Chapter 3

Sedimentology and paleoenvironment of the Santa Cruz Formation

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Abstract

The Santa Cruz Formation in the coastal area of Santa Cruz Province, Austral Patagonia, Argentina, is a continental succession characterized by fluvial sediments which are mainly fine and tuffaceous in the lower section (Estancia La Costa Member) and are coarser and siliciclastic towards the top (Estancia La Angelina Member). The lower member bears a rich mammalian association of Santacrucian Age (late Early Miocene). Compositional and paleoenvironmental analysis of the lower member, allows the differentiation of three sections: lower, middle and upper. The lower section crops out in the northern part of our study area. It is a succession of fine primary and reworked tuffs and massive silty sandstones with immature paleosols deposited in a relatively low energy fluvial system with vegetated floodplains with high sedimentation rates and a volcanic source. The middle section shows an evident increase in the coarse facies and paleosols, and a decrease in pyroclastic materials, which suggests a relatively higher energy for the system compared to the lower section, with a lower sedimentation rate and a more distal volcanic source. The upper section is compositionally even coarser and is exclusively siliciclastic in origin, and evinces even more energetic conditions of the fluvial system but with a fluctuating flow regimes and places where the vegetation was scant. During the deposition of Estancia La Costa Member the climate changed from warm with somewhat cooler and/or dryer intervals (lower and middle sections) to cool and dry conditions towards the top.

Resumen

En la zona costera de la provincia de Santa Cruz, Patagonia Austral, Argentina, aflora la Formación Santa Cruz (Mioceno temprano) portadora de fauna de mamíferos de Edad Santacrucense. Dicha unidad es una sucesión continental de origen fluvial, compuesta principalmente por material volcaniclástico fino en su sección inferior (Miembro Estancia La Costa) con mayor participación de material silicoclástico hacia la sección superior (Miembro Estancia La Angelina). Sobre la base del análisis composicional y paleoambiental desarrollado exclusivamente en el miembro inferior, se diferenciaron tres secciones: inferior, media y superior. La sección inferior, aflorante en la parte norte del área de estudio, es una sucesión compuesta por tobas primarias y retrabajadas y areniscas limosas masivas con procedencia de arco volcánico, con frecuentes niveles de paleosuelos inmaduros. Dicha sucesión representa un sistema fluvial de energía relativamente baja con llanuras de inundación vegetadas, acumulado con una tasa de sedimentación relativamente alta. La sección media muestra un incremento en las facies de mayor granulometría, una disminución en la participación de material piroclástico y una mayor participación de niveles edafizados, indicando una procedencia volcánica más distal y un ambiente con energía relativamente mayor que la sección inferior, acumulado bajo una tasa de sedimentación relativamente baja. Por último, la sección superior resulta exclusivamente de origen silicoclástico y de facies gruesas, lo cual evidencia condiciones aún de mayor energía del sistema fluvial con un régimen de flujo fluctuante. Durante la depositación del Miembro Estancia La Costa el clima osciló desde cálido, con algunos intervalos fríos y/o secos (sección media e inferior) a condiciones más frías y secas hacia la parte superior.

3.1. Introduction

Outcrops of the continental Santa Cruz Formation in the coastal area of Santa Cruz Province (late Early Miocene), Austral Patagonia, Argentina, present a record of fluvial deposits, which are mainly composed of volcaniclastic material, and are very rich in vertebrate fossils (Tauber, 1994, 1997; Kay *et al.*, 2008, among others). The Santa Cruz Formation is the most widespread and most richly fossiliferous of all Patagonian nonmarine Tertiary formations of southern Argentina (Tauber, 1994; Tejedor *et al*., 2006; Vizcaíno *et al*., 2006, 2010, Tambussi, 2011). For this reason, the unit has been intensely studied since the 1890s from a paleontological and biostratigraphical point of view (see references in Vizcaíno, Kay and Bargo, this volume), but the sedimentological aspects of the formation have been only briefly described (Bown and Fleagle, 1993; Tauber, 1994; Fleagle *et al*., 1995).

The deposition of the Santa Cruz Formation in the Austral geologic basin can be understood in the context of regional tectonic, geographical and climatic changes (Blisniuk *et al*., 2005, 2006; Barreda and Palazzesi, 2007; Tassone *et al*., 2008; Ramos and Ghiglione, 2008; Madden *et al*., 2010; Quattrochio *et al*., 2011) and during the time interval (17-15 Ma) that experienced a global climatic event named as Mid-Miocene Climatic Optimum (Zachos *et al*., 2001).

This sedimentological study of the Santa Cruz Formation has the following objectives: 1) to characterize compositionally the Estancia la Costa Member and to establish the source area of its sediments; 2) to present a description of the facies and facies association within the formation; 3) to reconstruct the paleoenvironment of deposition; 4) to infer the paleoclimatic conditions that prevailed in Austral Patagonia during the mid-Miocene; and 5) to consider the regional effects of the volcanism on the sedimentary environment.

3.2. Geological setting and stratigraphy

The Santa Cruz Formation is part of the fill of the cratonic area of the foreland Austral or Magellan Basin in southernmost South America (Russo *et al*., 1980; Olivero and Malumián, 2002, 2008; Menichetti *et al*., 2008). The basin follows a preferential NNW-SSE axis and is limited by the Mountain range of the Andes, toward the West, and by the Alto de Río Chico to the East (Biddle *et al*., 1986; Corbella, 2002; Peroni *et al*., 2002). The latter is the southern extension of the Deseado Massif that served as the basement of the Cretaceous sedimentation separating to the East the Austral-Magellan Basin from the Malvinas Basin (Rossello *et al*., 2008). Our study area comprises the southeastern part of this basin.

The geological history of the Austral Basin begins in the Triassic with the initiation of rifting between South America and Africa (Biddle *et al*., 1986). The Bahía Laura Group consists of volcaniclastic rocks deposited in grabens and half-grabens during the Jurassic (Uliana *et al*., 1985). During the Late Jurassic-Early Cretaceous the margin of the basin was closed by the uplift of the western arc (Arbe, 1987) and the deposition of the Springhill Formation occurred (Corbella, 2002). Subsequently, from the Early Cretaceous into the Miocene, the basin experienced repeated transgressions and regressions of the sea. Towards the east the marine Palermo Aike Formation (Campanian-Maastrichtian) was deposited, while to the north marine and continental deposition alternated: continental San Julián Formation (Late Eocene-Early Oligocene), marine Monte León Formation (Late Oligocene-Early Miocene), continental Santa Cruz Formation (late Early Miocene) and finally, the Pliocene marine terraces and continental Rodados Patagónicos (Late Pliocene-Quaternary) (Uliana *et al*, 1985; Corbella, 2002; Peroni *et al*., 2002). The continental deposits of the Santa Cruz Formation occurred during an important phase of deformation and uplift of the cordillera in the west. Its sedimentation clearly indicates that the regression of the marine deposits of the underlying Late Oligocene - Early Miocene Centinela Formation (= 25 de Mayo Formation, Cuitiño and Scasso, 2010) in the west was forced by the cordillera uplift (Ramos and

Ghiglione, 2008). The deposition of the Santa Cruz Formation occurred in a foreland basin where sediment supply exceeded the accommodation space. As a result, a prograding sequence expanded to the Atlantic coast (Nullo and Combina, 2002).

3.2.1. Distribution of Santa Cruz Formation and study area

The Santa Cruz Formation is developed over much of the south of Patagonian Argentina both in surface exposures and in drill logs, from the Eastern area of the South Patagonian Cordillera (Cordillera Patagónica Austral) (Bande *et al*., 2008; Cuitiño and Scasso, 2010) southwards from Lago Buenos Aires to the Río Turbio area, and eastward from Extra-Andean Patagonia to the Atlantic Ocean between Golfo de San Jorge and northern Tierra del Fuego (Marshall, 1976; Bown and Fleagle, 1993; Tauber, 1997; Malumián, 1999). Maximum thickness of these continental deposits is reached along the northern foothills of the Patagonian Cordillera with thicknesses up to 1500 m, decreasing to 225 m along the Atlantic coast (Riggi, 1979; Riccardi and Rolleri, 1980; Tauber, 1997).

The outcrops of the Santa Cruz Formation in the study area are arrayed parallel to the Atlantic coast of Santa Cruz Province between Parque Nacional Monte León and Río Gallegos (see Vizcaíno, Kay and Bargo, this volume, Figs. 1.1 and 1.2). The following localities were studied: north to the Río Coyle, Rincón del Buque (= Media Luna; S 50º 39' 41', W 69º 06' 52') and Cañadón del Cerro Redondo (S 50º 51' 25', W 69º 08' 03') (Fig. 3.1a); south of the Río Coyle from north to south, Punta Sur-Cañadón del Indio (S 50º 58' 59', W 69º 09' 56'), Campo Barranca (S 51º 00' 36', W 69º 09' 15'), Anfiteatro (S 51º 03' 12'', W 69º 08' 20'', Estancia La Costa (S 51° 04' 42.6", 69° 08' 02.2"), Cañadón Silva (S 51º 11' 03'', W 69º 05' 55'') and Puesto Estancia La Costa (S 51º 11' 47',; W 69º 05' 34') (Fig. 3.1b-e), This study area has an active sea cliff with numerous slumps, slips and scouring, but which subsumes most of the thickness the Santa Cruz Formation with excellent surface exposures. In this place the unit shows dips of 1-3º SE (Tauber, 1994, 1997). Lithologically, the exposures of the coastal Santa Cruz Formation (225 m-thick on average) are a succession of superimposed mudstones, fine to medium sandstones of volcaniclastic origin, and tuffs with light colors, containing immature paleosols lay down on a coastal plain incised by sand bodies, with some pebbles, representing river channels (Bown and Fleagle, 1993; Tauber, 1994, 1997). The basal limit of the Santa Cruz Formation is located below the last oyster bed (*Ostrea orbignyi)* (Griffin and Parras, this volume), located 23 m above current sea level at Punta Norte (Feruglio, 1938), and towards sea level near Rincón del Buque and Cerro Redondo, and buried south of Río Coyle (Fig. 3.1a). The contact between the units in this area is considered transitional and conformable (Tauber, 1994; Matheos *et al*., 2008). The upper limit of the Santa Cruz Formation is marked by the marine sediments of the Cape Fairweather Formation and/or by the Rodados Patagónicos (Fig. 3.1b and 3.2).

3.2.2. Lithostratigraphy

The Santa Cruz Formation was formally named near Lago Argentino, located approximately 300 km west of the coastal area, by Furque and Camacho (1972) and Furque (1973), and recently by Cuitiño and Scasso (2010). Furque and Camacho (1972) and Furque (1973) distinguished three members (Fig. 3.2). They are, from the oldest to the youngest, the Los Dos Mellizos Member (250 m-thick of gray, yellowish and greenish gray clays), the Bon Acord Member (150m-thick of conglomeratic sandstones and blue tuffs) and the Los Huelguistas Member (95 m-thick of sandstones and conglomerates).

Tauber (1994, 1997) recognized two members in the coastal outcrops of the Santa Cruz Formation south of Río Coyle: a lower very fossiliferous unit, the Estancia La Costa

Member, with a predominance of pyroclastic deposits with claystones and mudstones, and an upper fossil-poor unit, the Estancia La Angelina Member, chiefly composed of claystones, mudstones and sandstones (Figs. 3.2, 3.3 and 3.4). The two members are separated by a discontinuous surface evident on the sea cliffs from the north of Estancia La Costa to Cabo Buen Tiempo. Tauber (1994) and Matheos *et al*. (2008) states that in the coastal area, the base of the Santa Cruz Formation is transitional with the marine Monte León Formation (Griffin and Parras, this volume), meanwhile the top of the unit is unconformable overlaid by marine deposits of Cape Fairweather Formation or the Rodados Patagónicos (Fig. 3.2).

Tauber (1994), on the basis of the lithological similarity, suggested that the Estancia La Costa Member might correspond to the Bon Acord Member, and the Estancia la Angelina Member could be equivalent to the Los Huelguistas Member of Furque (1973) (Fig. 3.2).

On the base of the sedimentological characteristics of the Estancia La Costa Member and the location of its fossiliferous levels, we divided the member informally in three sections: lower, middle and upper section (see below and Figs. 3.2 and 3.4).

