Shushufindi—Reawakening a Giant

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In less than three years, a consortium led by Schlumberger has resuscitated the ailing giant Shushufindi oil field in Ecuador. The consortium's team assimilated what was known about the field and made recommendations to remedy problems and stimulate production. Soon after a contract was signed, the consortium was performing workovers, drilling new wells and continuously monitoring all field operations. As a result, oil production has increased by more than 60% over rates from three years ago.

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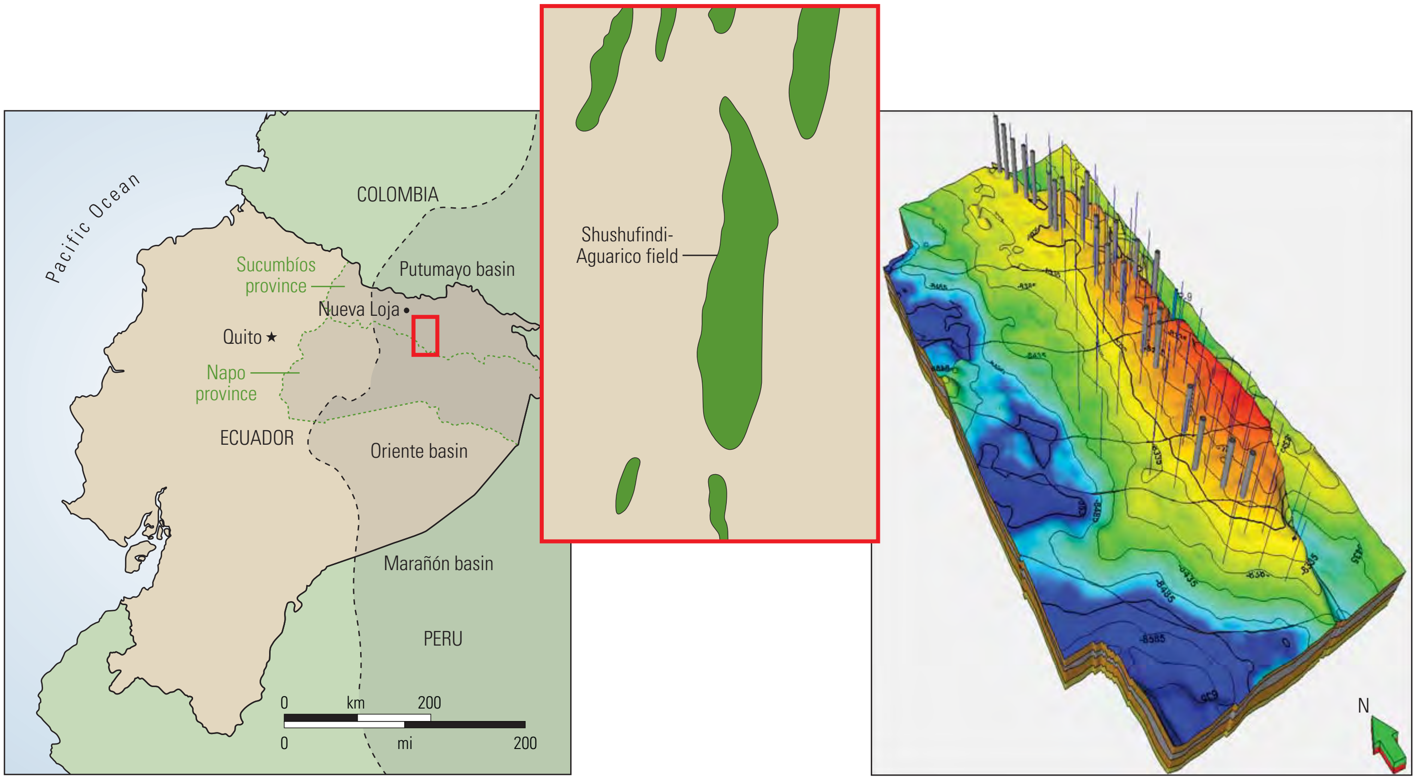
1. Alvaro M: "Companies Look to Boost Production at Mature Oil Fields in Ecuador," *The Wall Street Journal* (February 1, 2012), http://online.wsj.com/article/BT-CO-20120201-713643.html (accessed August 1, 2014).
2. A horst and graben system develops in an extensional or rifting tectonic regime, in which normal faults are the most abundant type of fault. A horst is a relatively high-standing block bounded on both sides by normal faults that dip away from each other. A graben is a relatively low-standing block—trough or basin—bounded on both sides by normal faults that dip toward each other. A horst and graben system is formed by alternating high- and low-standing blocks.



^ Shushufindi location. The Shushufindi-Aguarico oil field (*center*) is located in the Oriente basin, in the Sucumbíos and Napo provinces in northeast Ecuador (*left*). The gray shading indicates the Putumayo, Oriente and Marañón basins in eastern Colombia, Ecuador and Peru along the eastern front of the Andes Mountains (dashed black line). The field was discovered in January 1969, and its first oil was produced in 1972. The Shushufindi-Aguarico anticline (*right*) trends north to south and is 40 km [25 mi] long, 10 km [6 mi] wide and bounded on its east by a N–S reverse fault.

The Shushufindi-Aguarico field (collectively known as Shushufindi) is a mature giant field responsible for more than 10% of the total hydrocarbon production of Ecuador. Discovered in 1969 with an estimated 3.7 billion bbl [590 million m^3] of oil originally in place, it achieved a maximum production rate of about 125,000 bbl/d [19,900 m^3/d] of oil in 1986. Since then, the field has been in decline; the field produced less than 40,000 bbl/d [6,360 m^3/d] of oil in 2011.

In 2010, the government of Ecuador, concerned about declining oil revenues from existing oil fields in the country, actively sought partnership with a service company to reverse this trend. In late January 2012, the state-owned oil company Empresa Pública de Hidrocarburos del Ecuador (EP Petroecuador) signed a 15-year contract with the integrated services joint venture (JV) Consortium Shushufindi SA (CSSFD), led by Schlumberger, to manage production from Shushufindi.[1] The objectives were to optimize production, accelerate the development of proven reserves and evaluate secondary and tertiary recovery potential. In just a few years, the consortium has resuscitated the ailing giant, restoring oil production to 75,000 bbl/d [11,900 m^3/d].

As of August 2014, the consortium has increased oil production by more than 60%, drilled 70 wells, completed 60 workovers and built a state-of-the-art water treatment facility for a 40,000-bbl/d water-injection pilot project. Currently, production from Shushufindi has reached the limits of the available facilities.

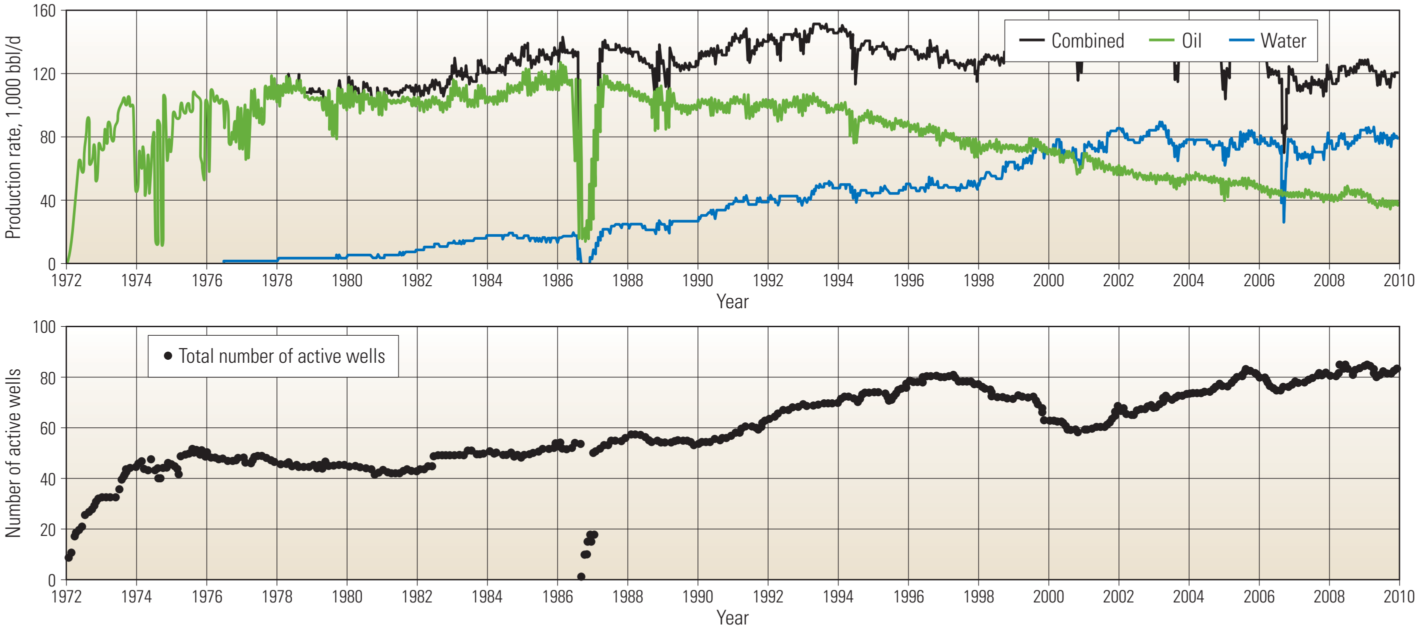
This article, which explains how the CSSFD JV revitalized production from the giant Shushufindi-Aguarico field, begins with the field's structure, discovery, early oil production and subsequent faltering production. It discusses the consortium's early interventions to increase production, simultaneous and parallel studies to understand the field's architecture, building of a digital oilfield operations center, efforts to maximize production through well construction and interventions and development of pilot programs to test production through waterflood secondary recovery.

The Rise and Fall of a Giant

The Shushufindi field is located in the Oriente basin in northeast Ecuador (above). Covering an area of 400 km^2 [150 mi^2], it is Ecuador's largest oil field: a giant estimated to contain 3.7 billion bbl of original oil in place (OOIP). As of January 2014, about 1.2 billion bbl [190 million m^3] of oil have been produced from the field.

The Ecuadorian Oriente basin is part of a Mesozoic-Cenozoic back-arc basin that formed in conjunction with the tectonic activity that created the Andes Mountains during the Cretaceous to Tertiary ages. Present-day structural traps were created by the compressional deformation and rejuvenation of pre-Cretaceous basement structures. The traps consist primarily of faulted anticlines or drapes over uplifted basement structures.

The Cretaceous Shushufindi-Aguarico reservoir structure consists of a low-relief, asymmetric anticline; the western limb dips 1° to 2° to the west. The field is about 40 km [25 mi] long and 10 km [6 mi] wide and has a structural closure of around 67 m [220 ft] in relief. The structure is closed to the east by a discontinuous north-south reverse fault, which has a minor component of strike-slip movement. Geoscientists believe this fault is sealing in some locations but partially sealing or nonsealing in others. The pre-Cretaceous basement is dominated by a horst and graben system, which has a direct influence on the Cretaceous sedimentary sequence and depositional environment.[2]



^ Production history. Since production (*top*) began in 1972, the Shushufindi field's oil production decreased as its water production increased. After 1986, the trend was independent of the number of active wells in the field (*bottom*).

