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Geology of the Golfo San Jorge Basin, Argentina

Geología de la Cuenca del Golfo San Jorge, Argentina

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ABSTRACT

The Golfo San Jorge basin is located in central Patagonia, between latitude 44º and 47ºS, covering a surface of approximately 170,000 km^2. Regarding hydrocarbon production the basin presents the highest cumulative value in Argentina, ranking in a second position after the Neuquén Basin. This intracratonic basin is predominantly extensional, trending roughly in an east-west direction, from the Andean belt to the Atlantic Ocean.

The economic basement of the basin consists of a sedimentary-volcanic complex associated to a rift process of Middle to Upper Jurassic age. These deposits cover almost the entire Patagonia. Subsequently, the Neocomian sedimentary cycle took place under late rift conditions, synsedimentary filling grabens and half grabens, mostly continental but with some marine Pacific transgressions. After a regional tilt of the main axis of the basin, the Chubutian sedimentary cycle starts. The Pozo D-129 Formation (Barremian-Aptian) of mainly lacustrine origin, with moderate organic content, is the most important source rock of the basin. Overlying it, a group of fluvial-shallow lacustrine units deposited under late sag conditions. These units contain the reservoirs that host the hydrocarbon accumulations of the basin. During the Tertiary the basin shows an alternation of marine

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and continental deposits. The main phase of compression uplifts the N-S trending San Bernardo foldbelt by reactivating previous normal faults. The Quaternary deposits, very widespread in the whole Patagonia, represent drastic climatic changes, such as glaciations, and the consequent sea level fall.

Volcanic activity throughout the history of the basin is expressed in the high tuffaceous content of the entire column, affecting the quality of the reservoirs.

Hydrocarbon generation and expulsion is thought to have begun at 50-80 Ma. After migrating through a network of faults and pathways, the oil is trapped in both extensional and compressional structures.

Keywords: Golfo San Jorge, Cretaceous, Argentina, hydrocarbon.

RESUMEN

La cuenca del Golfo San Jorge está ubicada en la Patagonia central, entre las latitudes 44° y 47°S, cubriendo una superficie de aproximadamente 170.000 km^2. Es la más prolífica productora de petróleo de la Argentina, ubicándose sus reservas en segundo lugar tras de la Cuenca Neuquina. De tipo intracratónica, predominantemente extensional, tiene una orientación general E-W, desde la Cordillera de los Andes al Océano Atlántico; su basamento económico está compuesto por un complejo volcánico-sedimentario, asociado a un proceso de rift de edad Jurásico Medio a Superior. Posteriormente, comienza el ciclo sedimentario Neocomiano, bajo condiciones de rift tardío, cuyos depósitos se encuentran rellenando sintectónicamente los grábenes y hemigrábenes con sedimentos lacustres y esporádicas transgresiones marinas del Pacífico. Luego de un basculamiento regional del eje principal de la cuenca hacia el Este, comienza el ciclo sedimentario Chubutiano. La Formación Pozo D-129 (Barremiano-Aptiano), de origen principalmente lacustre, es la roca madre más importante de la cuenca. Sobreyaciendo a esta unidad, un conjunto de sedimentos fluviales y lacustres someros se depositan en condiciones de subsidencia termal generalizada. Estos depósitos contienen los reservorios con las mayores acumulaciones de hidrocarburos de la cuenca. Durante el Terciario se alternan depósitos marinos y continentales. La fase compresional principal levanta la Faja Plegada de San Bernardo, de sentido N-S, por inversión tectónica de estructuras distensivas preexistentes. Los depósitos glaciales del Cuaternario, representan un drástico cambio climático.

La actividad volcánica a lo largo de la historia de la cuenca se refleja en la alta participación de material tobáceo en la columna sedimentaria, afectando la calidad de los reservorios.

La generación y posterior expulsión del petróleo comienza hace 80-50 Ma. La migración se ve favorecida por la presencia de fallas, que originan una red de migración a través de la cual los hidrocarburos alcanzan los niveles reservorio, para alojarse finalmente en trampas estructurales, estratigráficas y combinadas.

Palabras clave: Golfo San Jorge, Cretácico, Argentina, hidrocarburos.

INTRODUCTION

The Golfo San Jorge basin is located in central Patagonia, southern Argentina, between 44 and 47° of south latitude and between 66 and 71° of west longitude (Fig. 1). It covers a surface of approximately 170,000 km^2, being a third of it on the offshore sector. Politically, it lies on both the Santa Cruz and Chubut provinces and toward the east, on the continental shelf. The basin shows a clear elongated shape in the E-W direction.

The Golfo San Jorge basin is the most prolific basin in Argentina. It has produced about 487.3 x 10^6 m^3 (3064.6 x 10^6 barrels) of oil and 72.9 x 10^9 m^3 (2.6 tcf) of gas. Regarding remaining reserves, it ranks in the second place after the Neuquén basin, with about 149.9 x 10^6 m^3 (942.7 x 10^6 barrels) of oil, and 17.1 x 10^9 m^3 (0.6 tcf) of gas (Turic, 1999). Oil in the basin was discovered in 1907, close to the, at that time incipient, Comodoro Rivadavia city. Up to the present, more than 26,000 wells have been drilled throughout the basin.

The basin boundaries are the Norpatagónico or Somuncurá Massif to the north, the Deseado Massif to the south, the Cordillera de Los Andes to the west and the continental margin of the Atlantic Ocean to the east (Fig. 1). Although the main features show a general E-W alignment as a result of a dominantly extensional tectonics, the San Bernardo foldbelt runs in the north-south direction, dividing the basin into two sectors, the east and the west ones. At its turn, the east sector is divided into the northern flank, the southern flank and the basin center (Fig. 1). The offshore portion is considered to be a prolongation of the east sector (Baldi and Nevistic, 1996).

The economic basement of the basin is the so-called Volcanic-Sedimentary Complex (*Complejo Volcánico Sedimentario Jurásico superior*; Clavijo, 1986), of Middle to Upper Jurassic age. This is the most extent but not the only unit that underlies the sedimentary column. Depending upon the relative position into the basin there also are Precambrian to early Mesozoic igneous rocks as well as late Paleozoic to Mesozoic sedimentary units. The sedimentary column is, at the basin center, thicker than 8,000 m, and is, in general, dominated by continental Mesozoic and Tertiary sediments.

REGIONAL SETTING AND EVOLUTION

Geotectonically, the basin is located on the southern end of the South American Plate, which moving westward collides against the Nazca and the Antarctic Plates (Fig. 2).

Upon the basis of Carboniferous and Permian fossils occurrence in several Patagonian localities, a paleogeographic link with the Malvinas Islands at Godwana times has been postulated (Suero, 1962; Lesta *et al*., 1980). Moreover, most authors agree concerning the participation of Patagonia in the Godwana Supercontinent (i.e., Fitzgerald *et al*., 1990; Peroni *et al*., 1995). On the other hand, Ramos (1984, 1996), based upon structural and magmatic evidences proposes that Patagonia, and perhaps the Antarctic Peninsula and other minor fragments, may have been accreted to Gondwana along a northward-dipping subduction zone during Middle to Late Permian.

The first sedimentation event recorded in the region is probably related to NNW-SSE oriented depocenters originated during the Carboniferous-Permian times (Ugarte, 1966; Lesta *et al*, 1980), likely associated to the evolution of the Pacific margin (Forsythe, 1982). Urien *et al*. (1995) interpret this as a period of transtensive conditions which would have lasted until the Permian-Triassic, favoring the intrusion of granitic bodies into the Somuncurá and Deseado Massifs, and the generation of the small El Tranquilo basin south of the Golfo San Jorge basin.

During the Lias a marine basin of NNW-SSE alignment developed towards the Pacific. Some continental deposits of the same age are also reported at marginal positions. Subsequently, the Dogger records a period of generalized extensional processes on the whole Patagonia, being the depocenters, of a general half graben shape, filled with volcanoclastics, lacustrian and marine sediments, representing a stage of rifting tectonism. These half grabens, of varying orientation (but predominantly NW-SE in the west sector), are the depositional setting of the Neocomian deposits, which are characterized by a synchronous tectosedimentary timing, and represent the late-rift stage. In the San Bernardo sector major extensional faults of N-S alignment developed also during this period. These faults, are those which during the Tertiary would be affected by inversion tectonics building up the present Foldbelt. The east sector of the basin developed extensional faults in the E-W direction. This major normal faulting ceased by the time oceanic crust began to form the South Atlantic Ocean, about 120-130 Ma (Fitzgerald *et al*., 1990).

The Initial Patagonídica tectonic phase, is interpreted to be the responsible for the subsequent erosion event that affects the entire basin, which was likely caused by an acceleration of the Nazca Plate (Barcat *et al*., 1989; Chelotti, 1997). This event created both the space and the available sedimentary influx to start a new sedimentary cycle, known as the Chubutiano (formally Chubut Group; Lesta, 1968). This sedimentary cycle deposited on an angular unconformity, with its depocenter located to the east with respect to the former cycle's main depocenters (Figari *et al*., 1999). The prevailing orientation of this new sedimentary cycle is markedly E-W. According to Fitzgerald *et al*. (1990) this cycle represents the sag phase of the basin. On the other hand, Figari *et al*. (1999) interpret this cycle as the result of transtensional-extensional stresses different from the previous one, being developed from the latest Lower Cretaceous through the Paleogene, in back arc conditions.

During the Maastrichtian, the plate geometry of the Atlantic changed drastically (Chelotti, 1997). This took place in coincidence with an acceleration in the subsidence rate of the basin (Nocioni, 1993), in association with the transgression represented by the Salamanca Formation (Paleocene), and with it, the initiation of a new sedimentary cycle of Tertiary age. During the Middle Miocene, these extensional conditions changed, being the uplift of the N-S trending San Bernardo