3.2.3. Biostratigraphy-Biochronology

The continental Santa Cruz Formation was first recognized by Ameghino (1902) who named it "Piso Santacruzeño", based on its fossil vertebrate content. Later, Ameghino (1906) on the basis of its fossil vertebrate content recognized two continental *étages* within the *formation santacruzéen*: the *notohippidéen* and the *santacruzéen* (see Vizcaíno, Kay and Bargo, this volume and references therein. The "*étage Notohippidien*" is typically represented in Karaiken (Marshall and Pascual, 1977; Riccardi and Rolleri, 1980) and contains the *Notohippus* fauna. The "*étage Santacruzéen*" is typically represented in the Eastern region of the Santa Cruz Province in the Atlantic coast area (*e.g.* Marshall and Pascual, 1977), and according to Ameghino (1906), this stage is the youngest.

Mammal faunas from the richly fossiliferous Santa Cruz Formation were the basis for recognition of the Santacrucian Land Mammal Age of South America. However, the deposits corresponding to the "*étage Astrapothericuléen*" of Ameghino (1906) that outcrops in the northwestern part of Santa Cruz Province, along the banks of the Río Pinturas, were correlated with sediments belonging to "Colhuehuapense" (Frenguelli, 1931) and finally they were associated with the Santa Cruz Formation (De Barrio, 1984; Marín, 1984; Ramos, 1999). This assemblage of sediments received a new formal designation, the Pinturas Formation (Bown *et al.*, 1988; Bown and Ratcliffe, 1988; Fleagle, 1990). Biostratigraphic studies (Bown and Fleagle, 1993) and recent radiometric dates (Fleagle *et al*., 1995; Fleagle *et al*., this volume) suggested that part of this unit is older than the Santa Cruz Formation at the typical coastal localities (Kramarz and Bellosi, 2005). The last authors mentioned that the lower and middle sequences of the Pinturas Formation are older than the base of the Santa Cruz Formation at Monte León and, consequently, older than the Santacrucian age of Simpson (1940). Soria (2001) suggested that all the Miocene fauna from Pinturas Formation must be regarded as early Santacrucian in age, whereas those from the Santa Cruz Formation are late Santacrucian. A new date for the Pinturense (Upper Fossil Zone of Colhue-Huapi Member of Sarmiento Formation), that crops out at Gran Barranca, south of Chubut province, gives 18.7 to 19.7 Ma (Ré *et al*., 2010).

Tauber (1997) described two Biozones for the coastal Santa Cruz Formation, the *Protypotherium attenuatum* Biozone (the youngest) and the *Protypotherium australe* Biozone (the oldest).

3.2.4. Geochronology and Chronostratigraphy

The age of the Santa Cruz Formation has been a subject of debate over a century. Marshall *et al*. (1986) concluded that the Santa Cruz Formation range from 17.6 to 16.1 Ma (K/Ar from Monte León and Rincón del Buque localities). Later, Fleagle *et al*. (1995) dated levels from

Monte Observación (i.e. Cerro Observatorio at Cañadón de las Vacas) and Monte León localities, with Ar/Ar, and yielded an age of 16.5 Ma for the Santa Cruz Formation, and 19.33 Ma for the top of the Monte León Formation (Fig. 3.2). At the same time, Fleagle *et al*. (1995) dated samples of Pinturas Formation using Ar/Ar and obtained an age of 17.76 Ma for the lower sequence of the unit, and 16.5 Ma for the top and middle sequence of the unit (Fig. 3.2). These data and biochronologic evidence (see above) indicate that the Pinturas Formation lies below the levels of Santa Cruz Formation at Cerro Observatorio and that the Monte León Formation is older than the Pinturas Formation. Fleagle *et al*. (1995) indicated that the Pinturas Formation is intermediate in age between the Monte León and Santa Cruz Formations. Fleagle *et al*. (1995) proposed that the age of the Santa Cruz Formation at Monte Observación (i.e. Cerro Observatorio) and Monte León could be correlated with Chron 5Cn. The long section of reversed magnetic polarity above the dated levels would correlate with Chron C5Br which ranges from 15.2 to 16.0 Ma. In this volume Perkins *et al*. provide integrated results of the tephra correlations and radiometric ages indicating that the Santa Cruz Formation spans the interval ~18 to 16 Ma in the Atlantic coastal plain and ~19 to 14 Ma in the Andean foothills, with a chronologic overlap between the Pinturas Formation and lower part of the Santa Cruz Formation.

The radiometric dates mentioned above permit the assignment of the bulk of the coastal Santacrucian faunas to the late Early Miocene. At the same time, the beds below the Santa Cruz Formation, the Monte León Formation, are consistent with an Early Miocene age of the mollusc assemblage from that unit (del Río, 2004). In addition to this, new ages obtained by Parras *et al*. (2008) from the Centinela and San Julián formations, suggest that the age of the Monte León Formation along the coast should lie between 24.12 and 19.33 Ma (Fig. 3.2).

However, more recently Ar/Ar ages obtained by Blisniuk *et al*. (2005) of the Santa

Cruz Formation at the south of Lago Posadas, yielded 22.36 Ma for the base of the unit, and 14.24 Ma for the upper section (Fig. 3.2). On the basis of these data Ramos and Ghiglione (2008) interpreted that the continental foreland basin began at about 23 Ma along the foothills, and that progradation had reached the Atlantic coast by about 19 Ma.

3.3. Methodology and Techniques

3.3.1. Composition

In order to define the composition of the Estancia La Costa Member of the Santa Cruz Formation, to establish the source area and to evaluate its relationship with the paleoclimatic context, mudstones, sandstones and tuff samples of different localities were collected to carry out diffractometric analyses and petrographic studies.

A total of 24 samples, including siliciclastic, reworked and primary pyroclastic material from Campo Barranca, Anfiteatro and Estancia La Costa localities were analyzed using X-ray diffraction (XRD). Soft grinding with a rubber mortar was used to disaggregate the more indurated samples, followed by repeated washes in distilled water until deflocculating occurred. The <4 μm fraction was separated by gravity settling in suspension, and oriented mounts were prepared on glass slides. Clay mineralogy was determined from diffraction patterns obtained by using samples that were air dried ethylene glycol solvated and heated to 550 °C for 2 hours (Brindley and Brown, 1980). Diffractograms were run on X PANanlytical model X´Pert PRO diffractometer (Centro de Investigaciones Geológicas, Universidad Nacional de La Plata, Argentina), using Cu/Ni radiation and generation settings of 40 KV and 40 mA. Routine air dried mounts were run between 2 and 32 °2θ at scan speed of 2 °2θ/min. Ethylene glycol solvated and heated samples were run from 2 to 27 °2θ and 3 to 15 °2θ, respectively, at a scan speed of 2 °2θ /min. Semiquantitative estimates of the clay mineral relative concentrations were based on the peak area method (Biscaye, 1965) on glycolated samples (17 Å for smectite, 10 Å for illite and 7 Å for chlorite and kaolinite. The relative percentages of each clay mineral were determined with the application of empiric factors (Moore and Reynolds, 1989). Semiquantification was considered sufficient to define clay mineral composition because the presence/absence or dominate/subordination relationships clearly allowed establishing significant groups.

Rocks for petrographic studies included a total of 42 samples with 14 thin-sections of very fine to coarse-grained sandstone and 28 thin-sections of reworked and primary tuffs. These samples were analyzed with a Nikon Eclipse E-200 petrographic microscope. Criteria used to distinguish lithic types, matrix types and other components are those used by Dickinson (1970). A qualitative approach was made to characterize the main constituent of the rocks, matrix and cement. Both, roundness and sphericity of the clasts were estimated by visual comparison chart (Pettijohn *et al*., 1987).

3.3.2. Facies analysis and paleoenvironmental interpretation

With the aim of understanding the different sedimentary paleoenvironments and sedimentary conditions where the Estancia La Costa Member was deposited, facies and facies associations follows Miall (1996) and Bridge (2003) with modification for pyroclastic deposits (Smith, 1987) were analysed into the outcrops. The shape of the sandy bodies were classified following Friend *et al*. (1979) as tabular bodies (width/thickness ratio > 15), and lenticular or lens-shape bodies (ratio < 15).

3.4. Results

3.4.1. Composition

Clay mineralogy. Clay minerals identified in the early Estancia La Costa Member of the Santa Cruz Formation include smectite (Sm), illite (I), chlorite (Chl) and mixed layer clays containing illite/smectite (I/S). The results obtained from the XRD analysis in the <4 μm fraction are listed in Table 3.1. The non-clay minerals identified in this fraction, in decreasing order of abundance, are quartz and feldspars (plagioclases > K-feldspar), and small amounts of amorphous silica (opal), zeolite (clinoptilolite), carbonates and gypsum. In all the stratigraphic levels studied, the smectite is the most frequent clay mineral, and is present in almost all the analyzed samples, while illite, chlorite, and mixed-layer clays are less frequent.

On the basis of the presence, type and relative amount of the above mentioned clay minerals in the studied samples, three clay mineral assemblages have been defined (Table 3.1). The S1 assemblage is composed exclusively by Sm, the S2 assemblage is composed by Sm>I, I/S and the S3 assemblage is composed by Sm>I, Chl. Stratigraphic distribution and proportion of clay minerals and the X-ray diffraction patterns of the <4 μm fraction representative of each assemblages are shown in Figure 3.5a.

1) Smectitic Assemblage (S1): this assemblage is characterized by a total dominance of smectite (100%) and is better represented in the lower and middle section of Estancia La Costa Member at Campo Barranca, Anfiteatro and Estancia La Costa locality (Table 3.1, Fig. 3.5a-c).

2) Smectite-Illite and mixed layer clays bearing Assemblage (S2): the high proportion of smectite (90-95%) associated with illite (5%) and mixed layer clays of Illite/Smectite (5%) characterize this assemblage. The S2 assemblage dominates the lower section of Estancia La Costa Member at Anfiteatro and Estancia La Costa sections (Table 3.1, Fig. 3.5a-c).

3) Smectite-Illite-Chlorite Assemblage (S3) : this assemblage is the less representative of the studied units and is characterized by a lower proportion of smectite (65-80%) compared to the other clay assemblages, with small to moderate amounts of illite (15-25%) and/or chlorite (5-30%). The S3 assemblage has been only identified at Campo Barranca profile in levels corresponding to the lower section of the Estancia La Costa Member (Table 3.1, Fig. 3.5a -c).

Petrography of reworked and primary tuffs. Thin section analysis revealed that pyroclastic samples of Estancia La Costa Member are similar in general and classified as vitric tuffs, according to the scheme of Pettijohn *et al*. (1987) (Table 3.2). The samples show moderate to poor sorting and a mean size that is coincident with the range of coarse tuff (0.063-2 mm) (Fig. 3.6a) and fine tuff (< 0.063) (Fig. 3.6b) *sensu* Fisher, 1961). The framework grains are sub-angular to angular vitroclasts with low sphericity, sub-angular crystaloclasts and sub-rounded lithoclasts. The vitroclasts are composed by a great proportion of glass shards with platy and cuspades types (*sensu* Fisher and Schmincke, 1984) and pumice fragments with flattened or rounded vesicles (Fig. 3.6a). In general glass shards are more abundant than pumice fragments, and inside of these, cuspate glass shards and pumice with flattened vesicles are the most common. The vitroclasts are fresh and show few signs of diagenetic alteration. The crystaloclasts occur as euhedral to subhedral and fresh grains of twinned and oscillatory zoned plagioclases, monocrystalline quartz with straight extinction (Fig. 3.6b) and k-feldspar. The lithoclasts are composed by frequently unaltered volcanic lithic fragments with pilotaxitic, trachytic and felsitic textures. In addition to this, there are accessory minerals such as biotite, pyroxenes (hyperstene and augite), amphiboles (hornblende), zircon and opaque minerals like magnetite.

The principal cements are clay and Fe-oxides coatings and calcite in patches. Another feature of diagenetic alteration is the distortion of several vitroclasts by compaction. The analyzed tuffs were altered only by synsedimentary and pedogenic conditions.

