INFLUENCE OF TECTONICS AND SEA-LEVEL CHANGE ON SEDIMENTATION
OF THE JURASSIC SPRINGHILL AND TOBIFERA FORMATIONS,
CENTRAL TIERRA DEL FUEGO, CHILE - AN INTEGRATED STUDY.

by
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T-3603

A thesis submitted to the Faculty and Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Geophysics).

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ABSTRACT

An integrated exploration study of the central part of the island of Tierra del Fuego, Chile, reveals Late Jurassic rifting and the influence of tectonics and sea-level changes on deposition of the petroleum-prospective Tobífera Series synrift sediments and the overlying petroleum-productive post-rift Springhill Formation. A buried 35 km-wide Jurassic rift in the central part of the island was found using seismic data tied to well information. The rift trends northwest-southeast. There is a central-graben high within the rift. Other rifts are present in the region.

The thickest deposits of the synrift Tobífera Series are downthrown adjacent to the main graben-boundary faults. The Tobífera was subdivided based on seismic character. The youngest, more reflective section is thought to contain petroleum-prospective rocks and is limited in areal extent to the immediate downthrown sides of the major rift faults.

The Springhill is a transgressive deposit over a major unconformity on the top of the Tobífera Series. The Springhill consists of discrete subsequences (or parasequences) resulting from cyclical changes in relative sea level. These units are individually progradational and are bounded by marine flooding surfaces or their correlative
equivalents. At least seven distinct cycles are defined within the 200-m interval studied. In the deepest areas of the rift the lower part of the Springhill is dominantly continental deposits.

Springhill deposition was controlled by paleotopography shaped by differential erosion of the underlying Tobifera and reactivation of the rift faults. The thickest continental Springhill occurs in paleovalleys incised into the underlying Tobifera Series. These paleovalleys are controlled by the underlying rift faults. The areas of thickest Springhill are interpreted from the seismic sections by the presence of separate reflections from the top and base. At least one individual cycle within the Springhill is interpreted from the seismic sections and may be a separate facies. The thickness of the Springhill correlates positively to the thickness of overlying units within the Cretaceous and to the thickness of underlying Tobifera.

Application of the proposed models can reduce exploration risk. Division of the Springhill Formation into cycles may allow correlation of petroleum production to specific cycles or conditions. The areas most likely to have prospective Tobifera source and reservoir rocks can be defined using seismic data.
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INTRODUCTION

An integrated-exploration study was conducted in the Magallanes basin of Chile, the southernmost of the Subandean basins of South America (Figure 1). The study area lies in the central part of the island of Tierra del Fuego within the southern part of the Magallanes basin. The area of Chilean oil production, termed the Springhill District, is within the Magallanes basin and includes the northern part of Chilean Tierra del Fuego, adjacent Straits of Magellan, and land area north of the Straits (Figure 2).

Prior to 1917, exploration in this region consisted of the drilling of eight petroleum exploration wells without any success. Another seven wells were drilled in the thirties and early forties. None of these wells found oil in commercial quantities (Thomas, 1949a; Owen, 1975). The Corporación de Fomento de la Producción, from which the government oil company, Empresa Nacional del Petróleo (ENAP), was later formed, made the first commercial petroleum discovery in 1945 in what became the Manantiales field of northern Tierra del Fuego (Thomas, 1949b). Production was later established in other parts of Tierra del Fuego, in the Straits of Magellan, and on the mainland (Figure 2). These discoveries were primarily made using
Figure 1. Location map of study area with major geologic and geographic features. Structure contours are on the base of Cretaceous (from Russo et al., 1980).
Figure 2. Location of petroleum production in the Magallanes basin. Field outlines (black areas) from Petroconsultants (1989) and Robles (1987).
seismic data (Owen, 1975). Production during 1988 in the Chilean portion of the basin was about 24,400 barrels per day (González, 1989). Total production through 1987 is about 350 mmbbl (Oil and Gas Journal, 1988). Additional production occurs in the Argentine part of the basin.

Most of the petroleum production in the basin is from the Upper Jurassic to Lower Cretaceous Springhill Formation (Figure 3). The underlying Tobifera Series is considered by the author to also have potential. There is as yet no reported Tobifera production but ENAP is reportedly exploring for such (González, 1989).

Prior to starting this study the author worked periodically over several years for ENAP as a consulting geophysicist. It was felt that new exploration models could be obtained by integrating seismic data with other exploration tools to help control the interpretations. The integrated approach to this thesis included examining regional seismic data and extending the seismic interpretation to formations other than the Springhill, both above and below. The value of this integrated study is that the influence of tectonics on sedimentology of the Springhill and Tobifera Series is now recognized.

"Integrated exploration" as used in the first paragraph refers to integration of disciplines, tools, and geologic
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Figure 3. Stratigraphic column for Tierra del Fuego. Compiled by O. Jensen (unpublished).
ideas. The resulting ideas that are discussed in later sections are products of application of such thinking.

Data Base and Methods

The Empresa Nacional del Petroleo (ENAP) of Chile graciously provided proprietary seismic and well data for this study. Included were multifold seismic sections, and well logs and cores from 42 exploratory wells (Plate I; note that this plate is an index map of well and section locations, and place names). Twenty of the wells are located within the detail-study area.

All of the information remains the confidential property of ENAP and could not be revealed except as needed to illustrate the geological concepts and seismic phenomena interpreted during the study. Seismic-line locations and specific well identifications could not be shown due to confidentiality limitations.

Seismic and Well Data

About 2800 km of seismic sections collected from 1975 to 1987 were made available for this study. The bulk (78%) of the seismic records were recorded using explosive cord as a source. The rest of the seismic records were recorded half with vibrators and half with buried dynamite.
Reprocessing of 46% of the sections provided for the study had been done with modern techniques by ENAP. Many of the older sections were not of sufficient quality to contribute to this study. Those sections had one or more of the following problems: length of section too short to show the deeper Jurassic units, lack of deconvolution, poor stack (probably at least partially due to static problems). Most of the lines used had migrated sections. All figures show migrated sections unless otherwise noted.

Logs were provided from 42 wells that were drilled between 1948 and 1986. A length of 415m of the 675m of cores taken in those wells was examined for this study. Most of the wells had lithologic descriptions of the studied zone. Velocity surveys were available from 33 of the wells. Sonic logs were available for 20 of the wells and velocity surveys for 33.

Procedures Used

The study concentrated in the detail study area shown in Figure 2. Two sections of well and seismic data extending to the area of petroleum production to the north were also included to test how models could be applied to adjacent areas and to show a more regional geologic setting (Plate I).
The general procedures followed to accomplish this study included:

- Correlation of the well logs to determine depths of various formation tops and markers, and unit thickness. (Because various good markers exist the quality of the correlations is considered to be reliable).  

- Initial interpretation of Springhill configuration and sedimentation based on logs. This involved correlating downward within the Cretaceous section to the point where correlation was lost just above Springhill and then constructing cross sections hung on markers above the Springhill.  

- Interpretation of the Cretaceous and Jurassic structural configuration and formation thicknesses from the seismic sections tied to the wells. Synthetic seismograms and synthetic stratigraphic sections were used.  

- Correlation of various formation thicknesses measured in the wells and on the seismic sections.  

- Study and general description of the well cores.  

- Synthesis and integrated interpretation of all of the above information.
Seismic Interpretation Technique

Synthetic seismograms were generated for the twenty wells with sonic logs. Density logs were used where available. Frequency and phase scans were made. The best fit to the sections was a normal-polarity Ricker wavelet with frequency ranging from 20 to 25 Hz, depending on the section being matched. For other wells velocity-survey times were used to tie the wells to the seismic sections. Synthetics were displayed with the same amplitude and wavelet within each figure so that character variations seen are due only to acoustic impedance differences.

Seismic-stratigraphic modeling was performed to determine the variation in character expected with change in thickness of the Springhill. Time-structure contour maps of the top of Springhill and time isopachs from C-1 to Springhill and Springhill to base reflective Tobifera were made (Plates II, III, and IV).

The faults were located on the seismic sections using various criteria including bed terminations, bed offsets, structural discontinuity, dip changes, fault drag, flexure over the faults, sags over grabens, fault-related deposition, and loop misties. There are undoubtedly many more faults than are marked but just those considered reasonably reliably located are noted.
Organization and Contributions of Thesis

The discussion below is organized into four areas of contribution from this study. The study started with the seismic delineation of a previously unmapped 35 km-wide pre-Springhill Jurassic rift (graben system) and the definition of its structural character. The rift is one of several within the region. The mapped rift trends northwest-southeast. There is a central-graben structural high within the synrift Tobifera volcanics and in the overlying Springhill Formation. Many of the rift-related faults exhibited recurrent movement and influenced the distribution and thickness of Tobifera, Springhill, and overlying Cretaceous sediments.

The second contribution resulted from the examination of the seismic character of the Tobifera Series. The Tobifera Series was shown in this study to consist of at least four seismic-stratigraphic units. Tobifera sedimentary wedges as defined on seismic data may contain future targets for future exploration.

