block with a sinistral component.

Third deformation in the Micaschist Group

In the Ao. de los Manantiales section, F_3-folds on a dm- to several m-scale occur within m- to approx. 10 m-wide strips. They have axes parallel to the L_2-lineation, can interfere with F_1- and F_2-fold structures, record different vergences, and are accompanied by single C_3-shear planes or an S_3-cleavage. In the western parts of the other profiles, toward the contact

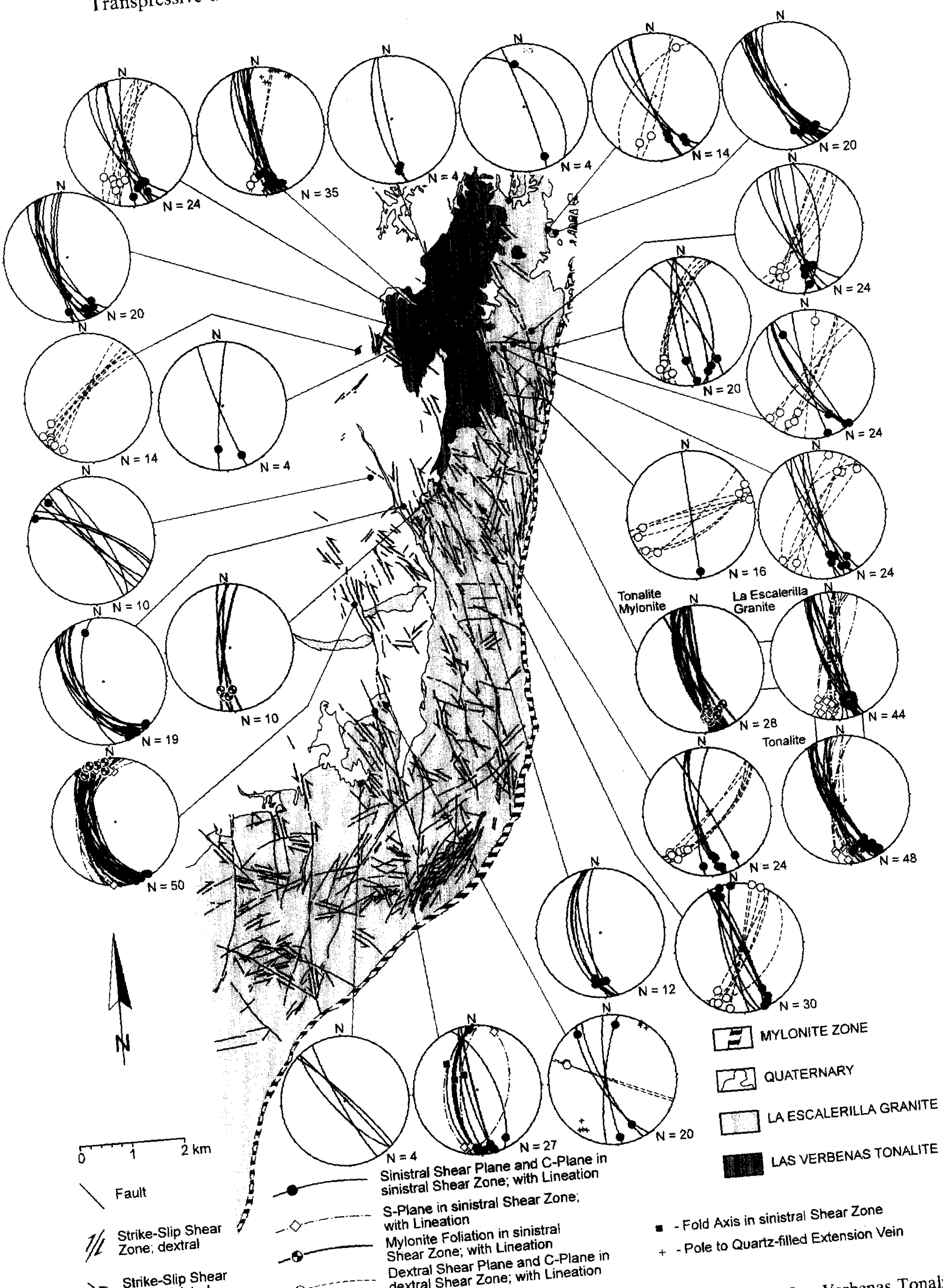

Fig. 12. Distribution of different fault and strike-slip fault lines within the La Escalerilla Granite, Las Verbenas Tonalite, and Phyllite Group to the west (white). Equal area, lower hemisphere stereographic projections of related fabric elements are indicated with their locations. Map based on interpreted aerial photographs and field studies; for location of La Escalerilla Granite compare Fig. 3.