Some micropaleoedaphic features like aggregates (blocky peds), variety of voids (Fig. 3.6b), clay-coatings, and concentric and typic Fe-nodules (*sensu* Bullock *et al*., 1985), can be recognized in certain tuff samples of the lower and middle section of the Estancia La Costa Member at Punta Sur-Cañadón del Indio, Cañadón del Cerro Redondo, Rincón del Buque, Campo Barranca, Anfiteatro, Estancia La Costa and Puesto Estancia La Costa localities

(Table 3.2). The characteristics mentioned before and the macroscopic paleoedaphic features shown in the outcrop (Table 3.3) can be associated with the development of incipient paleosols (Retallack, 2001). However, the presence of blocky peds suggests a better developed and more slowly forming paleosol (Retallack, 2001). Tauber (1994) classified the first paleosols as probably mollisol and immature, and the second ones as more mature.

Sandstone petrography. Sandy samples with scant matrix were studied from Rincón del Buque, Campo Barranca and Puesto Estancia La Costa localities (Table 3.2). In general the samples are moderate to well sorted and the framework grains are rounded to subangular with low sphericity (Fig. 3.6c, d). The texture of the sandstones is clast-supported and contacts between the grains are tangential or planar (Fig. 3.6c, d). The samples can be classified as litharenites (*sensu* Folk *et al*., 1970) corresponding to undissected to transitional arc provenance and lithic recycled orogen (*sensu* diagrams of Dickinson *et al*., 1983).

The framework grains are composed in decreasing order of abundance by rock fragments, feldspars, and quartz. The lithic fragments are volcanic in origin and have pilotaxitic, trachytic and felsitic textures and with fresh aspect (Fig. 3.6c, d). However, partially altered volcanic lithics are also present. Sedimentary fragments are identified in smaller proportions. The dominant feldspar is fresh plagioclase crystals with oscillatory zonation and twinning (Fig. 3.6d), but in a few cases the crystals show signs of dissolution (Fig. 3.6c, d) and replacement by clay-minerals or carbonates. K-feldspar is very rare or nonexistent. The quartz is generally monocrystalline with straight extinction and inclusion-free. Policrystalline quartz grains or monocrystalline grains with undulose extinction are detected less frequently. Some biotite, glauconite, hornblende, hyperstene and opaque minerals are also present.

The matrix is sparse and is of the orthomatrix and pseudomatrix type. The principal cements are clay and Fe-oxides coatings, but in several samples sparry calcite patches (Fig.

3.6d) and siliceous cement is observed. These diagenetic products suggest that the burial conditions were very shallow and coincident with synsedimentary or eodiagenetic conditions (Harwood, 1991; Morad *et al*., 2000; Worden and Burley, 2003).

Matheos *et al*. (2008) described similar petrographic and diagenetic characteristics for the sandstones and tuffs of the levels that form the transition between Monte León and Santa Cruz Formations in the area of the Parque Nacional Monte Léon.

3.4.2. Facies analysis

According to the lithology, sedimentary structures, thickness and geometry of the sedimentary bodies, eight principal lithofacies are identifiable in Estancia La Costa Member: 1) massive clast or matrix-supported fine conglomerates (Gm); 2) massive coarse and fine vitric tuffs (Tm); 3) massive lithic sandstones (Sm); 4) trough cross-bedded lithic sandstones (St); 5) planar cross-bedded lithic sandstones (Sp); 6) horizontal laminated sandstones, in places deformed, (Sl); 7) laminated mudrocks (Fl); and 8) massive very fine sandstones, tuff or reworked tuff and mudrocks (Fm). The characteristics of facies and a dynamic interpretation of each one are summarized in Table 3.3.

3.4.3. Facies associations

The deposits of Estancia La Costa Member have been grouped in four Facies Associations (FA).

Facies Association 1 (FA-1) is composed of lens- or tabular-shaped gravel-sandstones with cross-bedding, fining-upward bodies and slightly erosive-based with intraclasts (facies Gm, St, Sp), under and overlain by fine-grained facies (Sm, Sl, Fl, Fm, Tm) (Fig. 3.7a, b and c). FA-1 is mainly greenish-grey and brown to yellowish-green. The matrix of the coarser facies of this FA is composed of smectite and chlorite (S3 clay mineral assemblage). The sandstones (St facies) are rich in lithic clasts (litharenite), smectite, illite and chlorite (S3 clay mineral assemblage). In some sandy levels incipient paleosols and bioturbation is recognized. FA-1 is especially evident towards the middle and upper section of Estancia La Costa Member (Fig. 3.7b, c). This facies association can be interpreted as the infill of fluvial channels. The absence of lateral accretion surfaces implies that the channels were laterally stable. On the other hand, the absence of internal erosional surfaces, suggests deposition in a single channel (Miall, 1996). The presence of fine intraclasts on the base of the bodies is the result of the reworking of components of underlying fine sediments (Fm, Fl, Tm facies). These channel deposits are present as single bodies enclosed in floodplain facies (Fig. 3.7b and c); less frequently channels are multiple units that can crop out at the same stratigraphic horizon, suggesting the presence of multiple active channels (Makaske, 2001). The presence of pedogenic features and bioturbation in the upper levels of the filling indicates subaereal exposure suggesting that the water flow was ephemeral, not permanent. Especially, the development of iron-rich concretions in Sp facies indicates mobilization of iron, which suggests frequent fluctuation in groundwater levels (Retallack, 2001).

Facies Association 2 (FA-2) is composed of tabular to lens-shaped, greyish-green massive beds (facies Sm), and laminated and/or deformed lithic sandy or silty sandy beds (facies Sl), where paleoedaphic features and phytoliths remains are evident (Fig. 3.7b-d). Fossil leaves are encountered in medium to fine laminated sandstones in the lower levels at Rincón del Buque. Bioturbation is evident in FA-2, especially in the Sl facies (Fig. 3.7d). FA-2 assemblages are common in the lower and middle section of Estancia La Costa Member. This association is interpreted as deposits generated during periods of overbank flooding or sheet flooding and deposited in a proximal floodplain (crevasse or sheet splay deposits for tabular bodies and crevasse channels for lenticular bodies *sensu* Miall, 1996). The presence of laminated sandstones (Sl facies) suggests that the streams experienced variations in water discharge (Tunbridge, 1984). Following deposition, these bodies were levelled by subaerial exposure, bioturbation and pedogenesis. Deformation of soft sediment related to liquefaction and fluidization developed during or shortly after deposition (e.g. van Loon and Mazumder, 2011 and references therein), and can be interpreted as caused by high-sedimentation rates and sudden fluctuation in discharge (Owen, 1996). In particular, the presence of calcareous concretions (Fig. 3.7f) can be interpreted as an excess of alkaline solutes and precipitation due to fluctuations in ground-water table in a well-drained environment (Retallack, 2001).

Facies Association 3 (FA-3) consists of tabular bodies of massive or laminated grey and bluish-green very fine lithic sandstones and mudrocks (facies Fm and Fl), in part of volcaniclastic origin (vitric tuffs and reworked tuffs), bioturbated, pedogenically modified and with desiccation cracks (Fig. 3.7a-c). The clay-mineral composition of FA-3 is characterized by the presence of smectite, illite and chlorite (S3 clay mineral assemblage). Vertebrates and phytoliths are frequently found in this facies. FA-3 is the dominant association towards the middle and top sections of the Estancia La Costa Member. FA-3 is interpreted as material settling from suspension in distal setting of the floodplain. The presence of immature paleosols and desiccation cracks indicates fluctuating wet to dry surface conditions (Ghazi and Mountney, 2009) or desiccation of superficial sediments between flooding events (Collinson, 1996). The grey-green colour indicates a perennially water-logged, vegetated mudflat setting, indicative of an oxygen-poor environment and a ferrous state of the iron in the paleosols levels (Besly and Fielding, 1989). In addition, fine volcaniclastic levels may be aeolian deposits (loess) (Tauber, 1994, 1997).

Facies Association 4 (FA-4) consists of tabular massive bodies composed by Tm facies, non-graded, with planar basal surfaces (Fig. 3.7a, b, e). The finest tuffs are greyish-green in colour and in some occasions show carbonaceous remains; FA-4 also contains coarse white tuffs. Compositionally the Tm facies are vitric and rich in smectite (S1 clay mineral assemblage) or rich in smectite with small proportions of illite and chlorite (S2 clay mineral assemblage). Several beds are weakly pedogenized (Fig. 3.7e) and show bioturbation. Fossil vertebrates and the remains of carbonized logs and phytoliths (Brea *et al*., 2010 and Brea *et al*., this volume) are present in this facies association. FA-4 levels have great lateral continuity and constitute guide beds where the principal fossiliferous levels are found. In fine Tm facies at Killik Aike Norte, Monte León and Cerro Observatorio localities, Genise and Bown (1994) and A. Tauber, personal communication (2010) found burrows of solitary bees and nests of scarabeid dung-beetles (see also Krapovickas, this volume). FA-4 is present at lower and middle section of the Estancia La Costa Member but is most common in the lower section (Fig. 3.7a, b). This facies association was formed by intermittent deposition of tabular ash-fall beds in low-gradient, subaereal and subaqueous areas in a poorly drained floodplain (Cas and Wright, 1987). After deposition, pyroclastic-fall deposits were slightly modified by pedogenesis and bioturbation. The colour of the finest tuff could suggest that these paleosols were developed due to slight variation in drainage characteristics across the floodplain. The presence of calcareous steinferns of trees (Fleagle *et al*., 1995), carbonized fossil logs, phytoliths and carbonaceous remains attests to the availability of standing water on the floodplain (Roberts, 2007) and indicate that this floodplain were vegetated. However, the presence of burrows of bees and scarab beetles suggests that at least more open areas were developed (Genise and Bown, 1994; Tauber, 1997).

3.5. Implications for paleoenvironmental conditions of the Estancia La Costa Member

Sedimentological and compositional data of the Estancia La Costa Member provide a clearer understanding of the paleoenvironmental and paleoclimatic conditions and the nature of the source material that persisted during deposition in southern coastal Santa Cruz Province.

3.5.1. Depositional environments

Depositional processes, facies and facies associations can be used to interpret the paleoenvironmental setting for the succession and to reconstruct the depositional history of the unit (e.g. Paredes *et al*., 2007; Roberts, 2007).

The depositional paleoenvironment of the Estancia La Costa Member in the study area was previously interpreted by Tauber (1994, 1997) as a low energy fluvial system developed under warm and humid climatic conditions. On the other hand, he interpreted the upper member of the Santa Cruz Formation (Estancia La Angelina Member) as a more high energy fluvial system with sheet-like deposits and meandering channels formed under a more arid climate. Outcrops of the Santa Cruz Formation northwest of the study area (Lago Posadas) were interpreted by Bande *et al*. (2008) as representing a meandering or anastomosing fluvial system. At Lago Argentino, to the west of the study area, Cuitiño and Scasso (2010), interpret the lower section of Santa Cruz Formation as a meandering fluvial system. At San Jorge Basin, north of the study area, Bellosi (1998) suggested that the Santa Cruz Formation was deposited on a vegetated coastal and alluvial floodplain with sheet-like channels changing to meandering channels towards the top of the unit.

We interpret deposition of the Estancia La Costa Member as being dominated by a fluvial environment characterized by sheet-flooding, overbank-flooding and ash-fall deposits and single laterally stable channels. The preponderance of sheet-flood and overbank deposits compared to within-channel deposits, indicates a broad floodplain across which the channel was built. The common primary and reworked tuff deposits attest that the setting was influenced by ash-fall events. The vertical accretion of the floodplains was by the deposition from crevasse-splays and crevasse-channels, sheet-floods and settling from suspension. These deposits eventually became desiccated, allowing the formation of subaereal floodplain soils (incipient paleosols) with bioturbation. The development of paleosols was influenced by fluctuations in the groundwater table. In this sense, the presence of greyish colours, the occurrence of calcareous and ferruginous concretions and desiccation cracks suggest slight variation in drainage characteristics across the floodplain with fluctuating wet to dry surface conditions, even with periods of perennially water-logged and well-drained conditions, or desiccation of superficial sediments between flooding events. The presence of phytoliths, carbonaceous remains, fossil leaves, logs and steinferns of tress confirms the existence of large vegetation indicating the constant availability of water on the floodplains; also see Brea *et al.*, this volume.

