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Notes

Chapter 53

Las Ventanas and San Carlos formations, Maldonado Group, Uruguay

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Abstract: Together with the Playa Hermosa Formation (Fm.), the Las Ventanas and San Carlos formations constitute the Maldonado Group, which is better developed in the southeastern part of Uruguay and covers an area of *c.* 200 km^2. The total thickness of both units (i.e. Las Ventanas and San Carlos formations) reaches *c.* 1500 m, and comprises mafic and acidic volcanic rocks, pyroclastic rocks, diamictite, sandstone, conglomerate and pelite. Structurally, the Maldonado Group is extensively deformed, although variably, throughout the region. Strike–slip faults, westward-verging detachment faults, and folds with axis sub-parallel to the strike–slip planes are common features. The presence of pumpellyite, prehnite, chlorite and epidote in mafic rocks indicates very low- to low-grade metamorphic conditions. The Las Ventanas Fm. is characterized by basal conglomerate, diamictite, sandstone and siltstone that pass upwards into fine-grained rhythmites (pelite), and is the thickest unit of the Maldonado Group (*c.* 1250 m). The San Carlos Formation (*c.* 250 m) comprises fine-grained conglomerate, sandstone and mudstone towards the top. Both units lie on an angular unconformity above Palaeo- and Neoproterozoic basement and are overlain unconformably by late Ediacaran–lowermost Cambrian units. Reliable palaeomagnetic data indicate that the Maldonado Group accumulated at high palaeolatitudes; however, the palaeogeographical evolution of the Río de la Plata Craton during the Neoproterozoic remains conjectural. Radiometric data from intrusive bodies and cross-cutting strike–slip faults place the minimum age of the group at *c.* 565 Ma, whereas basement volcanic rocks dated at 590 $\pm$ 2 Ma interbedded with meta-sandstones hosting detrital zircons *c.* 600 million years old provide the best constraint on the maximum age of deposition. Given the absence of carbonate rocks, no chemostratigraphic studies (e.g. C, O, Sr) are available.

The Las Ventanas and San Carlos formations are largely interpreted as units within a thick glacially influenced fan-delta sedimentary system formed during the early Ediacaran in a strike–slip basin. Based on stratigraphic and sedimentological characteristics it has been suggested that this succession, containing glacially influenced diamictite and dropstones, records a glacial period that occurred sometime between *c.* 570 and 590 million years ago. Ongoing research is focused on establishing the precise age of deposition of the Maldonado Group and on reconstructing the tectonic evolution of the basin. Further palaeomagnetic studies will be especially useful for determining the palaeogeography of the Río de la Plata Craton during the Ediacaran and establishing its relationships with neighbouring strata hosting similar successions.

The Maldonado Group was formally erected by Pecoits *et al.* (2005) to include the Playa Hermosa (Pazos *et al.* 2011) and Las Ventanas formations, which are better exposed near the towns of Piriápolis and Pan de Azúcar (Figs 53.1 & 53.2). The San Carlos Fm. was informally included. Subsequent work showed that the succession continues to the SW and NE of Minas and Melo cities (Fig. 53.1). The group reaches a maximum thickness of *c.* 1500 m and covers an area of *c.* 200 km^2. It comprises acidic and basic volcanic rocks, pyroclastic and sedimentary strata generated in a tectonically active and glacially influenced basin (for a recent review see Pecoits *et al.* 2008).

Midot (1984) originally suggested the Las Ventanas Fm. included conglomerate, sandstone and pelite outcropping at De Las Ventanas Hill and in the surrounding areas (Fig. 53.3). This unit was considered by Midot (1984) and various other authors to be Ordovician in age (e.g. Bossi & Navarro 1991; Masquelin & Sánchez 1993; Pazos *et al.* 2003). This assumption was mainly founded on the inferred development of alluvial fans sourced from the Cambrian Sierra de las Ánimas Complex, located westward (Fig. 53.2). However, detailed mapping and stratigraphic analysis of the Las Ventanas Fm. led to its redefinition as a Neoproterozoic volcanic/sedimentary succession (Pecoits 2003*a*). The sections exposed in the northern and southern parts of the type area were designated as the stratotype and parastratotype of the unit, respectively (Pecoits 2003*a*). The former is located near Paso del Molino, where 1200 m of Las Ventanas strata are continuously exposed. The parastratotype is situated near the Burgueño Quarry and Apolonia Mine, where the unconformable contact between the Las Ventanas Fm. and the basement (Lavalleja Group) is exposed (Fig. 53.3).

The San Carlos Fm. was erected by Masquelin (1990), who documented that the unit consists of conglomerate, sandstone and pelite. The depositional environment was likely lacustrine or fluvio-lacustrine. The stratotype of the formation is located 6 km south of San Carlos town (Fig. 53.2), where 220 m of San Carlos strata are exposed with the base and top of formation not visible (Pecoits *et al.* 2008). The sedimentary facies and volcanic association of the San Carlos Fm. are similar to those of the middle Las Ventanas Fm. Likewise, palynological macerations carried out in the pelites of both units reveal the occurrence of similar microbiota (Pecoits *et al.* 2005). These observations led Pecoits *et al.* (2005) to propose a correlation between the San Carlos and Las Ventanas formations. Whether both units were deposited in the same basin, and subsequently dismantled by the displacement of the Sierra Ballena Shear Zone (Fig. 53.2), or were developed within different depocentres remains uncertain.

The first evidence of glacial influence in the Las Ventanas Fm. was recorded by Pecoits (2003*a*), comprising faceted, outsized clasts in finely laminated rhythmites that were interpreted as dropstones. Recently, Gaucher *et al.* (2008) reported glacial diamictite with associated dropstones occurring in laminated siltstone to the south of Minas (Fig. 53.2). Additionally, glacial diamictite and fine-grained rhythmites containing striated dropstones are well exposed *c.* 15 km NW (El Perdido area) of this locality (Pecoits *et al.* 2008). No glacial evidence has yet been recorded in the San Carlos Fm.