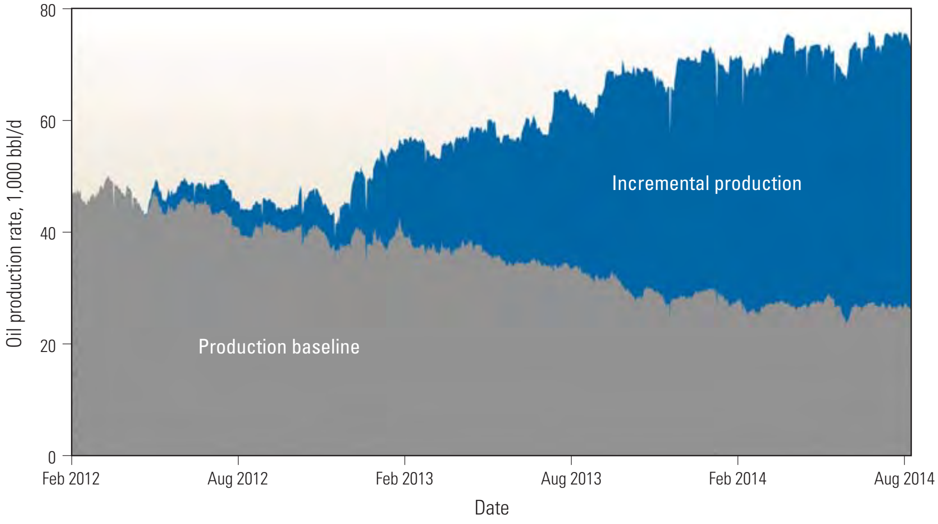
In the Oriente basin, the primary reservoir targets are the Cretaceous Hollin and Napo formations. Six clastic intervals form reservoirs; from the oldest to the youngest, they are the Hollin Formation, the T, U, M2 and M1 members of the Napo Formation and the basal member of the Tena Formation.[3] These formations were deposited in a transgressive-regressive sedimentary setting that occurred in response to global sea-level fluctuations.[4] The reservoirs are found within successions of fluvial, estuarine and deltaic deposits of sediments that flowed in from the east and prograded, or built up, successively seaward, first as shoreline and then as shallow-marine shelf deposits.

Shushufindi oil production comes from the T and U members of the Napo Formation and the basal Tena reservoirs. The thick and homogeneous sands of the Hollin Formation are present in the area but are water saturated. The Napo T and Napo U members are represented by estuarine to shallow-marine deposits; they are subdivided into the T Inferior (lower T), T Superior (upper T), U Inferior (lower U) and U Superior (upper U) submembers. The lower submembers are the main reservoirs in the field; they are formed from massive tidal and estuary sands and contain 90% of the OOIP of Shushufindi. The upper submembers are interbedded sandstones and mudstones that were deposited in a shallow marine environment. These reservoir intervals have little aquifer pressure support.

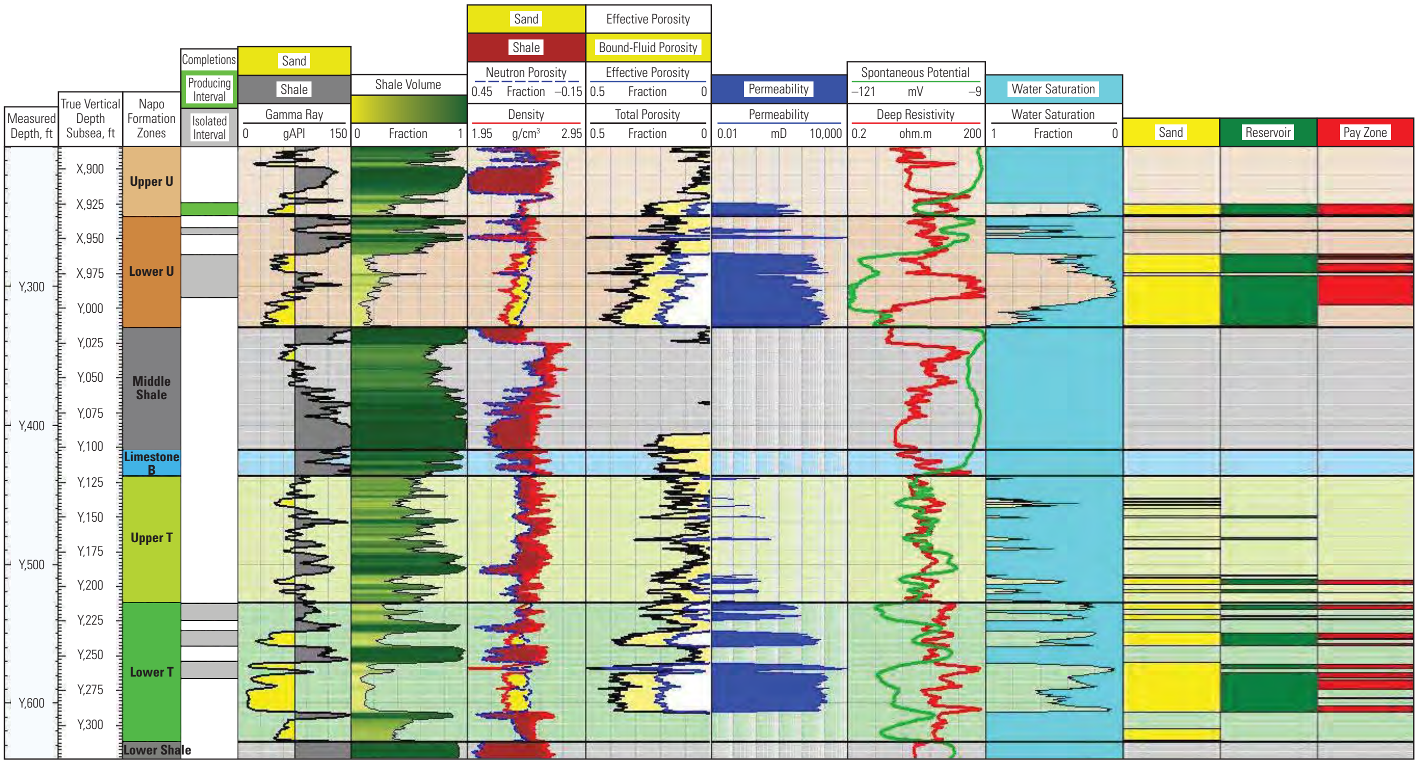
A Texaco-Gulf consortium (both companies are now part of Chevron) discovered the Shushufindi oil field in 1969. Initial tests in the discovery well yielded oil flow rates of 2,496 bbl/d [396.8 m^3/d] from the Napo U member and 2,621 bbl/d [416.7 m^3/d] from the Napo T member. During early production, the oil from these units was commingled. Lateral aquifer support to the reservoir units from the west provided the primary hydrocarbon drive mechanism.

Production from the Shushufindi field started in 1972 at a rate of 19,200 bbl/d [3,050 m^3/d] of oil with no water production. It peaked about 1977 at 120,000 bbl/d [19,100 m^3/d] with a low water cut (above). As formation pressure declined, the aquifer encroached upon the reservoir and the fault on the structure's east side leaked water into the reservoir. By 1994, oil production was 100,000 bbl/d [15,900 m^3/d] and water production was 40,000 bbl/d. Thereafter, total liquid production remained stable at roughly 130,000 bbl/d [20,700 m^3/d], although oil production gradually declined while water production increased proportionally.

By 2010, oil production was roughly 35% of total liquid production. To counter the declining



^ Incremental oil production. Since the Consortium Shushufindi contract was signed in late January 2012, oil production has increased to more than 75,000 bbl/d, which includes incremental oil production of more than 30,000 bbl/d above the baseline production. The calculation of baseline production is based on the assumption of no further action, and production from Shushufindi would be allowed to decline naturally.



^ Single-well display output from Techlog well log software. Analysts interpret every well in the field, and results are presented and available in a simple, comprehensive format, accessible to all personnel in subsurface, engineering production, drilling and workover teams. This single-well layout is used for all completions and recompletion and workover proposals.

oil-production trend, the government of Ecuador invited proposals from companies to revitalize the Shushufindi field. Schlumberger formed Consortium Shushufindi SA (CSSFD) with the Argentine E&P company Tecpetrol SA (25%) and the multinational private equity firm Kohlberg Kravis Roberts & Co. LP (10%).

In January 2012, the consortium signed a 15-year contract with EP Petroecuador, the national oil company of Ecuador, to form an integrated service JV to manage production from Shushufindi.[5] Subsurface studies and capital investment activities for the JV contract are managed by CSSFD. In February 2013, the upstream division of EP Petroecuador was merged with Petroamazonas Ecuador SA to become Petroamazonas EP, or PAM. As a result, PAM assumed responsibility as operator and as the CSSFD JV customer partner in the Shushufindi asset. At the time of contract signing, about 100 active wells were collectively producing 45,000 bbl/d [7,150 m^3/d] of oil.[6]

Production has since increased by more than 60% to about 75,000 bbl/d or about 30,000 bbl/d [4,770 m^3/d] more oil than when the contract started in January 2012 (previous page, bottom).

Precontract Intervention

In October 2011, four months before the contract was signed, CSSFD introduced a team of technical and operations professionals dedicated to studying the field and proposing specific actions to be taken immediately after contract execution. In less than four months, the team designed the annual work plan (AWP) for 2012, which included drilling 22 wells and conducting 25 workovers. The team developed strategies for reviewing existing surface facilities—looking for and addressing bottlenecks in the system—to improve the throughput at the facility.

Within four months of starting work, the team had assembled a comprehensive database of existing wells and developed a reliable static geologic model and a realistic dynamic reservoir model for Shushufindi.[7] In addition, the team had recommendations for 35 new well locations and 29 workovers. The team also devised plans for continuous monitoring and streamlining of facilities and production operations to minimize nonproductive time and deferred production. Six weeks into the contract, the asset team was operating one drilling rig and two workover rigs in the field. By the end of 2012, the number of drilling and workover rigs grew to four and three, respectively, and the CSSFD JV had completed the new wells and workovers from the 2012 AWP and had opened a computerized, state-of-the-art operations center.

Within two months after the contract had been signed, the team had evaluated 152 wells using the Techlog wellbore software platform. The results for each well were compiled and presented in a single format (above). In addition,