The third item discussed is the sedimentological character of the Springhill Formation. The post-rift Springhill Formation is interpreted in this study as a transgressive clastic sequence consisting of a generally
retrogradational set of at least seven discrete
progradational units, each bounded by marine flooding
surfaces. The sequence starts out as a continental
sediment-dominated valley-fill over a major unconformity on
top the Tobífera Series volcanics and volcanioclastics.

Finally, a model of Springhill deposition as controlled
by normal-fault reactivation, paleotopography, and
differential erosion of the Tobífera is presented. The
areas of thickest continental Springhill are in paleovalleys
whose locations were fault controlled. These areas of thick
Springhill can be recognized on the seismic sections by the
presence of two or more separate peaks. The thicker areas
of the Springhill correlate generally to the thicker areas
of overlying units within the Cretaceous and to the thicker
areas of underlying Tobífera Series.

The models and methods developed herein could apply to
petroleum exploration and development throughout the
Magallanes basin, in both Argentina and Chile. Hopefully,
models proposed herein will allow better prediction of the
areal extent and geometries of Springhill-Formation
sandstone reservoir facies. Separation of the Springhill
Formation into cycles may allow facies division of the
Springhill.

Areas more likely to contain prospective Tobífera rocks
can be outlined. Thicker wedges of Tobifera rocks that possibly contain source and reservoir rocks can be identified.
JURASSIC RIFT TECTONICS

Jurassic extensional rift-tectonic features are evident on many of the seismic sections in the study area (Plates V to VII). Locations of several major grabens (rifts) were defined (Plate I). These are the Calafate graben, the Chañarcillo/Manantiales graben, the Gaviota half graben, and the Central-Fueguinian graben (Plate I). The Central-Fueguinian graben (CFG) (name chosen by the author) was studied in detail and is the focus of this thesis. The term rift is herein used in the sense of Bates and Jackson (1987) to mean "a graben of regional extent" or "a long narrow continental trough that is bounded by normal faults".

The structural characteristics of the Central-Fueguinian graben were compared to those for rift, strike-slip, and other styles given by Wernicke and Burchfiel (1982), Lowell (1985), Lister et al. (1986), Park (1988), and Scott and Rosendahl (1989), and to characteristics of strike-slip styles given by Reading (1980), Christie-Blick and Biddle (1985), and Zolnai (1988). The majority of evidence supported a rift setting. For discussion on rift tectonics and extensional faulting the reader is referred to the above authors.

Seismic and well-log cross sections across the Central-
Fueguinian graben show that the configuration of the rift includes boundary faults that are larger than the numerous intra-rift faults, a mid-graben high, and thicker Springhill and younger section within the graben than outside of the graben (Plates IX-XI). These and other characteristics are discussed in detail below.

Pre-Tobifera basement was not encountered in any of the study wells. However, a few of the other wells on Tierra del Fuego encountered basement rocks. Halpern (1973) reported that Cuarto Chorillo #9 (near study well 32) and Maria Emilia #2 (near well 38) reached granodiorite. The Maria Emilia #2 well encountered crystalline basement below a little over 100 m of Tobifera. A date of 267 ±3 mybp for the basement of the latter well is reported by Natland et al. (1974). Cormoran #1 (near Maria Emilia), Posesión #1 (north of the Straits), and Dungeness #1 (in the Straits) encountered granodiorite gneiss (Natland et al., 1974).

Precambrian and Paleozoic metamorphic rocks are reported in some wells of the Manantiales oil field near the north end of Tierra del Fuego (Zambrano and Urie, 1970). The seismic data can only define basement as nonreflective section below the Tobifera. However, some of the Tobifera is also nonreflective so that the two cannot be distinguished (discussed later). There are a few possible reflections
within interpreted basement that are angular to the overlying Tobifera but the information is not considered reliable.

A schematic diagram of the tectonic sequence is shown in Figure 4. The basement was overlain by Tobifera volcanics and volcanioclastics that resulted from Middle to Late Jurassic extension (Gust et al., 1985). That extension produced a number of rifts; the Central-Fueguinian graben and the Calafate graben are two that are shown in the figure. The rifting produced rotated fault blocks of Tobifera-Series rock (Figure 4-A). Fault-controlled deposition occurred in response to tectonic activity. The seismic shows distinct depositional wedging within the uppermost part of the Tobifera in the margins of the Central-Fueguinian graben. At the end of Tobifera time a major unconformity formed. Paleotopography on the unconformity surface was influenced by the underlying rift tectonics and differential erosion (Figure 4-B).

Continental Springhill deposition followed by marine Springhill deposition occurred as the sea transgressed across the unconformity (Figure 4-C). Cretaceous marine rocks were deposited above the Springhill with "sags" above some of the earlier grabens due to recurrent fault-block tectonics. During the Tertiary the area tilted to the
Figure 4. Schematic diagrams showing tectonic development of study area. (A) Early-extension stage. (B) Development of erosional surface on the Tobifera with concurrent deposition of clastic wedges. (C) Marine transgression, deposition of Springhill Fm. (D) Deposition of Cretaceous marine sediments above the Springhill with continued lesser movement on rift faults. Ba = crystalline/metamorphic basement (cross pattern). T = Tobifera (lined). SH = Springhill Fm. (stippled). K = Cretaceous sediments. CFG = Central Fueguinian graben. CH = Cullen high. CG = Calafate graben. Not to scale.
southwest as the molasse wedge from a thrust belt to the southwest was deposited (Plate V).

Seismic Expression of the Rift within the Tobifera

The recognition criteria for structural styles defined by Harding and Lowell (1979) and Lowell (1985) for various tectonic conditions were augmented by the author (Table 1). The characteristics seen in the study area were compared to those criteria to identify tectonic style. Pre-Springhill rift tectonics (basement-involved extension of Lowell, 1985) are indicated within the study area by the comparison that used both section and map views (Plates I-VIII). Those characteristics, discussed below, include normal faults, tilted fault blocks (implying listric faults), straight dip within fault blocks, drape folds, zigzag fault pattern, relay faults, and overall graben shape.

The Tobifera series consists of tilted fault blocks with straight segments of bed dip between normal faults (Plate VI, Figure 5). The dip measured from the seismic sections is generally below 15°, with a few cases of 20-25° dips. The fault blocks are asymmetrical when viewed on a local scale. On a broader scale, the Central-Fueguinian graben is generally symmetrical to the depth seen on the seismic sections.
Table 1: Recognition criteria for tectonic styles. This was used to help define the structural style(s) in the study area. Modified and augmented from Lowell (1905).

<table>
<thead>
<tr>
<th>Style</th>
<th>Tectonic Environment</th>
<th>Recognition Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Convergent margins</td>
<td>Divergent plate margins</td>
</tr>
<tr>
<td>B</td>
<td>Convergent thrust belts</td>
<td>Continental rifts, back arc, accretionary wedge</td>
</tr>
<tr>
<td>C</td>
<td>Divergent thrust belts</td>
<td>Reverse-fault blocks, asymmetric folds</td>
</tr>
<tr>
<td>D</td>
<td>Tensional margins</td>
<td>High-angle, thrust-belt cores</td>
</tr>
<tr>
<td>E</td>
<td>Normal fault assemblage</td>
<td>Strain-dominated shear zones, strike-slip faults</td>
</tr>
</tbody>
</table>

Note: The table outlines various tectonic styles and their associated recognition criteria.
Figure 5. Seismic section across the San Sebastián fault (to the right of "B3"; see location in Plate I) showing the tilted Tobifera blocks. A, B1, B2, and B3 are seismic sequences within the Tobifera. T1 is top of Tobifera, S1 is top of Springhill, and G7 is approximate top of Cretaceous (see Figure 3). Note the continuous reflectivity of the Tobifera B3 zone. Note also the separate events for the top (S1) and base (T1) of the Springhill.
The volcanics in the Tobifera are a result of the rifting (Gust et al., 1985). The parallelism of the Tobifera units seen on most of the seismic sections within the graben and the distinct angular unconformity over the Tobifera (Figure 5, Plate VI) show there was major fault block movement and tilting after deposition of much of the Tobifera. Post-Springhill (Cretaceous and earliest Tertiary) normal reactivation or continued movement along the rift faults is expressed as upward continuation of the faults, distinct drape folds over the faults, and sags on the downthrown sides of the faults (Figure 6).

In rare cases there is folding within the Tobifera or Springhill in what appears to be fault drag, reverse drag, and/or drape, particularly along the San Sebastián fault (Figure 5). This folding is correlated to occurrence of additional synthetic faults parallel to the main boundary fault and is thought to be the same as folds seen on published seismic sections from the East African rift zone (Scott and Rosendahl, 1989). It is also very similar to commonly occurring downthrown folds seen by the author in the extensional setting of the Gulf Coast passive margin. Similar structures related to the extensional rifting of the Viking graben are interpreted by Bertram and Milton (1989) to be a result of early rapid fault movement and block
Figure 6. Seismic section to northwest of well 6 showing sag within the Cretaceous sediments (between G7 and S1) above a Jurassic graben. Section length is 16 km.
rotation followed by passive infilling, with the folds being a result of compaction drape and fault geometry. They interpreted "drape-slip faulting" that can be a non-tectonic result of compaction only.

