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Late Cenozoic of Península Valdés, Patagonia, Argentina

An Interdisciplinary Approach

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Climatic, Tectonic, Eustatic, and Volcanic Controls on the Stratigraphic Record of Península Valdés

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Abstract The Península Valdés region is situated in an intraplate position of the South American Plate, in the Patagonian foreland close to the Argentine Continental shelf. This region has a complex geotectonic evolution that started more than 400 Ma and involves the conformation of Northern Patagonia as a part of Gondwana during the Paleozoic, the opening of the Atlantic Ocean during the Mesozoic and the configuration of the Andean margin during the Cenozoic. At different scales, the interplay between climate, tectonic, sea-level, and volcanic processes, set the sedimentary routing system that had governed the final geologic records of the Península Valdés region and control the transfer of terrigenous sediments from source to sink. The stratigraphic record of the region was not only influenced by local factors. Processes developed far away from Península Valdés, both in the Southern Andes or in the continental shelf had influenced the late Cenozoic record of this region.

Keywords Sediment routing system · Climate · Tectonics · Eustasy · Volcanism

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1 Geotectonic Setting and Geodynamic Evolution

Península Valdés is located in the Patagonian foreland close to the Argentine Continental shelf, halfway from the Southern Andes and the Continental slope (Fig. 1). It is located in an intraplate position of the South American Plate which is moving to the NW 1.7 cm/a (Schellart et al. 2011; Fig. 1b).

From a geologic perspective, Península Valdés is located in northern Patagonia at the eastern edge of a main tectonic element: the North Patagonian Massif or Somuncurá Massif (Ramos 2008; Fig. 1b). At the same time, it is connected to the east with the marine continental shelf, a feature that dominates the geotectonic configuration of eastern Patagonia since the Late Jurassic (Fig. 1). The North Patagonian Massif limits to the north with two different basement terranes: the Pampia terrane to the northwest and the Río de la Plata craton to the northeast (Fig. 2). To the south it is connected to the Deseado Massif, the other main continental block that conforms the eastern margin of the Patagonia terrane

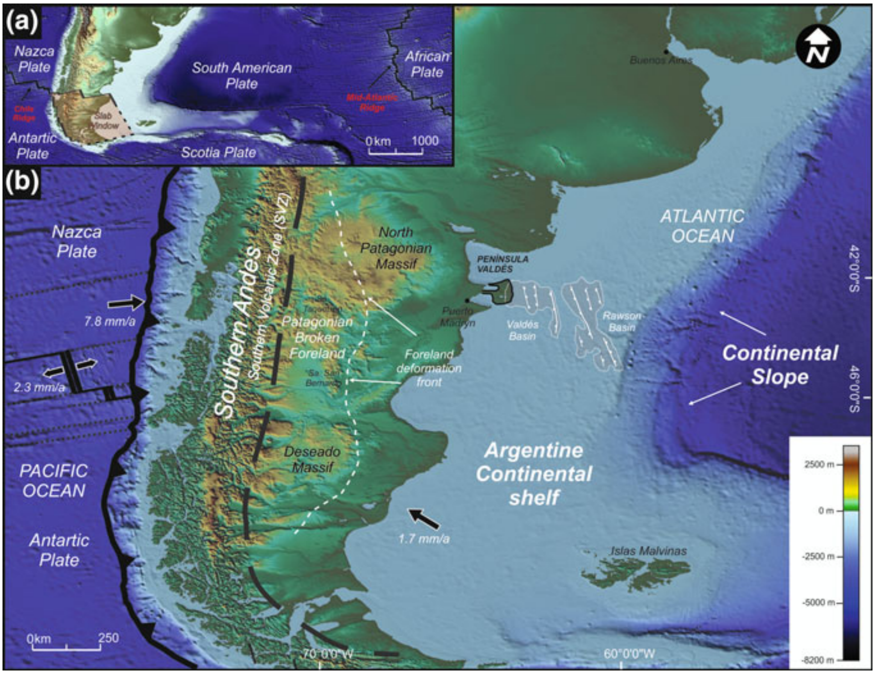

Fig. 1 Present geotectonic settings of Península Valdés, plate configuration and location of the study zone. **a** The South American Plate in the global geotectonic context. **b** Schematic regional map showing main morphotectonic characteristics of the Southern Andes, Southern Andes Foreland and offshore areas that are mention in this chapter. Subsurface normal faults in the Valdes and Rawson basins from Continanzia et al. (2011)