Structural framework

In Uruguay, a significant extensional and synkinematic magmatic event corresponding to the final stages of the SW-Gondwana assembly occurred during the Neoproterozoic–lowermost Cambrian (Bossi & Campal 1992; Pecoits 2003*b*; Oyhantçabal 2005). From a structural perspective, the Sierra Ballena Shear Zone (Figs 53.1 & 53.2) constitutes the largest remnant of the

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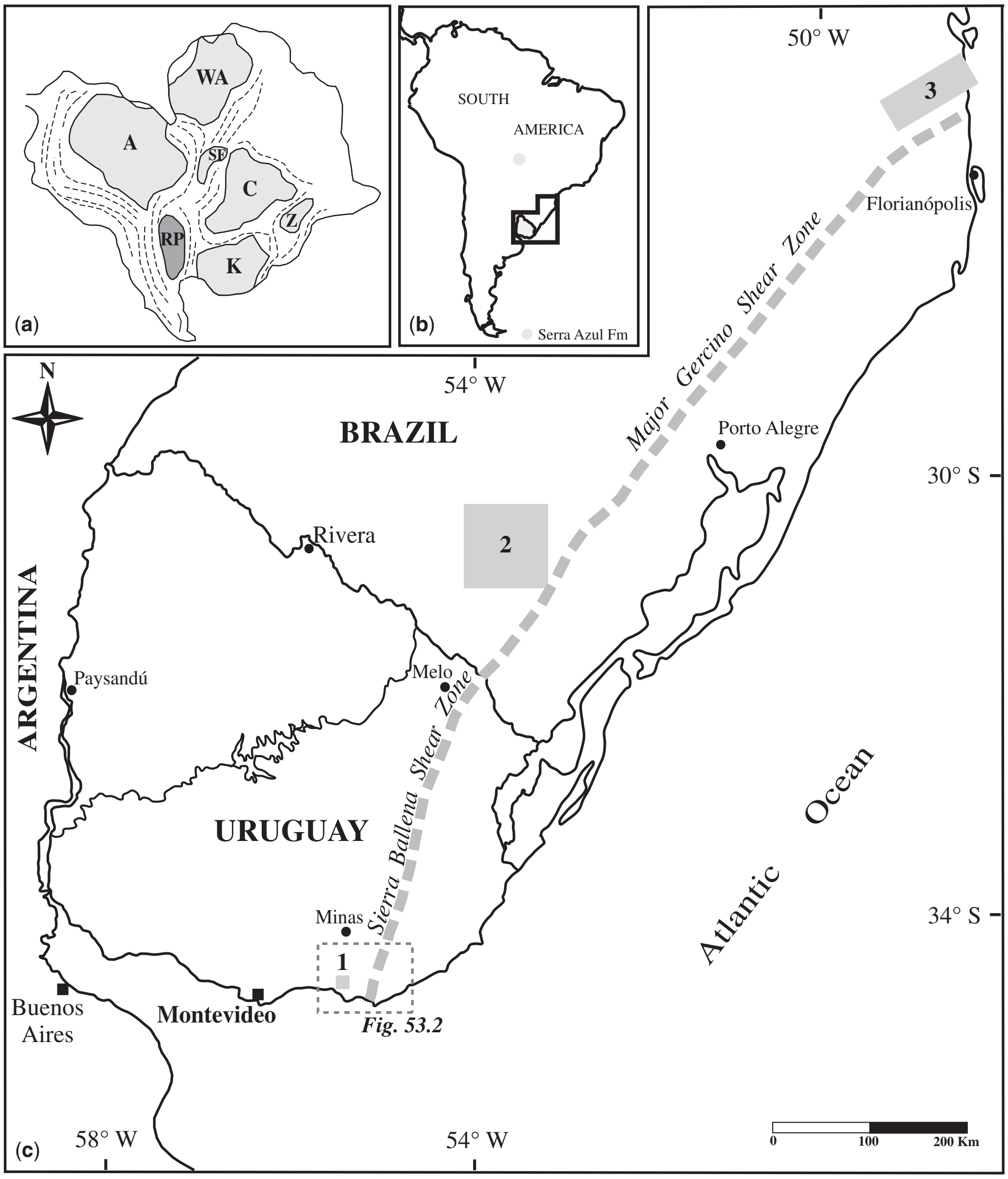

Fig. 53.1. (**a**) Distribution of cratonic blocks of west Gondwana: A, Amazonian; C, Congo; K, Kaoko; SF, São Francisco; RP, Río de la Plata; WA, West African; Z, Zaire. (**b**) Regional map showing the location of the units discussed in the text (see (c) for more detail). (**c**) Distribution of volcano-sedimentary early Ediacaran units of Uruguay and southeastern Brazil: 1, Las Ventanas-San Carlos formations; 2, Camaquã Basin; 3, Itajaí Basin.

Brasilian–Pan African Orogeny (*c.* 700–500 Ma). This high-strain transcurrent structure, which was operative primarily between *c.* 600 and 580 Ma, contributed significantly to the basin-fill architecture of the early Ediacaran units (Oyhantçabal 2005). In this regard, the Las Ventanas and San Carlos formations were deposited in a strike–slip basin, as indicated by (i) the diverse depositional facies and their abrupt lateral changes; (ii) apparent migration of the primary depocentre towards the south; (iii) the subparallel trend of the basin with respect to its strike–slip margins; and (iv) synchronous timing with regional shearing (Sierra Ballena Shear Zone). Following the development of the widespread transcurrent system, a gravitational orogenic collapse characterized by high-angle normal faulting and accompanied by marine transgression occurred during the late Ediacaran–Early Cambrian (Pecoits *et al.* 2008).

A similar geotectonic evolution is observed in the associated magmatism, which was initiated with highly fractionated calc-alkaline granite (*c.* 584 Ma), followed by mildly alkaline granite and shoshonitic volcanics (*c.* 575 Ma), and concluded with peralkaline intrusions and volcanics (*c.* 540–520 Ma) (Oyhantçabal *et al.* 2007). Therefore, the Ediacaran–Early Cambrian in Uruguay is characterized by a transition from a back-arc basin (underlying Lavalleja Group), followed by a strike–slip-related basin (Maldonado Group), to a foreland basin (overlying Arroyo del Soldado Group), where strike–slip shear zones of crustal scale played a major role in the evolution of the orogen.

At the outcrop scale, the Las Ventanas and San Carlos formations show evidence of both brittle and ductile deformation. Small- and large-scale strike–slip faults, westward-verging detachment faults, and folds with axis sub-parallel to the strike–slip planes are common features (Fig. 53.3). Axial plane slaty and sporadic millimetre-spaced fracture cleavages are present in fine-grained facies (pelite). The basic volcanic and pyroclastic rocks show abundant chlorite and epidote as well as pumpellyite and prehnite, demonstrating very low- to low-grade metamorphic conditions (Pecoits 2003*a*).

Stratigraphy

The Las Ventanas and San Carlos formations lie on an angular unconformity above a crystalline basement of undetermined age and the Lavalleja Group (Figs 53.4 & 53.5). Relatively well-dated basement granitoids are represented by the Campanero Complex and the Cerro Olivo Complex, with ages of *c.* 1750 Ma and 1006 ± 37 Ma, respectively (Table 53.1; Oyhantçabal 2005 and references therein). The lithostratigraphy of the Lavalleja