Some of the folding may be related to deposition of an alluvial wedge. In one nearby area (around well 12) is seen distinct wedging that is interpreted to be an alluvial fan that resulted from movement on the San Sebastián fault during deposition (Figure 7). The extent of that wedge is outlined on Plates I and IV.

Within the major grabens the Tobífera was eroded generally flat and then had recurrent movement before, during, and after deposition of the Springhill, with the thickest and oldest Springhill being deposited along the boundary faults. In the areas outside of the grabens such as around wells 39 to 42 the Tobífera was eroded to a surface with cuestas of more resistant rock. The Springhill filled the lower parts of that surface, onlapping onto the higher areas.

The major faults in the Central-Fueguinian graben are the boundary faults along the northeast and southwest sides (Plate I). Freund and Merzer (1976) noted that rift-border faults in their models are not only the largest but also occur earlier than the interior faults. There are many
Figure 7. Seismic section across the northern boundary fault of the Central-Fueguinian Graben (BF). Note the wedge of rock thinning to the left (south) that is interpreted to be Tobifera alluvial-fan deposits (within area marked with arrows) and the possible slumping within the Cretaceous section. S1 marks the top of the Springhill, G7 top of Cretaceous. Note possible seismic expression of thin Springhill fan near TD of well 12 between triangles.
smaller and less-continuous faults within the system of faults. The faults are labeled as normal on the plates but reactivation in other senses could have occurred.

**Zigzag Pattern of Faults**

Based on the pattern mapped using the seismic data, the average directions of the irregular faults in the Central-Fueguinian graben are parallel and trend NW-SE. However, in detail the faults are seen in plan view as shorter straight segments in a zigzag pattern (Figure 8 and Plate I). Many of the sharp bends could be drawn curved without dishonoring the data. However, where faults cut several of the more closely spaced lines they frequently were aligned as straight segments. Thus the straight-line style was used in areas of lesser control.

Lowell (1985) pointed out that there have been various explanations for the zigzag pattern of rift faults. He suggested a well developed dog-leg pattern of faulting would have originated as an extensional sag feature as opposed to arching or doming. Arching is thought to produce parallel faults that are unidirectional in strike. Those ideas are supported by the modeling of Lowell and by the modeling and theoretical analysis of Freund and Merzer (1976). Their calculations show that the maximum principal stress is
Figure 8. Tectonic framework of Tierra del Fuego with rose diagram of normal-fault directions within the Central-Fueguinian graben. Hachures on downthrown sides of normal faults. Circles are wells. More detail in Plate I.
horizontal parallel to the rift axis within the rift, and that it produces conjugate shears which control the orientation of the upward propagating normal faults. They showed with clay models that zigzag fault patterns develop due to horizontal attenuation.

Fault and Graben Orientation

The strikes of the better-controlled segments of the faults in the Central-Fueguinian graben were measured and plotted on a rose diagram (Figure 8 and Plate I). That plot shows the proportion by length of faults in each ten-degree segment of direction. The distribution of fault strike is bimodal with predominant directions of NNW-SSE (110°) and WNW-ESE (150°). When the major boundary faults and the faults within the graben were plotted separately a similar distribution was seen on both. The deviation angle (40°) between the predominant directions is within the range of 30 to 60° reported by Freund (1982) for zigzag faults in extensional rifts, and the range of 20-40° for the East Africa Rift Valley (Freund and Merzer, 1976).

The bimodal distribution indicates that the assumption of straight segments of faults is valid. A more even, unimodal distribution would have resulted from random sampling of curved faults.
The perpendicular to the weighted average of the directions was calculated to be along a bearing of 43° (NE-SW; Figure 8). That would be the direction of regional extension and minimum principal stress during the rifting. The orientation of the Calafate graben and the Gaviota half graben to the north is similar, but the less-clearly-defined fault system at Chañarcillo/Manantiales is oriented more northerly.

**Relay Zones**

In the Central-Fueguinian graben there are various fault-relay zones (mapped with the seismic) where the throw on one fault decreases in correspondence with the throw increasing on another parallel overlapping fault. Relay here refers to overlapping faults parallel with each other and with the general deformation zone, as opposed to en echelon faults which are oblique to the zone of deformation (Harding and Lowell, 1979; Christie-Blick and Biddle, 1985). The relay phenomenon occurs with both left and right stepping, even within a single fault system. Some of the relay zones are marked on Plate I. The pattern that develops is very similar to that shown by pull-apart modeling (Lowell, 1985, his Figure 4-18) and has been noted in rifts exposed at the surface (Baker, 1986). Christie-
Blick and Biddle (1985) note that the relay zones characterize regional extension or shortening as opposed to en-echelon faults which are associated with strike slip.

**Character of San Sebastián Fault**

An east-to-west sequence of seismic sections across the San Sebastián fault is shown in Figure 9. The north boundary fault is small in throw near the Argentina border (Figure 9, part a, top). To the northwest throw increases and the fault splits into two or more parallel faults near well 14 (Figure 9, part b). Further northwest it forks as it dies out toward the paleotopographic high at well 18 (Plate I).

The largest part of the fault movement occurred pre-Springhill. However, the San Sebastián fault cuts up through the entire Cretaceous section. At G-7 either the upper part of the main fault flattens upwards, or slumping occurred during Late Cretaceous or earliest Tertiary time (Figure 9, part b and c).
Figure 9(a). Caption on next page.
Figure 9(b) (continued). Successive parallel SW-NE sections from east to west across the San Sebastián fault. Horizontal and vertical scales are approximately equal and are same on all sections. Each section 14 km long. Middle section of 9(a) is unmigrated, others are migrated.
Figure 9(c) (continued). Caption on previous page.
Graben-Margin Thicks and Central-Graben Highs

The structural configuration on the top of the Springhill (Plate II) shows areas of closed lows concentrated along the major boundary faults of the Central-Fueguinian graben. The seismic sections across the graben also show the deeps (Plates V and VI). These deeps include the low at well 12 and the low area west and southwest of wells 3 and 4, and correspond to the areas of thickest reflective Tobifera (Plate IV). Some of the thickest Springhill section is also located there (Plate III). The lows also correspond to the more distinct sags of the entire Cretaceous section such as the one seen in Figure 6 (page 21).

Another general characteristic of the graben is the structural high in the central part of the graben that is seen on the well data and the seismic sections. The high follows an irregular line along the length of the graben (Plate IV). Axial highs are a characteristic of rift zones (Scott and Rosendahl, 1989)

Possible Strike-slip and Reverse Fault Movement

In any rift some component of strike-slip motion can be expected as an accessory element and evidence of such was
sought during this study. Also, rift faults could be reactivated with strike-slip component. Structural configurations which are difficult to explain could imply strike-slip movement occurred.

Models have been proposed that include both normal and strike-slip faults. For example, Bally and Snelson (1980) show a model that consists of rifts similar to the Central Fueguinian graben which are offset by strike-slip transforms. This is the "graben overstep" of Harding et al. (1985). The Central-Fueguinian graben would fit into such a model if a major transform existed to the northwest between it and the rifts on the north of the island.

Three items were seen in restricted parts of the study data that could be interpreted to indicate strike-slip motion. First, some transtensional strike-slip motion could be suggested by the location of the deepest areas of the rift basin at concave-inward bends in the boundary faults. The location of the thicker section at well 12 more to the southeast within the bend might suggest left-lateral movement. The pattern of lows could also be interpreted as alternating linked half grabens forming on opposite sides of the rift according to the rift models of Scott and Rosendahl (1989). That model is preferred by the author since most of the characteristics seen on the seismic sections would
better fit a rift model.

Some variation in structural character occurs due to the overprint of later Andean tectonics. In the southernmost part of the study area the development of the Tertiary fold and thrust belt to the south can be seen to extend into the rift. There are compressional folds and a distinct Tertiary molasse wedge above the Cretaceous sediments (Plates I, V). In the thrust belt the author has interpreted various Cenozoic thrusts that are in part bed parallel detachments. The northernmost limit of related detached compressional folding within the Tertiary rocks is noted on Plate I and is seen on Plate VIII at SP 210 above 1.5 sec.

Some of the Jurassic normal faults have been reactivated as reverse faults, transpressional wrench faults, or combination of the two. The example in Plate VIII (SP 240), near the northern limit of thrust influence, shows reverse throw at the top of the Cretaceous but normal throw at the Springhill. There is deformation and thickening above the fault, features that are very similar to the model shown for other basins by Cohen (1982; Figure 10) and Gibbs (1987).

The reactivated fault of Plate VIII could be interpreted from that section by itself as an effect of a
Figure 10. Model for reactivation of normal faults in reverse sense (from Cohen, 1982).
transpressional wrench fault or a lateral reactivation of a normal rift fault. The strike of the Cenozoic thrust faulting (Plate I) indicates a direction of compression to the NNE. Because the dip of the normal rift faults is more NE-SW we can expect some right-lateral slip to occur during reactivation if compression is perpendicular to the thrust front. This model may be complicated by the fact that the thrust belt turns more northward along trend to the northwest, becoming parallel to the rift trend across the Straits of Magellan due west of Bahía Inútil. Given the regional setting at the edge of the thrust belt the author feels that the reactivation is most likely reverse reactivation, perhaps with a minor lateral component of motion.