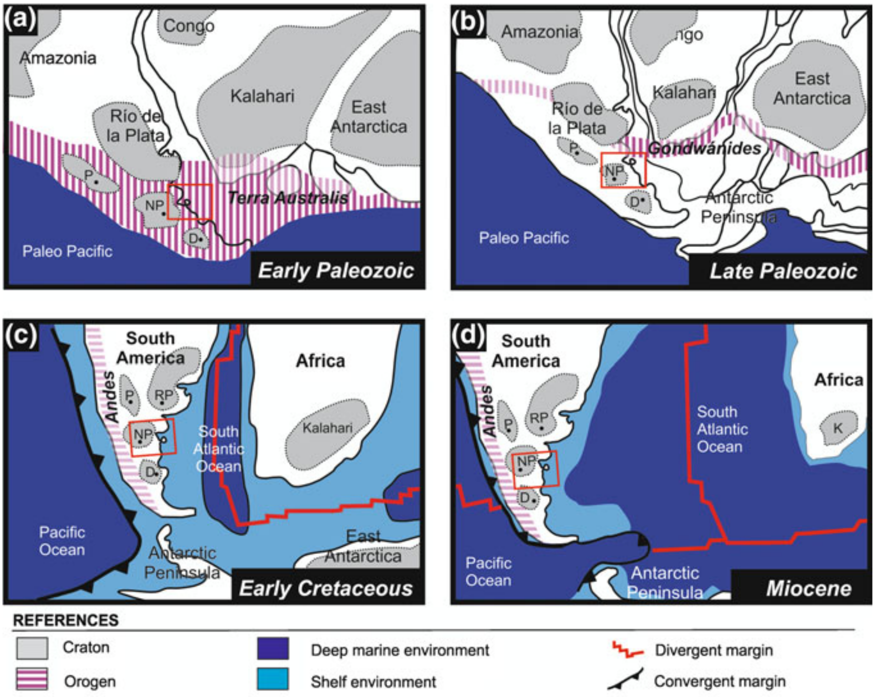

Fig. 2 Geodynamic evolution of the Península Valdés region during the Phanerozoic **a** and **b** Conformation of the Northern Patagonia during the lower Paleozoic and upper Paleozoic, respectively; **c** The *rifting* and opening of the Atlantic Ocean during the Mesozoic; **d** Andean and Andean Foreland configuration margin during the Cenozoic. Location of the Península Valdés region through time is highlighted with a *red line*; North Patagonian massif (NP); Deseado Massif (D); Rio de la Plata (RP); Pampia (P); Kalahari (K). Reconstruction taken from Scotese (2001)

(Ramos 2008; Fig. 2). It is important to highlight that the geotectonic setting of the region where Península Valdés is located has experienced several geotectonic settings in the past 400 Ma. For instance, until the Late Jurassic the landmasses that nowadays form the continents of South America and Africa were connected as part of the Gondwana super-continent, whereas before the Miocene the Andean chain had only a minor topographic expression (Fig. 2).

In summary, the tectonic framework of the region where Península Valdés is located, may be addressed by three "key events": the conformation of Northern Patagonia as a part of Gondwana during the Paleozoic, the opening of the Atlantic Ocean during the Mesozoic and the evolution of the Andean margin during the Cenozoic (Fig. 2).

1.1 The Conformation of Northern Patagonia During the Paleozoic

The evolution of northern Patagonia during the Paleozoic has been a matter of considerable debate during the last decades. While some authors consider Patagonia as an autochthonous part of Gondwana other hypotheses postulate an allochthonous origin (Ramos and Naipauer 2014 and references therein). In the last years, detailed geochronological and petrological studies together with new paleontological findings gathered new evidences in order to understand the tectonic evolution of the region.

The older known stratigraphic elements of Northeast Patagonia (not cropping out in the Península Valdés region) are Cambrian–Ordovician metamorphic rocks intruded by sinorogenic to postorogenic granitoids (Ramos 2008; López de Luchi et al. 2010; Rapalini et al. 2013; Greco et al. 2015). Many evidence support that the North Patagonian Massif was one of the blocks that conformed, together with the Pampia terrane, the Rio de la Plata terrane and the Kalahari terrane of southern Africa, the southern margin of Gondwana in Early Paleozoic times (Ramos 2008; González et al. 2011; Rapalini et al. 2013; Pángaro and Ramos 2012; Pankhurst et al. 2014; Fig. 2a).

During the Late Ordovician and Silurian extensional tectonics led to the origin of an ocean between Patagonia and the Río de la Plata craton. This extensional regime controlled the development of a passive margin represented by the Silurian–Devonian quartzites of the Sierra Grande Formation preserved in eastern Patagonia. It is important to note that sandstones located in the subsurface of Península Valdés can be correlated with the Sierra Grande Formation (Marinelli and Franzin 1996; Gregori et al. 2013; see Chapter "Geology of Península Valdés"), suggesting that the distribution of the Silurian–Devonian passive margin would have included the region of Península Valdés (Fig. 2a). This context of *rifting* and d*rifting* led to the final separation of part of the collided block as present Patagonia (Ramos and Naipauer 2014) and was possibly followed during the Early Carboniferous by the collision and amalgamation of other continental blocks that conformed the entire Patagonia terrane (e.g., The Deseado Massif or the Southern Patagonia terrane; Pankhurst et al. 2006; Chernicoff et al. 2013, respectively; Fig. 2a).

At Carboniferous times, the spreading in the narrow ocean developed between the Río de la Plata craton and northern Patagonia stopped. A major tectonic reconfiguration led to the development of a convergent margin with south-dipping subduction initiated at the northern margin of the Patagonia terrane (Chernicoff et al. 2013).

The final closure between Patagonia and Gondwana occurred during the Carboniferous, even though, collision, deformation and uplift took place in Early Permian times (Ramos 2008; Rapalini et al. 2013; Fig. 2b). The compressive stress regime lasted in this sector of South America until the Late Permian (Ramos 2008).

The Gondwanide Orogenic Belt was created in that period including deformational structures that extended across South America, Africa, and Antarctica (Keidel 1921; Fig. 2b).

1.2 *The* Rifting *and Opening of the Atlantic Ocean During the Mesozoic*

The Argentine Continental shelf is 2300 km long and has an average of 400 km wide reaching more than 800,000 km^2 (Fig. 1). This giant tectonic feature originated as a consequence of the thermotectonic processes that led to the breakup of Gondwana and d*rifting* of the South American and African plates since the Mesozoic era (Fig. 2c). *Rifting* and opening of the Atlantic Ocean progressed through different stages along a heterogeneous and highly segmented margin (Blaich et al. 2009). The process of continental extension started at the end of the Triassic and lasted until the opening of the South Atlantic in the Early Cretaceous (Macdonald et al. 2003; Fig. 2c). According to these authors, the early syn-rift phase was accompanied by strike-slip faulting and block rotation, whereas the later extension occurred along with magmatic cycles associated with the impact of the Karoo mantle plume in the Lower Jurassic. During the Middle Jurassic the development of a Large Silicic Igneous Province—the Chon Aike magmatic province—affected the most of northeastern Patagonia (Kay et al. 1989). Is important to note that for other authors initial *rifting* started at this time (c. 183 Ma) and non-earlier (Pángaro and Ramos 2012). Near Península Valdés the rocks of the Chon Aike magmatic province are observed as isolated outcrops and on the subsurface (see Chapter "Geology of Península Valdés"). These rocks are included in the Jurassic Marifil Formation (Cortés 1981; Haller 1982; see Chapter "Geology of Península Valdés").

