Geology of Península Valdés

Miguel J. Haller

Abstract The surface of Península Valdés is gently cut, characterized by plateaus, sea cliffs, and spits as well as depressions caused by a complex process of tectonic, deflation, fluvial erosion, and mass wasting. Subsurface geology comprises early Paleozoic rocks, Jurassic volcanics, Cretaceous continental deposits, and Paleogene and Neogene deposits. The oldest rock outcrops are the marine sediments deposits with pyroclastic contribution of early Miocene age. These deposits are covered by sandstones and mudstones of coastal environment and late Miocene age. On these sediments rest gravel beds of the late Pliocene—early Pleistocene. Other deposits, aeolian, coastal, and coastal marine origin are assigned to the Pleistocene and Holocene. The most important mineral economic resource of the region of geological origin is halite (NaCl) accumulated in the floor of the Salina Grande and Salina Chica endorheic basins. Salt has been exploited during the first quarter of this century. On the other hand, sand and gravel quarries are sporadically exploited for local use.

Keywords Paleogene · Neogene · Subsurface information · Geological resources

1 Previous Geological Work: Early Geological and Paleontological Studies

The first geological description of the Tertiary Neogene beds from the Península Valdés region was made by Malaspina in 1789 during his exploration trips around the world. Malaspina (1885, p. 62) wrote in his travel diary: "… the inner coast of

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San José seem to be formed by some horizontal layer of sandy blackish earth, others whitish, reddish, overlapping each other in number of twenty, and all probably composed by sand, marls, clay, etc., presenting a rather sterile soil and clear not only from large trees and also any kind of bushes."

Although Alcide d'Orbigny has not visited himself the Patagonian coast south of Carmen de Patagones, he observed the Tertiary beds in the cliffs of the mouth of Río Negro and he considered the Cenozoic marine sediments extending from Entre Ríos to the Strait of Magellan as a unit which he named Terrain Tertiarie Patagonien (d'Orbigny 1842) and assigned them an Eocene age similar to the Tertiary Paleogene beds in the Paris Basin.

Darwin made a short examination in the Golfo San José (North of the Península Valdés region Fig. 1) during his journey on board of the HCS Beagle in 1833. He describes (Darwin 1845) that "… the cliffs are about a hundred feet high; the lower third consists of yellowish-brown, soft, slightly calcareous, muddy sandstone …". Darwin (1845) found several fossils like *Ostrea*, *Pecten*, *Terebratula*, and *Turritella*,

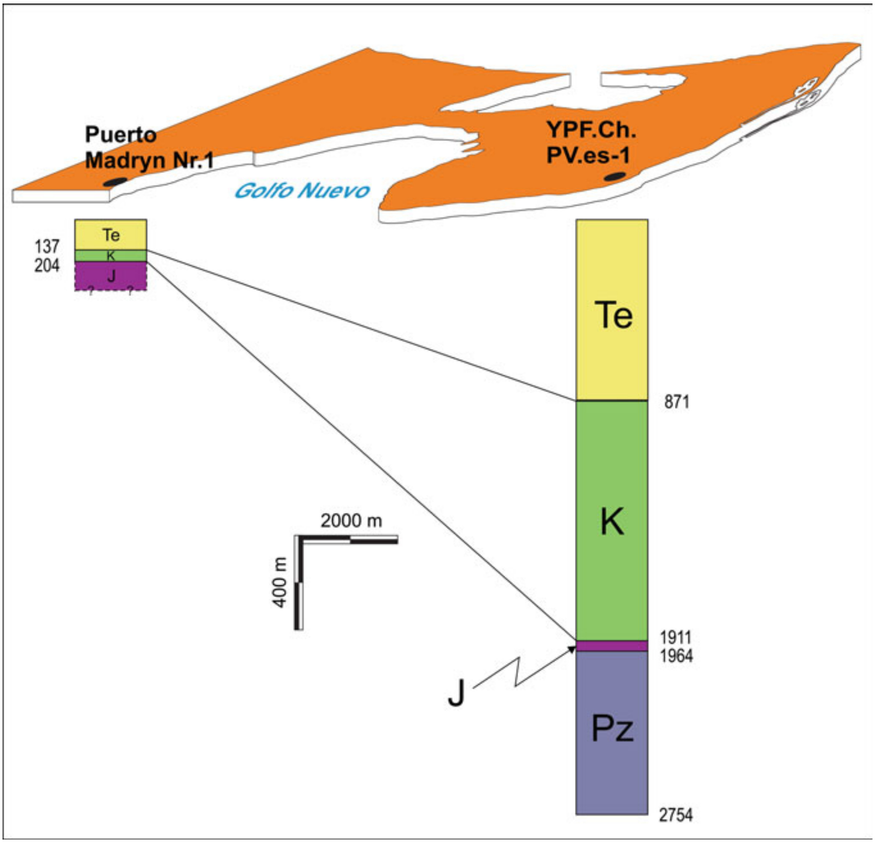

Fig. 1 Schematic chronological columns for YPF.Ch.PV.es-1 and Puerto Madryn Nr. 1 boreholes

and compared them with founding in Entre Ríos, Río Negro, San Julian and Puerto Deseado. He also mentions: "… al the strata appear horizontal, but when followed by eye for a long distance, they are seen to have a small easterly deep." He also saw the gravel on the surface (i.e., Rodados Patagónicos—Patagonian Gravels—), which he later recognized in other parts of Patagonia and named Patagonian Shingle Formation. In Golfo Nuevo (Fig. 1), Darwin described two strata of pale brown mudstone separated by a darker colored argillaceous variety. Darwin mentions that those strata extend along the Patagonian coast until Puerto Deseado, and then to the south they are found at intervals until Santa Cruz River. Darwin included all those beds cropping out on the coast in the Patagonian Tertiary Formation, and stated that they may belong to the same epoch, of "considerable antiquity." He was impressed by the outcrops extension, which he estimated in 27 degrees of latitude, extension he compares to the distance "from the Straits of Gibraltar to the south of Iceland."

With the support of his brother Carlos, Florentino Ameghino made a great contribution to the paleontology and stratigraphy of Patagonia. Ameghino (1890) considered that the Patagonian Tertiary beds were older than those of Entre Ríos.

