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Hydrocarbons and petroleum geology of Tierra del Fuego, Argentina

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ABSTRACT

The history of the hydrocarbon exploration and present production, as well as a compilation of their main tectosedimentary features in the Argentine territory of Tierra del Fuego Island are summarized in this paper. The exploration and production of hydrocarbons in the studied region is mostly restricted to both onshore and offshore portions of the Austral-Magellan Basin. Their infil is constituted by a Late Cretaceous to Tertiary sedimentary and volcanoclastic 8,000 m thick succession deposited on a folded and eroded basement cropping out along the northern foothill of the Fueguian Andes. The main productive levels are sandy layers of the Springhill Fm and Tobífera Fm in the eroded basement highs. Also, levels of the Tertiary sequences are currently under evaluation adding an exploratory potential ranging from conventional plays related to transpression and inversion structure to new scenarios based upon tectosedimentary concepts.

KEYWORDS **Hydrocarbons. Exploration. Austral-Magellan Basin. Tierra del Fuego.**

INTRODUCTION

The Austral-Magellan Basin with a total surface of 170,000 km^2 is located in the southernmost portion of the South American continent following a preferential NNW-SSE axis and is limited by the Mountain range of the Andes, toward the West, and by the Río Chico High to the East (Biddle et al., 1986; Alvarez-Marrón et al., 1993; Diraison et al., 2000; Schiuma et al., 2002). The latter is the southern extension of the Deseado Massif that behaved as the basement of the Cretaceous sedimentation separating to the East the Austral-Magellan Basin from the Malvinas Basin (Fig. 1).

About 1,037 wells have been drilled in the Argentine territory of Tierra del Fuego. The average depth is around 2,000 m, with the Springhill Formation (Fm) as the main producer, and only 148 of petroleum and 91 of gas and condensed are in production (Fig. 2).

The proven and probable total reserves for the whole Argentine sector of Tierra del Fuego are of 12.5 Mm^3 of petroleum and 15,750 Mm^3 of gas (Fig. 3), while the total production is 3,700 m^3/day of petroleum and 15.8 Mm^3/day of gas (Fig. 4).

The history of the hydrocarbon exploration and present production, as well as a compilation of their main tectosedimentary features in the Argentine territory of Tierra del Fuego Island are the main objectives of this paper.

GEOLOGICAL SETTING

The Austral-Magellan Basin (Robles, 1987; Arbe, 1989; Álvarez-Marrón et al., 1993; Diraison et al., 2000) constitutes a thick succession of sedimentary rocks and volcanoclastics deposited on a folded and eroded basement cropping out along the northern foothill of the Fueguian Andes (Fig. 1). According to the region, the diverse authors and the origin of the lithostratigraphic data obtained from these sequences, they received different names, situation that difficults the correlation between them.

In the foothills of the Southern Andean Cordillera there is a sharp transition, from thick-skinned tectonics, to a relatively undeformed foreland basin. In the cordillera itself, structures are mainly in-sequence thrusts, verging to the east, some of them with right-lateral strike-slip components.

In the foothills, Cretaceous sediments crop out in a thrust belt, which is about 20 km wide. Towards the foreland, Late Cretaceous to Tertiary sediments have been folded at kilometre-scale wavelengths. In the foreland basin, the only recognizable structures are grabens and half-grabens of Jurassic age, manly trending north-northwest (Uliana et al., 1989; Urien et al., 1995).

In the axial zone, located in the Chilean territory, the Cretaceous fold-and-thrust belt is wider and the clastic wedge in the foreland basin is considerably thicker. Cretaceous sediments are also offset by in-sequence thrusts. Nevertheless, a major back-thrust related to a triangle zone has controlled the Tertiary sedimentation (Bravo and Herrero, 1997). From the detailed stratigraphic relationships, it is possible to determine that the main deformation was active during the Tertiary.

In the Fueguian cordillera (Caminos, 1979), left-lateral faults and associated thrusts dominate the structural style whilst the fold-and-thrust belt is wider than elsewhere. Thrusts have propagated in-sequence north-eastwards and are related to detachment levels within Early Cretaceous marine shales. Deformation was active

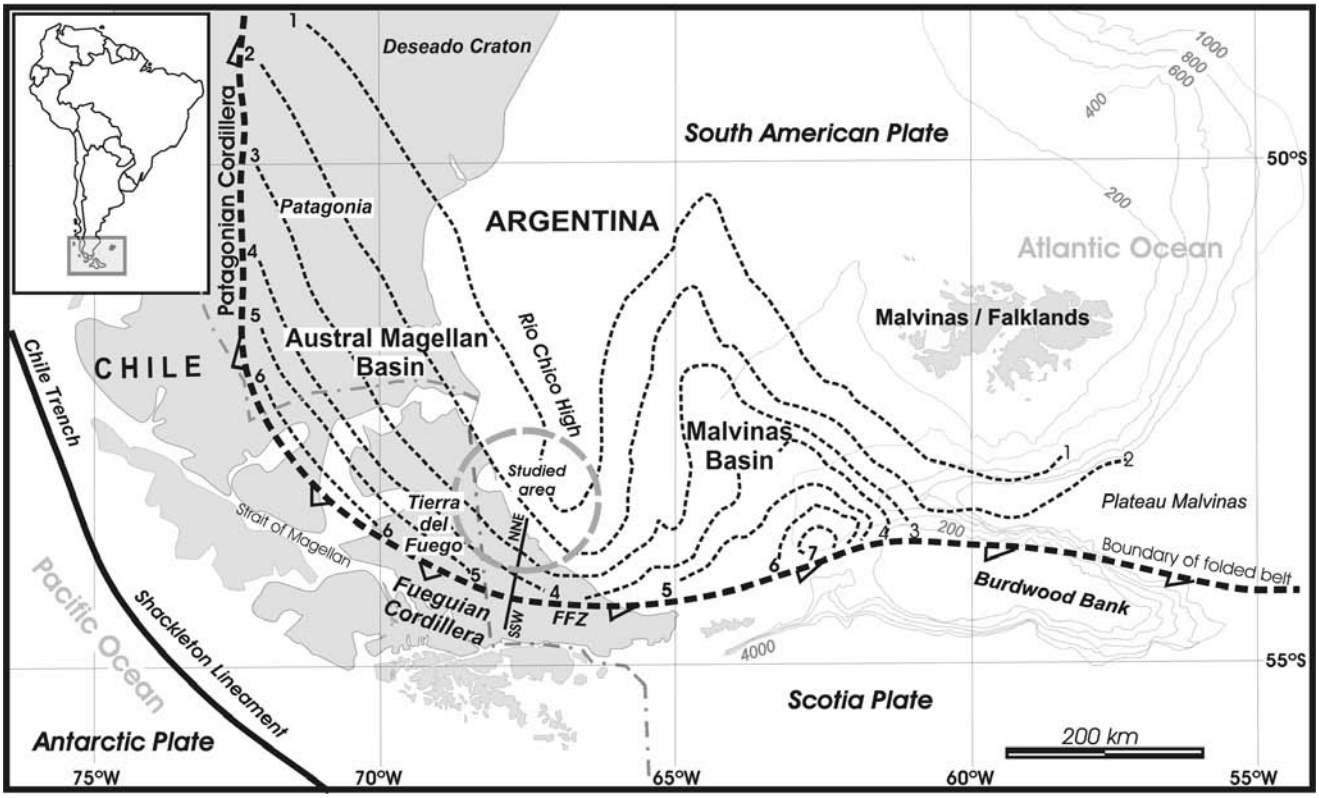

FIGURE 1 | **Localization and geotectonic setting of the Austral-Magellan and Malvinas Basin. Bold discontinuous contours indicate sedimentary cover thickness in kilometres. NNE-SSW line: cross-section of Figure 6. Discontinuous ellipse shows main Tierra del Fuego oil and gas production area. FFZ: Fagnano Fault Zone.**

