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ARTICLE

Lithologies, structure and basement-cover relationships in the schist belt of the Dom Feliciano Belt in Uruguay

Litologias, estrutura e relações embasamento-cobertura na Faixa de Xistos do Cinturão Dom Feliciano no Uruguai

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ABSTRACT: This work is the result of a multiyear effort to use field geology to describe lithologies, to establish contact relationships and to create a sketch of the tectonic evolution of the Meso- to Neoproterozoic metasedimentary successions within the Schist Belt of the Dom Feliciano Belt. This low-grade metamorphic cover rests on the high-grade metamorphic basement of the La China and Las Tetas complexes. This basement is Archean-Paleoproterozoic in age. The Schist Belt is overlapped unconformably by the Barriga Negra formation. The Lavalleja complex and the Barriga Negra formation both deformed together during the D2 deformation event (~ 570 –540 Ma), but the Barriga Negra only partially recorded the D2 transpressive event, whereas the Lavalleja complex was affected by both the D1 tangential event and the D2 event. Event D1 would have developed a fold nappe with vergence to the south. This hypothesis is supported by different structures: (i) recumbent and upright folds oriented E-W, (ii) subhorizontal mylonitic foliation in marbles (calc-schists), (iii) stretching lineations plunging towards the SW in metaconglomerates of the Las Tetas Complex, and (iv) a reworking of the subhorizontal foliation parallel to the Sarandí del Yí strike-slip shear zone.

KEYWORDS: Dom Feliciano Belt; Ediacaran; Deformation; Fold nappe; Tectonic evolution.

RESUMO: *Este trabalho resulta de um esforço de vários anos tentando usar a geologia de campo para descrever litologias, estabelecer relações de contato e perfazer a evolução tectônica das sucessões metassedimentares, de idades meso a neoproterozoicas, que foram deformadas dentro da Faixa de Xistos do Cinturão Dom Feliciano. Essas rochas constituem uma cobertura de baixo grau que repousa em cima do embasamento de alto grau metamórfico dos complexos La China e Las Tetas. Esse embasamento é de idade paleoproterozoica-arqueana. A Faixa de Xistos é sotoposta em discordância angular pela formação Barriga Negra. O Complexo Lavalleja e a formação Barriga Negra se deformaram junto durante o evento D2 (~ 570 – 540 Ma), mas a formação Barriga Negra registrou apenas parcialmente o evento transpressivo D2, enquanto o Complexo Lavalleja foi afetado pelos dois eventos (D1 e D2). O evento D1 teria desenvolvido uma dobra – nappe com vergencia para o sul. Essa hipótese é sustentada por diferentes estruturas: (i) dobras recumbentes e dobras retas orientadas E-W, (ii) Foliação subhorizontal milonítica em mármores (calco-xistos); (iii) lineações de estiramento mergulhando para SW em metaconglomerados do Complexo Las Tetas, e (iv) retrabalhamento da foliação subhorizontal, paralelamente à zona de cisalhamento transcorrente Sarandí del Yí.*

PALAVRAS-CHAVE: *Cinturão Dom Feliciano; Ediacarano; Deformação; Dobra-nappe; Evolução tectônica.*

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INTRODUCTION

In recent years, the number of isotopic data regarding absolute ages of the Precambrian rocks of the Dom Feliciano Belt (DFB), in Uruguay (Fig. 1), has exponentially increased (Hartmann *et al.* 2001, Mallmann *et al.* 2007, Oyhantçabal *et al.* 2009, 2011a, 2011b, Gaucher *et al.* 2011, Aubet *et al.* 2012, Rapalini *et al.* 2015, Peçoits *et al.* 2016, Oriolo *et al.* 2016a, 2016b). A review of the currently available information leads to the conclusion that, although variable, the stratigraphy, the distribution and the age of these units remain ambiguous (Aubet *et al.* 2014). Although geological maps of the area are scarce, several authors have coined new formations and magmatic and metamorphic complexes (*e.g.*, Bossi & Gaucher 2014). However, it is unclear whether many of these really exist or are only a result of overinterpretation of these isotopic data. Meanwhile, the physical criteria for separating basement from cover rocks are the metamorphic grade, contact relationships, cartographic limits and style differences in deformation. However, many contact relationships between basement and low-grade cover successions have been neglected, and cartographic boundaries changed with each stratigraphic interpretation. Furthermore, a detailed structural analysis was made in small areas to build up local tectonic sketches (Rossini & Legrand 2003, Mallmann *et al.* 2007, Scaglia *et al.* 2007, Cabrera 2014, Silva Lara *et al.* 2016, among others), but it was difficult to extrapolate their results to the whole study region.

The DFB is a rude set of crustal blocks of Paleoproterozoic/Archean ages that underwent significant orogenic reworking ca. 2.2 – 2.0, 1.7 and 0.6 Ga (Saalmann *et al.* 2011, Oriolo *et al.* 2016a, 2016c). Each Archean-Paleoproterozoic block is covered by Meso- to Neoproterozoic successions of the "Schist Belt" (Basei *et al.* 2000). Meanwhile, the entire structure of this belt is due to the last Ediacaran transpressive collision and exhumation stage (~ 580 – 550 Ma), which developed after a protracted and multiepisodic set of subduction-type orogens (Siegesmund *et al.*, 2011). However, many tectonic structures suggest the existence of an earlier fold-and-thrust belt (Basei *et al.* 2000).

The Schist Belt had been separated, so far, into three different successions:

1. late-orogenic "molassic" volcano-sedimentary deposits;
2. a metasedimentary preorogenic succession, related to a passive margin setting (Gaucher 2000) and deposited between ~ 1,000 and 650 Ma (Peçoits *et al.* 2016); and
3. Mesoproterozoic to Cryogenian metavolcano-sedimentary successions (< 1.7 Ga), affected by the most intense transpressive deformation.

The main controversy of interest here is the discussion regarding whether the complete tectono-metamorphic evolution of the DBF includes an early event related to the building of a fold-and-thrust belt, or if the fragmentary evidence of tangential tectonics simply constitutes remains of a previous orogen (Paleoproterozoic?) within terranes of cratonic affinity.

The aim of this work is to describe and discuss contact relationships between the Neoproterozoic cover successions and their plutonometamorphic basement, as well as to make a common structural evolution sketch in six detailed areas, using a combination of tools (Fig. 2).

GEOLOGICAL SETTING

Structure and evolution of the Dom Feliciano Belt

The assembly of West Gondwana was completed at the beginning of the Paleozoic Era, when the Amazonian, West African, São Francisco-Congo, Kalahari and Rio de la Plata cratons, as well as minor cratonic crustal blocks (Fig. 1A), were united by means of several collisional Neoproterozoic orogeneses (Cordani *et al.* 2013). The protracted accretionary orogenic cycle was active from the Tonian period to the early Paleozoic (Leite *et al.* 1998, Saalmann *et al.* 2011, Siegesmund *et al.* 2011) and involved different tectonic, magmatic and metamorphic events, related to the subduction and disruption of oceanic domains, and collisions registered within the resultant orogenic belts (*e.g.*, Dalla Salda 1980, Basei *et al.* 2000).

The DFB (Fragoso Cesar 1980, Fernandes *et al.* 1992) is a Neoproterozoic NNE-trending orogen that represents the South American half of an extended belt (1,200 km) shared with southern Africa (*i.e.*, the Kaoko-Gariep Belt; Fig. 1B). The DFB can be divided into three main geotectonic units:

1. the Granite Belt;
2. the Schist Belt; and
3. the Foreland Belt (Basei *et al.* 2000).

It can also be divided into two longitudinal domains (western and eastern) by the extended Sierra Ballena-Major Gercino transcurrent shear zone (Oriolo *et al.* 2016c; Fig. 1C).

The entire Neoproterozoic history involves two or three superimposed subductions and multiepisodic accreted terranes (Philipp *et al.* 2016). The Western Domain is an assembly of extended blocks of "African" provenance (Oriolo *et al.* 2016c, and references therein) between the Sierra Ballena Shear Zone and the Rio de la Plata Craton (Fig. 1C). One of those blocks contains a Neoproterozoic accreted terrane (*i.e.*, the São Gabriel Terrane) recording two juvenile magmatic arcs (~ 700 – 800 Ma; Passinho and São Gabriel) and fragments of ocean crust (Babinski *et al.* 1996, Leite *et al.* 1998, Philipp *et al.* 2016). Other blocks in this domain are the Encantadas (defined in Rio Grande do Sul, Brazil) and the Taquarembó, Pavas and Villa Serrana blocks, which are represented in Uruguay (Fig. 2A, 2B).

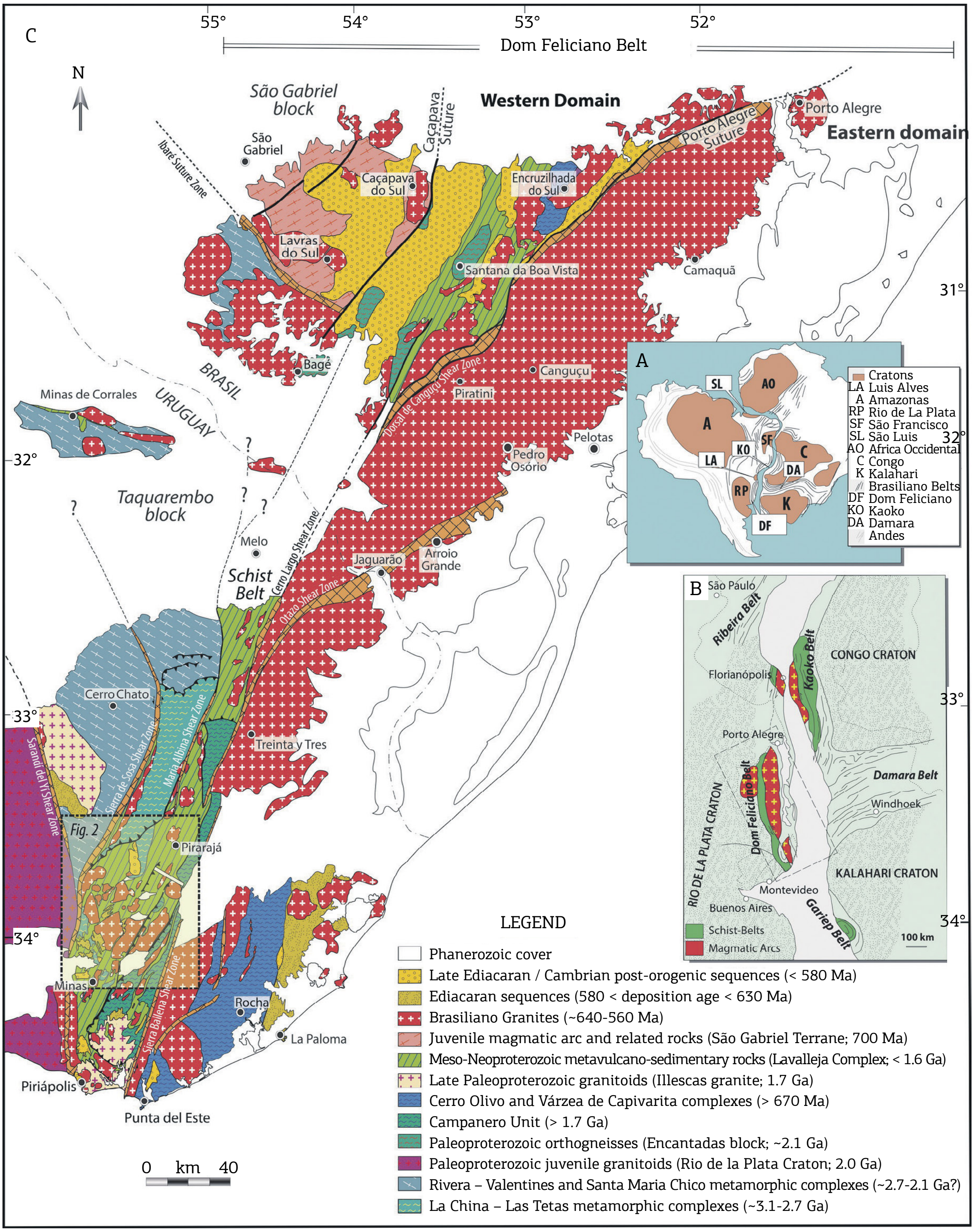

Figure 1. The main tectonic features of the Uruguayan Precambrian Shield. (A) Assembly of Gondwana; (B) the Pan-African-Brasiliano Kaoko-Dom Feliciano Belt; (C) detailed Dom Feliciano Belt and Rio de la Plata Craton border, indicating main structural features.