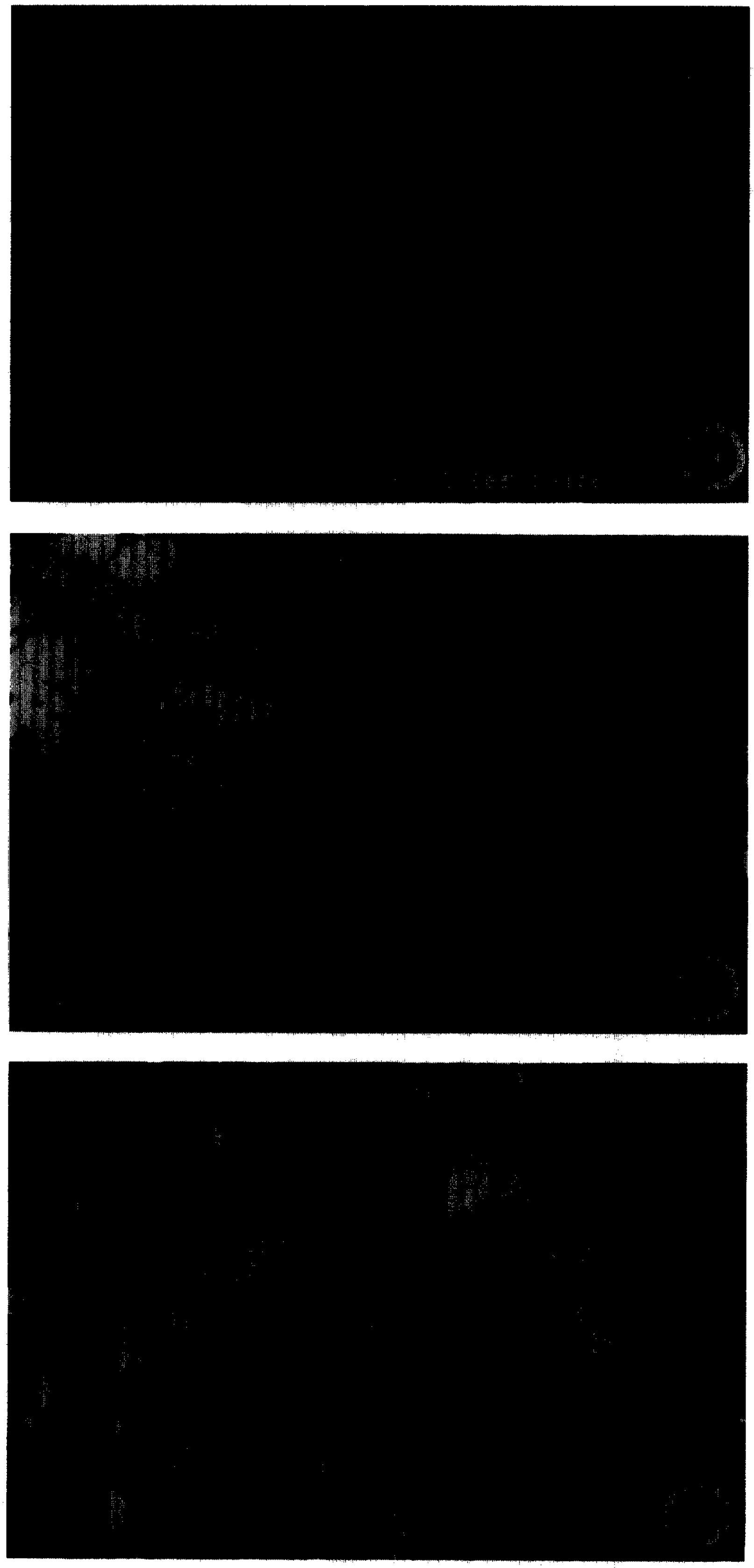

Fig. 13. Photomicrographs of thin sections. (a) Former chiastolithe porphyroblasts entirely converted into quartz–sericite aggregates within dark phyllite. In the aggregates, relics of the internal cross are preserved (SE of Bemberg pluton, scale bar = 1 mm, plane polarized light). (b) Staurolite porphyroblasts (st) in micaschists at the asphalt road to la Carolina without stretching phenomena (scale as in (a), crossed polarizers). (c) Microfabrics in mylonite of La Escalerilla Granite within sinistral shear zone. Rim of alkali feldspar (f) is replaced by recrystallization grains which also occur in the main foliation aside of quartz recrystallization grains and recrystallized mica (shear zone at northern granite margin south of Ao. Pancanta, scale as in (a), crossed polarizers).

with the La Escalerilla Granite, F_3-folds with axes either parallel or oblique to the L_2-lineation can occur within tens-of-metres wide strips.

In the profile B–B′ (Fig. 5), the eastern part of the micaschists is affected by E-vergent F_3-kink folds on a scale of several metres. They are combined with a W-dipping S_3-cleavage. To the east, it grades into a pronounced, vertical foliation related to tight and isoclinal F_3-folds. This zone is bordered by a ~30 m wide C_3-shear zone in the east where S/C-fabrics indicate a sinistral displacement parallel to a gently south–southeastwards plunging L_3-lineation (Fig. 9h). The shear zone shows that the D_3-deformation operated under a kinematic regime which was comparable to that of the compressive D_2-event at the eastern margin of the La Escalerilla Granite. As the F_3-structures it can be related to the latest stage of continuous compressive deformation.

MICROFABRICS AND METAMORPHISM

Contact metamorphism in the Phyllite Group

In the contact metamorphosed parts of the Phyllite Group west of the La Escalerilla Granite, muscovite and biotite porphyroblasts up to 1 mm long can contain planar inclusion trails (e.g. opaque dust) whilst s-shaped trails could not be detected. Since the trails are rotated with respect to bedding planes, the porphyroblasts are grown statically. This is supported by mica porphyroblasts which randomly grew across preserved (relics of) bedding.

Chiastolite in dark phyllites southeast of the Bemberg Tonalite, with relics of the internal cross, is grown pre-D_1 and entirely replaced by sericite + quartz (Fig. 13a). Sericite ± quartz aggregates could represent converted andalusites, related to the thermal overprint pre-D_1. In a few sections, up to 1.5 mm long chlorite aggregates represent converted pre-D_1 porphyroblasts (? biotite). Only in one (?) xenolith at the northern margin of the Bemberg Tonalite, small ? fibrolite needles occur within quartz grains. During the first metamorphic overprint, quartz recrystallized and the grain size increased. Single zoned plagioclase porphyroblasts grew prior to and were mechanically twinned during D_1.

With respect to the porphyroblast growth, a static metamorphism prior to the first deformational event is reasonable. It can be related to a contact metamorphism during intrusion of the Las Verbenas and Bemberg Tonalites as well as the La Escalerilla Granite. No evidence was found to postulate an emplacement-related deformation during contact metamorphism (e.g. clear synkinematic porphyroblast growth). Since former porphyroblasts are entirely replaced by phyllosilicates, the grade of the contact metamorphism can only be broadly estimated to lie in the range of the biotite–andalusite zone (converted chiastolite). There was no difference found between the effects of contact metamorphism of the older Las Verbenas and Bemberg Tonalites and the younger overprint by the La Escalerilla Granite.

Syn- to post-D_1-fabrics

Phyllites. Mostly at the rims, quartz is partly replaced by recrystallization grains with curved to nearly straight boundaries. Fine-grained quartz records complete statically-generated fabrics. Also near the granite contact, larger grains are replaced by coarse recrystallization grains from the rims with straight to slightly curved boundaries.

Old muscovite and biotite are bent, rotated, and reoriented between or on S_1-cleavage planes. Muscovite plates are disrupted, extended, or pieces slipped upon each other. During and after D_1, biotite and partly also muscovite recrystallized. In converted chiastolite, sericite is aligned parallel to S_1 while quartz is flattened and recrystallized. In sericite-aggregates, the fill is mostly aligned in S_1-planes. New muscovite, biotite, and sericite grow parallel to S_1-planes and, together with chlorite, surround rotated old muscovite plates. New biotite partly to entirely replaces biotite plates while sericite grows within muscovite.