The location of some of the Cenozoic compressional folding is felt to be at least partially controlled by the position of the underlying rift fault blocks. In particular, the major south-bounding fault is located below where thrusting is interpreted to cut up through the Tertiary section to form a fold. The comparison of the locations of the folds and the normal faults can be made on Plate I. The offset of the folds from the location of the earlier normal faults assures that these are detached structures and not a result of reactivation of the normal
basement-involved faults.

A third evidence of strike-slip motion could be interpreted from the fold near the San Sebastián fault at well 14. However, for the reasons explained above under Seismic Expression of the Rift, the author feels that the fold is an expression of extensional tectonics and if strike slip occurred at that point it was probably only a minor component.

The direction of the grabens may be influenced by basement structure. The overall strike of the Central-Fueguinian graben (N45W) is parallel to the direction of the underlying Lago San Martin Paleozoic basin (N40-50W from Figure 1 of Urien et al., 1981).

Influence of Tectonics on Sedimentation

Later sections will discuss in more detail the effect that the rift tectonics had on deposition of the Tobifera and Springhill Formations. The first direct result is the restriction of deposition to areas of limited lateral extent as controlled by the rift faults. Restricted basins formed during Tobifera time could have been the site of potential lacustrine source-rock deposition and the localization of fan-delta reservoir beds (for example, Figure 7, page 23). The rift faulting would have directly controlled the
deposition of alluvial fans and fan deltas within the Tobifera.

Shallow locations across the top of the upturned edges of the Tobifera fault blocks could have been areas of better development of reservoir sands within the Springhill. The Piper Formation in the North Sea is an example of tectonic control on sandstone development with some direct control on sediment thickness by faulting (Maher, 1980). In that case there was "a surface of very low relief where small fault displacements and local topography greatly influenced sedimentation". The level of detail of the information available for this study did not allow determination of such effects.

Another effect of the tectonics on reservoir quality could be fracturing. Fractures in the Springhill reservoirs near to the rift faults could localize areas of better reservoir permeability. Reactivation of faults could be important to the development of fracturing.
STRATIGRAPHY AND SEDIMENTATION OF THE TOBIFERA SERIES

The rocks that subcrop beneath the Springhill Formation vary in age across the Magallanes basin, but consist mostly of Jurassic-age volcanics and volcaniclastics of the Tobífera Series. These rocks include tuffs, sandy tuffs, tuffaceous sands, shales, ignimbrites, and volcanic breccias (González et al., 1966). They are variously named the Porfírica (porphyry) Series, Porfírica Complex (Russo et al., 1980), Quemado Formation (Katz, 1963; Leanza, 1972, cited in Russo et al., 1980), Bahía Laura Group (Lesta and Ferello, 1972, cited in Russo et al., 1980), Lemaire Formation (Borrello, 1969, cited in Russo et al., 1980), Tobífera Series (Thomas, 1949a), or simply the mid-Jurassic volcanic rocks (Gust et al., 1985). Name equivalence and usage were discussed by Cecioni (1955), Riggi (1977), and Robles (1982). Herein the term Tobífera Series is used.

A unit equivalent to the Tobífera was dated as Tithonian based on fossils in shales interbedded with the tuffs in an area on the northwest part of the basin (Gerth, 1935, cited by Katz, 1963; Feruglio, 1949). Gust et al. (1985) considered the Tobífera to be the volcanic culmination of Late Triassic to Early Jurassic extensional tectonics.
Seismic Character of the Tobifera

A division of the Tobifera into two seismic units was made. The lower unit, "A", is a nonreflective unit of which about 900 m is penetrated by well 39. An upper reflective unit, "B", (isopached in Plate IV) can be further divided into subunits (1, 2, and 3) based on seismic-reflection character (Figure 5, page 19). Any division is speculative because of the quality of the available data. The quality of the seismic data does not allow mapping of these units.

In the area with the most obvious Tobifera seismic events, near the San Sebastián fault, the reflective Tobifera B was divided into three zones (Figure 5, page 19). These three zones can be identified only on a few of the seismic sections. The lowest zone, B1, contains various reflections and is about 1000 m thick (0.44 sec). B2 has few reflections and is about 900 m thick (0.39 sec). The upper zone, B3, contains continuous reflectors and is at least 400 m (0.16 sec) thick in the vicinity of the San Sebastián fault. The B3 thickness is a minimum because there is no place where we can be sure of seeing the preserved top of the Tobifera. The minimum total thickness of the Tobifera series A and B together is at least 4200 m downthrown to the San Sebastián fault.
The presence of reflectors in the Tobifera is thought to correspond to the presence of shaly and sandy layers which are possible source rocks and reservoirs within the Tobifera. Well 30 penetrated about 1300 m of Tobifera interpreted to be unit B. The sonic log from the well shows distinctly lower velocity for the sandy and shaly zones (Figure 11, at 2500 m and 2900 m). There is also a distinct increase in velocity within the tuff (Figure 11, 3300 m depth). Of the corresponding events on the synthetic for the well, the strongest (2500 ft) ties to continuous B3-like reflections on the seismic section near the well. Thus it may be possible to identify prospective source and reservoir rocks within the synrift sequence based on seismic character. Good lacustrine source rocks can be expected in rift settings (Waples, 1985).

The wedge of B3 in Figure 5 (page 19) corresponds to the area of thick Tobifera around well 12 (Plate IV). This also is the area in which an alluvial wedge was interpreted on another seismic section (Figure 7, page 23; Plate IV). Other areas of thicker reflective Tobifera exist along the southern boundary fault near wells 4 and 5 where similar continuous reflectors are seen in the upper part of the reflective Tobifera.

Rock velocities and resistivities were used also in the
Figure 11. Synthetic seismogram for well 30 showing the variation in lithology (shown at the right) and velocity of the Tobifera rocks and the match to the seismic section. Lower-velocity zones of shale and sandstone are marked with arrows. S-1 is top of Springhill. T-1 is top of Tobifera. A 25-Hz Ricker wavelet was used.
attempt to correlate the Tobifera. The lowest 460 m of the 1400 m of Tobifera in well 30 is a volcanic tuff with velocity of 5.4 km/sec. This velocity is distinctly higher than the 3.9 to 4.6 km/sec noted for most of the tuffs. The resistivity is also distinctly higher. These characteristics are also present in well 5, which is interpreted from seismic to have penetrated the lowest part of the Tobifera B. It is felt that the two units are equivalent and are from the deepest part of the Tobifera B.

**Tobifera Thickness**

The thickness of the Tobifera is estimated as variable from zero to over 2500 m (González et al., 1966) or 3000 m (Hanson, 1988). Thomas (1949a) stated that the Tobifera does not exceed 3000 m. The maximum thickness estimated from the seismic and well data for this study, in contrast, is in excess of 4200 m.

The approximate thickness of the upper reflective portion of the Tobifera was mapped within the study area using seismic data (Plate IV). The deepest distinct reflection was used as the base of the reflective zone. The interpretation is in general reliable but in parts uncertain due to lack of modern data processing on some lines, insufficient record time displayed on the sections.
(especially in the deeper southern part of the grabens), and presence of some faint possible reflectors with angular discordance and of uncertain source below the reflective Tobífera. The latter may be reflections from metamorphic or crystalline basement.

Composition of the Tobífera.

In the cores examined for this study the Tobífera Series consists primarily of light green tuffs with some light gray tuffs. The cores in well 39, which penetrated over 2000 m of Tobífera, all consisted of light green tuff or volcanic breccia.

About 1000 m of Tobífera Series was penetrated by a well in the Manantiales area (Thomas, 1949a, b). That rock consisted of "volcanic ash and alteration products" with mica schist (possible basement) near the base. The ash was interpreted to be sedimentary and some shale was associated with it. The unit also included a 30 m-thick coarse-grained quartz sandstone near the top. The occurrence of such sands and shales within the Tobífera provide possible reservoir and source for petroleum-exploration targets below the Springhill.
Springhill/Tobifera Unconformity

Generally the contact between the Tobifera and the overlying Springhill is considered to be an unconformity (Riccardi, 1976) and is seen as a sharp erosional contact in cores. However, at other locations (outside the study area) the similarity of rocks in the Springhill to those in the Tobifera makes the unconformity difficult to identify. On the seismic sections the contact is usually seen as a angular unconformity (Plate VI). Tuffaceous material was seen in the Springhill cores, with a larger amount nearer the contact with the Tobifera. In some cases it was difficult to differentiate weathered tuff from tuffaceous Springhill. Also, as noted above, the Tobifera contains some sandstones and shales that may be similar to Springhill units.

Olea and Davis (1977) stated that the Springhill Formation is an erosional product of the Tobifera. Riccardi (1976) reported that at Lago San Martin the hiatus can only be identified by the gross change in lithology between the formations.
AREAL CONTROL ON DEPOSITION OF THE SPRINGHILL FORMATION

The term Springhill Sand was first used by Thomas (1949a) to refer to the sandstones encountered in the subsurface at the Manantiales field. Nomenclature in common use includes Springhill Formation and Springhill Sandstone (González et al., 1966). It has also been referred to as the basal sandstone complex.