Rifting prior to seafloor spreading in the southernmost Atlantic is believed to have occurred in the early Jurassic (190 Ma) and involved dextral movement between Patagonia and the northern subplates until the Early Cretaceous (126.7 Ma; Macdonald et al. 2003; Torsvik et al. 2010; Seton et al. 2012). As a result several basins along the Patagonian margin were developed (Autin et al. 2013; Fig. 1b). In the North Patagonian region, the structural trend of the Argentine continental platform abruptly changes from WNW (observed to the north) to NNW (observed in the Península Valdés region) (Fig. 1). In this segment of the continental shelf, in front of Península Valdés, two basins developed between the coast and the slope: the Valdés and the Rawson basins (Keeley and Light 1993). The Valdés Basin has an area of 57,000 km^2 and a maximum thickness of 3000 m (Fig. 1b). The evolution of this basin is relevant for the understanding of the study area because this basin extends to the subsurface of the Península Valdés region reaching a thickness of around 1100 m (borehole YPF.Ch PV.es-1; Marinelli and Franzin 1996; Barredo and Stinco 2010; see Chapter "Geology of Península Valdés"). The main structure is composed of half graben roughly oriented parallel to the coast (Fig. 1). The NNW trending normal faults fits with the amount of displacement of the late Paleozoic features and may have been controlled by the reactivation of the inherited structures (Urien and Zambrano 1996; Max et al. 1999; Macdonald et al. 2003; Ramos 2008; Pángaro and Ramos 2012).

Stabilized seafloor spreading in the southern segment of the South Atlantic rift commenced at around 127 Ma (Fig. 2c), after a prolonged phase of volcanism affecting the southern South Atlantic conjugate margins (Heine et al. 2013; Becker et al. 2012). In the Rawson Basin (Fig. 1b), the breakup unconformity that traces the change from *rifting* to d*rifting* is reported to be of Aptian age (c. 118 Ma; Franke 2013). Considering the close similarity in the evolution this age can be assumed as the passage from rift to drift also in the Valdés Basin. Since the Early Cretaceous, the region is involved in the Atlantic passive continental margin (Fig. 2c).

1.3 Configuration of the Andean Margin and Foreland During the Cenozoic

It is generally accepted that the beginning of the Andean margin configuration is determined by the start of the subduction at the western margin of the South American plate, a process synchronic with the *rifting* of the Atlantic Ocean. This process started in the Lower Jurassic with subduction-extension (190–185 Ma; Ramos et al. 2011; D'Elia et al. 2012) followed by a period of compression starting at 100 Ma (Ramos 2010; Tunik et al. 2010). The last period accelerated after 90 Ma, when the South American plate started to drift to the west as a consequence of the opening of the South Atlantic Ocean (Somoza and Ghidella 2012; Folguera and Ramos 2011; Fig. 2c). The configuration and development of the Andes and Andean Foreland was not a steady process, as was inferred in pioneer works (Feruglio 1949; Groeber 1956; among others). It includes diachronic deformational phases from the latest Cretaceous to the late Quaternary that affected simultaneously regions near the orogenic front and regions hundred kilometers from the trench in the Andean Foreland (Cobbold et al. 2007; Guillaume et al. 2009; Folguera and Ramos 2011; Orts et al. 2012; Bilmes et al. 2013; Allard et al. 2015; Gianni et al. 2015; Fig. 2d).

In the Patagonian Andes and foreland, deformational processes in the orogenic front started around 122 Ma and ended by 90 Ma (Baker et al. 1981; Suárez et al. 2010; Folguera and Iannizzotto 2004; Folguera and Ramos 2011). Then, previous to 80 Ma, contractional deformation shifted to the east, uplifting many of the present day mountains of the Andean foreland (e.g., Sierra de San Bernardo, Sierra de Taquetrén; Bilmes et al. 2013; Allard et al. 2015; Gianni et al. 2015; Fig. 1b). It was a period of important mountain uplift not only in the orogenic front, but also in the foreland region, with uplifts of up to 1600 m (Bilmes et al. 2013). From the Late

Cretaceous to the Paleocene magmatic belts near and far from the orogenic front were developed (i.e., Pilcaniyeu and Maiten belts; Rapela et al. 1984; Mazzoni 1994; Madden et al. 2005; Paredes 2008) interpreted as repeated eastward shifts of the arc in the region (Folguera and Ramos 2011). Later during late Oligocene to early Miocene a large mafic igneous province, known as the "Meseta de Somuncura" was developed in the foreland region, about 200 km west from the Península Valdés region (Kay et al. 2007; Fig. 1b).

A renewed episode of orogenic grow started in the lower Miocene around (18 Ma; Folguera and Ramos 2011; Orts et al. 2012; Fig. 2d) and shifted toward the foreland during the lower to middle Miocene (19–14.8 Ma; Guillaume et al. 2009; Giacosa et al. 2010; Bilmes et al. 2013; Gianni et al. 2015). Explosive volcanism coexisted with Miocene mountain-building processes (Mazzoni and Benvenuto 1990) interpreted by some authors as eastward arc expansion (Folguera and Ramos 2011) (Figs. 2d and 3).