Acid meta-magmatic dykes. The dykes consist of a fine-grained and recrystallized quartz–feldspar matrix. The S_1-foliation is indicated by aligned sericite ± muscovite. A few larger muscovite and biotite grains recrystallized syn- to post-D_1. Ductilely deformed quartz phenocrysts are indicated by corrosion embayments and tubes. Alkali feldspar phenocrysts partly enclose small garnet xenoblasts and contain single to densely distributed sericite.

At the rims of quartz, alkali feldspar, and ±plagioclase phenocrysts, neoblasts (recrystallization grains) grew syn- to post-D_1 since many of them are undeformed. The amount of recrystallization of quartz phenocrysts differs considerably: south of the Bemberg Tonalite recrystallization starts only at the margins while north of the tonalite they record advanced and in some pieces almost complete recrystallization. NE of the tonalite, recrystallization of corroded phenocrysts is widely reduced. Furthermore, some clasts are almost entirely recrystallized whilst adjacent phenocrysts do not record such fabrics. Hence, it can be assumed that some recrystallized clasts derived from the basement.

Tonalites. In the Las Verbenas Tonalite, magmatic quartz is elongated in S_1 and in many cases entirely recrystallized recording granoblastic textures. In some parts, it displays ductile deformation phenomena and, as partly zoned plagioclase, is surrounded by undeformed neoblasts (recrystallization grains) along the rims. Magmatic biotite plates display varying orientations with respect to, or are aligned in, the pronounced S_1-foliation together with metamorphic biotite. Many of them are partly to entirely replaced by metamorphic and undeformed biotite. A few chlorite plates grew parallel to or across S_1.

In the Bemberg Tonalite, mostly recrystallized magmatic biotite displays the S_1-foliation. Amphiboles are aligned with the long axes in S_1-planes and do not indicate an internal deformation. Magmatic quartz records ductile deformation phenomena and contains subgrains. Contrary to the Las Verbenas Tonalite, only a few recrystallization grains occur at the rims.

As in the Las Verbenas Tonalite, zoned plagioclase grains are filled with or contain single epidote and clinozoisite grains as well as additional sericite. However, no clear recrystallization grains could be detected. At the southern margin of the pluton, and within a cross-cutting granitic dyke, plagioclase is densely filled with epidote and clinozoisite, and quartz records an advanced stage of static recrystallization. In the dyke, most of the matrix consists of epidote minerals and only a few K-feldspar grains could be detected. On the contrast, a deformed granitic dyke, cutting across the northern margin of the tonalite, contains well-preserved plagioclase with minor alterations into sericite. The same could be found in the tonalite.

Micaschist Group

In the micaschists, muscovite plates are bent and kinked during D_2 and are partly replaced by smaller muscovite sheets and sericite which grew syn- to post-D_2. Recrystallized biotite plates are aligned parallel to S_2 together with new biotite and muscovite which grew also oblique to S_2. Old quartz grains are flattened in S_2 and are mostly replaced by recrystallization grains at the margins. Small plagioclase is flattened between mica-rich layers whilst only a few microcline could be detected. At some boundaries to plagioclase or quartz, heavy minerals are accumulated indicating pressure solution during D_2.

At one locality on the asphalt road to La Carolina, xenoblastic to hypidioblastic staurolite (Fig. 13b) partly encloses a planar internal fabric (opaque dust, quartz grains) which is approx. parallel to S_2-planes. Without distortion, opaque needles in the matrix are overgrown by rims of single staurolite. As no clear indication was found to postulate a growth pre- and/or syn-D_2, it can be assumed that staurolite grew after the D_2-deformation at this locality.

In the matrix of some samples, pre-D_2 sillimanite and fibrolite fibres are aligned with the long axes in S_2-planes, partly stretched and disrupted, while some of them are folded between S_2-layers. Sheared and flattened muscovite–sericite aggregates contain phyllosilicates and fibrolite needles aligned in S_2. Garnet is affected by S_2-shearing and stretching. In the hinge zones of F_3-microfolds, biotite and muscovite are polygonally recrystallized. Statically-grown quartz recrystallization grains record only a slight bending.

Shear and mylonite zones

In the shear zones of the Las Verbenas Tonalite, magmatic quartz and plagioclase are elongated in the mylonitic foliation and replaced by smaller recrystallization grains at the margins. Plagioclase is partly converted into clusters and single grains of epidote and clinozoisite which are also aligned in S_1-planes. Biotite is re-oriented in the foliation and partly to entirely recrystallized. Smaller new biotites are aligned in S_1.

In the shear zones at the northern contact of the La Escalerilla Granite (east of Ea. Pancanta), deformed magmatic quartz is partly replaced by undeformed recrystallization grains. Alkali feldspar and some microcline can be disrupted within the S_1-foliation. Recrystallization grains replace magmatic grains mostly at the rims. Recrystallized muscovite flakes are oriented parallel or at different angles to foliation planes whilst newly grown plates surround feldspar clasts. In the center of the shear zones, quartz recrystallization grains are either strain-free or record ductile deformation phenomena in distinct layers. Within some layers, magmatic alkali feldspar is entirely replaced by recrystallization grains which also cover the rims of larger porphyroclasts (Fig. 13c). In smaller

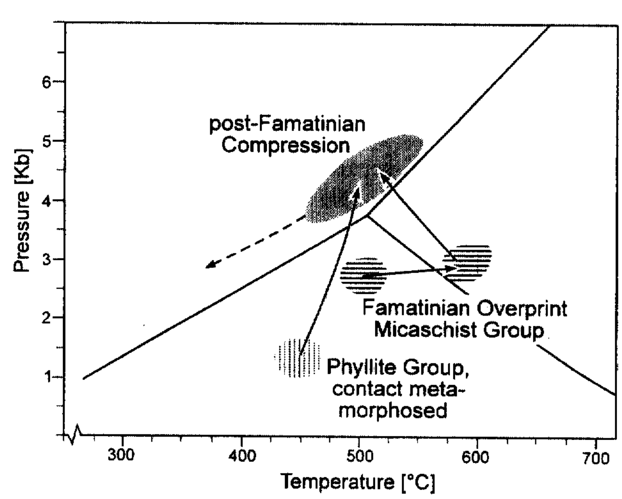

Fig. 14. Simplified P/T-diagram with broadly estimated conditions for the Famatinian and post-Famatinian metamorphic overprints in the different units of the study area. Solid arrows indicate the assumed paths for the Phyllite and Micaschist Group, dashed arrow the possible final stage of post-Famatinian compression. Aluminum silicate phase boundaries and triple point after Holdaway & Mukhopadhyay (1993).

shear zones and shear planes, the microfabrics are as in the normal granite without a clear mylonite foliation.