Other studies at the beginning of the twentieth century, other studies which made minor corrections in the stratigraphy of the Península Valdés region (were made by Roveretto 1921; Windhausen 1921 and Frenguelli 1927).

During the second half of the twentieth century several authors dealt with the marine Tertiary beds from Patagonia, like Bertels (1970), Camacho (1974, 1979a, b, 1980), Riggi (1979a, b, 1980), Di Paola and Marchese (1973).

In the last two decades of the twentieth century, Scasso and del Río (Scasso and del Río 1987; Scasso et al. 2001; del Río 1988, 1990; 1991, 1992) began systematical sedimentological and paleontological studies with modern criteria that allowed deepen understanding the origin, age, and deposition environment of these Tertiary Neogene formations.

2 Stratigraphy

The geology of the region is simple, above a basement of Paleozoic, Cretaceous and Paleogene rocks, only sedimentary rocks are outcropping. The late comprise a depositional record from late early Miocene to Holocene times (see Chapters "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity" and "Late Cenozoic Landforms and Landscape Evolution of Península Valdés"). On a relief developed in these Neogene units, recent sediments were deposited. The different units that make up the geology of the region are summarized in Table 1.

Table 1 Stratigraphy of the Península Valdés area

Era	Period	Epoch	Geological unit	Lithology	Maximum thickness (m)
Cenozoic	Quaternary	Holocene	Alluvium and colluvium deposits	Sand, gravel and silt	2–3
			Eolian deposits	Sand and silt	14
			Playa lake sediments and evaporites	Silt, clay, evaporites (halite, glauberite and gypsum)	1
			San Miguel formation	Gravel and sand	6
		Pleistocene	Caleta Valdés Formation	Gravel	25
	Neogene	Pliocene–Pleistocene	Patagonian gravels	Gravel	4
		Late Miocene	Puerto Madryn Formation	Sandstones, siltstones, mudstones and coquinas	80 (350)
	Paleogene	Early Miocene	Gaiman formation	Claystones, siltstones, tuffaceous mudstones, tuffs, and sandstones	20 (280)
		Oligocene		Mudstones, sandstones, calcareous siltstones, marls, claystones	(140)
		Danian	Marine	Claystones and mudstones	(60)
			Continental	Conglomeradic sandstones and claystones	(6)
Mesozoic	Cretaceous	Barremian–Maastrichtian	Continental/marine	Claystones, calcareous sandstones, conglomeradic sandstones, sandstones, conglomerates, siltstones, tuffaceous sandstones, tuffaceous claystones and mudstones	(1134)
	Jurassic			Volcanic agglomerate Rhyolitic volcanics	(53)
Paleozoic	Early?			Mudstones, tuffs, quartzites, quartzitic sandstones and calcareous siltstones	(737)

Shading indicates subsurface units. In brackets: thickness from subsurface data

2.1 Subsurface Information

The state oil company YPF started in 1975 an exploration drilling on the Península Valdés region with the objective of the acquisition of subsurface data on the stratigraphy, lithology, and thickness of the sedimentary rocks of the western flank of the sedimentary Valdés Basin (Mainardi et al. 1980) which extends offshore eastward in the Atlantic Ocean. The results provide a first glimpse of the subsurface stratigraphy of the Península Valdés region.

The YPF.Ch.PV.es-1 well (Fig. 1) is located in the southeast of Península Valdés region. The borehole wellhead elevation is 51 m and reached a depth of 2754 m. According to YPF (1976), the stratigraphic column comprises Paleozoic, Cretaceous, Paleogene and Neogene and Tertiary rocks (Fig. 1).

Paleozoic rocks drilled section is 737 m thick without reaching the base of the unit. These rocks are dominated by slightly micaceous gray siltstones and silty argillites, interbedded, with fine to very fine grained and very consolidated quarzitic sandstones. Based on the lithology and the stratigraphic position, these rocks were correlated with marine quartzites of the Sierra Grande Formation (Harrington 1962), that are outcropping 175 km northwest in the southwestern province of Río Negro, whose age was assigned to the Silurian-Devonian (Spalletti et al. 1991).

A 53 m-thick igneous body of rhyolitic composition covered by a volcanic agglomerate separates the Paleozoic rocks from the Cretaceous deposits. Following Continanzia et al. (2011), those igneous rocks may correlate with a very important igneous event which took place during the Jurassic in Patagonia and has been dated in 183 ± 2 Ma (Rb/Sr) by Rapela and Pankhurst (1993), and 186.2 ± 1.5 Ma (Ar/Ar) by Alric et al. (1996). In the Atlantic coast where the Península Valdés is located, these rocks are included in the Marifil Formation (Malvicini and Llambías 1974).

The Cretaceous rocks thickness is 1089 m thick. The Cretaceous deposits constitute the initial filling of the Valdés basin. The section consists of reddish brown and light greenish gray claystone, partly slightly sandy, with quartz pebbles. Toward the base, fine green and whitish pyroclastic beds are dominant with participation of mud and sand. The pyroclastic rocks are interbedded with fine to very fine grained reddish brown sandstones with clay matrix. These rocks are correlated with continental sediments of the Chubut Group (Lesta 1968) outcropping west of Península Valdés. The age of the Chubut Group is assigned to Barremian—Maastrichtian (Chebli et al. 1976; Casal et al. 2015). Caramés et al. (2004) postulate that some Maastrichtian arenaceous foraminifera found in the uppermost beds of the Cretaceous section of well YPF.Ch.PV.es-1 indicate a shallow marine environment.