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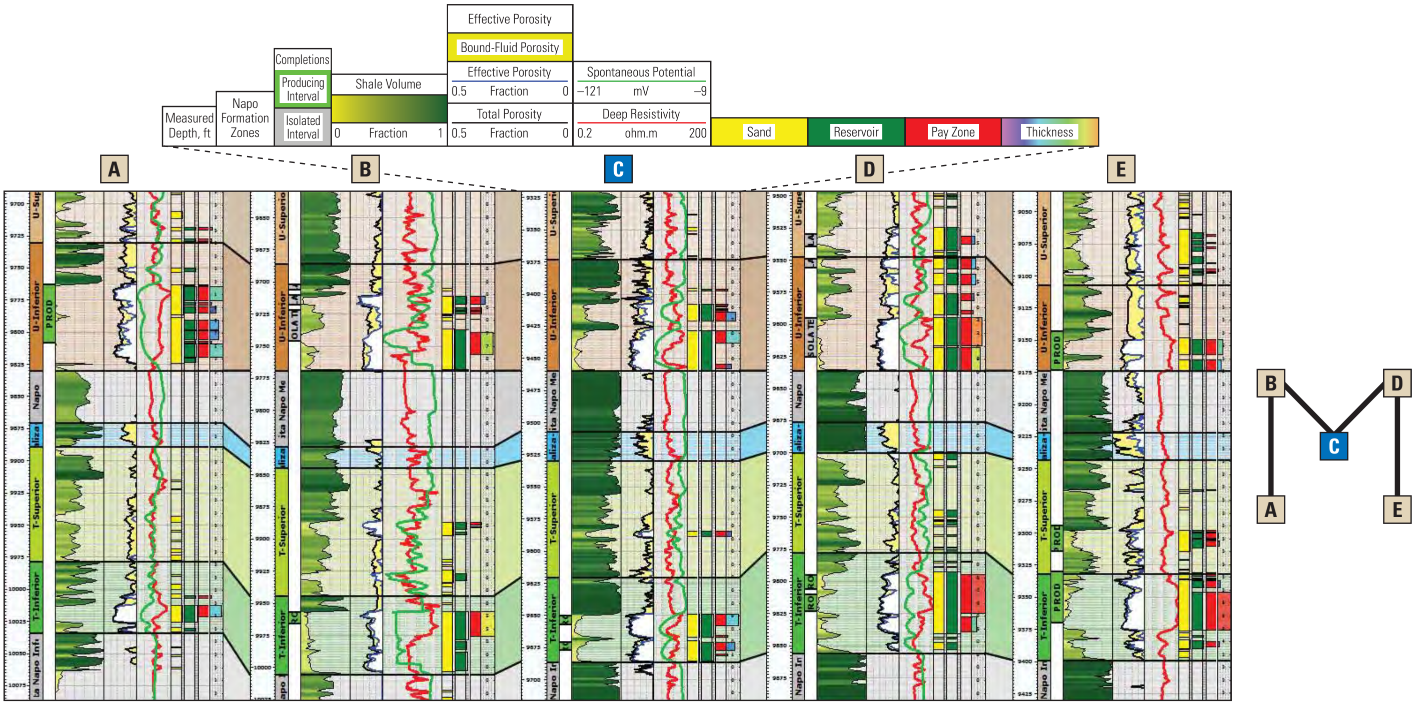
3. A clastic sedimentary rock consists of broken or eroded fragments derived from preexisting rocks, transported elsewhere and redeposited before forming another rock. Examples of common clastic sedimentary rocks are conglomerate, sandstone, siltstone, mudstone and shale. Carbonate rocks can also be broken and reworked to form clastic sedimentary rocks.
4. In sequence stratigraphy, a transgressive-regressive sedimentary package is a unit of related sequential layers of sediments formed during a cycle of sea-level rise and fall. Transgressive sediments are deposited during rising sea level as water advances over land. Regressive sediments are deposited during falling sea level as water retreats from the land.
5. Alvaro, reference 1.
6. Lafournere J-P, Dutan J, Naranjo M, Bringer F, Suter A, Vega J and Bolaños J: "Unveiling Reservoir Characteristics of a Vintage Field, Shushufindi Project, Ecuador," paper SPE 171389, presented at the SPE Western Venezuela Petroleum Section Second South American Oil and Gas Congress, Porlamar, Venezuela, October 22–25, 2013.
7. A static model describes a single moment in time. Geologic models are static because on the human timescale, geologic characteristics, for the most part, vary imperceptibly. In contrast, a dynamic model describes events as they evolve through time. Reservoir models are dynamic because they account for the behavior of time-dependent properties—temperature, pressure, flow rate, volume, saturation, compressibility and others—that vary during the operating life of a reservoir.



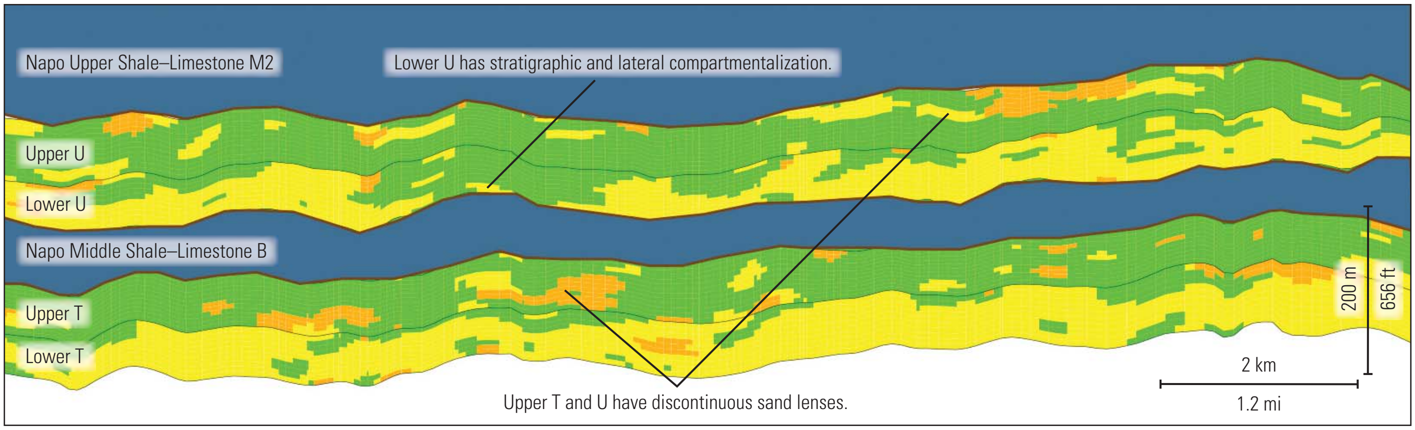
^ Multiwell "M" section output from Techlog well log software. For each well, the tracks are from left to right: measured depth; Napo Formation zones (Track 1); completion information (Track 2); shale volume (Track 3); porosity (Track 4); deep resistivity and spontaneous potential (Track 5); lithology (Track 6); reservoir (Track 7); pay zone (Track 8); and pay zone thickness (Track 9). Each well in the field is correlated with its immediate neighbors.

each well was correlated to the four closest offset wells; each correlation cross section formed an "M" pattern with the well of interest in the center (above). Because these displays had simple formats, the subsurface, engineering production, drilling and workover teams could easily plan well interventions. In addition, the displays facilitated picking locations for drilling new infill wells. Focus was initially on characterizing the lower T and lower U Napo sandstones, which are the principal reservoir units within Shushufindi. The team developed a well-history card—a digital record—for each well, listing production and pressure data and estimated remaining reserves along with significant events such as completions and workovers. The records allowed the team to perform a methodical review of all well characteristics, prioritize workovers and select locations for new wells.

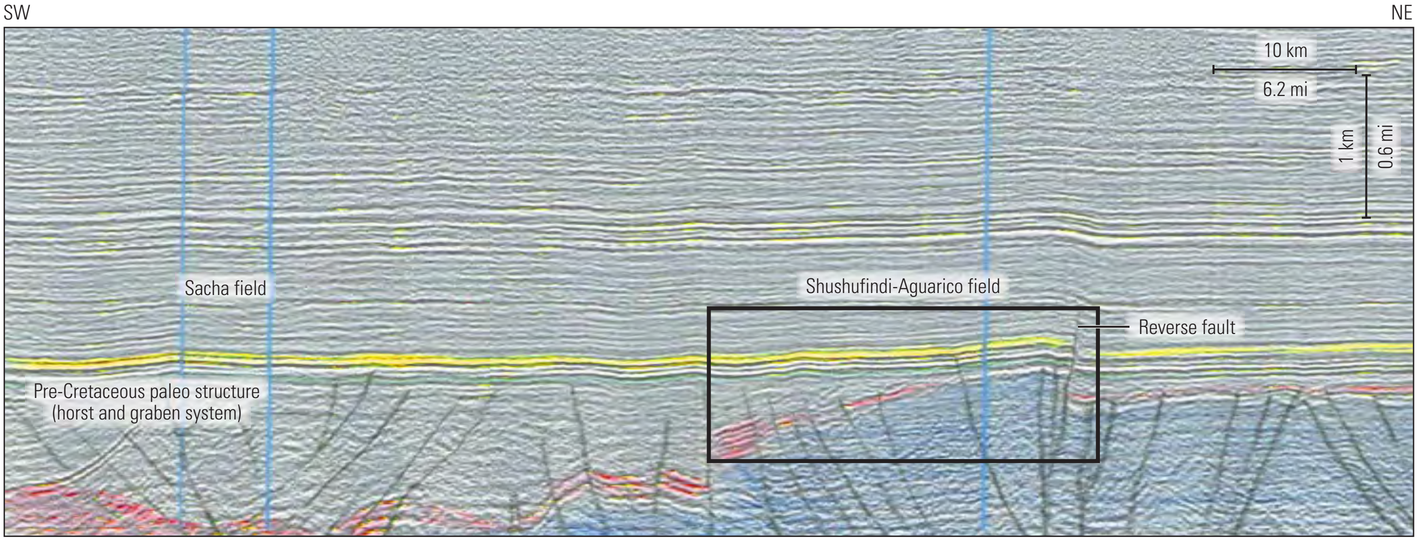
Reservoir Architecture and Field Redevelopment Strategy

In a parallel effort to understand the reservoir architecture and prepare a fieldwide redevelopment strategy, the team designed and implemented a comprehensive data acquisition campaign. The campaign included core analysis, comprehensive suites of logs, fluid analysis and seismic reprocessing to reduce reservoir uncertainty and build a database for updating the static model; such data were based on improved understanding of the reservoir architecture and dynamic behavior of the field. From 2012 to 2013, geologists, geophysicists, petrophysicists and reservoir engineers worked closely with drilling, completions and facilities engineers to build a long-term field development strategy.

Structural framework—The Shushufindi structure is a large asymmetric anticline closed



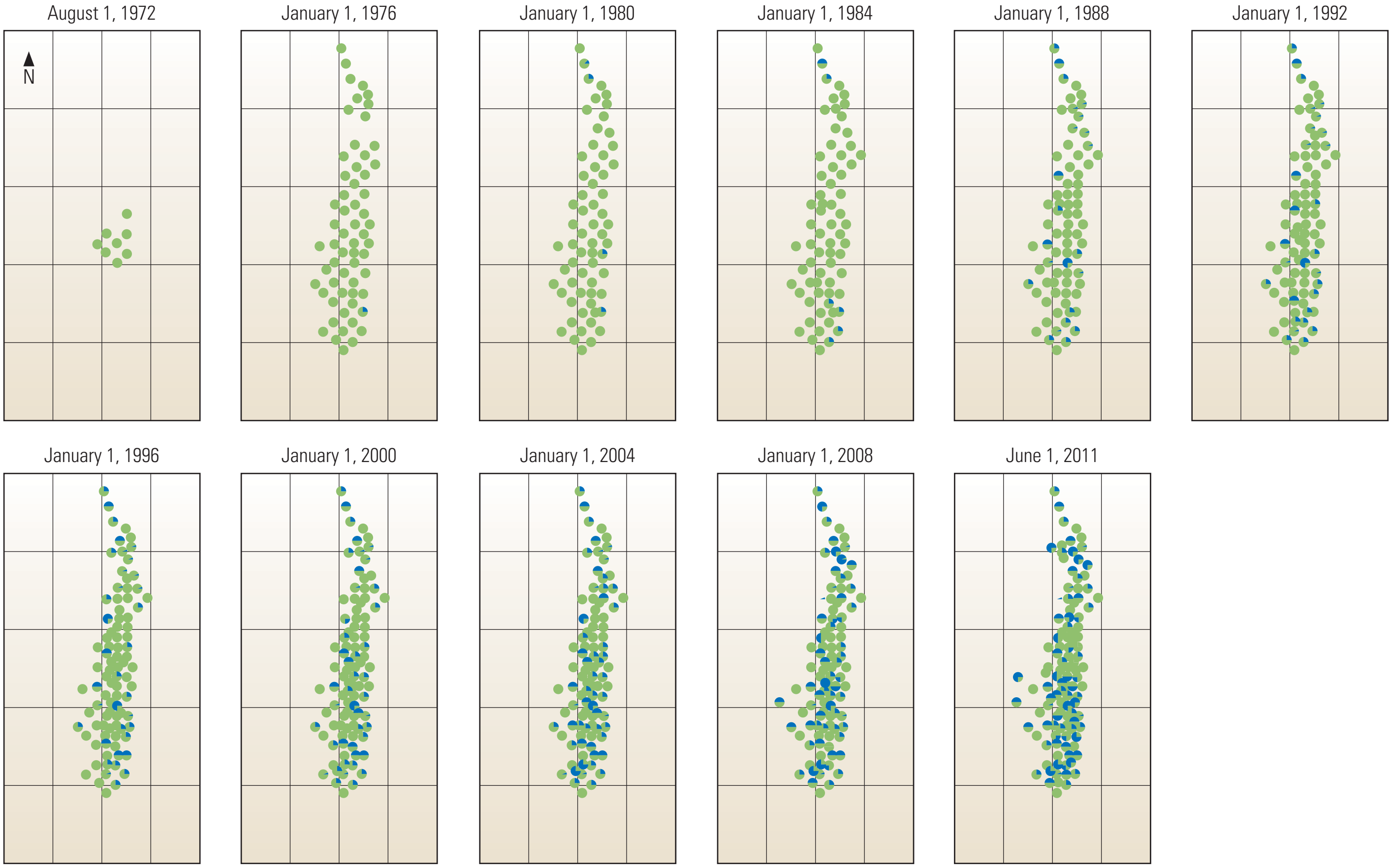
^ Reservoir architecture. In the Napo Formation and its members, blue indicates low-permeability shale and limestone units, yellow indicates good quality sands, orange indicates low-quality sands and green indicates shales. The lower T submember, the main reservoir, is continuous and massive across the field and results from coalescing sands piled vertically. The lower U submember reservoir is also continuous across the field but has a higher degree of stratigraphic variation than the lower T submember. The upper T and U submembers contain secondary reservoirs that have little lateral continuity and occur mostly as localized lenses.