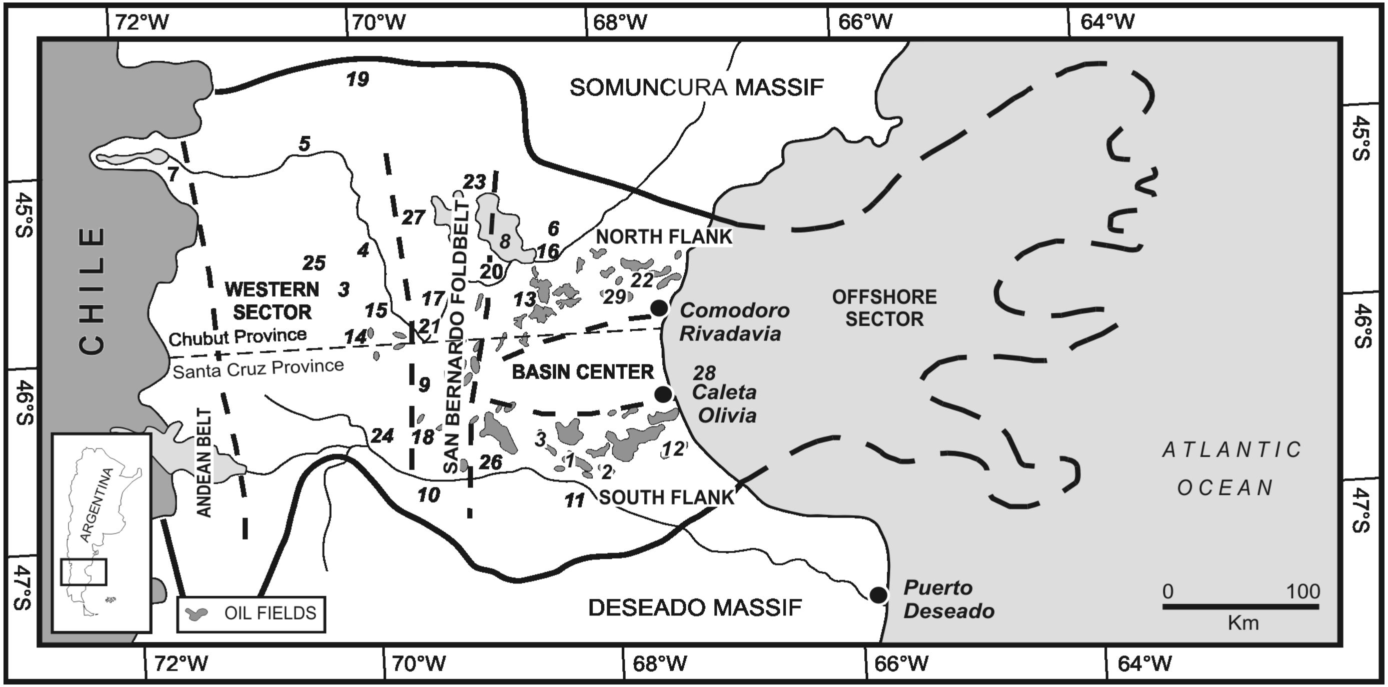


FIG. 1. Golfo San Jorge Basin. Location map. Sites referred in the text: **1**- O-110 well, **2**- O-120 well, **3**- EH.xp.307 well, **4**- Ca.es-1 well, **5**- CPB.es-1 well, **6**- LA-1, LA.x-2 & PO.x-2 wells, **7**- Lago Fontana, **8**- Lago Colhué Huapi, **9**- AAB.x-1 well, **10**- SRD.es-1 well, **11**- LE.x-1 well, **12**- Cañadón León oil field, **13**- Cerro Dragón oil field, **14**- MMO.xp-7 well, **15**- CRM.x-1 well, **16**- RChN.x-1 well, **17**- AdP.es-1 well, **18**- CGu.es-1 well, **19**- Cerro Guadal-Ferrarotti sector, **20**- EZ.x-1 well, **21**- CDS.x-1 well & outcrop Codo del Senguerr, **22**- D-129 well, **23**- Cerro Chenque site, **24**- CEP.es-1 well, **25**- UO.Simms-1 well, **26**- Cerro Ballena, **27**- Cerro Colorado de Galveniz, **28**- Albatros well, **29**- El Tordillo oil field.

FIG. 1. Ubicación geográfica de la Cuenca del Golfo San Jorge, con las localidades citadas en el texto: **1**- Pozo O-110 , **2**- Pozo O-120, **3**- Pozo EH.xp.307, **4**- Pozo Ca.es-1, **5**- Pozo CPB.es-1, **6**- Pozos LA-1, LA.x-2 & PO.x-2, **7**- Lago Fontana, **8**- Lago Colhué Huapi, **9**- Pozo AAB.x-1, **10**- Pozo SRD.es-1, **11**- Pozo LE.x-1, **12**- Yacimiento Cañadón León, **13**- Yacimiento Cerro Dragón, **14**- Pozo MMO.xp-7, **15**- Pozo CRM.x-1, **16**- Pozo RChN.x-1, **17**- Pozo AdP.es-1, **18**- Pozo CGu.es-1, **19**- Sector Cerro Guadal-Ferrarotti, **20**- Pozo EZ.x-1, **21**- Pozo CDS.x-1 & afloramiento Codo del Senguerr, **22**- Pozo D-129, **23**- Cerro Chenque, **24**- Pozo CEP.es-1, **25**- Pozo UO.Simms-1, **26**- Cerro Ballena, **27**- Cerro Colorado de Galveniz, **28**- Pozo Albatros, **29**- Yacimiento El Tordillo.

foldbelt a result of transpressive and inversion tectonics (Chelotti, 1997) related to the development of the Andean Cordillera. Peroni *et al*. (1995) interpret this belt as not formed by a unidirectional deformation wave but the result of deformation by regional collapse ("accordion" mode).

STRATIGRAPHY

Rapidly after the discovery of oil in the northern flank of the basin, in 1907, the geological studies of the basin were encouraged by the Argentinian State. Description and correlation of the stratigraphic units started from surface outcrops as well as from well data. Later on, exploration in the other portions of the basin (i.e. southern flank, western sector) resulted in the description of “new” stratigraphic units, and most of them, after review, were correlated with the previous ones. This resulted in a stratigraphic nomenclature which is not homogeneous for the entire basin, though, some of the major units are recognized under the same name in the whole basin. The stratigraphic column shown in figure 3, is a synthesis of the nomenclature of the basin, according to the geographic sector of occurrence.

This paper will follow the stratigraphic subdivision used by Figari *et al*. (1999) based on the concept of megasequences (Hubbard, 1988). This subdivision is useful because, on the one hand, the megasequences represent evolutionary phases of the basin bounded by regional unconformities, and on the other hand, they can be divided into sequences that agree fairly well with the formal stratigraphic units. Then the formal stratigraphic units will be followed and described as a guideline herein.

Thus, according to Figari *et al*. (1999) the following nomenclature will be used: Economic Basement (Megasequence 0), represents the Mesozoic rift stage and its record of Complejo Volcánico Sedimentario Jurásico superior . The Neocomian cycle (Megasequence I) is a stage of mature half graben, associated to a typical starved basin (Pozo Anticlinal Aguada Bandera Formation; Brown *et al*., 1982) first, followed subsequently by a maximum flooding, influenced by the Pacific sea (Pozo Cerro Guadal Formation; Barcat *et al*., 1989; Figari *et al*., 1999). According to Fitzgerald *et al*. (1990) this represents the late rift stage of the basin. The Chubutian cycle (Megasequence II), overlaying a regional angular unconformity, represents an eastward tilt of the main axis of the basin. This change is observed in the thickness of Pozo D-129 Formation and partially in the Castillo Formation; for the overlying units, the volume they occupy is likely to be generated by thermal subsidence. Then, the Tertiary cycle (Megasequence III), represents a period of extensive events (with the exception of the San Bernardo uplift), which along with eustatic oscillations caused a series of Atlantic transgressions and regressions. And finally, the Quaternary cycle (Megasequence IV) that represents a post-tectonic period whose depositional mechanisms were driven by drastic climate changes and sea level fall associated to the Pleistocene glaciations.

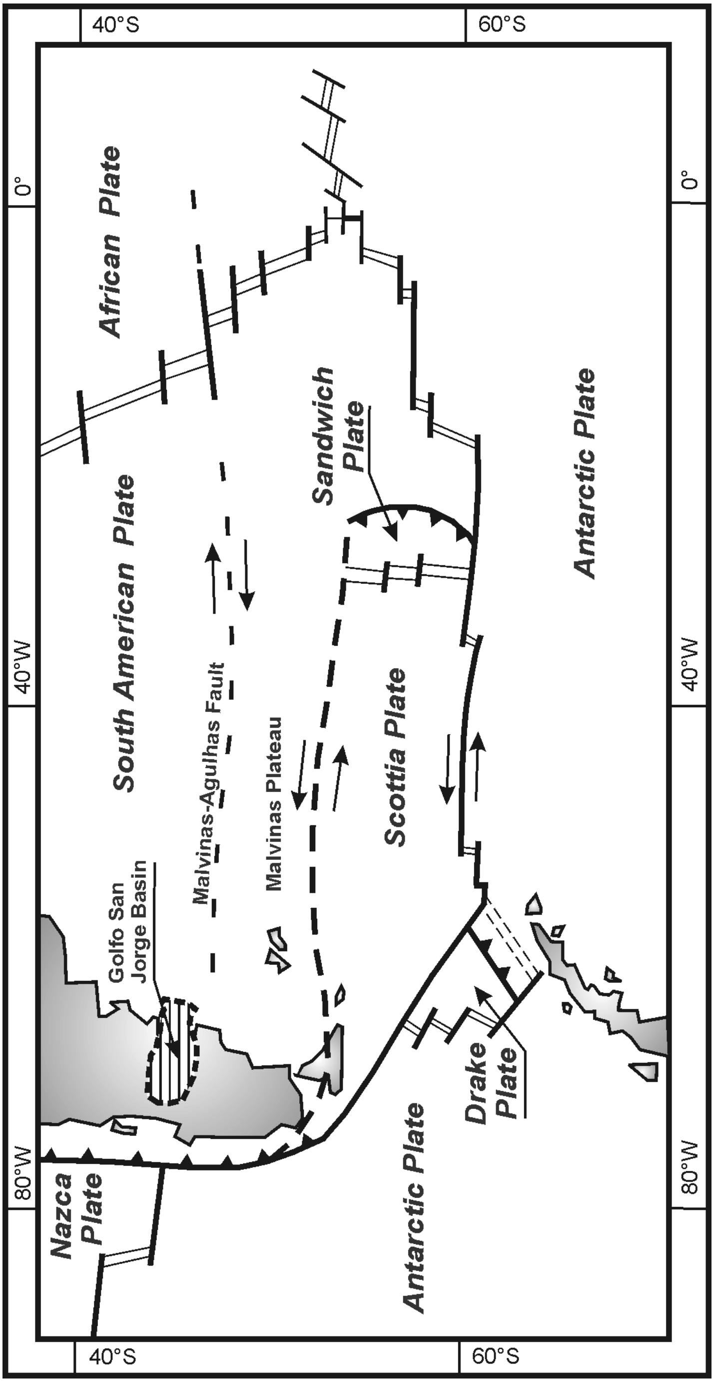


FIG. 2. Present macrogeotectonic map of the region. Redrawn after Biddle *et al.*, 1996.
FIG. 2. Mapa macrogeotectónico de la región. Modificado de Biddle *et al.*, 1996.