The Eastern Domain is essentially a granite belt (*i.e.*, the Aiguá-Pelotas Batholith; Masquelin 2006), but there is a high-grade metamorphic complex as well (*i.e.*, the Cerro Olivo complex; Masquelin 2004; Fig. 1C), which contains remnants of I-type metagranitoids in granulite facies yielding ~ 800 Ma magmatic ages (Lenz *et al.* 2011, Masquelin *et al.* 2012). These ages indicate that Tonian juvenile magmatic arcs could be present in the Eastern Domain of the DFB.

Both domains seem to have the same bulk Neoproterozoic history, but the evidence is indisputable in the Ediacaran, which relates a common event of post-collisional transpressive and semi-brittle tectonic escape along several strike-slip shear zones (*e.g.*, Soares & Rostirolla 1997, Passarelli *et al.* 2011, Oyhantçabal *et al.* 2011b, Oriolo *et al.* 2016c).

Previous data and interpretations for the Western Domain of the Dom Feliciano Belt

The Western Domain of the DFB in Uruguay, namely, the Nico Pérez Terrane (NPT; Bossi & Campal 1992; Fig. 2A, 2B), is an assemblage of crustal blocks involved in the Ediacaran orogenesis. However, the structure is the result of a complex history of terrane disruptions that began in the Paleoproterozoic. The main Archean-Paleoproterozoic blocks are:

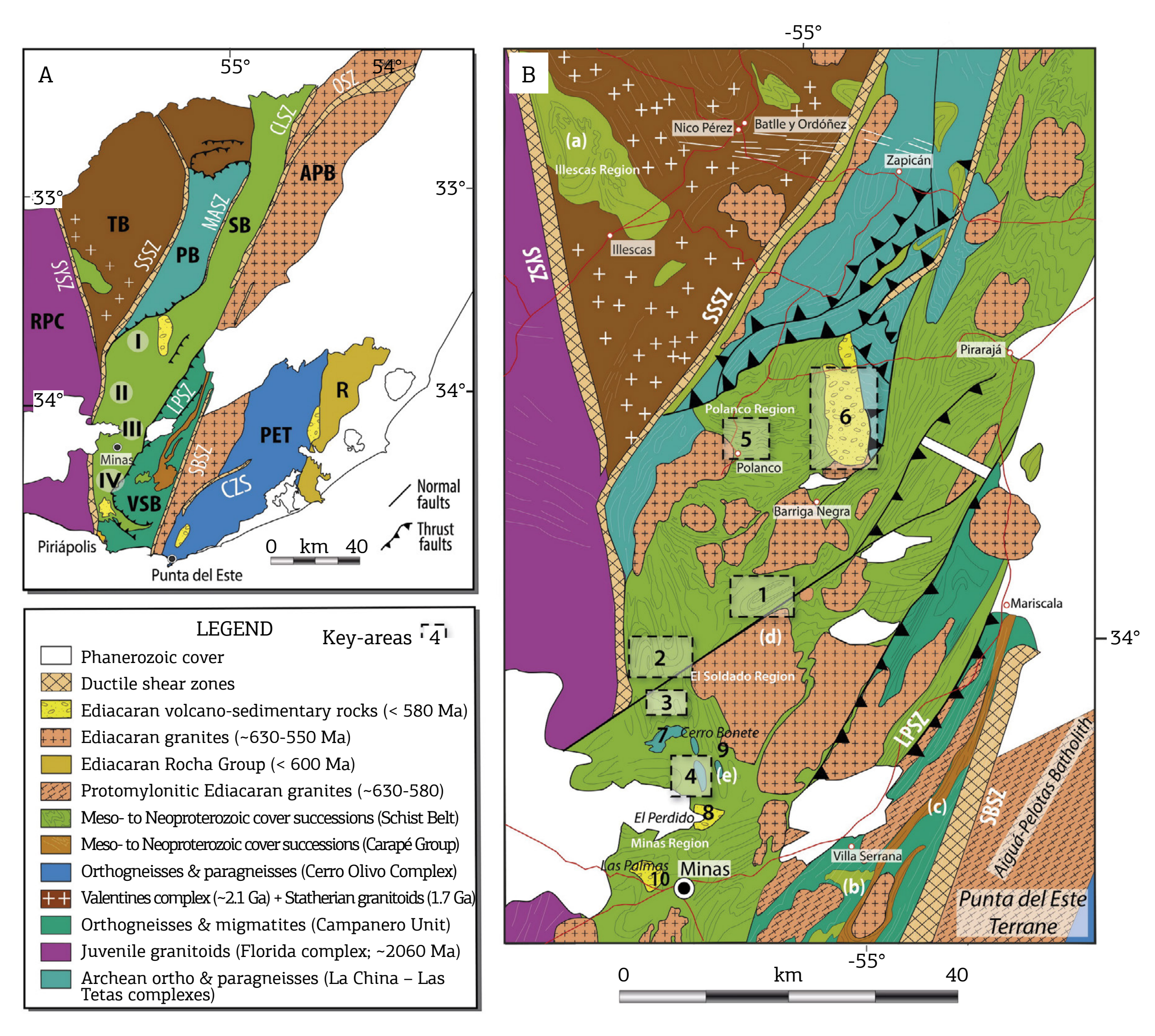

Figure 2. Geological map of the study region, showing key area locations. (A) Blocks: RPC – Rio de la Plata Craton; TB – Taquarembó; PB – Pavas; SB – Schist Belt; VSB – Villa Serrana. Regions: I – Polanco, II – Arroyo del Soldado, III – Minas, IV – Pan de Azúcar. Shear zones: SYSZ – Sarandí del Yí; SSSZ – Sierra de Sosa; MASZ – María Albina; CLSZ – Cerro Largo; SBSZ – Sierra Ballena; LPSZ – La Posada; OTZ – Otazo; CSZ – Cordillera; (B) Key areas: 1. Sepultura, 2. Espuelitas, 3. Romerillos, 4. Buena Vista-Orthez, 5. Barriga Negra, 6. Polanco, 7. Villalba, 8. El Perdido, 9. Cerro Bonete, 10. Las Palmas. Units: (a) Arroyo La Pedrera group; (b) Zanja del Tigre Unit; (c) Carapé Unit; (d) Santa Lucía Granite; (e) Arroyo Perdido Granite.

1. the northern Taquarembó block (Masquelin 2006);
2. the central Pavas block (Preciozzi *et al.* 1985, Oriolo *et al.* 2016a); and
3. the southern Villa Serrana block (Bossi & Gaucher 2004; Fig. 2A).

All the strike-slip shear zones that separate them yield Neoproterozoic (U-Pb in zircon) ages and evolved from amphibolite to greenschist facies conditions (Oriolo *et al.* 2016c). The Schist Belt partly overlies the three blocks.

Different blocks and basement rocks

The Taquarembó block is made up of the Santa Maria Chico (Nardi & Hartmann 1979) and the Valentines-Rivera metamorphic complexes (Oyhantçabal *et al.* 2011a; Fig. 1C). The Santa Maria Chico complex is defined in Rio Grande do Sul and contains ortho- and paragneisses reaching granulite facies at ~ 2.4 Ga (Hartmann 2008). The Valentines-Rivera complex is constituted by mafic and felsic orthogneisses, yielding multistage magmatic ages of ~ 2.17 – 2.11 Ga and reaching granulite facies at ~ 2.08 Ga (Oyhantçabal *et al.* 2012). This block is separated from the Pavas block by the Sierra de Sosa Shear Zone (Preciozzi 1987, Oriolo *et al.* 2016a, 2016c; Fig. 2B).

The Pavas block is constituted by amphibolite-facies metamorphic rocks (*i.e.*, the La China complex) made up of mafic orthogneisses with bulk tonalite–trondhjemite–granodiorite (TTG) protolith composition and U-Pb (SHRIMP in zircon) ages between 3.0 and 2.7 Ga (Hartmann *et al.* 2001, Mallmann *et al.* 2007, Gaucher *et al.* 2011, Oyhantçabal *et al.* 2011a, 2012, Oriolo *et al.* 2016a). This complex outcrops mainly westward of the Maria Albina Shear Zone (Fig. 2B), which is evidenced by a geochemical pattern matching the concentration of chalcophile elements, typical of the presence of mafic rocks (Filippini *et al.* 2001). In contrast, the Las Tetas complex is defined as a succession of metaconglomerates, fuchsite-bearing meta-quartzites, staurolite-garnet micaschists, muscovite-tourmaline gneisses, banded iron formations (BIF) and dolomitic marbles under amphibolite facies (Hartmann *et al.* 2001, Preciozzi 1987, Oyhantçabal & Vaz 1990, Mallmann *et al.* 2007, Bossi & Gaucher 2014, Oriolo *et al.* 2016a). This complex presents solely Archean-aged detrital zircons and is cut thus far by the ~ 2.04 Ga Arroyo Perdido granite (Fig. 2B; Bossi & Gaucher 2014, chap. 6).

Finally, the southern Villa Serrana block (Bossi & Gaucher 2004), named as Eden Terrane (Peçoits *et al.* 2016), is the closest to the Sierra Ballena Shear Zone (Fig. 1C) and is separated from the Pavas block by the La Posada Shear Zone (Guerrero 2016). The basement here is represented by the Campanero Unit, which contains orthogneisses, scapolite marbles, amphibolites, micaschists and BIF (Oyhantçabal 2005). The Campanero Unit yields magmatic ages up to ~ 1.7 Ga (Mallmann *et al.* 2007).

Mesoproterozoic to Cryogenian Lavalleja complex

Under the name of the Lavalleja complex, we grouped different successions of the Schist Belt, containing Mesoproterozoic to Cryogenian metamorphic rocks. A comparative chronostratigraphic table shows the choice adopted for this work (Fig. 3).

The supracrustal association of the Schist Belt was first named the Minas Series (Mac Millan 1933). Thereafter, it was replaced by the Lavalleja group, but without being able to establish boundaries between internal units (Bossi & Navarro 1991). Midot (1984) separated two units, one of metasediments (*i.e.*, the Minas formation) and another of metavolcano-sedimentary rocks (*i.e.*, the Fuente del Puma complex). Therefore, the metasedimentary unit was separated into six formations made up of interbedded sandstones, siltstones and limestones and named the Arroyo del Soldado Group (Gaucher *et al.* 2008, Aubet *et al.* 2012). This group had the virtue of separating units by lithological affinity for the first time (*e.g.*, the Yerbal pelitic formation, Polanco carbonate formation, and Espuelitas black slates formation), but it was wrong to assume stratigraphic profiles that ignored ductile deformation as well as the transposition and duplication of strata. Its deposition age is considered pre-Ediacaran (Peçoits *et al.* 2016).

The Fuente del Puma complex (Sánchez Bettucci & Ramos 1999) contains marbles, phyllites, quartzites and metavolcanic acidic and mafic rocks that were strongly deformed and tectonically intercalated. This assemblage passes laterally through the Minas formation and is now considered Cryogenian-Ediacaran in age (Peçoits *et al.* 2016). The Carapé and Zanja del Tigre units represent Proterozoic cover rocks of the Villa Serrana block (Rossini & Legrand 2003). The Zanja del Tigre unit is made up of dolomitic marbles, calc-silicate rocks, phyllites, metasiltstones, quartzites and metaconglomerates and could represent a lateral equivalent of the Fuente del Puma complex (Sánchez Bettucci *et al.* 2001). The Carapé unit is composed of calcitic marbles, metamarls, garnet-muscovite metapelites, metavolcanic rocks and kyanite-bearing quartzites and reached amphibolite facies metamorphism (Rossini & Legrand 2003). The two units are considered Mesoproterozoic in age (Peçoits *et al.* 2016).