^ Structural framework from seismic data. The Sacha and Shushufindi-Aguarico oil fields are low-relief asymmetric anticlines. The Cretaceous-age Hollin, Napo T and Napo U reservoir sequences (yellow reflectors) drape over the pre-Cretaceous basement, which is dominated by a horst and graben system (red reflectors). The Shushufindi-Aguarico structure is bounded on its east by a reverse fault. Blue vertical lines are intersections with other seismic lines.

on the east by a reverse fault (above). The structure is flat and has a vertical closure of only 67 m from crest to flank over a distance of 7 km [4 mi]. In addition, the eastern fault is patchy and discontinuous in its sealing effect and locally allows a strong influx of water from the east (below).

The architecture of the Napo Formation is varied. The lower T submember is characterized by continuous, high-quality sands with little compartmentalization, whereas the lower U submember exhibits both stratigraphic discontinuities and compartmentalization. The upper T and U submembers are characterized by discontinuous and isolated sand lenses (previous page, bottom).



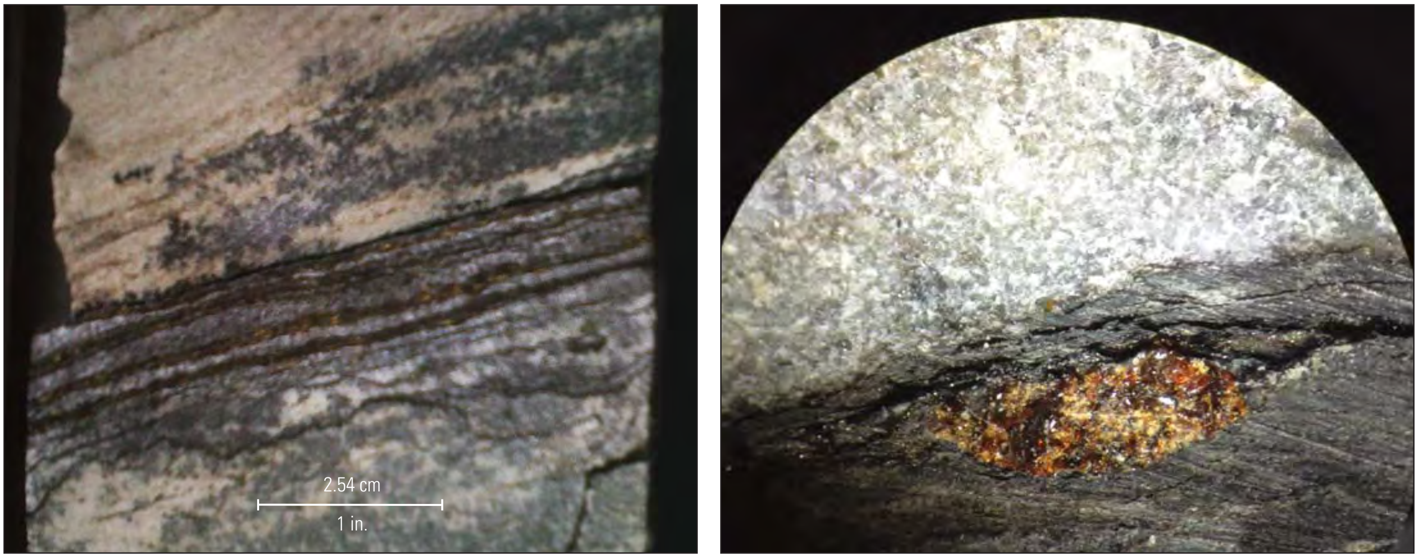
^ Water encroachment. Bubble maps show the active wells (circles) and their liquid production; green indicates oil, blue indicates water and both colors indicate commingled liquid. The progression, mapped about every four years, shows water encroaching into the field as a result of oil production and declining reservoir pressure.

^ Present-day analog for depositional environment. A large, flat and tidally dominated estuary that invades into a shallow carbonate platform is the general sedimentological model for the Ecuador Cretaceous basin that holds the Shushufindi field. This photograph, from the eastern Australia coast, is of a depositional environment similar to those found in many other parts of the world.

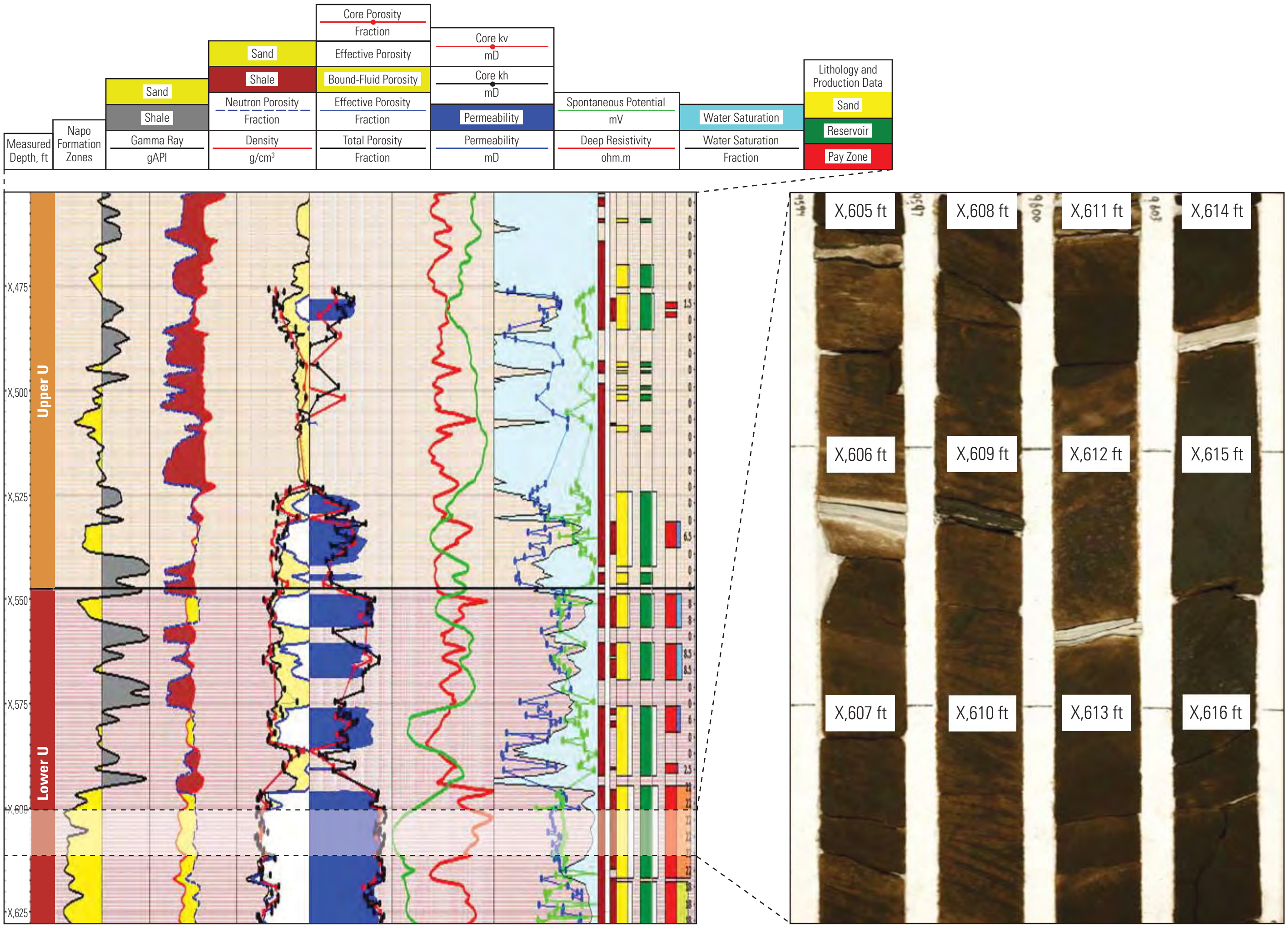
The fault's irregular sealing and the reservoirs' architecture are important in understanding today's reservoir fluid distribution, which is controlled mainly by variations of rock properties and facies in reservoir zones. In addition, engineers consider the distribution of cumulative oil and water production, and each well's contribution to it, when selecting locations for new infill wells within the structure's flank.

Geologic framework and sedimentology—The sediments that formed the Shushufindi oil field are near-shore to shallow-marine deposits of Late Cretaceous age. The depositional setting is characterized by features such as sand bars, beaches, tidal channels, estuaries, shallow lagoons, marshes and streams (above).[8]

The Napo T and U sands were deposited in shallow water.[9] After deposition of each sand unit,



^ Cores from the Shushufindi field. Fine layers of coal and amber intercalate between clean siltstone mixed with shale (*left*). These dipping layers are preserved at the base of the sand bedsets and are typical of tidally dominated sediments. A photomicrograph (*right*) shows amber within coal. The preservation of amber is indicative of a quiet, low-energy sedimentary environment.



^ Well interpretation. The Techlog well data display (*left*) shows the upper and lower U submembers of the Napo Formation. It includes data from the core interval in the lower U submember. The log tracks are from left to right: measured depth; Napo Formation zones (Track 1); gamma ray (Track 2); neutron porosity and density (Track 3); effective, total and core porosity (Track 4); NMR and core permeabilities (Track 5); deep resistivity and spontaneous potential (Track 6); Archie water saturation and core water and oil saturation (Track 7); lithology (Track 8); reservoir (Track 9); pay zone (Track 10); and pay zone thickness (Track 11). The core (*right*) shows thin horizontal layers—streaks of quartz, lignite and amber—which form barriers to vertical flow and may be correlated over large areas. These thin layers do not appear in the well logs, which show the interval as a massive, homogeneous sandstone reservoir.

sea level rose—as evidenced by repeated cycles of an upward succession of shallow-shelf carbonates and marine shales deposited on top of the sands. Examination of core cut through the Napo T and U sandstones suggested that the sands were deposited in low-energy environments that supported various types of wetlands such as marsh and forest wetlands.[10] Within the core were thin layers of fine-grained, quartz-rich, tightly cemented and impermeable siltstones and thin layers of coal (above). Both types of thin layers contain amber—fossilized resin from coniferous trees—which is typically preserved in low-energy environments (previous page, bottom).[11] These thin siltstones and coals are traceable in cores from well to well and extend over large areas; therefore they are potential barriers or baffles to the vertical migration of fluid.

Although geoscientists surmise that layering is the fabric controlling fluid migration, some zones contain coalescing sands, which are sand units deposited one on top of another to produce a sand body that is effectively continuous. When present, coalescing sands can aid vertical fluid flow.