In the Patagonian Andes and Andean Patagonian Foreland the late Miocene–Pliocene is characterized by a regional uplift, a process that is still observed today (Guillaume et al. 2009; Pedoja et al. 2011; Folguera et al. 2015a; Fig. 3). As a consequence of this foreland uplift several Late Miocene–Pliocene fluvial terraces were tilted (Guillaume 2009) and all Pleistocene Atlantic shorelines were remarkably elevated, in some cases more than 100 m with respect to present day sea-level (Pedoja et al. 2011). The uplift rate of the Península Valdés region has been estimated based on the age and topographic position of these shorelines in 0.14 ± 0.02 mm/a (Pedoja et al. 2011). This enhanced uplift along the Patagonian coast is linked to dynamic uplift, a particular geotectonic mechanism that is related to the subduction of a mid-ocean ridge (i.e., Chile ridge) and the opening of a *slab window* (Guillaume 2001; Pedoja et al. 2011; Folguera et al. 2015a) (Figs. 1a and 3).

2 Controls on the Stratigraphic Record of the Península Valdés Area

The evolution of the region where nowadays is Península Valdés started more than 400 Ma ago. Thus, it is essential to understand processes that operate on Earth at a time scale people most often not used to. The geological processes operating on Earth's surface produce only subtle changes in the landscape during human lifetime, but over a period of thousands or millions of years, the effect of these processes can be significant. Given enough time, an entire mountain range can be reduced to a featureless lowland, and clastic material derived from the erosion can be transported and deposited hundred kilometers away. The preservation of sedimentary record can form vertical rock successions of thousands of meters thick, as those observed in subsurface in Península Valdés, where there is a thick sedimentary pile of more than 2000 m (see Chapter "Geology of Península Valdés"). A pile of sediments and rocks constitute the stratigraphic record of a region and represent a valuable dataset about the past events in the Earth's history of the area (Fig. 3).

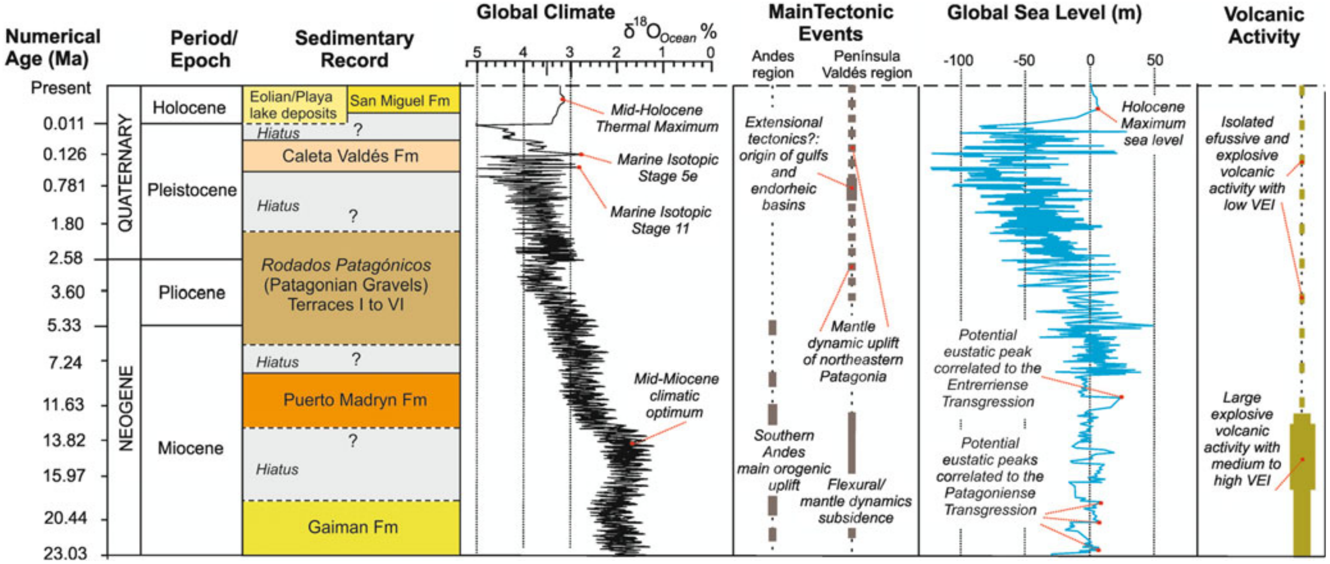

Fig. 3 Controls that influence the stratigraphic record of the Península Valdés region during the late Cenozoic. Numerical age not at scale. Global deep-sea oxygen isotope data from Zachos et al. (2001), Rohling et al. (2014); Deep-sea oxygen isotopes are used as a *proxy* of global average paleo temperature. Global Sea-level data from Miller et al. (2011), Violante et al. (2014). Tectonic and volcanic data of the Southern Andes—Foreland from Mazzoni and Benvenuto (1990), Orts et al. (2012), Bilmes et al. (2013), Morabito and Ramos (2012), Ramos et al. (2015). *Volcanic Explosivity Index* (VEI)

The stratigraphic record of a region is also determined by the dynamic interplay between erosion, sediment transfer, temporary storage, and long-term deposition of the sediments, from source to sink: the sediment routing system (Allen 1997, 2008; Allen and Allen 2013; Fig. 4). From the catchment areas to the sea, the system is controlled by a distinctive set of variables including climate, tectonics, sea-level changes and eventually volcanism. Each of these factors has different influence depending on both the position and the stage within the sediment routing system, from the erosional engine in *proximal areas* to become the infill of the *Sedimentary basin*. The nature of the stratigraphic record may be summarized taking into account the factors that (1) determine the sediment supply to the *Sedimentary basin* and (2) originate the available space for the accumulation of sediments, termed as accommodation space. In coastal and shallow marine areas the accommodation space is determinate by sea-level, whereas in continental environments it is set by base-level, since it determines the geomorphologic *equilibrium profile* of the alluvial-fluvial systems (Muto and Steel 2000; Spalletti and Colombo 2005; Nichols 2009; Allen and Allen 2013).