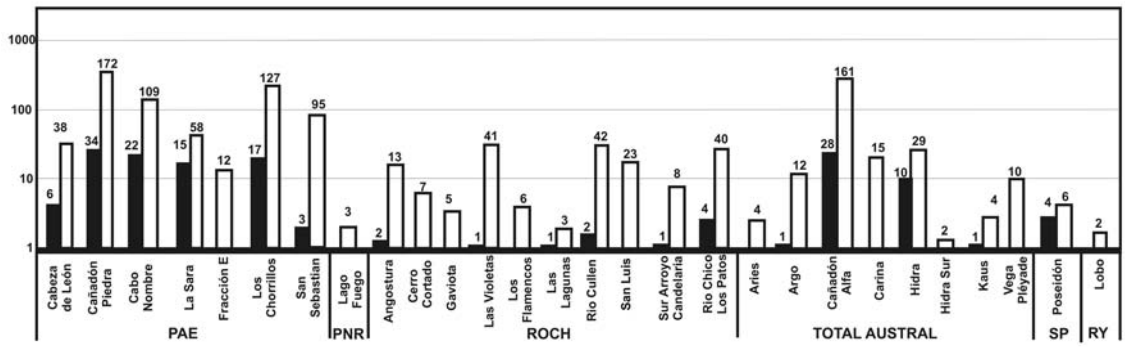

FIGURE 2 | **A comparative analysis between the drilled wells (white) and those in production (black) for the different locations of Tierra del Fuego, Argentina. PAE: Pan American Energy; PNR: Pionner Natural Resources; SP: Sipetrol; RY: Repsol YPF.**

until the Miocene or Pliocene (Diraison et al., 1997b; Ghiglione et al., 2002).

Fault-slip data provide information on the relative importance of strike-slip and dip-slip faulting. This can be visualized by plotting the pitch of striations versus the strike of the corresponding fault plane. For localities in Fueguian foothills there is a predominance of strike-slip faults (where striations pitch between 0° and 45°), left-lateral and right-lateral ones being equally numerous whereas two families trend more nearly N and E, respectively (Diraison et al., 2000; Rossello, 2005).

If the cordillera has undergone extension along strike, it may have contributed to the exhumation of Darwin Cordillera. To account for exhumation, Dalziel and Brown (1989) invoked extension, but in a direction perpendicular to the cordillera; while Cunningham (1995) and Klepeis and Austin (1997) invoked transtensional wrenching. Another feature not well constrained is the timing of the Magellan rift system (Diraison et al., 1997a). It is active today and it was active during the Neogene, after the opening of Drake's Passage. However, it may have initiated well before, in the Paleogene or even the Late Cretaceous.

Although corner conditions seem to account for most of the structures in southern Patagonia, subduction of the Chile ridge during the last 14 Ma may also have had an influence. North of the triple point, the convergence rate between Nazca and South America is currently about 80 mm/year; whereas South of the triple point, between Antarctic and South America, it is about 20 mm/year (Lagabrielle et al., 2004). Such a drastic decrease in convergence rate may have triggered crustal extension, producing the rift valleys that have been tentatively identified at the north-western corner of the Magellan Basin.

Paleomagnetic studies have been used to constrain models of the Patagonian Orocline (Cunningham et al.,

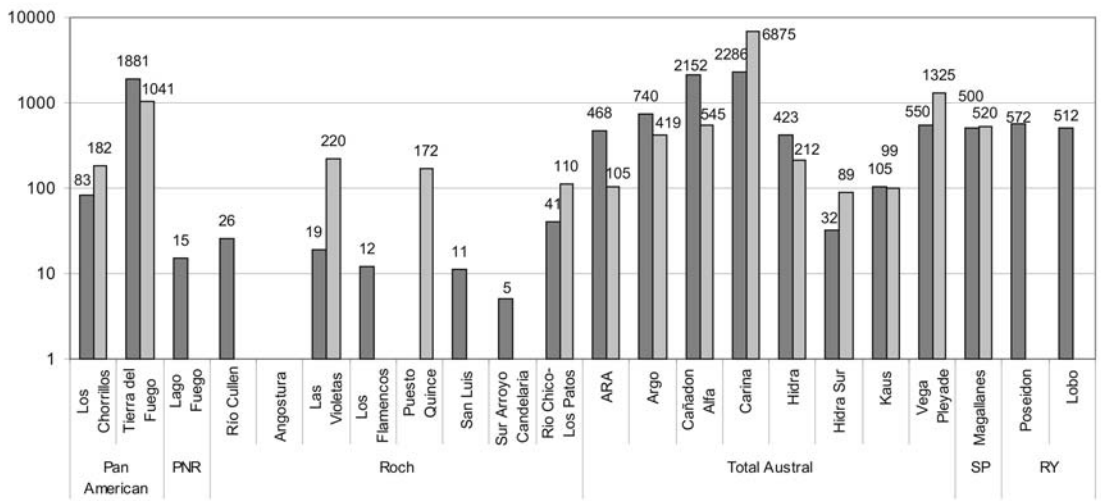

FIGURE 3 | **Oil reserves for the different oil-fields (dark grey: proved oil in K-m³; light: probable oil in K-m³). PNR: Pioneer Natural Resources. SP: Sipetrol; RY: Repsol YPF.**

1991, 1995; Cunningham, 1993; Rapalini, 2007). These models assume bending of the cordillera with respect to a fixed continental shelf, implying that shortening increases from northwest to southeast, within both the cordillera and the Austral-Magellan Basin. In the main cordillera, such gradient has never been described, although Cordillera Darwin is the most metamorphosed part of the cordillera and has been overthrusted toward the northeast (Klepeis, 1994). Regional cross sections in the basin show that shortening increases toward the southeast, but probably not enough to account for the orocline. Perhaps the assumption of a fixed foreland is too simplistic. Bending of the Patagonian Orocline may be associated with regional block rotations, at the scale of the southern tip of South America, including Tierra del Fuego Island and parts of the Austral-Magellan Basin.

In the Fueguian Cordillera, as wells as in its oriental continuation, the Burdwood Bank, the strike-slip faulting prevails relative to the Patagonian Cordillera where the crustal thickening dominates over wrenching. The kinematics reflects a thrusting combination and wrenching and is consistent with the information provided by the major scale structures.

The absence of subduction on the southern wrenching margin (between the Scotia and South American plates) determines the lack of a related magmatic activity and it allows considering it as a passive margin. This way, the passage from the continental South America to the oceanic Scotia Plates, during the Cretaceous, was preferentially transitional (passive Atlantic type) being its different mechanical competence one of the substantial causes of wrenching control and the deformation toward the continental compartment that took place later.

The Fagnano-Magellan Faulting (FFM) is a major regional wrenching zone with sublatitudinal arrangement and senestral displacement affecting the northern foothill of the Fueguian Range along the whole Island of Tierra del Fuego. This structure has been recognized by several investigators who attributed it diverse geotectonic connotations and mechanical operations. This way, it was considered the suture between the South America and Scotia Plates (Olivero and Martinioni, 2001) like a continental transform fault (Lodolo et al., 2002a, 2002b, 2003, 2007). Some of them consider the FFM as the superficial expression of the suture separating the continental South American and oceanic Scotia Plates, remarked as one of the few emerged locations where it takes place. However, the same continental acid or mesosilicic crystalline nature of the metamorphic terranes of the nucleus of the Fueguian Cordillera south of the FFM would contradict this statement supporting instead the presence of equally continental materials. Also, the regional geologic reports on the western projection toward Magellan Strait and neighbouring regions in the Peninsula Brunswick and Riesco Island in the Chilean territory (Cunningham, 1993; Klepeis and Austin, 1997) do not show significant changes of its trace to both the north and south of the FFM.

This structure has a very strong surface expression on the whole of Tierra del Fuego Island and in order to describe more easily it was divided in the three segments: 1) Eastern segment, 2) Central segment, and 3) Western segment (Rossello et al., 2004a; Rossello, 2005).