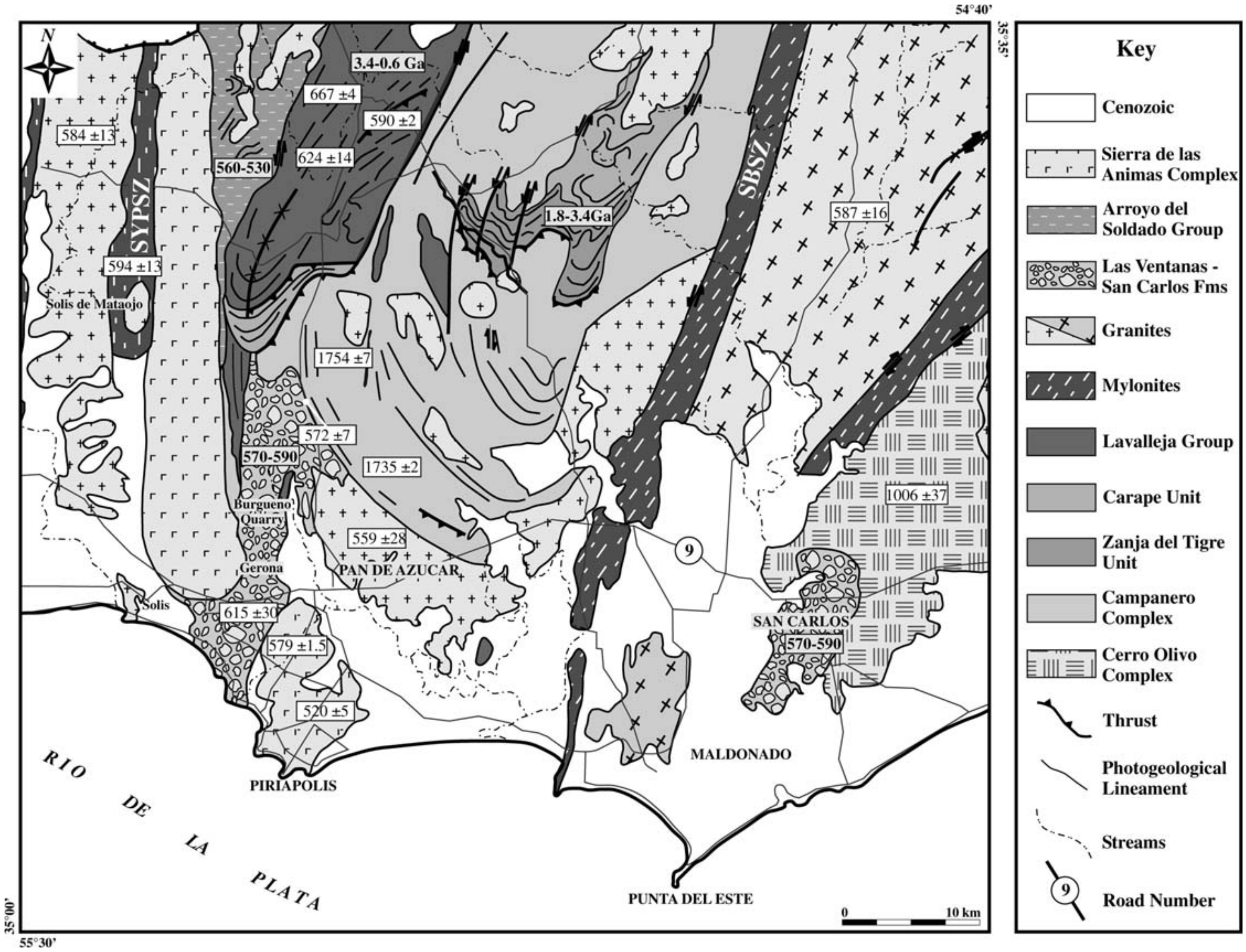

Fig. 53.2. Simplified geological map showing the distribution of the Las Ventanas and San Carlos formations (Maldonado Group) and selected age determinations of southeastern Uruguay (see Table 53.1 and text for explanation). Sources of geological information: Bossi & Navarro (1991), Pecoits *et al.* (2005), Oyhantçabal (2005) and references therein. SYPSZ, Sarandí del Yí-Piriápolis Shear Zone; SBSZ, Sierra Ballena Shear Zone.

Group, although poorly known, is different from that of the Las Ventanas and San Carlos formations. According to Midot (1984), the Lavalleja Group is a volcanosedimentary succession dominated by immature fine-grained siliciclastics, marl, basalt and limestone towards the top. This limestone hosts columnar stromatolites assignable to *Conophyton* (Poiré *et al.* 2005), and although their occurrence extended from the early Proterozoic to the Ediacaran, preliminary radiometric studies suggest an early Ediacaran age for this unit. SHRIMP U–Pb detrital zircon analyses from the Lavalleja Group display ages between 3.4 and 0.6 Ga (Basei *et al.* 2008). Likewise, interbedded basalt shows a crystallization age of 590 $\pm$ 2 Ma (U–Pb SHRIMP; Mallmann *et al.* 2007), indicating that the deposition must have occurred *c.* 590 million years ago.

The whole succession (i.e. the Las Ventanas and San Carlos formations) can be divided (from base to top) into three informal intervals: (i) volcanic and pyroclastic deposits, (ii) conglomerate-dominated lithofacies and (iii) pelite-dominated lithofacies. Volcanic and pyroclastic rocks including basalt, mafic hyaloclastic breccias and subaqueous tuff, as well as rhyolite, acidic volcanoclastic and pyroclastic rocks, have been recognized as part of the Maldonado Group (Fig. 53.4a). This bimodal volcanism has long been thought to represent part of the Sierra de las Ánimas Complex (e.g. Sánchez & Rapalini 2002 and references therein). The latter, however, shows geochemical signatures, radiometric ages and structural features indicating anorogenic magmatism, which was extruded after the main deformational phase that affected the Maldonado Group (Oyhantçabal 2005). In fact, the Sierra de las Ánimas Complex systematically displays radiometric ages younger than those of the volcanics assigned to the Maldonado Group (see 'Geochronological constraints') and it displays neither ductile deformation nor metamorphism. Field relationships show that the Sierra de las Ánimas Complex intrudes the Las Ventanas Fm., providing definite evidence of the older age of the Las Ventanas.

Conglomerate-dominated lithofacies (proximal facies association of Pecoits 2003*a*) dominate the basal part of the Las Ventanas Fm., including clast-supported conglomerate and breccia, diamictite, massive sandstone and conglomerate–sandstone couplets. Upwards, pelites are abundant with occasional conglomerate beds (pelites-dominated lithofacies or distal facies association of Pecoits 2003*a*). This lithofacies includes laminated siltstone and sandstone-pelite rhythmites, and massive sandstone and conglomerate. Likewise, the San Carlos Fm. consists of basal conglomerate- and upper pelite-dominated lithofacies, but the clast size in the lower conglomerate never reaches that of the Las Ventanas Fm. In this sense, two possible explanations can be drawn. First, the San Carlos Fm. represents a lateral equivalent