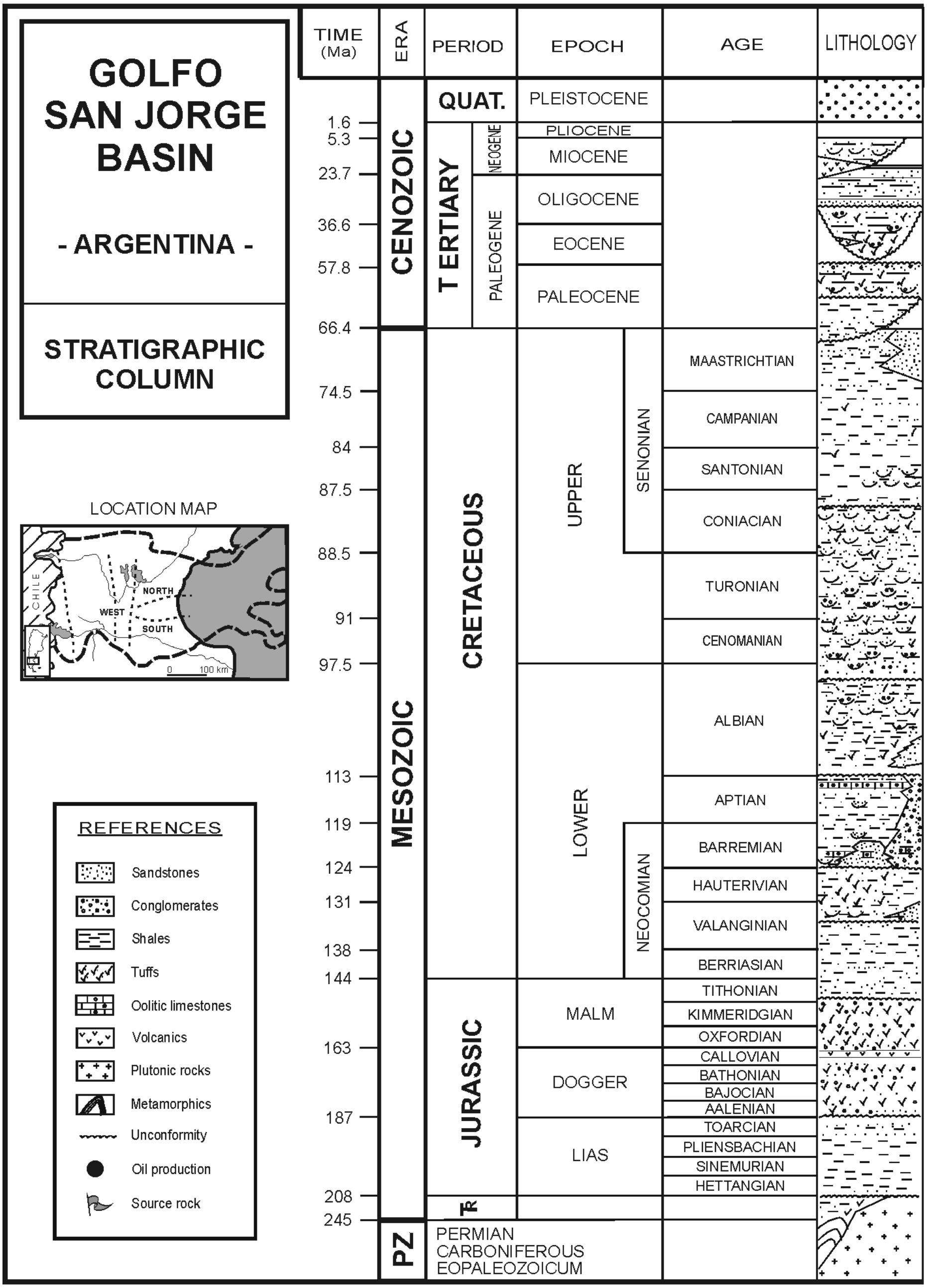


FIG. 3. Stratigraphic column of the Golfo San Jorge basin. Megasequences according to Figari *et al*. (1999), events, taken from Fitzgerald *et al*. (1990), time scale (from "Decade of North American Geology, 1983") in Linares and González (1990).

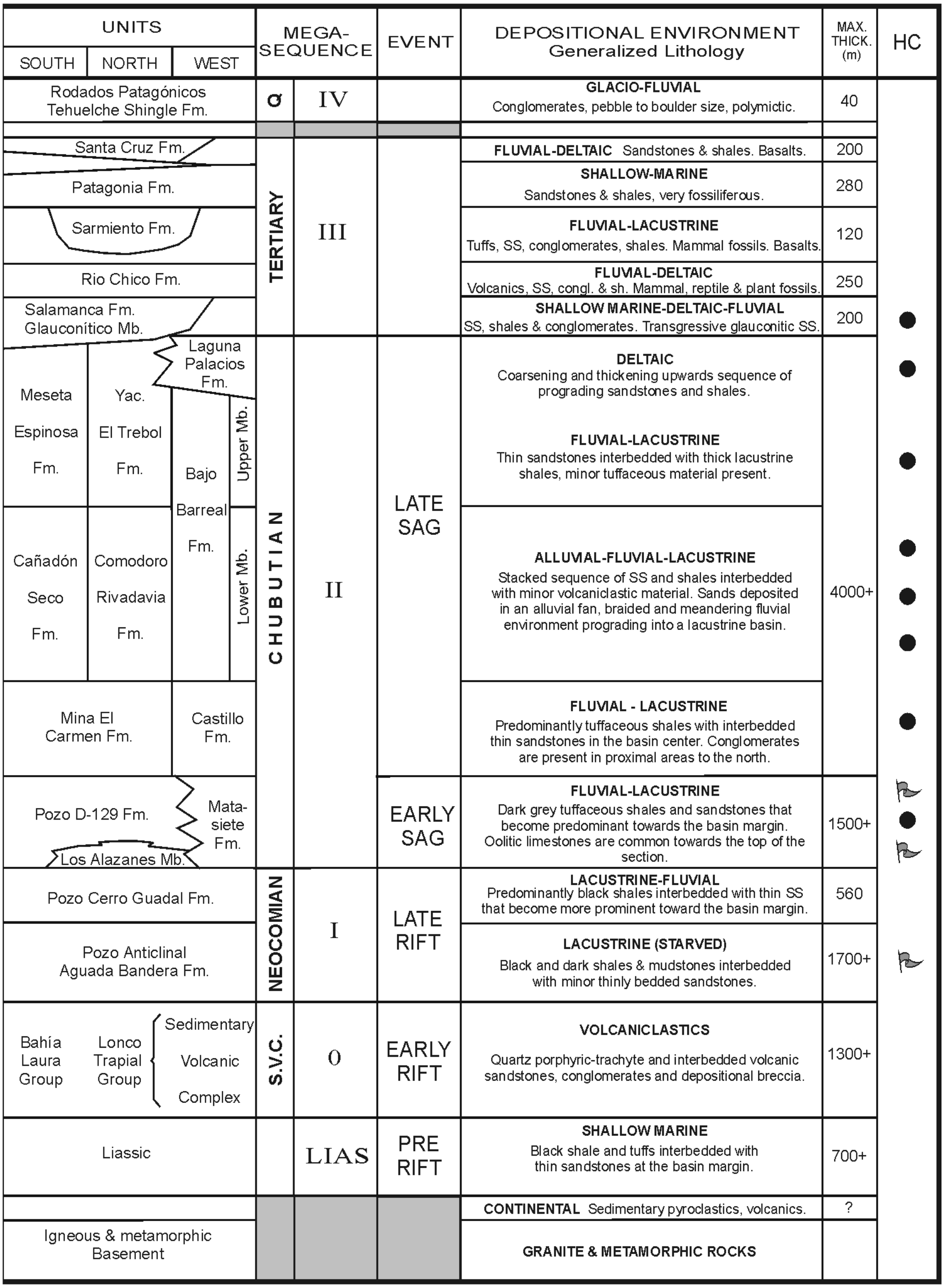


FIG. 3. Columna estratigráfica de la Cuenca del Golfo San Jorge. Megasecuencias de acuerdo a Figari *et al.* (1999), eventos según Fitzgerald *et al.* (1990), escala temporal (de "Decade of North American Geology, 1983") en Linares y González (1990).

Pre-Cretaceous Basement

The Golfo San Jorge is an intracratonic basin placed in between two structural highs, namely the Somuncurá Massif (also known as Norpatagónico Massif) to the north and the Deseado Massif to the south. These positive elements represent the pre-Cretaceous basement of the basin. Lithologically, they consist of a series of distinct rocks that include metamorphics and intrusives (Lower Paleozoic-Precambrian), granites and schists (Devonian), sedimentary units (Carboniferous to Permian), igneous rocks (Permo-Triassic), pelites, psamites and pyroclastics (Triassic), sedimentary and volcanoclastics, marine and its continental equivalents (Lias), and the Volcanic-Sedimentary Complex (Middle to Late Jurassic). Many authors have carried out comprehensive investigations on these pre-Cretaceous units with a detailed degree. Lesta and Ferello (1972), De Giusto *et al*. (1980), Lesta *et al*. (1980), Mazzoni *et al*. (1981), Gabaldón and Lizuain (1982), González (1984), Clavijo (1986), among others, have published the most complete ones. Despite of the diversity of lithologies and ages that compose the Pre-Cretaceous basement, it is worth to describe and analyze more carefully the Volcanic-Sedimentary Complex, since it is intimately related to the overlying Cretaceous sediments, and thus considered to be the "economic basement" of the basin.

Economic Basement

The Complejo Volcánico Sedimentario Jurásico Superior (usually cited as Complejo Volcánico Sedimentario or simply CVS) is a unit proposed by Clavijo (1986). This, consists mainly of Middle to Late Jurassic volcanics, volcanoclastics and in a lesser degree sedimentary rocks. Regionally, this complex is interbedded with marine sediments to the west, while it interfingers with continental deposits to the east (Scasso, 1989).

This complex includes a number of stratigraphic units that have been studied in different places of the basin, i.e. Lago La Plata Formation (western sector; Ramos, 1976), Lonco Trapial Group (northern flank; Lesta and Ferello, 1972), Bahía Laura Group (southern flank; Feruglio, 1949), which at its turn, this Group is divided, by Stipanicic (1957), into Chon Aike and La Matilde formations.

Lesta *et al*. (1980) describe these volcanoclastic sedimentary deposits and their distribution in detail. They are present all over the Patagonia, from latitude 42 to 55°S, with the exception of some "windows" where the Cretaceous sediments overlay older units, probably old topographic highs. This lack or absence is observed in the wells O-110 (El Valle; #1 in Fig. 1), O-120 (El Destino; #2 in Fig. 1) and EH.xp-307 (El Huemul; #3 in Fig. 1) where igneous and/or methamorphics underlie the sedimentary Cretaceous column (Lesta *et al*., 1980), in the wells Ca.es-1 (Cayelli; #4 in Fig. 1) where the Lias is overlain by the Neocomian deposits, and in the CPB.es-1 (Cañadón Pastos Blancos; #5 in Fig.1) where the Neocomian Paso Río Mayo Formation overlies Paleozoic deposits (Clavijo, 1986). In the northern flank, at the Los Alazanes wells (#6 in Fig. 1), the Pozo D-129 Formation lies unconformably over a Permian granite (LA.x-2 well, 263±10 Ma; Linares and González, 1990).

Lithologically, the Chon Aike Formation and its equivalent units in the northern flank consist mainly of tuffs, rhyolites, ignimbrites and porphyric aglomerates, all derived from acid magmas, whereas the La Matilde Formation consists of sedimentary layers, conglomerates, tuffs and sandstones, with abundant continental fossils, interbedding or overlaying the Chon Aike Formation. The Lonco Trapial Group, to the north, presents lithologies of a mesosilicic to basic composition (frequently basalts; Lesta *et al*., 1980). Clavijo (1986), recognizes this compositional change in the volcanics and volcanoclastics, which is apparently more acid and explosive to the south and to east than in the west and north.

Regarding the age of this unit, there are both paleontologic and radiometric data that support a Middle to Upper Jurassic age, e.g. Stipanicic and Bonetti (1970) found Callovian flora in the La Matilde Formation, whereas Spalletti *et al*. (1982) obtained Bathonian-Kimmeridgian K-Ar ages for the Bahía Laura Group at Bajo San Julián site.

The Complejo Volcánico Sedimentario Jurásico Superior is similar in age and composition to the Tobífera Series in the Austral or Magallanes Basin (Fitzgerald *et al*., 1990). In addition, Scasso (1989) suggests that these two basins should have been interconnected through the west, where the Chilian territory is located today.

Neocomian cycle

The Neocomian is represented by the sediments that fill the grabens and half grabens which started developing during the previous megasequence. Figari *et al*. (1999) interpret this as a mature half graben stage under starving basin conditions, whereas Fitzgerald *et al*. (1990) understand this to be a late rift stage. A typical characteristic of these deposits is that they fill syntectonically the frequent grabens and half grabens. These deposits show a maximum thickness towards the west of the basin, whereas they are thinner and more scattered represented to the east. It should be mentioned that there are few wells that penetrate these deposits, and despite the outcrops on the western sector, much of the information comes from seismic interpretations.