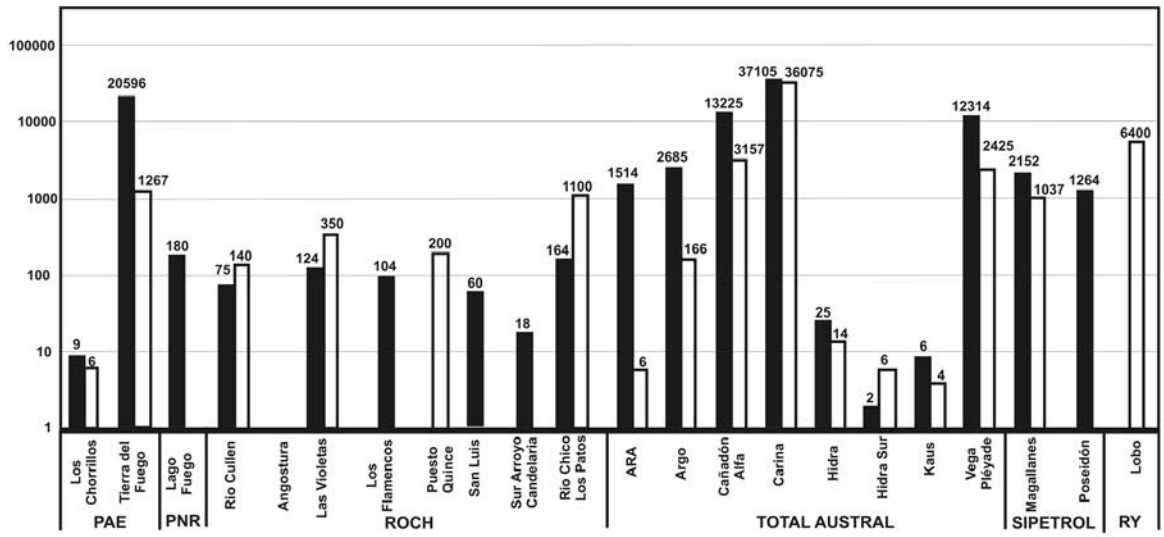

FIGURE 4 | **Gas reserves for the different gas fields (black: proved gas in Mm³; white: probable gas in Mm³). PAE: Pan American Energy; PNR: Pioneer Natural Resources; RY: Repsol YPF.**

1) Eastern segment: Oriented sublatitudinal at about 54° 32´ South between the Atlantic coast and Tolhuin town as a rectilinear feature in the depressed and filled topography of the area (Landsat and SPOT images) where it controls the disposition of the Turbio river (that flows toward the Lake Fagnano) and part of Irigoyen river that drains toward the Atlantic ocean. In the Atlantic coast, it is located in the proximity of the end Malengüena where it puts in contact the Paleocene and the Oligocene units limiting to the north the Cretaceous metamorphic outcropping units.

2) Central segment: There is no outcrop since it coincides with the position of the Fagnano Lake, most of it inside the Argentine territory. This lake occupies a narrow glacial valley and is limited in its oriental extreme by front moraines oriented East-West and controlled by the FFM. It limits the outcropping of the Jurassic Lemaire Fm to the south and of the Cretaceous Beauvoir Fm, to the north.

3) Western segment: It runs from the Fagnano Lake to the west coinciding with the sublatitudinal disposition to WNW of the Almirantazgo fiord of Magellan's Strait, totally inside the Chilean territory. It is also controlled by its glacial nature.

THE AUSTRAL-MAGELLAN BASIN IN THE FOOTHILLS OF THE FUEGUIAN ANDES

The thickness of the sedimentary fill of the Austral-Magellan Basin is very variable. In their axial portion (Última Esperanza Region, Chile) thickness of up to 8,000 m of sediments has been recognized corresponding mostly to the Upper Cretaceous and Tertiary and resting on thinner Early Cretaceous units. On the coastal portion away from the Austral-Magellan Basin the thicknesses of the sedimentary series vary between 1,000 and 2,000 m (Pittion and Gouadain, 1992), but on the northern end of Tierra del Fuego Island these thicknesses decrease notably.

The stratigraphic column shown in the Fig. 5 summarizes comparatively the more frequently used lithoestratigraphic terminologies in Tierra del Fuego Island in Chile as well as in Argentina (see Olivero and Malumián, this issue). The outcrops of the main sedimentary units are arranged in a concave form which surrounding the Fueguian-Patagonian Arch were rejuvenated toward the east, being the thickness of the sedimentary fill of the Austral-Magellan Basin is very variable.

Traditionally, the basement of the Southern portion of the Basin has been considered as of crystalline cratonic nature and attributed different ages. However, in the suture area between the Scotia and South America plates, the lithologic characteristics of the "technical" basement of the adjacent middle Cenozoic basins, vary highly from volcanic rocks of oceanic affiliation to progressively higher grade metasedimentites from the foreland toward the south. With regard to the crystalline rocks, very scarce Precambrian records are recognized: in the General Belgrano cape outcrop (Meredith Cape), in Malvinas Islands and in some cores radiometrically dated from the bottom of some wells of the oriental mouth of the Magellan Strait (Rio Chico High) and of the Ewing Bank (Deep Sea Drilling Project, 1977). Data from Biddle et al. (1986) allowed us to compile a structural map of the basement top (Tobífera Fm) in the Austral-Magellan Basin, based on 8,500 km of seismic data and 115 wells.

However, for the Argentine portion of Tierra del Fuego, Diraison et al. (1997b) remapped this surface increasing the depth in about 500 m, placing it at levels oscillating between -2,500 and -6,500 m. The geometry that exhibits this surface is rather homogeneous with an inclination toward the mountain front supporting the consideration of the sedimentary fill that recovers it as characteristic of a typical foreland basin.

Regarding the fossil dated Paleozoic sedimentary rocks in the southern Patagonia, they crop out only in the Malvinas Islands (Malvinas Group), in the *Deseado Nesocratón* (La Golondrina Fm) and in the Patagonian Cordillera of Santa Cruz's province (Bahía La Lancha Fm), although it is very difficult to correlate them (Limarino et al., 1999). Some scarce outcrops of polideformed rocks with no fossils on the Beagle Channel (Lapataia Fm) were attributed to the Paleozoic, but at present they are considered to be Jurassic-Cretaceous.

The absolute slope of the top of the basement from NE to SW dips 1.75° to the North and it is consistent with the slopes generally measured at different perpendicular directions to the Patagonian-Fueguian Arch front (Fig. 6).

Some seismic off-shore registration north of the Burdwood Bank exhibits great width seismic intervals attributed to Jurassic times (Oxfordian). Also, toward the southeast of Tierra del Fuego Island, metamorphic rocks of the Early Cretaceous (Yaghan Fm) are considered to belong to the Fueguian Cordillera.

The lithoestratigraphic record of the Austral-Magellan Basin begins with volcanosedimentites of the Tobífera Fm deposited during Jurassic times varying in thickness through the basins rift, reaching locally more than 2,000 m (Fig. 5). However, the sedimentation in the Austral-Magellan Basin begins with the Springhill Fm (Lower Cretaceous), constituted by basal deltaic fluvial sands

(Continental Springhill or Salmon facies, related to Oxfordian?). Shallow marine facies interfinger to their cuspidal portion (Springhill marine) with a thickness that varies from 0 to 200 m (Robles, 1984; Covellone et al., 1987).

The previous units are covered by the marine pelites of the Lower Inoceramus, Pampa Rincón and Rio Mayer Fms and/or equivalent. Marine marls of the Margas Verdes Fm were deposited under anoxic to sub-anoxic conditions within the Valanginian to Albian. These formations in the Patagonian-Fueguian Arc have a thickness of 1,000 m in the Southwest to 500-700 m in the northeast and they were first deposited in an extensional environment and then in marginal back arc basins. This paleogeographic location accounts for irrelevant change from East to West of the thickness of the Lower Cretaceous's units. In the Malvinas Basin, the units attributed to the Cretaceous reach maximum thickness of about 2,500 m (Galeazzi, 1998).