The Springhill is interpreted as a transgressive clastic sequence deposited on the eroded surface of the tilted Tobífera and older rocks during a period of general rise of relative sea level (Biddle et al., 1986). The unit has previously been divided into an upper marine member and a lower continental member (Cecioni, 1955). The transgressive nature of the Springhill Formation can be seen among the wells of the study area. The distinctly angular relationship of the Springhill with the underlying Tobífera is seen on many of the seismic sections (Plate VI).

About 415 m of unslabbed cores from 29 wells were examined and described in the facilities of ENAP in Punta Arenas, Chile. The cores were interpreted as showing that the Springhill was deposited in a continental to shallow-marine depositional environment. The Springhill is interpreted to have formed during a relative sea-level rise
during the Late Jurassic, filling the low areas within the grabens and then onlapping the higher topographic areas (Plates IX to XIII) as in the valley-fill model of Weimer et al. (1988). Due to the relative sea-level rise the deposits at each point became generally more marine upwards with as many as eight distinct cycles of relative rise and fall within the Springhill of the study area. The cycles identified in the cores were correlated to the well logs which enabled extension of the interpretation of cycles to areas and intervals where cores were not available (Figure 12; Plates IX to XIII). The correlation of the cycles is considered generally reliable. The cycling is similar to, but on a much shorter time scale than, the backstepping within a basal transgressive sheet noted for the Springhill in the Magallanes basin to the north by Biddle et al. (1986).

The Springhill is interpreted to have formed as discrete sandstone units because of the steps in relative sea-level rise (the marine-flooding episodes). Each of these generally time-stratigraphic parasequences comprises various environments of deposition with the coastline of successive parasequences moving to the northeast with time. Thus the continental part of the Springhill does not correspond to any particular one of the time-stratigraphic
Figure 12. Sample of well logs with core description for well 12. S1 and T1 are tops of Springhill and Tobifera respectively. A through E are interpreted parasequences. Arrows indicate upward coarsening sequences.
units defined in this study, but rather spans various ages.

The Springhill thickness varies from zero to over 110 m within the wells studied, with an average of about 30 m. Its thickness is reported to reach 130 m in La Sara in Argentina about 30 km east of well 10 and also to the northwest of Punta Delgada, Chile (González et al., 1966).

The Springhill Formation is of Late Jurassic age within the study area. A transgressive range of ages was postulated by Cecioni and Charrier (1974; Cecioni, 1955; Cecioni, 1959; Charrier and Covacevich, 1978). Cecioni and Charrier (1974), Riccardi (1976), and Natland et al. (1974) all interpreted deposition starting in Oxfordian-Kimmeridgian time. The Springhill age range given by Riccardi (1976) is Oxfordian to Hauterivian-Barremian. The range given by Natland et al. (1974) is Oxfordian to Kimmeridgian. Biddle et al. (1986) show the Springhill as old as Oxfordian in Tierra del Fuego and as young as Hauterivian in Argentina to the north. Leanza (1963) interpreted an age as young as Aptian; however, such an age was shown by Riccardi (1976) to be unlikely. Fuenzalida (1986) gave an Oxfordian-Kimmeridgian age for the Springhill on the Springhill Platform.

Much of the paleontological evidence for the age of the Springhill has been summarized by Riccardi (1988). Evidence
for the dating of the formation has come from ammonites, belemnites, and foraminifers.

Two types of control on the deposition of the Springhill were identified using the seismic sections: a previously recognized passive (topographic) control, and, recognized in this study, an active (tectonic) control. The passive control is recognized mostly outside of the grabens in areas where there was little tectonic activity during the deposition of the Springhill. The active control occurred mostly within grabens where tectonic activity was modifying the paleotopography before and during deposition of the Springhill.

**Topographic Control on Springhill Deposition**

The thickest deposition of Springhill occurred in paleotopographic lows. There is an absence of deposition over many of the paleohighs (altos pelados) such as seen at wells 40 and 42 (Plates IX and X). This has been recognized by various authors (for example Natland et al., 1974; Olea and Davis, 1977; Russo et al., 1980; Marinelli et al., 1980; Robles, 1982, 1984). The paleotopographic variation on the Tobífera surface is evident on the seismic sections in the area north of the San Sebastián fault (Figures 13, 14, and 15). There the paleotopography on the
Figure 13. Cuestas (at arrows) developed on the post-Tobifera erosional surface near well 41. Left-dipping events are Tobifera B. S1 marks top of Springhill and G7 top of Cretaceous. Timing lines are at 100 ms.
Figure 14. Paleo-cuestas (left arrows) and paleotopographic high (right arrow) near well 42.
Figure 15. Area of undulant paleotopography related to subcropping pre-Springhill. This is an area of thin Springhill.
seismic includes cuestas and isolated hills, a topography that resulted from differential erosion of the Tobifera. The higher paleotopography would include the more resistant units such as the ignimbrites (Natland et al., 1974).

The cuestas can be followed from line to line and tied to specific seismic events within the Tobifera. By mapping the structure, subcrops, and isopachs of the Tobifera we can define the trends of the paleocuestas and consequently the trends of some of the Springhill sands. A small area was mapped using a few seismic lines (Figures 15, 17, and 18) to show an elongate ridge that is caused by a subcropping unit of the Tobifera (Figure 19). By first mapping the resistant Tobifera units more-realistic contouring of the Springhill structure can be done.

Tectonic Control on Deposition

Reactivated rift-tectonic fault movement influenced the deposition of the Springhill and younger units in select areas. A positive correlation among thicknesses of successive depositional units occurs. The thickness correlation was identified in the areas of the major grabens. Thus isopach maps of the Cretaceous can be used to approximate Springhill thickness variations.

The resolution of the existing seismic data is
Figure 16. Paleotopography about 4 km north of well 13. This section is line A of map in Figure 19. P is a reflector near the top of Tobifera unit B1.

Figure 17. Same area as Figure 16. Line B of Figure 19.
Figure 18. Same area as Figure 16. Line C of Figure 19.

Figure 19. Time structure on top of Springhill showing an erosional high along the subcrop of a unit ("P") near the top of Tobifera unit B1. Note structural elongation in the direction of strike of the underlying beds.
generally not sufficient to see the Springhill directly; but
an indirect correlation between Springhill thickness and the
overlying overall Cretaceous thickness and subunit
thicknesses of the Cretaceous occurs.

Three methods were used to show that there are positive
correlations among the thicknesses of the various Jurassic
and Cretaceous units and with their location in rift. Such
relationships indicate that the phenomenon that controlled
the thickness of deposition of the Springhill continued to
exert influence throughout most of the Cretaceous. The
control could have been 1) simply that a basin was
continuing to fill with maximum accumulation in the deeper
parts, 2) that the basin was tectonically active during the
deposition, and/or 3) that there was differential
compaction.

The fault reactivation seen on the seismic supports the
interpretation of continued, though greatly reduced,
tectonic activity. Many of the normal faults that had pre-
Springhill movement are seen on the seismic sections to cut
Cretaceous formations with lessening throw upwards
(Figure 9c, page 31; plate VI). Fault reactivation, not
just stable-basin filling, is interpreted to have influenced
the deposition of the Cretaceous units.

Relatively constant thickness of the Springhill units
implies there was no large amount of movement during Springhill deposition. Correlation among the wells also shows that the study area was eroded relatively flat although there was about 150 m relief across the area at the start of deposition of Springhill. That relief also controlled the location of Springhill deposition.

**Thickness Cross Plots**

To test the correlation using isopachs between the well markers, cross plots of the Springhill thickness against two Cretaceous units were made. The comparison of the Springhill thickness with the thickness of the overlying C-1 to S-1 for the wells in the detail-study area (squares in Figure 20) shows a distinct positive correlation. The correlation is not quite as good when the younger G-7 to C-1 interval is used (Figure 21). The lower-left points do not fall within the relationship because the Cretaceous units continue to get thinner over the paleohighs even beyond the point at which there is no Springhill. Well 7 has missing section due to faulting and so is out of place on the first plot.

Other variations from linear relationship are caused by the picks for the tops of the Springhill not being time correlative. For instance the S-1 pick in well 14 is
Figure 20. Comparison of thickness of Springhill Formation to the thickness of the C-1-to-Springhill interval. Number inside symbol is well number. Symbols distinguish three separate areas with the squares in the main area of study.
Figure 21. Comparison of thickness of Springhill Formation to the thickness of the G-7 to C-1 interval. Number inside symbol is well number. Symbols distinguish three separate areas with the squares in the main area of study.
stratigraphically higher than in the other wells to the south. The result is to give a thicker-than-expected Springhill and a thin C-1 to S-1. With the 26 m shift to match the picks in the other wells the alignment is better. Using a fixed-time marker, C-15, rather than S-1 corrected for these differences and gave a somewhat tighter set of points (Figure 22).

The points for wells to the north and west (circles and triangles in Figure 20) show a similar trend but the entire set of points is shifted to thicker Cretaceous. The cross plot using the upper part of the Cretaceous (Figure 21) shows similar relationships except that the western group of wells falls with the points of the Central-Fueguinian graben rather than with the points of the grabens in the north of Tierra del Fuego. The positive correlation shows that the control on thickness continued through the Cretaceous.