The upper section of borehole YPF.Ch.PV.es-1, of 830 m thickness, consists of Tertiary Paleogene and Neogene sediments represented by yellowish gray and greenish gray siltstones; gray and green slightly marly and partially sandy mudstones and claystones. They are interbedded with fine to medium grained green and gray sandstones, sometimes conglomeratic. The Tertiary beds contain abundant fossil remains of shells, coral, and spicules. Microfossils allowed Masiuk et al. (1976) to differentiating differentiate sections of lower Paleocene, Eocene, and Miocene age deposited in a medium shelf depositional environment. Later, Caramés et al. (2004) based on foraminifera content established that the Cenozoic deposits of the well YPF.Ch.PV.es-1 is represented by four sections: (1) 60 m deposits of late Danian age; (2) 140 m deposits of Oligocene age; (3) 280 m deposits of late Oligocene—Lower Miocene age and; (4) 295 m deposits of middle to late Miocene age. The lower, Danian section, is composed by pale brown silty sandstones and fine to coarse gray sandstones containing fossil remains of shells, corals and equinoderms. These deposits are partially correlated with Arroyo Verde Formation cropping out in coastal Patagonia. The following section, of Oligocene age, is formed by gray mudstones, limy siltstones, marls, and claystones with fossil fish remains and abundant pyrite. This section is correlated by Caramés et al. (2004) with the San Julian Formation from southern Patagonia. The late Oligocene—early Miocene section is composed by an assemblage of interbedded claystones, siltstones, mudstones, tuffaceous mudstones, tuffs, and sandstones with disseminated pyrite and equinoderm spicules. This section is correlated by Caramés et al. (2004) with Gaiman Formation and should be the subsurface continuation of the strata cropping out west of Península Valdés. The upper section—middle to late Miocene—is formed by interbedded siltstones, fine to medium sandstones, silty sandstones, and mudstones with shell remains. This upper section is correlated by Caramés et al. (2004) with the Puerto Madryn Formation cropping out in several places of the Península Valdés region.

It is interesting to point out that the Large Igneous Province event of Jurassic age represented in northern Patagonia by the extended Marifil Formation (Malvicini and Llambías 1974), appears in the hydrogeological exploration borehole Puerto Madryn Nr. 1 at a depth of 189 m (INGyM 1965, Fig. 1) in contrast to the well YPF.Ch.PV.es-1 where it appears at a depth of 1964 m. In the Drilling Puerto Madryn Nr. 1, Cretaceous sediments reach 52 m in thickness, while the Tertiary is 137 m thick. Figure 1 shows schematic chronological columns for YPF.Ch.PV.es-1 and Puerto Madryn Nr. 1 boreholes, showing the thickness increase of Cretaceous and Tertiary strata toward the East, consistent with the development of the sedimentary Valdés Basin.

2.2 *Surface Geology*

Surface outcrops comprise Tertiary Neogene and Quaternary rocks (Fig. 2). On a relief carved in these units, recent sediments were deposited. Figure 2 shows the geological map of the Península Valdés region.

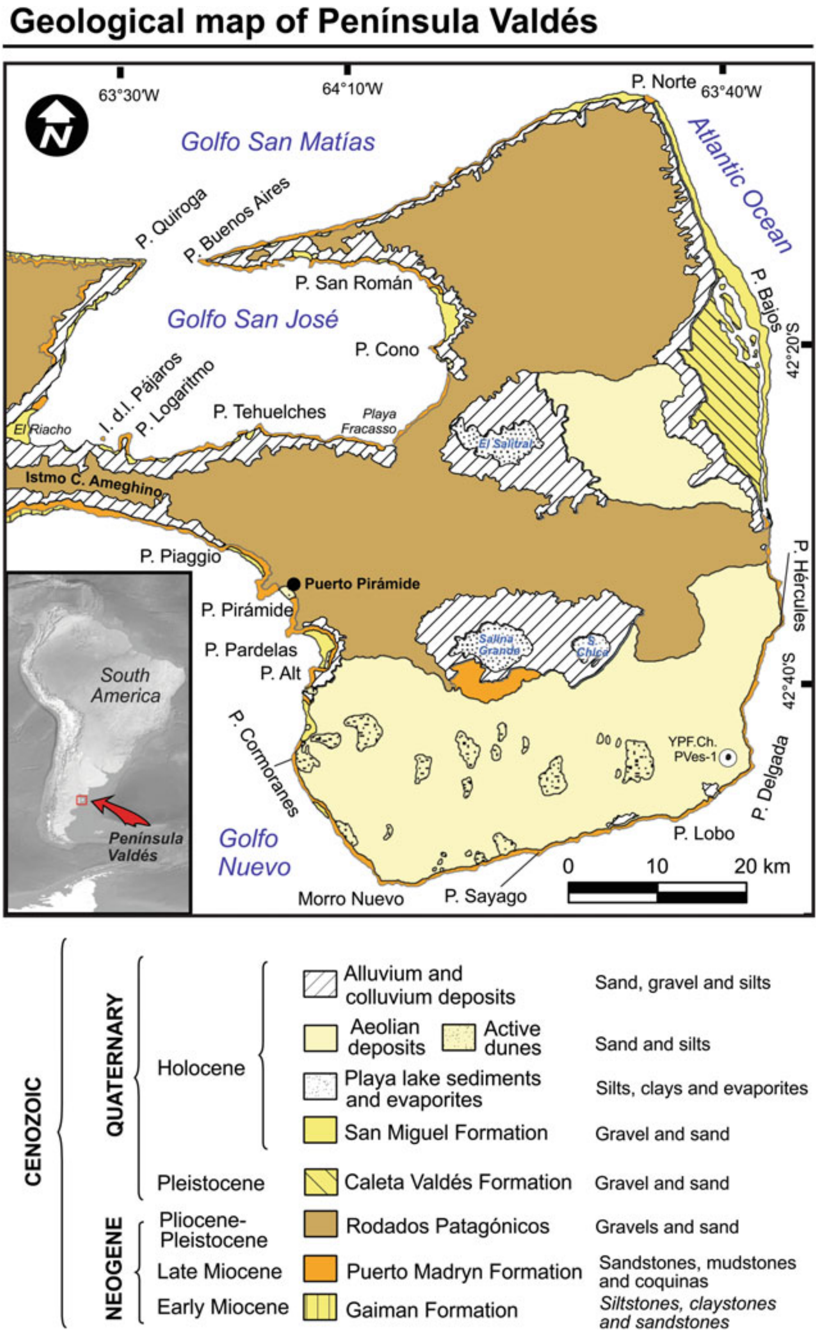

Fig. 2 Geological map of Península Valdés. Modified from Haller et al. (2001)

2.2.1 Gaiman Formation (Haller and Mendía 1980; Early Miocene)

Background

The Gaiman Formation denomination is used here to name the mudstones of tuffaceous volcanoclastic nature deposited during the Patagonian Marine Cycle and cropping out on the Atlantic coast of north Patagonia.