Ediacaran cover successions

Based on detrital zircon contents (Basei *et al.* 2005, Blanco *et al.* 2009, Rapalini *et al.* 2015, Peçoits *et al.* 2016), the clearly discordant formations are younger than ~ 580 Ma (*i.e.*, the Las Ventanas, Barriga Negra, San Carlos and Playa Hermosa formations); others could be younger than ~ 620 Ma (*i.e.*, the Rocha group). Meanwhile, the preorogenic successions (*e.g.*, the Minas formation) provide only zircons older than 1.7 Ga.

The Barriga Negra formation is a ruditic-pelitic-volcanic assemblage, long considered to be discordant with the rest (Midot 1984, Fambrini *et al.* 2005, Núñez Demarco 2014). Conversely, other authors considered this unit as intraformational within the Arroyo del Soldado group (Gaucher 2000). The Las Ventanas formation is considered to be a southern equivalent of the Barriga Negra formation due to the faciological analysis that is easy to perform among these volcano-sedimentary units.

Ediacaran granitic magmatism and metamorphism

The Ediacaran granitic magmatism is not restricted to the Eastern Domain (Masquelin 2006, Oyhantçabal *et al.* 2009, Oriolo *et al.* 2016c). The Western Domain shows an evolving relationship between granitic intrusions and progressive deformation, during the interval ~ 630 – 570 Ma, which led to strain localization and magmatism decrease (Oriolo *et al.* 2016c). Therefore, some I-type plutons are extended and show NE-trending solid-state foliation, whereas many A-type granitoids are round and circumscribed without deformation (Fig. 2B), but the bulk magmatic volume is less than in the Eastern Domain. The most extended one is the Santa Lucía Granite (Mallmann *et al.* 2007), dated by U-Pb (SHRIMP in zircon) at ~ 630 Ma (Hartmann *et al.* 2002). The latest plutonic magmatism is represented by the Mangacha hornblende-bearing granite dated at ~ 584 Ma (Gaucher *et al.* 2008).

The Ediacaran dynamothermal metamorphic conditions exceptionally reached low-amphibolite facies in the Western Domain. Metapelites of the Carapé complex rarely reached the biotite isograd (Sánchez Bettucci *et al.* 2003, Rossini & Legrand 2003). However, greenschist facies contact-aureoles with tremolite-rich marbles are conspicuous in the Schist Belt. Metamorphism does not reach high temperatures in the absence of subduction-related heat sources. Conversely, the metamorphism in the Eastern Domain reached granulite facies conditions long before, during the Cryogenian (~ 670 Ma; Lenz *et al.* 2011).

Structural analysis of cover successions

In Uruguay, all the Ediacaran successions (< 580 Ma) have been deformed ductilely, at least in an incipient way. Midot (1984) interpreted the structure of the Barriga Negra formation as monoclinal, dipping 10 – 25°NE, and considered that it had no deformation. Conversely, he shows that the Las Ventanas formation has been folded and therefore was probably "older".

However, the deformation of the Lavalleja complex (> 580 Ma) was poorly studied, and their interpretation is confusing. In the Minas Region (Fig. 2B), the structural analysis of this unit began with Midot (1984), who found three tectonic events:

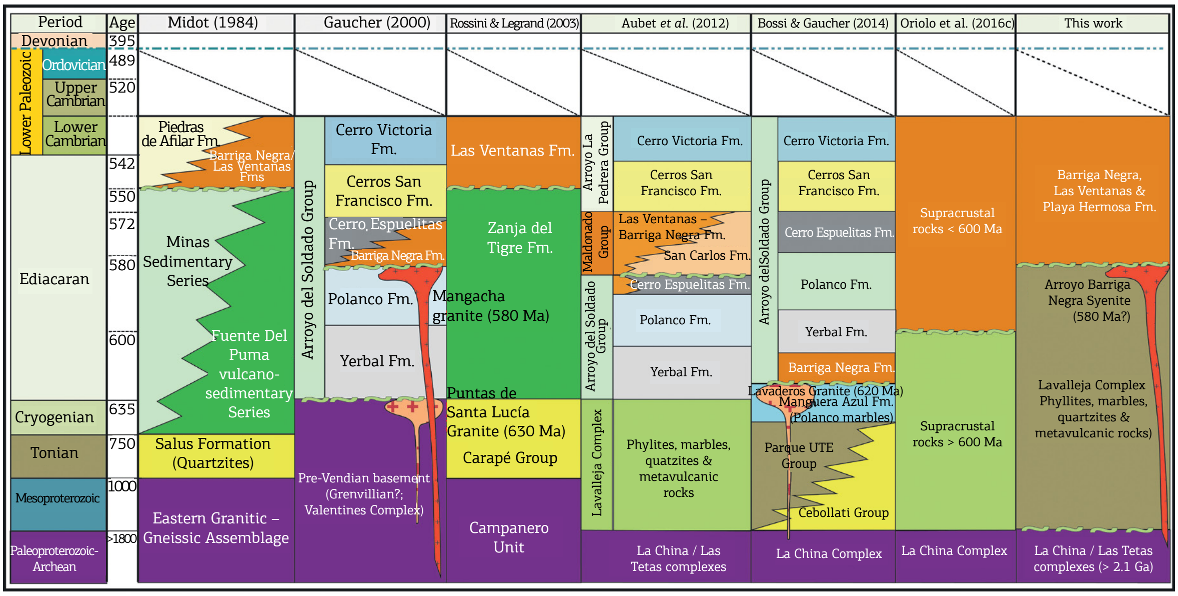

Figure 3. Comparative chronostratigraphic scheme for the NPT, showing different proposals and the scheme adopted for this work.

1. folding phase I, giving large recumbent folds synchronous to the metamorphic peak (Ms+Chl);
2. folding phase II, giving subisoclinal vertical folds and interference patterns; and
3. NE-trending strike-slip dextral brittle faults and kink-folds.

In the Polanco Region, Mac Millan (1933) recognized a flat-lying foliation in marbles, which becomes vertical toward south, for several kilometres. In the same marbles, Preciozzi and Fay (1988) suggested the presence of a dome-and-basin interference pattern, whereas Cabrera (2014) reported recumbent folds of the bedding. Silva Lara *et al.* (2016) showed that these recumbent folds are crosscut by a subhorizontal mylonitic foliation that produced calc-schists.

In the Arroyo del Soldado Region, Spoturno *et al.* (1986) described "remnants of major folds" affecting the bedding of ripple-bearing quartzites, whereas Gaucher (2000) interpreted the structure of the Sepultura Area as a synform. In the same region, Scaglia *et al.* (2007) showed that these quartzites have been ductilely deformed.

RESULTS

The study region is divided into six detailed key areas, all located in the Schist Belt:

1, Sepultura,
2. Espuelitas,
3. Romerillos,
4. Buena Vista-Orthez,
5. Polanco, and
6. Barriga Negra. Each key area has its own geological map.

Other neighbouring areas are cited just briefly:

7. Villalba,
8. Cerro Bonete,
9. Las Palmas and
10. El Perdido (Fig. 2B).

This study highlights the lithological and structural correlations among the areas as well as contact relationships between basement and cover units, when possible.

Sepultura Area

The Sepultura Area is located between the coordinates Latitude 34°1.188'S, Longitude 55°8.386'W and Latitude 34°3.906'S, Longitude 55°6.256'W (Fig. 2B). The geological map (Fig. 4A) shows a landscape of NE-trending extended hills. There is a succession of quartzites, marbles and black shales of the Lavalleja complex. Some stocks of the Mangacha granite were emplaced within the marbles and produced metamorphic contact aureoles with tremolite-rich hornfels.

The deformation of the quartzites is variable. Each hill has its own structural pattern (Fig. 4B):

1. the eastern hill shows quartzites affected by an NE-trending, gently dipping recumbent fold (Fig. 5A);
2. the central hill shows quartzites with well-preserved S_0 bedding (Fig. 5B) and ripple marks (Fig. 5C) and with incipient bulging recrystallization between quartz grains (Fig. 5D);
3. the westernmost hill shows quartzites with heterogeneous ductile deformation and mylonitic foliation that obliterates the S_0 isoclinal folds observed on the map related to the folding of a mylonitic foliation (S_2) in quartzites (Fig. 4C).

There are some underlying stretched metaconglomerates at the foot of the eastern hill that could be localized near the contact with the basement (Fig. 5E). Meanwhile, the marbles rarely show clear contact relationships with the ripple-bearing quartzites (Fig. 5F).

The stereograms (Fig. 4D) show that the S_0 attitude is N50°E, 70°SE, whereas the S_1 attitude of black shales is E-W, 60°-70°N.

The D2 deformation event defined here is represented by NE-trending cylindrical folds and S_2 mylonitic foliation (Fig. 4C). The quartzites were already tilted and folded by a previous D1 event before being subjected to these localized and partitioned deformations.

Espuelitas Area

The Espuelitas Area is located between the coordinates Latitude 34°1'56"S, Longitude 55°17'39"W and Latitude 34°6'24"S, Longitude 55°14'12"W (Fig. 2). The geological map (Fig. 6A) shows a succession of quartzites, black shales and foliated marbles (*i.e.*, the Lavalleja complex) that overlie flat-lying stripped gneisses and amphibolites (*i.e.*, the La China complex). The quartzites are pebbly at the bottom (Fig. 6B), and rest in subhorizontal contact on the stripped gneisses (Fig. 6C).

The stereogram analysis shows NNW-trending upright cylindrical folds that affect both the quartzites and the stripped gneisses (Fig. 6D). The black shales are intercalated with the marbles and show an S_1 foliation with an attitude S70°E, 20°NE. There are slickenlines plunging 20°SW on the quartzite foliation (S_1), subparallel to the hinges of the folds. The cross-section (Fig. 6E) is interpreted as the result of a second D2 deformation event, which reworked a pregranitic flat-lying foliation (S_1).

Romerillos Area

The Romerillos Area is located between the coordinates Latitude 34°8'28"S, Longitude 55°13'8"W and Latitude

34°9'39"S, Longitude 55°12'11"W (Fig. 2) and shows a landscape of rounded hills. The main lithology is made up of metamorphic ripple-bearing sandstones and polymictic conglomerates with angular clasts of Kfs-rich granite and quartz (Fig. 7A). The lower beds are crosscut by aplitic veins (Fig. 7B). Mylonitic rocks of the basement contain mafic layers (*i.e.*, the La China complex).

The structural analysis shows that the main layering surface is the bedding (Fig. 7C), which is affected by NW-trending cylindrical upright box folds (Fig. 7C, 7D). The SW-plunging fold hinges pass laterally towards vertical shear zones along the limbs of these folds. The pole-isodensity stereogram shows a maximum concentration of S_0 at 76°/345°, and the axial plane of those folds is N55°E, vertical (Fig. 7E). In the field, ripple marks have shorter wavelength than natural current, which may be due to deformation. There are two paleocurrents from the ripple-mark lineations, but the maximum is located around the fold axis, which indicates that these ripples could have rotated to become parallel to the fold axis (Fig. 7F). Jointing indicates three master joint families (Fig. 7G). All the stereograms are equal-area lower hemisphere.

Under the microscope, the quarzitic sandstone shows a few rounded (detrital) quartz grains coated by sericite and many grains sutured, which indicates bulging recrystallization (*i.e.*, low-temperature grain-boundary migration; Passchier & Trouw 2005).