The Neocomian series is represented by two formal stratigraphic units, namely: Pozo Anticlinal Aguada Bandera Formation (Lesta *et al*., 1980) and Pozo Cerro Guadal Formation (Ferello and Lesta, 1973). Originally, Lesta *et al*. (1980) included these formations together with the Pozo D-129 Formation into the Las Heras Group. Clavijo (1986), recognizes two different sedimentary cycles with distinct lithological characteristics which, at its turn, are separated by a regional erosional unconformity, therefore, he proposed the Pozo D-129 Formation be excluded from the Las Heras Group. This proposal has been accepted by most authors and it is agreed, in general, to include the Pozo D-129 Formation into the Chubut Group (i.e. Chelotti, 1997) or into the Chubutian (Figari *et al*., 1997; 1999; Hechem, 1998). The Neocomian is also represented in the basin under other formal nomenclature which is beyond the scope of this paper (i.e. Tres Lagunas, Katterfeld and Apeleg formations at Lago Fontana site, #7 in Fig. 1, Hechem *et al*., 1993; Pozo Paso Río Mayo Formation, at Río Mayo Sub-basin or western sector, Clavijo, 1986; "Pelitas Laminares" at the center of the basin, Ferello and Lesta, 1973; and "Sección Pelítica Basal", at the Lago Colhué Huapí sector, #8 in Fig. 1, Barcat *et al*., 1989).

Pozo Anticlinal Aguada Bandera Formation.

The oldest unit, Pozo Anticlinal Aguada Bandera Formation consists mainly of fine grey sandstones, with tuffaceous matrix, interbedded with laminated black shales, siltstones and dark mudstones at its base. The mid sections is richer in black shales and dark mudstones while towards its top the granulometry increases showing conglomeratic sands, conglomerates and mudstones (Barcat *et al*., 1989). Originally, this unit was described in its type section at YPF.SC.AAB.x-1 (Anticlinal Aguada Bandera) well (#9 in Fig. 1), where it is thicker than 1360 m, being its base not reached (Lesta *et al*., 1980). Fitzgerald *et al*. (1990) seismically mapped a sequence that they recognized to be equivalent to the Pozo Anticlinal Aguada Bandera Formation. They found its maximum development at the southwest sector of the basin, at the YPF.SC.SRD.es-1 ("Sur Río Deseado") well (#10 in Fig. 1), where its thickness is calculated to be around 5000 m, whereas at other portions of the basin it ranges between 600 and 1200 m, approximately.

This unit is deposited in half grabens, in which the shales are interfingered with fine agradational sands whose provenance is related to the unfaulted margin (hinged margin) of the rift, and with coarser clastics constituting alluvial fans associated to the faulted margin (escarpment margin; Fig. 4). Figari *et al*. (1997) show a detailed model for half grabens located at the western sector of the basin where these grabens are larger and deeper than those occurring at other sectors of the basin, for example the southern flank, i.e. the BS.SC.LE.x-1 (La Emilia) well (Sylwan *et al*., 1998; #11 in Fig. 1 and Fig. 5), Cañadón León (Vela and Hechem, 1997; #12 in Fig. 1) as well as in the northern flank, at the Cerro Dragón oil field (#13 in Fig. 1).

Although the Pozo Anticlinal Aguada Bandera Formation is mainly of a lacustrine origin, to the west the lower Neocomian shows evidence of marine deposition. Laffitte and Villar (1982) reported the presence of an Upper Jurassic microfauna of foraminifera in the YPF.SC.AAB.es-1 ("Anticlinal Aguada Bandera") well, probably related to a marine transgression from the northwest. Vela and Hechem (1997) reported marine microplankton at the top of Pozo Anticlinal Aguada Bandera Formation in the YPF.Ch.MMO.xp-7 (Mata Magallanes Oeste) well (#14 in Fig. 1). Rodrigo Gainza *et al*. (1984) report the occurrence of "clearly marine levels" at YPF.Ch.CPB.x-1 (Cañadón Pastos Blancos) and YPF.CRM.x-1 (Confluencia Río Mayo) wells (#5 and #15 in Fig. 1).

In 1996, the RChN.x-1 (Río Chico Norte) well, in the northern flank of the basin (#16 in Fig. 1) provided the presence of an association of marine elements, belonging to an outer platform depositional environment (Seiler and Viña, 1997) with the following biota identified: *Gonyaulacysta* sp.cf.*G. jurassica*, *Microdinium* sp.*A*, *Pareodinia* cf. *ceratophora*, *Epistomina* sp.*A* and *Epistomina* sp.*B*., assigning to this association a Malm age (Kimmeridgian?). According to

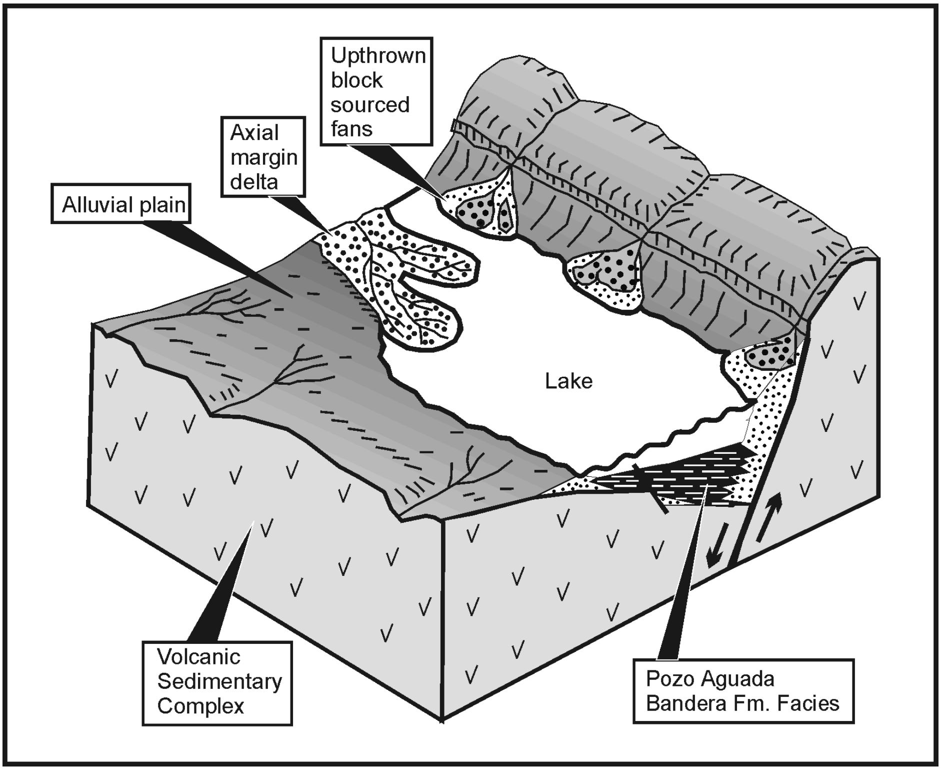


FIG. 4. Paleogeography and sedimentary model postulated for the Neocomian half grabens, showing the occurrence of source rock (Pozo Anticlinal Aguada Bandera facies) and the depositional setting of the potential reservoirs (fans and deltas). Drawing modified after Banks *et al*. (1995).
FIG. 4. Paleogeografía y modelo sedimentario postulado para los hemigrábenes neocomianos. Se observa el desarrollo de las facies de roca madre (Pozo Anticlinal Aguada Bandera facies) y la formación de los potenciales reservorios (abanicos y deltas). Dibujo modificado de Banks *et al*. (1995).

Seiler and Viña (1997), similar associations were also found in the YPF.SC.AAB.x-1 ("Anticlinal Aguada Bandera") well (#9 in Fig. 1) and in the YPF.Ch.AdP.es-1 ("Anticlinal de Papelía") well (#17 in Fig. 1) within the Pozo Anticlinal Aguada Bandera Formation. At the Río Chico Norte well, this biota was found in cuttings from the interval 2733-2827 m. This interval has been correlated with the YPF.Ch.PO.x-2 ("Pico Oneto") well (#6 in Fig. 1) by means of electric logs and seismics, concluding that it is equivalent to the "Sección Pelítica Basal", informal unit, which is commonly accepted to belong to the Neocomian s.l. (Fig. 6). This evidence of a marine record indicates, up to now, the easternmost recorded point reached by the Neocomian sea during the Upper Jurassic.

In the whole basin, the lower Neocomian, namely the Pozo Anticlinal Aguada Bandera Formation or its equivalents, have provided records of Late Jurassic biota, i.e. foraminifera (Laffitte and Villar, 1982), marine elements of Tithonian-Berriasian age in the Tres Lagunas Fm (in Barcat *et al*., 1989), as well as palynomorhs of Lower Cretaceous age (Archangelsky *et al*., 1984). On the basis of non marine ostracodes and charophytes Masiuk and Viña (in Barcat *et al*., 1989) give to this unit a lower Berriasian-lower Valanginian age. On the basis of the eustatic curve of Haq *et al*. (1987) Fitzgerald *et al*. (1990) locate this unit in the Berriasian-Valanginian interval

The Pozo Anticlinal Aguada Bandera Formation is a source rock whose oil generating capability has been proved in the western sector of the basin (Figari *et al*., 1999). Good geochemical characteristics, but in an inmature stage, were also found for this unit in the southern flank of the basin (Sylwan *et al*., 1998). Lacustrine shales showing good oleogenetic characteristics have been often found associated to levels with the incertae sedis *Celyphus rallus* in several sectors of the basin.

Pozo Cerro Guadal Formation

Overlying the Pozo Anticlinal Aguada Bandera Formation, is the Pozo Cerro Guadal Formation (Ferello and Lesta, 1973). The contact between both units is unconformable. This fact was first analyzed by Ferello and Lesta (1973) who on the basis of a dip-meter electric log suggested the presence of an angular unconformity. This unconformity is interpreted by Barcat el al. (1989) to represent the Intra-Valanginian diastrophic phase. Concerning the subsidence rate, it shows a decrease with respect to the rate that affected the deposition of the Pozo Anticlinal Aguada Bandera Formation.

The type section of this unit is described at the YPF.SC.CGu.es-1 (Cerro Guadal) well (#18 in Fig. 1), where the complete unit was drilled (560 m). There, the unit is lithologically characterized by quartz sandstones, hard and compact, with tuffaceous matrix, tuffaceous siltstones, light colored tuffs and silicified black shales.

The syntectonic depositional setting of the Pozo Anticlinal Aguada Bandera Formation (filling of grabens and half grabens) continues during the deposition of Pozo Cerro Guadal Formation. However, according to Barcat *et al*. (1989) and to Figari *et al*. (1999) this unit would represent a maximum flooding stage, with a Pacific marine influence. The geographic distribution of the Pozo Cerro Guadal Formation is linked to the occurrence of the NW trending grabens and half grabens, which present their maximum development to the west. Fitzgerald *et al*. (1990) published a thickness map of the unit, in which it can be observed a mean thickness of approximately 300 m, being its maximum about 1600 m, close to the YPF.SC.SRD.es-1 ("Sur Río Deseado") well (#10 in Fig. 1).

The Pozo Cerro Guadal Formation deposited in shallow lacustrine environments, or at least in waters shallower than those of the Pozo Anticlinal Aguada Bandera Formation. With respect to this, Peroni *et al*. (1995) suggest a secular change in the productivity and preservation regime. Thus, lower Neocomian deposits (Pozo Anticlinal Aguada Bandera Formation) present organic rich accumulations of deep anoxic waters of mildly brackish conditions and humid climates, while the upper Neocomian´s (Pozo Cerro Guadal Formation) organic facies are less prolific, representing shallower lakes containing brackish to saline (alkaline) waters promoted by semiarid climates (Peroni *et al*., 1995). Towards the north, at Ferraroti-Cerro Guadal area (# 19 in Fig. 1), Cortiñas and Arbe (1981) recognized lacustrine and fluvial paleoenvironments, with episodes of fluvio-deltaic progradations, and non marine ostracodes.