Cross Sections

The seismic sections themselves show continued movement of the Jurassic rift faults during Cretaceous time (Figure 5, page 19; Plates V, VI, VII). It is apparent on the sections that the Cretaceous is usually thinner over the horsts and thicker over the grabens formed during rifting.
Figure 22. Comparison of thicknesses of the C-15-to-T-1 and the C-1-to-C-15 intervals. Number inside symbol is well number. Symbols distinguish three separate areas with the squares in the main area of study.
One of the better seismic profiles was timed and plotted at a reduced scale (Figures 23 and 24). The structural depression, the thickening within the graben area, and the mid-graben high can be seen.

**Map Comparisons**

The structural map on the Springhill and the isopach maps of the Springhill and Tobífera (Plates II, III, and IV) cover the Central-Fueguinian graben and can be compared to show the recurrence of structural movements in the area. Both formations thin across the mid-graben high and upthrown to the faults. The thickest areas of both formations are located along the downthrown side of the northern and southern boundary faults on the Central-Fueguinian graben; these are areas where prospective Tobífera rocks are more likely to be found.

In the southernmost part of the area next to the boundary fault the Tobífera seismic events were used to map an isopach between a marker within the Tobífera and the Springhill event (Figures 25 and 26). Those maps show a general correlation between the Cretaceous thickness and past movement of the Tobífera fault blocks. The main difference is a shifting of the Cretaceous thick away from the fault.
Figure 23. Section E-E' derived from seismic times. Location is shown on Plate I. Note sag of Cretaceous (S-1 to G-7) over the graben. Deepest horizon is from a reflector within the Tobifera.
SECTION E-E'

![Diagram showing stratigraphic section with markers for sections I-10, C-1, and S-1, and a notation for basement.]

Figure 24. Section E-E' stratigraphic section of previous figure hung on G-7. Note thickening of Cretaceous unit S-1 to C-1 over the graben.
Figure 25. Seismic isopach (using 4500 m/s) from a marker within Tobifera unit B to S-1. Area is in the southeastern corner of the study area. CI is 100 m. Numbers are wells. Wells do not penetrate mapped unit.
Figure 26. Cretaceous isopach (G-7 to S-1) covering same area as previous figure. Numbers 1 through 5 are wells. Contour interval is 50 m. Well and seismic values used.
Control in a Paleovalley Interpretation in Argentina

On the Argentine side of Tierra del Fuego north of Bahía San Sebastián the paleogeographic surface below the Springhill was mapped by Robles (1984) using seismic and well data. His map shows dendritic valleys separated by high areas over which the Springhill was not deposited. Robles developed a model that he felt could be applied over all of Tierra del Fuego. Robles interpreted that the basement highs were in existence before the deposition of the Lemaire (Tobifera) and that during the deposition of the Tobifera the lows were filled. The lows continued to exist after Tobifera deposition and influenced the deposition of the Springhill sandstones.

That idea differs from my interpretation of the areas of the grabens of the current study, where significant faulting occurred after deposition of the Tobifera as opposed to the Tobifera only filling preexisting lows. The faulting after deposition is evidenced by a distinct angular unconformity over tilted fault blocks of Tobifera and by high-relief paleotopography, which indicate a major hiatus below the Springhill. The areas of thicker pre-Springhill reflections are areas of structurally lower section that was preserved from erosion. This tectonic-control model may
also apply to the area of Robles' study better than a static model.

The area Robles studied is adjacent to the general Cullen/Tres Lagos/Maria Emilia area where various erosional paleohighs were identified by the author (Plate I). The area of highs in the northern part of his study would extend into Chile to include the Maria Emilia high with its subcropping granodiorite (Halpern, 1973). His northern valley would run into the Calafate graben. His southern valley connects to the graben between the Cullen and Maria Emilia areas. This is seen on a line in Chile adjacent to his study area as a distinct paleotopographic low coincident with the area of pre-Springhill reflections that appears to be fault bounded. There is also a sag within the Tertiary sediments above the graben.
CYCLIC DEPOSITION WITHIN THE SPRINGHILL FORMATION

The deposition of the Springhill sandstones, besides being influenced by paleotopography, is interpreted by the author to be controlled by changes in relative sea level. Various cycles in relative sea level were identified, with each being recorded by a separate unit within the Springhill.

Springhill Lithology and Sedimentology

The Springhill Formation consists primarily of sandstones and interbedded shales with some minor carbonates. It is at the base of a long sequence of marine sediments that were deposited through the Cretaceous and much of the Tertiary. Sediments of the Springhill are frequently very immature mineralogically and texturally, especially in the lower parts. The immaturity may be an indicator of the tectonic instability discussed above (Riggi, 1977). Some of the angular grain shape that gives immature look on hand-lens examination to otherwise mature rock is seen in thin section to be caused by quartz overgrowths of previously rounded quartz grains (D. Lindsey, 1989, personal communication).
**Continental Springhill**

The continental parts of the Springhill typically consist of quartz sandstone with interbedded shales and contain abundant carbonized plant remains. Stacked upward-fining sandstones of alluvial/fluviatil systems were identified in the cores above the post-Tobifera surface of subaerial erosion.

The thickest continental Springhill drilled in the area is in well 4, where Moraga (1983) described the lowest 60 m as continental deposits. This site is near the low point of the major half graben on the south side of the Central-Fueguinian graben. The unit there consists of sandstones and shales with carbonaceous vegetal remains (including some thin coals in the lower two thirds). The carbonaceous material and lack of glauconite were used to help identify continental origin of the sediments. The lowermost part contains shale and tuff clasts eroded from the underlying Tobifera. Wells 7 and 9 also have over 30 m of continental Springhill in unit A.

**Marine Springhill**

The marine parts of the Springhill consist of commonly glauconitic quartz sandstones, glauconite sandstones, and finer-grained clastics (Figure 12, page 48). In most cases
the marine rock is seen as a series of progradational, shoaling-upwards, coarsening-upwards sequences with the following characteristics:

1. Less glauconite upwards, sometimes to complete absence.
2. More quartz upwards.
3. Coarser grains upwards.
4. Less clay matrix and fewer clay units upwards.
5. Lighter color upwards.
7. Much bioturbation and Cruziana ichnofacies with Terebellina and Teichichnus in the lower part of the sandy section.
8. Burrows (Skolithos facies including Ophiomorpha) in the upper coarser parts.

The sequences are similar to those likely for a prograding, wave-dominated coast like that shown for the Holocene at Nayarit, Mexico, by Davis and Clifton (1987).

One or more shallowing-upwards sequences are seen in most of the wells. They are usually distinctly glauconitic within the Central-Fueguinian graben and the Calafate graben except for the uppermost sandy cycle in each well. In the western part of Tierra del Fuego glauconite was not seen in the sandstones.
As an example of the areal extent of the depositional environments, those for unit E are shown in Figure 27. The coastline and the base of the foreshore align in a NW-SE direction. Several areas were emergent at the time. Shallow-marine sands separated from the coastline are interpreted to be offshore bars.

**Springhill Environments in Argentina**

In the Argentine section of Tierra del Fuego, just to the east of the study area, Covellone et al. (1987) interpreted from core studies various facies within cycles of the Springhill Formation. They identified two sedimentary units, the lower of which was interpreted as a marginal-marine estuary system with channels and tidal-flat deposits. It was thought to represent the earliest sedimentation on top of the eroded Lemaire (Tobifera) Formation, recording the transgression of the Springhill sea. The sequence occurs in a narrow zone that widens southwest towards the area of the Central-Fueguinian graben of Chile (Plate I). Covellone et al. defined the NE-SW depression in which the lower sequence was deposited (Plate I) using isopachs between the top of the Lemaire Formation and a marker in the Pampa Rincón Formation overlying the Springhill. They also defined secondary
Figure 27. Paleoenvironment of upper part of Unit E (see Fig. 28). The map shows more-marine conditions generally to the southwest. Compare to faults in Fig. 8 (page 25).
transverse depressions.

Covellone et al. (1987) interpreted the unit to be from deposits in an estuary at the mouth of a river flowing from a fluvial system to the northeast. The estuarine channels are restricted to the area of thicker Springhill Formation and the tidal flats are located in the margins where a higher percentage of mudstone was found. They stated that open sea would lie to the west along the Chilean border (that is, in the Central-Fueguinian graben). As relative sea level rose the shoreline was displaced to the northeast and the upper unit was deposited by a tidal-dominated, wave-influenced deltaic system. Some of the upper Springhill sandstones in the Chilean portion of Tierra del Fuego could be offshore bars related to that system.

**Springhill Relative Sea-Level Fluctuations**

Detailed well-log correlation is interpreted to show that the top of the Springhill corresponds to a number of superposed sand bodies of different ages (Plates IX to XIII). High-resistivity limy markers and high-conductivity shale breaks within the shale section above the Springhill were considered to be time-stratigraphic units and were used to correlate the various Springhill sandstone units with laterally equivalent rock of different type. Figure 28
Figure 28. Schematic diagram of extent and relationships of the various Springhill units. Horizontal scale is variable; overall section represents wells seen in an area of 130 km (NS) by 80 km (EW). Wells numbered along top (locations in Plate I). Thicknesses are from well 12. Variation in thickness occurs but is not shown here. The S-1 marker is the top of the shallow-marine/coastal-plain section. Horizontal lines are time-stratigraphic markers.
shows a schematic diagram of the correlations across the Central Fueguinian graben, the Cullen high, and the Calafate graben. The correlations across the Cullen high are not as accurate as those within the Central Fueguinian graben but are considered reliable enough to support the models discussed below. The correlation shown in the figure was aided by the other regional section along the northern part of the Island (Plate I). Unit thicknesses range from 6 to 20 m except for unit A, which is thicker and may comprise several parasequences. Each unit does not vary greatly in thickness within the study area, but some thickening is seen into the grabens.