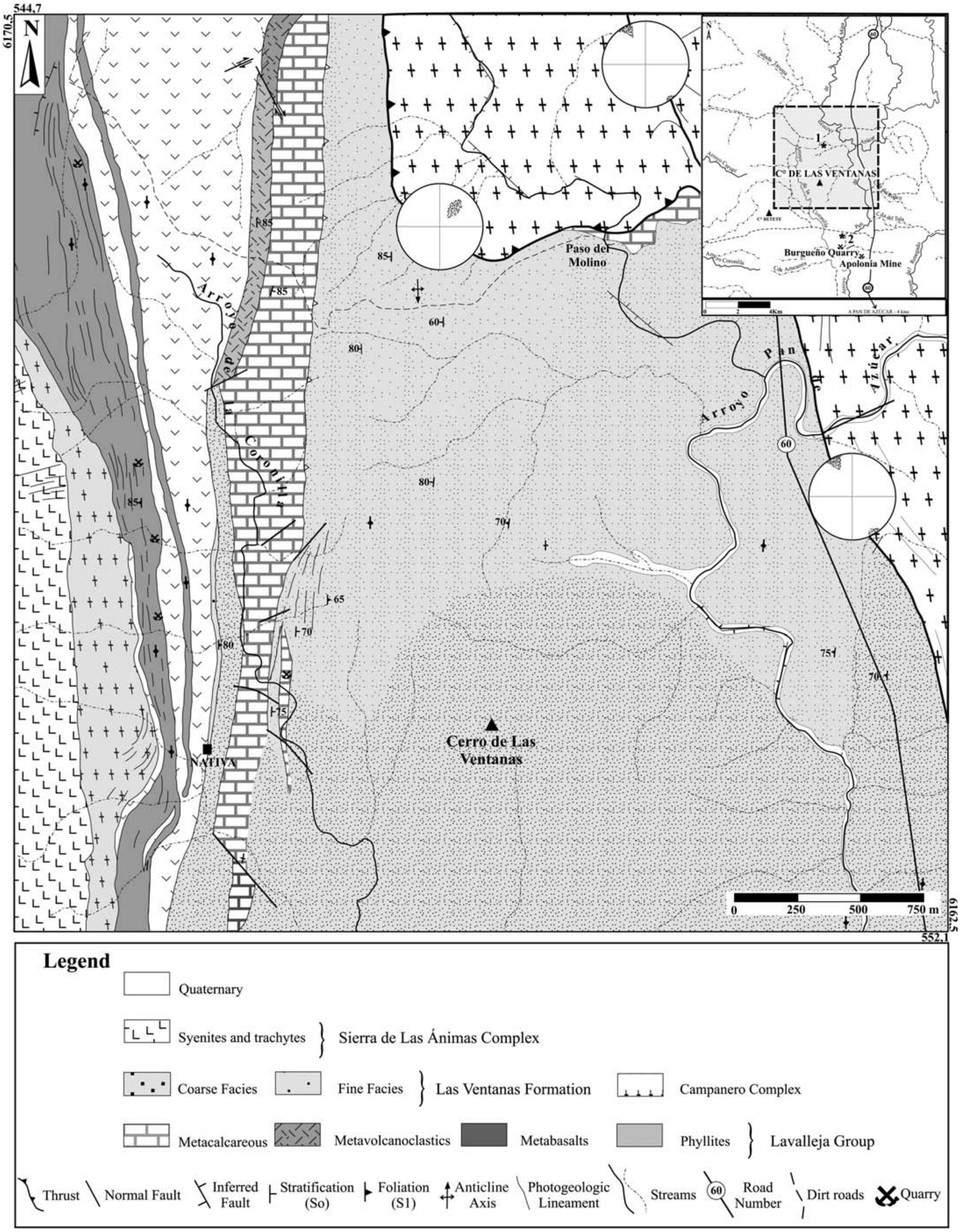

Fig. 53.3. Geological map of the type area of the Las Ventanas Fm. The inset shows the location of the stratotype (1) and parastratotype (2) (modified from Pecoits *et al.* 2008).

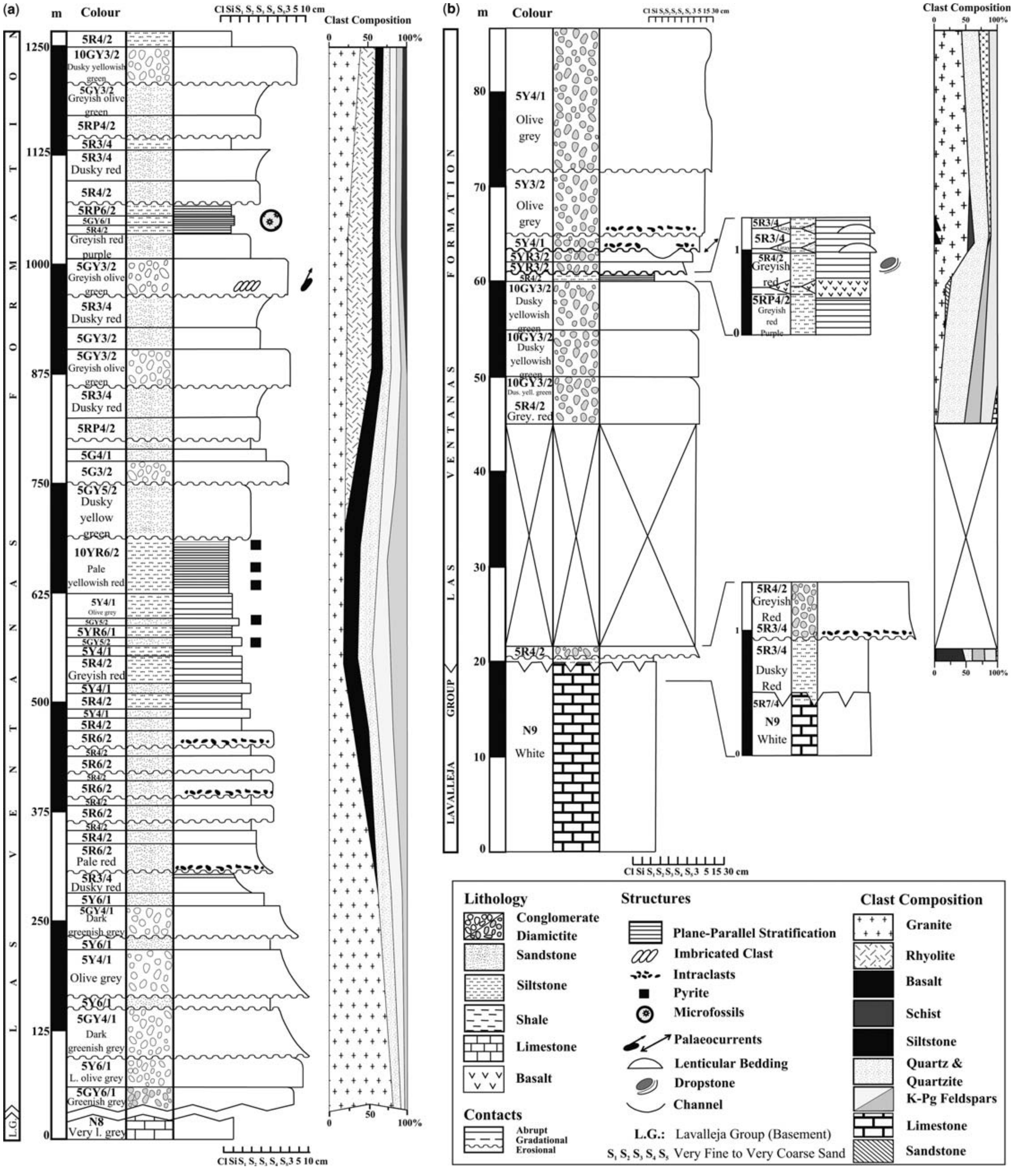

Fig. 53.4. (**a**) Stratigraphic column of the Las Ventanas Fm. at its stratotype (point 1, Fig. 53.3). (**b**) Stratigraphic section for the lower Las Ventanas Fm. at its parastratotype (point 2, Fig. 53.3) (modified from Pecoits *et al.* 2008). K-Pg, potassium and plagioclase.

to the middle and uppermost part of the Las Ventanas Fm., where coarse-grained conglomerate is rare (see 'Glaciogenic deposits and associated strata'). Second, both units, although potentially contemporaneous (see below), were deposited in different basins.