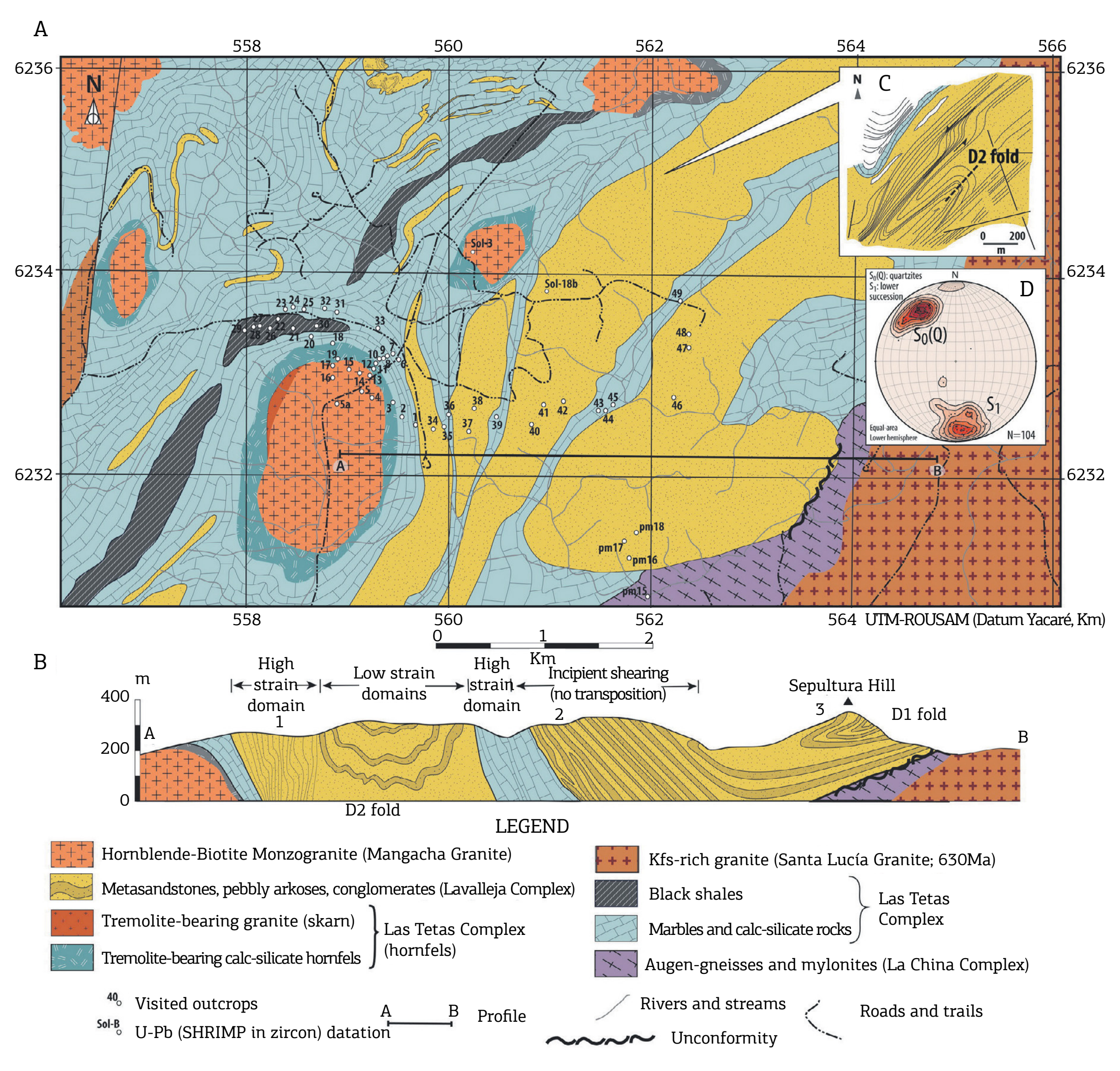

Figure 4. (A) Geological map of the Sepultura Area; (B) NW-SE cross-section A-B of the Sepultura Area geological map; (C) Quartzite folds; (D) S_0 in quartzites and S_1 in black shales.

Buena Vista-Orthez Area

The Buena Vista-Orthez Area is located within the coordinates Latitude 34°13.536'S, Longitude 55°14.261'W and Latitude 34°14.649'S, Longitude 55°11.984'W (Fig. 2). The geological map (Fig. 8) shows that there are two different lithological associations:

1. upper ripple-bearing quarzitic sandstones and conglomerates, outcropping in the Buena Vista Hill (*i.e.,* the Lavalleja complex); and
2. fuchsite-bearing medium-grade metamorphic quartzites and orthogneisses, outcropping in the eastern Orthez Hill (*i.e.,* the Las Tetas complex; Fig. 9A).

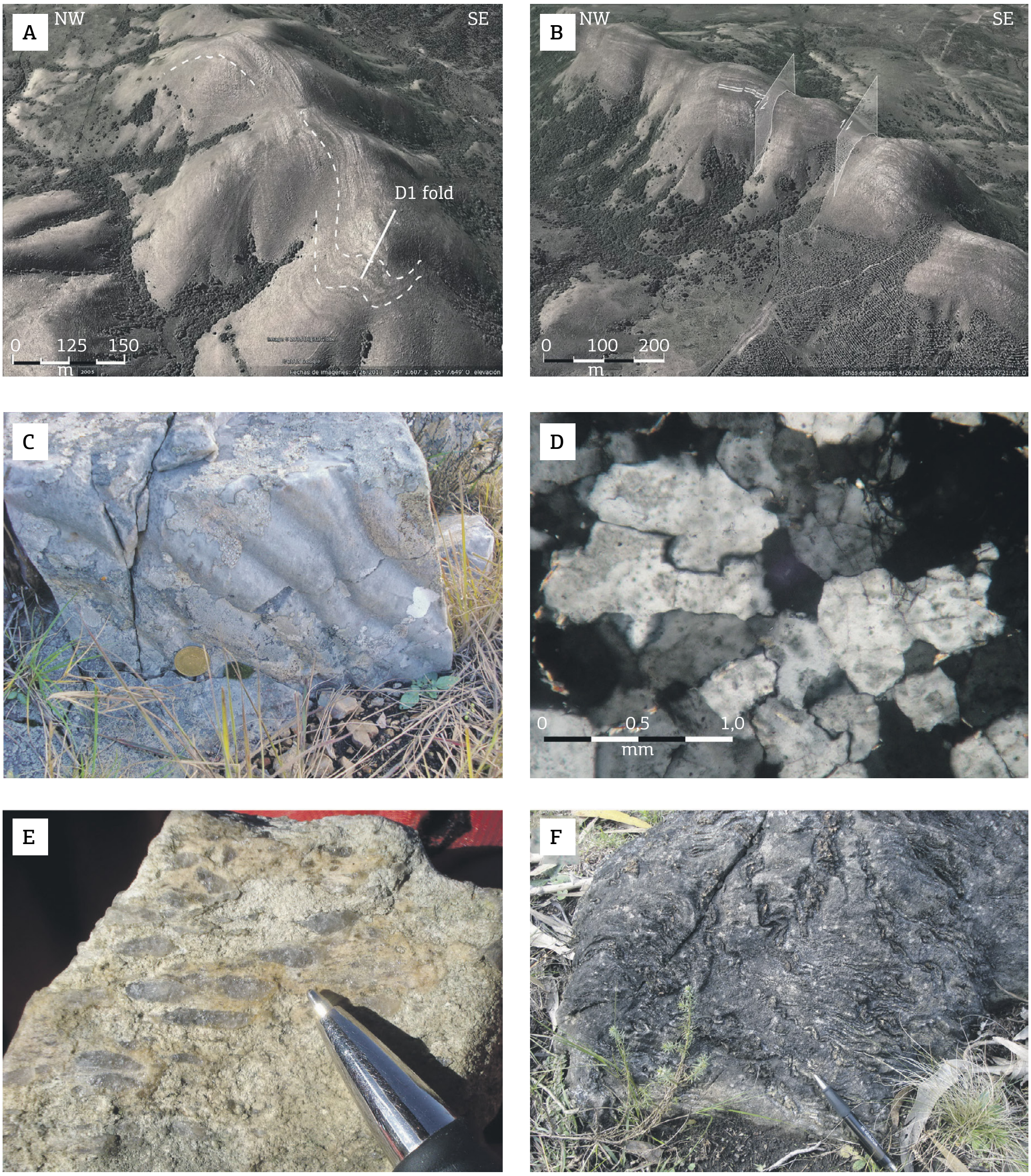

Figure 5. Lithological and structural features of the Sepultura Area. (A) Aerial view of the SE hill showing the recumbent fold; (B) Aerial view of the central hill showing the quartzite bedding and faults oriented 290°/65°; (C) Tilted wavy stratification; (D) Quartzite in thin section showing incipient bulging recrystallization; (E) Orthogneiss of the La China complex; (F) Very folded marble of the Las Tetas complex near the contact with the Santa Lucía Granite.

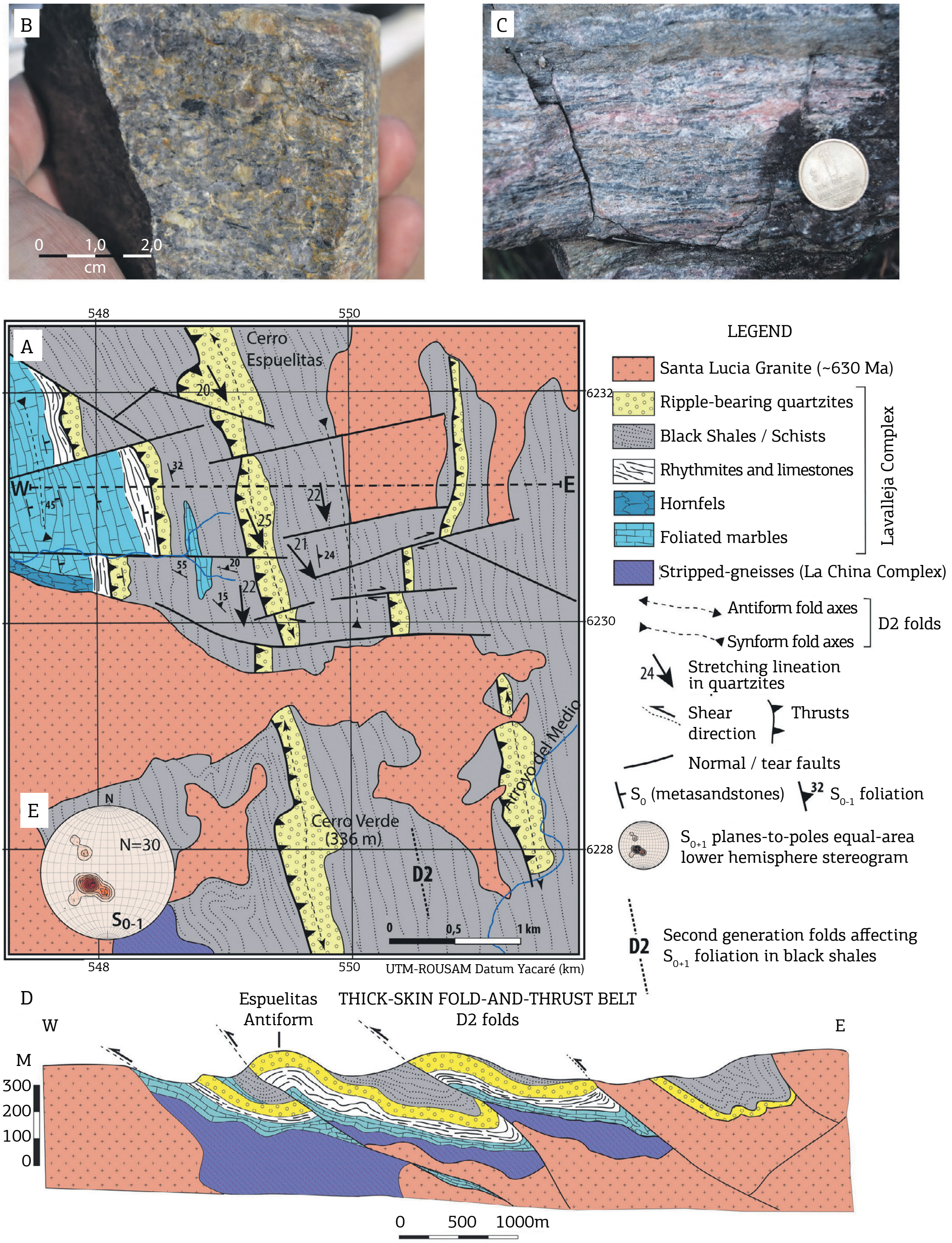

Figure 6. (A) Geological map (Gaucher, 2000); (B) Cross-section of the Espuelitas Area; (C) S_{0-1} pole isodensity stereogram; (D) Strained conglomerate at the base of the Lavalleja complex quartzites; (E) Stripped gneisses of the La China complex.

