In late 2006, Apache became operator of several license blocks totaling 2950 km² in the province of Tierra del Fuego, Argentina. As the first part of an extensive exploration and development program, Apache’s Exploration and Technology group immediately started work on covering the newly acquired blocks with fit-for-purpose 3D seismic, intending to acquire all the areas in a single campaign lasting up to 12 months. The imaging objectives of the surveys ranged from development of existing fields to pure exploration in the sparsely mapped blocks that formed the majority of the area, and led to several geometries and acquisition solutions being developed, some redesigned and implemented on the fly during acquisition.

Background

La Isla Grande de Tierra del Fuego is a land of extremes. It lies between 52 and 55°S and is divided politically between Argentina and Chile. It contains the world’s most southerly producing oil and gas fields in the Austral basin east of the Andes as the chain curves east and dips into the Atlantic close to Cape Horn. The island is surrounded by the southern oceans that create the subpolar climate of the region; the inhospitable weather is characterized by single-digit (0°C) high temperatures and fierce winds in summer and cold, short days in winter with barely eight hours of daylight. The landscape is mostly rolling hills, a wide open savanna of grass, and scrub dissected by four significant rivers and hundreds of small channels, or chorrillos, from which one of the blocks gets its name. There are also a number of permanent lakes, or lagunas, which vary in size dramatically through the year with rainfall.

Figure 1 and Figure 2 show more detail of the area at the southern tip of South America, the individual projects, and their location; the Cabo Nombre and Cañadon Piedras surveys to the north of the Bahia, and Los Chorrillos/Uribe and Lago Fuego to the south.

Three small 3D surveys had been acquired onshore in the past, two in the Cañadon Piedras block north of the Bahia San Sebastian, and one across the San Sebastian Field immediately to the south. A sparse network of 2D had been acquired also, allowing a general structural map of the area to be created, and giving useful information on prior acquisition and processing techniques.

The previous 3D projects had been small, of the order of 100 km², and had been primarily onshore vibroseis surveys acquired in summer exclusively on higher, dry ground, seemingly to avoid the lagunas and chorrillos. Explosive sources had been used for one survey on the coastal mud flats to the north of the Bahia San Sebastian, and on the southern fringe of another. These legacy surveys produced acceptable quality volumes (these areas did not require reshotting) but had not recorded as wide a range of offsets and azimuths found useful by initial modeling; our intention was to acquire all useful
offsets at all azimuths, requiring much higher channel counts than had previously been utilized.

**Timing and scouting**

Discussing optimum start dates with contractors revealed a distinct polarization of opinions. There were those who insisted that winter was the best time to work, when the ground is frozen and vibrator mobility is high, and those who believed that the long days and dryer ground of summer were better suited to acquisition, despite the stronger winds. Landowners told us of past cold winters with months of continuous freeze, but also that in recent years the frozen ground had been limited to only the highest points. Facing a recording program that would outlast any single season, it was decided to equip the crew with both explosive and vibroseis sources, and changing ground conditions would be handled by adjusting the division of effort between the two.

Scouting the area in November 2006 revealed the landscape to be low rolling grassland hills separated by broadly meandering rivers and streams or chorrillos in wide valleys (Figure 3), giving way to coastal mudflats surrounding the Bahia San Sebastian. The primary land use in the region is sheep farming, the hillside grasslands being irrigated by man-made channels to improve the grazing conditions for the sheep. Discussions with contractors and analysis of satellite imagery reinforced the decision that these would be dual-source programs, taking advantage of the efficiency of vibroseis on the higher, dry ground with apparently firm soils, and using explosive sources in the softer, broad valley bottoms and close to the coast.

For Cañadon Piedras and CaboNombre, there was a clear division of surface conditions defined by an ancient shoreline that separated upland from coastal flats. In Los Chorrillos/Uribe, the river valleys defined the division, and in Lago Fuego the heavy forest precluded any use of vibrators.