Marine sediments from the Atlantic coast of Patagonia are part of the *Tertiarie Patagonien* from d'Orbigny (1842), who named this way to all the strata of the Patagonian Atlantic margin. These sediments have also been observed in the Golfo Nuevo and elsewhere in Patagonia by Darwin (1846), who grouped them in the Patagonian Tertiary Formation.

The ages, correlation, and nomenclature of the Patagonia Paleogene and Neogene deposits of the Atlantic coastal cliffs have been the subject of long-lived discussion (Hatcher 1900; Ameghino 1906; Feruglio 1949; Camacho 1967; Riggi 1979a; Chiesa and Camacho 1995; Frassineti and Covacevich 1999; Casadío et al. 2000; Parras et al. 2008 among others). Haller and Mendía (1980) recommend restricting the use of the term Patagonia Group or Patagonia Formation to its type area in southern Patagonia and use another lithostratigraphic name for the sediments cropping out in other basins. In that sense, they proposed the name Gaiman Formation for these deposits for the area between Camarones and Sierra Grande. Later, for the Atlantic coastal region of Comodoro Rivadavia (46º S.L.) Bellosi (1990) defined as Chenque Formation the strata previously named as Patagoniano or Patagonia Formation.

Areal Distribution and Lithology

In the Península Valdés area, only reduced outcrops are found in the cliffs bordering the Golfo San Matías to the south, extending to Punta Quiroga. From here, outcrops extend along the west bank of the Golfo San José 3000 m to the southwest. Other reduced outcrops are found in the north western bordering cliffs of Golfo Nuevo.

The Gaiman Formation consists of tuffaceous mudstones with a few interspersed sandy levels. They are generally light-colored and have a massive structure, but in some banks normal or lenticular lamination can observed. Bioturbations—similar to those described by Lech et al. (2000) in the Río Chubut valley outcrops—are common, with many tracks of annelids and marks of perforating organisms. Trace fossils are the main source of paleoenvironmental information within this unit (see Chapter "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity").

Stratigraphic Relationships

The base of this unit is unknown in the field of Península Valdés. To the west it is based on the limestones of the Arroyo Verde Formation (Haller 1982) of late early Paleocene age. It is covered by erosional unconformity by the Puerto Madryn Formation.

Age

As mentioned above, the age of the Gaiman Formation has been the subject of numerous discussions. In the Puerto Madryn area, the Gaiman Formation strata lie on the Sarmiento Group, carrying Colpodon fossils of late Colhuehuapian age. According to Marshall (1985), the Colhuehuapian beds cover the early Miocene. On the basis of their stratigraphic relationships, the correlation with the sea-level curves and fossil content, Scasso and Castro (1999) assigned an early Miocene age for the Gaiman Formation. More recently, Cuitiño et al. (2015) obtained very precise ^{86}Sr/^{87}Sr ages for the Chenque Formation in Golfo San Jorge Basin which indicate early to middle Miocene age fort those deposits.

2.2.2 Puerto Madryn Formation (Haller 1979, Late Miocene)

Background

Puerto Madryn Formation includes the sandstones and mudstones outcropping in the cliffs of Golfo San José and Golfo Nuevo and in the cliffs bordering the Península Valdés (Fig. 2). As mentioned previously, these layers were first observed by Malaspina in 1789 during his exploration trips around the world. Malaspina (1885) wrote in his travel diary: "… the cliffs seemed to be formed by horizontal beds of … probably sands, marls, clays, etc. …". Darwin (1846), who considered the strata from Península Valdés contemporaries to the Patagonian Tertiary Formation, as he named the marine Tertiary strata outcropping along the eastern coast of Patagonia. Carlos Ameghino was the first scholar to describe these strata after Malaspina and Darwin. Ameghino (1890) distinguished three chronostratigraphic units: the lower, called Paranaense with fossil content similar to that of Parana, Entre Rios; the Mesopotamiense similar to the banks of Rio Negro in Carmen de Patagones; and the Patagoniense of Golfo Nuevo composed by sandstones and volcanic marlstones which corresponds to the Gaiman Formation, but its age was misinterpreted by C. Ameghino because the latter occupies sometimes higher topographic levels.

The famed argentine paleontologist Florentino Ameghino, Carlos' brother, correctly locate stratigraphically this unit, by separating them with the name "Entrerriana Formation" in a later work (Ameghino 1897). That "Entrerriana Formation" is characterized by a fauna composed of *Ostrea patagonica*, *O. alvarezi*, *Pecten paranaensis*, etc. Subsequently, Wilckens (1905) considered these layers as the product of a transgression occurred in the late Tertiary, contemporary to the one that occurred in the Paraná basin, transgression which he called "Parana Stuffe".

In his important contribution, Ihering (1907) establishes the criteria followed by later paleontologists, assigning the Entrerriana Formation marine deposits containing *Ostrea patagonica* and *Ostrea alvarezi* and the layers with *O. madryna* to Rionegrense Formation. Roveretto (1921) specified the boundaries between the two units and found the existence of a Rionegrense characterized by the presence of *O. madryna* and *O. ferrarisi*.

Windhausen (1921) separated an Entrerriana Formation of marine origin, from the "Rio Negro Sandstones" of continental origin. The author admits a transitional passage between the two units. Frenguelli (1927) made a detailed stratigraphic and paleontological study in the region, considering that there are two chronostratigraphic units: Patagoniano and Entrerriano. In the latter, he distinguished three units: Entrerriense, Continental Rionegrense, and Marine Rionegrense. Between the last two mentioned units, there would have been a period of erosion. Meanwhile, according to Feruglio (1949), there would not be a definite boundary between Entrerriense and Rionegrense but a gradual passage. Feruglio (1949) considered that the disconformity between the two units are local phenomena and do not necessarily indicate a significant hiatus.

Distribution and Lithology

The Puerto Madryn Formation extends on the cliffs surrounding San José and Nuevo gulfs as well on the cliffs of the north, west, and south coast of Península Valdés (Figs. 2 and 3a). Some minor exposures are found on the southern border on the depression of Salinas Grande and Chica.

The Puerto Madryn Formation includes mudstones, sandstones, siltstones, bioclastic sandstones, and intraformational conglomerates. According with Scasso et al. (2012), the sedimentary assemblage represents a transgressive-regressive cycle (Scasso et al. 2012; and Chapter "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity"). The lower section of the Puerto Madryn Formation represents the transgressive phase while the upper section shows a regressive phase.