The Cretaceous rocks of the Andean region of Tierra del Fuego Island are formed mainly by marine dark

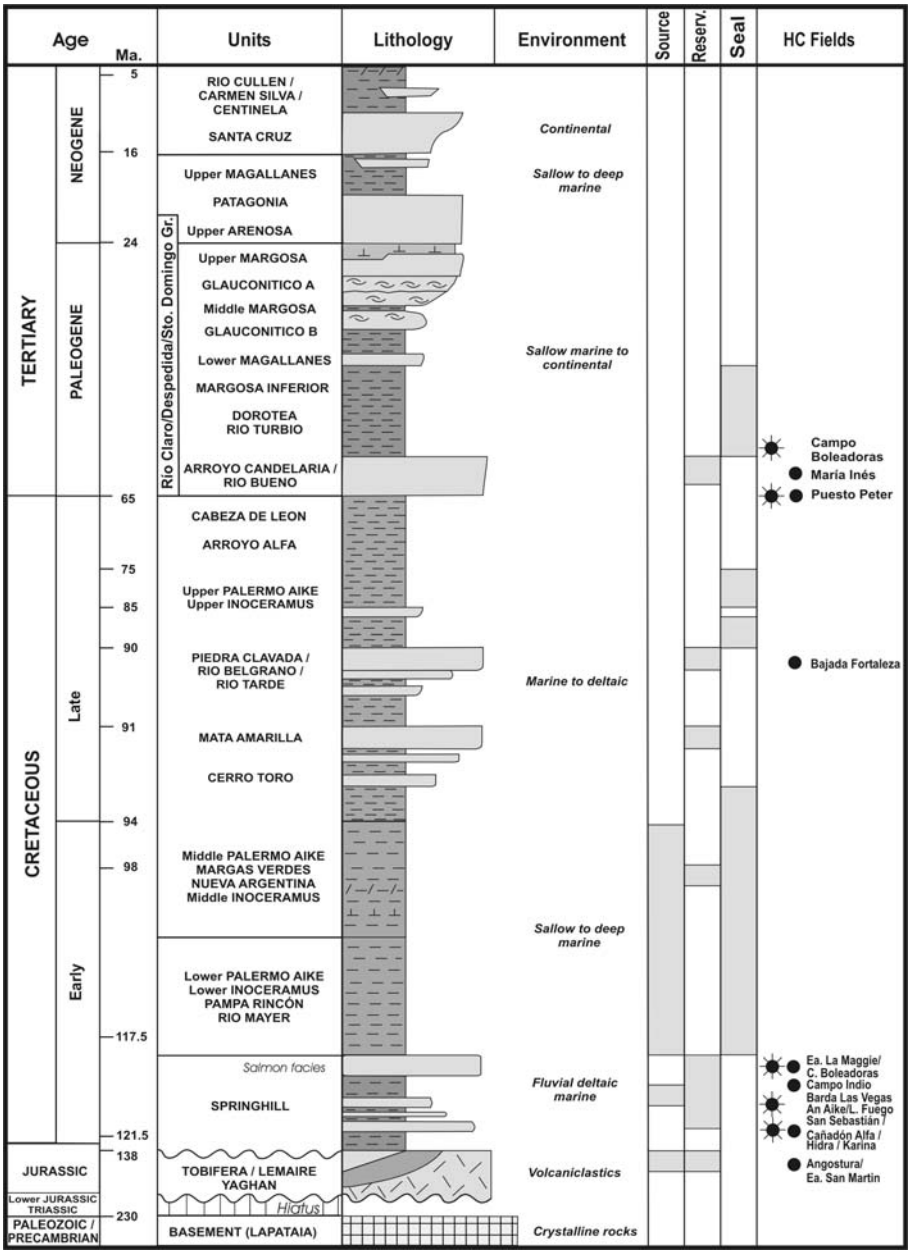

FIGURE 5 | **Lithostratigraphic column of the Austral-Magellan Basin displaying the most accepted unit names both in onshore and offshore portions and their HC properties. HC Fields: oil and gas (black stars) and oil producers (black circles) .**

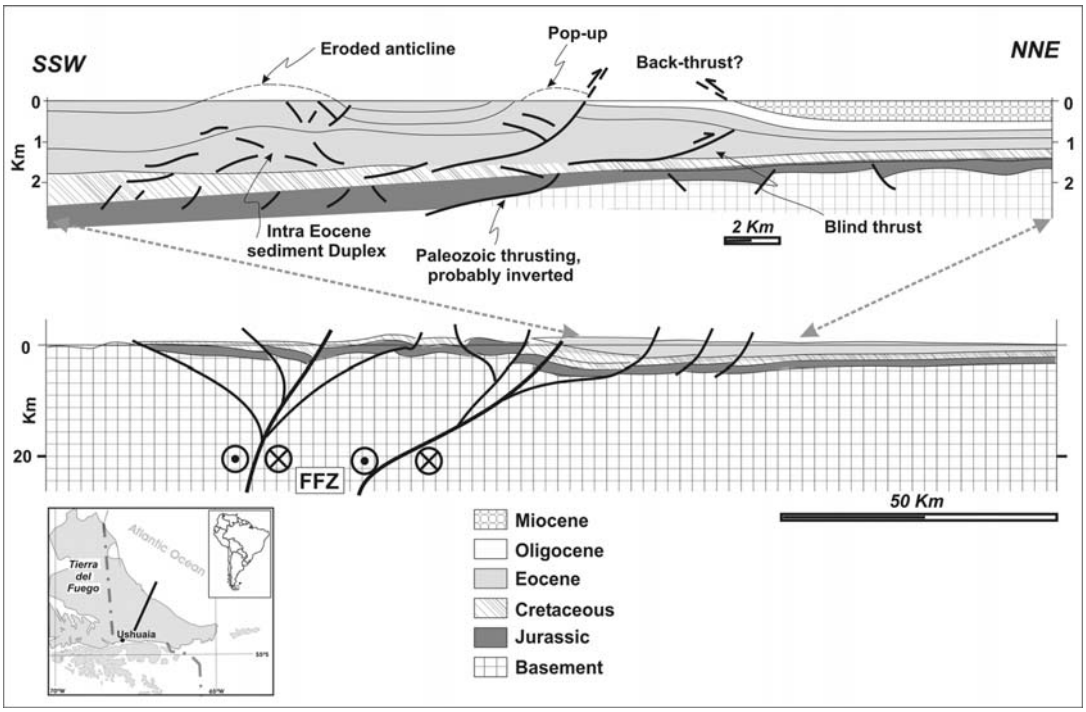

FIGURE 6 | **NNE-SSW trending schematic section (location in Figure 1) across the northern foothills of the Fueguian Cordillera (taken from Diraison et al., 2000). FFZ: Fagnano Fault Zone.**

pelites and mudstones. The apparent lithological homogeneity of these rocks, their complex structure and their scarce paleontological content, hinders its stratigraphic division and frequently makes difficult to differentiate the Lower Cretaceous from the Upper Cretaceous rocks in the field. On the other hand, in the steppe located north of the Fueguian Andes, the Cretaceous stratigraphy is better known through subsurface studies and drill cores (Flores et al., 1973; Biddle et al., 1986; Galeazzi, 1998).

The Late Cretaceous sedimentation reaching up to 3,000 m in thickness in the central portion of the Austral-Magellan Basin coincides with changes produced by the adjacent tectonic plates and the first stages of foreland development. The basin fill in the southern part consists of dark pelites that pass laterally to the north to sandstones with interbedded conglomerates (Río Belgrano, Piedra Clavada or Río tarde Fms; Fig. 5).

During the Upper Cretaceous and Early Tertiary the compression of the Andes range imposed a new deformational regime determining a depositional environment next to the foreland basin. Due to this Andean tectonic load, a strong basin subsidence took place along the eastern front of the Andes respect to the Patagonian foreland. The thickness increment of the Upper Cretaceous-Tertiary units from East to West is also well recognized in the Tierra del Fuego Island. From a depositional viewpoint, the sedimentary facies vary from deep water pelites and fan conglomerates in the southwest to glauconitic sandstones in the northeast, where they progressively overlap on the Río Chico High (Fig. 1).

The sedimentary record of the Lower Tertiary is represented in the Tierra del Fuego Island by the Río Bueno Fm that crops out along the East coast and includes well stratified coquiniferous and coaly levels, yellowish shales and sandstones with typical micropaleontology associations dated as Lower Eocene (Masiuk et al., 1990; Olivero and Malumian, 1999; Rossello et al., 2004b).