The Orthez Hill is the southernmost of a series of NS-oriented fault-bounded blocks exposing rocks from the La China and Las Tetas complexes. The La China complex is made up of:

1. flat-lying stripped gneisses;
2. amphibolites; and
3. stretched Kfs-rich pegmatites (Fig. 9A)

Whereas the Las Tetas complex contains:

1. fuchsite-bearing quartzites (Fig. 9B);
2. chlorite schists;
3. tourmaline-rich metatuffs; and
4. BIF (Fig. 9C).

Two kinds of granitoids intrude in these rocks:

1. Muscovite granites (Fig. 9D); and
2. Kfs-rich granites (both massive).

The structure of the Las Tetas complex shows subhorizontal folded layers (S_0?) in green to white quartzites, which are affected by upright folds whose horizontal axes strike S70°E-S50°E (Fig. 9B).

The Buena Vista Hill contains upper conglomerates (Fig. 9E) interbedded with ripple-bearing quarzitic sandstones (Fig. 9F) that overlie the Orthez Hill basement rocks. Clasts of fuchsite-bearing quartzite and muscovite granite of the Las Tetas and La China

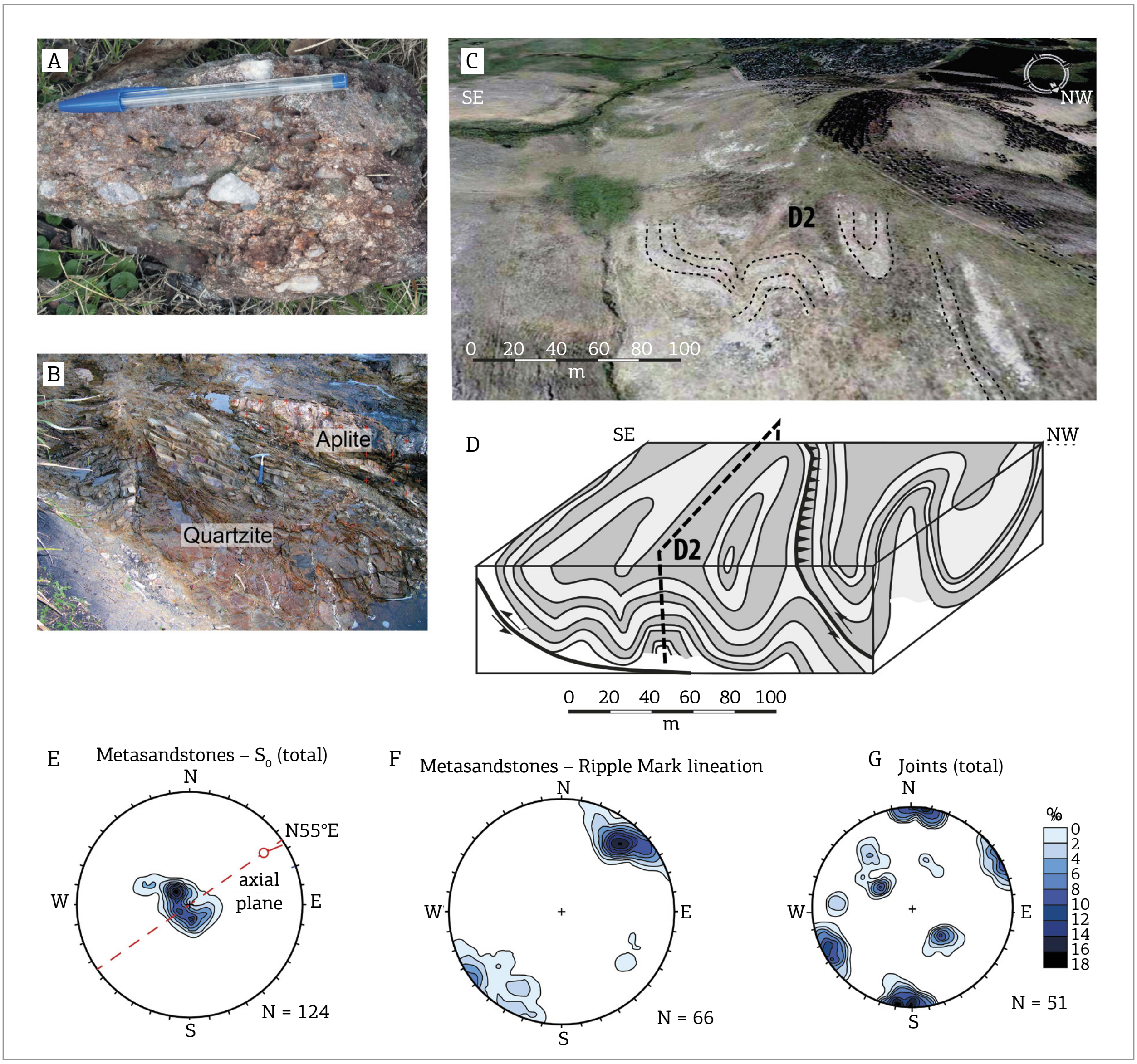

Figure 7. Ediacaran structures in the Romerillos Area. (A) Basal conglomerate of the quarzitic sandstones; (B) Quarzitic sandstones at the foot of the hill, crosscut by aplitic dykes; (C) NE-trending upright folds at the top of the hill; (D) Idealized geometry of upright box folds. Stereograms: (E) S_0 density-pole stereogram interpreting an upright fold with N55°E, 90° axial-planar surface; (F) Ripple-mark lineation, interpreting two different paleocurrents: 13° to 40° and 30° to 130°; (G) Stereogram interpreting three joints families.

complexes were found in the conglomerate, which means that these rocks could be the source area of the upper quartzites.

The structure of the Buena Vista Hill shows an S_0 striking EW and dipping 55°-75°SW on average (Fig. 8). Moreover, the underlying marbles (Fig. 8) show a subhorizontal crenulation cleavage (S_1) that obliterates the metamorphic banding (S_0) affected by recumbent folds. This structure cannot be observed in the upper quartzites.

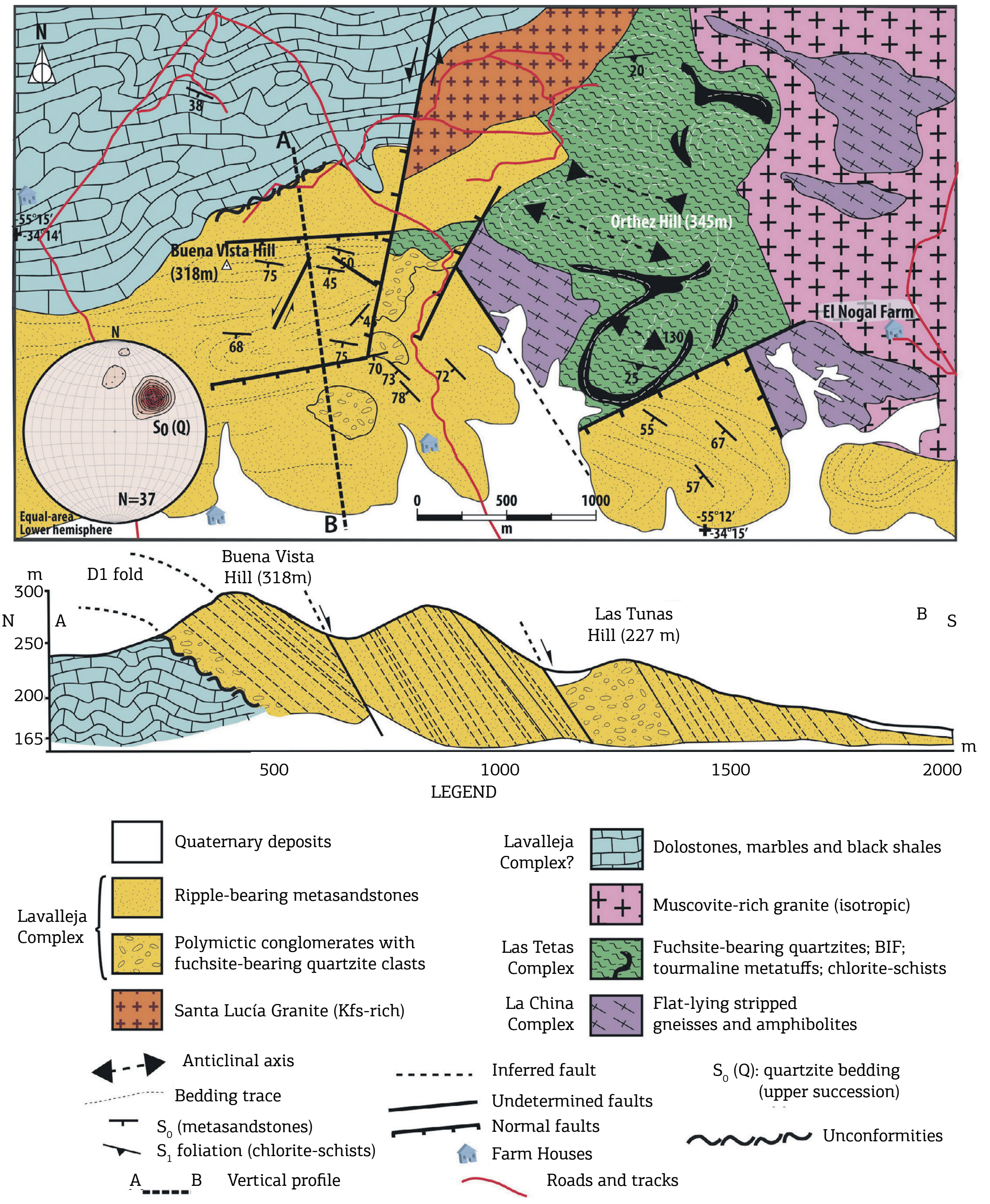

Figure 8. (A) Geological map of the Buena Vista-Orthez Area; (B) N-S cross-section of the Buena Vista Hill, showing the unconformity beneath the Orthez Hill marbles and fuchsite-bearing quartzites (Las Tetas complex).

Polanco Area

The Polanco Area is located between the coordinates Latitude S33°49’43”, Longitude W55°5’20” and Latitude S33°52’9”, Longitude W55°8’32” (Fig. 2B). The rocks of the Lavalleja complex in this area are essentially marbles, intercalated with a few quartzites and phyllites (Fig. 10). The marbles are fine-grained blue-grey rocks and often contain layers composed entirely of stromatolites (Fig. 11A). The stromatolites are domal and lamellar-concentric and could be way-up structures, as the convexity is always oriented toward the sun.