The profile in Punta Cono in the eastern coast of the Golfo San José (Fig. 2) begins with yellowish gray mudstone and massive structure. Continue white siltstones with pyroclastic contribution. Above there is a coquina of *Ostrea patagonica* which in turn is covered by a succession of mudstones and sandstones. A bank with diatoms and volcanic glass stands out. On the top lies friable mudstone with abundant gypsum. Total thickness is 80 m.

In Punta San Román in the northern coast of Golfo San José, the profile of Puerto Madryn Formation shows white mudstone with pyroclastic components, covered by pale gray fine grained polymictic sandstones. The sandstones contain several coquina levels with Ostrea. Upwards crop out tuffaceous fine grained friable volcaniclastic friable fine grained sandstones. They have a bluish gray color and show normal lamination and calcareous interbedding. On the top are oyster banks with abundant *O. madryna* and less common *O. alvarezi*.

On the northern coast of Península Valdés, between Punta Buenos Aires and Punta Norte, the Puerto Madryn Formation crops out continuously on the coastal cliffs. In Punta Norte, the thickness of Puerto Madryn Formation reaches 45 m.

On the eastern coast of the Península, this unit crops out in the cliffs close to Punta Cero and extends to the south until Punta Delgada and continues toward the West on the southern margin of Península Valdés.

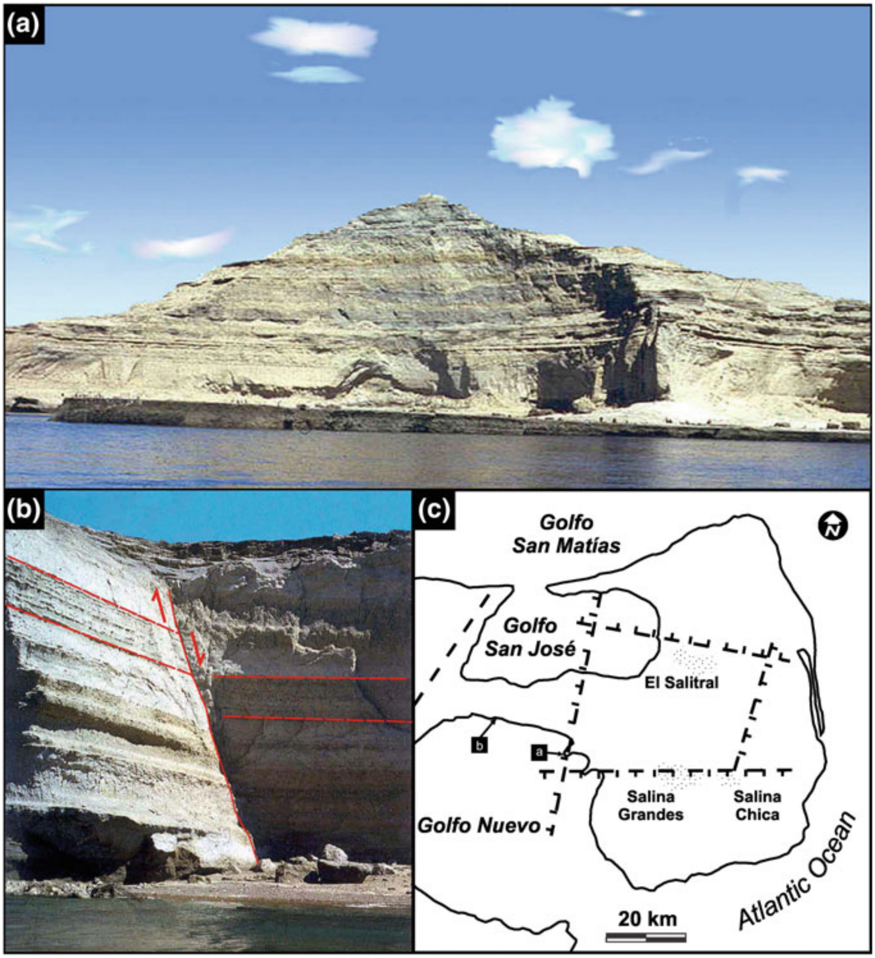

Fig. 3 **a** Puerto Madryn Formation. Cliff at Punta Pirámide, Golfo Nuevo; **b** Fault affecting the Puerto Madryn Formation in the northern shore of Golfo Nuevo (fault throw is approximately 2 m); c Structural sketch based on geophysical data according to Kostadinoff (1993). The *dotted lines* indicate basement faults. Letters inside squares indicate location of pictures of Fig. 3a, b

In Punta Hércules, the profile starts with very fine grained coquina sandstone with calcite cement. It shows cross-bedding where coarse-grained sandstones alternate with more bioclastic beds. Upwards, continues an alternation in normal bedding of fine-grained sandstones and siltstones. The set has a pale yellowish brown color. They are covered by yellowish gray sandy mudstones. Follow mudstones of pinkish gray color with levels with ostrea and casts of pectinidae. To the top, alternate sandstone and mudstone banks. The total thickness is 44 m.

The outcrops of Puerto Madryn Formation extend almost continuously on the northern coast of Golfo Nuevo from Morro Nuevo to the west.

Stratigraphic Relations

The Puerto Madryn Formation rests is uncomfortably upon the Gaiman Formation, as can be seen in Punta Quiroga. On the other hand, it is uncomfortably covered, by the Caleta Valdés Formation and Patagonian Gravels, of Pleistocene age.

Age

Field relations indicate an age between the lower Miocene and the Quaternary. Ostracods present suggest, according to García (1970) a late Miocene age. $^{40}K/^{39}Ar$ dating on three glass concentrates from a tuff in the upper part of the marine upper beds of Puerto Madryn Formation yielded an average age of around 9.4 Ma (Zinsmeister et al. 1980). $^{87}Sr/^{86}Sr$ dating from pectinidae and oyster shells from beds of the lower section of Puerto Madryn Formation yielded a mean age of 10 ± 0.3 Ma (Scasso et al. 2001). Malacofauna studied by del Río (1988), Martínez and del Río (2002) and del Río (2004) in turn indicate a late Miocene age for this unit. A palynological study (Palazzesi and Barreda 2004) supports a late Miocene age as well the Mammalian fossil content (Dozo et al. 2010) supports the late Miocene age for Puerto Madryn Formation. Given the consistency of the above results, a late Miocene age for the Puerto Madryn Formation is accepted.