Both fabrics—laterally extensive impermeable layers and locally coalescing sand bodies—affect original fluid migration and the behavior of the natural water drive, secondary waterflood and tertiary recovery operations. Production

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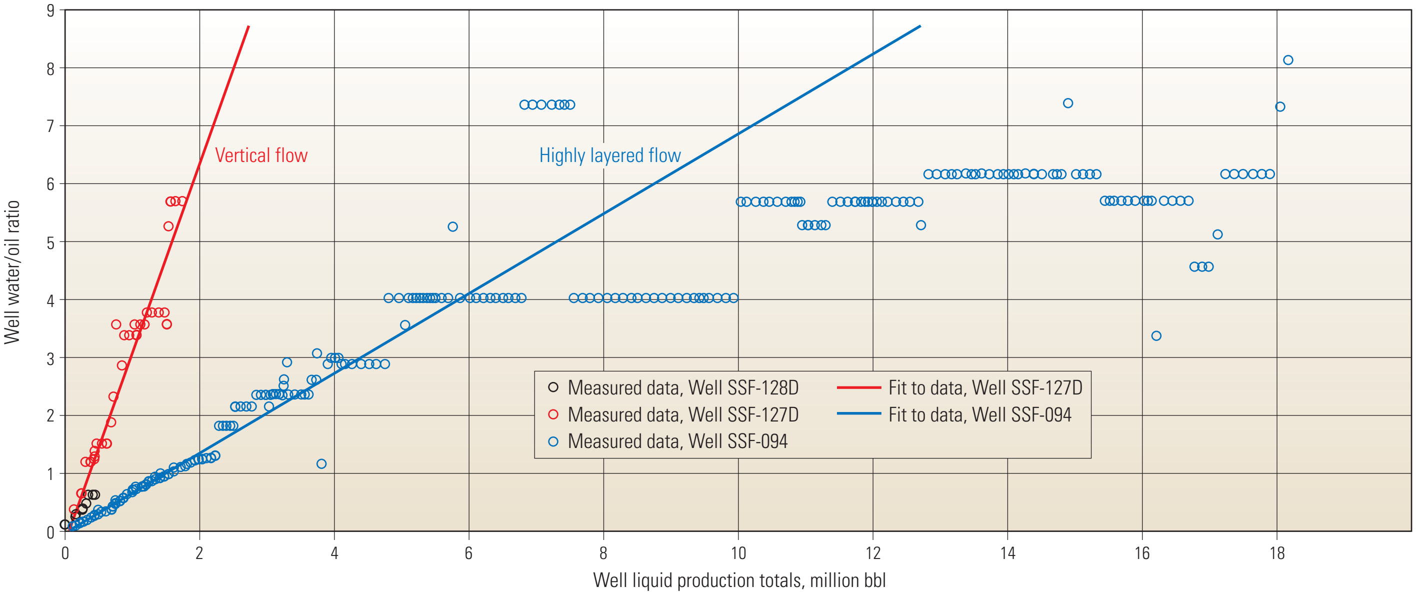
8. White HJ, Skopec RA, Ramirez FA, Rodas JA and Bonilla G: "Reservoir Characterization of the Hollin and Napo Formations, Western Oriente Basin, Ecuador," in Tankard AJ, Suárez Soruco R and Welsink HJ (eds): *Petroleum Basins of South America*. Tulsa: American Association of Petroleum Geologists, Memoir 62 (1995): 573–596.
9. Corbett C, Lafournere J-P, Bolanos J, Bolanos MJ, Frorup M and Marin G: "The Impact of Layering on Production Predictions from Observed Production Signatures, Shushufindi Project, Ecuador," paper SPE 171387, presented at the SPE Western Venezuela Petroleum Section Second South American Oil and Gas Congress, Porlamar, Venezuela, October 22–25, 2013.
10. Greb SF, DiMichele WA and Gastaldo RA: "Evolution and Importance of Wetlands in Earth History," in Greb SF and DiMichele WA (eds): *Wetlands Through Time*. Boulder, Colorado, USA: The Geological Society of America Special Paper 399 (2006): 1–40.
11. Lafournere et al, reference 6.

    The presence of amber indicates that a low-energy environment existed at the time of its deposition. Coniferous trees grew in the wetlands and dropped resin, which was not washed away and remained in place long enough to be preserved as amber.



^ Production signatures. A typical water/oil ratio (WOR) is charted versus cumulative liquid (oil and water) production for wells drilled through a highly layered reservoir (blue) and through a reservoir with more vertical flow (red). The circles are WORs from wells in the Shushufindi field. The lines are best linear fits to the early production. In comparison to that in wells with a dominantly vertical flow component, the rise in WOR from a highly layered reservoir is more gradual.

profiles from many Shushufindi wells indicate a steady increase in water production caused by lateral aquifer encroachment; these characteristics confirm the presence of a dominant layered system (above).[12]

The CSSFD geoscientists and engineers demonstrated this interpretation to be incomplete. After establishing the geologic framework, the team used the ECLIPSE reservoir simulator to incorporate more knowledge of the geology to model the water cut. Numerical reservoir simulators use various parameters to account for unusual reservoir behavior. To model layered geologic strata in which fluid migration is primarily horizontal, reservoir simulators have a parameter called the vertical transmissibility multiplier (MULTZ) that represents vertical communication between geologic layers; MULTZ varies from zero to one, and when it is set to zero, a permeability barrier blocks vertical flow between layers. Setting MULTZ to zero for the top horizon of each layer creates a permeability barrier and results in a gradual rise in the water cut from a well, somewhat similar to what is observed. However, the modeled water cut exhibits a series of pulses as water from individual layers breaks through at the well. The pulses were not observed in the Shushufindi field data.

The CSSFD team then used a Petrel E&P software platform workflow to modify the vertical transmissibility multiplier.[13] The asset team modeled the horizons between layers as baffles, or broken and leaking barriers, representing amounts of sand coalescence. For 80% of the grid cells making up a layer, flow was horizontal only; the top grid-cell faces were "no flow," or zero permeability, barriers. For the rest of the grid cells, vertical flow occurred in accordance with the permeability and fluid transmissibility properties across layer boundaries.[14] The result of this model more closely matched the water cut history. The modeled water production increased gradually and did not exhibit the pulsing caused by layer-by-layer water breakthrough.

Understanding the reservoir architecture of the Shushufindi field is important for planning infill drilling and completions programs. The CSSFD team plans to increase the well density from nominally 125-acre [0.506-km^2] spacing to approximately 60-acre [0.243-km^2] spacing; these spacings correspond to well-to-well distances of about 2,630 ft [802 m] and 1,820 ft [555 m], respectively.

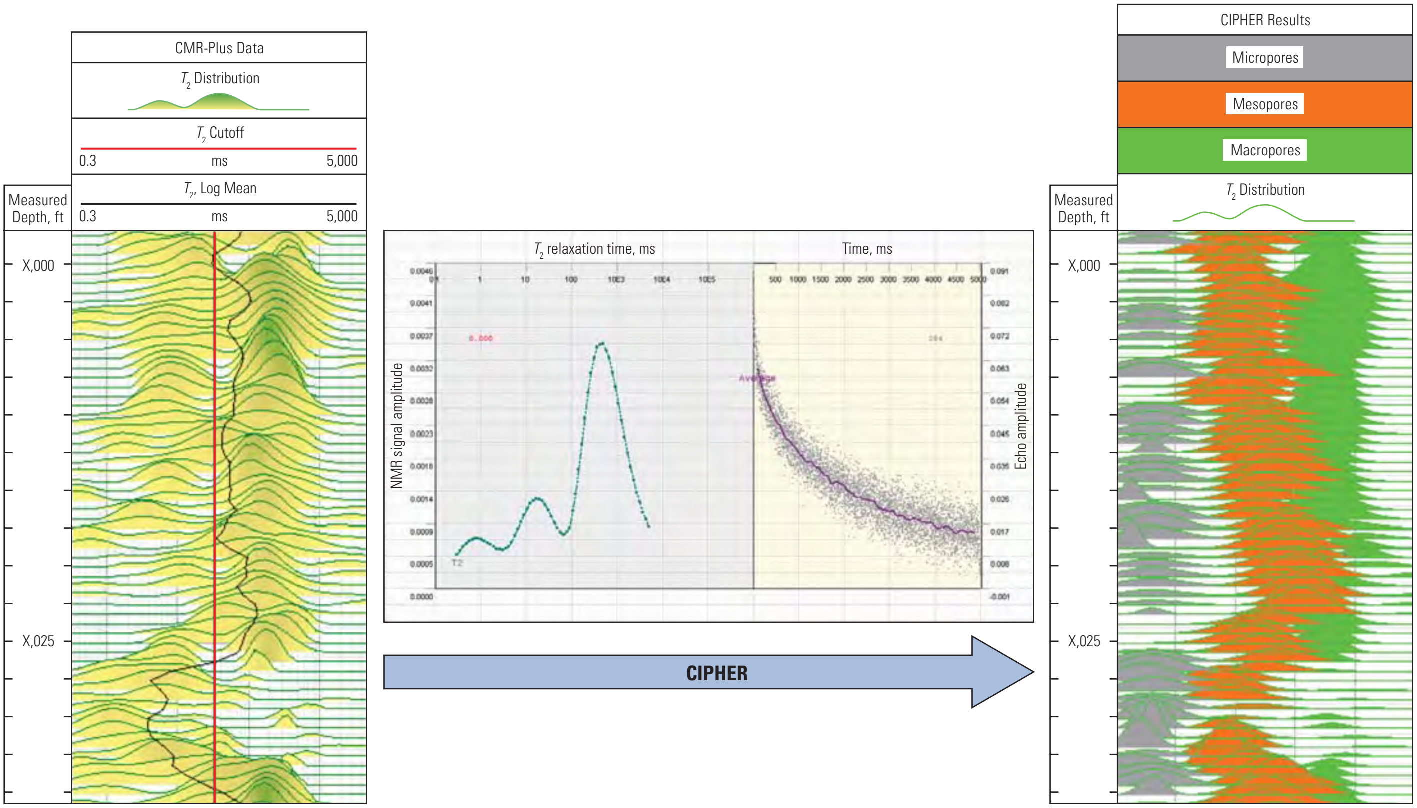
Characterization of the porous media—The CSSFD team wanted to perform reservoir characterization by establishing sequential objectives. The immediate objective for the contract was to rejuvenate recovery from the primary reservoir zones. Therefore, the AWPs for 2012 and 2013 focused on the reservoirs in the lower Napo T and U submembers.

After recovery from the primary reservoirs is rejuvenated, analysis will focus increasingly on providing results for the field development plan, which includes planning for secondary and tertiary recovery phases, a waterflooding pilot and, possibly, an enhanced oil recovery (EOR) pilot. In addition, the reservoir characterization effort will produce a quantitative evaluation of OOIP in the highly laminated secondary reservoirs of the upper Napo T and U submembers.[15]

To characterize porous media, the CSSFD team made extensive use of routine and advanced core studies, high-resolution magnetic resonance data, advanced processing of CMR-Plus combinable magnetic resonance tool data and, to a lesser extent, Dielectric Scanner multifrequency dielectric dispersion service data.[16] The objective was to characterize grain size, pore size, pore throat size and in situ residual oil saturation at reservoir conditions. Results allowed the CSSFD team to define four rock types based on advanced CIPHER processing of pore size, pore throat, productivity index, permeability and hydraulic behavior (next page).[17]

The CSSFD team used the rock typing data to choose reservoir intervals for completions, optimize electric submersible pump (ESP) operating parameters within completion zones and assess particle sizing for drilling and completion fluids to prevent and mitigate formation damage.