Within the shear zones of the Phyllite Group, the S_1-foliation is depicted by aligned and recrystallized (asymmetric) muscovite and biotite. In S_1-planes, quartz is flattened and recrystallized. Late chlorite grew at the expense of recrystallized biotite.

In the mylonite zones of the eastern basement rocks, isolated clasts of plagioclase, alkali feldspar, and quartz–feldspar aggregates are surrounded by ductilely elongated quartz layers which are partly to entirely replaced by recrystallization grains. The clasts are partly disrupted and plagioclase contains deformation twins. Recrystallization grains at and along the margins of both feldspars display granoblastic textures with straight boundaries. In some layers, feldspar is entirely replaced by recrystallization grains. These features of recrystallization could be also detected in the granite mylonite at the eastern margin of the La Escalerilla Granite. In the wide mylonite zone at the La Melada Complex, however, feldspar is dynamically recrystallized in fine-grained layers, and such recrystallization also occurs at and within feldspar clasts or aggregates.

Garnet xeno- to idioblasts were affected by stretching. Biotite fills their pressure shadows, cracks, and joints or entirely converted them. Recrystallized biotite and muscovite are aligned parallel to the S_{my}-foliation. In parts of the mylonites, sillimanite needles are aligned, stretched, bent, and/or kinked in the foliation. They are either overgrown by biotite flakes or surrounded by layers of biotite and/or ductilely deformed quartz.

In the shear and mylonite zones, shear sense indicators on a micro-scale are asymmetric σ-clasts (e.g. mica, plagioclase, alkali feldspar, polycrystalline quartz–feldspar and sericite–muscovite aggregates), shear bands, and S/C-fabrics. With additional, single quartz δ-clasts and ~W-vergent microfolds in the mylonites, they support the sense of shear found in the field.

Regional metamorphism

The different minerals and mineral reactions suggest that during D_1-deformation the regional metamorphic overprint in the Phyllite Group, its contact metamorphosed equivalents, and different intrusions exceeded temperatures at least of the higher greenschist facies. Such a thermal overprint is also shown by comparable microfabrics within cleaved, foliated, and mylonitized parts of the meta-sediments and magmatics and is supported by recrystallization of feldspar. Chiastolite as well as additional porphyroblasts, related to the initial contact metamorphism, were entirely replaced by sericite ± quartz aggregates.

The D_2- and D_3-deformations of the Micaschist Group were accompanied by a comparable greenschist facies overprint which also led to recrystallization of feldspar. The only local occurrence of staurolite indicates amphibolite facies conditions probably after the D_2- and prior to the D_3-deformation. The areal extent of the amphibolite facies, however, is unclear since additional locations with staurolite were not found in the study area. The broadly estimated conditions of the different metamorphic overprints in the Phyllite and Micaschist Group are depicted in a simplified and preliminary diagram (Fig. 14). There, andalusite growth is assumed for the initial stage of the prograde, Famatinian metamorphism in the micaschists (see above).

After cessation of compression, greenschist facies metamorphism continued under static conditions. These are recorded by statically annealed quartz fabrics, which were also found in shear and mylonite zones, and a random growth of muscovite, biotite, and final chlorite which partly replaces biotite. With respect to recrystallization of quartz, both feldspars, and micas, outlasting deformation, the mylonites can be ascribed as blastomylonites. Also comparisons of recrystallization, grain growth, and microfabrics in the mylonites of the La Escalerilla Granite and eastern basement suggest that intense shearing took place during the D_2-event of the micaschists although some older or reactivated basement mylonites cannot be excluded.

In parts of the mylonite zones, however, continuing deformation led to dynamic recrystallization of quartz and feldspar. This accounts for those in the La Melada Complex while thinner mylonites to the west are more statically annealed. Such differences could be detected also in the micaschists and are related to continued shearing under greenschist facies conditions within distinct layers whereas adjacent parts were affected by static grain growth. A subsequent slight ductile deformation within a few parts, was also found in the units to the west.

BENDING OF THE LA ESCALERILLA GRANITE

With respect to the present curved shape of the La Escalerilla Granite, several facts have turned out to be important.

The western contact of the granite against the Phyllite Group or Las Verbenas Tonalite is intrusive. The same applies to the western contact of the tonalite against the Phyllite Group. The eastern margin of the granite is indicated by a mylonite zone along