2.2.3 Rodados Patagónicos/Patagonian Gravels (Pliocene–Early Pleistocene)

Background

According to the criteria set by Fidalgo and Riggi (1970), the Rodados Patagónicos are here named for the sandy gravel deposits that cover the highest mesa-like landforms. Despite some authors (Panza 2002; Martínez and Coronato 2008) suggest abandoning the name Rodados Patagónicos arguing that this denomination applies to different genetic processes and different formation periods. However Rodados Patagónicos is here used considering that the name is self-descriptive and has a historical root in the geological literature of Patagonia.

Distribution and Lithology

The Rodados Patagónicos are distributed on the remains of the oldest aggradation plain, whose remnants are in the central sector of the isthmus Carlos Ameghino and on the western region of the Península Valdés.

These deposits are made up of banks polymictic conglomerates with sandy-silty clay matrix, cemented partly by limy material. The gravels banks show an extended lateral continuity. The upper section of the gravel banks does not show a definite fabric, with the major axes of the clasts randomly arranged. However, the lower section shows a noticeable orientation of the elongated clast forms. The clasts are well rounded and are predominantly subspherical to slightly elongated and their composition are of siliceous, andesitic, and basaltic volcanics. Sometimes, loessial brown fine sands are intercalated at the base of the Patagonian Gravels. The thickness of this unit reaches 3 m. Clast size decreases progressively toward the east; in the isthmus Carlos Ameghino the clasts reach a diameter larger than 3.5 cm, while in the east coast of the Península Valdés, the maximum larger diameter size is 2 cm.

The presence of cryogenic disturbances in the Patagonian Gravels like fossil ice wedges cryodisturbances is known since the description of Liss (1969) of fossil ice wedges is present on this unit (see Chapter "Late Cenozoic Landforms and Landscape Evolution of Península Valdés"). Other observable features are calcareous carbonate crusts and disturbance of the primary sedimentary fabric (Vogt and del Valle 1994; Trombotto and Ahumada 1995 and Trombotto 1996; see Chapter "Soil–Geomorphology Relationships and Pedogenic Processes in Península Valdés").

Sedimentary Environment

According to Cortelezzi et al. (1965, 1968), the Patagonian Gravels were deposited by a braided fluvial system. Beltramone and Meister (1993) stated that the dispersant river environment would have high energy, with variations of the flow system during the sedimentation cycle.

Stratigraphic Relations

The Patagonian Gravels rely on erosional unconformity above the Miocene sediments of the Puerto Madryn Formation separated by an unconformity. On the other hand, they constitute the highest level of aggradation in the Península Valdés region, currently being destroyed by erosion by surface water runoff and partially by the wind. They are only covered by a skeletal soil with sparse vegetation and thin aeolian sand dunes.

Age

Field relations indicate a post-Miocene age for this unit. Considering the degree of evolution of the landscape, the tabular deposits of the Patagonian Gravels are in an advanced state of erosion, so that in the region of the isthmus Carlos Ameghino connecting the Península Valdés to the mainland, the mantle of gravel reaches only a few hundred-meter width. Furthermore, the deposition of such volumes of gravel requires the availability of large amounts of water on the continent, as during interglacial periods of deglaciation. The presence of cryodisturbances implies a periglacial environment during or short after the deposition of the gravels, also coherent with a deglaciation stage. For these reasons the Patagonian Gravels are given a Pliocene—early Pleistocene age.

2.2.4 Caleta Valdés Formation (Haller et al. 2001, Middle—Late Pleistocene)

Background

The first description of the beach ridges on the eastern margin of Península Valdés was provided by Roveretto (1921). He distinguishes two older levels and two younger levels formed by recent marine action (see Chapter "Late Cenozoic Landforms and Landscape Evolution of Península Valdés"). The name Caleta

Valdés Formation is given to the polymictic conglomerates with sandy matrix that make the ancient shorelines at the eastern end of the Península Valdés, presently at an altitude of 15–20 m (Kokot et al. 2005).

Distribution, Lithology, and Fossil Content
These deposits are spread throughout the west bank of the creek Valdés. Its thickness reaches 25 m. They are composed of well-rounded medium to coarse gravel. They have coarse sand matrix. Among the pebbles are found remains of *Adelomedon ancilla*, *Ameghinomya antigua*, *Aulacomya magallánica*, *Brachidontes rodriguezi*, *Crepidula dilatata*, *Lucapinella henseli*, *Mytilus edulis*, *Panopea abreviatta*, *Patinigeria magallanica*, *Pitaria lahillei*, *P. rostrata*, *Protothaca antiqua*, *and Saramangia exalbida* (Codignotto 1983; Fasano et al. 1983; and Rutter et al. 1989).

Depositional Environment
Gravels of the Caleta Valdés Formation were deposited by the action of longshore currents and therefore represent accretion marine deposits.

Stratigraphic relations
The Caleta Valdés Formation rests uncomfortably on the late Miocene sediments of the Puerto Madryn Formation. It is located on a lower topographic level than the Patagonian Gravels but above the present level of beach ridges. Its surface has a limited developed sandy soil and has an herbaceous cover with scarce bushes (see Chapter "Soil–Geomorphology Relationships and Pedogenic Processes in Península Valdés").

Age
Stratigraphic relations indicate a post-Miocene and pre-Holocene age for this unit. The geological literature presents several radiometric dating for Caleta Valdés Formation in its type locality. Codignotto (1983) reports a ^{14}C age of 38,700 years old done on samples of Chione sp. in life position. Fasano et al. (1983) ^{14}C yielded ages of 41,000 $\pm$ 4000; 39,000 $\pm$ 3200 and 34,000 $\pm$ 1700 years on articulated mollusk shells. Meanwhile, Rostami et al. (2000) obtained 115,000 $\pm$ 5000 and 126,000 $\pm$ 10,000 years Th/U ages for the topographically higher levels of Caleta Valdés Formation. Other ESR ages have been given by Schellmann (1998) comprised between 136,000 and 46,000 years for the uppermost level of Caleta Valdés Formation. Based on the cited radiometric ages and the topographic position above the Holocene beach ridges, Caleta Valdés Formation is assigned to the Pleistocene.