In the geological map (Fig. 10A), the structural analysis reveals a general ‘dome-and-basin’ interference pattern,

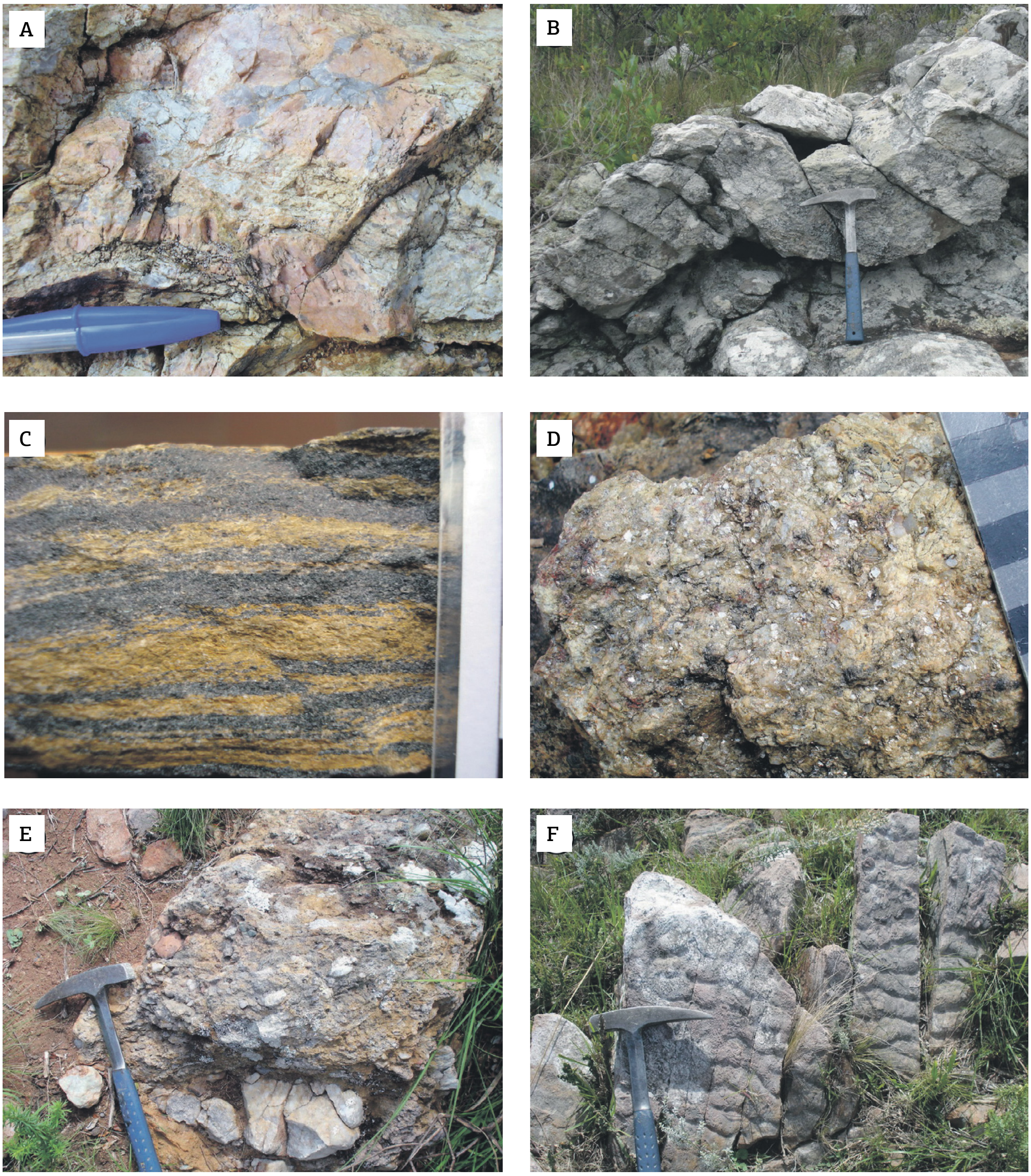

Figure 9. Lithologies of basement and cover rocks in the Buena Vista-Orthez Area. Basement: (A) Flat-lying strained pegmatite; (B) Upright-folded fuchsite-bearing quartzites; (C) Banded iron formation; (D) Muscovite-bearing granite. Cover: (E) Conglomerate intercalated within ripple-bearing sandstones and containing muscovite-bearing granite clasts; (F) Upper quarzitic sandstones with wavy stratification.

as inferred previously (Preciozzi & Fay 1988). At the outcrop, there is an axial-planar mylonitic foliation (S_1) dipping 10°-20°SW, parallel to S_0 (Fig. 11B). The metamorphic banding is composed by the S_0 and carbonate veins, which show minor recumbent folds (Fig. 11C). The pole stereogram shows an S_1 orientation of N85°E, 28°SE on average (Fig. 10B), but cartographically, it is affected by open folds, and the dip can change towards the north. In northern outcrops, the grey-and-white decimetre-thick layering (S_0) can be subvertical and is crosscut by parallel quartz veinlets that are crenulated by the subhorizontal S_1 crenulation cleavage (Fig. 11D).

In thin section, the marbles show mylonitic textures with talc and white mica as retrograde fabrics that obliterated an older granoblastic polygonal texture of calcite-dolomite with coarse tremolite (Fig. 11E). Moreover, there are impure bands containing plagioclase grains that produced excellent kinematic markers (s). The porphyroclasts indicate an average of counterclockwise top-to-north sense of shearing (Fig. 11F; Silva Lara *et al.* 2016).

Barriga Negra Area

This is the type locality of the Barriga Negra formation, which is situated between the coordinates Latitude S33°54'2", Longitude W55°5'19" and Latitude S33°43'47", Longitude S54°57'25" (Fig. 12A). The cross-section shows that the dip of bedding varies from 50° to 20° towards the NE and confirms a monoclinal structure (Fig. 12B).

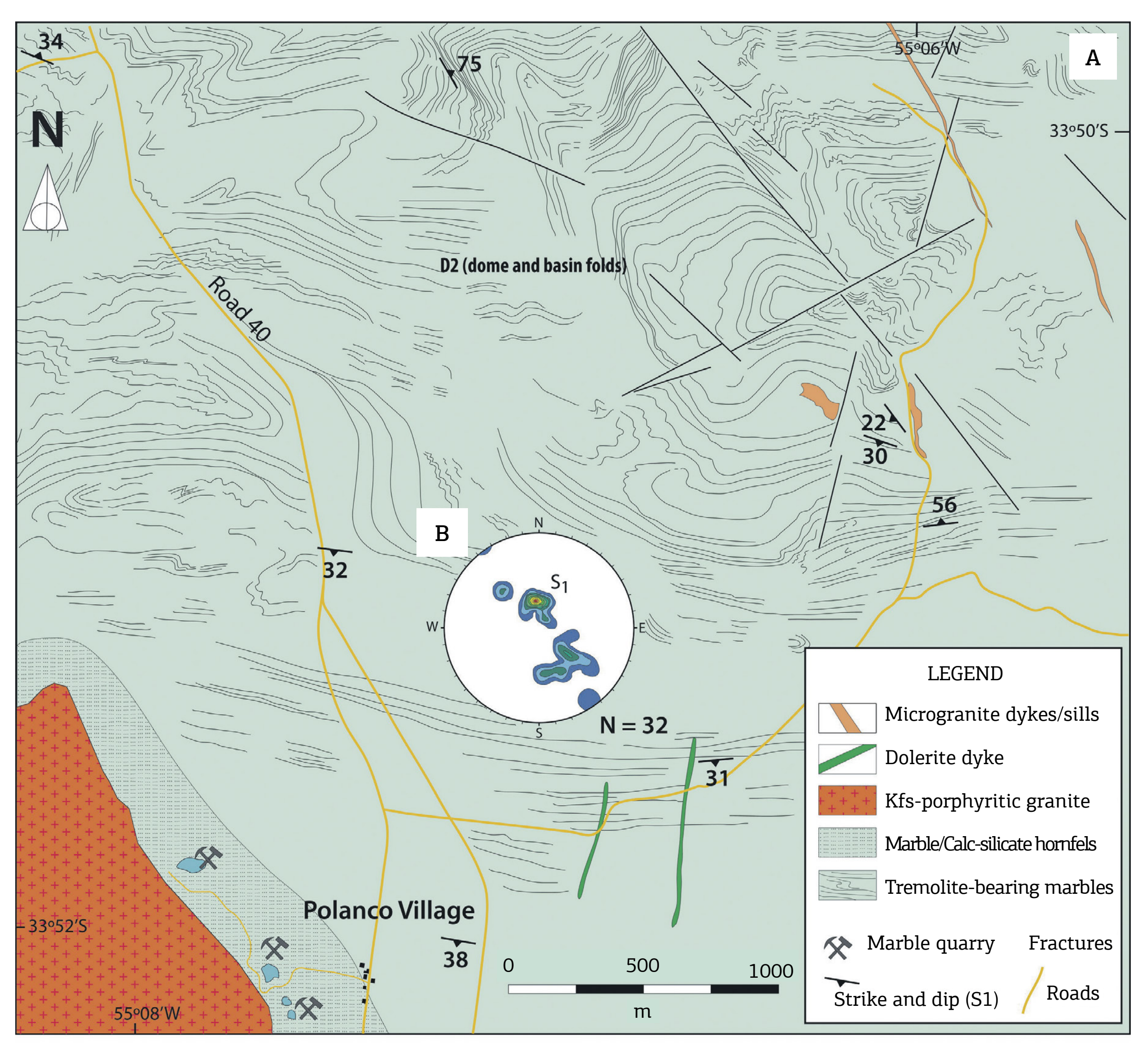

Figure 10. (A) Geological map of the Polanco Area, showing the intrusion of different kinds of magmatic rocks and structural lineaments, which suggest a dome-and-basin interference pattern and shear zones; (B) S_1 stereogram showing a flat-lying foliation.

The best exposures of the unconformity over the rocks of the Lavalleja complex (*i.e.*, marbles) can be seen in the western lip of this area.

The Barriga Negra formation begins with purple sandstones and polymictic conglomerates containing abundant marble clasts, continues with boulder breccias containing orthogneissic

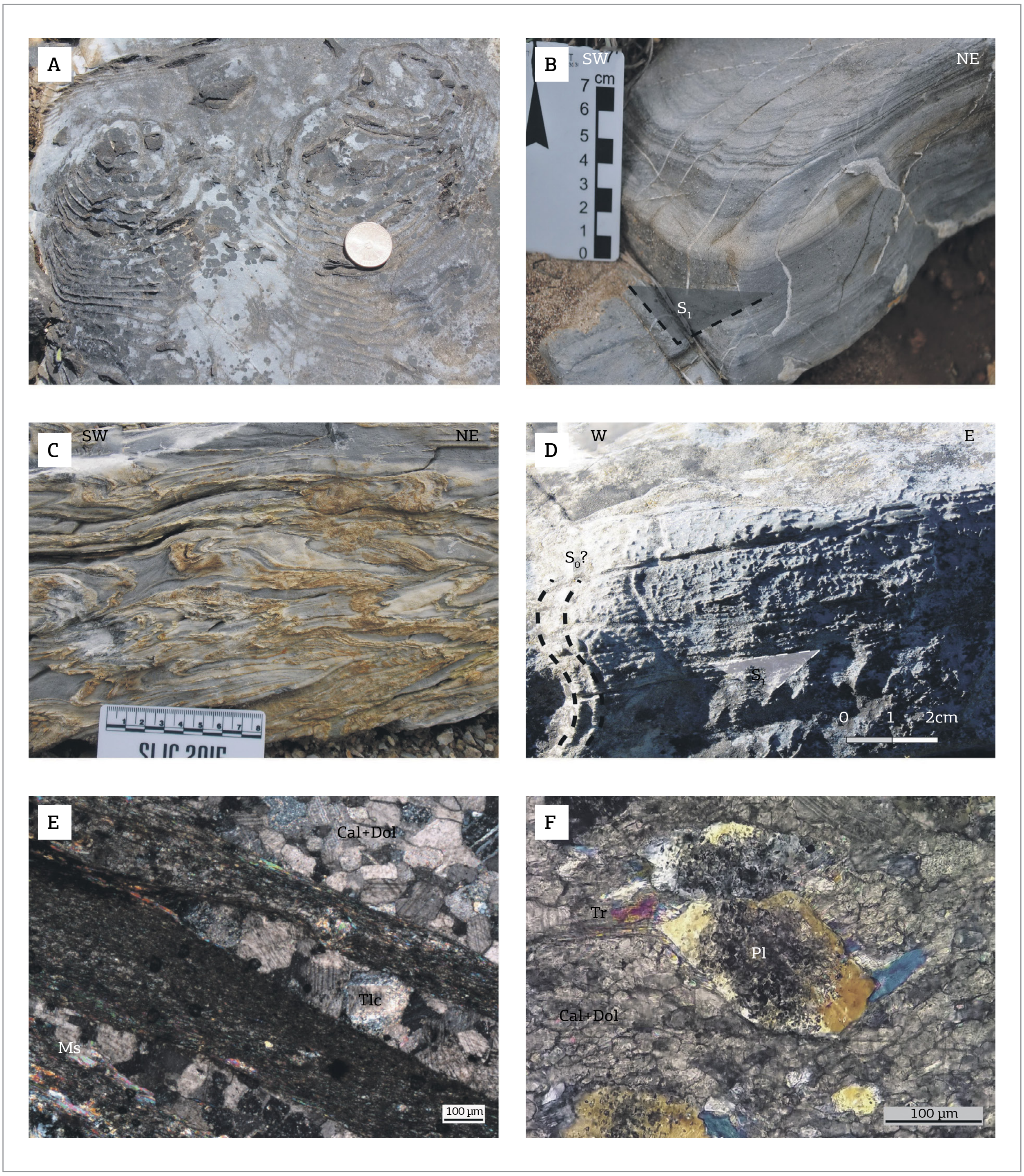

Figure 11. Lithologies and structures of the Polanco Area. (A) Domal stromatolites within the marbles (*i.e.*, the Lavalleja complex); (B) S_{1+0} subhorizontal mylonitic foliation in marbles; (C) Recumbent folds affecting veins within the marble layering and reworking of S_{1+0}; (D) Subhorizontal crenulation cleavage (S_{2+1}) crosscutting the vertical decimetre-thick layering with parallel veinlets; (E) Granoblastic texture in Tremolite-bearing marbles with mylonitic domains containing talc and white mica; (F) Plagioclase sigma-porphyroclast in calc-silicate layers showing top-to-north clockwise sense of shear in one limb.

clasts and ends, at the top, with pale-green to purple slates. There are no carbonates of chemical precipitation, and the total thickness reaches ~ 3.2 km (Núñez Demarco 2014).