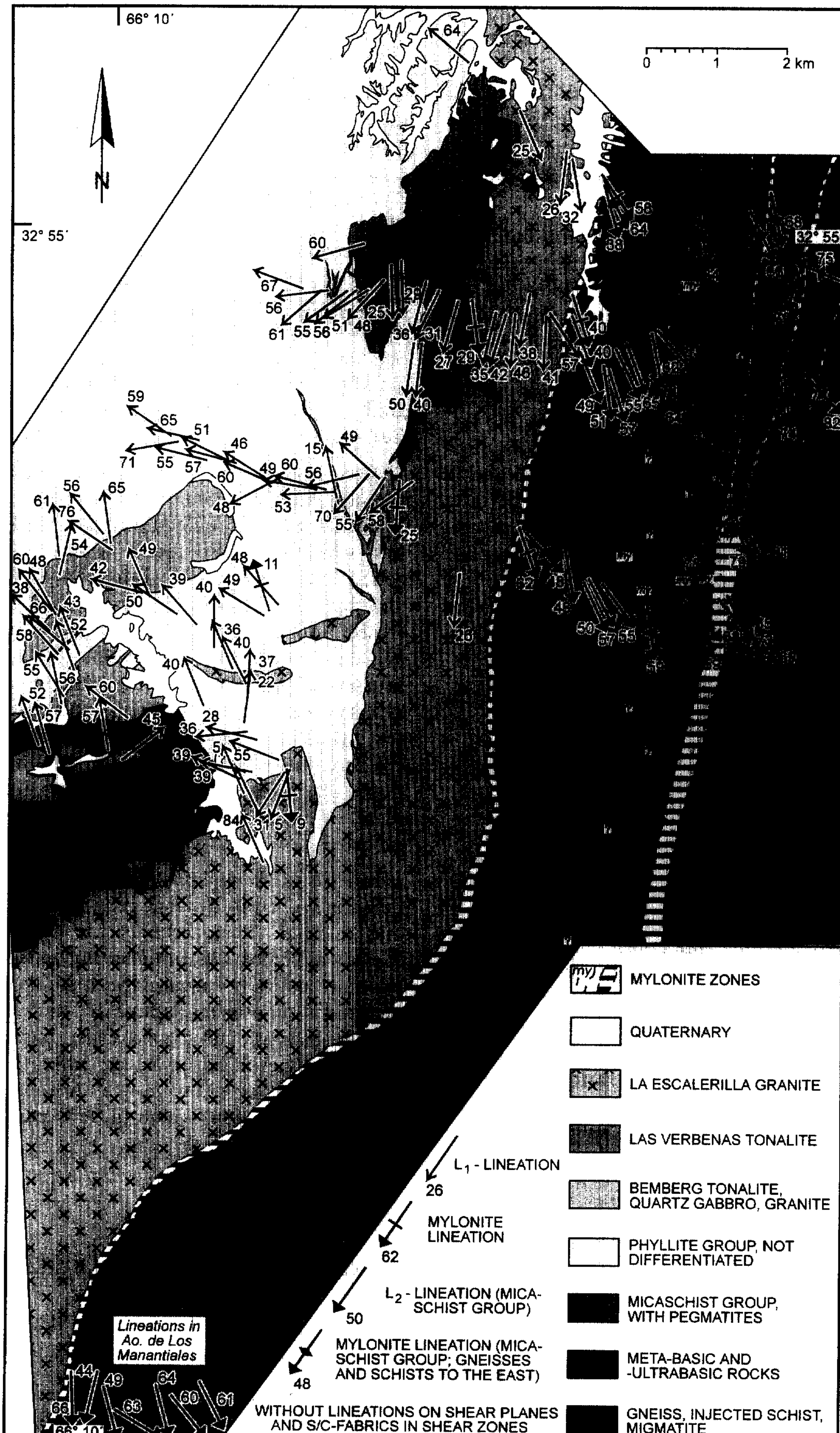

Fig. 15. Orientations of lineations in the different units south of Valle de Pancanta; lineations on strike-slip faults in the intrusions are omitted. See Fig. 2 for location of map.

which the eastern Micaschist Group was thrust over the pluton. A sinistral component led to a ~NW- to NNW-directed displacement which was also found in the northern along-strike continuation south of La Carolina (v. Gosen & Prozzi, 1996). East of the Micaschist Group, some mylonite zones also record an oblique, sinistral component during high-angle reverse faulting.

The granite is truncated by mostly ~NNW–SSE trending sinistral shear zones which also displace the contacts with the Phyllite Group and Las Verbenas Tonalite (Fig. 12). They are oblique to the NNE–SSW trend of the granite in the north and almost perpendicular to its ~W–E trending part in the south. Together, the ~NNE–SSW trending dextral shear zones and ~NNW–SSE sinistral zones represent a conjugate set indicating ~WNW–ESE compression. The shear zones do not cut across and displace the mylonite zone along the eastern granite margin. This suggests that the shear zones and mylonite zone were generated simultaneously which is also supported by the microfabrics. Since the shear zones and eastern mylonite zone are directly related to the S_1-foliation and L_1-lineation within the granite and tonalite, they are not the effect of a later deformation post-D_1.

Sinistral shear zones within the contact metamorphosed Phyllite Group to the north of the ~W–E trending part of the La Escalerilla Granite can be directly compared or connected with equivalents in the granite. F_1-folding in the Phyllite Group, related S_1-cleavage planes, and L_1-lineations are connected with the sinistral shear zones which are not the effect of a later deformational event. Hence, the bending of the Phyllite Group, following the trend of the granite margin, took place together with the bending of the granite.

This all suggests that F_1-folding with related fabrics, ductile shear zone deformation, and mylonite formation along the eastern granite margin took place during one single deformation which is the first event in the Phyllite Group and different intrusions. It can be related to the fabrics of the D_2-event within the Micaschist Group in the east. This deformation was the result of an overall ~WNW–ESE compression. Such a common deformation of the different units was also found in the area south of La Carolina (v. Gosen & Prozzi 1996) where the Phyllite Group is tightly folded around NNE–SSW trending axes.

Based on these observations, it is reasonable to suggest that the present shape of the granite is the result of compressive deformation. Thus, only the fabrics of the D_1-deformation (D_2 in the micaschists) can be related to the compressive event which led to the bending of the granite and adjacent units. The dominant sinistral shear zones, indicating a relative uplift of the eastern blocks, and the mylonite zone with an oblique sinistral displacement of the Micaschist Group, suggest that an overall sinistral component affected the granite, tonalite, Phyllite and Micaschist Group during ~WNW–ESE compression.