The biostratigraphic record of this unit is scarce, in part because few wells penetrate the interval, and in part because most samples are sterile. The age of the unit is controversial, as can be appreciated from the following datations:

- The western lying outcrops exhibit Valanginian-Hauterivian marine fauna (Barcat *et al*., 1989).
- Fitzgerald *et al*. (1990) based on the fact that the Pozo Cerro Guadal Formation underlies Hauterivian-Barremian sequences, interpret this unit to be of Valanginian age.
- Some biota have been identified at EZ.x-1 (El Zanjón) well (#20 in Fig. 1) as follows: palynomorphs (3019-3196 mbgl): *Coptospora striata*, *Cyclusphaera psilata*, *Cicatricosisporites australiensis*, also the calcareous fossils *Candona* sp.*1* and *Candona* sp.*2* (Seiler and Viña, 1996). This association has also been found at the YPF.SC.AAB.x-1 ("Anticlinal Aguada Bandera"), YPF.Ch.AdP.es-1 ("Anticlinal de Papelía") and YPF.Ch.CDS.x-1 ("Codo del Senguerr") wells (#9, #17 and #21 in Fig. 1), giving a Berriasian age to these deposits (Seiler and Viña, 1996).

The occurrence of the incertae sedis *Celliphus rallus* is also reported in the "Río Chico Norte" well, being this important from the oleogenetic point of view (Peroni, *et al*., 1995; Figari *et al*., 1999; Uliana *et al*., 1999).

Neocomian deposits are found to become thinner and of a marginal character towards the east (Fitzgerald *et al*., 1990; Figari *et al*., 1999). However, Brown *et al*. (1982) report the occurrence of oblique progradations (of onlap type) interpreted to be deltaic fans generated by braided fluvial systems at the easternmost onshore sector of the basin. Furthermore, Baldi and Nevestic (1996), dealing with the offshore sector of the basin, state that there is an important sedimentary column underlying the Pozo D-129 Formation, estimating the thickness of the Pozo Anticlinal Aguada Bandera Formation in approximately 800 m.

Chubutian cycle

This cycle is composed of four fomations, namely: Pozo D-129 (equivalent to Matasiete Formation in the western sector), "Mina El Carmen" (equivalent to Castillo Formation in the western sector), "Comodoro Rivadavia" (equivalent to Cañadón Seco Formation in the southern flank, and to lower Bajo Barreal Formation in the western sector) and "Yacimiento El Trébol" (equivalent to Meseta Espinosa Formation in the southern flank and to Upper Bajo Barreal Formation in the western sector; Fig. 3).

The Chubutian cycle represents the first stage of a sag basin evolution (Fitzgerald *et al*., 1990) coinciding with the tilt of the basin axis and the consequent movement of the main depocenter towards the east (Hechem *et al*., 1990; Figari *et al*., 1999).

The units of this cycle host the bulk of the hydrocarbons discovered in the basin up to now in the basin.

Pozo D-129 Formation

The Pozo D-129 Formation (Lesta, 1968) is the oldest unit of this cycle. As already mentioned, originally it was included in the Las Heras Group, but due to their stratigraphic relationship it is now accepted to be included in the Chubutian cycle. The base of the Pozo D-129 Formation is a major regional angular unconformity. Figari *et al*. (1999) interpret this unconformity as representing a tilt of the basin axis with an associated movement of its depocenter to the east. This interpretation is based on the rapid facial and thickness changes observed at the base of Pozo D-129 Formation (Gómez Omil *et al*., 1990 in Figari *et al*., 1999). The erosive character of the base of the Pozo D-129 Formation is clearly observed in the northern flank (Fig. 6) or in the western sector of the basin, where often the entire Pozo Cerro Guadal Fm. is eroded away (Clavijo, 1986). According to Fitzgerald *et al*. (1990) this unit is marking the first stage of the sag basin evolution.

The type section of this unit is located between 2305 and 3020 mbgl at the D-129 well in the Diadema oil field (#22 in Fig. 1), drilled in 1954. Lithologically, this unit is dominated by generally small sized clastics plus an important contribution of pyroclastic components, carbonate participating in small amounts, specially in the form of oolites. The depositional environment grades from deep lacustrine to fluvial. Consequently, depending on it the lithology varies widely. Deep lacustrine environments are represented by dark to black shales and mudstones, with certain fine pyroclastic content including pyrite. High organic content is found in these type of rocks, which are the most important source rock for hydrocarbon in the basin. Shallow water environments are represented by silt, silty and/or sandy tuffs, claystones, sandstones and limestones whose colors vary from grey to green. Limestones are in general oolitic or pisolitic, and rarely coquinoid. Most common cements are zeolites and calcites. Tuffaceous matrix occurs frequently. As the environment becomes subaerial sands, tuffaceous mudstones and conglomeratic sandstones are more common, often of brown-red colors, associated to fluvial and deltaic environments.

Towards the west, at about the San Bernardo hills, the Pozo D-129 Formation starts gradually changing its fine lacustrine facies into red sands and conglometrates of fluvial and lacustrian environment, which prograde south- and southeastwards (Barcat *et al*., 1989). This facies has been gathered under the name of Matasiete Formation (Ferello and Tealdi, 1950, in Lesta and Ferello, 1972).

The Pozo D-129 Formation is developed in the whole basin, with thickness that vary between more than 1.5 km in the center of the basin and a few hundred meters at marginal positions. During many years this unit was believed to be only of subsurficial occurrence until Hechem *et al*. (1987) recognized exposures of this unit northwest of Lago Colhué Huapi, at Cerro Chenque site (#23 in Fig. 1).

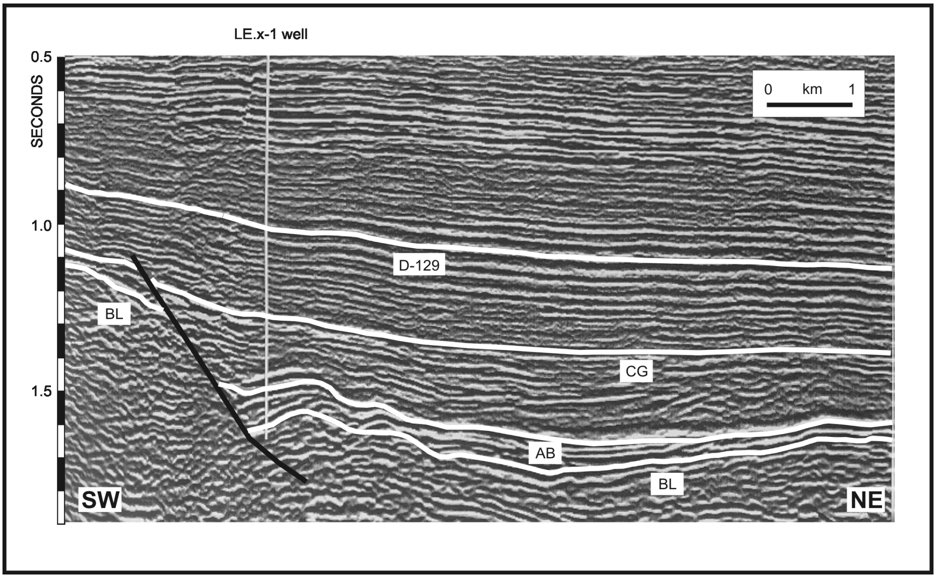


FIG. 5. Seismic line showing the half graben shape of a structure on the southern flank. SW (46°57'S, 68°20'W) NE (46°53', 68°15'W). D-129=Pozo D-129 Fm., CG=Pozo Cerro Guadal Fm., AB=Pozo Anticlinal Aguada Bandera Fm., BL=Bahía Laura Gr. (economic basement).
FIG. 5. Línea sísmica mostrando la estructura de un hemigraben en el flanco sur de la cuenca. SO (46°57'S, 68°20'W) NE (46°53'S, 68°15'W). D-129=Fm. Pozo D-129, CG=Fm. Pozo Cerro Guadal, AB=Fm. Pozo Anticlinal Aguada Bandera, BL=Gr. Bahía Laura (basamento económico).

These outcrops are interpreted as a gradual interbedding within the Matasiete Formation, representing a stage of lacustrine expansion.

A sandy rich section is often observed at the base of the Pozo D-129 Fm. This facies, probably related to the unconformity between this unit and the underlying Neocomian, has been described by Vela and Hechem (1997) mainly for the southern flank. This can also be observed in the northern flank. Figure 6 depicts a rather NE-SW cross section with the development of a sandy deposit at the base of the Pozo D-129 Formation. Pezzi and Medori (1972, in Barcat *et al*., 1989) identified it as a member of the Pozo D-129 Formation, namely the Los Alazanes Member, being its type section in the UE.LA-1 (Los Alazanes) well (#6 in Fig. 1 and Fig. 6). Later, Barcat *et al*. (1984) correlated the UE.LA-1 well with two seismic lines lying 30 km apart from that well and proposed to give "Los Alazanes" the category of Formation, being it an equivalent of the Pozo Cerro Guadal Formation.

Recent paleontological studies in the Oxy.RChN.x-1 ("Río Chico Norte") well allowed the recognition of the following species: *Cyclusphaera psilata*, *Balmeiopsis limbatus*, *Callialasporites trilobatus*, *Taurocusporites segmentatus* and *Candona* sp. (Seiler and Viña, 1997). This biota was found within the interval 2505-2665 mbkb (Fig. 6) along with alpha-spherical oolites, concentric and with ostracods in its core, indicating a shallow lacustrian environment, of warm and clear waters. Seiler and Viña (1997) correlate this interval with the Pozo D-129 Formation present in the YPF.SC.AAB.x-1 ("Anticlinal Aguada Bandera"), YPF.Ch.AdP.es-1 ("Anticlinal de Papelía"), YPF.Ch.CDS.x-1 (Codo del Senguerr), and YPF.Ch.CEP.es-1 ("Cordón El Pluma") wells (#9, #17, #21 and #24 in Fig. 1). Based on paleontological evidence, the presence of oolites in all the wells included in the cross section (Fig. 6) and the electric log correlation it is suggested that Los Alazanes Member be kept as originally proposed by Pezzi and Medori (1972), actually the basal member of the Pozo D-129 Formation. In its type section it contains grey and green sandstones, fine to coarse, occasionally conglomerates, tuffs, red, grey and green with variable sandy content, at the base there is a 12 meter thick conglomerate with micaceous clasts, product of the alteration of the granite below (Fig. 6).

Despite of its predominant continental origin, some reports of marine fossils such as foraminifers and dinoflagellates (Archangelsky and Seiler, 1980; Lesta *et al*., 1980; Fitzgerald *et al*., 1990) in wells located in the western sector of the basin (e.g. UO.Simms-1 well; #25 in Fig. 1) suggest an intermittent or temporary connection to the sea through the west/northwest sector of the basin. This evidence seems to indicate that the isolation from the Pacific realm during the Chubutian claimed by Figari *et al*. (1999) did not occur in the western sector during at least the initial times of the Chubutian cycle. The fact mentioned by Fitzgerald *et al*. (1990) by which the Neocomian deposits are thinner immediately south of the San Bernardo hills seems to validate the occurrence of a N-S paleo-ridge as proposed by Ferello and Lesta (1973). If so, could this ridge have performed as a hinge, at least at the beginning of the Chubutian, allowing a Pacific connection to the west and at the same time an eastward movement of the main depocenter in the eastern sector of the basin? Reinforcing this hypothesis, there is a secondary depocenter at the west/northwestern sector of the basin, identified by Fitzgerald *et al*. (1990; in their thickness map of lower Pozo D-129 mapping sequence) and by Figari *et al*. (1999; thickness map of Pozo D-129 Fm.; geographical location in Fig. 1 among sites #25, #15 and #4).