The Las Ventanas is thought to be overlain by the Arroyo del Soldado Group, a thick (3000 m) mixed siliciclastic–carbonate succession, mainly represented by intercalating conglomerate, sandstone, siltstone, thick carbonate, Fe-formation, black- and iron-rich shale and chert. It contains a rich fossil assemblage

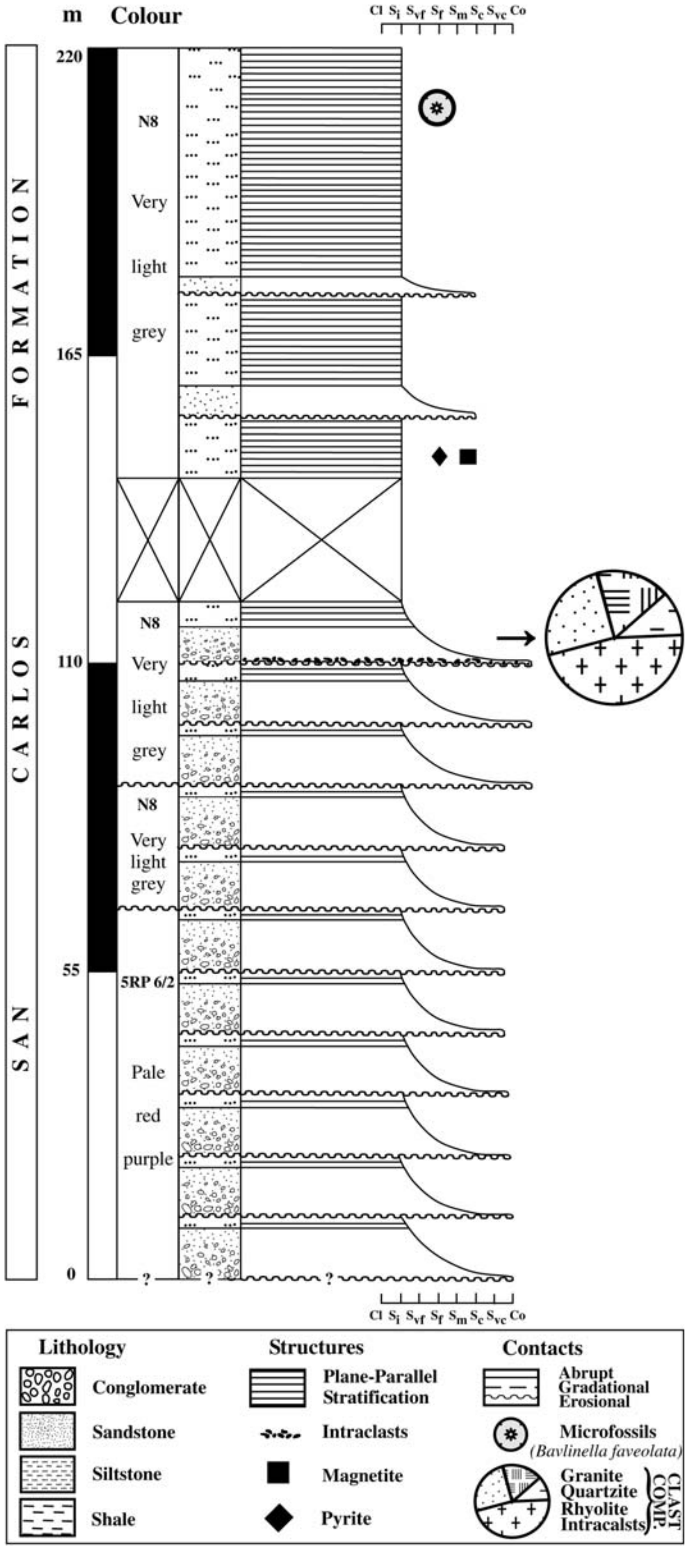

Fig. 53.5. Simplified stratigraphic column of the San Carlos Fm. at its stratotype, 6 km SE of San Carlos town (see Fig. 53.2) (modified from Pecoits *et al.* 2008).

composed of organic-walled microfossils and small shelly fauna, including the index fossil *Cloudina riemkeae* (Gaucher *et al.* 2004). The distinct lithological differences between Las Ventanas and San Carlos formations with the Arroyo del Soldado Group have been explained by different prevailing climatic conditions and tectonic settings. Whereas an evolution towards tropical conditions (Gaucher *et al.* 2004) and a marine transgression in a foreland setting (Pecoits *et al.* 2005; Basei *et al.* 2008) have been proposed for the latter, a glacially influenced system in a strike–slip setting was suggested for the Las Ventanas and San Carlos formations (Pecoits *et al.* 2005, 2008). The presence of abundant organic-walled microfossils and shelly fauna in the Arroyo del Soldado Group points to high biological productivity and an elevated nutrient supply, possibly related to increased weathering during warmer conditions (Gaucher *et al.* 2004). Based on available geochronology, chemostratigraphy and biostratigraphy, Pecoits *et al.* (2008) proposed a maximum depositional age of *c.* 560 Ma for the group, which is younger than earlier suggestions (Gaucher *et al.* 2004).

Glaciogenic deposits and associated strata

Palaeoenvironmental interpretations indicate that the Las Ventanas–San Carlos system records sheet flood-dominated fan-delta deposits in a glacially influenced setting. Direct evidence of ancient glacial activity comes from the basal and uppermost facies of the Las Ventanas Fm., where some deposits have been described and interpreted as ice-rafted diamictite with striated and faceted clasts and rhythmite-hosting dropstones (Pecoits 2003*a*; Pecoits *et al.* 2008).

Diamictites are mainly coarse-grained and matrix-supported lithofacies with a massive structure displaying normal and occasionally reversed grading. Clasts are rounded to angular and range from granule to boulder size. Compositionally, the diamictite dominantly contains extrabasinal clasts (rhyolite, basalt, granitoid, gabbro, quartzite). Two types of diamictite can be distinguished: sub-rounded pebbles and cobbles in a massive muddy matrix, and angular to sub-rounded cobbles to boulders in a massive to horizontally laminated silty/clayey matrix. These deposits have a polymodal texture and form relatively thick (2–10 m) tabular beds with faceted and occasionally striated clasts.