However, some paleoenvironmental changes in the Estancia La Costa Member are noted. Informally, we consider the member to contain three sections (Fig. 3.4). A lower section of this member, outcropping in Rincón del Buque (=Media Luna), Cañadón del Cerro Redondo, Punta Sur-Cañadón del Indio and Campo Barranca, had a greater input of pyroclastic material and a relatively lower energy for the fluvial system based on the greater proportion of tuff beds interbedded with mudrock or silty sandstone beds deposited by ash-fall events with sheet-flooding and overbank-flooding. In this part of the unit the paleosols are less evident than the middle and upper sections, suggesting a higher sedimentation rate and a relatively continuous volcanic source due to the pyroclastic composition of the facies. In addition to this, the presence of soft-sediment deformational structures in the lower section of the unit is consistent with high sedimentation rates and decrease in discharge (Owen, 1996). Fossil leaves and logs are exclusively present in this interval and phytoliths remains are common. This situation can be linked with paleoenvironments with both arboreal and shrub vegetation (interspersed woodlands and grasslands).

Throughout the middle section of the member (upper outcrops of Rincón del Buque and outcrops of Anfiteatro, Estancia La Costa, Cañadón Silva and Puesto Estancia La Costa) there is an evident increase in the participation of coarse facies (Tm, Gm, St, Sp), which suggests a relatively higher energy for the system. However, towards the upper zone of the middle section we again see a gradual decrease in the proportion of sandstones, an increased participation of pyroclastic material and an increase in mudrocks. We can interpret this as the resumption of a paleoenvironment with lower energy and with more siliciclastic source. More developed paleosols and bioturbated beds are frequent in middle and upper parts of the middle section. This situation could reflect a lower sedimentation rate compared to the lower section of the member, and probably several interruptions in the volcanic source, which favoured increased landscape maturity and pedogenesis. The principal fossiliferous levels and the phytolith remains are concentrated in the basal and upper parts of the middle section (Tauber's fossil levels FL-1 to FL-4.1 in the former, and FL-5 to FL-7 for the latter). The existence of these fossils can be linked with densely vegetated paleoenvironments.

The base of the upper section of Estancia La Costa Member (outcropping at Puesto Estancia La Costa and Monte Tigre-Cañadón Las Totoras) shows more energetic conditions with a greater participation of sandstones which are finer towards the middle zone of the upper section. The top of the upper section is composed of both sandstones and mudrocks. The absence of pyroclastics and phytolith remains suggests respectively that those environments only received siliclastic material and that were more openly vegetated (grasslands). Paleosols and fossiliferous levels are found in the basal (FL-7.1 and FL-7.2) and upper zones in the upper section (FL-8 to FL-10). The most remarkable feature is that the paleosols have a clear colour and are marked by the presence of calcareous concretions and desiccation cracks consistent with a fluctuating flow regime.

3.5.2. The record of paleoclimatic change

Clay minerals in sedimentary sequences provide important information on pre- and post-burial conditions. Pre-burial controls include source area lithology, paleoclimate (chemical and physical weathering), depositional environment and topography, among other things (*e.g.* Chamley, 1989; Inglés and Ramos-Guerrero, 1995). Although this information can be altered by diagenesis that changes the original clay mineral composition (*e.g.* Egger *et al*., 2002), the study of the change of detrital clay minerals in sequences that did not undergo intense diagenesis becomes a significant tool to understanding the environmental conditions of deposition (Net *et al*., 2002; Raucsik and Varga, 2008; Do Campo *et al*., 2010). The abundance of smectite with limited amounts of illite and chlorite throughout the studied sections in the Santa Cruz Formation, together with the low abundance of mixed-layer clays and the compositional-diagenetic aspects of sandstones and tuffs, indicate that these deposits were not affected by deep-burial diagenesis. This suggests that diagenetic effects (post-burial conditions) on the composition of clay mineral assemblages were mimimal, and that the assemblages reflect the conditions at deposition.

Due to the existence of a volcanic source areas and the recurrence of tuffaceous beds, the great participation of smectite, together with opal and clinoptilolite registered in the <4 μm fraction, suggests the partial devitrification and alteration of volcanic ash under relatively warm and wet climatic conditions (De Ros *et al*., 1997; Dingle and Lavelle, 2000). Smectite is typically formed with chemical weathering in weakly drained soils under warm and seasonal climates with alternating wet and dry conditions (Chamley, 1989; Robert and Kennett, 1994; Thiry, 2000). On the other hand, illite, chlorite and mixed layer illite/smectite can be developed in immature soils that have undergone little chemical weathering. In general, illite and chlorite are indicators of mechanical erosion that affected the parent rocks either as a result of cool and dry climatic conditions or as a consequence of a pronounced relief (Robert and Kennett, 1994; Thiry, 2000).

In this context, the three clay-mineral assemblages recognized (S1, S2 and S3) can be related mainly to different weathering histories of a similar source material. The presence of smectite with illite, chlorite and illite/smectite mixed layers (S2 and S3 assemblages) in the lower section of Estancia La Costa Member (Campo Barranca, Anfiteatro and Estancia La Costa localities) probably indicates periods with cool or cool and dry climatic conditions (Chamley, 1989; Robert and Kennett, 1994; Thiry, 2000). Nevertheless, the presence of smectite as sole clay-mineral towards the middle section of Estancia La Costa Member (S1 assemblage) could indicate a shift to warmer and seasonal climatic conditions (Fig. 3. 5c). In addition, the upper levels of the Estancia La Costa Member rich in smectite and illite were interpreted by Matheos *et al*. (2010) as indicating a more persistent cool and dry climate.

Paleofloristic evolution of the Late Oligocene-Early Miocene of southern Patagonia demonstrated that forest elements are gradually replaced by other shrubby and herbaceous forms, signaling the beginning of the expansion of xerophytic environments determined by a cooling and drying trends (Barreda and Palazzesi, 2007). This is concordant with the existence of both closed and open environments for the Santa Cruz Formation (Vizcaíno *et al*., 2010; Tambussi, 2011) and would be comparable with temperate forests and bushland with less than 1000 mm of annual rainfall (Vizcaíno *et al*., 2010).

Isotopic studies from pedogenic carbonate contained in outcrops of the Santa Cruz Formation at Lago Posadas (northwest of Santa Cruz Province) demonstrated that surface uplift of the southern Andes occurred at 16.5 Ma led to a climatic deterioration with a strong aridification in the eastern foreland and presumably, strongly increased precipitation rates on the windward western side of the mountains (Blisniuk *et al*., 2005; 2006). These conditions were apparently accompanied by a transition from balanced subtropical woodlands and grasslands to predominantly grasslands (Blisniuk *et al*., 2005), corresponding with the lower and middle section of the Estancia La Costa Member and with the upper section of this member and Estancia La Angelina Member, respectively. In this scenario, the change trend towards the youngest zone of the section may reflect that the initial phase of this uplift caused an increased supply of moisture to the eastern foreland prior to rain shadow effect became much stronger at 15–14 Ma.

The late Early Miocene clay-mineral composition of coastal Estancia La Costa Member indicates some cooling and/or drying alternating with warmer, more humid periods registered globally during the Early Miocene (Zachos *et al*., 2001) (Fig. 3.5c). A shift to warmer and seasonal climatic conditions showing at the middle section of the member probably will be coincident with part of the global Middle Miocene warmth known as Mid-Miocene Climatic Optimum (Zachos *et al*., 2001) that took place between 17 and 15 Ma (Fig. 3.5c). Tauber (1997) interpreted that this stratigraphic interval, where fossiliferous levels from 1 to 4 occur, as indicating a wooded environment (woodlands and grasslands) with more humid and warmer climatic conditions that the upper interval (fossiliferous levels from 8 to 11). The return to cooler and dryer conditions towards the upper levels of the member (ca. 16 Ma) is consistent with the interpretation of Tauber (1997) and Vizcaíno *et al*. (2006). These authors proposed an environment with open vegetation developed in relatively dry conditions with marked seasonality, similar to that recorded today in the Chaqueña Biogeographic Province, for the upper levels of Estancia La Costa Member and part of the Estancia La Angelina Member (ca. 16 to 14 Ma). Moreover, Brea *et al*. (2010) and Brea *et al*. (this volume) demonstrated that prevail climate during the lower part of Estancia Las Costa Member was temperate to warm and subhumid to dry with marked seasonality. In addition, ichnoassemblages of the Estancia Las Costa Member defined by Krapovickas (this volume) show a general trend from the bottom to the top of the unit from more humid to dryer conditions.

The decreasing temperatures implied by the fossil and isotopic record and clay-mineral composition may be related to gradual global cooling after ~14.5 Ma (Fig. 3.5c), which was associated with rapid Antarctic ice sheet growth, and major biogeographic changes on all continents (Zachos *et al*., 2001). At the same time, the change in clay-mineral composition registered at the analyzed section of Estancia La Costa Member would be correlated with changes in erosion rates identified by Blisniuk *et al*. (2005). The presence of illite together with smectite towards the upper section of the member (Matheos *et al*., 2010) would be a consequence of an increase of precipitation and erosion rates on the humid windward western side of the mountains. Blisniuk *et al*. (2005) indicated that the increasing surface elevation would have blocked more moisture from reaching the leeward eastern side of the mountains.

3.5.3. Source areas and volcanic influence

The compositional analysis of sandstones is a useful tool to characterize the source area of sediments (Dickinson and Suczek, 1979; Dickinson *et al*., 1983). On the other hand, the compositional study of volcaniclastic and pyroclastic rocks helps clarify the clast-forming processes and establish the character, composition, and setting of the volcanic source (McPhie *et al*., 1993). Nevertheless, diagenesis and weathering are the major factors in altering volcanic glass and minerals, and depositional texture destruction (Tucker, 1996).

The great participation of lithic fragments of volcanic origin, together with the preponderance of plagioclase, and the presence of inclusion-free quartz with straight extinction in the sandstone samples, indicate that the source-area for these deposits was dominated by volcanic rocks (Folk, 1964; Dickinson and Suczek, 1979), as confirmed by the abundance of plagioclase crystals with oscillatory zonation (e.g. Spalletti *et al*., 1993). In this context, the presence of volcanic fragments with pilotaxitic and trachytic textures are linked with an intermediate volcanic source-rock, and volcanic fragments with felsitic texture with a more acidic volcanic source-rock (Dickinson, 1970; Scasso and Limarino, 1997). Both the fresh aspect and a bigger size of the volcanic fragments compared with the other components of the sandstones suggest that the lithics and the volcanism are contemporaneous (Critelli and Ingersoll, 1995). Similarly, the small contribution of quartz and feldspar crystals in the lithic fragments confirms active volcanism (Scasso and Limarino, 1997). At the same time, the sedimentary lithics and the polycrystalline quartz fragments are derived from deformed sedimentary units of the thrust belt (Critelli and Le Pera, 1994). Sources from magmatic arc and recycled orogen frequently coexist, especially when the evolution of the orogenic belt included active volcanism (Critelli and Ingersoll, 1994). The dominance of vitric fragments with glass shards (cuspade and platy-shape) and pumice fragments (flattened- and rounded-vesicles) in the tuffaceous samples is linked with plinian-like explosive eruptions of felsic to intermediate magmas (McPhie *et al*., 1993; Mazzoni, 1996; Umazano *et al*., 2009).

Based on the inferred composition, tectonic setting of source-area (volcanic arc) and the characteristic of the volcanism that could have generated the tuffaceous material; the main source-area for the sediments of Estancia La Costa Member must be related to the Miocene volcanic cycle described by Ardolino *et al*. (1999). This volcanism was explosive and fragmentary (acidic to intermediate in composition) and took place in the Patagonian Andes region and Austral Basin during the Early Miocene (Ardolino *et al*., 1999). However, no Miocene volcanic unit crops out in this area and the only evidence of this coeval Miocene volcanism is given by the pyroclastic detritus in the clastic sedimentary beds of the Santa Cruz Formation. At the same time, the emplacement of subvolcanic bodies (18-16 Ma) and the contemporary intrusion of granitic and dioritic rocks in the Andes region (Argentina and Chile) were interpreted by Ramos (1999) and Nullo and Otamendi (2002) as the magmatic phase related with the uplifting of the Austral Patagonian Andes. In addition, Hatcher (1897, 1903) described several craters that cross the lower beds of Santa Cruz Formation and considered the possible existence and activity of these craters before and during the sedimentation of the unit, and proposed that this volcanism could be the source of the youngest tuffaceous material of this unit.