					CIPHER			
Core MICP and SEM								Production Tests and Nodal Analysis
Neutron-Density Log and CMR Log					Core NMR		CMR Log	
Rock type	Porosity, %	Permeability, mD	Average grain diameter, µm	Median pore throat diameter, µm	Median pore body diameter, µm	Primary CIPHER pore description	CMR porosity bin number	Average productivity, bbl/ft/d [m^3/m/d]
1	Greater than 17	Greater than 800	Greater than 30	Greater than 20	Greater than 120	Macropores	7 to 8	Greater than 160 up to 400 [Greater than 63.5 up to 209]
2	14 to 17	400 to 800	25	10 to 20	40 to 80	Mesopores to Macropores	6 to 7	68 [35.5]
3	12 to 16	150 to 250	5 to 10	2 to 10	8 to 40	Mesopores	3 to 5	28 [14.6]
4	Less than 12	Less than 10	Less than 5	Less than 2	Less than 8	Micropores	1 to 2	No flow



^ Rock typing. The Consortium Shushufindi team used a variety of data sources (*top*) to define four rock types. Rock-type classifications integrated core analysis results (green) from mercury injection capillary pressure (MICP) porosimetry, scanning electron microscopy (SEM) and nuclear magnetic resonance (NMR); well log results from neutron, density and CMR combinable magnetic resonance logs; and processing results from CIPHER software (blue); and production data and nodal analysis (orange). The rock types are defined by their respective porosity, permeability, grain size, pore throat size, pore diameter, pore families, CMR porosity bin families and productivity ranges based on advanced CIPHER processing (*bottom*). CMR-Plus data (*left*) are processed using CIPHER software (*middle*) to quantify pore dimensions and associated pore volume (*right*). The CIPHER window shows a decay spectrum, or transverse relaxation time (T_2) distribution, on the left and an NMR echo amplitude decay plot on the right; through mathematical inversion, the decay plot on the right is converted to the T_2 distribution on the left. The T_2 distribution directly relates to the capillary properties of pore size distribution. The T_2 cutoff is an empirical fixed T_2 value—typically 33 ms in sandstones—that relates to the capillary properties of fluids in pores; it separates pores into those that are large enough for free fluid flow from those that are too small for free fluid flow; in the latter case, fluid is bound, or trapped, by capillary forces.

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14. Corbett et al, reference 9.

15. Gozalbo E, Bourge JP, Vargas A, Lafournere JP and Corbett C: “Geomodel Validation Through Pressure Transient Analysis (PTA) and Simulation in the Shushufindi Field, Ecuador,” paper GEO-DE-EG-04-E, presented at VIII INGEPET, Lima, Peru, November 3–7, 2014.

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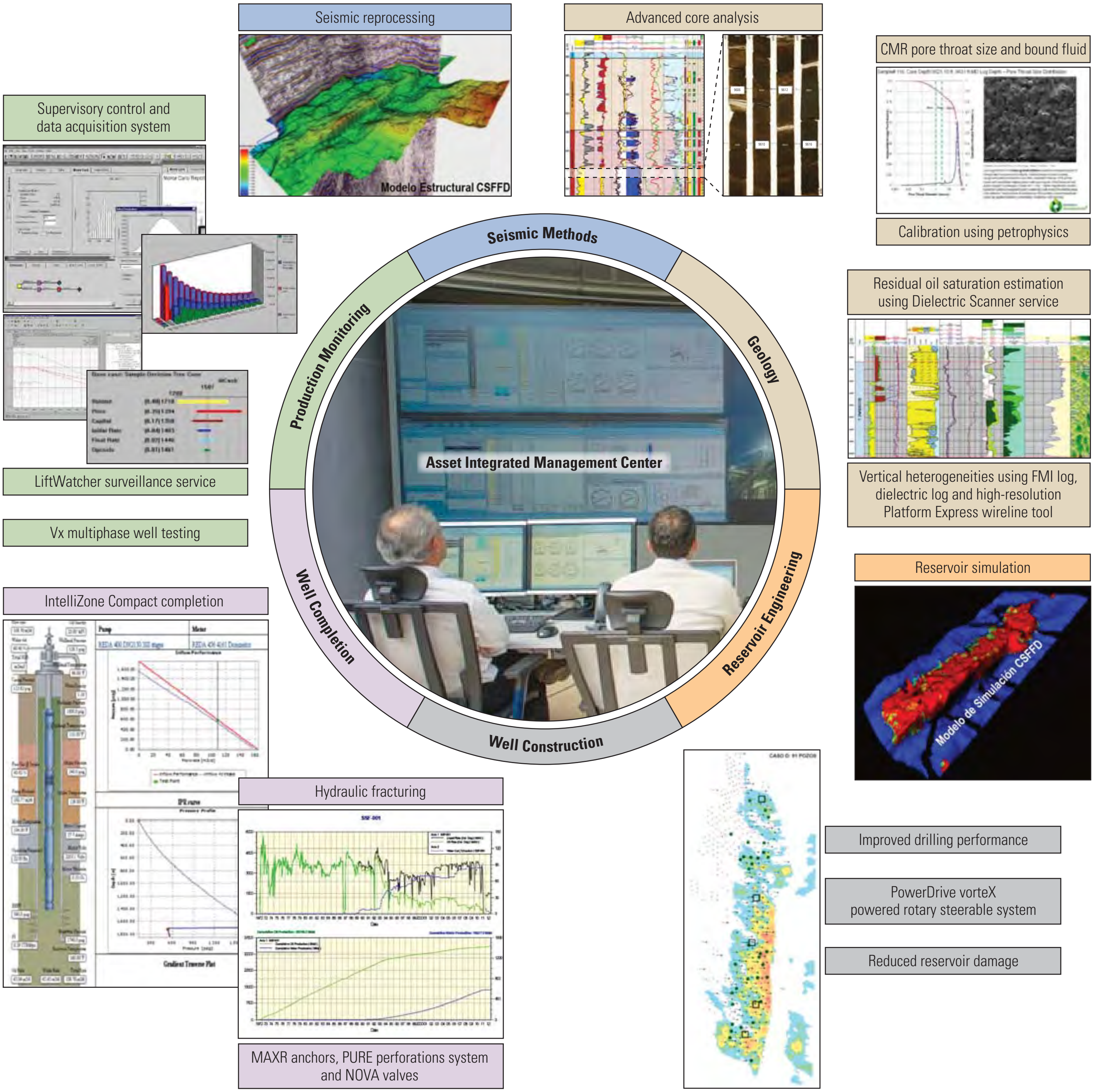
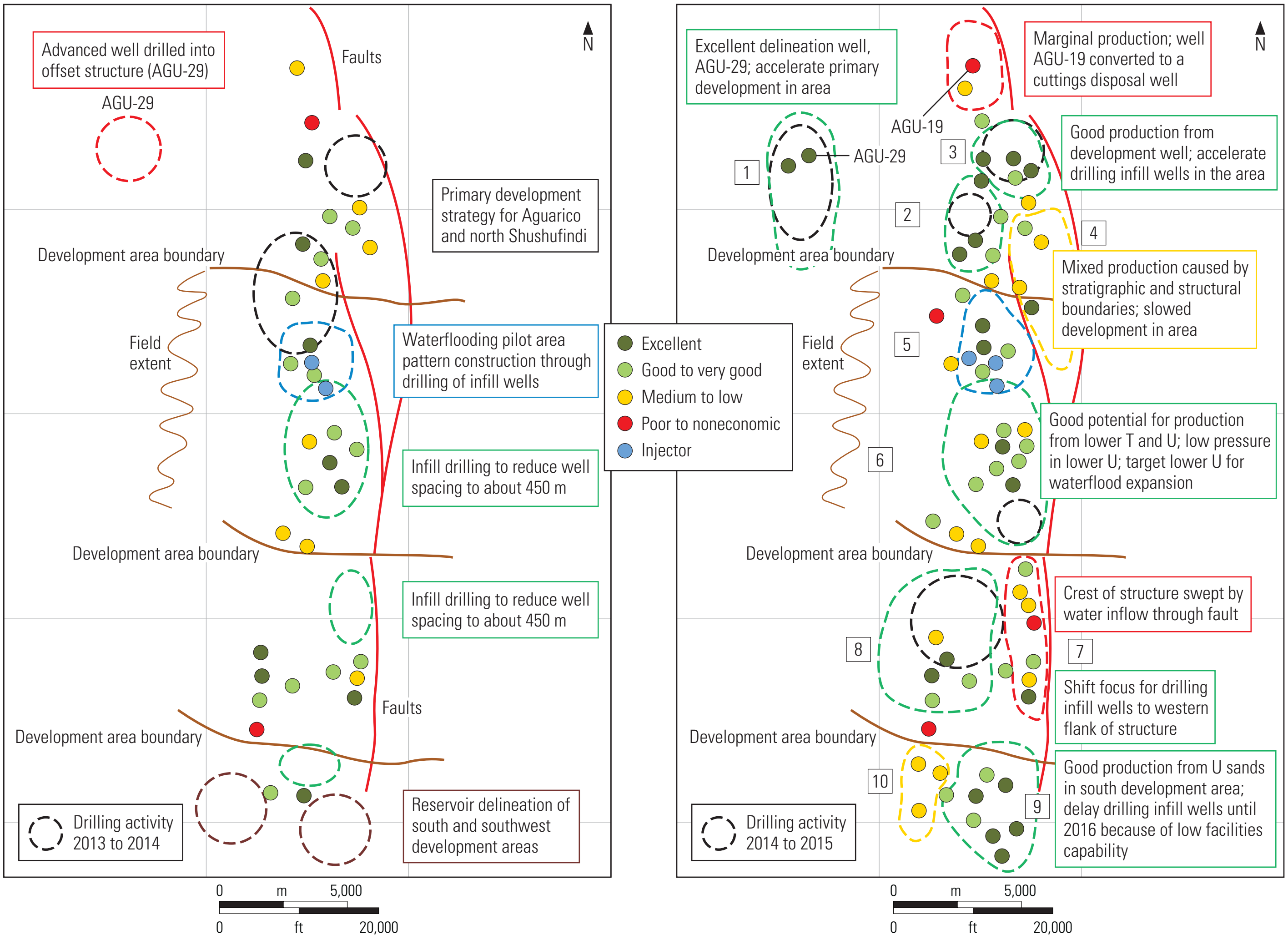
Field redevelopment strategy—The revival of Shushufindi is a result of the integration of disciplines, expertise and more than 50 specialized technologies used in this field (below).

Consortium Shushufindi leads the contract's production management team. Various groups from CSSFD and PAM were assigned specific responsibilities.[18] The subsurface teams included geophysicists, petrophysicists, geologists, geologic modelers and reservoir engineers. Their purview included short-term events such as determining casing points and completion intervals on new wells and a responsibility to longer term deadlines that resulted in annual work plans and defining the field development plan; the latter was based on a detailed reservoir characterization that identified remaining reserves and areas for drilling delineation wells and intervention opportunities.

In 2012, the CSSFD team developed a field redevelopment strategy for each production area



^ Multidisciplinary integration. The asset integrated management (AIM) center coordinates collaboration and flow of information from the various Shushufindi teams: seismic, geology, reservoir engineering, well construction, well completion and production monitoring.



^ Field development strategy. These maps summarize the development plans from the second half (H2) of 2013 through the first half (H1) of 2015. In the H2 2013 through H1 2014 plan (*left*), the Shushufindi-Aguarico field is divided into five development areas; from the north, these areas are the Aguarico and north, central, south and southwest Shushufindi. New wells (colored circles) are classified according to their production. The dashed ovals indicate areas of drilling activity in the field; their colors indicate the activity described in the corresponding colored rectangles. For the H2 2014 through H1 2015 plan (*right*), the field was subdivided into 10 areas of development and drilling activity (dashed outlined areas and numbers). The outlines are colored according to risk and production potential; green indicates low risk, good production and accelerated development; yellow indicates medium risk, moderate production and slowed development; red indicates high risk, poor production and stopped development; blue indicates waterflood expansion; and black indicates drilling activity. New wells are colored and rated as they are on the left. The CSSFD field development program is dynamic and can change over time to adapt to new data and situations, as these maps illustrate.

of Shushufindi for the first half of 2013 through the first half of 2014 (above). The plan included drilling low-risk development wells on the flanks of the structure to add oil reserves and reducing well spacing to reach bypassed oil that had good pressure support. This strategy relied on characterization of the pressure depleted areas, in which secondary recovery will take place with a waterflooding pilot program. In addition, the plan contained high-risk, step-out delineation wells on the periphery of the main structure. New results and lessons learned during this period allowed the CSSFD team to formulate a drilling and development strategy with specific objectives for each area of the field for the period from the second half of 2014 through the first half of 2015.