The age of the unit is considered to be Barremian to Aptian according to paleontological studies carried out by several authors (Archangelsky and Seiler, 1980; Archangelsky *et al*., 1981; Cortiñas and Arbe, 1981; Laffite and Villar, 1982; Hechem *et al*., 1987).

From an economic point of view, the Pozo D-129 Formation represents the rock that is responsible for the generation of the bulk reserves of the basin. Several authors agree on the good oil generating capability of the unit (Ylláñez *et al*., 1989; Fitzgerald *et al*., 1990; Peroni *et al*., 1995; Villar *et al*., 1996). A roughly average of the unit allows to assign a mean of 1% of total organic content (TOC), although values up to 3% are not uncommon. Kerogens of amorphous type are commonly reported, being their Rock Eval characterization from (I)-II to II-III (Uliana *et al*., 1999; Figari *et al*., 1999).

Mina El Carmen and Castillo Formations

The Mina El Carmen Formation defined by Lesta (1968) as a subsurface unit, is characterized in central sectors of the basin by pyroclastics, mainly greenish grey tuffs, and shales, with scarce interbedded tuffaceous sandstones. Towards the flanks of the basin this unit is dominated by sandstones of fluvio-deltaic depositional environments, thin and showing an irregular distribution. Alluvial lobes have been interpreted in proximal areas of the flanks, while meander belts and ephemeral lakes are thought to occur in distal sector of the basin (Vela and Hechem, 1997).

In the western sector and in the San Bernardo foldbelt, this unit is exposed and there, it has been described as Castillo Formation (Ferello and Tealdi, 1950 in Lesta and Ferello, 1972). Its lithology is very homogeneous and monotonous, consisting of green and yellow lithic tuffs, tuffaceous sandstones of brown, yellow and pink colors. All these rocks are well stratified showing a clear alternation of friable and hard levels. Associated to the tuffs there are some beds of sandstones and conglomerates, almost always with a tuffaceous character. They use to fill fluvial channels showing structures such as cross bedding with erosive base. Regionally, these sands vary in distribution from almost absent to abundant.

The thickness of these equivalent units ranges from 200-300 m in the marginal sectors to approximatelly 1600-2000 m in the center of the basin. Both base and top surfaces have been described as unconformities (Barcat *et al*., 1984).

Regarding oil production, this unit represents an important reservoir, being productive in most oil fields. Their sandstone layers are usually thin and discontinuous, but become more frequent to the top of the unit. The age of these units has not yet been well constrained, but it is considered to be Albian (Barcat *et al*., 1989; Figari *et al*., 1999). Fitzgerald *et al*. (1990) assigned an Aptian-Albian age to these formations.

Comodoro Rivadavia, Cañadón Seco and Lower Bajo Barreal Formations

The Comodoro Rivadavia Formation is a subsurface unit described by Lesta (1968) in the northern flank of the basin. Its subsurface equivalent in the southern flank is the Cañadón Seco Formation (Lesta, 1968). This unit is exposed in the San Bernardo hills, where it was described as the Lower Member of Bajo Barreal Formation (Ferello and Tealdi, 1950 *in* Lesta and Ferello, 1972). Their lithological composition is characterized by the presence of white lithic tuffs, stratified in thin beds, greyish white sandstones and conglomerate, well rounded, with volcanic clasts and quartz, tuffaceous sandstones and red and yellow shales that host discontinuous coarse sandstone lenses.

In the northern flank the sandy layers are thicker and the occurrence of them are more frequent with respect to the southern flank, suggesting a more active behavior and a larger subsidence rate (Lesta, 1968). This fact is reflected in the curves of subsidence constructed by Nocioni (1993) for the different sectors of the basin.

In general, it can be stated that a diagnose characteristic of these units is the increase of sand amount with respect to the previous units of the Chubutian cycle. As in the rest of the units in this cycle the sand deposition is controlled by individual faults. Most of the sand bodies have been deposited by ephemeral fluvial systems. Hechem (1998) was able to identify sand layers with sheet and lobate architecture that were interpreted as deposited at the base of slopes in synsedimentary normal faults. He also found lens shaped and crossbedded sand bodies interpreted to be originated by tractive channelized currents. According to this author, the drainage of the fluvial system would have been transversal in the northern flank whereas longitudinal in the southern flank and the west sector. Bellosi *et al*. (1997) describe multi-channelized sandy fluvial systems, with moderate sinuosity and well developed alluvial plains for the Caleta Olivia Member (Cañadón Seco Formation).

Typical geometry for these deposits show a volume increase due to both vertical multistory patterns and lateral amalgamations (Fig. 7). Bridge *et al*. (2000) analyzed the spatial distribution of fluvial sandstones in the Bajo Barreal Formation at several outcrops ("Codo del Senguer", "Cerro Ballena" and "Cerro Colorado de Galveniz"; #21, #26 and #27 in Fig. 1), averaging that single channel widths were on the order of tens of meters (35 to 65 m) and depths on the order of meters (2 to 6 m). These data led them to conclude that the width of subsurface sand bodies estimated from well to well correlation is greater than measured in outcrop, being overestimation of lateral sand bodies dimension frequent when dealing with well data.

The thickness of these units varies between 200-300 m at marginal locations and 1000-1200 m at distal positions (basin center).

Age is not accurately assigned. Fitzgerald *et al*. (1990) report ages obtained in the Albatros offshore well (#28 in Fig. 1) to be Cenomanian-Coniacian. Bellosi *et al*. (1997), on the basis of palinological studies, assign a late Albian-Cenomanian age to the Cañadón Seco Formation, adding that the upper levels could be of an early Turonian age. According to these authors, the palinomorphs indicate a continental humid climate, template to warm during the mid Cretaceous.

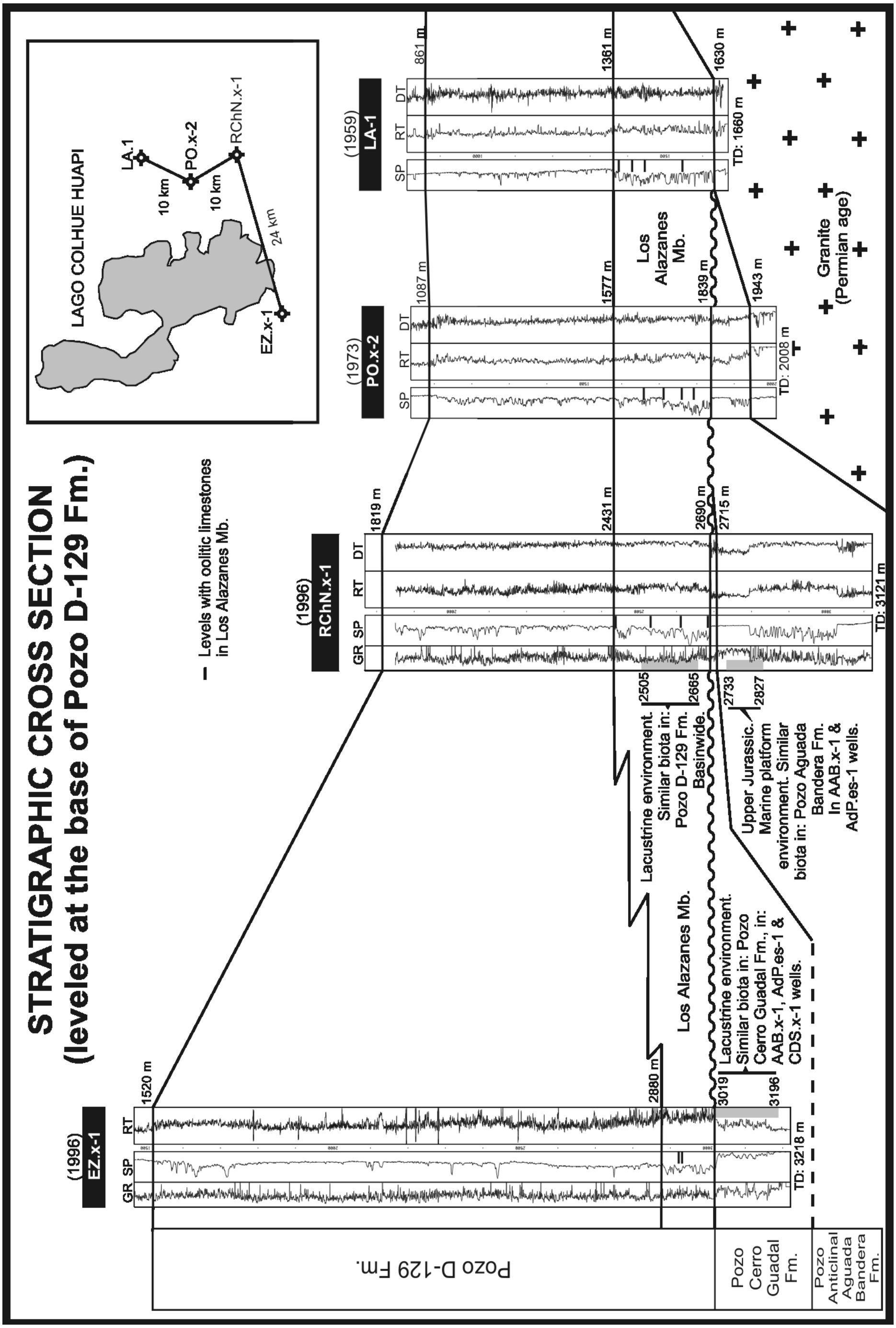
From the economic point of view, these units represent the most important reservoir in the basin, participating in the oil production of almost all the oil fields.

Yacimiento El Trébol, Meseta Espinosa and Upper Bajo Barreal Formations

A reactivation of the subsidence and a basin expansion episode is observed during the late Cretaceous, that recorded finer facies than in the underlying deposits. From the formal point of view this event is represented by Yacimiento El Trébol (northern flank) and Meseta Espinosa formations (southern flank; Lesta, 1968) and the Upper Member of Bajo Barreal Formation (western sec-

FIG. 6. Schematic stratigraphic NE-SW cross section, datum: base of Pozo D-129 Formation. Northern flank of the basin, close to the Lago Colhué Huapi. Wells EZ.x-1 (El Zanjón), RChN.x-1 (Río Chico Norte), PO.x-2 (Pico Oneto) and LA-1 (Los Alazanes).

FIG. 6. Corte estratigráfico esquemático de sentido NE-SO, nivelado a la base de la Formación Pozo D-129, en las cercanías del lago Colhué Huapi. Correlación entre los pozos EZ.x-1 (El Zanjón), RChN.x-1 (Río Chico Norte), PO.x-2 (Pico Oneto) y LA-1 (Los Alazanes).