The interplay between climate, tectonic, sea-level, and volcanic processes, set the sedimentary supply and accommodation space of a sedimentary routing system, which will rule the final geological record of a given region (Figs. 3 and 4). Climate affects the stratigraphic record at different scales. Regional climate, combined with topography and the nature of the vegetation and bedrock, determines the erosional rates (weathering and sediment flux) of a sedimentary routing system, controlling the sediment supply to the *Sedimentary basin*. Climate may also affect the accommodation space. For instance, global climate change may cause variations in the volume of the oceans, affecting sea-level, whereas a regional climate change in a closed basin will adjust the lake level, modifying the available space for the accumulation of sediments. Tectonic processes, such uplift or subsidence, are the most important controls on the stratigraphic record. They involve relative

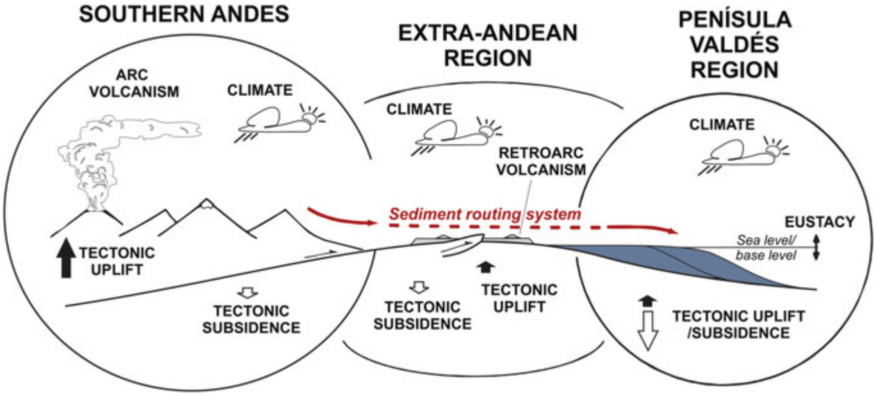

Fig. 4 Conceptual model of the Sediment routing system of the Península Valdés region. Modified from Castelltort and Van Den Driessche (2003)

movements of the substratum at different scales. For example, tectonic uplift affects the topographic relief, modifying the *equilibrium profile* of the alluvial-fluvial systems. Therefore, a change in the *equilibrium profile* has an impact on the erosional rates, as well as in the available space for the accumulation of sediments, adjusting both the sediment supply and accommodation space of the systems. Additionally, tectonic subsidence is the main factor controlling long- or short-term space availability for the accumulation of sediments (i.e., accommodation space). In regions close to the sea, subsidence could produce a relative sea-level rise increasing the accommodation space of sub-aerial depositional areas as well as coastal and shallow marine areas. Finally, volcanism may affect in different ways the sediment routing system. At proximal zones, close to volcanic areas, volcanoes produce as new relief, modifying, or creating new source or catchment areas. During eruptive cycles a volcano or a volcanic chain will deliver different proportions of volcanic particles to the *sedimentary environments*. Depending on the eruption style (effusive or explosive) and magnitude of the eruptions, volcanic materials will affect the sediment flux from *proximal area*s to distal areas (up to hundreds kilometers from the volcanic centers; Fig. 4). Large explosive eruptions introduce huge amounts of sediments in a geologically instantaneous time, producing temporary changes in the mechanism of transport, drainage patters, and depositional features, as well as an increase in sediment supply to the sedimentary systems, until they recover the pre-eruption conditions.

As described in the first part of this chapter, Península Valdés, is located halfway from the Patagonian Andes and the Continental slope (Fig. 1). During the late Cenozoic, climate, sea-level changes, tectonic, and volcanic processes related to the evolution of the Andes and the opening of the Atlantic Ocean are recorded (Fig. 3). In the following sections, each of these stratigraphic controls that affected the geological record of Península Valdés during the late Cenozoic will be considered in detail, introducing key concepts for the reading of the subsequent book chapters.

2.1 Climate

One of the main contributions of paleoenvironmental and paleoclimatic research to the reconstruction of past climate has been the validation that during much of the last 65 million years and beyond, Earth's climate system has been continuously changing. The study of sedimentary archives using a wide variety of well-dated proxies has shown that our planet has been switching from intervals with warm and ice-free poles (*greenhouse-world*), to cold intervals characterized by massive continental ice-sheets and polar ice caps (*ice-world*; e.g., Zachos et al. 2001 and references therein). This should not be surprising since Earth's orbital parameters and plate tectonics—the main forces triggering long-term and global climate—are changing permanently (Fig. 3). Orbital factors vary at different rhythms that remain stable for millions of years. Most of the higher frequency changes result from periodic and quasi-periodic oscillations in Earth's orbital parameters affecting both distribution and amount of solar energy arriving to our planet. Whilst *eccentricity* (~100,000 years) rules the amplitude of *precession* (~23,000 years) and as a result the total annual/seasonal solar energy budget, *obliquity* (~41,000 years) changes the latitudinal distribution of insolation. Hence, orbital factors provide even and mostly predictable long-term fluctuations of climate that are known as Milankovitch cycles. There is good evidence that they regulate the amount of insolation reaching our planet and thus global climate. However, these orbital changes alone are insufficient to explain past climate and hence other features are also important to consider. They include variations in the configuration and distribution of the continents; the opening and closing of oceanic gateways that in turn are ruling ocean circulation; and changes in the atmosphere composition particularly concerning greenhouse gases. These three aspects are closely related and most of all driven by plate tectonics. To the previously described changes in the Earth orbital and tectonic boundary conditions it is necessary to superimpose more regional features that can have a large impact in local climate patterns. One of them is the rain shadow effect associated to emerging mountain chains such as the Himalayan or the Andean cordillera that produce intensification of rainfall on the wind-ward side of the range and an effect of aridity on the leeward side (Blisniuk et al. 2005; Barry 2008).