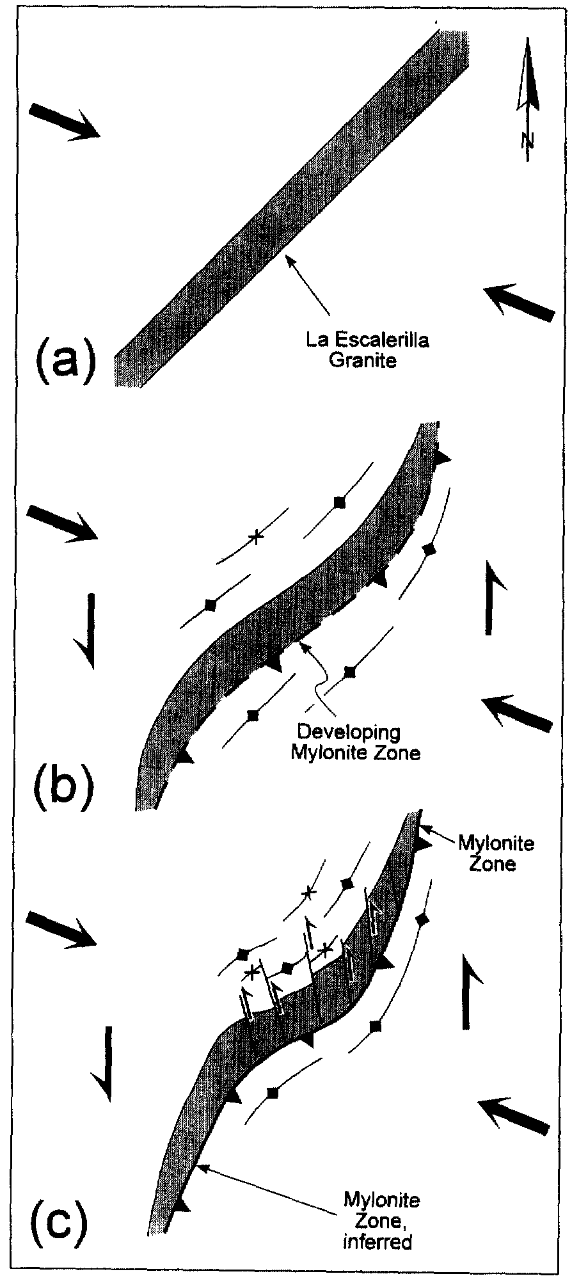

Fig. 16. Schematic cartoons to illustrate the bending of the La Escalerilla Granite and adjacent meta-clastic units under sinistral transpression. (a) Initial situation with an elongate, ~NE–SW orientation of the granite pluton. (b) ~WNW–ESE compression leads to bending of the stiff pluton with an onset of folding in the incompetent country rocks and mylonite formation at the eastern granite margin. (c) Final stage of compressive movements is indicated by a combination of folding, mylonite formation at the eastern granite margin, and sinistral shear zone deformation in the bent granite. The interpretation assumes a rigid pluton with respect to the incompetent and more ductilely deformed country rocks.

This is also supported by the different orientations and distributions of fabric elements within the granite and Phyllite Group. As an example, the trend of the lineations is depicted on Fig. 15. To the west of the granite, the L_1-lineations are more or less perpendicular to the curved trend of the main units. In the Micaschist Group they have a southeastern plunge, while in the La Escalerilla Granite and Las Verbenas Tonalite SSE to S plunging lineations dominate (see also Fig. 12). The studied mylonite zones in the eastern basement record ~WNW-directed high-angle reverse displacements with or without a sinistral component.

With these observations taken together, it can be postulated that the initial shape of the La Escalerilla Granite after emplacement was elongated in a ~NE–SW trend (Fig. 16a) and probably followed an old fault zone. During ~WNW–ESE compression, leading to folding in the country rocks, the northern (and possibly also southern) parts of the elongated, more competent pluton were passively rotated counterclockwise and forced into the general (NNE–SSW) structural trend (Fig. 16b). The central part of the pluton, however, remained in the initial position. Such a model implies a sinistral component during compression which is documented by the displacements along dominant sinistral shear and mylonite zones (Fig. 16c). It also explains the differences in intensity of the D_1-deformation within and between the northern and central part of the granite pluton.

The interpretation implies that the deformation took place under sinistral transpression. A synkinematic emplacement of the granite could not be proved but cannot be excluded. In the units to the east of the study area, however, only minor fabrics of a sinistral transpression were found, whereas to the west, major fault lines record a clear sinistral component (v. Gosen & Prozzi 1998). Thus, the transpressive effects cannot be related only to the initial shape and orientation of the granite pluton within the more incompetent country rocks.

TIMING OF EVENTS

The Lower Ordovician age of the Bemberg and Tamboreo Tonalites (Sims *et al.*, 1997) and initial contact metamorphism probably also applies to the Las Verbenas Tonalite. Since the undeformed clastic sequence of the Phyllite Group was intruded by the tonalites, it is reasonable to postulate that it represents a time equivalent of the Puncoviscana Fm.s.l. of northwest Argentina which has a Late Precambrian–Early Cambrian age (e.g. Aceñolaza *et al.*, 1978; Toselli & Aceñolaza, 1978; Ježek *et al.*, 1985; Willner *et al.*, 1987; Aceñolaza *et al.*, 1988; Adams *et al.*, 1989).

The age of deposition of the Micaschist Group s.l. to the east of the La Escalerilla Granite is difficult to constrain. As the micaschists were deformed at least once prior to the intrusion of the La Escalerilla Granite, which has an Early Devonian age of crystallization (Sims *et al.*, 1997), they either could be older than the (undeformed) Phyllite Group or represent their deeper crustal equivalents. Since gradual metamorphic and structural transitions between both units exist in the western part of the Sierra de San Luis (v. Gosen, 1998), the Micaschist Group could represent a higher-temperature equivalent of the Phyllite Group in the west. This is supported by a comparable lithologic content indicating a turbiditic succession.

East of the study area, Llambías *et al.* (1991) have reported a Rb–Sr whole rock age from the Paso del Rey Granite. The 454 ± 21 Ma age can be related to a Middle to Upper Ordovician intrusive activity. Since first deformation and metamorphism of the micaschists also affected this granite, they probably took place during ? Middle to Upper Ordovician times and can be compared with the D_1-event plus metamorphism in the micaschists of the study area during the Famatinian cycle.

Deformation and regional metamorphism, affecting the La Escalerilla Granite, should be Devonian (post-Famatinian) in age (see also Sims *et al.*, 1997). This also accounts to equivalent fabrics in the tonalites, Phyllite Group, and Micaschist Group along with the transpressive mode of compression. From the Río de la Carpa and Paso del Rey Granite, Varela *et al.*, (1994) report biotite K–Ar data of 372 ± 20, 381 ± 13, and 391 ± 9 Ma which are older than one date from the La Escalerilla Granite (353 ± 15 Ma; Linares & Latorre 1973). They can be related to the closure of the K–Ar system in the Phyllite and Micaschist Groups within the Devonian interval. This would suggest that compressive deformation in the Phyllite Group and Micaschist Group were finished prior to the Upper Devonian. A comparable timing can be inferred for the study area.

REGIONAL IMPLICATIONS

Given that the Phyllite Group represents an equivalent of the Late Precambrian–Early Cambrian Puncoviscana basin of northwest Argentina, then the clastic deposits had a wide areal extent also outside the Sierra de San Luis with a thickness of more than 3 km (v. Gosen & Prozzi, 1996; see also Prozzi & Ortiz Suárez, 1994; v. Gosen, 1998). As the Micaschist Group can be interpreted as an equivalent of the Phyllite Group, the maximum initial thickness of the clastic succession was much greater.