The Despedida Group attributed fundamentally to the lower to middle Eocene, crops out extensively along the northern Fueguino foothill and is constituted according to Olivero and Malumián (1999) by the following Formations: Punta Torcida (200 m of pelites), Leticia (500 m of sandstones) and Cerro Colorado (600 m predominantly pelitic), as determined along the Atlantic coast. The interbedded thick shale levels that would be involved in the structures constitute possible reservoirs. Figure 7 shows the remarkable discordance recognized to the bottom of the sequences of the Despedida Group.

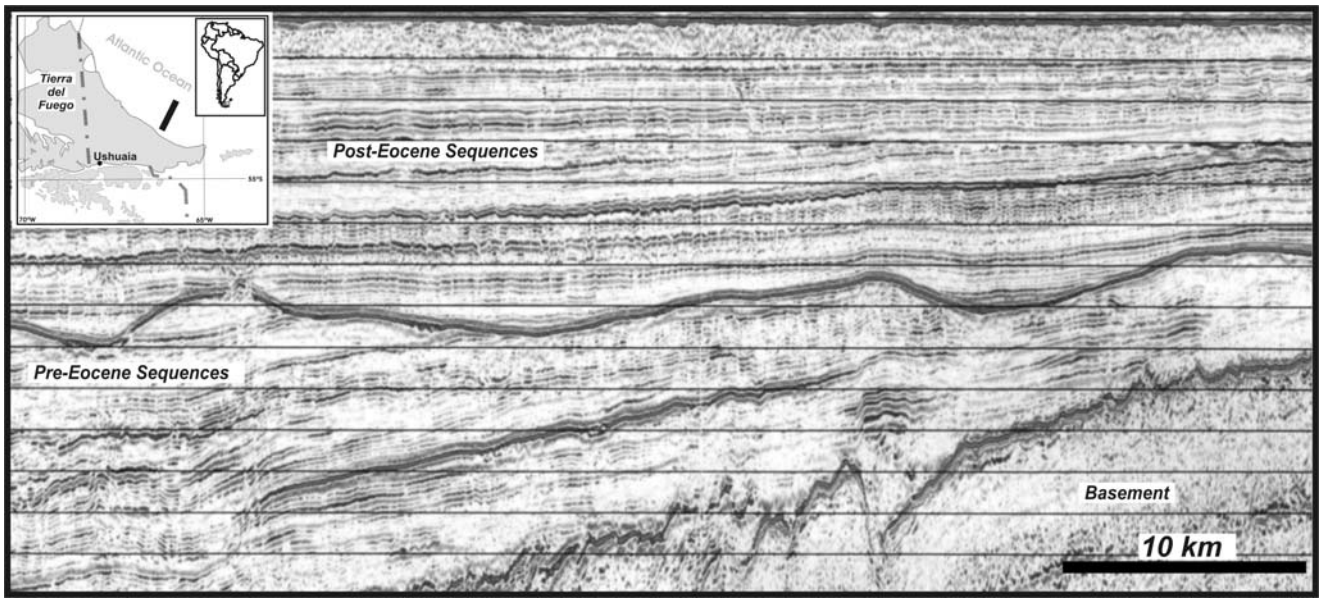

FIGURE 7 | **Seismic line showing the unconformity at the bottom of the Tertiary. Horizontal lines: 100 msec.**

The Upper Tertiary is mostly constituted by pelitic sedimentary units (Río Cullen Fm equivalent to Carmen Silva and Centinela Fms) disposed subhorizontally with very few evidences of constrictive deformation. In the northern end of the Tierra del Fuego Island normal faulting related to extension are recognized being subperpendicular to the orogenic front. These younger units are excellent regional seals.

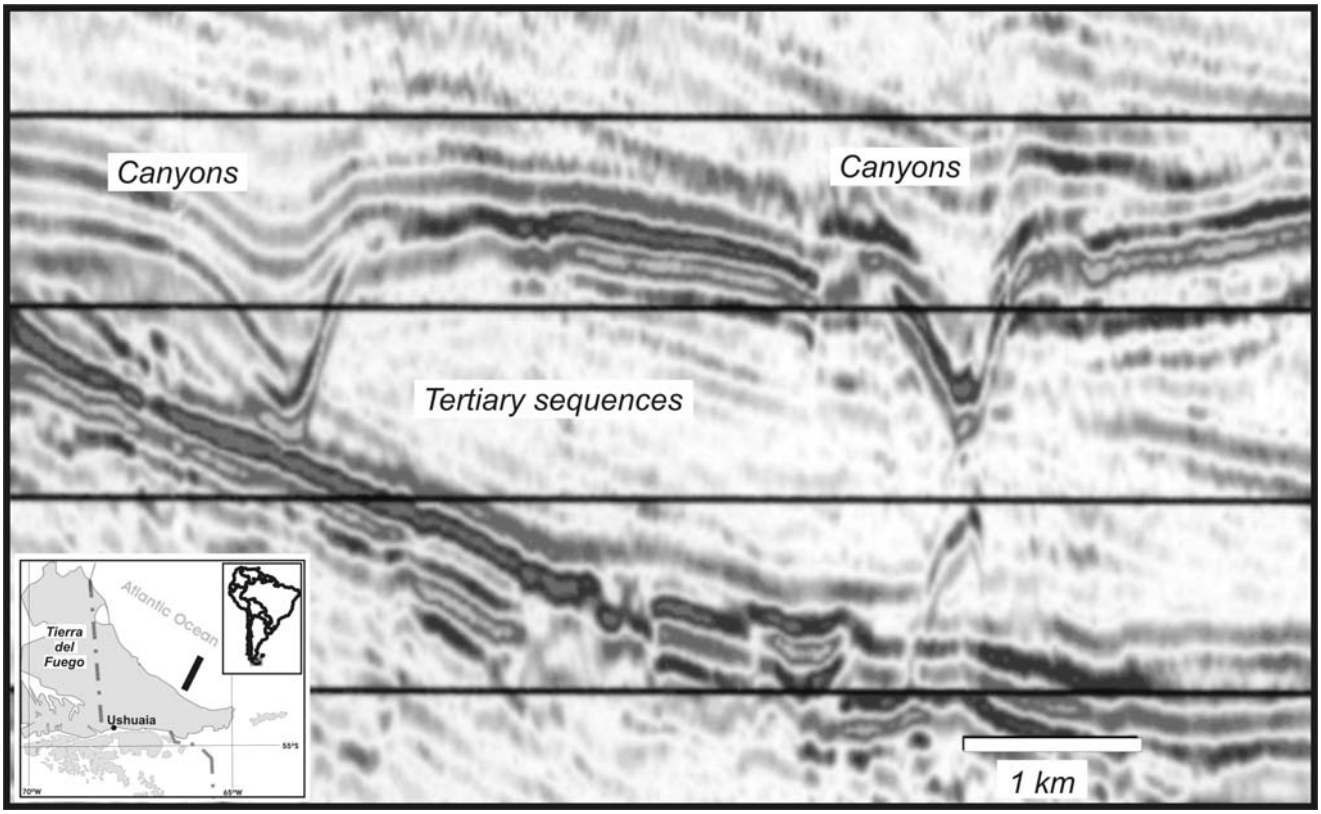

FIGURE 8 | **Seismic line showing canyons into the Tertiary sequences. Horizontal lines: 100 msec.**

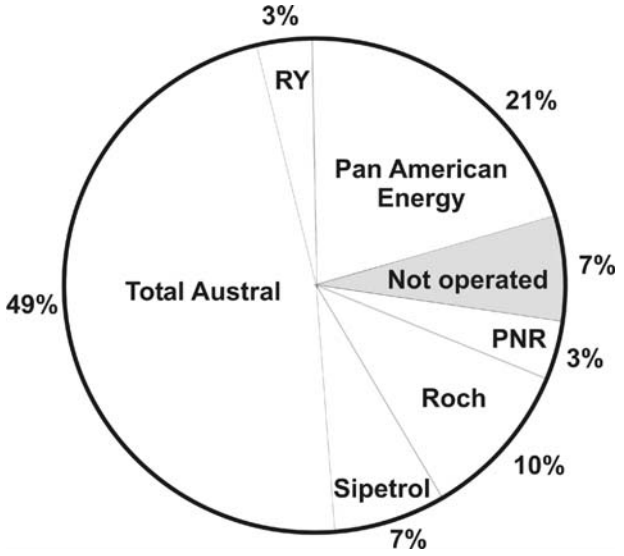

FIGURE 9 | **Surficial distribution of blocks by operating companies. PNR: Pioneer Natural Resources; RY: Repsol-YPF.**

It is also possible to recognize north-south trending canyons developed into the Tertiary sequences (Fig. 8).