The late Cenozoic climate in the Península Valdés region has been far from static (Fig. 3) including periods with much warmer or much cooler conditions than today. Fossil tropical fauna from the Puerto Madryn Formation suggest that climate during the Middle Miocene was more humid and warmer than today's (see Chapter "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity"). Ice-wedge casts and cryoturbation structures developed in the Rodados Patagonicos (Patagonian gravels) suggest a cooler climate during the Pliocene–lower Pleistocene associated with persistent arid periglacial conditions (see Chapter "Late Cenozoic Landforms and Landscape Evolution of Península Valdés"; Fig. 3). Conversely, the isotopic composition of calcretes embedded in the Rodados Patagónicos (see Chapter "Soil-Geomorphology Relationships and Pedogenic Processes in Península Valdés"; Fig. 3) indicate a warmer and drier interglacial with an average annual temperature of approximately 20 °C during the middle Pleistocene (today is 13.6 °C, see Chapter "The Climate of Península Valdés Within a Regional Frame").

At present there is not a model that could explain alone the causes that have triggered late Cenozoic climate changes in the Península Valdés region. However, some scenarios have been proposed for specific time intervals. Milankovich cycles have been associated with glacial/interglacial changes that are documented in the Rodados Patagónicos (Clapperton 1993; Trombotto 2002; Bouza 2012). On the other hand the absence of an Andean rain shadow effect during the middle Miocene has been proposed to explain the warmer and more humid climate conditions that existed in the Península Valdés region during the accumulation of the Puerto Madryn Formation (Palazzesi et al. 2014; see Chapter "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity"; Fig. 3).

2.2 Tectonics

The tectonic uplift and subsidence involve relative movement of the substratum produced by crustal or mantle processes. Both mechanisms may proceed at different scales, such as block uplift or fault subsidence located close to tectonic faults, or uplift/subsidence related to lithospheric processes (e.g., flexural subsidence, thermal uplift) involving regional scales. Fault block uplift or fault subsidence are spatially associated, as its name indicates, with faults. For instance, in contractional tectonic regimes, reverse faults are mainly related to elevated blocks, whereas in extensional tectonic regimes, faults are not only related to fault block uplift, but also are the main inducing factors of mechanical subsidence. At a larger scale, subsidence or uplift may involve lithospheric processes, such as orogeny overload caused by thrust tectonic, which may originate long-wavelength subsidence related to flexure of the lithosphere: isostatic topography. In this case, *orogenic wedge* in *Retroarc foreland basins* or isolated load in Retroarc broken foreland basins (i.e., a foreland basin that is segmented by isolated or partially connected basement uplifts) may originate the flexural subsidence of the lithosphere. In addition, mass anomaly and heat transfers in the upper part of the mantle may trigger other kind of long-wavelength tectonic processes which are referred to as dynamic topography. This large-scale tectonic process may be developed in convergent margins, passive margins, as well as in intraplate settings. For example, slab pull associated to a subduction system in convergent margins may drive dynamic topography subsidence by mantle flow, whereas a thermal anomaly driven by intracontinental hot spot or *slab window* creates a regional uplift.

During the late Cenozoic the Península Valdés area was closely related to the tectonic processes associated with the evolution of the Andean Orogeny (Fig. 3). The two principal tectonic processes occurring at the Andean margin at this latitude are the variations in the angle of the subducted plate (Folguera and Ramos 2011; Orts et al. 2012; Folguera et al. 2015b) and the subduction of the Chile Ridge (Guillaume et al. 2009; Pedoja et al. 2011). The dynamic of the subduction controlled the tectonic evolution of the Andean orogeny as well as of the retroarc areas. During the Neogene, the retroarc of the North Patagonian Andes was configured as a broken foreland basin (Bilmes et al. 2013), whereas the influence of the subducted Chile Ridge become to act, at this latitude, from late Miocene times (Guillaume et al. 2009; Pedoja et al. 2011). In this tectonic setting, several fault tectonics, and lithospheric processes of uplift and subsidence were mentioned. The Miocene contractional tectonics related to the configuration of the Patagonian Broken Foreland involved fault block uplifts as far as 700 km east of the Andean Trench (Bilmes et al. 2013). Thus, the source and catchment areas of the fluvial systems that flow to the Península Valdés area were affected, controlling the depositional scenario of the sediments of the Puerto Madryn Formation (see Chapter "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity"). In turn, contractional tectonic would have driven major tectonic effects in the extra Andean areas. Recently, some authors have suggested that the tectonic subsidence associated with either flexural subsidence or dynamic effect of the mantle (dynamic topography), could have caused accommodation space of the continental and marine Miocene–Pliocene succession preserved in extraandean regions of northern Patagonia, near the Atlantic coast (Folguera et al. 2015b). At the Península Valdés area, this lapse corresponds to deposition of the Gaiman and Puerto Madryn formations (see Chapters "Geology of Península Valdés" and "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity"), for which the accommodation space would be also associated with the same process of tectonic subsidence (Fig. 3). For the Quaternary other kind of tectonic processes have been recorded in the Península Valdés area. To this latitude, the subduction of the Chile Ridge associated to other coupling mechanisms (see Folguera et al. 2015b) resulted in a long-wavelength (>1000 km) dynamic uplift of northern Patagonia (Guillaume et al. 2009; Pedoja et al. 2011). Thus, the tectonic uplift would be mainly responsible of the exposure of the Pleistocene marine terraces in the Península Valdés area (see Chapter "Late Cenozoic Landforms and Landscape Evolution of Península Valdés"). In addition, a tectonic control associated to extensional faults that affected the pre-Quaternary successions of the area has been proposed to explain the origin of the sea gulfs and Salinas of the Península Valdés region (see Chapter "Late Cenozoic Landforms and Landscape Evolution of Península Valdés"; Fig. 3).