**Survey designs**

Objectives for the survey ranged from development of existing fields to broad exploration of over 1300 km² of previously underexplored territory in this remote region. Target depths increased from 1500 m in the northern fields, to approximately 2500 m in the south of Uribe, and around 3500 m in Lago Fuego. Consequently, three regular orthogonal geometries were used for the different parts, two of which were combined to cover the development and exploration areas of the Los Chorrillos/Uribe area (Table 1). Lago Fuego was acquired with a variable line interval to optimize target imaging while limiting new line cutting to almost zero by using the existing network of 2D lines.

**Acquisition start-up and testing**

Importing equipment from mainland Argentina turned out to be fraught with administrative hurdles and took many weeks and delayed the full start-up of the crew. Initial source test-
ing and acquisition of the Cabo Nombre vibroseis program was completed in March, before operations were suspended awaiting full mobilization of the crew and equipment.

As equipment was being laid out in Cabo Nombre, one receiver line was acquired a number of times as a 2D test to compare vibroseis effort, and determine optimum start and end frequencies and tapers. At this time the data quality appeared excellent, and vibroseis impact was minimal.

Early in the mobilization, we had the opportunity to drill, load, and record a test line to evaluate source performance using a small quantity of explosives remaining in the possession of the contractor in Argentina; despite all the relevant handling and shooting permits being held, the process to get the explosives onto the island took many weeks pending permission to cross out of Argentina into Chile for transit to the island, then back into Argentina for the project.

The test line was laid out in northern Los Chorrillos, and at each shotpoint a pattern of shots was drilled, loaded, and recorded individually to compare charge size and source depth.

### Table 1. Survey design parameters for Cañadon Piedras (CP), Cabo Nombre (CN), Los Chorrillos/Uribe (LC/U), and Lago Fuego (LF).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CP / CN</th>
<th>LC/U N</th>
<th>LC/U S</th>
<th>LF (nominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP/RP Int.</td>
<td>50 m</td>
<td>60 m</td>
<td>60 m</td>
<td>60 m</td>
</tr>
<tr>
<td>SL/RL Int.</td>
<td>300 m</td>
<td>420 m</td>
<td>540 m</td>
<td>600–840 m</td>
</tr>
<tr>
<td>Active Spread</td>
<td>16 × 120</td>
<td>12 × 112</td>
<td>12 × 108</td>
<td>10 × 120</td>
</tr>
<tr>
<td>Nom. fold</td>
<td>80</td>
<td>48</td>
<td>36</td>
<td>30</td>
</tr>
<tr>
<td>Dec. fold</td>
<td>n/a</td>
<td>24</td>
<td>18</td>
<td>n/a</td>
</tr>
<tr>
<td>SP / km² nom.</td>
<td>66</td>
<td>40</td>
<td>30</td>
<td>28</td>
</tr>
<tr>
<td>SP / km² dec.</td>
<td>n/a</td>
<td>20</td>
<td>15</td>
<td>n/a</td>
</tr>
<tr>
<td>SP count nom.</td>
<td>7986/3276</td>
<td>30,540</td>
<td>34,236</td>
<td>10,758</td>
</tr>
<tr>
<td>SP count final</td>
<td>7713/3123</td>
<td>21,230</td>
<td>17,118</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Figure 4 and Figure 5—stacks from a test line, each with 2 kg per shotpoint, one loaded at 5 m and one loaded at 15 m—clearly show the area’s data to be remarkably insensitive to shot depth. With the drill equipment initially available to us in Argentina being man-portable Robin or “wagon wheel” drills (Figure 6), the minor improvement of the 15-m hole versus the 5-m hole was judged insufficient to justify the additional cost for each shothole, given that these were intended as infill sources in areas inaccessible to vibrators. Making this decision early, and knowing the data quality that was achievable, simplified and increased confidence in the difficult decisions that were to follow.