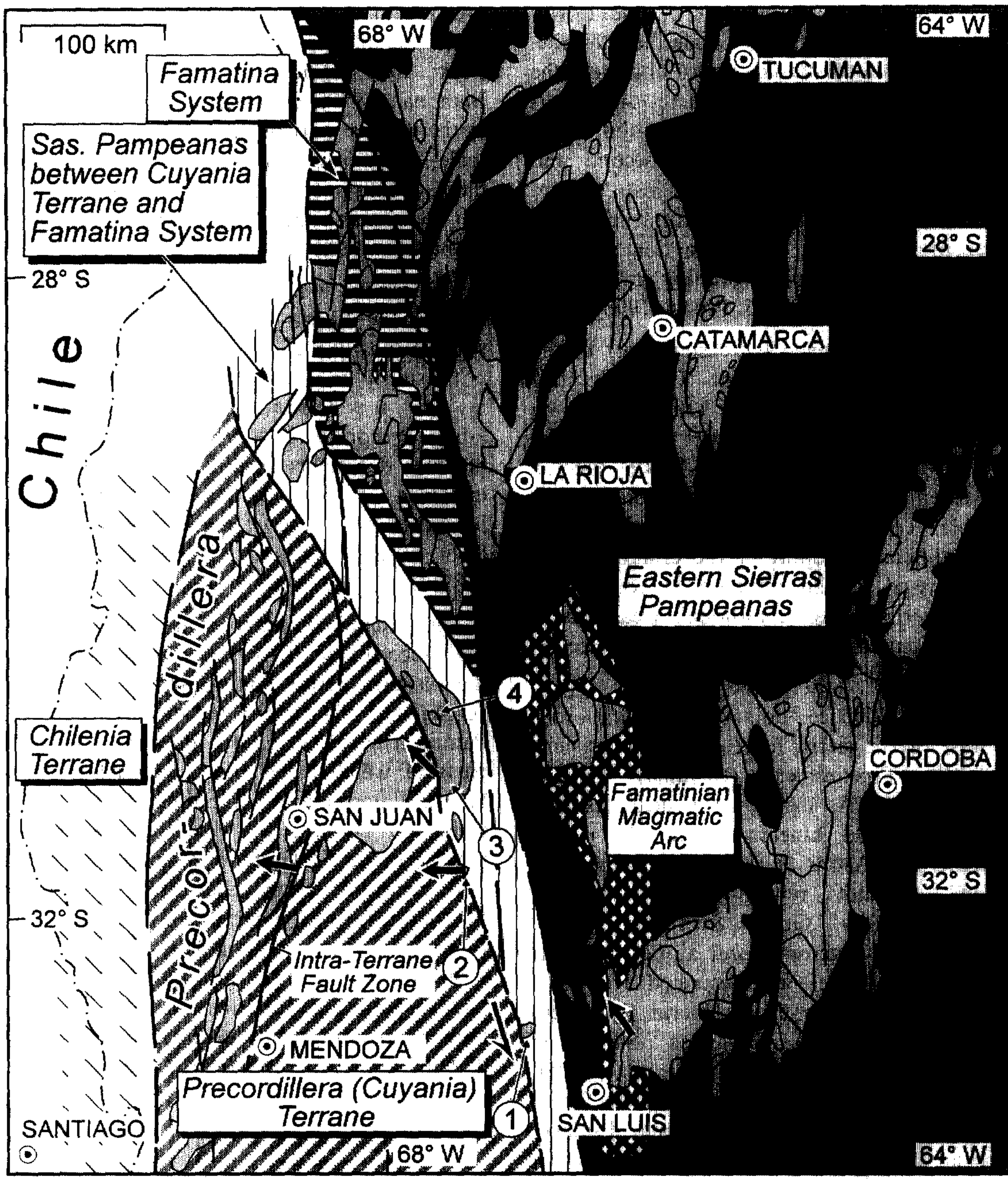

Fig. 17. Simplified and interpretative sketch map of the main geotectonic units in the west-Argentine Andes, based on Willner *et al.* (1987), Miller & Neugebauer (1990), Simon & Rossello (1990), Vujovich (1994), Schmidt *et al.* (1995), Ramos et al. (1996), Schetselaar *et al.* (1996), v. Gosen & Prozzi (1998), and own investigations. Tectonic boundaries are inferred, arrows indicate tectonic transports; 1–Sierra de El Gigante, 2–Sierra de Guayaguas, 3–Sierra de La Huerta, 4–Sierra de Valle Fértil.

This "cover sequence" can be separated from the pre-Famatinian basement complex in the western part of the sierra (Llambías *et al.*, 1996b; v. Gosen & Prozzi, 1998). This is supported by the fact that the Gasparillo Tonalite intruded both the western basement and the adjacent Phyllite Group to the east in a high crustal level (v. Gosen & Prozzi 1998). The same accounts for the basement in the western part of the study area which also must have been juxtaposed against the Phyllite Group prior to the intrusion of the tonalites of the Bemberg pluton and the muscovite granite at the contact.

The tonalite intrusions in the study area, as well as those to the north, are part of the Famatinian magmatic arc (e.g. Sato *et al.*, 1996; present Fig. 17) due to east-directed subduction beneath the Eastern Sierras Pampeanas (Ramos, 1991; "Pampean Terrane": Ramos, 1988). Famatinian deformation of the Micaschist Group was followed by the Lower Devonian intrusion of the La Escalerilla Granite. Based on the first deformational fabrics observed, the western strip of the Phyllite Group in the sierra was affected only by compression during the post-Famatinian cycle which comprises the second and partly third event within the Micaschist Group. Contraction with regional metamorphism led to a sinistral transpressive mode of deformation which is supported by sinistral strike-slip faulting in the western part of the sierra (v. Gosen & Prozzi, 1998).

The thick mylonite zone in the eastern part of the study area represents one part of the "Faja milonítica La Arenilla" of Ortiz Suárez *et al.* (1992) extending through the entire south western part of the sierra. Within the mylonites, high-angle, ~WNW-directed reverse movements with a partial sinistral component are reasonable. To the south, comparable displacements led to differential uplift of the eastern blocks and are interpreted as the response of contraction within the "cover sequence", although (reactivated) Famatinian mylonites cannot be excluded (see v. Gosen & Prozzi 1998).