In this geological context, Ramos (1999) and Ramos and Ghiglione (2008) interpreted the succession of Santa Cruz Formation as synorogenic deposits that mark the uplifting of the Austral Patagonian Andes. Bellosi (1998) mentioned that the paleocurrent orientation in the Santa Cruz Formation north of our study area is predominantly eastward, and this is in concordance with the uplifting of the Austral Patagonian Andes and foothill areas.

Considering the presence of subduction processes at the western margin of Patagonia during the Early Miocene (Ramos, 1999; Ardolino *et al*., 1999; Nullo and Otamendi, 2002; Ramos and Ghiglione, 2008; among others), contemporaneous with the deposition of the Santa Cruz Formation, the tuffaceous material of this unit is likely to represent the distal eruptive phase of a coetaneous explosive volcanism generated in an arc magmatic setting. This is related to the uplift of the Austral Patagonian Andes, located about 300 km westwards of the study area. The ash was probably transported towards the coast by the westerly winds.

3.6. Conclusions

The coastal Santa Cruz Formation has two members: the Estancia La Costa Member (pyroclastic deposits, claystones and mudstones rich in fossils), and the Estancia La Angelina Member, (fossil-poor claystones, mudstones and sandstones). On the basis of sedimentological features we divided the first member informally into a lower, middle and upper section.

Clay minerals identified in the lower section Estancia La Costa Member of Santa Cruz Formation include smectite (Sm), illite (I), chlorite (Chl) and mixed-layer clays containing illite/smectite (I/S). The smectite is the most frequent clay mineral, and is present in almost all the analyzed samples, while illite, chlorite, and mixed layer clays are less frequent. Three clay mineral assemblages have been defined: S1 assemblage composed exclusively by Sm, S2 assemblage composed by Sm>I, I/S and the S3 assemblage composed by Sm>I, Chl. The presence of S2 and S3 assemblages in the lower section of Estancia La Costa Member probably results from periods with cool or cool and dry climatic conditions, and this can be related with cooling and/or drying alternated with warmer periods. Meanwhile, the upper levels of the member are rich in smectite and illite suggesting a more persistent cool and dry climate regime.

The pyroclastic samples of Estancia La Costa Member are vitric tuffs. The sandstones are litharenites. The tuffaceous material represents the distal eruptive phase of an explosive volcanism generated in an arc magmatic setting and related to the uplift of the Austral Patagonian Andes, located about 300 km westwards of the study area. This episode is related with the Miocene volcanic cycle.

The lower section of the Estancia La Costa Member is dominated by pyroclastic material deposited in a relatively low energy fluvial system with a high sedimentation rate; the environments were vegetated. The middle section of this member shows an evident increase in coarse facies which suggests a relatively higher energy of the system compared to the lower section, but with a lower sedimentation rate. The upper section of the member evinces even more energetic conditions of the fluvial system but with a fluctuating flow regimes and places where the vegetation was more open.

During the deposition of Estancia La Costa Member the climate was seasonal and changed from warm with some cooler and/or dryer intervals (lower and middle section) to cool and dry conditions towards the top.

The climate and the source of volcaniclastic material played important roles in the evolution of this system. Based on the clay-mineral assemblages and paleoedaphic features, we conclude that during the deposition of the Estancia La Costa Member the climate was seasonal and warm trending towards cooling and/or drying stages towards the top. The volcanic deposits in the Estancia La Costa Member reflect distal pyroclastic events related to the uplift of the Austral Patagonian Andes. Uplift of Patagonian Andes created an effective barrier to the prevailing winds, producing one of the most severe rain shadows in the world.

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Figure captions

Figure 3.1. a- Photograph showing the lower and middle section of Estancia La Costa Member at Punta Sur of Rincón del Buque locality. White arrows indicate the first conspicuous tuff level of the unit, close to the last oyster bank that outcrops (black arrow). b- View of the lower section of Estancia La Costa Member at Punta Sur-Cañadón del Indio locality. Arrows indicate the first three more conspicuous tuff levels of the unit. The person in the bottom is working at the beds that contain the fossil logs (detail in picture c). The dashed line marks the contact between Santa Cruz Formation and the Rodados Patagónicos. d- Outcrops of the lower and middle section of Estancia La Costa Member at Campo Barranca locality. Arrows are indicating the same tuffaceous levels that in picture b. e- General view of

the middle and upper section of Estancia La Costa Member and the lower levels of Estancia La Angelina Member at Puesto Estancia La Costa locality. The contact between both members is indicated by the dashed line.

Figure 3.2. Proposed lithostratigraphic correlation of units exposed in the west, northwest and east part of the Santa Cruz Province. The different ages of the stratigraphic units are according to the authors mentioned in the chart, to Blisniuk *et al*. (2006) and to Parras *et al*. (2008).

Figure 3.3. Representative sedimentary profile of coastal Santa Cruz Formation modified from Tauber (1994).

Figure 3.4. Representative sedimentary profile of Estancia La Costa Member of Santa Cruz Formation (modified from Tauber, 1994 and Krapovickas *et al*., 2008) with the three sections in which the member is divided in this paper. Information on the left corresponds to the position of the fossiliferous levels (FL) at Rincón del Buque-Media Luna (RB-ML), Cañadón del Cerro Redondo (CCR), Punta Sur-Cañadón del Indio (PS-CI), Campo Barranca (CB), Anfiteatro (ANF), Estancia La Costa (ELC), Cañadón Silva (CS), Puesto Estancia La Costa (PLC) and Monte Tigre-Cañadón Las Totoras (MT-CT) localities. Lithological references are in Figure 3.

Figure 3.5. a- Representative X-ray diffraction patterns (A: air dried; E: ethylene-glycol solvated; H: 550°C-heated) of the each clay-mineral assemblage recognized in the < 4 μm fraction in the lower and middle section of the Estancia La Costa Member. Sm: smectite; C: chlorite; I: illite; IS: illite-smectite mixed layer. b- Triangular sketch showing the distribution of clay minerals and the clay-mineral proportion in the samples analyzed. c- Neogene global ocean temperature curve after Zachos *et al*. (2001) showing the possibly geochronological position (see figure 2) of the Monte León and Santa Cruz formations, the two members of the former unit and the three sections of the Estancia La Costa Member, in relation with the

global climatic events. ELC Mb.: Estancia La Costa Member; ELA Mb.: Estancia La Angelina Member; l: lower section; m: middle section; u: upper section.

Figure 3.6. Microphotographs of the Estancia La Costa Member rocks. a- (4X, parallel nicols): general view of coarse vitric tuff (Campo Barranca locality) showing cuspate glass shards (GS) and pumice with flattened vesicles (PF). b- (4X, parallel nicols): view of a fine vitric tuff with micropaleoedaphic features (voids), a quartz fragment (Q) and fine glass shards (GS) (Campo Barranca locality). c- (4X, parallel nicols), and d- (4X, crossed nicols): general view of a lithic sandstone (Puesto Estancia La Costa locality) showing different volcanic lithic fragments, plagioclase fragments (P) and sparry calcite cement (CC).

Figure 3.7. Selected photographs of facies and facies associations of Estancia La Costa Member. a- Tabular bodies of FA-2, 3 and 4, composed of facies Sm, Sl, Fm, Fl and Tm, and a tabular sandstone body of FA-1 integrated by Gt, St and Sp facies. White arrows point the Tm facies and the dotted line indicates the upper contact of the unit with the quaternary deposits. This picture is representative of the lowest section of the unit (Punta Norte of Rincón del Buque locality). b- Outcrops of the lower and middle section of the unit at Punta Sur-Cañadón del Indio locality. The lower section is characterized by tabular bodies of massive and laminated silty sandstones (Sm, Sl facies) interbedded with massive or laminated pyroclastic and siliciclastic mudrocks (Fm, Fl facies) (FA-2 and FA-3). The middle section is integrated by tabular bodies (Tm, Fm a facies) of FA-3 and 4 that enclose a lenticular coarse sand body (Gt, St facies) of FA-1. The dashed line indicates the upper contact of the unit with the quaternary deposits. c- Photograph of the middle and upper section of the member at Puesto Estancia La Costa locality. Note that the composition is essentially siliciclastic and the arrangement of FA-1 with FA-2 and 3. The dashed line indicates the upper contact of the unit with the quaternary deposits. d- Bioturbated and laminated fine sandy beds (Sl facies) with evident soft-deformation towards the top (Cañadón del Cerro Redondo). e- Detail of fossil

root traces and Fe-nodules in an edaphized reworked tuff (Tm facies) at Punta Norte of Rincón del Buque Locality. f- Calcareous concretion in a paleoedaphized Fl facies at Campo Barranca locality.

Table 3.1. Clay mineral composition from the Estancia La Costa Member in the fraction < 4 µm.

LOCALITY	SAMPLE	Sm	K	I	Ch	I/S	CLAY MINERAL ASSEMBLAGE	FACIES	FA
		RELATIVE PERCENTAGE							
Campo Barranca	CB-2	100	0	0	0	0	S1	Tm	FA-4
	CB-1	70	0	0	30	0	S3	Gm	FA-1
	CB-O	100	0	0	0	0	S1	Tm	FA-4
	CB-T-2	100	0	0	0	0	S1	Tm	
	CB-T-3-4	100	0	0	0	0	S1	Tm	
	CB-22	70	0	20	10	0	S3	St	FA-1
	CB-21	80	0	15	5	0	S3	Fm	FA-3
	CB-19	65	0	25	10	0	S3	Fm	
Anfiteatro	ANF-3	100	0	0	0	0	S1	Tm	FA-4
	ANF-2	100	0	0	0	0	S1	Tm	
	ANF-1	100	0	0	0	0	S1	Tm	
	MR-5	95	0	0	0	5	S2	Tm	
	MR-6	95	0	0	0	5	S2	Tm	
	MR-7	100	0	0	0	0	S1	Tm	
	MR-8	95	0	0	0	5	S2	Tm	
	MR-9	100	0	0	0	0	S1	Tm	
Estancia La Costa	MR-1	90	0	5	0	5	S2	Tm	FA-4
	MR-2	90	0	5	0	5	S2	Tm	
	MR-3	100	0	0	0	0	S1	Tm	
	MR-4	100	0	0	0	0	S1	Tm	

Note: Sm: smectite; **K**: kaolinite; **I**: illite; **Chl**: chlorite; **I/S**: mixed layer illite-smectite. **S1**: Smectitic Assemblage; **S2**: Smectite-Illite and mixed layer clays bearing Assemblage; **S3**: Smectite-Illite-Chlorite Assemblage. **Gm**: massive clast or matrix-supported fine conglomerates; **Tm**: massive coarse and fine vitric tuffs; **Sm**: massive lithic sandstones; **St**: trough cross-bedded lithic sandstones; **Sp**: planar cross-bedded lithic sandstones; **Sl**: horizontal laminated sandstones, in places deformed; **Fl**: laminated mudrocks; **Fm**: massive very fine sandstones, tuff or reworked tuff and mudrocks. **FA-1**: Fluvial channel facies association; **FA-2**: Proximal floodplain facies association; **FA-3**: Distal floodplain facies association; **FA-4**: Pyroclastic-fall deposits facies association.