With 5 m set as the source depth, drill production got off to a good start, but crews were forced to case holes with PVC after drilling as more administrative delays getting explosives onto the island left the magazines empty and little optimism for a quick resolution.

Once recording production began, we had an opportunity to compare vibroseis records against nearby dynamite records, loaded with the last of the early stock of explosives (Figure 7 and Figure 8). Energy and frequency content were comparable, and both looked to generate excellent records; the biggest difference was the cost per shotpoint, but the consistency of the data gave confidence that we had the right tools to tackle these programs.

Once mobilization of the crew was complete and acquisition began, all the original decisions appeared to be valid. Vibrators were making good production and able to reach all the areas planned for them, while making a minimal impact on the ground. Apart from a trail of flattened grass, there was no evidence of passage; even the pad marks were hard to find (Figure 9).

Full-scale acquisition restarted in April 2007 with acquisition of the vibroseis section of the Cañadon Piedras 3D to the north of Bahia San Sebastian. Unfortunately, when the vibroseis section was completed, there were still no explosives on the island, and the crew was forced to move south to begin Los Chorrillos with only vibrators. Completion of Cañadon Piedras would have to wait.

Vibroseis acquisition in Los Chorrillos/Uribe began toward the end of April 2007 to the south of the La Sara Field and working to the north, with production and data quality initially both very high, and few gaps left in the valleys where we had holes drilled but not loaded. All went well for the first week, but at the end of April the summer ended abruptly and everything changed.

**Winter**

Through April, the initial decisions appeared to have been ideal. Vibrator acquisition production had been on target, data quality had been excellent, and ground conditions had been such that in many areas it was even difficult to find pad marks following acquisition of a vibrator point (VP), such was the firmness and elasticity of the near surface.

The onset of the winter rains in late April changed the picture entirely; vibrators and line trucks were immobilized by the now soft terrain, and by early May production had ground to a halt. The highlands became a minefield of soft spots where a vibrator would sink up to its axles in seconds with no warning. With no reasonable expectation of a hard freeze to allow vibroseis recording to continue, a decision was faced to either suspend operations until the following summer or continue in a 100% explosive-source mode.

The decision was made easier by the fact that there were already rigs en route to Tierra del Fuego to drill prospects yet to be identified by these surveys. To return in summer would have resulted in multiple mobilization and demobilization
charges, and years of delay to the exploration and development programs for the area. In short, we had to find a way to proceed.

Remobilization
The conventional approach to seismic acquisition in this region had been to work only during the summer months using vibroseis and then patching together smaller surveys recorded over multiple seasons. However, already knowing the effectiveness of small shallow charges, and with the cooperation and support of contractors, it was decided to make dramatic changes to the crew composition and continue operations using 100% explosive sources going forward. The vibrators were demobilized, and portable six-man drill crews were increased from 12 to 34 to allow production targets to be met. Explosives orders were multiplied, and alternative vehicles were mobilized to allow efficient operations in the newly prevailing conditions.

The earlier decision to leave Cañadon Piedras incomplete left the only contiguous drill lead far from where the line equipment was laid out. Consequently, when explosives finally arrived in June, the crew had to pick up all the lines and relay the Cañadon Piedras spread in order to complete that survey, while drill crews built lead back in Los Chorrillos. The acquisition of the area across the mudflats took place through the coldest weeks of the winter when shifting ice sheets blown by the wind snapped and cut line cables on a daily basis. On completion of Cañadon Piedras, it was again necessary to pick up and move the spread back to the Los Chorrillos program area.

With the decision to use a 100% explosive source for all of the Los Chorrillos and Uribe surveys, a total of 1800 km², it became necessary to look for ways to reduce the newly escalated cost of the survey. There were two options to achieve this—either to reduce the cost per shotpoint or reduce the number of shotpoints—and both were achieved as described below.