The structural evidence points to a first-order fault line west of the sierra representing the eastern margin of the Precordillera (Cuyania) Terrane (Ramos *et al.*, 1996). As location for such a suture zone, the "Valle Fértil Lineament" can be postulated (compare e.g. Astini *et al.*, 1995; Schmidt *et al.*, 1995; C. Schmidt: report during the 1995 Penrose Conference; v. Gosen & Prozzi, 1998). Although only a few outcrops occur along the lineament (Fig. 17), mylonites are described from the western slope of the Sierra de la Huerta (Vujovich, 1994) and the Sierra de Guyaguas (Simon & Rossello, 1990; see also Schmidt *et al.*, 1995). Observations from the western margin of the Sierra de El Gigante suggest a sinistral strike-slip displacement along an inferred Early Paleozoic fault which was reactivated during Andean compression (Schmidt *et al.*, 1995; Schetselaar *et al.*, 1996). My observations support those of the above authors. In addition, the sense of shear, deduced from the thick pile of eastward-dipping mylonites at the western slope of the Sierra de la Huerta and the Sierra de Guyaguas, indicates that ~W-directed displacements of the eastern hanging wall blocks were partitioned along distinct layers recording NW- to N-directed transports.

Combined with the sinistral transpressive mode of post-Famatinian compression in the western part of the Sierra de San Luis, an oblique collision with the Precordillera (Cuyania) Terrane can be assumed although its precise timing outside the sierra is not constrained by radiometric dating. Such a general mechanism, resulting in a partitioning between strike-slip displacements and structures of orthogonal compression in the overriding plate and a rearrangement of crustal blocks at and along its leading edge (e.g. Beck, 1983; Oldow *et al.*, 1990, Tikoff & Saint Blanquat, 1997), could explain sinistral transpression in the western part of the Sierra de San Luis. A large-scale, transcurrent transfer of its western basement block during post-Famatinian contraction, however, is not reasonable but cannot be excluded for pre-Famatinian fault tectonics.

The present observations from the "suture zone" outside the Sierra de San Luis suggest that compression partly was oblique, however, it probably did not result in an overall, sinistral strike-slip transfer. In my view, it is more reasonable to assume that the colliding Precordillera (Cuyania) Terrane acted as an indenter due to its curved outer shape (Fig. 17). An influence of indenting terranes/plates or a reverse indenting of a cratonic promontory are described from other orogens (e.g. Eisbacher, 1985; Hatcher, 1989; Lu & Malavielle, 1994).

This preliminary interpretation shows that between the Precordillera (Cuyania) Terrane in the west and the Eastern Sierras Pampeanas in the east, an intervening slice of (? mixed and/or tectonically disturbed) Pampean basement can be postulated (Fig. 17), most parts of which have been attributed to the Western Sierras Pampeanas by Caminos (1979). This is indicated, for example, by widely distributed marbles in the Sierra de El Gigante (Gardini, 1993) which are not reported from the Sierra de San Luis. Furthermore, the pinched in tectonic body of the Famatina System to the north (Miller & Neugebauer, 1990) suggests a separation from this basement slice and a southward continuation of at least one major fault line passing through the area west of the Sierra de San Luis (see Aceñolaza & Toselli, 1988).

CONCLUSIONS

The different stages of the evolution of the metamorphic complex can be summarized and interpreted as follows.

(1) The monotonous clastic sedimentary sequence of the Phyllite Group is interpreted as a turbiditic succession of probably Late Precambrian–Early Cambrian age. The Micaschist Group presumably represents a deeper crustal equivalent with a comparable age.

(2) The Phyllite Group clastics were intruded by widely distributed acid magmatic dykes and the younger Bemberg and Las Verbenas Tonalites. The Lower Ordovician tonalites led to a contact metamorphism of the country rocks and are related to the Famatinian magmatic arc. The pre-Famatinian basement in the western part of the

study area was lifted prior to the intrusion of the plutons (v. Gosen & Prozzi 1998).

(3) Prior to intrusion of the La Escalerilla Granite, the Micaschist Group was affected by at least one compressive deformation, injection of widely distributed pegmatitic layers, and an amphibolite facies metamorphism. These events can be assigned to the ? Middle to Upper Ordovician interval and belong to the Famatinian cycle.

(4) The Lower Devonian La Escalerilla Granite (Sims *et al.*, 1997) intruded the undeformed clastic sequence of the (later) Phyllite Group plus acid magmatic dykes and the Las Verbenas Tonalite. The clastic sediments were affected by a thermal overprint.

(5) All above units were deformed under ~WNW–ESE compression which is the second event within the Micaschist Group. The Phyllite Group was folded and cleaved, and the tonalites and granite were (heterogeneously) foliated.

(6) Mostly sinistral shear zones within the La Escalerilla Granite, Las Verbenas Tonalite, and adjacent parts of the Phyllite Group were generated during compressive deformation which led to folding in the Phyllite and Micaschist Groups. They were formed together with a mylonite zone at the eastern margin of the granite along which the Micaschist Group was thrust northwestwards with an oblique sinistral component. These fabric elements are related to the bending of the granite under sinistral transpression. It presumably was also influenced by an initial, ~NE–SW elongated shape of the pluton and is supported by strike-slip faulting in the western part of the sierra. East of the granite, a sinistral component is partly recorded in some mylonite zones.

(7) Compressive deformation was accompanied by a greenschist facies metamorphism which also led to ductile deformation and recrystallization of feldspar. Only at one locality in the micaschists, amphibolite facies conditions are indicated by the growth of staurolite. Static metamorphic conditions outlasted compression while some parts of the different units record continuing ductile deformation.

(8) The age of crystallization of the La Escalerilla Granite and a few radiometric data from other areas of the Sierra de San Luis suggest that post-Famatinian compressive deformation and regional metamorphism are Devonian in age (see also Sims *et al.*, 1997).

Some evidence from outside the sierra makes it possible to assume that displacements along the major boundary within the basement of the Sierras Pampeanas ("Valle Fértil Lineament") were combined with the sinistral transpressive mode of compression in the study area and related to the indenting Precordillera (Cuyania) Terrane in the west. By this, a Devonian age for this major event within the Sierra Pampeanas can no longer be excluded.

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