2.3 Eustasy and Relative Sea-Level

The original idea of a varying sea-level appeared during the late nineteenth century, when geologists realized that some ancient marine sediments and fossils indicate water depths different from present day. The term eustasy refers to changes of sea-level—i.e., the sea-level can raise or fall referenced to center of the Earth—occurring at a global scale (Fig. 3). The concept implies long-term (more than 100 years) fluctuations not related to geologically instantaneous meteorological or tidal sea-level variations. Recent eustatic variations (1–10 ka; 1 ka = 1000 years) can be estimated by measuring and dating shoreline markers and tropical reefs and atolls in quiet tectonic areas of the world. In the ancient geological record (1–100 Ma), the correlation of erosion surfaces caused by sea-level falls, and marine flooding deposits caused by sea-level rises, are estimates of the eustatic worldwide variations.

The eustatic sea-level fluctuations are produced by several mechanisms. One of the most relevant processes in the variation of the water volume in the ocean is related to continental ice-sheets expansion or decay (*glacioeustasy).* Another geologically significant process is the variations in the volume of the oceanic basins worldwide, triggered by tectonic forces such as the rate of spreading of the mid-oceanic ridges (*tectonoeustasy*). Minor processes that affect water volume in the oceans include: desiccation and inundation of marginal seas; thermal expansion and contraction of seawater; and variations in groundwater and lake storage. Eustatic changes produced by thermal expansion/contraction of seawater and desiccation/inundation of marginal seas occur at rates of 1 cm/a but with low amplitudes (5–10 m; Miller et al. 2011), and are hardly recognized in the ancient stratigraphic record. Thermal expansion coupled to glacier melting is responsible for milimetric sea-level rise measured during the last century caused by global warming (IPCC 2014). Eustatic changes produced by glaciation/deglaciation of the poles (i.e., glacioeustasy) occur in the order of 1–10 ka and the magnitude of sea-level oscillation is up to 200 m with higher rates of 2 cm/a (Miller et al. 2011). These time lapses are strongly related to the astronomically forced climate changes, referred as Milankovitch cycles. During the Pleistocene, when glaciation events are well constrained, several large eustatic sea-level variations were recorded. During this period, a large area of the Patagonian continental shelf experienced sub-aerial exposure due to a eustatic sea-level fall (see Chapter "Late Cenozoic Landforms and Landscape Evolution of Península Valdés"). Variations in the volume of the oceanic basins are long-term and slow processes which are in the order of 1–100 Ma and the magnitude of the sea-level variation for such processes is in the order of several tens of meters, up to 200 m. This process cause large-scale stratigraphic features such as thick marine sediment accumulation (sea-level rise) or large erosion surfaces (sea-level fall). The sedimentation of the early Miocene Gaiman Formation, that is part of the continental-scale Patagoniense Transgression (see Chapter "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity"), can be explained by means of this long-term eustatic mechanisms (Fig. 3).

Regarding relative sea-level change, modern geology recognizes the influence of tectonic processes in uplifting and subsiding continental areas. It is easy to understand that the presence of marine fossils at the top of the Southern Andes (2000–3000 m a.s.l.) was produced by strong tectonic forces that moved those marine rocks upward (Fig. 1b). However, in continental margins close to sea-level the distinction between eustatic versus tectonic controls on sea-level is not straightforward. Subtle tectonic subsidence in these areas will produce a marine flood, and then the record of the flood itself is not a "proof" of a eustatic variation, but a relative sea-level change. As an example, Pleistocene marine terraces lying above the present day sea-level coast of the Península Valdés region are linked to tectonic uplift and not to a eustatic sea-level change (see Chapter "Late Cenozoic Landforms and Landscape Evolution of Península Valdés").

2.4 Volcanism

Volcanic activity has an effect of great magnitude on the stratigraphic record (Fig. 4). The type of the volcanic edifices—composite volcano or calderas—is superimposed over the tectonic relief (topography) and tectonic subsidence (overload or volcanic subsidence). On the other hand, the influence of volcanic activity on *Sedimentary basin*s is substantial due to the volume and rate of supply which is generally orders of magnitude larger than nonvolcanic sedimentary systems (Fisher and Smith 1991; Manville et al. 2009). For instance, the average present day discharge of the Brahmaputra River is ~0.67 km^3/a (Goodbred and Kuehl 2000), whereas the 1991 eruption of Mount Pinatubo or the 2008 eruption of the Chaitén volcano, delivered around 5–8 km^3 in less than 6 months (cf. Scott et al. 1996a, b; Lara 2009) modifying completely the *sedimentary environment* (Hayes et al. 2002; Umazano et al. 2014). Volcanic products have a strong aggradational tendency (Smith 1987; Smith and Lowe 1991; Haughton 1993), either as topographic positive features or by filling preexisting depressions. During volcanic eruptions, the depositional landscape may be modified in only a matter of hours or days *in proximal areas* (e.g., Cas and Wright 1987; Thouret 1999; Davidson and De Silva 2000; Németh and Ulrike 2007). Depending on the type and magnitude of the volcanic eruption, the material delivered to the *Sedimentary basin*s may affect the stratigraphic record up to hundreds of kilometers from the volcanic centers (Cuitiño and Scasso 2013; Fig. 4).