Mechanization
One possibility for reducing drill cost was mechanization. While the portable rigs have their place in the seismic world, it is not in a high-production open area where some vehicular movement was possible. Discussion with contractors and other Apache regions led to the selection of two types of tracked drills from North America to be used in Argentina. The most successful of these were the Canadian low-impact seismic (LIS) drills, mounted on Morooka rubber-tracked...
carriers (Figure 10). Despite the high cost of transporting these units by air from Canada to Argentina, their massive boost to the drilling production covered the cost of transportation in their first two weeks of operation.

**Shot-density reduction**

Numerous geometry changes to reduce shotpoint count were examined and modeled, most of which involved changes in source- and receiver-line interval, but in midsurvey these were found to be operationally undesirable. The solution chosen was to eliminate every second shot on every second shot line, thus reducing the shot count per square kilometer by 50% (Figure 11).

This was verified by taking the northwestern section of the 3D and processing it through to poststack migration with all shots as input, and then through the same sequence with 50% of the shots removed (Figure 13). The resulting migrations are shown in Figure 12 and Figure 13. Based on this comparison, it was decided that the shot density should be reduced with immediate effect; this change removed 25,000 shotpoints from the survey and reduced shot density from 32 or 40 points per square km to 16 or 20 points per square km, depending on the area, and similarly reduced fold from 48 and 36 to 24 and 18.

**Wind noise issues and tests**

Following the successful implementation of the shot reduction program, the crew was approaching summer, and with summer in this region come very high winds for days at a time. This 50% reduction in fold raised the issue of data sensitivity to wind noise; the shot records shown in Figure 14 and Figure 15 illustrate how wind noise can completely mask signal on shot records.

At latitude 54°S, Argentina and Chile form the only land mass that encounters the winds known as the “furious fifties.” With no other land to interrupt them, the winds regularly blow at a steady 60 km/h or greater with peak recorded winds approaching 160 km/h, at which speed field operations are simply impossible.

At the start of the project, the wind noise specifications written in the contract in microvolts and followed in the recorder resulted in recording standby whenever sustained winds exceeded 50 km/h, resulting in approximately 15% of recording time standing by for wind.

In order to test the validity of this limit, two “wind test” areas thought to be of lower prospectivity were defined where all wind noise limits were eliminated and the crews were allowed to shoot in any weather considered safe for operations; the comparisons of impact on data quality would then be made based on processed, not raw data. In Figure 16, the impact of the wind can be seen in the shallow, low-fold section,
but the deeper interval of interest (below 1.5 s) is relatively unaffected.

Analysis of the recorded wind-speed data by area and study of the field cube from those areas led to a relaxation of the noise limit to allow recording to continue in winds up to 75 km/h even with the reduced shotpoint density, thus increasing the productivity of the crew by reducing time lost to wind noise. From this point forward, the noise specifications were written in kilometers per hour, and not microvolts.

**Lago Fuego 3D**

At 54°S, the Lago Fuego gas field represents the world’s most southerly hydrocarbon production. Following completion of the Los Chorrillos/Uribe survey, the drilling and recording crews moved south to acquire an additional 500 km² of 3D data. Because of all the experiences of the program to date, the crews were well equipped to deal with most aspects of the area, the main exception being the heavily wooded terrain. The program was designed with variable line spacing to optimize coverage in target areas while taking advantage of existing 2D lines and open spaces to allow maximum usage of the mechanized drills. The existing lines were bulldozed through the forest by a previous operator in the 1950s and no significant regrowth has occurred. Apache wished to avoid this scale of environmental impact, and did so through the use of these existing lines and access. In the forests, the portable drills were used with air compressors instead of water to boost mobility and limit the need for vehicle access. Recording crew mobility was improved with the replacement of the original recorder with a lighter, more flexible system more suited to a portable operation through the forests.

The new recorder was key to the last major request made of this vibroseis crew that had been completely re-equipped over the previous 12 months. An early shot-parameter test 2D line recorded from the LF-x1 well to the coast revealed that the structure continued to climb toward the coast, and indicated a fault lay parallel to the shoreline bounding a higher structure offshore. Consequently, we needed to image as far offshore as was possible with a land crew.