Although common in the uppermost part of the succession, fine-grained rhythmites are also found interbedded with diamictite at the base of the Las Ventanas Fm. The $<$3-m-thick beds are characterized by a millimetre- to centimetre-intercalation of silty and sandy material with clay and also by the presence of out-sized clasts deforming the layering. Based on the diverse composition of these large clasts (granite, basalt, gabbro, etc.), and on the presence of pre-depositional foliation, an interpretation of the clasts as volcanic bombs or other ballistic/pyroclastic material is discarded. These lithofacies (i.e. rhythmites with out-sized clasts and diamictite) were first described at the parastratotype section of the unit (Burgueño Quarry and Apolonia Mine; Fig. 53.3), but later discovery in other localities (e.g. NE Minas and Melo; Fig. 53.1) suggesting that they are more extensive than originally thought.

The type section of the Las Ventanas Fm. is largely dominated by conglomerate, sandstone and finely laminated siltstone. It begins with a 690-m-thick fining- and thinning-upward cycle (Fig. 53.4a). Conglomerate, sandstone and laminated siltstone dominate the lowermost, medial and uppermost sub-cycles, respectively. The conglomerate is typically granitic and clast-supported with arkosic sandstone present at the top of each sub-cycle. The following changes occur up-section within the lower major cycle: (i) bed thickness progressively decreases, from metre-scale to a few millimetres (laminae); (ii) average grain size decreases from pebbles to silt; (iii) the proportion of granitic clasts becomes smaller; and (iv) planar parallel stratification and lamination become a common feature in the siltstone but are absent in the lower and middle part of the cycle. This finely laminated siltstone shows similar features to those described in the basal part of the unit. Here, the lithofacies is considerably thicker, but the out-sized clasts (dropstones) identified in it are smaller and rarely reach more than 10 cm.

The formation passes up-section into a second major cycle that is nearly 560 m thick, and is composed of minor subcycles of

Table 53.1. *Summary of geochronological data available from southeastern Uruguay (see Fig. 53.2)*

Stratigraphic unit	Rock type	Method	Age (Ma)
Sierra de las Ánimas Complex	Porphyres	Rb–Sr	520 ± 5
	Syenite	Ar–Ar	579 ± 1.5
A° del Soldado Group*		Depositional age: *c.* 560–530 Ma	
El Renegado	Granite	Rb–Sr	559 ± 28
Puntas del Pan de Azúcar Lineament	'Mylonite'	$K–Ar_{Musc}$	572 ± 7
Aiguá Batholith	Granite	Rb–Sr	587 ± 16
Solís de Mataojo	Tonalite	U–Pb	584 ± 13
Aguas Blancas	Mylonite	$K–Ar_{Musc}$	594 ± 13
Las Ventanas and San Carlos formations*		Depositional age: *c.* 590–570 Ma	
Las Flores	Trachybasalt	K–Ar	615 ± 30
Lavalleja Group*	Quartz-sericite schist	$U–Pb_{(SHRIMP)}$	600–3400
	Metabasalt	$U–Pb_{(SHRIMP)}$	590 ± 2
	Metarhyolite	U–Pb	624 ± 14
	Metarhyolite	U–Pb	667 ± 4
Cerro Olivo Complex	Orthogneiss	U–Pb	1006 ± 37
Zanja del Tigre Fm.*	Meta-sandstone	$U–Pb_{(SHRIMP)}$	1800–3400
Campanero Complex	Orthogneiss	U–Pb	1735 ± 2
	Orthogneiss	U–Pb	1754 ± 7

Source: Oyhantçabal (2005) and references therein, Mallmann *et al.* (2007), Basei *et al.* (2008), Pecoits *et al.* (2008). *Volcanic-sedimentary units.

sandstone and fine-grained conglomerate. The sandstone has a tabular geometry, is massive in appearance, and occasionally has non-erosive basal contacts. The conglomerate is clast-supported, polymictic and has a modal grain size of 3–10 cm. The clast composition is variable, and includes rhyolite (32%), granite (2%), quartz (12%), basic volcanic rocks (11%), alkaline feldspar (10%), plagioclase feldspar (8%) and schist (5%). Clasts, either in conglomerate or sandstone, are fresh and show no signs of chemical weathering.

Boundary relations with overlying and underlying non-glacial units

The Las Ventanas Fm. rests unconformably on the Lavalleja Group. Palaeoproterozoic orthogneiss (Campanero Complex) and Monzogranite (La Nativa) are of unknown age (Pecoits *et al.* 2008). A nonconformity separates the San Carlos Fm. from Palaeoproterozoic ortho- and paragneiss (Cerro Olivo Complex; Fig. 53.2). Particularly important is the relationship with the Lavalleja Group. This unit is largely dominated by basalt and immature fine-grained siliciclastic rocks (Midot 1984). An evolution towards warm climate and stable tectono-magmatic conditions is evidenced by thick stromatolitic limestones developed in the uppermost part of the unit (Poiré *et al.* 2005), upon which the Las Ventanas Fm. uncomformably lies. However, as discussed below, the hiatus between both units is poorly constrained. Despite this, the transition from the Lavalleja Group to the Las Ventanas Fm. is not only indicated by an angular unconformity but also by a strong change in climatic and tectono-magmatic activity.

The relationship and nature of the contact between Las Ventanas and San Carlos formations with the overlying late Ediacaran Arroyo del Soldado Group is not firmly established. The best locality to study such transition is to the north of Minas (Fig. 53.2) where both units are closely exposed. Detailed geological mapping of the area indicates stratal juxtaposition due to tectonic shortening in a zone of major thrusting. In other words, both units would be separated by major structural discontinuities (i.e. thrusts oriented SW–NE), and no conformable contacts have been recorded. The contact between the units – although not well exposed – suggests the presence of an angular unconformity separating the uppermost fine-grained rhythmites of the Las Ventanas Fm. and the sandstone of the basal Arroyo del Soldado Group (Yerbal Fm.).

Chemostratigraphy

Owing to the lack of carbonate rocks directly associated with the Las Ventanas or San Carlos formations, no chemostratigraphic studies (e.g. C, O, Sr) have been performed.

Other characteristics

No evidence of mineral deposits was found in any of the units described here.

Palaeolatitude and palaeogeography

The location and kinematic history of the blocks involved during the assembly of West-Gondwana in the late Neoproterozoic is poorly known (Rapela *et al.* 2007). In particular, the palaeogeographical position of the Río de la Plata Craton (Fig. 53.1 inset) during the Ediacaran is highly disputed (e.g. Cordani *et al.* 2000). In this regard, no palaeomagnetic studies have been performed either in the sedimentary rocks of Las Ventanas Fm. or in the San Carlos Fm. Preliminary mean geomagnetic poles were only obtained from sedimentary rocks of the Playa Hermosa Fm., volcanics from the Las Ventanas Fm., and volcanics and intrusives from the Sierra de las Ánimas Complex (Sánchez & Rapalini 2002). According to the same authors, the new data support the *Apparent Polar Wander Path* (APWP) previously suggested for the entire Gondwana since *c.* 550 Ma, indicating that the Río de la Plata Craton was indeed at that time part of the supercontinent. Furthermore, it was suggested that a mean geomagnetic pole obtained from the Playa Hermosa Fm. ($12.7\ +9.5/-8.1^\circ$) meant that another example of Neoproterozoic low-latitude glaciation is evident in Uruguay.