STRATIGRAPHIC CROSS SECTION
(leveled at the base of Pozo D-129 Fm.)
LAGO COLHUE HUAPI
LA.1
PO.x-2
RChN.x-1
EZ.x-1
10 km
10 km
24 km
Levels with oolitic limestones in Los Alazanes Mb.
(1996)
EZ.x-1
GR SP RT
1520 m
2880 m
3019
3196
TD: 3218 m
(1996)
RChN.x-1
GR SP RT DT
1819 m
2431 m
2690 m
2715 m
2505
2665
2733
2827
TD: 3121 m
(1973)
PO.x-2
SP RT DT
1087 m
1577 m
1839 m
1943 m
TD: 2008 m
(1959)
LA-1
SP RT DT
861 m
1361 m
1630 m
TD: 1660 m
Lacustrine environment. Similar biota in: Pozo D-129 Fm. Basinwide.
Upper Jurassic. Marine platform environment. Similar biota in: Pozo Aguada Bandera Fm. In AAB.x-1 & AdP.es-1 wells.
Los Alazanes Mb.
Lacustrine environment. Similar biota in: Pozo Cerro Guadal Fm., in: AAB.x-1, AdP.es-1 & CDS.x-1 wells.
Los Alazanes Mb.
Granite (Permian age)
Pozo D-129 Fm.
Pozo Cerro Guadal Fm.
Pozo Anticlinal Aguada Bandera Fm.

tor). These units are the final event of the sag basin, and consist of predominant pelitic deposits. In distal positions they are red, green and grey shales , with scarce sandstone occurrence likely originated by shallow water turbidites (Brown *et al*., 1982). In the northern flank the Member Pozo S-83 (Lesta, 1968), composed by abundant sandstones, is thought to have been deposited by deltaic fans.

Towards the west, where the Upper Member of the Bajo Barreal Formation is defined, the lithology presents siltsones and mudstones of grey and reddish brown colours, with scarce and thin sand beds and a variable pyroclastic participation, indicating a palustrine and alluvial plains with scarce channelized fluvial facies (Barcat *et al*., 1989). Further to the west the deposits are eroded away because of the unconformity at the base of the Tertiary. Here, the Bajo Barreal Formation is overlain by the Laguna Palacios Formation (Flores, 1955 in Lesta and Ferello, 1972). It is formed by a monotonous succession of tuffs, sandy tuffs and conglomeratic sandstones of yellow, pink and light brown colors, where paleosols occurrence is common.

These units are well represented in the basin being its thickness between 100-200 m in the margin and 700-800 m in the distal sectors.

Its age is considered to be late Coniacian-Maastrichtian. Fitzgerald *et al*. (1990) by comparisons with the global eustatic chart (Haq *et al*., 1987) assign them to the mentioned interval, in broad agreement with the Senonian age attributed to the sauropods collected in the upper part of the Chubut Group (Bonaparte and Gasparini, 1978).

Although not very important, some hydrocarbon production is exploited from these units.

To the top these deposits show an erosive unconformity, related to the Laramic phase (Lesta, 1968). This is very clear towards the margins of the basin where the underlying deposits are eroded, becoming paraconcordant towards the center of the basin

Tertiary cycle

A 500-1300 m sedimentary column represents the Tertiary sedimentary cycle. It is composed by clays and tuffs with occasional interbedding of continental sandstones, alternating with tongues of shallow marine deposits of episodical Atlantic transgressions.

Formally, five units represent the Tertiary cycle: Salamanca, Rio Chico, Sarmiento, Patagonia and Santa Cruz formations.

Salamanca Formation

This unit represents the first Tertiary marine transgression from the Atlantic in the Golfo San Jorge Basin. It was first described by Ihering (1903 *in* Feruglio, 1949), and then by Windhausen (1924), Pianitzky (1933) who called it "Salamanqueano", being Lesta and Ferello (1972) who formalized the unit's present name.

Lithologically, these deposits consist of shales, sandstones and conglomerates. Lesta *et al*. (1980) point out that lithologic characteristics of this unit vary widely depending on the shore line position when deposition took place. Thus, to the west, interbedding of conglomerates and sandstones with ocassional tuffaceous shales predominates, while to the east shales, siltstones and sandstones, of conglomeratic and coquinalike type, occur commonly.

The abundant fossil material indicates a Paleocene age for this unit (Danian; Lesta *et al*., 1980). Due to the presence of *Arkhangelskiella cymbiformis*, and other calcareous nannofossils, Barcat *et al*. (1989) assign a Maastrichtian age to the base of the unit.

The Salamanca Formation contains a glauconitic sandstone layer that produce hydrocarbons in the northern flank of the basin.

Río Chico Formation

The top of the Salamanca Formation is followed concordantly by the Río Chico Formation (Simpson, 1933) being the pass of a gradual character (Feruglio, 1949), which makes the identification of an accurate limit difficult. In view of this problem, the formational boundary is today accepted as located at the base of the black claystone known as "Banco Negro", overlaying a glauconitic psamite of the Salamanca Formation.

The continental Río Chico Formation has a vast areal distribution in the Golfo San Jorge basin. It consists mainly of multicolored shales, fine tuffs, tuffaceous sandstones and conglomerates, all of a friable characteristics. Its thickness is not larger than 150-250 m.

On the basis of faunistic criteria, Pascual and Odreman (1973) place the Río Chico Formation in the Upper Paleocene.

Sarmiento Formation

The Sarmiento Formation (Lesta *et al*., 1980; previously "Tobas Sarmiento" Feruglio, 1949) is known both in exposures and in subsurface, in the central-east Chubut Province as well as in northern Santa Cruz Province. The base of the Sarmiento Formation represents an erosive unconformity

Lithologically, it consists mainly of white, yellow, pink, light brown, fine grained tuffs, occasionally cinerites, well stratified. Bentonite lenses and some friable conglomerate interbeds occur regularly. Basalts, staked up to 6 distinct flows, appear frequently. The thickness of the unit varies between 200 and 300 m. They are simply recognized at the field by its typical "organ tube" shape.

The abundance of flora and fauna within this unit has given to paleontologists a real research field for the late Paleogene. Four stages of evolution have been identified, coinciding respectively with four mammal ages, namely: Casamayorense, Musterense, Deseadense and Colhuehuapense (Pascual and Odreman, 1973).

Age determinations place this unit in the interval Eocene-Oligocene.

Patagonia Formation

The Patagonia Formation (Zambrano and Urien, 1970) includes the deposits of a new Tertiary Atlantic transgression. It has a great areal development in the Golfo San Jorge Basin. Dealing with the "Patagonian" transgression, Ameghino (1906) distinguished three marine stages: "Juliense", "Leonense" and "Suprapatagoniense". Bellosi (1987 *in* Bellosi, 1990), gathered the "Patagonian" deposits, developed in southwest Chubut and northwest Santa Cruz provinces, into the Chenque Formation, consisting of five coarsening up sequences that are about 500 m thick.

The contact at the base of this unit is unconformable, and overlies the Sarmiento Formation as well as the Río Chico Formation.

The Patagonia Formation deposits indicate a neritic and litoral marine environment. Evidences of it are the abundant rests of marine organisms spread out in the sediments, such as coquinas and the frequent occurrence of glauconite. Layers of reworked fossils and the abundance of clastics are indicating a wave cut zone. Tuff layers as well as sandstones containing pyroclastic material indicate volcanic episodes contemporary to the deposition of the unit.

The age of the unit is placed at the interval upper Oligocene-Lower Miocene (Bellosi, 1990).

Santa Cruz Formation

The Santa Cruz Formation (Zambrano and Urien, 1970) consists of a group of continental sediments and pyroclastics, very well developed in Pampa del Castillo, close to Las Heras city and north of the Lago Musters, where they reach a thickness of about 200 m. Its base is conformable with the underlying Patagonia Formation (Bellosi, 1995). It is constituted by friable greyish blue sandstones, conglomerates, tuffs and tuffaceous shales of varying colours. Paleosols with fossils are frequent. The depositional environment of this succession varies from eolian dunes to high sinuosity fluvial systems in extent alluvial plains, small lakes and estuarine coasts.

The age of the unit is given by the finding of *Astrapotherium* (Feruglio, 1949) of undoubted Miocene age.

Quaternary cycle

With the end of the Tertiary, the basin enters a cycle of post-tectonism. The Quaternary sedimentary record is represented by marine and continental deposits. The marine ones, Araucanense and Entrerrianense, are very poorly developed in the Golfo San Jorge basin. The continental ones are recording a drastic climatic change which produced glaciations in vast areas of the continent, and its consequent sea level fall.

The Rodados Patagónicos Formation (Windhausen, 1914) is a Quaternary deposit that is developed all over the Patagonia. It is composed of shingle and

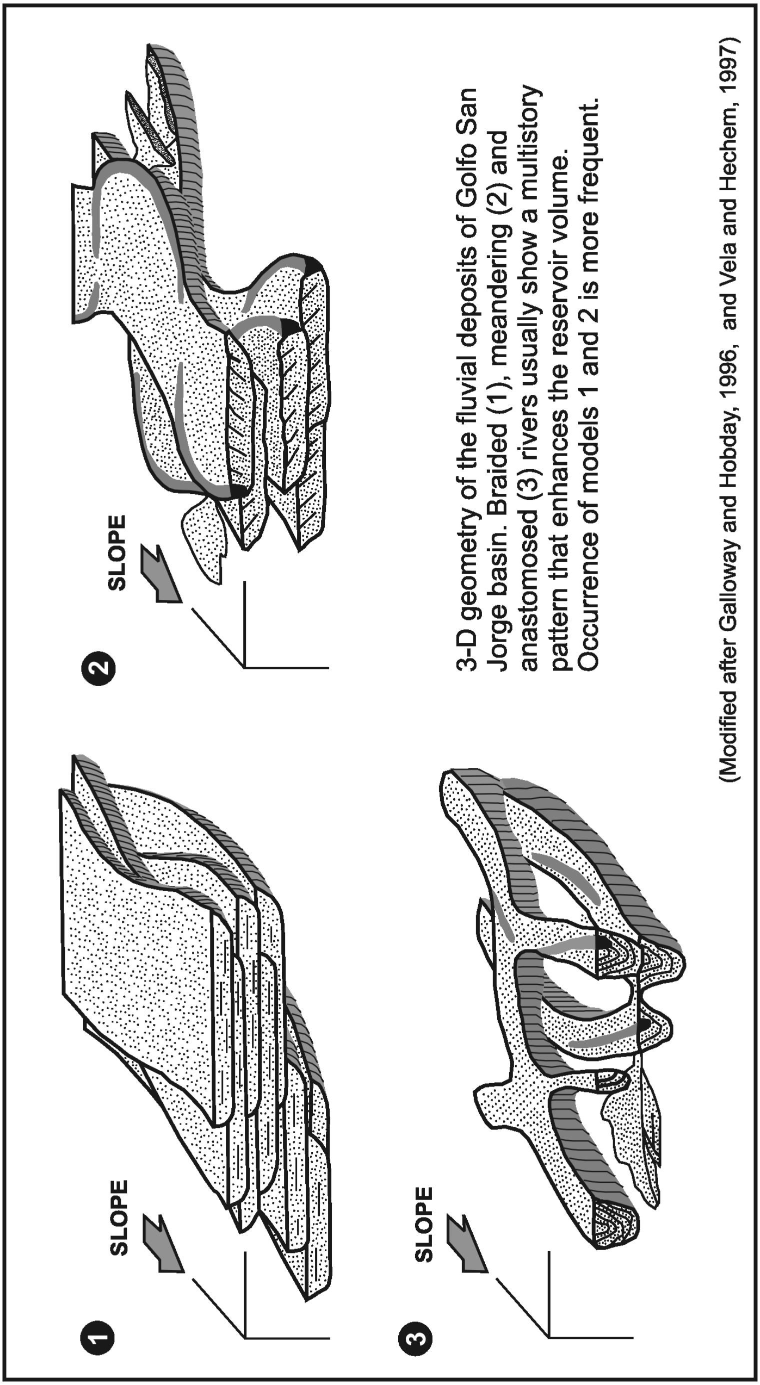


FIG. 7. Geometry of the fluvial sandstone bodies of the Chubutian deposits.
FIG.7. Geometría de los cuerpos arenosos de origen fluvial de los depósitos Chubutianos.

boulders whose sizes vary widely between 1 up to 10 or even more centimeters, showing well polished surfaces that denote long transport distances. Compositionally, they are volcanics and porphyrys of varying colours, sourced mostly at the Andes Cordillera. They usually present a sandy matrix and calcareous cement. Their thickness ranges between 2 and 20 m., although in some places (e.g. Valle Hermoso) they can be up to 150 m thick (González, 1971).