This was achieved by importing 1000 channels of submersible 408ULS equipment, navigation equipment, and two locally rented boats, in order to extend the receiver lines 3000 m offshore (Figure 17). Land lines were laid on foot at low tide (Figure 18), and connectors picked up from boats at high tide and connected with submersible equipment. The crew was also able to drill a small number of shotpoints below the high tide line to further push coverage offshore.

**Westward to Chile**

The final chapter in the 2007–2008 Tierra del Fuego seismic campaign began in November 2007 during the acquisition of the Uribe section of the program with the award to Apache of two exploration blocks in Chile immediately adjacent to Los Chorrillos/Uribe. The lessons learned during the Argentina surveys became invaluable as we had the opportunity...
to go back to the drawing board and equip a new crew with the best tools for the job, plus we had a proven acquisition geometry from the start, so the Chile survey was laid out as a westward extension of the Argentina program. The biggest challenge faced was to achieve a seamless tie between the data sets in the two countries.

A number of solutions were examined in search of the one that would allow smooth continuous operations for the primary crew in Chile while avoiding any reliance on cross-border traffic or communication. The solution chosen was to use an autonomous continuous data recorder, the OYO Geospace GSR, operated by a small crew in Argentina that laid out receivers on stations previously occupied in the Los Chorrillos/Uribe survey (Figure 19). By coordinating the deployment and retrieval of these stations with the roll of receiver lines in Chile, we effectively acquired complete tailspreads in Argentina for shots taken in Chile. The only modification to the Chile recording system was a GSR Synchronizer that captured shot times to enable the extraction of individual traces from the continuous data recorded at each station.

This new data set will be migrated along with the adjacent strip of the Argentina survey in order to create one seamless volume covering the Apache acreage in both countries with no interruption to imaging along the frontier.

**Conclusions**

Despite the physical and commercial obstacles created by the initial choice of equipment, and difficulties with the terrain and the weather, the 2500-km² 3D acquisition in Argentina was completed with no work-related lost time incidents in over one million hours and has resulted in three excellent data sets, the Cañadon Piedras and Cabo Nombre 3Ds being merged with two legacy surveys in that area.

Weather, terrain, and governmental red tape played parts in changing the acquisition plan during the survey from the initial operational concept to a very different final outcome that enabled acquisition to continue through the winter and to complete recording the program in 15 months. Throughout the project, a sense of urgency from operator and crews, along with continuous evaluation of equipment, technique, and results enabled many efficiency increasing changes to be tested and implemented.

The decision to continue operations and not wait out the winter accelerated the delivery of final processed data over crucial areas by several years, and the exploration acreage now has first class 3D seismic to guide prospecting for many years to come; it is estimated that these data sets will generate drilling prospects in Tierra del Fuego for the next 10 years. The first prospects identified from these surveys were on production 12 months after the last shot was recorded.

At the time of writing, products of the 2007–2008 Tierra del Fuego seismic program had already enabled doubling of oil production in the operated fields.

The Chile/Argentina data set covered 2666 km² when processing was completed in April 2009, and we believe this is the largest onshore 3D recorded in South America. Processing of the Lenga/Russfin 3D was still under way when this article was written, and it is hoped that the data continuity achieved will permit exploitation of the entire area without any impact from survey edge effects.

**Acknowledgments:** The authors thank the management and staff of the following companies for their efforts that made these programs a success: Apache’s partners (Repsol-YPF and ENAP); WesternGeco Party 1799 Argentina; Global Geophysical Party 423 Argentina (GSR crew); Global Geophysical Party 426 Chile; WesternGeco Buenos Aires Data Processing Center; Wicap SA; Jackson Environmental Seismic Services; Excalibur Seismic Drilling Company; and RPS Energy.

**Corresponding author:** mike.yates@apachecorp.com