EXPLORATORY HISTORY

The Magellan-Austral basin is the youngest of the 5 productive basins of the Argentina Republic (see more details in Turic, 2000; Schiuma et al., 2002). Their discovery history rendered positive results in 1949 (Thomas, 1949), 42 years after the first discovery of petroleum in the Gulf San Jorge Basin.

In the Argentine Tierra del Fuego Province the oil production is distributed among 6 operator companies in 28 blocks (Fig. 9). The Total Austral Company has 11 fields (Antares, Ara, Argo, Aries, Cañadón Alfa, Carina, Fénix, Hydra, Hydra Sur, Kaus and Vega Pléyade); Pan American Fueguina Company has 12 fields (Arroyo Gamma, Bajo Grande, Cabeza de León, Cabo Nombre, Cañadón Piedras, Carmen Silva, Laguna Escondida, La Sara, Los Chorrillos, O`Connor, San Goyo and San Sebastián); the Roch Company exploits 12 fields (Angostura, Cerro Cortado, Gaviota, Las Lagunas, Las Violetas, Los Flamencos, Puesto Quince, Rio Chico-Los Patos, Río Cullen, San Luis-Punta María, Sección Treinta and Sur Arroyo Candelaria). Finally, the Sipetrol Company produce from the fields Magellan and Poseidón, the Pioneer Company has the location Lago Fuego, and Repsol-YPF the Lobo field (Fig. 10).

The oil interest in the Argentine portion of Tierra del Fuego arose as a reflection of the activity developed in the neighbouring area of the Republic of Chile where, in 1945, commercially exploitable petroleum was discovered, after the Department of Mines and Petroleum of Chile carried out seven exploration drillings during the years 1930 and 1942 (Decastelli, 1984; Turic, 2000). Other wells had petroleum and natural gas shows but they were not commercial. The obtained results prompted YPF to begin field studies and the perforation of some study wells in Santa Cruz Province.

In the Tierra del Fuego Island subsurface studies was delayed for several years due to beginning of Second World War, since the Argentine company began to invest only in the other productive basins of the country. However, in the year 1946, the former Argentine state oil company YPF renewed the exploratory activity with seismic works and gravimetry north of Río Grande resulting in the confirmation of anticline axes and a closed structure on the Río Chico.

The drilling of the TF.x-1 well began at the beginning of 1949, finding accumulations of light hydrocarbons at a depth of 2,000 m in what today is known as the Springhill Fm. With this discovery, YPF continued with the exploration activities in the Island perforating up to 12 exploration wells and 18 development wells at the end of 1959.

Following this activity it was possible to delimit the location of the gas of Río Chico gas field and to discover the Los Patos (1952), Arroyo Gamma (1954), Río Avilés (1955), San Goyo (1956) and La Sara (1957) fields.

In 1959, YPF transferred to the Tennessee Argentina Corporation the management and execution of the exploration works and oil development in an area of approximately 14,000 km^2 in the island of Tierra del Fuego. Three years later the company had already been able to drill 70 wells, and discovered the Cabo Nombre, Las Lagunas, La Sara Norte, Sección Treinta, Arroyo Gamma Sur, Río Avilés Este, Laguna Escondida and Castillo fields. In 1960 the first shipment of oil from Tierra del Fuego was carried out for its refinement passing from 268,000 m^3 in 1960 to 590,000 m^3 by the middle of 1962.

Exploration continued through the following years being able to discover other fields: San Sebastián (1963), Cañadón Piedras (1966) and Cabeza de León (1968) fields.

New interpretations and geologic studies were finished in 1971 with the result of the discovery of the Cañadón Alpha field. In 1978 a law establishing the regime of risk contracts for hydrocarbon exploration and explotation was promulgated, and consequently several international companies launched exploration plans. In this way, off-shore areas were awarded to Exxon, Shell and Total. The axis of the search moved toward the sea.

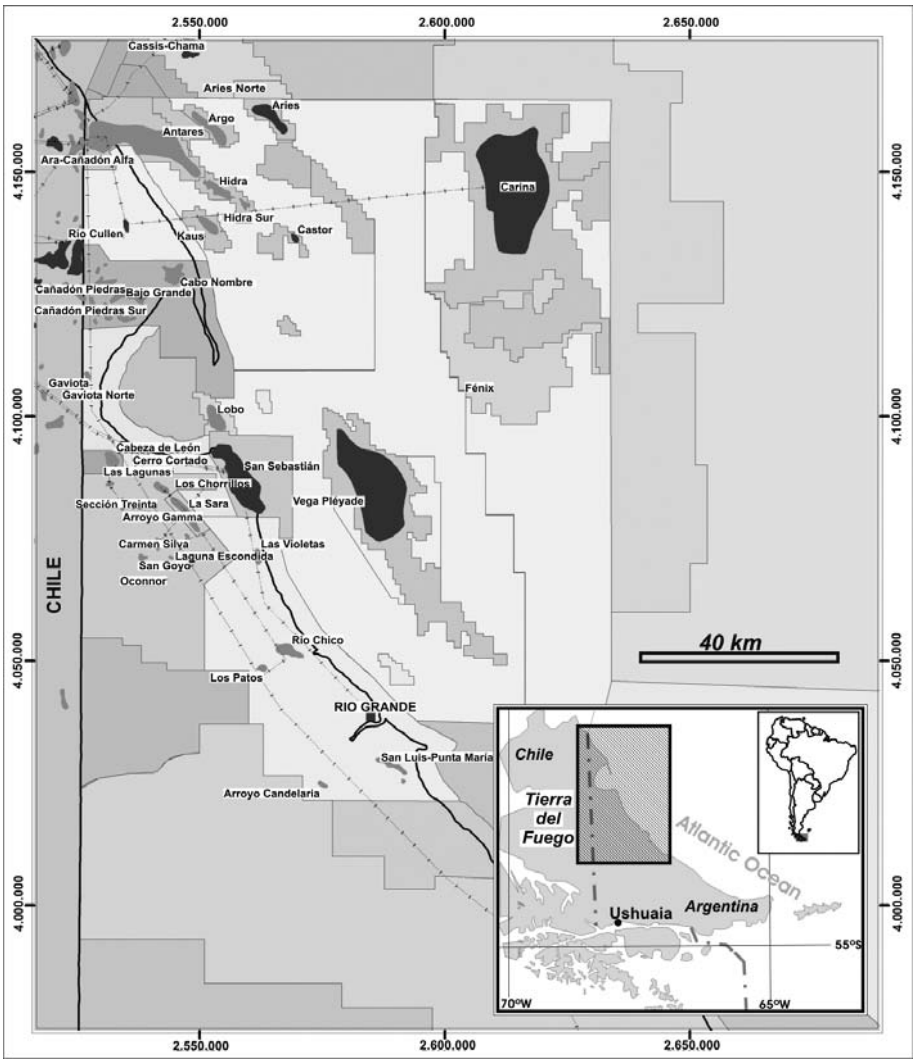

FIGURE 10 | **Oil and gas fields (black) distributed by operating companies in the Argentine Tierra del Fuego region.**

Of these three companies, Total was the one that achieved economically profitable discoveries in the Argentinean offshore associating with Deminex Argentina S.A and Bridas Austral Corporation to put into operation a study group dedicated to analyse the exploratory possibilities of the awarded blocks.

As a result of the exploratory effort the following discoveries were achieved: Carina (1988), Hydra (1989), Antares (1990) and Ara (1990).

Finally, in 1991, the joint venture between the Chilean state company Sipetrol and YPF put in production the Magellan field following the discovery carried out by Shell.

The significative number of both offshore as onshore wells drilled as well as the fields already discovered show the high potential of this part of the Austral-Magellan Basin. At present, the exploratory activity continues with great intensity for there are still unexplored zones, and favoured by the current market conditions.