Asset Integrated Management Center

The economic success of the field is measured by incremental production above the baseline production, which assumed a no-further-action scenario. The Shushufindi contract also obligates CSSFD to make direct investments in capital expenditures (capex).

The CSSFD JV hired Schlumberger Production Management to design and build a digital oilfield operations center to acquire data, monitor activities and manage the Shushufindi oil field. In December 2012, CSSFD opened its Centro de Manejo Integrado del Activo (Centro MIA), or

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18. Marin G, Paladines A, Suter A, Corbett C, Ponce G and Vela I: "The Shushufindi Adventure," paper SPE 173486, presented at the SPE Western Venezuela Petroleum Section Second South American Oil and Gas Congress, Porlamar, Venezuela, October 22–25, 2013.

^ Asset integrated management (AIM) center. The CSSFD team continuously monitors drilling, workover and production operations to improve efficiency at the field. Whenever there is an outage such as equipment failure, center staff alerts the field to minimize nonproductive time and deferred production. All field activities are monitored from the AIM center in Quito to optimize production and reduce operating costs.

asset integrated management (AIM) center.[19] The CSSFD JV decision processes consist of multidisciplinary integration of drilling, completions, workover, production and surface facilities data and include extensive use of real-time data from the AIM center. Fit-for-purpose software applications on a common platform, state-of-the-art visualization technologies and revisions to the traditional decision-process loop have made data integration possible.

The AIM center operates on three time loops—fast, intermediate and slow. The fast loop encompasses daily real-time surveillance and monitoring of activities related to well status, ESPs, well tests, drilling, completions and workovers.

The intermediate loop covers activities that occur in 1 to 90 days and addresses optimization activities, in which the AIM center plays a key role as enabler for collaboration between all CSSFD teams in the field and Quito, Ecuador, offices. These activities include scheduling daily and weekly ESP operations and maintenance, monitoring and follow-up of special completion operations such as hydraulic fracturing or overbalanced perforating, managing deferred and lost production and administering surface facilities.

The slow loop focuses on reservoir management. The AIM center provides the daily, weekly and monthly data to the subsurface team experts, who integrate them with results from reservoir, facilities and economic models to plan field development, infill drilling and annual workflow operations.

Continuous monitoring at the AIM center is well on its way to becoming a reality (above). Monitoring and surveillance hardware have been installed in the field; these devices include downhole pressure gauges, inflow control valves, compact intelligent completion equipment and distributed pressure and temperature monitoring sensors. The status of every operation in the field is summarized daily and displayed on the video walls in a format that is easy to understand at a glance.

The Shushufindi field relies on artificial lift, and 99% of the wells in the field are equipped with ESPs.[20] To maximize run life of the pumps and minimize deferred production, the AIM center monitors every ESP well with an array of sensors that measure downhole pressure, temperature, ESP functions and wellhead parameters such as pressure, temperature and flow rates. These data are compiled to determine whether the pumps are on or off and how this status compares with a schedule of planned shutdowns and well testing. For both scheduled and unscheduled shutdowns, the center alerts the field and records the shutdown time and lost production until the well comes back online.[21] The ultimate objective is to have no unscheduled downtime or unscheduled lost production (next page, top).

During well construction, the objective of the AIM center team is to minimize nonproductive time and capex. The team continuously monitors critical drilling parameters such as weight on bit, rate of penetration (ROP), torque, drillstring depth and pressure. If drilling parameters deviate from acceptable ranges, AIM experts alert the onsite drilling team. Completion and workover operations follow a similar process.

Enabling an ideal collaborative environment is another key objective for the AIM center. Collaboration rooms with visual aid and communication devices make this possible. For example, during the design and selection of multizone intelligent completions, multidisciplinary teams from the field, Quito offices and Houston technical support staff shared information in real time to facilitate and speed the decision process workflow (next page, bottom).

Well Construction Solutions

Drilling new wells is an activity that consumes the attention of a project team. The CSSFD JV formed a drilling team that evaluated the geomechanical aspects and trajectory of each well. The drilling team modified several drilling practices to reduce risk, drilling costs and formation damage and improve well integrity. For example, to minimize environmental impacts to this sensitive Amazon region, every well is drilled from a multiwell pad.

The team used technologies designed to increase hole quality. The PowerDrive Orbit motorized rotary steerable system (RSS) achieved good hole cleaning, which resulted in reduced circulation and tripping times. The PowerDrive vorteX powered RSS effectively converted mud hydraulic power to additional mechanical power for improved ROP.[22] Bottomhole assembly designs from the i-DRILL engineered drilling system design software contributed to higher ROP, decreased drillstring vibration and increased bit footage in heterogeneous reservoir sections.[23] Drilling fluids were designed to be compatible with the formation and the in situ stress regime, ensuring chemical and mechanical stability in the wellbore. Thanks to the combination of RSSs, suitable bits and the appropriate drilling fluids, the occurrence of stuck pipe was less frequent and less severe than in previous drilling campaigns elsewhere in the field.

Perdidas Total de Producción: 858.57

Numero de pozos cerrados:

Perdida de Producción pozos no programados: 40.07

Perdida de Producción pozos programados:

^ Daily well monitoring status report. For each production area in the Shushufindi-Aguarico oil field—Aguarico, north, central, south and southwest—a panel contains four columns of the well status data, unscheduled downtime, lost production and latest well test flow rate. The circles on the left of each panel are color coded for the well status: normal (green), shutdown for well test (blue), scheduled shutdown (yellow), unscheduled shutdown (red), no signal from monitoring equipment (black) and not monitoring (white). At the bottom of each panel is the total unscheduled lost production for the area. The summary below the panels gives the cumulative production lost for the day, the number of shut-in wells and the production lost from unscheduled shutdowns and scheduled shutdowns.

^ Collaboration rooms. At the AIM center, a multidisciplinary team makes final adjustments on the design of a multizone intelligent completion. Using state-of-the-art visualization and communication capabilities, engineers are able to display reservoir attributes, mechanical design and key performance indicators on the video wall and collaborate with the Houston support center via video conferencing.

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19. Rodriguez JC, Biedma D, Goyes J, Tortolero MA, Vivas P, Navarre P, Gozalbo E, Agostini D and Suter A: "Improving Reservoir Performance Using Integrated Asset Management in Shushufindi Asset," paper SPE 167835, presented at the SPE Intelligent Energy Conference and Exhibition, Utrecht, The Netherlands, April 1–3, 2014.

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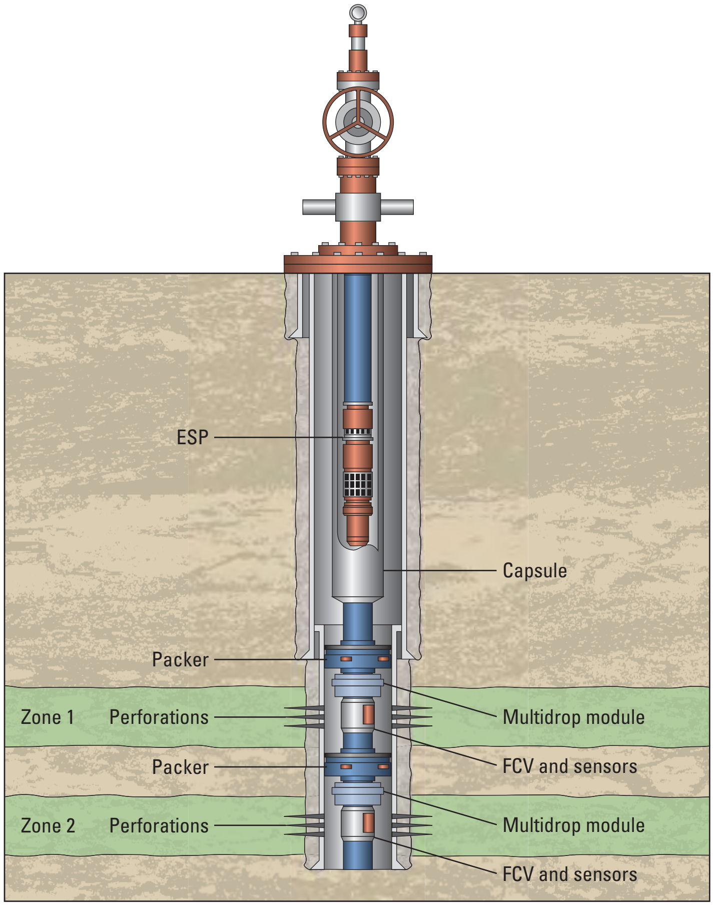
23. For more on the i-DRILL engineered drilling system: Centala P, Challa V, Durairajan B, Meehan R, Paez L, Partin U, Segal S, Wu S, Garrett I, Teggart B and Tetley N: "Bit Design—Top to Bottom," *Oilfield Review* 23, no. 2 (Summer 2011): 4–17.



^ Intelligent completions. In this configuration, the electric submersible pump (ESP) is encapsulated for easy maintenance and replacement. Using multidrop modules at each zone gives engineers remote control of downhole flow control valves (FCVs) and the ability to monitor downhole sensors that record flowing bottomhole pressure and temperature, reservoir pressure and temperature, and tool position. This setup gives the Shushufindi AIM center flexibility to monitor simultaneous production, calculate liquid production with intelligent FCVs and isolate zones for three-phase metering, stimulation work, rigless mechanical cleaning or well tests.

To minimize formation skin, engineers used fluids with relatively low solids content such as the M-I SWACO FLO-PRO reservoir drilling fluid systems to drill the reservoir section.[24] Using a permeability plugging tester, laboratory analysts tested cores for mudcake competency.[25] These results were used to design an efficient sealing fluid with minimal damage for objective sands. These new drilling technologies, in combination, allowed the drilling times for each well in this field to go from an average of 30 days per well in 2011 to 22 days in 2014.

Separate teams have been created for the construction of new well completions and for well interventions. The well completions team investigated intelligent completion technologies and, specifically, compact concentric intelligent completions.

The success of this operation relies on the accuracy of drilling targets defined by the subsurface team. Engineers log the wells with LWD and wireline tools. A rapid turnaround of petrophysical evaluation provides engineers with the necessary data to quickly design the casing program and to choose perforation depths.

The CSSFD JV also applies advanced completion technologies to reduce formation damage by designing completion fluids according to core flow tests, mineralogy and compatibility with the reservoir. For example, the completion team has applied perforating techniques such as the PURE clean perforations system, CLEANPERF noninvasive perforating fluid and P3 PURE post-perforating controlled implosions to clean out perforations.[26] Application of these techniques and tools helped reduce formation damage from a skin factor of 6 to that of 1 (see "Perforating Innovations—Shooting Holes in Performance Models," *page 14*). Hydraulic fracturing has been used successfully in some of the wells completed in the upper Napo U submember to enhance production; this completion technique adds another level of complexity to the operations.

Since 1994, Agencia de Regulación y Control Hidrocarburífero (ARCH)—the hydrocarbon regulatory authority in Ecuador—has prohibited commingling of oil recovered from the reservoirs in the T and U members of the Napo Formation with that from the basal Tena Formation member. Most of the wells in Shushufindi have been completed in both the T and U sands, and to abide by ARCH regulations, the sands are produced sequentially.