A clast study of this unit helps to understand its provenance and stratigraphic position. There are different conglomerates of clastic provenance:

- 80% orthogneiss boulders from the La China complex (Fig. 13A);
- 80% granite clasts from the Mangacha and Santa Lucía granites (Fig. 13B); and
- 80% marble clasts of the Lavalleja complex.

Marble clasts often register primary (*e.g.*, stromatolitic; Fig. 13C) or secondary structures (*e.g.*, folds; Fig. 13D). In the Las Palmas area (Fig. 2B), the Barriga Negra conglomerates show a few clasts of rhythmic black-and-white metasiltstones with slaty cleavage of the "Yerbal formation" (Fig. 13E) and abundant purple sandstone-mudstone intraclasts (Fig. 13F).

The underlying rocks beneath this formation are essentially metadolostones with quartz injections and marbles with a few quartzite and phyllite intercalations of the Lavalleja complex. These rocks include the stretched metaconglomerates, metadolostones and BIF assigned to the Las Tetas complex as well as the orthogneisses of the La China complex. Finally, the porphyritic "Arroyo Barriga Negra syenogranite" (Díaz *et al.* 1990) crosscut the Lavalleja complex but is covered by the Barriga Negra formation.

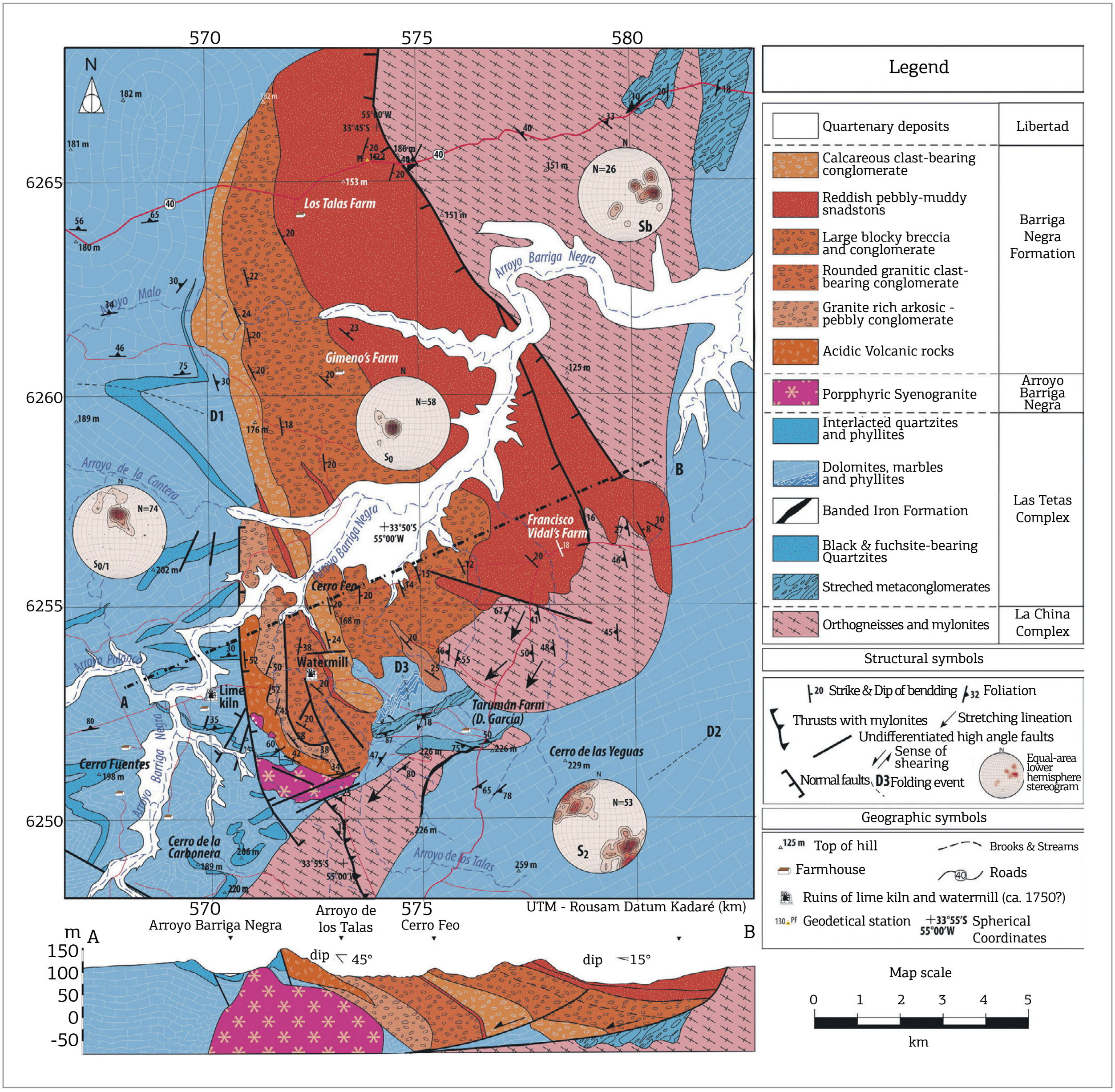

Figure 12. Geological map and cross-section of the Barriga Negra Area (*modif.*, Núñez Demarco 2014), showing the S_0 pole stereogram for the Barriga Negra formation and S_{0+1} and S_2 pole stereograms for the basement rocks.

The structural analysis of these underlying rocks shows that the quartzites and phyllites of the Lavalleja complex are difficult to separate from the fuchsite-bearing metaconglomerates and quartzites of the Las Tetas Complex, which develop sericite flakes as a mineral lineation within the subhorizontal foliation (S_{0+1}). The Las Tetas complex metaconglomerates show a quartz stretching lineation plunging 22°SW and locally yielding the strain

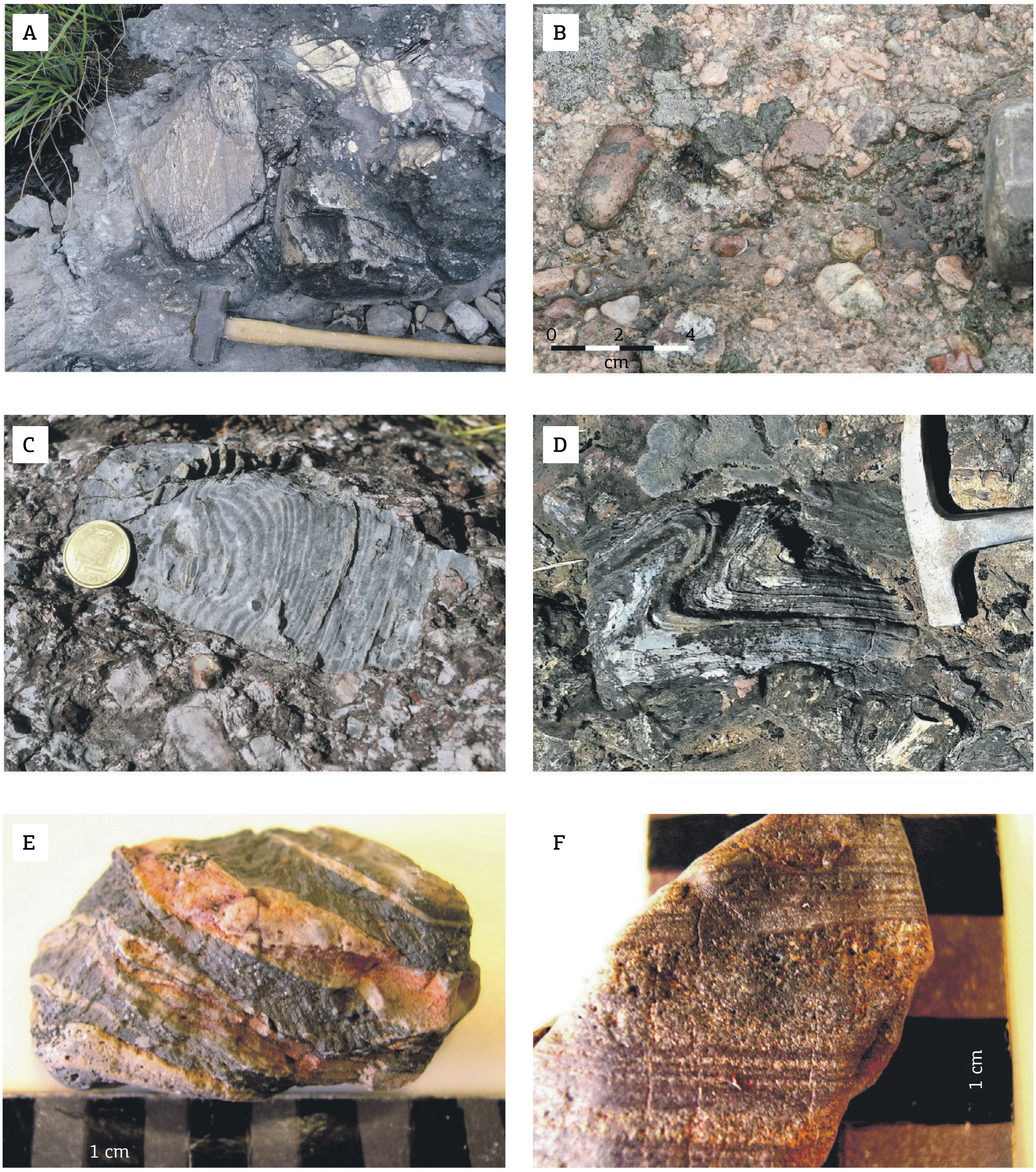

Figure 13. Clast provenance in the Barriga Negra conglomerates. (A) Polymictic boulder breccia (*i.e.*, the La China complex clasts); (B) Granitic-clast conglomerate (80% porphyritic granite clasts); (C) Clast of domal stromatolite within a marble-clast breccia (*i.e.*, the Polanco Fm. marble clast); (D) Boulder of folded marble; (E) Rhythmic-laminated siltstone clast with slaty cleavage (*i.e.*, the Yerbal formation); (F) Sandy-pelitic intraclast of a purple laminated mudstone-sandstone.

parameter g_m=4.5 (g_{max}=16; g_{min}=1.5; Núñez Demarco 2014). Meanwhile, the orthogneisses of the La China complex are intercalated with amphibolites and show a stretching lineation that plunges 20°SW. Their fabric is either prolate or oblate. The amphibolites show rigid asymmetric boudins, which give a top-to-north clockwise shear sense.