The San Sebastián field

In order to exemplify the main characteristics of the locations of Tierra del Fuego, some aspects are described for the San Sebastián Field (Fig. 11). Located in Tierra del Fuego, in the south end of San Sebastián Bay, this field was discovered by YPF in 1963; it produces gas, petroleum and condensed from the Springhill Fm, i.e. the classic basin reservoir.

This field constitutes an elongated anticline with axis oriented NW-SE, being limited in its oriental flank by an important normal fault with the same orientation.

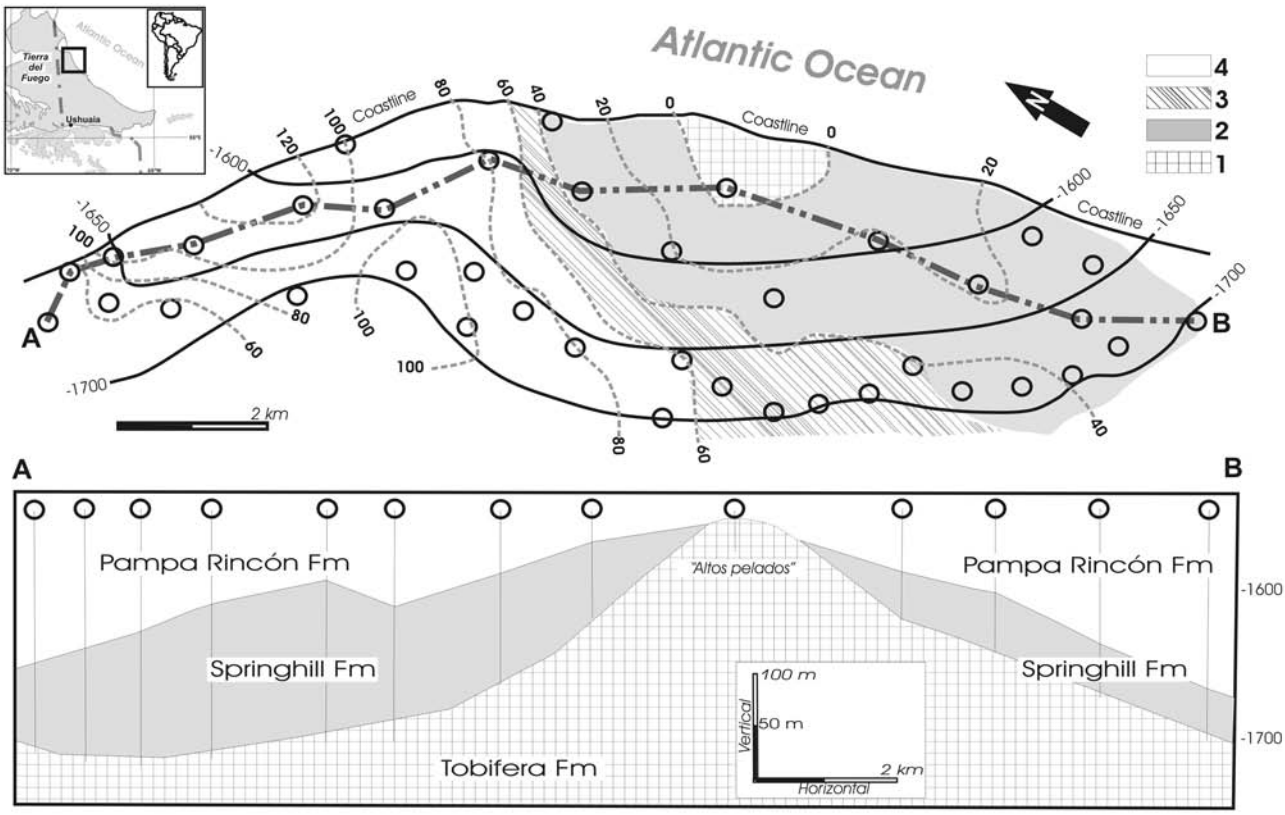

FIGURE 11 | **Onshore San Sebastián oil field characteristics (see location in Figure 10). Isopach and contour map of the top of the Springhill Fm and A-B cross section showing the productive structure (circles: production wells). Springhill Fm deposits: 1: missing; 2: continental; 3: transitional; and 4: marine and continental. Continuous line: structure contour on top of Springhill Fm (depth in meters below sea level). Discontinuous lines: isopach of total Springhill Fm (thickness shown in meters).**

Sandstones of the Springhill Fm compose the reservoir with a total thickness of 120 m with 20 producing m. It has an average porosity of 24% and a permeability that it varies from 42 md to 63 md. The depth of the top of the productive unit is of 1,632 mbbp (Fig. 12).

The total reserves of gas is 20,000 Mm^3 with a production of 4.75 Mm^3/d, and of petroleum they are 2 Mm^3 with a production of 400 m^3/d corresponding to June 2004.

PETROLEUM SYSTEMS AND HYDROCARBON MIGRATION IN THE FUEGUIAN AUSTRAL BASIN

Petroleum systems

In the basins Austral-Magellan and South Malvinas basins most of the hydrocarbons would have been generated in the context of two main oil systems: i) the Lower Inoceramus-Springhill (Robles, 1987; Decastelli and Arias, 1989; Pittion and Gouadain, 1992; Galeazzi, 1998; Schiuma et al., 2002), and ii) the Margas Verdes-Magellan (Villar and Arbe, 1993). In both cases the source rocks are the Lower Inoceramus and Margas Verdes Fms and their equivalents (Fig. 5), constituded by marine pelites and marls Valanginian to Aptian in age.

The mentioned marine deposits present good to regular generating potential with variable organic contents within 1 to 2% of TOC and a hydrogen index ranging from 150 to 550 mg/g (Pittion and Arbe, 1999). These authors mentioned the presence of continental shales with good organic matter contents associated to the main reservoir of the basin (Springhill Fm, Berriasian to Valanginian) whose contribution to the accumulations of hydrocarbons is not very well known to date.

In the Malvinas Plateau and diverse locations of Austral-Magellan basin Oxfordian synrift organic-rich matter deposits occur associated to the Serie Tobífera (Galeazzi, 1998; Uliana et al., 1989; González et al., 1998). Another remarkable mention of these deposits corresponds to Gran Bajo de San Julián in the northeastern end of the Austral Basin, where they appear to be lacustrine pelites assigned to the Upper Jurassic La Matilde Fm.

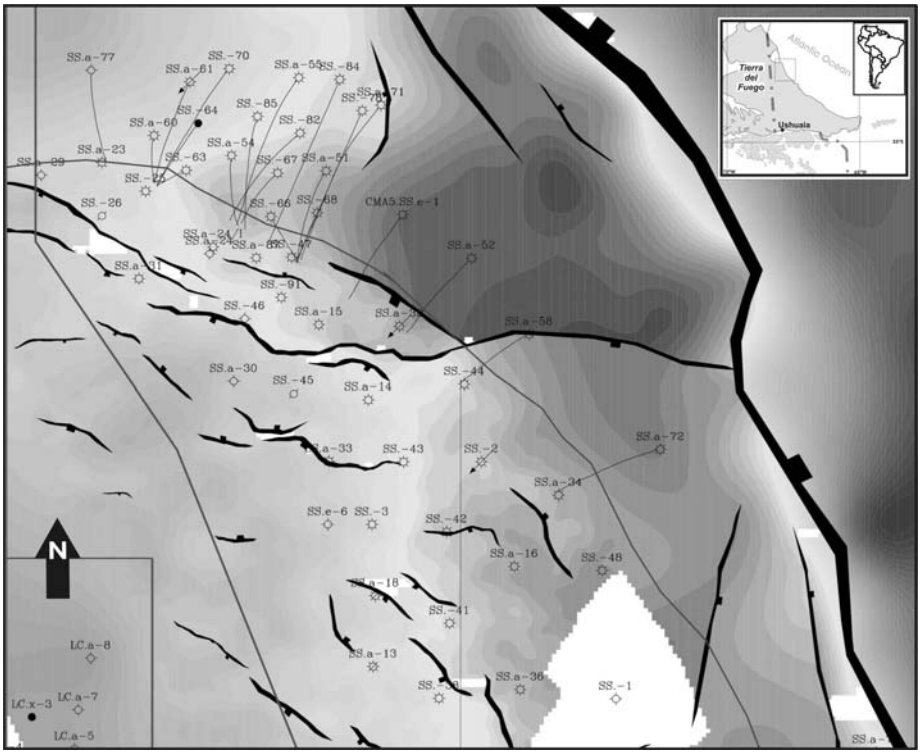

FIGURE 12 | **San Sebastián oil field, structural map (near top of Tobífera Fm), and producing wells (see location in Figure 10).**

The study of these pelites showed an organic content near to 10% of TOC of mixed organic matter of amorphous and structured material, a higher organic matter content that the one previously mentioned (YPF unpublished report, 1999). Thermal maturity ranges between 0.8 to 1.0% of Ro. In the environment of Tierra del Fuego two cases of Jurassic sedimentites belonging to the Serie Tobífera and with interesting organic matter contents and associated hydrocarbons have been reported.