Its origin is not clear yet, but most authors accept fluvioglacial processes combined with later redepositions. Taking into account that the "Greatest Patagonian Glaciation" took place between 1.01 and 1.17 Ma (Ton-Taht *et al*., 1999), the age of the formation is Pleistocene.

Other Quaternary deposits, of more restricted occurrence, are related to the increased fluvial activity that took place during the glaciar retreat stage, such as terraced and non terraced alluvial deposits along the major rivers of Patagonia.

STRUCTURE

Three zones with distinctive structural styles can be recognized in the Golfo San Jorge Basin (maps showing the different sectors are published by Barcat *et al*., 1989; Fitzgerald *et al*., 1990; Figari *et al*., 1999):

1. Eastern sector of the Basin. It presents tensional deformation. There, normal faults, both synthetic and the subordinate antithetic, are of a prevailing of E-W and ESE-WNW alignment. This could also be applied to the offshore sector. In general major faults dip 60-65° and are even affecting the economic basement. The evolution of the faults are synchronous with deposition, therefore they usually show fault-offsets at deeper levels larger than at shallower ones.

2. San Bernardo foldbelt: compressional deformation. This N-S trending belt runs throughout the entire basin, affecting also older levels of the Somuncurá (Figari and Courtade, 1993) and the Deseado massifs (Homovc *et al*., 1996). Tertiary compression affecting older depocenters is the main mechanism responsible for this deformation. This compression produced inversion tectonics folding and the uplift of the San Bernardo belt. This compressional event, whose main phase is of middle Miocene age (Chelotti, 1997), is believed to have been expressed only where the deformation stresses (west to east) met perpendicularly pre-existent structures and alignments of N-S orientation (Figari *et al*., 1999).

3. The western sector. Even though this sector is close to the Andean belt, it has been affected by extensional deformation, with none or poor compressive deformation. The alignment of these normal faults is in general NW-SE.

The structures of the Golfo San Jorge Basin can be divided basically into two types, extensive and compressive. However, to accept this simple division, it must be taken into account that many of the structures in the basin present, in a greater or lesser degree, the effects of strike slip deformation, a subject that is beyond the scope of this paper.

The hydrocarbon bearing traps that most commonly occur in the Golfo San Jorge Basin can basically be classified as of belonging to the structural type.

However, it should be kept in mind that stratigraphic factor in this basin represents a very important trap mechanism, since the reservoirs usually have depositional pinch out (Fig. 7).

Extensional structures

Normal faults are the most common and economically the most important traps basinwide. They usually show rollovers in the downthrown blocks (Fig. 8), while 4 way closures in the upthrown blocks they are less common. Rollovers are developed, in general, in association with synthetic major faults, but also with antithetic ones. Faulted and tilted blocks with closures against faults represent also effective traps (Fig. 8). Horst structures, limited by opposite dipping normal faults are likely related to the near presence of half graben structures (Fig. 8).

A structure that is not common in the basin but represents an interesting exploratory play is the so-called interference zone (Figari *et al*., 1999). These zones develop inbetween regional normal faults generating a complex microfracture and dissolution porosity. This mechanism can generate major traps, as the case of El Tordillo oil field (Figs. 1 and 8; Boll *et al*., 2000). Mina El Carmen Formation provides a lithology that favors the development of this kind of traps.

Compressional structures

Compressional structures are developed in the N-S trending San Bernardo foldbelt. These structures appear to be discontinuos and sometimes curved, but keeping roughly the N-S alignment. Faults do not present any predominant vergence.

High angle reverse faults as the result of reactivation of normal faults develop anticlines of box fold type (Sciutto, 1981; Fig. 8) as well as fore- and backtrusts (Fig. 8). These major faults involve usually the economic basement.

Anticlines associated to low angle reverse detached faults have also been identified (Fitzgerald *et al*., 1990). These faults detach with low angles from shaly deeper levels, getting the steeper the shallower the levels are cut (Fig. 8). These structures do not involve the economic basement but paleotopography on this basement may actually favor their development.

HYDROCARBON HABITAT

The oils of the Golfo San Jorge Basin ranges between 15 and 30° API. In general, they are parafinic and have a low sulfur content. The oils are frequently biodegraded, as demonstrated by detailed chromatography and biomarker analyses (Villar *et al*., 1996) in the southern flank, mainly as the result of the entrance of fresh water into the system.

The oils are mainly accumulated in the fluvial sandstones deposited during the Chubutian sedimentary cycle. In general their petrophysical characteristics are

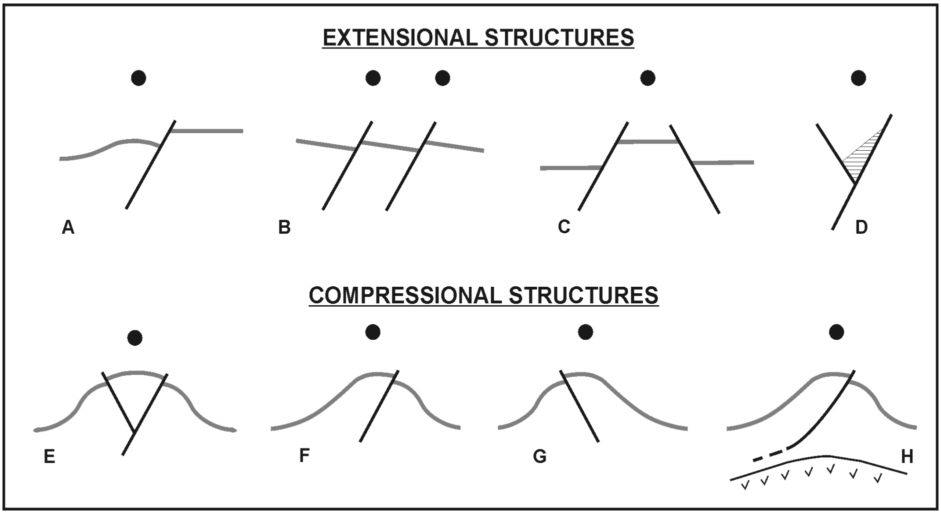


FIG. 8. Geometry of the structures most commonly present in the Golfo San Jorge Basin.: A) Rollovers ,B) Faulted and tilted blocks, C) Horsts, D) Interference zone, E) Box fold anticlines, F) Forethrust anticlines, G) Backthrust anticlines, H) Detached ramp anticlines.

FIG. 8. Geometría de las estructuras más comunes en la Cuenca del Golfo San Jorge. A) "Rollovers", B) Bloques fallados y basculados, C) "Horsts", D) Zona de interferencia, E) Anticlinales tipo "cajón", F) Anticlinales producidos por fallas de tipo "forethrusts", G) Anticlinales asociados a fallas de retrocarga ("backthrusts") y H) Anticlinales producidos por fallas de despegue.

poor, due to the presence of tuffaceous materials, obliterating original porosity. Reservoirs are commonly thin multistory sand beds that exhibit a discontinuous pattern. All these sedimentary characteristics (lenses, channels, point bars) plus the sometime structural complexity result frequently in sets of layers with several and different oil-water tables.

Traps are of both structural and combined types. The major faults appear to be still active synchronously with respect to the thermal subsidence of the basin (lower post-Neocomian to Upper Cretaceous). Compressional deformation is thought to have had its most important phase during the middle Miocene. Primary faults, and those that were reactivated afterwards, originated a network of pathways for the hydrocarbons generated and expulsed from the Pozo D-129 Formation.

As mentioned previously, the Pozo D-129 Formation is the main source rock of the basin, being responsible for the bulk production and reserves of hydrocarbons (Ylláñez *et al*., 1989; Fitzgerald *et al*., 1990; Villar *et al*., 1996). The Pozo D-129 Formation presents a wide stage of maturity throughout the basin, ranging from post mature in the deep central sectors to inmature at the margins. However, the main generating zone should have entered the oil window at 80 Ma in the northern flank, due to a higher subsidence history, while at the southern flank it should have entered at 50-60 Ma (Villar *et al*., 1996).

Low gas/oil ratios are characteristic for the basin. According to Fitzgerald *et al*. (1990) this would suggest that most of the liquids were drained from the source rock before reaching the gas stage. Wavrek *et al*. (1997) identified condensate-like molecular weight fraction in a number of crude oils suggesting that condensate may be more common than previously thought, thus openning new exploratory opportunities.

It is worth to point out the high degree of knowledge about the Chubutian deposits, due mainly to the occurrence of economic hydrocarbon accumulations. The Chubutian has all the components for a successful development: a widespread and thick source rock with a wide range of thermal maturity, rather shallow reservoirs which although of poor petrophysics are present in almost all the basin, and a structuration that allows the presence of a variety of traps. On the contrary, the Neocomian levels are underexplored, but their exploratory potential should not be underestimated. The Neocomian has a source rock whose oil generating capability has been proved in the west sector, but its potential is still valid for other sectors, where may be its maturity is more related to gas accumulations. With respect to reservoirs, they should be studied in detail, since the active rift tectonism during deposition should have sourced large amounts of clastics. A decrease in the porosity could be expected by depth and tuffaceous participation, but gas at considerable depths is high pressured and even if low porosities it can be produced. The sandy base of the Pozo D-129 Formation should not be kept out of sight either as potential reservoirs.

CONCLUSIONS

The first sedimentation event in the region takes place during Carboniferous-Permian times, filling depocenters of NNW-SSE orientation, probably associated to the evolution of the Pacific margin. During the Permian-Triassic granitic bodies intrude the Somuncurá and Deseado massifs. The Triassic record consists of continental deposits, followed by marine dark shales of Lias age.

The Dogger-Malm records an initial period of rift process during which large half graben shaped depocenters are filled with volcanoclastics that constitute the economic basement of the basin. During the Neocomian the rift process is in its late phase. Still active half grabens are filled with lacustrine sediments. Environmental lacustrine conditions were deep and anoxic in the beginning, becoming shallower and less prolific at the end of this cycle. The oil generating capability of these sediments has been proved in the western sector of the basin. Although this period is characterized by continental conditions, episodical marine transgressions occurred as well.

The end of the rift is followed by a tectonic event that tilt the main axis of the basin to the East. Due to this tilt the main depocenters moved eastwards. This caused a regional erosive unconformity that eroded the underlying Neocomian deposits. Subsequently, generalized thermal subsidence conditions take place. Under these conditions the lacustrine Pozo D-129 Formation is deposited all over the basin. This unit is the responsible for the generation of the bulk reserves of the basin. During the period Albian-Maastrichtian the main reservoirs of the basin deposited, consisting of a series of alternating fluviolacustrine sandstones and shales.

During the latest Cretaceous-earliest Tertiary the first Atlantic transgression takes place, representing the initiation of a sedimentary cycle characterized by the alternation of continental/marine deposits. Although extensional conditions prevailed during the Tertiary, a major compressional pulse uplifts the N-S trending San Bernardo fold belt during the middle Miocene.

The Quaternary is dominated by drastic climatic changes. Glaciation, abrupt sea level fall and rapid melting processes influenced immensely the depositional settings of this period.

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