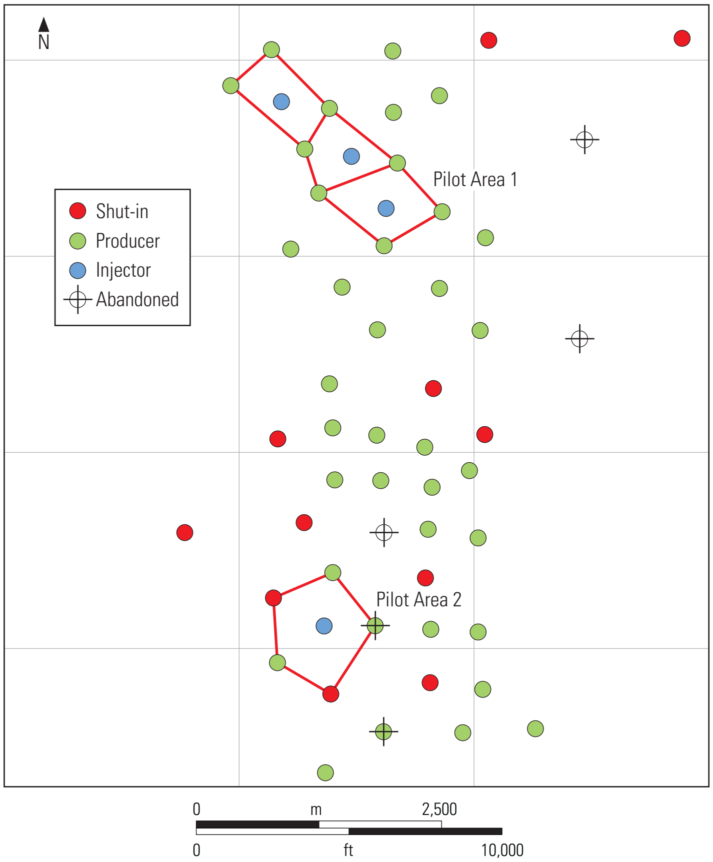
This practice is not conducive to optimizing incremental production because it defers oil production; therefore CSSFD evaluated wells to identify candidates for installing the IntelliZone Compact modular multizonal management system for intelligent completions.[27] This technology allows simultaneous flow and metering of multiple reservoir zones (left). The system includes downhole pressure and temperature sensors and provides surface measurements of oil, gas and water production. These capabilities enable the CSSFD JV to assign production to each sand and thus satisfy requirements imposed by ARCH. In addition, engineers at the AIM center continuously monitor the intelligent completion system to identify the behavior of producing intervals and to make adjustments accordingly.

In December 2013, after a year of study, engineers began installing the IntelliZone Compact system in the SSF-136D well according to the program objectives prescribed by CSSFD. The following project objectives were established:

- Produce T and U sands simultaneously
- Perform pressure buildup tests in one sand while flowing from the other sand
- Provide accessibility for independent stimulations
- Configure the well for faster ESP replacements
- Perform rigless pressure buildup analysis surveys
- Continuously monitor real-time flowing bottomhole pressures and temperatures at CSSFD offices and the AIM center
- Allow downhole chemical injection at the sandface
- Isolate sands during workovers to minimize formation damage
- Reduce the footprint of well operations.

Following installation, engineers tested the system's features. They performed individual production tests in the T and U sands using the IntelliZone Compact downhole chokes in the two-thirds open and full open positions while monitoring flowing pressures and temperatures with the IntelliZone Compact sensors and redundant gauges. Technicians monitored surface flow rates using Vx multiphase well testing technology and later performed pressure buildups in the lower T and U zones.[28] Oil production from the sands was 700 and 350 bbl/d [110 and 56 m^3/d], respectively.

The workover team evaluated wells across the field to identify wells with high water cut and low oil production. Engineers then devised a suitable solution set and ranked the workover candidates. Schedulers assigned wells to workover rigs and coordinated operations with a new well drilling schedule that avoided having rigs on the same pad simultaneously.



^ Waterflood pilot area wells. Two waterflood pilot areas have been selected in the central production area of the Shushufindi field. Pilot Area 1 contains three adjoining inverted five-spot patterns. To its south, Pilot Area 2 is a single pattern, which is on hold because the CSSFD JV is considering it for an EOR pilot.

Pilot Waterflood

As stated in the requirements of the contract, the CSSFD JV must conduct a waterflood pilot project. Accordingly, the consortium planned and is on schedule to start water injection during the fourth quarter of 2014. Two areas of the central producing region of Shushufindi field were selected for conducting waterflood pilots. Reservoir zones in the lower Napo U submember, in which oil production rates and reservoir pressures have declined to subeconomic levels, are the target horizons.

At the start of the CSSFD contract, the existing nominal distance between injection and production wells was approximately 600 to 800 m [1,970 to 2,620 ft], resulting in pattern areas of about 125 acres; the size of the area depended on the pattern configuration. Because the team deemed this pattern area too large, it reviewed smaller pattern areas with closer well spacing in an effort to select injection sites that represent the typical lower U reservoir in the central area. The JV team decided that pattern injection—instead of peripheral, or flank, injection from down structure—was more suitable because pattern injection has better injection efficiency and flexibility and faster response time, which allow it to be modified easily. The team also decided to retain the 125-acre pattern area for the pilots.

In May 2012, CSSFD engineers selected two locations in central Shushufindi to conduct waterflood pilots; Pilot Area 1 (PA1) contains three contiguous inverted five-spot patterns and, to its south, Pilot Area 2 (PA2) is a single 125-acre pattern (above).[29] The recovery factors for PA1 and PA2 are about 20% and 27% OOIP, respectively. The CSSFD engineers evaluated the use of 30-acre [0.121-km^2] and 60-acre pattern areas and decided to preserve the current 600- to 800-m pattern spacing. To ensure that PA1 and PA2 conformed to this spacing, the team had to drill six wells in PA1 and two wells in PA2. The wells will drain the reservoir in the lower T submember under primary conditions

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24. Skin is a term used in reservoir engineering theory to describe the restriction to fluid flow in a geologic formation or well. Positive skin values quantify flow restrictions, whereas negative skin values quantify flow enhancements.
25. A permeability plugging tester is a device used to evaluate filtrate development over time as well as assess mudcake thickness and appearance. Results from this test allow engineers to evaluate the potential for fluid invasion into formations.
26. For more on PURE technology: Bruyere F, Clark D, Stirton G, Kusumadjaja A, Manalu D, Sobirin M, Martin A, Robertson DI and Stenhouse A: "New Practices to Enhance Perforating Results," *Oilfield Review* 18, no. 3 (Autumn 2006): 18–35.

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27. Rodriguez JC, Dutan J, Serrano G, Sandoval LM, Arevalo JC and Suter A: "Compact Intelligent Completion: A Game Change for Shushufindi Field," paper SPE 169483, presented at the SPE Latin American and Caribbean Petroleum Engineering Conference, Maracaibo, Venezuela, May 21–23, 2014.

    For more on intelligent completions: Dyer S, El-Khazindar Y, Reyes A, Huber M, Raw I and Reed D: "Intelligent Completions—A Hands-Off Management Style," *Oilfield Review* 19, no. 4 (Winter 2007/2008): 4–17.

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28. For more on Vx multiphase well testing technology: Atkinson I, Theuveny B, Berard M, Conort G, Groves J, Lowe T, McDiarmid A, Mehdizadeh P, Perciot P, Pinguet B, Smith G and Williamson KJ: "A New Horizon in Multiphase Flow Measurement," *Oilfield Review* 16, no. 4 (Winter 2004/2005): 52–63.
29. A five spot is a quadrilateral injection pattern that comprises four injection wells at the corners and a production well in the center. An inverted five spot has production wells at the corners and the injection well in the center.

^ State-of-the-art water treatment plant for the waterflooding pilot.

and serve as injectors into the lower U submember, avoiding casing and cementing problems that may have occurred if older wells had been used.

The SSFD-151D well was drilled and cored in June 2012; the core was delivered to the Schlumberger Reservoir Sampling and Analysis laboratory in Houston in August 2012. Core testing indicated that rock quality, initial water saturation, wettability and heterogeneity varied by reservoir zone. The CSSFD team concluded that conventional injection string designs would not be satisfactory nor would they meet the requirements to maximize injectivity by zone, increase vertical efficiency and control injection rates by zone; achieving these objectives would require pulling the injection string. Injection in PA2 has been halted while the CSSFD JV considers it for an EOR pilot.

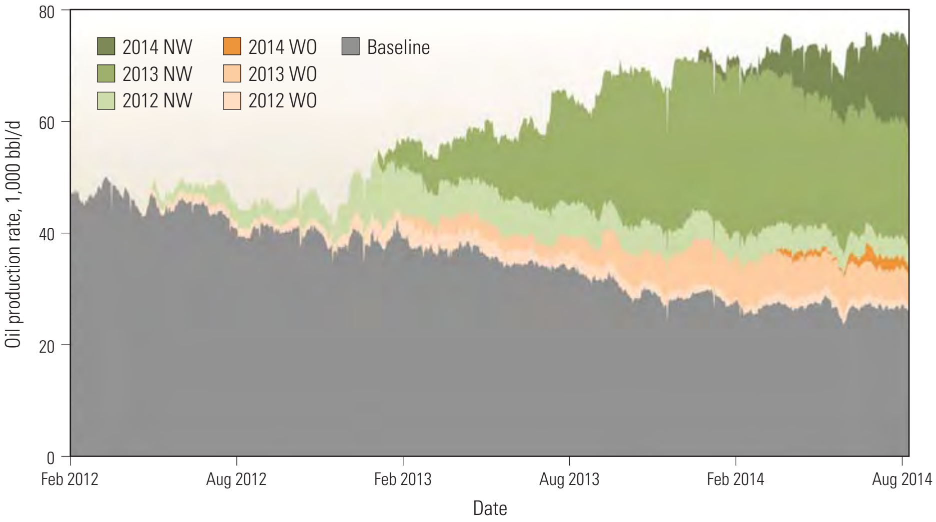
Early in the contract, CSSFD recognized that the existing facilities were inadequate to handle the water injection volume and quality requirements. Because of the long lead times required for the facility design, material fabrication, delivery and installation, the facilities group needed to have a general plan for water quality specifications and injection volumes. The CSSFD JV has constructed a water treatment plant that treats 40,000 bbl/d of water that is in compliance with water quality specifications (left). The anticipated start of injection is during the fourth quarter of 2014.

Revived Giant

In the nearly three years since the contract began, the partnership between Consortium Shushufindi and the field's operator, Petroamazonas EP, has successfully reversed the field's more than 20-year decline. Since February 2012, oil production has increased by more than 60%, from 45,000 bbl/d to 75,000 bbl/d (below left).

The foundation of this rapid turnaround is the dedicated integrated team of technical and operational experts working with Petromazonas EP professionals in the field and in the Quito offices. In addition to providing new reservoir insight, the team focused on introducing select technologies to the field that improved operational efficiencies and addressed the subsurface uncertainties. As a result, production has increased throughout the field. The CSSFD JV established an AIM center to coordinate continuous real-time monitoring across all operations in the Shushufindi field. Workover, drilling and completion operations are remotely monitored to increase safety, anticipate problems, maximize efficiency and minimize nonproductive time.

The steps that the consortium has taken and the technologies that it has used to revive Shushufindi and regain control of its production have helped the consortium attain its contractual objective of optimizing incremental production. In the years ahead, the CSSFD JV will continue its drilling and IntelliZone Compact completion strategy, expand secondary recovery waterflooding operations to the entire field and evaluate the potential for EOR. The giant Shushufindi, rescued from its continued decline, has been given new life and a brighter future. —RCNH



^ Proportioning oil production. Total oil production has risen since the contract began in January 2012. Baseline oil production is in gray. Incremental oil production has been broken out by the year and divided between workover (WO) activity and drilling and completing active new wells (NW). The largest and increasing contribution to incremental oil production came from drilling and completing new wells and from decreasing well spacing. The secondary contribution from workovers has been steady at about 10,000 bbl/d [1,590 m^3/d] since January 2013.