DISCUSSION

How many cover successions are there in the Schist Belt?

Based on detrital zircon contents, the rocks of the Schist Belt can be grouped into three main tectono-stratigraphic successions:

1. the Las Tetas complex;
2. the Neoproterozoic Lavalleja complex; and
3. the Barriga Negra formation.

Many authors agree that an angular unconformity underlies the ripple-bearing quartzites of the Lavalleja complex (Spoturno *et al.* 1986, Aubet *et al.* 2012, Peçoits *et al.* 2016), which is essential to fix the boundary beneath the Cryogenian-Ediacaran units (such as the "Yerbal formation") and their older basement, as shown by the scarce zircon grains of ~600 Ma ages contained in those units (Blanco *et al.* 2009). This contact has been inferred indirectly in some areas (*e.g.*, the Buena Vista-Orthez and Villalba Areas). Those quartzites could rest on an angular unconformity over the ~ 630 Ma Santa Lucía Granite (*e.g.*, the Sepultura and Bonete areas; Fig. 14A), but this evidence needs confirmation. Conversely, the same quartzites intersperse with low-angle mylonites of the Sarandí del Yí shear zone (*e.g.*, the Espuelitas Area) and are crosscut by aplite dykes (*e.g.*, the Romerillos Area). In the Villalba Area, this unconformity can be considered as having been subjected to a tangential deformation affecting both the upper quartzites and the fuchsite-bearing rocks of the Las Tetas complex (Fig. 14B). The evidence here exposed is likely to define a regional discordance between the two units:

1. a low-grade metamorphic Mesoproterozoic to Cryogenian succession; and
2. a medium-grade metamorphic unit that is pre-Neoproterozoic in age (*i.e.*, the Las Tetas complex).

The difference between the two is subtle, considering that carbonate successions, which were subjected to ductile flow, are difficult to characterize stratigraphically. In addition, zircon provenance does not help much, since the supposedly "Ediacaran units" of the passive continental margin and the Las Tetas complex both have the same detrital inheritance (Peçoits *et al.* 2016).

On the other hand, the other discordance below the Barriga Negra formation is the best known of the Neoproterozoic in Uruguay. It is a subaerial, erosive and angular unconformity, indicating a nondeposition interval between two different tectonic environments (Masquelin *et al.* 2016). This fact opposes the idea of an intraformational wedge within the Arroyo del Soldado Group (Gaucher *et al.* 2008). Meanwhile, the Neoproterozoic detrital zircons indicate a minimum provenance age of 566 Ma (Blanco *et al.* 2009), which may approach the age of deposition. The appearance of metapelite clasts of the Yerbal Formation in the conglomerates confirms that the Barriga Negra formation is clearly a younger unit. The presence of intraclasts in the conglomerates means that they have recycled themselves in a continental environment. This is corroborated by the lack of Ediacaran zircons, which are ubiquitous in the Barriga Negra, Playa Hermosa, San Carlos and Las Ventanas formations, within the Yerbal formation (Peçoits *et al.* 2016).

A Neoproterozoic tectonic evolution with two main deformation events: D1 and D2

With the help of absolute ages, Oriolo *et al.* (2016c) showed that the D2 transpressive deformation in the Western Domain of the DFB is ubiquitous. However, there are E-W tectonic structures that are mechanically incompatible. These structures could have been formed in another tectonic event (D1), pre-Ediacaran in age, prior to the formation of the Schist Belt.

In the marbles of the Lavalleja complex, D1 deformation is due to tangential tectonics. The evidence is observed in the central-western part of the Schist Belt (the Polanco region), which is less affected by the NE-SW transpressive deformation (D2). The evidence includes:

- recumbent bedding folds cut by a mylonitic subhorizontal foliation with kinematic indicators;
- a subhorizontal crenulation cleavage perpendicular to the vertical bedding; and
- a subhorizontal stretching lineation in quartz clasts of metaconglomerates (among others).

There is enough recurrence of these structures towards the south (*e.g.*, the Villalba and Espuelitas Areas) to allow a regional event of tangential tectonics (D1) to be sketched. To the east of the Polanco region, the marbles show the NE-trending vertical foliation (S2) of the Schist Belt itself, which is accompanied by very tight folds, visible in quartz veins that cut the marbles.

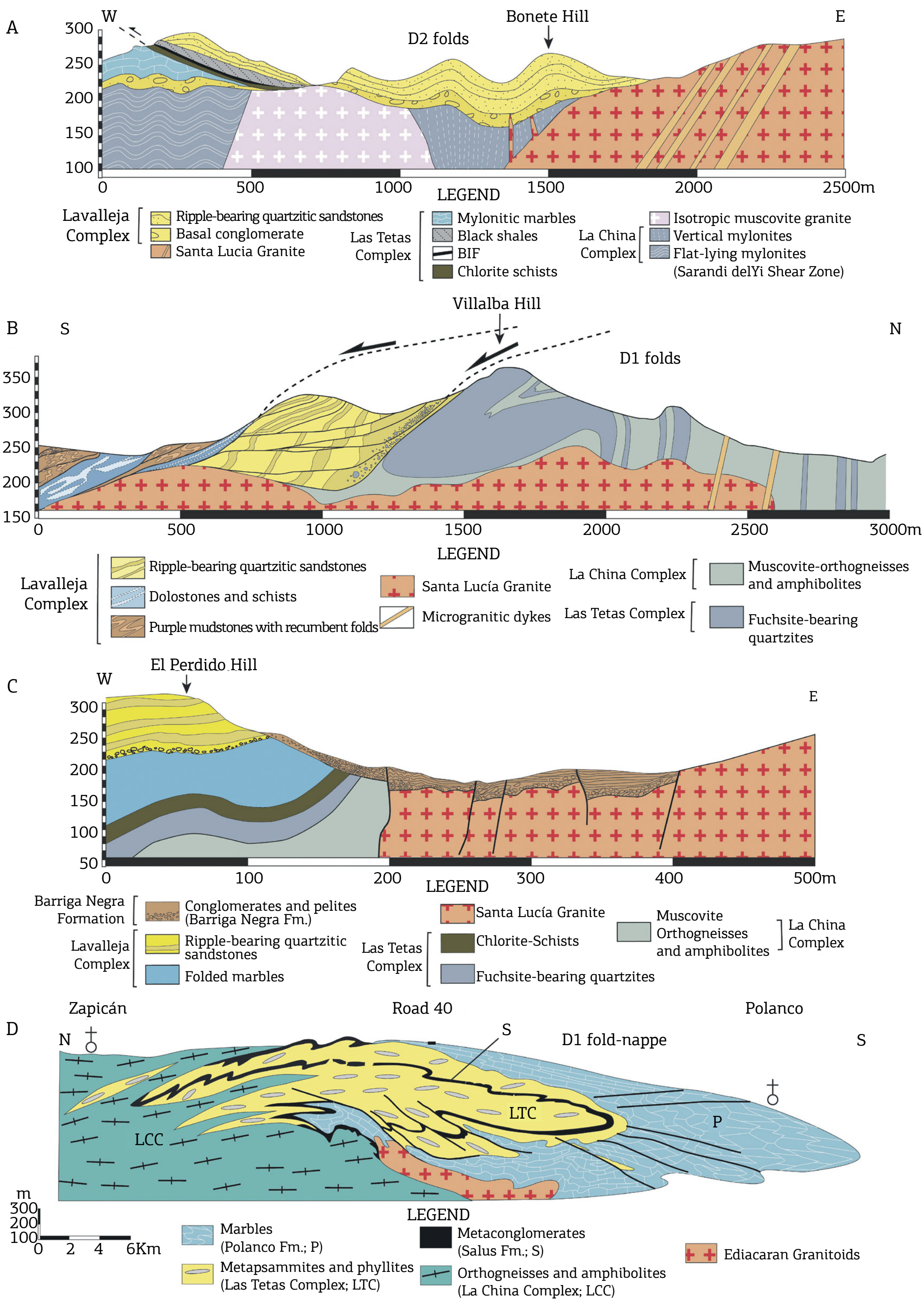

Figure 14. Different basement-cover relationships in the Schist Belt. (A) Detached unconformity between the quarzitic sandstones of the Arroyo del Soldado Region and its basement rocks at the Bonete Area (9 in Fig. 2B); (B) Ediacaran thrusts in the Villalba Area (7 in Fig. 2B), with upper quartzites of the Lavalleja complex sharing the same tangential deformation as the Las Tetas complex; (C) Local deformation of the Barriga Negra Fm. by fault slip among blocks of the Santa Lucía Granite; (D) Regional Neoproterozoic (?) fold nappe verging towards the south in the Polanco Area, having the La China complex as the core

In the quartzites, the evidence of the D1 deformation is the EW-trending recumbent or upright folds, but also the presence of slickensides in the subhorizontal foliation plunging towards the SW. However, the transpressive deformation shows NE-trending cylindrical folds that evolved towards the NE-SW shear zones, leading to the heterogeneous ductile deformation and generating a mylonitic foliation in quartzites that was folded by late oblique folds (*e.g.*, the Sepultura and Romerillos Areas).

In general, transpressive deformation (D2) is characterized by a progressive counterclockwise rotation of the D1 folds, while these are transected by NE-SW strike-slip shear zones that are in part high-angle thrusts with the top towards the NW. At the end of D2, even the purple and green slates of the Barriga Negra and Las Ventanas formations, which did not register the D1 event, were affected by open folds of medium-structural-level and "pencil" cleavage, but both conserved the pelitic S_0 without transposition. In the El Perdido area, the deformation of the same slates and conglomerates could have been due to basement tectonics (*i.e.*, the Santa Lucia granite) produced by fault movements that deformed the cover (Fig. 14C).

In summary, the tangential deformation event (D1) is characterized by the development of E-W folds (right or recumbent) and S_1 foliation parallel to the folds. This hypothesis is proposed for the development of a fold nappe in the Polanco marble formation, with a core made up of rocks from the La China-Las Tetas complexes (Fig. 14D). This fold nappe could be drained by gravity to an allochthonous terrain to the south. Its root zone could be the straight and extended septa of metadolostones located between the Zapicán granodiorite and the Sierra de Sosa shear zone.

CONCLUSIONS

The highlights of this comparative geological survey are the following:

1. In all the areas, a quartzite-carbonate-metapelitic succession (*i.e.*, the Lavalleja complex) has been correlated in lithology and structural style;
2. It was possible to identify contact relationships between the Lavalleja complex and its granitic-gneiss basement (*i.e.*, the La China complex) as well as an older paraderived succession (*i.e.*, the Las Tetas complex);
3. The Barriga Negra formation overlies rocks of the three complexes (*i.e.*, the Lavalleja, Las Tetas and La China complexes);
4. Some evidence (*i.e.*, ripple-bearing quartzites) points to the existence of an earlier discordance at the base of the "Arroyo del Soldado sandstones" overlying the Santa Lucía granite (*ca.* 650-630 Ma.);
5. In many places, the Lavalleja complex attests to the existence of a deformation event before the Ediacaran times. This is characterized by E-W-oriented structures (*i.e.*, recumbent and upright folds and S_1 foliation) that occurred in the absence of granitic intrusions;
6. There is a mechanical disconnection everywhere within the Lavalleja complex between rocks having good preservation of primary structures (*i.e.*, quartzites) and rocks that under the same metamorphic conditions have undergone multiepisodic fracturing, ductile flow and runoff (*i.e.*, marbles). Therefore, it is quite difficult to recognize the bedding as well as contact relationships among the rocks;
7. The Schist Belt is characterized by a tectonic evolution of two events (D1 and D2): the D1 event produced a tangential deformation of regional extent with the development of a fold nappe that involves stromatolitic marbles, and the D2 event produced NE-trending upright folds, a disturbance of early D1-folds near the transpressive strike-slip shear zones, and accommodation of the horizontal transport parallel to the Sarandí del Yí shear zone.

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