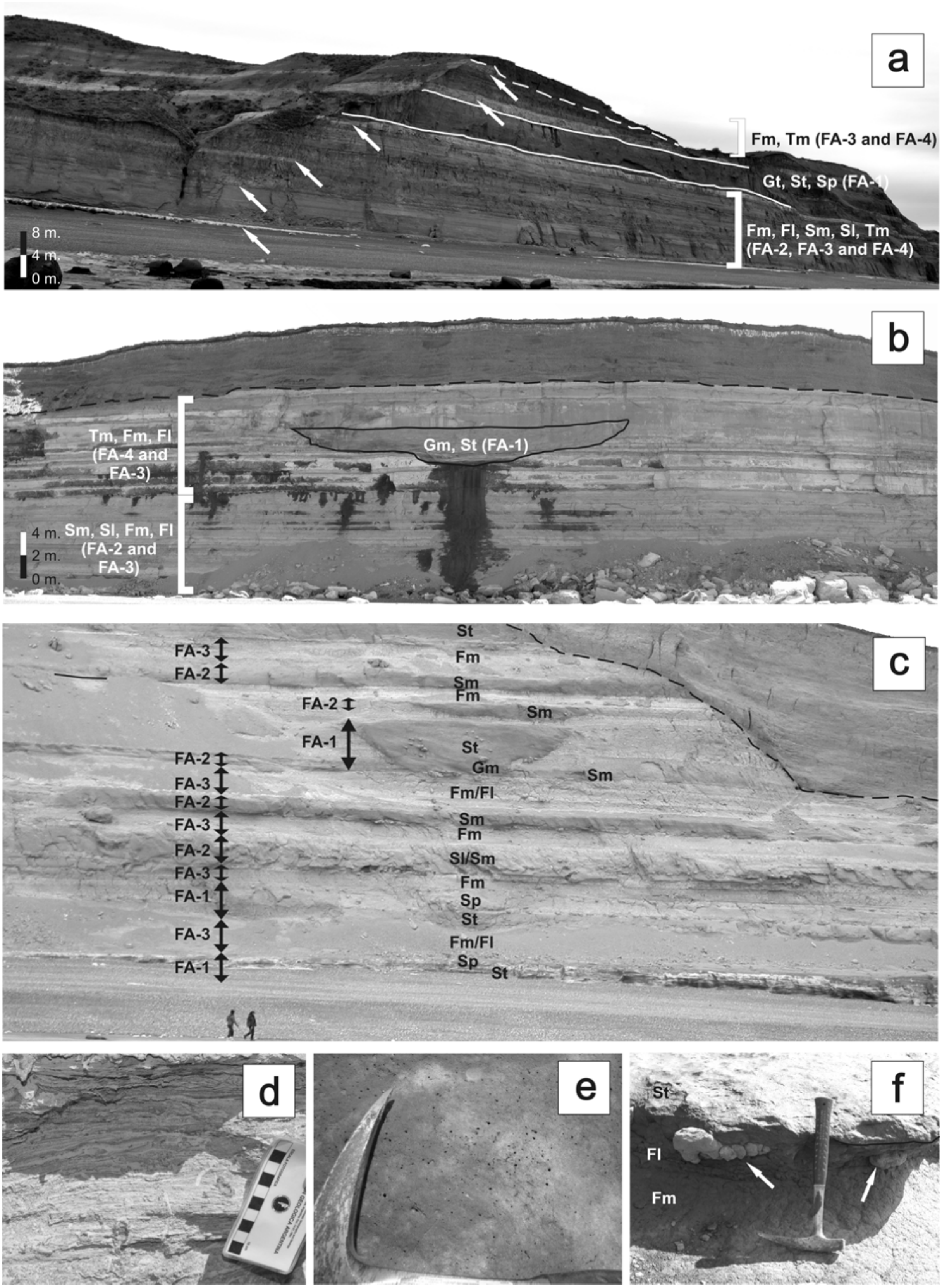
Table 3.2. Classification of sandy and tuffaceous samples of Estancia La Costa Member.

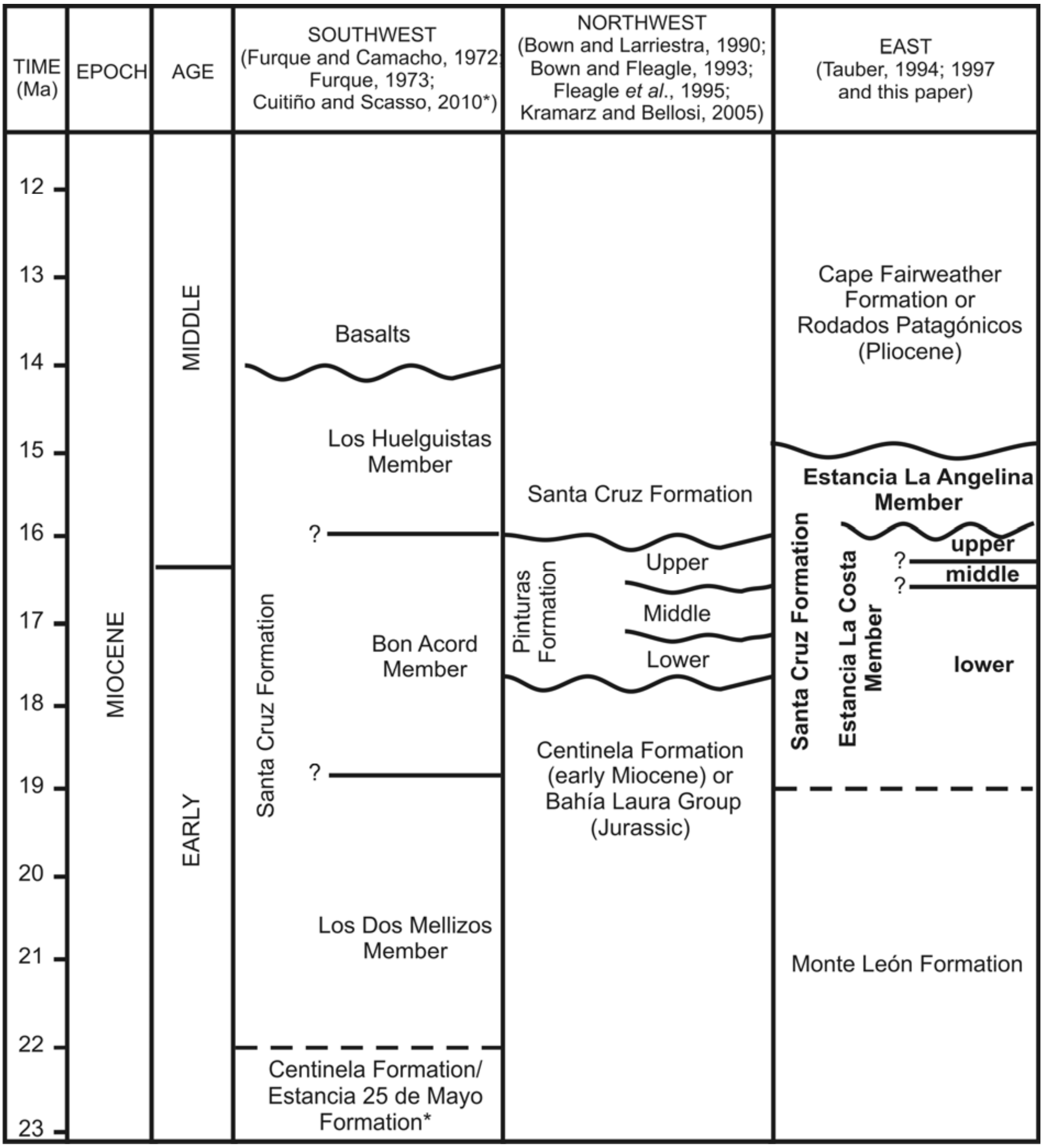
LOCALITY	SAMPLE	CLASSIFICATION	FACIES	FACIES ASSOCIATION
Punta Sur-Cañadón del Indio	CÑ-1	medium vitric reworked tuff	Tm	FA-4: Pyroclastic-fall deposits
	CÑ-2	medium vitric tuff	Tm	
	CÑ-3	medium vitric tuff with paleoedaphic features	Tm	
	CI-1	fine vitric reworked tuff with paleoedaphic features	Tm	
	CI-2	fine vitric tuff with paleoedaphic features	Tm	
Cañadón del Cerro Redondo	CCR-1	fine vitric tuff with paleoedaphic features	Tm	FA-4: Pyroclastic-fall deposits
	CCR-3	very fine vitric tuff	Fm	FA-3: Distal floodplain
	CCR-10	medium vitric tuff	Tm	FA-4: Pyroclastic-fall deposits
Rincón del Buque (Media Luna and Punta Norte)	PRB-ML-1	medium vitric tuff	Tm	FA-4: Pyroclastic-fall deposits
	PRB-10	medium vitric tuff with paleoedaphic features	Tm	
	PRB-11	very fine vitric tuff	Fm	FA-3: Distal floodplain
	PRB-12	fine to medium litharenite	St	FA-1: Fluvial channel
	PRB-13	medium vitric tuff	Tm	FA-4: Pyroclastic-fall deposits
	PRB-14	medium vitric tuff	Tm	
Campo Barranca	MR-9	medium vitric tuff	Tm	FA-4: Pyroclastic-fall deposits
	CB-2	fine vitric reworked tuff	Tm	
	CB-3-4	medium vitric tuff	Tm	
	CB-CM	coarse litharenite	St	FA-1: Fluvial channel
	CB-24	medium litharenite	St	
	CB-23	fine vitric tuff with paleoedaphic features	Tm	FA-4: Pyroclastic-fall deposits
	CB-22	medium litharenite	St	FA-1: Fluvial channel
	CB-20	medium litharenite	St	
	CB-19-b	very fine litharenite with paleoedaphic features	Fm	FA-3: Distal floodplain
Anfiteatro	MR-8	fine to medium vitric tuff	Tm	FA-4: Pyroclastic-fall deposits
	MR-7	medium vitric tuff	Tm	
	MR-6	medium vitric tuff	Tm	
	MR-5	medium vitric tuff	Tm	
	ANF-4	medium vitric tuff	Tm	
	ANF-3	medium vitric tuff	Tm	
	ANF-2	fine vitric tuff with paleoedaphic features	Tm	
Estancia La Costa	MR-2	fine vitric reworked tuff	Tm	FA-4: Pyroclastic-fall deposits
	MR-1	medium vitric tuff with paleoedaphic features	Tm	
Puesto Estancia La Costa	PPLC-4	medium vitric tuff with paleoedaphic features	Tm	FA-4: Pyroclastic-fall deposits
	PPLC-2	fine litharenite	Sm	FA-2: Proximal floodplain (overbank and sheet-flood)
	PPLC-OB	medium litharenite	St	FA-1: Fluvial channel