2.2.5 San Miguel Formation (Haller 1982, Holocene)

Background
Haller (1982) applied this term to gravels and sands with abundant mollusk shell fragments that are cropping out in the vicinity of Puerto Madryn at higher elevation than present beach deposits. Following these criteria in this chapter all deposits of beach and beach ridges of the high margins of the Península Valdés, and the Golfo Nuevo, Golfo San José, and Golfo San Matías gulfs are named in this way.

Distribution and Lithology

The San Miguel Formation is topographically eight meters above the current line of high tide. In the Golfo San José, there are reduced outcrops to the east and west of the Punta San Roman and north and south of Punta Cono (Fig. 2). In the Golfo Nuevo the outcrops are located east of Punta Pardela (Fig. 2). On the east coast of Península Valdés, the San Miguel Formation constitutes the Holocene beach ridges that limit the Caleta Valdés lagoon (Kokot et al. 2005).

The San Miguel Formation is mainly composed of medium to coarse gravel, with a matrix of fine gravel, coarse sand, and fragments of bivalves. The lithology of the gravels corresponds to mesosiliceous volcanics rocks with varying degrees of alteration and very subordinately to plutonic rocks and flint.

There is a relationship between the sizes of the boulders and distribution of deposits. Those deposits that are surrounded by paleo-cliffs such as those to the east of Punta Pardelas, west of Punta Ninfas in the Golfo Nuevo, and at the north of Punta Cono in Golfo San José, are made up of rounded and subspherical gravel pebble size. Meanwhile the other side, deposits facing the open sea and unprotected from cliffs are formed by boulders, cobbles, and pebbles showing low sphericity and flattened shapes. The San Miguel Formation contains numerous fragmented remains of bivalves and gastropods.

Depositional Environment

The textural characteristics of the San Miguel Formation and its relationship to the location on the coast, suggest that this unit was deposited in two coasts sub-environments. Those located within the gulfs formed by medium-sized gravels, protected by paleo-cliffs were deposited in a beach sub-environment subject to wave action of high to medium energy. On the other hand, the thicker deposits of flattened shapes were accumulated by the action of littoral drift currents in the form of beach ridges.

Stratigraphic Relations

The San Miguel Formation is sparsely vegetated on its surface. It passes laterally to present-day beach deposits. On the east coast of the Península Valdés region, the accumulation process continues currently (Kokot et al. 2005).

Age

Characteristics mentioned above indicate that the San Miguel Formation was deposited during the Holocene. Several ^{14}C ages for these deposits are found in the geological literature: Codignotto (1987) and Codignotto and Kokot (1988) yielded ^{14}C ages between 5725 ± 105 and 1330 ± 80 years AP. Weiler and Meister obtained coherent ^{14}C ages in El Riacho area of 6250 ± 90; 6090 ± 110; 5990 ± 60; and 1140 ± 50 years AP. More recently, Brückner et al. (2007) published ^{14}C ages comprised between 334 ± 50 and 6518 ± 61 years BP. Those data indicate, as pointed out by the mentioned authors, that a sea level highstand occurred about 6500 years ago with the deposition of elevated beaches at an altitude of ≈ 8 m above actual sea level.

2.2.6 Unconsolidated Deposits not Grouped Within a Formal Lithostratigraphic Unit

Playa Lake Sediments and Evaporites

The endorheic depressions in the region have their bottoms covered by very fine sediments, like silt, clayed silt, and clay, clear brown to light gray colored. In many cases, fine sediments may bear associated with evaporites, predominantly halite. In the Salitral closed depression, these mineral are accompanied by sulfates as glauberite and gypsum. The thickness of the evaporites ranges between 1 and 3 mm.

In the Salinas Grande and Salina Chica there are accumulations of evaporite crusts. There is an alternance of muds and evaporites whose thickness is larger than one meter.

Aeolian Deposits

The southern surface of Península Valdés shows an accumulation of sediments deposited by wind action (Fig. 2). Among them, it is possible to distinguish active sand dunes and slightly also older aeolian deposits, colonized by vegetation and subjected to erosion by subaerial agents.

Lithologically, it is fine-to-medium sand with a minor pelitic fraction and very low fraction of gravel size. The composition is feldspathic quartz, with little involvement of volcanic glass and fragments of organic origin, such as remains of shells. The heavy fraction that concentrates on levels distinguishable by their color is formed of tourmaline, epidote, amphibole, and pyroxene.

Alluvium and Colluvium Deposits

Alluvium and colluvium deposits cover areas scattered throughout the region. They consist of unconsolidated deposits of light gray to light brown color, whose grain size corresponds to medium-fine sand, mixed with varying proportions of silt, clay, and scattered pebbles.

The accumulations are relatively thin and they have their origin in the material eroded from the different geological units cropping out in the península.

3 Structural Geology

The region is characterized by a series of gravitational type faults (Fig. 3b, c). The Quaternary cover makes the structural features observable only in the cliffs bordering the sea. Subvertical faults are observed and the maximum throw are about four meters. Most fractures are observed submeridional direction. A series of joints with the same direction complete the structural features of the region. The mentioned tectonic disturbances affect the Puerto Madryn Formation of Neogene age.

Other structural features are interpretable from the geomorphological features. Thus, the straight path of the coast bordering Golfo San Matias in the south and the east coast of the Península Valdés region, suggesting a structural control on the morphology.

Strata of the Gaiman and Puerto Madryn formations have soft warping with slopes not exceeding 5°, so it is not possible to establish whether they are of syngenetic or tectonic nature.

Geophysical studies by Kostadinoff (1993) allowed postulating the existence of a structural high on the Península Valdés, which is separated westward from the mainland by a structural low (Fig. 3c). The structural low location is approximately coincident with the gulfs Golfo San José and Golfo Nuevo (Fig. 3c). This structure is derived from former crustal heterogeneities and possibly defines a horst-graben morphology.

4 Historical Geology

Considering only the surface geology, the following historical geology can be proposed:

During the early Miocene the area was covered by a continental shelf sea, which had an important pyroclastic contribution as a result of volcanic eruptions that occurred in the Andean chain (see Chapter "Climatic, Tectonic, Eustatic and Volcanic Controls on the Stratigraphic Record of Península Valdés" and this chapter). This sea deposits remained registered in the Gaiman Formation.