The Península Valdés is located in a distal position with respect to the volcanic centers of the Andean Southern Volcanic Zone (SVZ) or the volcanic centers associated with the evolution of the basaltic retroact plateau (Fig. 1). However, the volcanic influence on the geological record is important and evidence of its direct and indirect impact on the stratigraphic units of the area (Figs. 3 and 4). During the late Oligocene-early Miocene the large back-arc mafic volcanic field of Somuncurá took place (Kay et al. 2007). The volcanic activity was mainly related to alkali and tholeitic lava flows with, to a lesser extent, the development of monogenetic eruptive cones. By its low value in the *Volcanic Explosivity Index*, this type of volcanic activity did not have a direct influence on the surrounding *sedimentary environment*s. However, the basaltic volcanic activity caused a delayed effect in the source regions and catchment areas of the fluvial systems, controlling the provenance of the sediments of the Puerto Madryn Formation and the Rodados Patagónicos deposits (see Chapters "Geology of Península Valdés", "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity" and "Late Cenozoic Landforms and Landscape Evolution of Península Valdés"). During the Miocene, an important period of silicic magmatic activity was recorded in the North Patagonian Andes, evidenced by exhumed plutonic stocks in the Main Cordillera and the occurrence of widespread ignimbrite units in retroarc regions (Pankhurst and Rapela 1998; Mazzoni and Benvenuto 1990; Fig. 3). A huge volume of silicic volcaniclastic materials was delivered to the *Sedimentary basin*s. It not only affected the sedimentary record in the retroarc foreland basins (Franzese et al. 2011; Orts et al. 2012), but also affect the provenance of the geological record up to the continental shelf sedimentary system. This is the case of the de deposits of the Miocene Gaiman Formation of the Península Valdés region (see Chapter "Miocene Marine Transgressions: Paleoenvironments and Paleobiodiversity"), which even though were deposited at ~600 km from the magmatic arc (Fig. 1), they show an extremely important influence of pyroclastic material associated with the Miocene silicic arc volcanism.

3 Perspectives and Future Work

The interplay between climate, tectonic, sea-level, and volcanic processes, set the sedimentary routing system that had governed the final geologic records of the Península Valdés region (Fig. 4). Whereas climate and volcanic processes predominantly control the sedimentary supply to the sedimentary environments of Península Valdés, tectonics, and eustasy mainly control the available space for the accumulation of sediments. This stratigraphic record was not only influenced by local controls. Processes developed far away from Península Valdés in the North Patagonian Andes or in the continental shelf had also influenced (Figs. 3 and 4). Despite the significant volume of previous work, including the detail list of this volume, studies related to the late Cenozoic sedimentary routing system of Península Valdés are still in their infancy. One of the key problems in this region are the uncertainties associated with the ages of the stratigraphic record. New geochronological calibrations in the Península Valdés region are necessary. Further studies would probably tackle some of the standing questions dealing with the interplay between subsidence and eustasy of the Puerto Madryn and Gaiman formations; the interrelation between eustasy and uplift during the deposition of Quaternary shorelines; or the influence of climate and tectonics in the deposition of the Rodados Patagónicos. Understanding the interrelation and effect of climate, tectonics, esutasy, and volcanism in the stratigraphic record of Península Valdés are far from being clear and will offer significant potential for further work that has global implications.

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Glossary

Drifting	This term refers to the passage from the rift to passive continental margin as a result of rapidly attenuated lithosphere and the creation of a proto-oceanic trough
Eccentricity (orbital)	Parameter that determines the shape (and variations) of the ellipsoidal orbit of the Earth around the Sun. The shape of the Earth's orbit has a variation period of about 100,000 years
Equilibrium profile	Is a theoretical surface relative to a local base-level or sea-level that control erosion or deposition of the fluvial/alluvial system. In response to a landscape change the fluvial/alluvial system would react to reestablish equilibrium conditions

Greenhouse-world	Long-term climatic stage of the Earth characterized by global warm temperatures and lack of continental glaciers in the poles, caused by the accumulation of certain gases in the atmosphere
Ice-world	Long-term climatic stage of the Earth's characterized by global cold temperatures and continental ice-sheets in the poles. Glacial-interglacial periods occur during this stage
Obliquity	Is the inclination of the Earth's axis in relation to its plane of orbit around the Sun. Oscillations in the degree of Earth's axial tilt occur on a periodicity of 41,000 years
Orogenic wedge	Part of the foreland basin system with wedge-shape originated by contractional tectonics, including the orogenic belt with the wedge top basins (piggy back and thrust top basins)
Precession (axial)	Is the trend in the direction of the Earth's axis of rotation. It has a period of 23,000 years
Proximal areas	In the sedimentary routing system concept, it is the region where the sediments are created or the depositional zone close to these sources (e.g., mountain ranges, volcanoes, or hillslopes)
Proxy	Environmental parameters of the past that are preserved in the stratigraphic record and can be measured for reconstructing conditions that prevailed during the Earth's history (e.g., oxygen isotopes)
Retroarc foreland basins	A *Sedimentary basin* developed on continental crust along the length of compressional destructive margin (i.e., Andean-type orogen) behind the arc, in which subsidence is caused flexure-induced by thrust loading
Rifting	The process by which the continental lithosphere stretches by extension. It is produced by a system of normal faults
Sedimentary basin	Regions of the earth in which the place to the preservation of sediments occurs as a result of long-term subsidence, creating accommodation space for the infill
Sedimentary environment	A place where sediment is deposited and the physical, chemical, and biological conditions that exist there. Examples: lakes, rivers, marine shelves, deltas

Sedimentary flux	The rate of sediment supply to any depositional basin, governed by the complex interaction of several parameters, such as: bedrock-type, uplift, weathering, climate, erosion, and transportation through drainage systems
Slab window	It is a gap in the subducted oceanic plate through which asthenospheric mantle can flow directly in contact with the overriding plate. It is formed when an oceanic spreading ridge reaches a subduction trench and is subsequently subducted
Volcanic explosivity index (VEI)	A relative measure of the explosiveness of volcanic eruptions, determined by the total volume of volcanic products, the eruption cloud height, and qualitative observations. The scale is open-ended from 0 (nonexplosive eruptions) to 8 (largest volcanoes in history given).

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