The most reliable palaeomagnetic pole for early Ediacaran units of the Río de la Plata Craton is derived from the Campo Alegre lavas (Sánchez & Rapalini 2002). The Campo Alegre Fm., dated by the U–Pb method at 595 ± 5 Ma (Citroni *et al.* 1999), is located in the Itajaí Basin, SE Brazil (Fig. 53.1). Palaeomagnetic reconstructions indicate a moderate palaeolatitude of $33.3 \pm 9.5^\circ$S (D'Agrella & Pacca 1988), in marked contrast to the low palaeolatitudes ($12.7 + 9.5/-8.1^\circ$) proposed for the Playa Hermosa Fm. (Sánchez & Rapalini 2002).

In contrast to the scarce database for the early Ediacaran units, the APWP for Gondwana since 550 Ma is better known. Since 550 Ma, poles for the Río de la Plata Craton and other Gondwanan continents have tended to form a single APWP ranging from *c.* 30°S in the late Ediacaran towards lower palaeolatitudes during the Lower Cambrian (Meert & Van der Voo 1996).

Geochronological constraints

Since the definition of both units, the age of the Las Ventanas and San Carlos formations was considered Ordovician (e.g. Midot 1984; Masquelin & Sánchez 1993; Pazos *et al.* 2003). This assumption was challenged by Pecoits *et al.* (2008) in reporting cross-cutting relationships with several intrusive Ediacaran bodies and major faults that indicated a minimum depositional age of *c.* 570 Ma. The age of deposition of the Las Ventanas and San Carlos formations is now relatively well constrained to *c.* 590–575 Ma by radiometric data based on K–Ar, Rb–Sr and U–Pb dating techniques on basement rocks, interbedded basalt, intrusive syenite, granitic and trachytic dykes, and cross-cutting faults (Table 53.1).

This inference is supported by the 590 ± 2 Ma age (SHRIMP U–Pb) obtained for a metabasalt (Mallmann *et al.* 2007), the detrital zircons from the Lavalleja Group in the basement of the Las Ventanas Fm., which show U–Pb (SHRIMP) ages between 3.4 and 0.6 Ga (Basei *et al.* 2008), and an intrusive syenite that yields Ar/Ar ages of 579 ± 1.5 Ma (Oyhantçabal *et al.* 2007). Furthermore, the ages are corroborated by (i) basic volcanics interbedded with sedimentary rocks of the Las Ventanas Fm., which display ages between 615 ± 30 and 565 ± 30 Ma (K–Ar method; Sánchez & Linares 1996); (ii) Rb–Sr ages from intrusive granite with an age of 559 ± 28 Ma (Preciozzi *et al.* 1993) and trachyte of the Sierra de Las Ánimas Complex, which intrude and overly the Las Ventanas Fm., dated between 520–530 Ma (Bossi *et al.* 1993; Linares & Sánchez 1997); (iii) basic dykes cross-cutting the Las Ventanas Fm. to the south of Minas yielding a K–Ar age of 485 ± 12.5 Ma (Poiré *et al.* 2005); (iv) the last reactivation of the Puntas del Pan de Azúcar Lineament, which cross-cuts the Las Ventanas Formation (Fig. 53.3), and occurs at 572 ± 7 Ma (K–Ar in syn-kinematic muscovites) (Bossi & Campal 1992); and (v) the San Carlos Fm., which is intensively deformed by the Sierra Ballena Shear Zone, in which the third and last deformation phase occurred at *c.* 550–500 Ma (Oyhantçabal 2005). Finally, the transcurrent tectonics that occurred during the early Ediacaran, which is closely related to the generation of strike–slip basins recorded for example by the Las Ventanas and San Carlos formations, is also associated with a voluminous syn-kinematic magmatism (Pecoits 2003*a*; Pecoits *et al.* 2005). Radiometric studies performed in all these bodies yield ages systematically between 570 and 590 Ma (Rb–Sr and U–Pb methods) (Bossi *et al.* 1993; Hartmann *et al.* 2002; Oyhantçabal 2005).

According to Gaucher *et al.* (2008), the acritarch assemblage recovered from the Las Ventanas Fm. indicates a depositional age between 635 and 582 Ma, supporting previous data (Pecoits 2003*a*, *b*). This assemblage, however, comprises and is dominated by individuals with no stratigraphic value, such as *Leiosphaeridia* and others of doubtful origin (e.g. *Soldadophycus*) (Butterfield, pers. comm. 2008).

Discussion

The facies associations point to the development of sheet flood-dominated alluvial fans (Blair & McPherson 1994) intercalated with minor lake deposits in a glacially influenced, transtensional tectonic setting. The proximal facies association comprises massive and horizontally stratified clast-supported conglomerate and rare breccia, massive sandstone, conglomerate–sandstone couplets and diamictite, while the distal facies includes massive and normally graded sandstone, pebbly sandstone, laminated siltstone, and fine-grained massive and graded conglomerate. The proximal facies association was interpreted by Pecoits (2003*a*) as a subaerial alluvial fan in which debris-flow deposits (diamictite) and sheet flood deposits (stratified conglomerate and sandstone) constitute the dominant facies. The subaerial alluvial fan succession is characterized by upward-coarsening and upward-thickening trends resulting from fan progradation. The restricted occurrence of debris flow beds and the comparatively high roundness of the clastic fraction indicate that the preserved succession represents middle and outer regions of the alluvial-fan complex. The distal facies association is thought to represent a submarine delta subenvironment with sediment gravity-flow deposits occasionally interbedded with turbidites (massive and graded conglomerate and sandstone) and suspension fallout deposits (laminated siltstone). Although some conglomeratic levels are interpreted to represent shoreline deposits along the distal fan, no evidence of wave reworking has been observed (Pecoits 2003*a*).

The proximal facies association offers evidence of sedimentation under arid climatic conditions, as shown by exceptionally fresh well-rounded clasts (e.g. basalt) in conglomerate and sandstone. Glacial sedimentary evidence comes from the distal facies association. Therein, outsized clasts within finely laminated siltstone have been recorded and interpreted as dropstones. This lithofacies has been described at the base and top of the Las Ventanas Fm. In the first case, the laminated strata are 'sandwiched' between massive and bedded diamictite, mostly containing extrabasinal clasts. Faceted, striated and bullet-shaped clasts are consistent with glacial transport and suggest a glacial influence during the deposition of laminated siltstone and diamictite facies. In contrast, the laminated siltstone described at the top of the unit overlies laminated siltstone and fine-grained sandstone, which are interpreted as turbiditic deposits (Pecoits *et al.* 2008). Here, the glacially influenced laminated siltstone is differentiated from the turbidites by the lack of turbidity current structures, finer grain size and numerous dropstones with impact-induced deformation of underlying laminae.