Subsequently, during the middle Miocene, the region was raised accompanying the Andes uplift, producing the tectonic readjustment of the Patagonian foreland. Later, in the middle-late Miocene, there was a new marine ingression in the region with the deposition of Puerto Madryn Formation. The depositional environment of the base of the Puerto Madryn Formation was a temperate sea near the coast. The marine sedimentation was gradually replaced due to a larger continental contribution of sediments.

During Pliocene-Pleistocene times, fluvial systems deposited the Patagonian Gravels which formed an extended aggradation surface.

In the area located to the west of what is now the Caleta Valdés an accretionary regime deposited beach ridges during the Pleistocene, registered in the Caleta Valdés Formation. Probably in this period, the intense winds existing in the periglacial system of the region, caused deflation of Nuevo and San José gulfs favored by old tectonic discontinuities, and began the formation of Salinas Grande and Chica depressions.

During the Holocene postglacial, the waters reached approximately its present level and about 6500 years ago there was another relative sea level rise, leaving the San Miguel Formation record, formed by gravel and shell fragments in a beach environment.

5 Geological Resources

Mineral resources within the area of Península Valdés are limited to salt deposits, located in Salina Grande and Salina Chica. Also, sporadically, sand and gravels are extracted.

The mining history of the region has its beginnings in the late nineteenth century, with the installation of a company dedicated to the exploitation of the salt flats. The extracted salt was transported by railroad to the natural port of Pirámide being shipped to Buenos Aires.

Mining continued until 1920; after a period of inactivity around 1950 it resumes operation in the southern area of Salina Grande. At this stage the production supplied the fishing industry based in the city of Puerto Madryn.

During the decade of 1990 only one mine operated in Salina Chica providing salt for an aluminum slag recovery factory in Puerto Madryn. During 1995 the mine produced 1520 tons of salt with 98% of Na Cl content.

Presently, there are no operating salt mines in Península Valdés although several mining claims are still valid.

5.1 Salt Deposits

Several authors have contributed to the knowledge of the salt deposits in Península Valdés. Brodtkorb and Re (1962) and Brodtkorb (1980) described in their works the geological features and the possible origin of the depressions containing the salt; the latter author also indicates economic parameters and chemical characteristics of these deposits.

The following geological features were obtained from the above-mentioned works and complemented by own field observations. The deposits are composed of salt layers of variable outlines and thickness which rest on mud.

The salt bodies present in the base several glauberite horizons whose thicknesses vary from 0.20 to 1 m; especially in certain parts of the central area. Glauberite is manifested as isolated individuals or as clustered gypsum pseudomorph rosettes.

The typical profile (top-down) of the salt is according to Brodtkorb (1980), 1–3 mm white salt which overlies a crust of silt and salts 1–3 mm thick. Underneath, about 1 m foul-smelling blackish green mud. Thin horizons of 1–2 mm in thickness of halite crystals were also observed. Continues a layer of volcanic ash from about 50 mm thick, followed by a layer of silt with 2 m glauberite and gypsum crystals.

Mud plasticity silt gradually decreases downwards increasing the sand percentage in the mud.

According to Brodtkorb (1980), indicated reserves for Salina Grande are 52,222,300 tons; while for Salina Chica measured reserves are 6,013,600 tons. Chemical composition is indicated in Table 2.

Table 2 Chemical composition of the salt in Salina Grande and Salina Chica, after Brodtkorb (1980)

	Salina Grande	Salina Chica
	% weight	% weight
NaCl	80.25	82.50
$MgCl_2$	0.83	0.63
$CaCl_2$	0.19	1.72
Na_2SO_4	0.97	2.17
$CaSO_4$	6.99	5.88
Insoluble	10.65	7.09

5.2 Industrial Rocks (Sand and Gravels)

This material is circumstantially worked out for its use in the scarce building activity in the region.

The sector of dunes located in the vicinity of Puerto Pirámide and in the southern part of the Península is exploited in a very primitive form using shovels and small trucks.

The material—called by the villagers "blasted sand"—is a loose aggregate of particles whose particle size varies from fine to medium sand.

Gravels are used for the construction and improvement of the road network. It is common to see the gravel quarries on the road sides that are operated at certain times of the year.

The mined material comes from the Patagonian Gravels covering part of the surface of the Península.

6 Perspectives and Future Work

While the simple stratigraphy of the region is well understood, further attention should be given to framework of facies and sequence stratigraphy. Further attention must be paid to precise the chronostratigraphy and biostratigraphy of the Miocene deposits. There is considerable scope to precise the dating of the Pliocene-Quaternary coastal sediments. There is also considerable scope for structural geology of Península Valdés and surrounding gulfs as well with its relation with the Valdés sedimentary basin.

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Glossary

Boulder	Large rock fragment formed by detachment from its parent consolidated rock by weathering and erosion, which has one linear dimension of at least 25.4 cm
Cenozoic	The current geologic era, which began 66.4 million years ago and continues to the present
Cobbles	Clast of rock having a particle size of 6,4–25,6 cm
Formation	Primary rock unit used in the subdivision of a sequence and may vary in scale from tens of centimeters to kilometers
Glauberite	Sodium calcium sulfate mineral with the formula $Na_2Ca(SO_4)2$
Gravel	Unconsolidated rock fragments that have a general particle size range of 2–64 cm
Lithostratigraphy	Part of stratigraphy that deals with the description and nomenclature of the rocks of the Earth based on their type and their stratigraphic relations
Neogene	A geologic period starting 23 million years ago and ending 2.6 million years ago with the beginning of the Quaternary
Paleogene	A geologic period and system that began 66 and ended 23 million years ago
Pebbles	Rock fragments (often rounded) of around 1–10 cm in size
Polymictic	Composed of several minerals or rock types
Pyroclastic	Fragments of rock and volcanic ash thrown out of a volcano
Quaternary	Is the current and most recent geological period
Sedimentary basins	Are regions of Earth of long-term subsidence creating accommodation space for infilling by sediments
Subsidence	Is the motion of the Earth's surface as it shifts downward relative the sea level
Volcanics	Volcanic rocks formed from magma erupted from a volcano

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