The uppermost sandstone unit (S-1) in some wells is correlated to finer-grained rocks that are above the S-1 sandstone in adjacent wells. For example, the marker C-15, which in most areas is not the top of the Springhill, correlates to the Springhill unit G (S-1) in well 14 (Plate IX).

Well-log sections across the rift (Plates IX, XI, XIII) show the correlation of the sandstones. Some of the correlations are less certain to the north of well 12 due to the distances between wells. The uppermost (S-1) units are interpreted to be successively younger to the north and east (Figure 29) save for unit E at wells 2 and 4 (Plate XIII)
Figure 29. Identification of the sand unit defined as top of Springhill (S-1) in each of the wells. Letters define units as in Figure 28. "X" means no Springhill sand is present. See Figure 2 for location of detail study area.
and unit G at well 14 (Plate IX) which may be isolated bars.

The discrete sandstone development is presumably related to stepwise changes in relative sea level. Distinct cyclic sequences (herein termed parasequences) of shallowing marine deposition separated by apparently rapid relative sea-level rise were identified from the well cores (Figures 30 and 31). The upward change from coarse-grained to fine-grained sediments over a short distance at the marine flooding surface at the top of each parasequence is considered evidence of rapid relative sea-level rise. Another indication of rapid rise in relative sea level is the preservation of the sequences (Davis and Clifton, 1987). Major rises in relative sea level mark the top of units A, C, E, and G. Lesser rises mark the tops of B, D, and F. Drops in relative sea level were due to progradation as the accommodation (space available for sediment accumulation, Jervey, 1988) was filled by advancing fluvial systems (shoaling upwards) during a time of relative stillstand.

In sequence-stratigraphy terminology these units are interpreted to be progradational parasequences bounded by marine-flooding surfaces (Van Wagoner et al., 1988; Figure 32). They are part of a retrogradational parasequence set, the bottom of which is the pre-Springhill unconformity (compare Figure 28, page 76, with Figure 32).
Figure 30. Core showing glauconitic marine sediments overlying non-marine sediments. Top of core is upper right hand corner of this page. Core boxes are 1 m long.
Figure 31. Detail from 4.7 m below top of core in previous figure. This shows the transition from non-marine to marine sediments with sharp contact and a transgressive lag. The contact represents one of the parasequence boundaries. Core is 9 cm in diameter.
Figure 32. Stratigraphic model consisting of a retrogradational (transgressive) parasequence set similar to the Springhill shown in Figures 28. Each parasequence is progradational. Modified from Van Wagoner et al., 1988. Scale varies with unit to which the model is applied.
The existence of shallowing cycles explains and supports the interpretation of discrete units within the Springhill. Furthermore, the cycles seen in the cores can be used to aid correlation among the wells.

Additional sea-level cycles probably occurred during the deposition of unit A but were not identified within the continental deposits. Above unit H there are probably even more cycles. For example, the sandy zone at C-11 in well 39 (Plate X) may represent the offshore limit of sand deposition of a younger cycle. To identify younger cycles wells to the north of the study area must be used.

**Paleogeography During Springhill Deposition**

The oldest Springhill unit in each well was mapped to analyze the paleotopography and the progression of the transgression. This onlap map (Figure 33) shows a general direction of transgression from the southwest within much of Tierra del Fuego. Exceptions to this direction are seen locally in the Calafate graben, where transgression was from the north or northwest (Moraga, personal communication, 1989) and within the Central-Fueguinian graben, where deposition was influenced by the fault-controlled valleys. The topographic relief on the pre-Springhill unconformity was approximately 150 m (Figure 28, page 76).
Figure 33. Onlap map showing which unit is at the base of the Springhill. Youngest unit, A, is found only in the lowest parts of the valleys. Compare with faults of Fig. 8.
During transgression the stream base level rose, causing deposition of fluvial continental sediments of unit A in the lower areas of the eroded pre-Springhill surface, the Central-Fueguinian graben and the Calafate graben (Figure 33). The first deposition was valley fill in valleys that run NW-SE, perpendicular to the regional slope indicated on Figure 29 (page 78). The lowest areas in the Central-Fueguinian graben are noted in wells 4, 7, 9, and 12 (locations on Plate I) and correspond to two areas near the major boundary faults of the Central-Fueguinian graben (the thicker areas on Plates III and IV). Covellone et al. (1987) show another valley in Argentina adjacent to the study area which runs NE-SW, parallel to regional slope (Figure 33; Plate I).

Drainage from the more northerly valley in the Central-Fueguinian graben was probably to the southeast due to the generally high ground to the north and northwest (Plates I and III). The southerly valley could have drained to the northwest or southeast. The southeasterly drainage is more likely because the deepest valley (based on thickness of continental unit A) is at well 4 to the southeast. Also the section above the Springhill thickens generally in that direction (Plate III). The drainage system defined by Covellone et al. (1987) in the adjacent area in Argentina
(Plate I) would be tributary to the same system.

With marine transgression the area of deposition within the graben expanded and deposition started in a broad area to the west and northwest of the Central-Fueguinian graben (area of unit C in Figure 33). As noted in the previous section, the transgression was stepwise with deposition by progradation during stillstands. By F time the sea had transgressed onto the higher areas north of the Central-Fueguinian graben, leaving several islands. By G time some of the islands were covered with sediments, although they were isolated from substantial sources of sand and thus are locations of chalco directly on Tobifora (wells 5, 11, 19). During the H through J time intervals marine transgression continued and even the highest areas such as Cullen where submerged (wells 39, 40).

Springhill Seismic-Stratigraphic Interpretation

Synthetic seismograms were produced and combined in a well cross section to show the variation among the wells (Figure 34). Also, interpolated well logs were used to make synthetic stratigraphic seismic sections showing the effect of changing thickness of the Springhill (Figure 35). The synthetics were made using various Ricker wavelets of frequency ranging from 25 to 30 Hz, a range which matched
Figure 3.4. Comparison of synthetic seismograms of various wells in the Central
Fuegian Graben (partially coincident with cross section A-A', Plate IX).
This synthetic section represents the Springhill in the left half of the
schematic geologic section of Figure 28 between wells 3 and 4. The section is
hung on the C-I marker. Wavelet is 25 Hz Ricker. Time scale in seconds.
Correlation markers are noted at the right.
Figure 35. Synthetic stratigraphic section interpolated between wells in the Central-Fueguinian Graben system. Upper part of figure shows the geologic model used for the interpolation (flattened on C-1). Note the changes in amplitude and character of the T-1 and S-1 events. Wavelet is 30 Hz Ricker.
the better quality sections with normal polarity.

Because of seismic-character changes across the study area the integrated sonic-time picks for the Cretaceous and Jurassic events do not match consistently to a particular point in a wavelet. For example, the well pick for the I-10 event is on a trough at some wells while in others it falls on an adjacent zero crossing (Figure 34). The C-1 marker, a resistive marker just below the top of a calcareous zone, is consistently at the zero crossing below a distinct peak and thus is a good reference horizon for isopaching above the Springhill (Figure 34; Plate III).

The Springhill event is usually a strong seismic peak on normal-polarity (that is, trough for a decrease in velocity) sections. Where the Springhill is absent the response from the underlying Tobifera (T-1) is also a strong peak because both the Springhill and Tobifera are of similar high velocity compared to the overlying shales. A Springhill event combined with the top of Tobifera can be expected in much of the study area. As is seen on the synthetics by comparing wells 1, 5, 6, and 8 (Figure 34), areas with thin (<30-40 m for the wavelet used) Springhill may not be distinguished from areas in which Springhill is absent. With broader-bandwidth wavelets thinner Springhill could be distinguished.
The synthetic stratigraphic sections generated by the author show the tuning effect of the amplitude of the Springhill event is too small to be used for thickness estimates. This is illustrated by the similarity of the S-1 event for thicknesses of 40 m and less on the synthetics and interpolated synthetics of Figure 35. Synthetic stratigraphic sections using data from a single well by varying thickness of the Springhill gave similar results, both with onlapping and thinning models for the Springhill. Some variation is seen in the synthetics but not enough in the author’s opinion to be used for thickness prediction. Synthetics that varied the Tobífera velocity over the range of velocities measured in the wells show amplitude variations greater than seen by varying Springhill thickness.