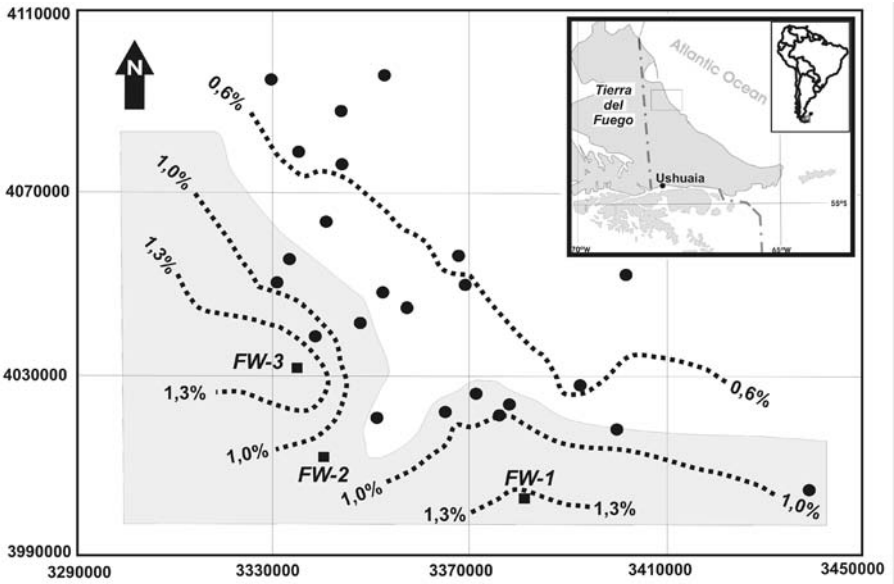

FIGURE 13 | **Maturity map at the bottom of the Pampa Rincón Fm on the northern part of Tierra del Fuego showing main production wells (black circles). The greyish area shows the hydrocarbon kitchen and black squares are the modelled fictitious wells.**

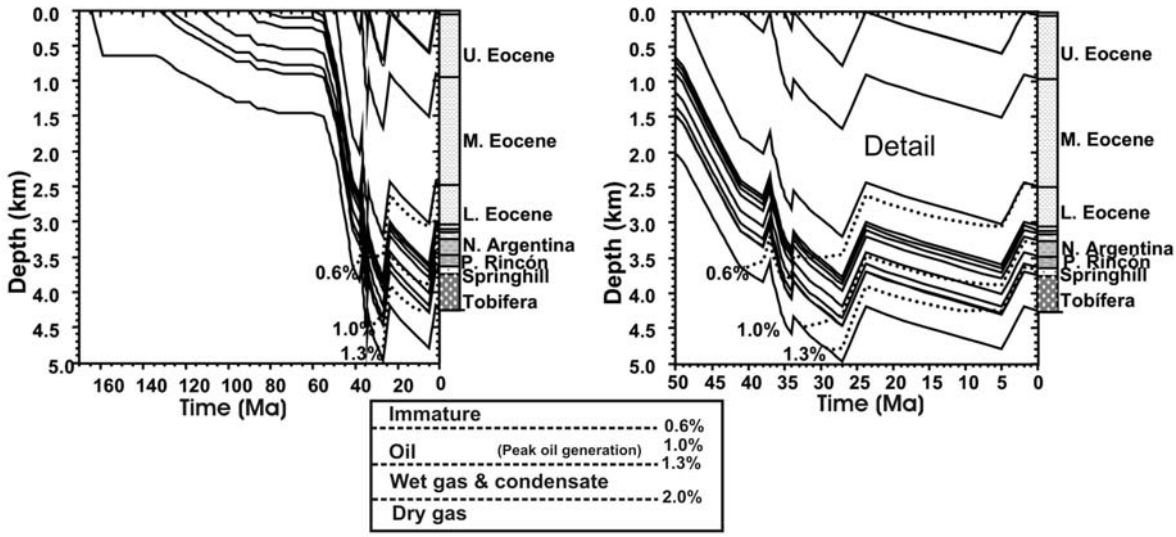

FIGURE 14 | **Burial history diagram and hydrocarbon generation zones of the northern part of Tierra del Fuego.**

Cagnolatti et al. (1996), describe Jurassic continental deposits for the floor of the Lemaire Fm with very good organic contents (2-7% of TOC) and proportions of organic matter ranging from the terrestrial types to sapropelic-amorphous. It is added to this that a petroleum sample hosted in the Springhill Fm of the Angostura field compared with rocks samples from Pampa Rincón, Springhill and Lemaire Formations correlate satisfactorily.

Bravo and Herrero (1997) described in the Chilean sector of Tierra del Fuego Island lacustrine pelites of Jurassic half grabens with TOC values of up to 6% and predominantly vitrinitic organic matter, partly sapropelic. These authors also mentioned the presence of oils that correlate to the mentioned lacustrine pelites.

Maturity and thermal modelling

The characterization of the thermal maturity at a regional scale shows that in Tierra del Fuego the generation windows adopt a half-moon pattern up to the west and south limits following the orientation of the folded and faulted belt (Laffitte et al., 1986). Figure 13 shows the distribution of the maturity areas referred to floor of Pampa Rincón Fm at present.

The models obtained show that the petroleum window runs from approximately 2,300 m up to 4,400 m. The area of humid and condensed gas expands and from this depth the dry gas window begins.

The modelling of a fictitious well located to the south of the producing areas (oil kitchen) shows that the generating intervals for the Cretaceous would fall into the oil window since 37 Ma (Fig. 14).

Migration of the hydrocarbons and timing

Pittion and Arbe (1999) proposed that the hydrocarbons of Lower Inoceramus migrated laterally and acumulate in Springhill Fm, due to the contact between both units. Since there is no physical relation between the source rock and a porous carrier, the hydrocarbons of Margas Verdes would have migrated vertically and accumulated in the Lower Tertiary.

Next to the continental shelf the fluids would have moved towards the sandy levels of the Springhill Fm (primary migration) to subsequently migrate laterally and cumulate in high sectors of the shelf (secondary migration). Towards the interior of the Austral-Magellan basin, several tectonic and sedimentary events would have contributed to the accumulation of hydrocarbons in areas not yet drilled.

CONCLUSIONS

The exploration and production of hydrocarbons in the studied region is mostly restricted to sandy levels of the Springhill Fm of both onshore and offshore portions of the Austral-Magellan Basin. Their infill is constituted by a Late Cretaceous to Tertiary sedimentary and volcanoclastic 8,000 m thick succession deposited on a folded and eroded basement cropping out along the northern foothill of the Fueguian Andes.

The main productive levels are sandy layers of the Springhill Fm and Tobífera Fm hydraulically related to the edging of Springhill Fm in the eroded basement highs known as "Altos Pelados" (translated as bolded highs). Also, diverse sandy levels of the Tertiary sequences are currently under study in order to evaluate their exploratory potential with no economic results up to date.

The foreseen exploratory potential includes both conventional plays related to transpression and inversion structural scenarios as well as new plays under study favoured by new tectosedimentary concepts influencing the petroleum systems as much as the market. Eventually, an additional energy potential for this region is estimated from the possible discovery of gas hydrates in the offshore portions of the area (Kostadinoff, 2001).

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