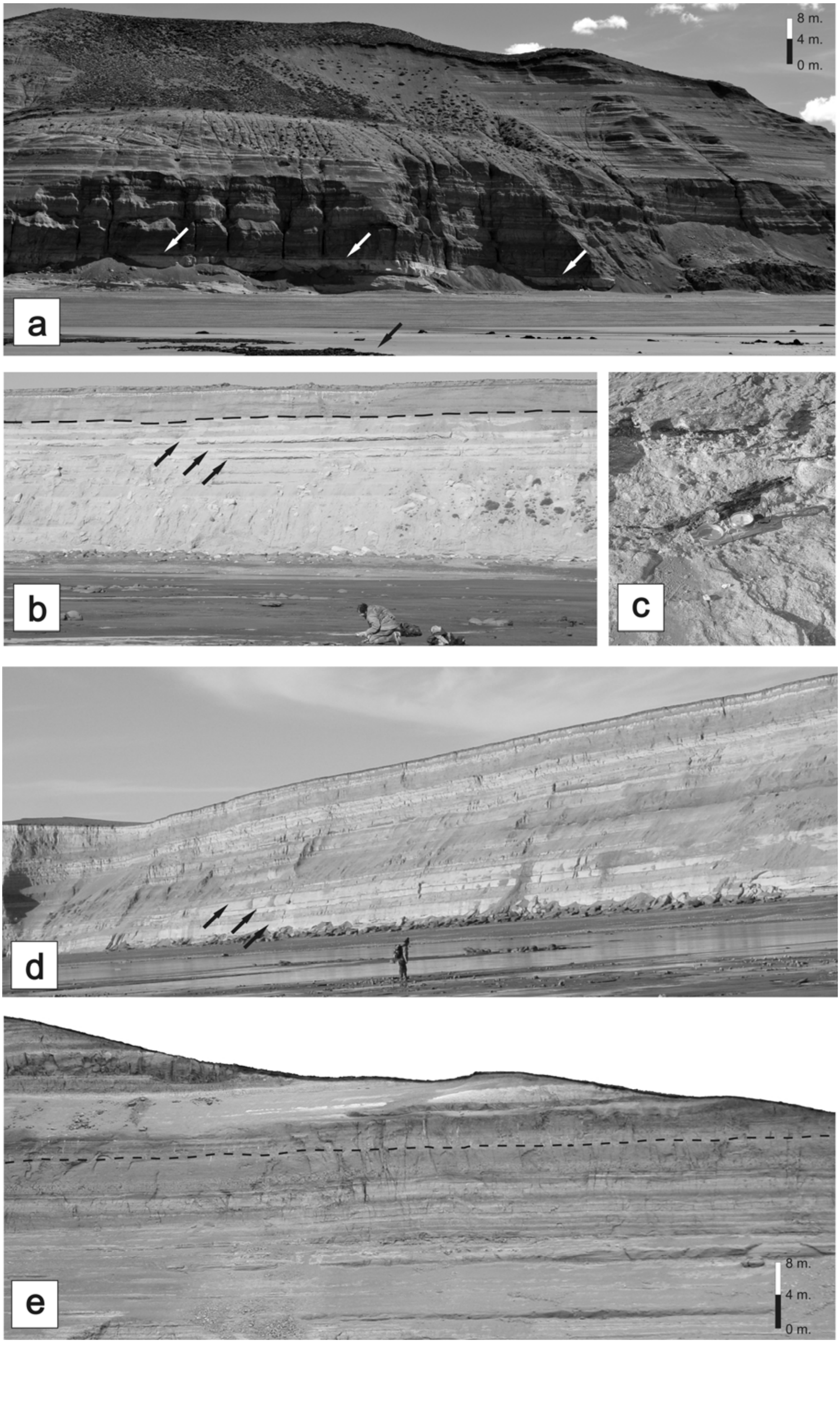
Note: Abbreviations as in table 3.1

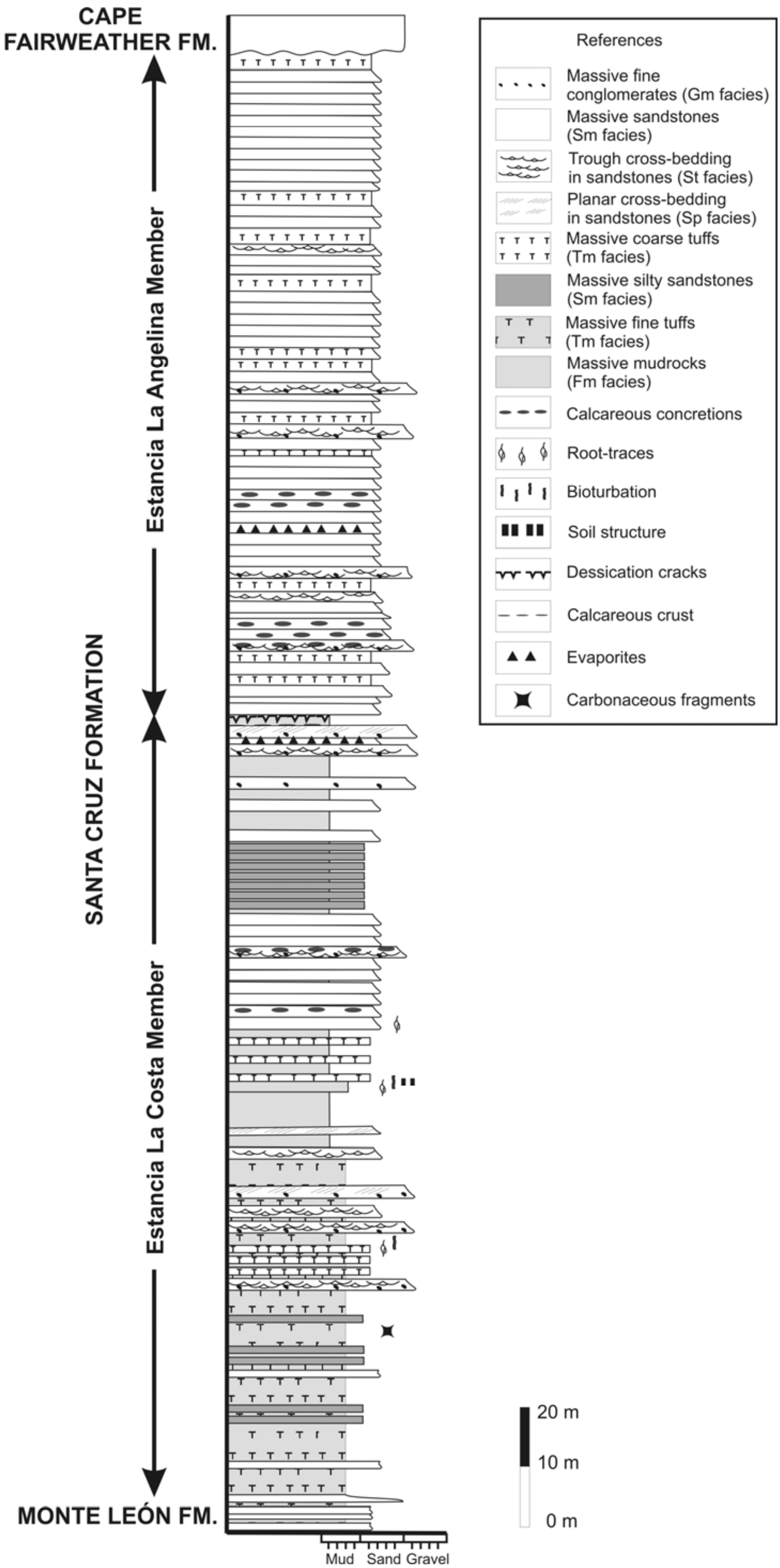
Table 3.3. Lithofacies identified in the Estancia La Costa Member.

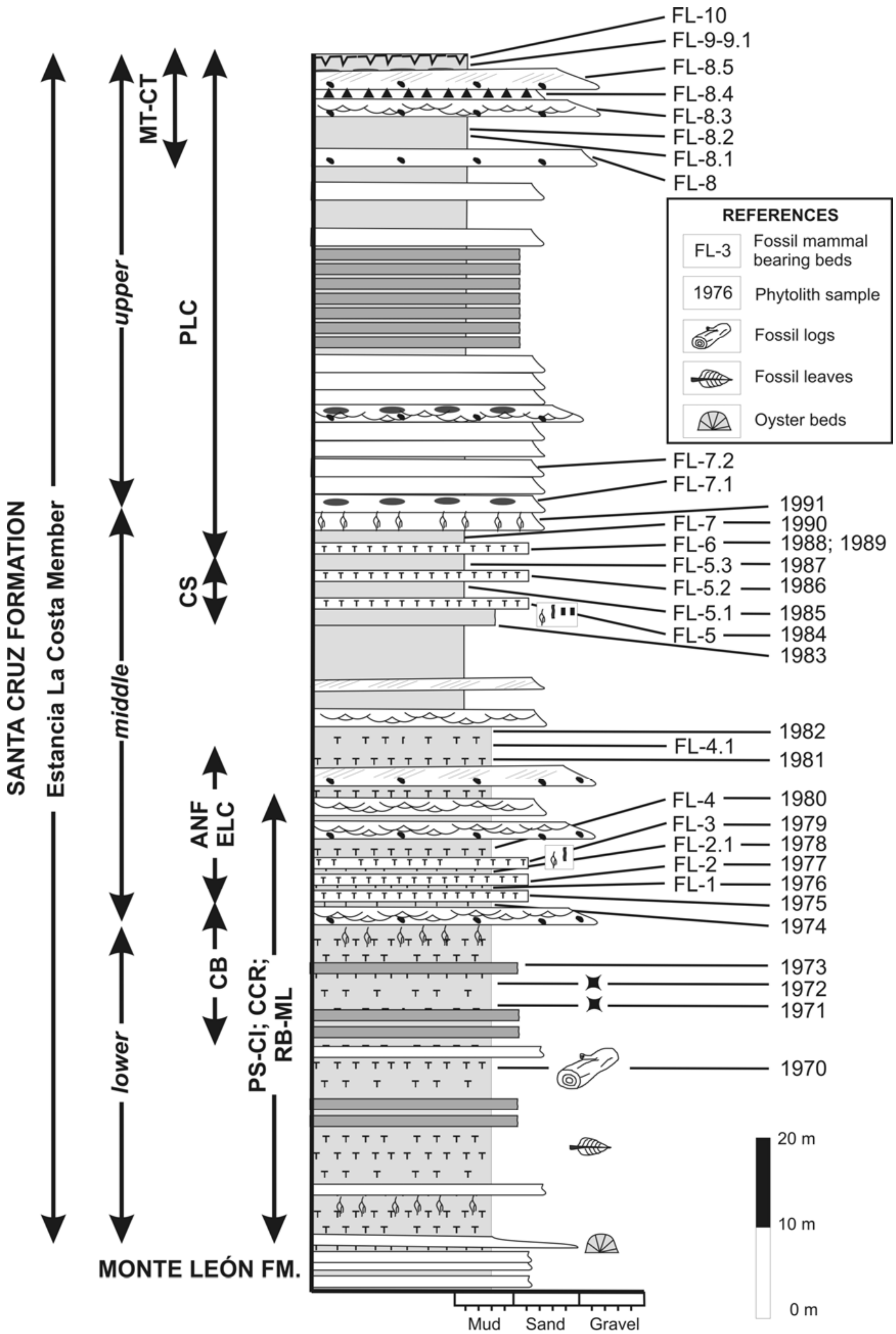
FACIES CODE	LITHOLOGY AND COMPOSITION	SEDIMENTARY STRUCTURES	THICKNESS AND BOUNDARIES	FOSSIL CONTENT	PALEOEDAPHIC FEATURES/ BIOTURBATION/ OTHERS	INTERPRETATION
Gm (massive conglomerates)	Clast or matrix-supported fine grained conglomerates with intraclasts	Massive	0,2-0,3 m. Erosive, concave upward lower boundary	Frogs	-	Lag deposits, small cores of longitudinal bars. Moderate to high flow regime
Tm (massive tuffs and reworked tuffs)	Coarse to fine vitric tuffs and reworked vitric tuffs	Massive to poor lamination	0,2-1,5 m. Sharp boundaries	Vertebrates, logs and phytoliths	Paleoedaphic features, bioturbation and carbonaceous remains	Ash-fall events. Pedogenic processes
Sm (massive sandstones and silty sandstones)	Medium lithic sandstones and silty sandstones	Massive	< 2,5 m. Sharp or slightly concave upward lower boundary and sharp or transitional upper boundary	Phytoliths	Paleoedaphic features (calcareous concretions)	Stream-flow during high discharge conditions with subaereal exposure and pedogenic modification
St (trough cross-stratified sandstones)	Fine to very coarse lithic sandstones	Trough cross-bedding, fining-upward trend	< 3,5 m. Sharp or slightly concave upward lower boundary and sharp or transitional upper boundary	Vertebrates including frogs	Intraclasts in the bases	Subaqueous sandy 3-D dunes. Lower flow regime
Sp (planar stratified sandstones)	Fine to medium lithic sandstones	Planar cross-bedding, fining-upward trend	0,1-3 m. Slightly concave upward lower boundary or sharp boundaries	-	Paleoedaphic features (iron-rich concretions)	Deposits of sandy 2-D bars. Transitional to lower flow regime. Subaereal exposure and pedogenic modification
Sl (laminated sandstones)	Fine to medium sandstones	Horizontal lamination (in places deformed)	< 1 m. Sharp boundaries or transitional lower boundary	Leaves	Bioturbation. Carbonaceous remains	Upper stage plane-bed flow (synsedimentary deformation). Subareal exposure with bioturbation
Fl (laminated very fine sandstones and mudrocks)	Very fine sandstones and mudrocks	Horizontal lamination	< 1 m. Sharp boundaries	-	Bioturbation, paleoedaphic features (calcareous concretions and root traces). Carbonaceous remains	Settling from suspension with subaereal exposure, pedogenetic processes and bioturbation
Fm (massive very fine sandstones, tuffs, reworked tuffs and mudrocks)	Very fine sandstones, tuff or reworked tuff, and mudrocks	Massive	< 1 m. Sharp or transitional boundaries	Vertebrates and phytoliths	Bioturbation, paleoedaphic features (calcareous concretions, root traces, blocky peds) and dessication cracks	Settling from suspension with subaereal exposure, pedogenetic processes and bioturbation. Aeolian deposition of pyroclastic origin


a
Fm, Tm (FA-3 and FA-4)
Gt, St, Sp (FA-1)
Fm, Fl, Sm, Sl, Tm
(FA-2, FA-3 and FA-4)
8 m.
4 m.
0 m.
b
Tm, Fm, Fl
(FA-4 and
FA-3)
Gm, St (FA-1)
Sm, Sl, Fm, Fl
(FA-2 and
FA-3)
4 m.
2 m.
0 m.
c
FA-3
FA-2
FA-2
FA-1
FA-2
FA-3
FA-2
FA-3
FA-2
FA-3
FA-1
FA-3
FA-1
St
Fm
Sm
Fm
Sm
St
Gm
Sm
Fm/Fl
Sm
Fm
Sl/Sm
Fm
Sp
St
Fm/Fl
Sp
St
d
e
f
St
Fl
Fm