Despite the lack of evidence for glacially influenced sedimentation in the San Carlos Fm., the structural and geochronological framework, stratigraphy and fossil content support the premise that the San Carlos Fm. is correlative with the middle–upper part of the Las Ventanas Fm. (Figs 53.4a & 53.5). This would explain the absence of the basal and uppermost glacially influenced facies described for the Las Ventanas Fm.

Only one systematic palaeomagnetic study has been performed in glacial Ediacaran units and associated rocks of Uruguay (Sánchez & Rapalini 2002); however, none of the sampled sites corresponds to the Las Ventanas and San Carlos formations. Unfortunately, all the samples from this work were collected near the border of the Dom Feliciano belt, in an area affected by intense Neoproterozoic–Cambrian tectono-magmatic activity, and thus probably affected by widespread remagnetization (e.g. Rapalini & Sánchez 2008). The two palaeopoles obtained from volcanic and hypabyssal rocks of the Sierra de las Ánimas Complex are, from geochronological and structural points of view, poorly constrained. Much of the radiochronology is based on the K–Ar method, which usually provides a minimum age, and recent dating on the same lithologies using more precise methods has yielded ages as much as 30 Ma older (Oyhantçabal *et al.* 2007). Although the early Ediacaran units of Uruguay are extensively deformed, the interbedded basalt samples for palaeomagnetism were not corrected with respect to the palaeohorizontal. Field relationships have extensively shown that even the youngest rocks of the Sierra de las Ánimas Complex (i.e. *c.* 525 million years old), although not folded, are tilted. Therefore the integrity and usability of these palaeomagnetic data are problematic.

Recent palaeogeographical reconstructions locate the Río de la Plata Craton at high palaeolatitudes *c.* 580 million years ago

(Trinidade & Macouin 2007). Inclination data from deposits slightly older than the Gaskiers equivalent in the Avalon Terrane (Newfoundland) similarly indicate a palaeolatitude of 35°S during the early Ediacaran (*c.* 608 Ma, U–Pb zircon age; Myrow & Kaufman 1999). However, palaeogeographical models between 590 and 560 Ma (i.e. when Gaskiers deposits and their possible Ediacaran correlatives, Squantum, Loch na Cille, and Moelv, were formed) are controversial due to the ambiguous results presented by the Laurentian palaeopoles (Trinidade & Macouin 2007 and references therein). For instance, both low and high latitudes for Laurentia at *c.* 580 Ma have been proposed. If the latter configuration is confirmed, the glacial strata observed in Laurentia, Baltica, Cadomia, Avalonia and Río de la Plata cratons are compatible with a palaeoclimatic scenario similar to the Phanerozoic glaciations rather than 'snowball' conditions.

Although early proposals promoted a 'Marinoan' age for Las Ventanas and San Carlos formations (Pecoits *et al.* 2005), an Ediacaran event seems to be a more reasonable alternative (Pecoits *et al.* 2008) based on the radiometric constraints. Indeed, this would explain the absence of thick 'cap carbonate' facies immediately overlying these deposits as is distinctive of Ediacaran glacial deposits. Alternatively, the absence of cap carbonates might be due to deposition in a highly active tectonic setting, characterized by high rates of subsidence and high accumulation rates of siliciclastic sediments, lack of preservation because they were eroded; or, they may simply not have been found yet. However, the typical facies of the Las Ventanas and San Carlos formations indicates an active participation of the hydrological cycle that is incompatible with the 'Snowball Earth' model for Cryogenian glaciations (e.g. Hoffman & Schrag 2002).

Recently, a similar glacial succession (Tacuarí Fm.) was described in NE Uruguay (Veroslavsky *et al.* 2006). These deposits were long-considered a classic example of the Carboniferous–Permian glaciation in Gondwana (e.g. Bossi & Navarro 1991). According to Veroslavsky *et al.* (2006) and mainly based on a very similar fossil content to that described for the Las Ventanas Fm., this unit was tentatively assigned to the Neoproterozoic. Ongoing research using radiometric dating on cross-cutting granitic dykes (U–Pb TIMS) and detrital zircons (LA-ICP-MS) has confirmed the Ediacaran age of the succession. The obtained ages constrain the deposition of the unit between 590 and 570 Ma. This is in agreement with the age proposed for the Las Ventanas Fm. (570–590 Ma) and would suggest regional glacial conditions.

Sedimentological, tectonic and magmatic evidence, supported by radiometric ages, suggests some similarities between the Maldonado Group and other successions in Brazil. In this regard, the Las Ventanas and San Carlos formations have been correlated with the Bom Jardim (*c.* 592–573 Ma) and Cerro do Bugio (573–559 Ma) allogroups of the Camaquã Basin located in Rio Grande do Sul, southern Brazil (Pecoits 2003*b*; Fig. 53.1). The Bom Jardim Allogroup is composed of basic to intermediate volcanic rocks, alluvial conglomerate and turbidites (Paim *et al.* 2000). SHRIMP age dating of the volcanics yielded an age of *c.* 580 Ma (Paim *et al.* 2000). The Cerro do Bugio Allogroup consists of acidic and basic rocks, alluvial conglomerate, rhythmites (sandstone-pelite) and pelite. Geochronological studies on acidic rocks yielded a U–Pb age of 573 ± 8 Ma (Paim *et al.* 2000). Both the Bom Jardim and Cerro do Bugio allogroups were deformed by sinistral transcurrent displacement dated to *c.* 570 Ma and were subsequently intruded by granitic bodies dated at 559 ± 7 Ma and 565 ± 14 to 561 ± 6 Ma (Paim *et al.* 2000 and references therein). Evidence of a seasonal glacial influence has been suggested by Eerola (2001, 2006) for the Bom Jardim Allogroup.

Recently, Alvarenga *et al.* (2007) reported glacial deposits in the Ediacaran Serra Azul Fm. in the Paraguay belt, Brazil (Alvarenga *et al.* 2011). The Paraguay belt is located on the south-eastern edge of the Amazon Craton (Fig. 53.1), which in conjunction with the Río de la Plata Craton was probably already amalgamated into a single crustal block by the Ediacaran (e.g. Cordani *et al.* 2000). Unlike the Las Ventanas–San Carlos formations and their Brazilian correlatives Cerro do Bugio–Bom Jardim allogroups, the Serra Azul Fm. was deposited on a passive margin (Alvarenga *et al.* 2007), showing no comparable tectono-magmatic activity but probably similar palaeolatitude (see above). The correlation between Ediacaran (*c.* 590–570 Ma) glacially influenced successions of Brazil and Uruguay strengthen the notion of a post Cryogenian glaciation and suggests that these deposits are distributed more extensively than previously recognized in South America. Future efforts focused on the sedimentological constraints of these and other successions (e.g. Itajaí Basin in Brazil) are required to determine the glacial influence on the Brazilian units.

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