In areas of thicker Springhill there is sometimes a larger proportion of low-velocity material that causes a weaker reflection at S-1 (well 4 in Figures 34 and 35). Where the Springhill is thick enough (above about 40 m) the top and bottom can be distinguished both on the section of synthetic seismograms (Figure 34, wells 4, 9, 12, and 14; Figure 35) and on the reflection sections (Figure 36). In such areas the Springhill thickness could be approximated from the peak-to-peak time interval.
Figure 36. Seismic section illustrating character of thickening Springhill in a syncline. Compare to previous figure. Note the appearance of a lower peak (bottom arrow) representing the separate T-1 event in the central part of the section and the split (top arrow) of the S-1 peak similar to the synthetic of well 4 in the previous figure. Timing lines at 100 ms; section length 12 km.
On synthetics where the Springhill is the thickest it contains three peaks with a 30-Hz Ricker wavelet (Figure 35, well 4). An example of thick Springhill is shown in Figure 37 and Plate V in the sag north of well 5. The sag corresponds to the paleovalley with thick Springhill that was penetrated by well 4. One or possibly two additional peaks within the Springhill are seen in those examples but over a larger time interval than at well 4. Only the best-processed sections have the frequency content needed to match the resolution of the synthetic in Figure 35.

In most areas where Tobifera events could be identified the Springhill overlies it at an angular unconformity. Thus the reflection coefficient at the contact will vary depending on the velocity of the particular Tobifera unit at the contact. Where the Tobifera is resolved as an event separate from the Springhill the strength of the reflection varies laterally.

As discussed above, the well picks for the Springhill vary in age depending on location. The corresponding seismic event does not resolve the 6-20 m parasequences and so follows the Springhill well pick as a continuous event. Therefore the seismic event can be time transgressive.

In at least one case within the Central-Fueguinian graben a seismic event does appear to follow a parasequence
Figure 37. Area of thick Springhill north of well 5. Arrows mark top and bottom of Springhill. Note that three to four peaks occur within the Springhill. See Plate V for scale.
boundary as a time-stratigraphic pick within the Springhill. The picked top of the Springhill is usually the first strong peak below a nonreflective shale zone. However, at well 12 the well-log correlation puts the Springhill (S-1B) below the strong peak rather than at or above it as in the other wells (Figure 38). The Springhill pick in well 14 (S-1A) is on the strong peak and is interpreted from the well logs to be laterally equivalent to the C-15 zone (unit G) in well 12 above the S-1 pick (unit E, Plate IX). Thus the well pick drops below the seismic event at well 12 and the seismic horizon follows the unit-G (C-15) horizon.

The synthetic stratigraphic section through those wells shows how the unit-G (C-15 or S-1A) event reduces amplitude to the south (left) of well 12 (Figure 38, compare with Plate IX).

Recently reprocessed seismic sections show the C-15 event as described above (Figure 39). Similar events are seen above the S-1 pick in the area downthrown to the San Sebastián fault and in the graben northwest of the Marazzi area. Reprocessing of all sections to obtain a bandwidth equivalent to that seen on the few reprocessed lines is needed to interpret the extent of the unit-G sandstone.
Figure 38. Synthetic stratigraphic section (flattened on C-1) between wells with and without the G-unit sandstone. S-1A is the top of the Springhill (unit G) in well 14 but is correlative to a non-sandstone marker in wells 9 and 12. S-1B is the Springhill pick (unit E) in wells 9 and 12. 30 Hz Ricker wavelet.
Figure 39. Seismic section showing the split of the Springhill event because of suspected existence of separate sandstones (arrows). Upper leg is possible unit G.
It may be possible to identify alluvial fans within the Springhill by use of the seismic sections. Alluvial-fan deposits interpreted from cores in the continental Springhill in well 12 correspond to a lateral variation in seismic character that may indicate the extent of the fan (Figure 7, page 23).

Summary

The Springhill Formation includes continental and marine sandstones. Well-log correlation shows that the Springhill can be divided into a number of discrete 6 to 20 m cycles. The cycles are caused by stepwise variation in relative sea level. Cores define the cycles to be progradational, upward shallowing parasequences within an overall transgressive sequence. Deposition was also influenced by paleotopography which consisted of regional slope to the southwest, fault-related valleys, and isolated highs. Springhill thickness and some stratigraphic information can be determined from the existing seismic data, but broader bandwidth could reduce the minimum identifiable thickness and increase the amount of stratigraphic detail seen.
RECOMMENDATIONS

The results of this study could be applied to:
1) include the entire basin, 2) incorporate complete set of
data sets, and 3) improve seismic data quality through
reprocessing and new acquisition.

The regional cross sections outside of the detail study
area show that the models may be applied to other parts of
the Magallanes basin. A expanded study should be done to
include such areas.

The study included only part of the total data set
existing in Tierra del Fuego. Incorporation of the complete
data set into an expanded study will provide more detail to
the study.

Seismic reprocessing is needed to provide a more
reliable structural and stratigraphic interpretation by
improving resolution and continuity. The seismic sections
with recent processing show that distinct improvement in
seismic resolution and in the ability to make reliable
geological interpretation can be made. The wavelets for the
existing sections are quite variable and make interpretation
of Springhill thickness rather uncertain. Thus processing
should attempt to make all sections match in frequency and
phase. Major improvements can be expected with the use of
refraction statics and surface-consistent deconvolution. Other modern methods should be tested. Reprocessing should use and display the entire five seconds of record that was usually recorded. Recording and processing of new lines should be to at least six seconds to properly image the Tobifera events at three to four seconds. Changed field techniques could improve quality and resolution, particularly the use of deeply buried charges.

Tobifera Exploration

Exploration for petroleum within the Tobifera requires more than the search for fault and unconformity traps in the tilted blocks. Sedimentological and stratigraphic analysis should be made using better-quality seismic data and additional well data. The expected rapid lateral changes in sediments can be better predicted with detailed analysis of the tectonic pattern. Presence and characteristics of possible source rocks need studied.

All of the seismic data should be incorporated into a detailed interpretation of the Tobifera structure and stratigraphy after reprocessing of the lines. Interpretation should concentrate on structural definition, sequence stratigraphy, and geologic history. Existing wells provide little information about the
Tobifera, especially in the lower areas of the graben where thicker Tobifera occurs. A stratigraphic well is needed at a location of thick Tobifera such in the wedges downthrown to the boundary faults. This could provide the lacking critical information about source rocks and reservoirs.

**Springhill Exploration**

For future exploration it is recommended that the generalized model presented here be refined by the use of the other information that was not available for this study. The work should be continued outside the areal limits of this study. For each of the parasequences detailed determination of the depositional environments should be made and the lateral extent of each should be defined. Petroleum production should be correlated to environment and unit within the Springhill.

The rocks from depositional settings that would be expected to provide good reservoir character in the study area are in some cases lacking in porosity due to diagenesis (D. Lindsey, 1989, personal communication). Thus diagenetic history must also be studied. Geochemical source and maturity analyses and modeling should be done for both the Springhill and the Tobifera.

Analysis of the source of sediments for the Springhill
units may prove useful. The provenances of sediments in the study area include both local areas and distant areas to the northeast. Subcrop lithology varies across those areas and will affect reservoir quality.
CONCLUSIONS

From this study the following conclusions are drawn:

1. Jurassic grabens (rifts) were identified within north-central Tierra del Fuego area using seismic data integrated with well logs and cores. The largest rift, the Central Fueguinian graben, is 35 km wide and bounded by major normal faults on the northeast and southwest sides.

2. The thickest Tobífera synrift deposits were identified on the seismic sections at locations adjacent and downthrown to the boundary faults of the rift.

3. The Tobífera was divided on the basis of seismic character into a lower transparent unit and an upper reflective unit. More continuous events in the upper part of the reflective unit are interpreted as possible clastic source and reservoir units.

4. The faults had a continued influence on sedimentation by reactivation in normal-fault sense during the deposition of the Upper-Jurassic Springhill Formation and the Cretaceous beds. Depositional influence on the Springhill sandstones were both tectonic and topographic. Infilling of paleodepressions between paleohighs of resistant Tobífera occurred as well as active control by
tectonic movements of the fault blocks. Other types of reactivation of the earlier normal faults has occurred.

5. The Springhill is interpreted as a transgressive sequence that initially filled the valleys within the rifts. Several subsequences are identified. The discrete cycles are interpreted to be due to stepwise changes in relative sea level which resulted in the deposition of progradational parasequences within a retrogradational parasequence set. At least one of the parasequences (G) can be resolved on the seismic sections.

6. The lowest unit of the Springhill in the study area is dominantly continental valley fill and is found within fault-controlled valleys.

7. A general northeast direction of transgression occurred as determined from the areal extent of the various Springhill sands. Specific depositional environments moved generally northeast with time. However, the direction of transgression is locally changed by the horst/graben structures of the rifts.

8. Springhill thickness was shown to correlate with changes in character of the Springhill seismic event, with thickness of the Tobifera units below the Springhill, and with the thickness of units above the Springhill. A tectonic influence on sedimentation occurred. Areas of
thicker Springhill can be determined using the seismic data.

9. The tectono-stratigraphic model developed for the Springhill could be used throughout the Magallanes basin to identify individual Springhill units and predict their areal extent. This would be done by defining the units from well data and predicting their extent with the aid of detailed seismic maps of the geologic structure. More accurate definition of the type of sand bodies and their lateral extent can reduce the risk of petroleum exploration and development drilling. Division of the Springhill Formation into cycles could allow correlation of production to particular units or depositional conditions within the Springhill. Areas more likely to contain prospective Tobifera rocks were outlined.
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