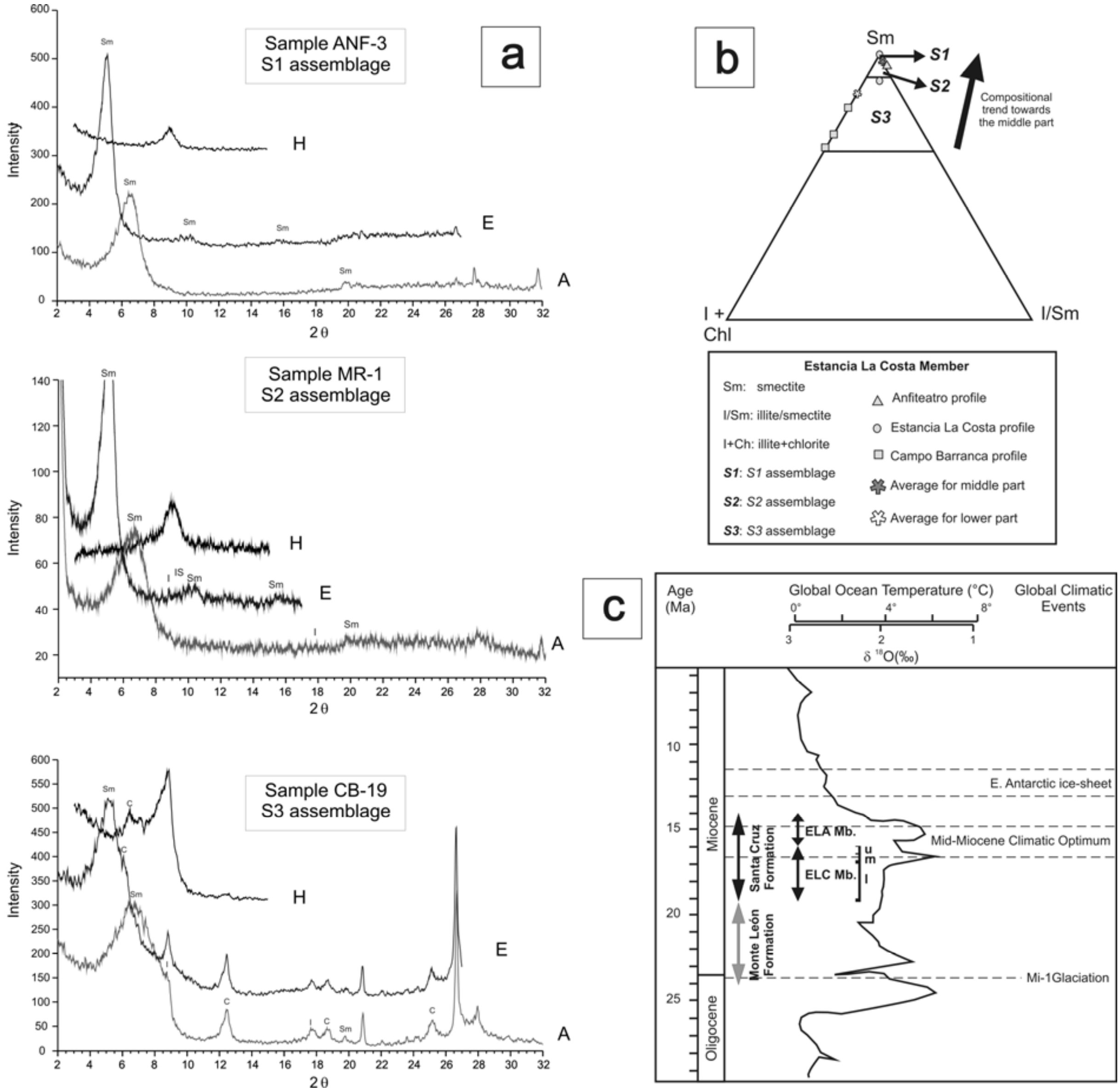

TIME (Ma)
EPOCH
AGE
SOUTHWEST (Furque and Camacho, 1972; Furque, 1973; Cuitiño and Scasso, 2010*)
NORTHWEST (Bown and Larriestra, 1990; Bown and Fleagle, 1993; Fleagle et al., 1995; Kramarz and Bellosi, 2005)
EAST (Tauber, 1994; 1997 and this paper)
12
13
14
15
16
17
18
19
20
21
22
23
MIOCENE
MIDDLE
EARLY
Basalts
Los Huelguistas Member
Bon Acord Member
Los Dos Mellizos Member
Santa Cruz Formation
Centinela Formation/ Estancia 25 de Mayo Formation*
Santa Cruz Formation
Pinturas Formation
Upper
Middle
Lower
Centinela Formation (early Miocene) or Bahía Laura Group (Jurassic)
Cape Fairweather Formation or Rodados Patagónicos (Pliocene)
Estancia La Angelina Member
Santa Cruz Formation
Estancia La Costa Member
upper
middle
lower
Monte León Formation

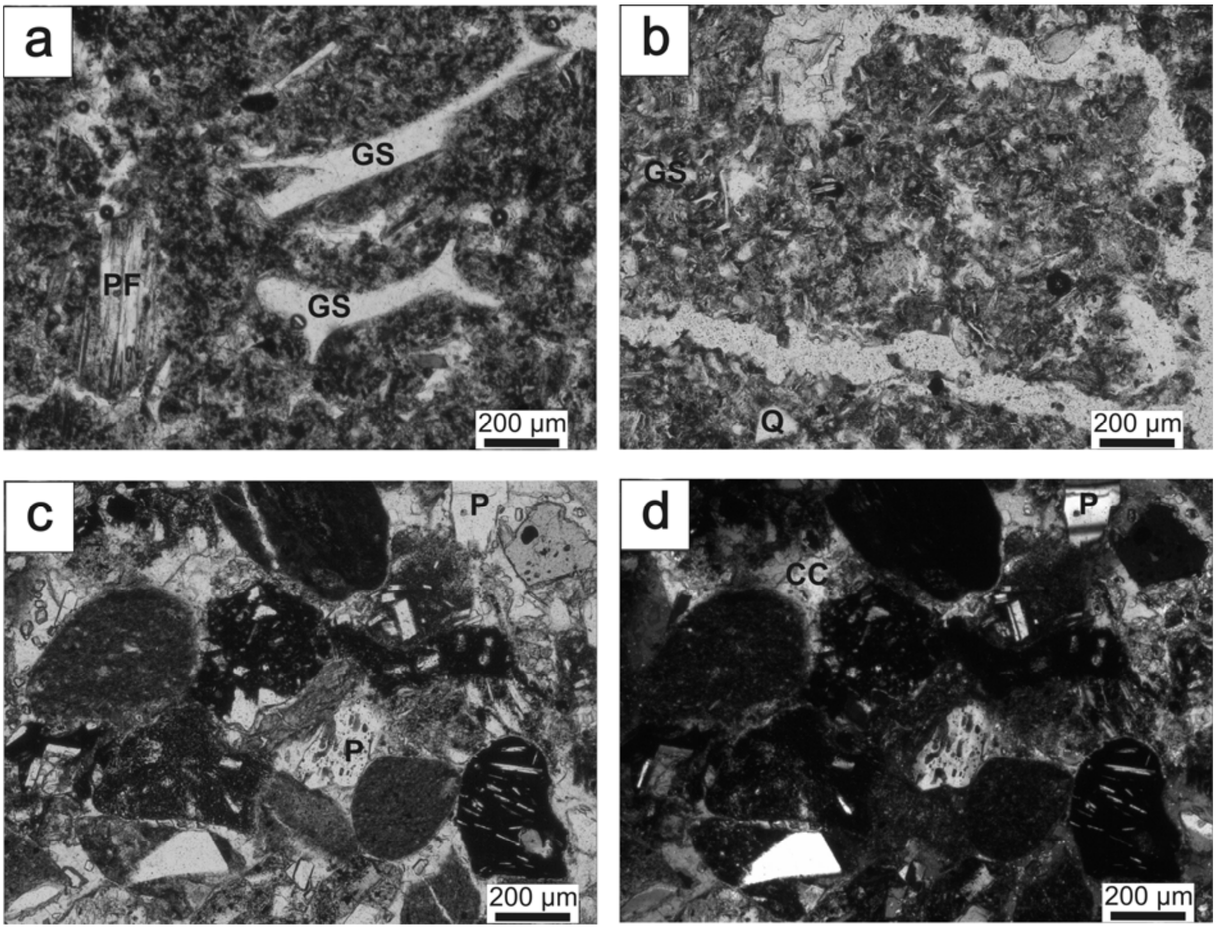

8 m.
4 m.
0 m.
a
b
c
d
8 m.
4 m.
0 m.
e


CAPE FAIRWEATHER FM.
Estancia La Angelina Member
SANTA CRUZ FORMATION
Estancia La Costa Member
MONTE LEÓN FM.
Mud Sand Gravel
20 m
10 m
0 m
References
Massive fine conglomerates (Gm facies)
Massive sandstones (Sm facies)
Trough cross-bedding in sandstones (St facies)
Planar cross-bedding in sandstones (Sp facies)
Massive coarse tuffs (Tm facies)
Massive silty sandstones (Sm facies)
Massive fine tuffs (Tm facies)
Massive mudrocks (Fm facies)
Calcareous concretions
Root-traces
Bioturbation
Soil structure
Dessication cracks
Calcareous crust
Evaporites
Carbonaceous fragments



SANTA CRUZ FORMATION
Estancia La Costa Member
upper
middle
lower
MT-CT
PLC
CS
ANF
ELC
CB
PS-CI; CCR; RB-ML
MONTE LEÓN FM.
FL-10
FL-9-9.1
FL-8.5
FL-8.4
FL-8.3
FL-8.2
FL-8.1
FL-8
REFERENCES
FL-3 Fossil mammal bearing beds
1976 Phytolith sample
Fossil logs
Fossil leaves
Oyster beds
FL-7.2
FL-7.1
1991
FL-7 1990
FL-6 1988; 1989
FL-5.3 1987
FL-5.2 1986
FL-5.1 1985
FL-5 1984
1983
1982
FL-4.1
1981
FL-4 1980
FL-3 1979
FL-2.1 1978
FL-2 1977
FL-1 1976
1975
1974
1973
1972
1971
1970
20 m
10 m
0 m
Mud
Sand
Gravel


a
Sample ANF-3
S1 assemblage
Sample MR-1
S2 assemblage
Sample CB-19
S3 assemblage
Intensity
2θ
H
E
A
Sm
b
Sm
S1
S2
S3
Compositional trend towards the middle part
I + Chl
I/Sm
Estancia La Costa Member
Sm: smectite
I/Sm: illite/smectite
I+Ch: illite+chlorite
S1: S1 assemblage
S2: S2 assemblage
S3: S3 assemblage
Anfiteatro profile
Estancia La Costa profile
Campo Barranca profile
Average for middle part
Average for lower part
c
Age (Ma)
Global Ocean Temperature (°C)
Global Climatic Events
δ 18O(‰)
Miocene
Oligocene
Santa Cruz Formation
Monte León Formation
ELA Mb.
ELC Mb.
E. Antarctic ice-sheet
Mid-Miocene Climatic Optimum
Mi-1Glaciation



a
GS
GS
PF
200 µm
b
GS
Q
200 µm
c
P
P
200 µm
d
P
CC
200 µm